67th Annual Gaseous Electronics Conference
Raleigh, North Carolina
http://www.aps.org/meetings/meeting.cfm?name=GEC14
Monday, November 3, 2014 8:00AM - 3:00PM —
Session AM1 Advanced RF Systems for Plasma Control  State EF - David Coumou, MKS Instruments

8:00AM AM1.00001 Introduction DAVID COUMOU, —

8:15AM AM1.00002 Time-Modulated Inductively Coupled Plasmas for Advanced Dry Etching Processes, WAHEB BISHARA SAMER BANNA, Applied Materials Inc. —

9:00AM AM1.00003 The Electrical Asymmetry Effect in capacitive RF plasmas: Past, Present, and Future, J. SCHULZE, A. DERZSI, I. KOROLOV, S. BRANDT, Z. DONKO, West Virginia University; Hungarian Academy of Sciences —

9:45AM AM1.00004 Break —

10:15AM AM1.00005 Control of Ion Energy Distributions Through the Phase Difference Between Multiple Frequencies in Capacitively, YITING ZHANG MARK J. KUSHNER, University of Michigan —

11:00AM AM1.00006 EEDf, IEDf and some of the physics of the Non-ambipolar Electron Plasma (NEP), LEE CHEN ZHIYING CHEN, Tokyo Electron America, Inc. —

11:45AM AM1.00007 Lunch —

1:00PM AM1.00008 Centralized and Coherent Feedforward Impedance Tuning Control and Feedback Power Regulation for the Enhancement of RF Plasma Processing Systems, DAVID COUMOU, ENI Products, MKS Instruments, Inc —

1:45PM AM1.00009 Inductively Coupled Plasma Sources for Dry Etching and Annealing Processes, TOMOHIRO OKUMURA, Panasonic —

2:30PM AM1.00010 Panel Discussion —

Monday, November 3, 2014 8:00AM - 5:00PM —
Session AM2 Workshop: Plasma Verification and Validation  State C - John Verboncoeur, Michigan State University

8:00AM AM2.00001 Validation and Verification with Applications to a Kinetic Global Model\(^1\), J.P. VERBONCOEUR, Michigan State University — As scientific software matures, verification, validation, benchmarking, and error estimation are becoming increasingly important to ensure predictable operation. Having well-described and consistent data is critical for consistent results. This presentation briefly addresses the motivation for V&V, the history and goals of the workshop series. A roadmap of the current workshop is presented. Finally, examples of V&V are applied to a novel kinetic global model for a series of low temperature plasma problems ranging from verification of specific rate equations to benchmarks and validation with other codes and experimental data for Penning breakdown and hydrocarbon plasmas. The results are included in the code release to ensure repeatability following code modifications.

In collaboration with G. Parsey, J. Kempf, and A. Christlieb, Michigan State University.

\(^1\)This work is supported in part by a U.S. Air Force Office of Scientific Research Basic Research Initiative and a Michigan State University Strategic Partnership grant.

8:50AM AM2.00002 Verification and Validation of Kinetic Codes, ANDREW CHRISTLIEB, Michigan State University — We review the last three workshops held on Validation and Verification of Kinetic Codes. The goal of the workshops was to highlight the need to develop benchmark test problems beyond traditional test problems such as Landau damping and the two-stream instability. These test problems provide a limited understanding how a code might perform and mask key issues in more complicated situations. Developing these test problems highlights the strengths and weaknesses of both mesh- and particle-based codes. One outcome is that designing test problems that clearly deliver a path forward for developing improved methods is complicated by the need to create a completely self-consistent model. For example, two test cases proposed by the authors as simple test cases turn out to be ill defined. The first case is the modeling of sheath formation in a 1D 1V collisionless plasma. We found that losses to the wall lead to discontinuous distribution functions, a challenge for high order mesh-based solvers. The semi-infinite case was problematic because the far field boundary condition poses difficulty in computing on a finite domain. Our second case was flow of a collisionless electron beam in a pipe. Here, numerical diffusion is a key problem we are testing; however, two-stream instability at the beam edges introduces other issues in terms of finding convergent solutions. For mesh-based codes, before particle trapping takes place, mesh-based methods find themselves outside of the asymptotic regime. Another conclusion we draw from this exercise is that including collisional models in benchmark test problems for mesh-based plasma simulation tools is an important step in providing robust test problems for mesh-based kinetic solvers.

In collaboration with Yaman Guclu, David Seal, and John Verboncoeur, Michigan State University.

9:40AM AM2.00003 Break —
10:00AM AM2.00004 Benchmark solutions for simulations of capacitively coupled discharges
MILES TURNER, Dublin City University — Benchmarks are an important element of Verification and Validation strategies. Such strategies define a process for increasing confidence in the fidelity of computer simulations, with the aim of making confident predictions of physical behaviour under conditions of practical interest. Such confidence can be increased by developing benchmark solutions for representative conditions. A benchmark solution is a high quality solution that is accepted to be correct. In this paper, we describe an attempt to develop such solutions for capacitive discharges, and we show that a number of independently developed particle-in-cell simulations can reproduce the benchmark solutions. These solutions are useful not only for particle-in-cell simulations, but also for other kinds of plasma simulations. We will show comparisons of fluid model solutions with the benchmarks.

10:50AM AM2.00005 LXCat: A web-based, community-wide project on data for modeling low temperature plasmas
L.C. PITCHFORD, LAPLACE (Laboratoire Plasma et Conversion d’Energie); CNRS and Universite de Toulouse — LXCat is an open-access website (www.lxcat.net) for exchanging data related to ion and electron transport and scattering cross sections in cold, neutral gases. At present 30 people from 12 countries have contributed to the LXCat project. This presentation will focus on the status of the data available for electrons on LXCat. These data are primarily in the form of “complete” sets of cross sections, compiled or calculated by different contributors, covering a range of energies from thermal up to about 1 keV. The cross section data can be used directly in Monte Carlo simulations and can also be used as input to Boltzmann equation solvers. Solution of the homogeneous, steady-state Boltzmann equation yields electron energy distribution functions (edf) as a function of reduced electric field strength, E/N, integrals over which yield electron transport and rate coefficients. The transport and rate coefficient data are required input for fluid models of low temperature plasmas. Evaluation of the cross section data sets available on LXCat is a key issue. To this end, the LXCat team has been making systematic intercomparisons of cross section data and comparisons of calculated and measured transport and rate coefficients. Our evaluations have been reported previously for noble gases and for common atmospheric gases. The LXCat team is now evaluating data for more complex molecules.

11:40AM AM2.00006 Lunch —

1:10PM AM2.00007 Richardson Extrapolation Based Error Estimation for Stochastic Kinetic Plasma Simulations1, KEITH CARTWRIGHT, Sandia National Laboratories — To have a high degree of confidence in simulations one needs code verification, validation, solution verification and uncertainty qualification. This talk will focus on numerical error estimation for stochastic kinetic plasma simulations using the Particle-In-Cell (PIC) method and how it impacts the code verification and validation. A technique is developed to determine the full converged solution with error bounds from the stochastic output of a Particle-In-Cell code with multiple convergence parameters (e.g. Δt, Δx, and macro particle weight). The core of this method is a multi parameter regression based on a second-order error convergence model with arbitrary convergence rates. Stochastic uncertainties in the data set are propagated through the model using standard bootstrapping on a redundant data sets, while a suite of nine regression models introduces uncertainties in the fitting process. These techniques are demonstrated on Fokker-Poisson Child-Langmuir diode, relaxation of an electron distribution to a Maxwellian due to collisions and undriven sheaths and pre-sheaths.

1Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. DOE’s National Nuclear Security Administration under contract DE-AC04-94AL85000

2:00PM AM2.00008 The Role of V&V in Total Prediction Uncertainty, CHRISTOPHER ROY, Aerospace and Ocean Engineering Department, Virginia Tech — Computational Fluid Dynamics (CFD) simulations are frequently used for decision making in scientific and engineering systems. However, the accuracy and reliability of CFD simulations is often poorly understood. There are three sources of uncertainty in CFD predictions: uncertainty in model inputs, uncertainty due to numerical errors, and uncertainty due to modeling errors. When model input uncertainties are stochastic, they are appropriately described by precise probability distributions, and their effects on output quantities are often determined by standard techniques. In general, not all inputs have precisely specified probability distributions. In such cases, different techniques, such as segregated uncertainty propagation, are needed to propagate mixed aleatory and epistemic uncertainty. Verification and Validation (V&V) address the processes used to estimate uncertainties due to numerical errors and modeling errors, respectively. During Verification, one estimates the numerical errors in a simulation. This estimation process leads one to treat these as uncertainties; however, they are not random (aleatory) uncertainties, but are instead lack of knowledge (epistemic) uncertainties. During Validation, one estimates the errors due to model form. This process usually involves comparison of non-deterministic outcomes from simulation and experiment the estimation process leads us to treat the modeling errors as uncertainties. Finally, estimating the total prediction uncertainty requires that all three sources be accounted for: input uncertainty (via uncertainty propagation), numerical uncertainty (via Verification), and model form uncertainty (via Validation).

2:50PM AM2.00009 Break —

3:10PM AM2.00010 What is Necessary To Succeed in V&V? Experience From The DOE ASC V&V Program, WILLIAM RIDER, Sandia National Laboratories — Verification and validation is a route toward examining the credibility and confidence in computations. These are inter-dependent and complementary activities that are usually combined with uncertainty quantification. Validation is usually the emphasis for most scientific endeavors being predicted upon experimental science and physical theory. Verification is similarly based upon the mathematical basis of the numerical methods. Upon this point PIC methods in particular are disadvantaged as the mathematical basis is quite weak. Nonetheless useful empirical results can be examined. A great deal of experience has been gained in the application of a systematic V&V process including uncertainty quantification. The lessons from these efforts can be applied profitably to PIC methods.

4:00PM AM2.00011 Panel Discussion: Future of V&V in Low Temperature Plasma Community —

Tuesday, November 4, 2014 8:00AM - 9:30AM –
Session CT1 Plasma Boundaries, Sheaths, and Basic Plasma Physics I Ballroom EF - JP Sheehan, Plasmadynamics & Electric Propulsion Laboratory, University of Michigan
electrical field. Both in the experiment and simulation we found non-monotonic change in sheath structure near the plate depending on $U$ for the experimental conditions. We solved self-consistently the Boltzmann equations for the electron and ion distribution functions and Poisson equation for structure near the plate with enhanced SEE is the subject of our experimental and theoretical study. The experiment was carried out in multidipole plasma is separated by the sheath potential drop to provide the condition of zero - current on the surface with floating potential. The rearrangement of the sheath Hall thruster is restricted by plasma-wall interaction if the wall has an enhanced secondary electron emission (SEE) yield. It is known that the plasma and wall are made as both the size and the bias placed on the electrode are varied. Size dependent transitions in the voltage dependence of the plasma parameters are measured on bulk plasma parameters such as the collected current density, plasma potential, electron density, electron temperature and optical emission. This was accomplished using a segmented disk electrode in which individual segments were individually biased to change the effective surface area of the anode.

Measurements on bulk plasma parameters such as the collected current density, plasma potential, electron density, electron temperature and optical emission are identified in both argon and helium discharges and are compared to the interface transitions predicted by global current balance [1].

1Work supported by the University of Iowa, and the USDOE Fusion Energy Sciences Postdoctoral Fellowship Program.

8:30AM CT1.00002 Ion Energy and Angular Distribution Functions at the Material Wall of a Magnetized Plasma Sheath, DAVIDE CURRELI, RINAT KHAZIEV, Nuclear, Plasma, and Radiological Engineering Department, University of Illinois at Urbana Champaign, USA — We present a calculation of the ion energy distribution and the ion angular distribution at the material wall of a magnetized plasma sheath. The calculation has been done using two different techniques: a Monte-Carlo method, propagating the trajectories of a Maxwellian population of ions across the E×B field of the magnetized sheath, and a Particle-in-Cell, giving a self-consistent treatment of the plasma behavior from the quasi-neutral region to the material boundary. Data are presented for magnetic fields inclined at angles from 0.0 to 88 degrees with respect to the normal to the surface, and field magnitudes up to 1.0 Tesla. The plasma sheath accelerates the ions up to energies scaled with the electron temperature. The ion angular distributions exhibit surprising non-linear trends, depending on both the plasma conditions and magnetic field. Ions can hit the wall at angles close to the surface normal with single-lobe IADF’s, or at grazing angles with double-lobe IADF’s. The energy-angle distributions strongly affect the material response, comprising electron secondary emission and material sputtering.

8:45AM CT1.00003 Analytical model of plasma sheaths at intermediate radio frequencies. MARK SOBOLEWSKI, National Institute of Standards and Technology — Analytical models of plasma sheaths provide physical insight and are useful in 2-d and 3-d plasma simulations, where numerical solution of the sheath equations at each boundary point is impractical. Analytical models have long been known for the high-frequency and low-frequency limits, where the ion transit time is either much greater than or much less than the rf period. At intermediate frequencies, however, sheath behavior is more complicated. In addition to the well-known narrowing of ion energy distributions (IEDs) there are other, lesser known effects, including changes in the ion current (which becomes strongly time-dependent within the sheath) and in IED peak intensities, average ion energy, shear impedance, and shear power. Here, we describe a new approach for modeling intermediate-frequency, collisionless sheaths. It captures the essential elements of ion dynamics yet still provides analytical expressions for most sheath properties. Predictions of the analytical model are compared to previous analytical models, numerical models, and, where possible, experimental data. The model yields new insights into ion dynamics and may serve to increase the accuracy of plasma simulations, particularly their predictions for average ion energy and power.

9:00AM CT1.00004 Size dependent transitions induced by an electron collecting electrode near the plasma potential. EDWARD BARNAT, GEORGE LAITY, MATT HOPKINS, Sandia National Laboratories, SCOTT BAALRUD, Department of Physics and Astronomy, University of Iowa — As the size of a positively biased electrode increases, the nature of the surface formed between the electrode and the host plasma undergoes a transition from an electron-rich structure (electron sheath) to an intermediate structure containing both ion and electron rich regions (double layer) and ultimately forms an electron-depleted structure (ion sheath). In this study, measurements are performed to further test how the key scaling relationship relating the area of the electrode to that of the area of the vessel containing the plasma discharge impacts this transition. This was accomplished using a segmented disk electrode in which individual segments were individually biased to change the effective surface area of the anode. Measurements on bulk plasma parameters such as the collected current density, plasma potential, electron density, electron temperature and optical emission are made as both the size and the bias placed on the electrode are varied. Size dependent transitions in the voltage dependence of the plasma parameters are identified in both argon and helium discharges and are compared to the interface transitions predicted by global current balance [1].


9:15AM CT1.00005 Sheath structure transition controlled by secondary electron emission at low gas pressure. IRINA SCHWEIGERT, George Washington University Washington, D.C. 20052 USA, SAMUEL J. LANGENDORF, Georgia Institute of Technology Atlanta, GA 30332 USA, MICHAEL KEIDAR, George Washington University Washington, D.C. 20052 USA, MITCHELL L.R. WALKER, Georgia Institute of Technology Atlanta, GA 30332 USA — Previously the experiments [1] demonstrated that the growth of the electron temperature with power in the Hall thruster is restricted by plasma-wall interaction if the wall has an enhanced secondary electron emission (SEE) yield. It is known that the plasma and wall is separated by the sheath potential drop to provide the condition of zero - current on the surface with floating potential. The rearrangement of the sheath structure near the plate with enhanced SEE is the subject of our experimental and theoretical study. The experiment was carried out in multidipole plasma device, where plasma is maintained by the negatively-biased emissive filament. The plate with sapphire surface is placed 50 cm apart from the filament. The plasma parameters were measured for different negative biases $U_0$ and discharge currents $J$ at $P=10^{-4}$ Torr. In our PIC simulations the plasma was calculated for the experimental conditions. We solved self-consistently the Boltzmann equations for the electron and ion distribution functions and Poisson equation for electrical field. Both in the experiment and simulation we found non-monotonic change in sheath structure near the plate depending on $U_0$ and $J$. The kinetic simulations allowed us to describe the sheath rearrangement in terms of the electron energy distribution function.

8:00AM CT2.00001 Using the DC self-bias effect for simultaneous ion-electron beam generation in space thruster applications1, DMYTRO RAFAKSYKI, ANE AANESLAND, Laboratoire de Physique des Plasmas (CNRS, Ecole Polytechnique, Sorbonne Universités, UPMC Univ Paris 06, Univ Paris-Sud), Ecole Polytechnique — In this work we discuss ways to use the self-bias effect for broad ion-electron beam generation and present recent experimental results. In asymmetrical systems the self-bias effect leads to rectification of the applied RF voltage to a DC voltage dropped across the space charge sheath near to the electrode having smaller area. Thus, continuous ion acceleration is possible towards the smaller electrode with periodical electron extraction due to the RF plasma potential oscillations. We propose a new concept of neutralizer-free gridded space thruster called NEPTUNE. In this concept, the RF electrodes in contact with the plasma are replaced by a two-grid system such that “the smaller electrode” is now the external grid. The grids are biased with RF power across a capacitor. This allows to locate RF space charge sheath between the acceleration grids while still keeping the possibility of a DC self-bias generation. Here we present first proof-of-concept of the NEPTUNE thruster prototype and give basic parameters scaling for such thruster. Comparison of the main parameters of the beam generated using RF and a classical “DC with neutralizer” acceleration method shows several advantages of the NEPTUNE concept.

1This work was supported by a Marie Curie International Incoming Fellowships within the 7th European Community Framework (NEPTUNE PIIF-GA-2012-326054).

8:15AM CT2.00002 Experimental Study of RailPAC Plasma Actuator for High-Authority Aerodynamic Flow Control in One Atmosphere, MILES GRAY, YOUNG-JOON CHOI, LAXMINARAYAN RAJA, JAYANT SIROHI, University of Texas at Austin — Dielectric barrier discharge (DBD) actuators, a type of electrohydrodynamic (EHD) plasma actuator, have generated considerable interest in recent years. However, theoretical performance limitations hinder their application for high speed flows1. Magnetohydrodynamic (MHD) plasma actuators combined with the use of this mechanism in an electric thruster will also be discussed. The rail plasma actuator (RailPAC) is an MHD actuator which uses Lorentz force to impart momentum to the surrounding air[2]. RailPAC functions by generating a fast propagating arc column between two rail electrodes that accelerate the arc through $J \times B$ forces in a self-induced B-field. The arc column drags the surrounding air to induce aerodynamic flow motion. Our study of the RailPAC will include a description of the transient arc discharge structure through high-speed imaging and a description of the arc composition and temperature through time-resolved emission spectroscopy. Time-resolved force measurements quantify momentum transfer from the arc to the surrounding air and provides a direct measure of the actuator control authority.

1D. F. Opaits et al., J. Appl. Phys. 104, 043304
2B. Pafford et al., J. Appl. Phys. D. 46, 485208

8:30AM CT2.00003 Enhanced momentum delivery by electric force to an ion flux due to collisions of ions with neutrals1, AMNON FRUCHTMAN, H.I.T.–Holon Institute of Technology — A major figure of merit in propulsion in general and in electric propulsion in particular is the thrust per unit of deposited power, the ratio of thrust over power. We have recently demonstrated experimentally and theoretically [1-4] that for a fixed deposited power in the ions, the momentum delivered by the electric force is larger if the accelerated ions collide with neutrals during the acceleration. The higher thrust for given power is achieved for a collisional plasma at the expense of a lower thrust per unit mass flow rate, reflecting what is true in general, that the lower the flow velocity is, the higher the thrust for a given power. This is usual trade-off between having a large specific impulse and a large thrust. Broadening the range of jet velocities and thrust levels is desirable since there are different propulsion requirements for different space missions. The mechanism of thrust enhancement by ion-neutral collisions has been investigated in the past in the case of electric pressure, what is called ionic wind [5]. We will describe in the talk experimental results for an enhanced thrust due to ion-neutral collisions in a configuration where the thrust is a result of magnetic pressure [1. 3]. The plasma is accelerated by $\mathbf{J} \times \mathbf{B}$ force, in a configuration similar to that of Hall thrusters. Our measurements for three different gases and for various gas flow rates and magnetic field intensities, confirmed that the thrust increase is proportional to the square-root of the number of ion-neutral collisions [3]. Additional measurements of local discharge parameters will be shown to be consistent with the force measurements. Issues that are critical to the design include the optimal gas composition and temperature through time-resolved emission spectroscopy. Time-resolved force measurements quantify momentum transfer from the arc to the surrounding air and provides a direct measure of the actuator control authority.


1Supported by Grant no. 765/11 from the Israel Science Foundation

9:00AM CT2.00004 Optical Diagnostics of Air Flows Induced in Surface Dielectric Barrier Discharge Plasma Actuator, TAKUYA KOBATAKE, MASANORI DEGUCHI, JUNYA SUZUKI, KOJI ERIGUCHI, KOICHI ONO, Kyoto University — A surface dielectric barrier discharge (SDBD) plasma actuator has recently been intensively studied for the flow control over airfoils and turbine blades in the fields of aerospace and aeromechanics. It consists of two electrodes placed on both sides of the dielectric, where one is a top powered electrode exposed to the air, and the other is a bottom grounded electrode encapsulated with an insulator. The high-speed gas flow along the dielectric surfaces is induced by the electrohydrodynamic (EHD) body force. It is known that the thinner the exposed electrode, the greater the momentum transfer to the air is [1], indicating that the thickness of the plasma is important. To analyze plasma profiles and air flows induced in the SDBD plasma actuator, we performed time-resolved and -integrated optical emission and schlieren imaging of the side view of the SDBD plasma actuator in atmospheric air. We applied a high voltage bipolar pulse (4-8 kV, 1–10 kHz) between electrodes. Experimental results indicated that the spatial extent of the plasma is much smaller than that of the induced flows. Experimental results further indicated that in the positive-going phase, a thin and long plasma is generated, where the optical emission is weak and uniform; on the other hand, in the negative-going phase, a thick and short plasma is generated, where a strong optical emission is observed near the top electrode.


9:15AM CT2.00005 Time-Resolved Laser-Induced Fluorescence Measurements of Ion Velocity Distribution in the Plume of a 6 kW Hall Thruster with Unperturbed Discharge Oscillations, CHRISTOPHER DURcot, ALEC GALLMORc, University of Michigan — We present laser-induced fluorescence (LIF) measurements of the time-resolved ion velocity distribution in the plume of a 6 kW laboratory Hall thruster. To our knowledge, these are the first measurements of time-resolved ion velocity distribution on completely unperturbed Hall thruster operating conditions. To date, time-resolved LIF measurements have been made on Hall thrusters with oscillations driven or perturbed to be amenable to averaging techniques that assume a periodic oscillation. Natural Hall thruster breathing and spoke oscillations, however, are not periodic due to chaotic variations in amplitude and frequency. Although the system averages over many periods of nonperiodic oscillation, it recovers the time-resolved signal in part by assuming that a constant transfer function exists relating discharge current and LIF signal and averaging over the transfer function itself (http://dx.doi.org/10.1063/1.4856635). The assumption of a constant transfer function has been validated for a Hall thruster and the technique is now applied to a Hall thruster for the first time.
**9:30AM CT2.00006** The physics, performance and predictions of the PEGASES ion-ion thruster, ANE AANESLAND, LPP - Ecole Polytechnique — Electric propulsion (EP) is now used systematically in space applications (due to the fuel and lifetime economy) to the extent that EP is now recognized as the next generation space technology. The uses of EP systems have though been limited to attitude control of GEO-stationary satellites and scientific missions. Now, the community envisages the use of EP for a variety of other applications as well, such as orbit transfer maneuvers, satellites in low altitudes, space debris removal, cube-sat control, challenging scientific missions close to and far from earth etc. For this we need a platform of EP systems providing much more variety in performance than what classical Hall and Gridded thrusters can provide alone. PEGASES is a grid thruster that can be an alternative for some new applications in space, in particular for space debris removal. Unlike classical ion thrusters, here positive and negative ions are alternately accelerated to produce thrust. In this presentation we will look at the fundamental aspects of PEGASES. The emphasis will be put on our current understanding, obtained via analytical models, PIC simulations and experimental measurements, of the alternate extraction and acceleration process. We show that at low grid bias frequencies (10s of kHz), the system can be described as a sequence of negative and positive ions accelerated as packets within a classical DC mode. Here secondary electrons created in the downstream chamber play an important role in the beam space charge compensation. At higher frequencies (100s of kHz) the transit time of the ions in the grid gap becomes comparable to the bias period, leading to an “AC acceleration mode.” Here the beam is fully space charge compensated and the ion energy and current are functions of the applied frequency and waveform. A generalization of the Child-Langmuir space charge limited law is developed for pulsed voltages and allows evaluating the optimal parameter space and performance of PEGASES.

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**Tuesday, November 4, 2014 8:00AM - 9:15AM – Session CT3 Plasma Chemistry**

**8:00AM CT3.00001** Measurements of Nitric Oxide in a Plasma Generated by a Variable-Width, Constant Energy Discharge, DAVID BURNETTE, IGOR ADAMOVICH, WALTER LEMPERT, The Ohio State University, NON-EQUILIBRIUM THERMODYNAMICS LABORATORY TEAM — A diffuse plasma filament within a low pressure sphere gap was generated using a high voltage, solid state switch. For a constant pressure and overvoltage, the peak current and voltage drop were altered by a change in the ballast resistor while a simultaneous adjustment to the variable pulse width was used to maintain a constant pulse energy. The discharge parameters were chosen to result in a quasi-steady state discharge with near constant current and very little change in size and uniformity for each condition studied. The absolute density and temporal evolution of nitric oxide (NO) was measured via laser-induced fluorescence for each condition. The effect of the pulse characteristics and estimated E/N on the formation of NO are discussed.

**8:15AM CT3.00002** Characterization of Atmospheric Pressure Carbon Dioxide Dissociation in Arrays of Microplasma Channels by Emission Spectroscopy and Effluent Analysis, ZHEN DAI, CHUL SHIN, SUNG-JIN PARK, JAMES GARY EDEN, University of Illinois at Urbana-Champaign — Levied by rigorous regulations, the enormous cost of atmospheric carbon dioxide emission urged voracious demands on remediation technologies globally. Microplasma technology is being investigated as a new candidate to efficiently dissociate or remediate carbon dioxide contained in atmosphere. At a flow rate of 60 sccm of pure CO₂ feedstock gas, dissociation degree of up to 14% has been achieved with stable glow discharges in an array of Al/Al₂O₃ microplasma channels. In-situ characterizations of the effluent gases were conducted with residual gas analysis, gas chromatography, and infrared spectroscopy. Furthermore, time and spatially resolved emission spectroscopy recorded with an intensified charge-coupled device in the 300-800nm region revealed the excitation of CO and C₂ species. The implications on the possible plasma chemistry and its reaction mechanisms in the microdischarge will be discussed.

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**8:30AM CT3.00003** Plasma activated dissociation of CO₂ studied in a dielectric barrier discharge, RICHARD ENGELN, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands, FLORIAN BREHMER, AFS GmbH, Von-Holzapfel-Straße 10, 86497 Horgau, Germany, STEFAN WELZEL, Dutch Institute for Fundamental Energy Research, P.O. Box 1207, 3430 BE Nieuwegein, The Netherlands, BART KLARENAAR, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands, RICHARD VAN DE SANDE, Dutch Institute for Fundamental Energy Research, P.O. Box 1207, 3430 BE Nieuwegein, The Netherlands, TU/E COLLABORATION, AFS GMBH COLLABORATION, DIFFER COLLABORATION — The ever-increasing emission of carbon dioxide into the atmosphere as well as the intermittency problem of electricity produced by renewable energy sources are challenges that urgently need to be addressed. An approach addressing both issues at the same time is converting CO₂ to a fuel using plasma driven by electricity from renewable sources. We will present in this contribution the results of a study on the conversion of CO₂ to CO in a dielectric barrier discharge in pure CO₂ at pressures up to 100 mbar: FTIR absorption and Raman spectroscopy were applied to measure CO number densities and gas temperatures as function of the specific injected energy. CO densities with a maximum at 10¹⁸ cm⁻³ (mixing ratio of 4.4%) at 46 kJ/s, energy efficiencies in the range of a few percent and gas temperatures up to 550 K were detected. The CO production is directly linked with the total number of transferred charges q during the residence time tₑ, of CO₂ molecules. Also ozone has been detected with a maximum mixing ratio of 0.075%.

**8:45AM CT3.00004** Core and afterglow plasma chemistry of a kHz-driven atmospheric-pressure plasma jet operated in ambient air, TOMOYUKI MURAKAMI, Tokyo Institute of Technology, KARI NIEMI, TIMO GANS, DEBORAH O’CONNELL, University of York, WILLIAM GRAHAM, Queens University Belfast — When atmospheric-pressure plasma jets (APPJs) are operated under an open-air condition, the plasma tends to produce numerous reactive species and the plasma-induced chemical reactions are complex. The purpose of this paper is to quantify the relevant reactive species, e.g. RONS, H₂O₂, NOₓ and HNOₓ, and to analyse their formation in the core and afterglow regions of helium-based kHz-driven APPJ by using a 0D time-dependent global simulation (comprising 1360 elementary reactions among 65 species) [1] as well as to compare the predictions with independent diagnostics. The interacting kinetics of long-lived and short-lived species is clarified. The metastable species, e.g. He* and He²*, positive ions, negative ions and electrons are strongly modulated at the driving frequency, while the most neutral reactive species are not. Those responses are influenced by the humid air fraction.

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**9:30AM CT2.00006** The physics, performance and predictions of the PEGASES ion-ion thruster, ANE AANESLAND, LPP - Ecole Polytechnique — Electric propulsion (EP) is now used systematically in space applications (due to the fuel and lifetime economy) to the extent that EP is now recognized as the next generation space technology. The uses of EP systems have though been limited to attitude control of GEO-stationary satellites and scientific missions. Now, the community envisages the use of EP for a variety of other applications as well; such as orbit transfer maneuvers, satellites in low altitudes, space debris removal, cube-sat control, challenging scientific missions close to and far from earth etc. For this we need a platform of EP systems providing much more variety in performance than what classical Hall and Gridded thrusters can provide alone. PEGASES is a grid thruster that can be an alternative for some new applications in space, in particular for space debris removal. Unlike classical ion thrusters, here positive and negative ions are alternately accelerated to produce thrust. In this presentation we will look at the fundamental aspects of PEGASES. The emphasis will be put on our current understanding, obtained via analytical models, PIC simulations and experimental measurements, of the alternate extraction and acceleration process. We show that at low grid bias frequencies (10s of kHz), the system can be described as a sequence of negative and positive ions accelerated as packets within a classical DC mode. Here secondary electrons created in the downstream chamber play an important role in the beam space charge compensation. At higher frequencies (100s of kHz) the transit time of the ions in the grid gap becomes comparable to the bias period, leading to an “AC acceleration mode.” Here the beam is fully space charge compensated and the ion energy and current are functions of the applied frequency and waveform. A generalization of the Child-Langmuir space charge limited law is developed for pulsed voltages and allows evaluating the optimal parameter space and performance of PEGASES.
9:00AM CT3.00005 On the Role of Metastable Argon in Cold Atmospheric Pressure Plasma Jets with Shielding Gas Device1, ANSGAR SCHMIDT-BLEKER, JORN WINTER, ZIK plasmatis at the INP Greifswald e.V., JOAO SANTOS SOUSA, VINCENT PUECH, Laboratoire de Physique des Gaz et des Plasmas (LPGP), CNRS & UNIVERSITÉ PARIS-SUD, KLAUS-DIETER WELTMANN, STEPHAN REUTER, ZIK plasmatis at the INP Greifswald e.V., ZIK PLASMATIS AT THE INP GREIFSWALD E.V. TEAM, LABORATOIRE DE PHYSIQUE DES GAZ ET DES PLASMAS (LPGP), CNRS & UNIVERSITÉ PARIS-SUD TEAM — Shielding gas devices are a valuable tool for controlling the reactive species output of Cold Atmospheric Pressure Plasma (CAPP) Jets for biomedical applications. In this work we investigate the effect of different shielding gas compositions using a CAPP jet (kipen) operated with argon. As shielding gas various mixtures of N₂ and O₂ are used. Metastable argon (Ar*) has been quantified using laser absorption spectroscopy and was identified as an important energy carrier in the CAPP jets effluent. The Ar⁺ excitation dynamics was studied using phase resolve optical emission spectroscopy. Based on these findings, a kinetic model for the gas phase chemistry has been developed that uses the Ar⁺ density and dynamics as input and yields densities of O₂, NO₂, HNO₂, H₂O₂, N₂O₃, H₂O₂ and N₂O produced by the CAPP jet for different shielding gas compositions. The results are in good agreement with Fourier-Transform Infrared Spectroscopy measurements on these species.

1 Authors gratefully acknowledge the funding by German Federal Ministry of Education a Research (BMBF) (grant # 03ZZDN12).

Tuesday, November 4, 2014 10:00AM - 11:30AM
Session DT1 Plasma Diagnostics I State EF - Jean-Paul Booth, Ecole Polytechnique

10:00AM DT1.00001 Surface wave discharge in helium: evolution of metastable density and temperatures with operating parameters, AHMAD HAMDAN, JOELLE MARGOT, University of Montreal, FRANCOIS VIDAL, INRS, PLASMA PHYSICS TEAM, EMT TEAM — Metastable and resonant-state atoms play an important role in the kinetics of gas discharges (e.g., stepwise ionization and excitation processes). In this contribution, we study a surface-wave discharge in helium. Properties of the plasma such as metastable density, gas temperature and excitation temperature were studied as a function of the operating parameters (pressure, power and axial position z). Rotational temperatures of OH, NH and N₂⁺ (impurities) are estimated by fitting the experimental rotational spectra by synthetic spectra. It was observed that the rotational temperature of N₂⁺ is far to be in thermal equilibrium with the gas. The temperature of the latter T_e is better described by the rotational temperature of the OH radical. Its evolution was studied as a function of z, power and pressure. T_e was found to change from 400 to 1000 K, depending on discharge conditions. The excitation temperature was estimated to be about 0.55 eV using the Boltzmann plot method. The corresponding electron temperature and density were assumed to be 3 - 4 eV and 1 - 4 10¹⁴ /cm³, respectively, based on the results of collisional-radiative models presented in literature. The metastable density n* in the 2ª5 level was determined using absorption spectroscopy. It was observed that n* depends neither of the power nor of the axial position. However, an important dependence of the pressure was observed. n* decreases from 10¹¹ to 10¹⁰ /cm³ when the pressure increases from 5 to 50 Torr.

10:15AM DT1.00002 Spectroscopic Examination of Vibrational and Rotational Properties of NO A²Σ⁺ Metastable State from NO γ-Band Spectra in N₂-O₂ Mixture Microwave Discharge, HAO TAN, ATSUSHI NEZU, HARUAKI MATSUURA, HIROSHI AKATSUKA, Tokyo Institute of Technology — The spectra are observed in our microwave discharge plasma experiments. N₂-O₂ mixture plasma is generated by using a rectangular waveguide. We measured the spectra at 0, 60, 100 and 140 mm with the discharge pressure several Torrs. From these results, we can find that both NO and N₂ molecules experience a cooling down process both on vibrational and rotational temperatures as the plasma flows to the downstream direction. And NO molecule has always a higher rotational temperature than N₂. Meanwhile, we can see that in this nonequilibrium plasma, both NO and N₂ molecules tend to get higher energy for vibrational motion than for rotational motion. We also change the gas partial pressure rate, when O₂ molar ratio of the mixture increases, the NO experiences an increasing vibrational temperature. This is because that the NO A²Σ⁺ metastable state is excited from two main paths: N₂(A-XΣ⁺)+NO(X Σ⁺II) →N₂(X-XΣ⁺)+NO(A²Σ⁺), (1) NO(X Σ⁺II)+e⁻→NO(A²Σ⁺)+e⁻ (2) When O₂ or N₂ is the majority of the discharge species, reaction (2) or (1) dominates the excitation process of NO A²Σ⁺, respectively. Therefore, under our plasma conditions, vibration-rotation energy transition of the reaction (1) results in a strong vibrational relaxation of NO A²Σ⁺ state molecules when N₂ is the majority in the discharge gas. In conclusion, the admixture of N₂ gas can lead to the reduction of average vibrational temperature significantly.

10:30AM DT1.00003 Diagnostics of Pulsed Hydrogen Plasmas, JEROME DUBOIS, GILLES CUNGE, OLIVIER JOUBERT, MAXIME DARNON, LAURENT VALLIER, Univ. Grenoble Alpes, CNRS, CEA-Leti, LTM, F-38000 Grenoble, France, NICOLAS POSSEME, CEA, LETI, MINATEC Campus, F-38054 Grenoble, France, ETCHING GROUP TEAM — Hydrogen plasmas present a great potential interest for new materials such as graphene or C-nanotubes. To modify or clean such ultrathin layers without damaging the material, low ion energy bombardment is required (conditions such as those obtained in pulsed ICP reactor). By contrast, for other applications the ion energy must be high, to get a significant etch rate for example. To assist the development of innovative processes in H₂ plasmas, we have thus analyzed systemically CW and pulsed H₂ plasmas both with and without RF bias power. In particular, we carry out time-resolved ion flux, and time-averaged ion energy measurements in different pulsing configurations. A large variety of ion energies and shapes of IVDV are reported depending on pulsing parameters. The IVDV are typically very broad (due to the low ion transit time of low mass ion through the sheath) and either bi or tri-modal (H⁺, H₂⁺ and H₃⁺ contributions). The time variations of the ion flux in pulsed plasmas also presents peculiar features that will be discussed. Finally, we show that a specific issue is associated to H₂ plasmas: they reduce the chamber walls material therefore releasing impurities (O atoms…) in the plasma in important consequences on processes.

10:45AM DT1.00004 Characterization of a Diverging Cusped Field Thruster Operating on Krypton, NATALIA MACDONALD-TENENBAUM, Air Force Research Laboratory, LANDON TANGO, ERC, Inc., WILLIAM HARGUS, JR., Air Force Research Laboratory, MICHAEL NAKLES, ERC, Inc. — The Diverging Cusped Field Thruster (DCFT) is a low-power plasma with a cusped magnetic field profile. The magnetic fields have strong gradients that cause energetic electrons to mirror back and forth within the discharge chamber, enhancing propellant ionization. Radial portions of the magnetic field are seen only at magnet interfaces, thereby mitigating the ion impingement and heat flux to the channel walls that reduces thruster lifetime. The DCFT has been studied extensively while operating on xenon. This work represents the initial efforts at characterizing the DCFT operating on krypton. Krypton has gained interest in recent years as an alternate propellant for plasma propulsion, mainly because its lower cost has the potential to provide great savings for satellite missions. The results presented include a mapping of changes in the DCFT’s discharge current with varying applied anode voltages and propellant mass flow rates, and frequency analysis of the discharge current oscillations. Additionally, time-averaged and time-synchronized laser induced fluorescence velocimetry are used to examine the ionization and acceleration regions of the discharge channel in an effort to better understand the dynamics of the thruster operation on krypton.
11:00AM DT1.00005 Optical emission spectroscopy at different timescales: nanoseconds, microseconds, milliseconds\textsuperscript{1}. JOHN B. BOFFARD, University of Wisconsin-Madison — Analysis of plasma optical emissions can provide a simple, non-invasive way of measuring key plasma parameters such as the electron temperature and electron density. Due to the short radiative lifetimes of excited states, the plasma emissions can be used to track the near-instantaneous state of time-varying plasmas. Using a small set of argon emission lines along with a low-resolution spectrometer we have monitored the effective electron temperature, electron density, and number densities of long-lived excited Ar\textsuperscript{3p}\textsuperscript{1s}\textsuperscript{4s} atoms in near real-time (update rate 10 Hz, \( T \approx 100 \text{ ms} \)) for an inductively-coupled plasma (ICP) under a wide variety of plasma conditions\textsuperscript{2}. When this same set of Ar emission lines are measured with a faster time-response by using a monochromator/PMT, the plasma conditions on a microsecond timescale can be monitored in pulsed plasmas. Time-resolved measurements of neon emission lines at an even higher time resolution (~5 ns) have been used as a probe for the presence of high energy electrons which occur during only select portions of the 13.56 MHz rf cycle in Ne/Ar ICP discharges\textsuperscript{3}.

\textsuperscript{1}This work was supported by NSF grants CBET 0714600 and PHY-1068670.


Tuesday, November 4, 2014 10:00AM - 12:00PM –
Session DT2 Plasma Modeling and Simulations I

State C - Miles Turner, National Center for Plasma Science Technology, Dublin City University

10:00AM DT2.00001 Numerical Simulations for ICP Source for Implant Applications, VLADIMIR KUDRIAVTSEV, BABAK ADIBI, TERRY BLUCK, Intevac, Santa Clara, CA, VLADIMIR KOLOBOV, CFDRC, Huntsville, Al — ICP Plasma source characteristics depend significantly on cavity aspect ratio and operating pressure \([1]\). In this work we investigate the effect of chamber height and antenna coil placement on current flux and plasma uniformity at pressures in 5morr – 1torr range and also study computationally appropriate scaling laws. Cavity dimensions are 0.2x0.2 m. CFD-ACE/Plasma software is used to conduct 2D planar plasma simulations for Ar and H\textsubscript{2} plasmas. Software allows use of unstructured and non-uniform mesh to resolve geometry details. At low pressure plasma peaks in the middle of the cavity even when RF antenna is placed on top. Results show that there is a maximum in plasma density that corresponds with a unique aspect ratio.

\textsuperscript{1}C. Bilou, et al., US Patent 8,590,485B2

10:15AM DT2.00002 Hybrid Global Model Simulations of He/N\textsubscript{2} and He/H\textsubscript{2}O Atmospheric Pressure Capacitive Discharges\textsuperscript{1}. M.A. LIEBERMAN, E. KAWAMURA, Univ of California - Berkeley, DING KE, Donghua Univ - China, A.J. LICHTENBERG, Univ of California - Berkeley, P. CHABERT, Ecole Polytechnique - France, C. LAZZARONI, Universite Paris 13 France — We used 1D particle-in-cell (PIC) simulations of an atmospheric He/0.1\%N\textsubscript{2} discharge with simplified chemistry to guide the development of a hybrid analytical/numerical global model that includes electron multiplication and two classes of electrons: “hot” electrons associated with the sheaths, and “warm” electrons associated with the bulk. The model and PIC results show reasonable agreement and indicate a transition from a low power \( \alpha \)-mode with a relatively high bulk electron temperature \( T_e \) to a high power \( \gamma \)-mode with a low \( T_e \). The transition is accompanied by an increase in density and a decrease in sheath widths. Water is a trace gas of bio-medical interest since it may arise from contact with skin. We use the hybrid global model to simulate a chemically complex, bounded He/H\textsubscript{2}O atmospheric pressure discharge, including 148 volume reactions among 43 species, and including clusters up to \( \text{H}_{19}\text{O}_{11} \). For a planar discharge with a 1 cm electrode radius and a 0.5 mm gap driven at 13.56 MHz, we determine the depletion and diffusion effects and the \( \alpha \) to \( \gamma \) transition for secondary emission \( \gamma_{\alpha\to\gamma} = 0.25 \) over a range of rf currents and external H\textsubscript{2}O concentrations. Each simulation takes about 2 minutes on a moderate laptop.

\textsuperscript{1}This work was partially supported by the Department of Energy Office of Fusion Energy Science Contract DE-SC000193 and by the Natural Science Foundation of China Contract 11375042.

10:30AM DT2.00003 The effect of including fast neutrals and energy-dependent \( \gamma \)-coefficients in PIC simulations of capacitive RF plasmas, JULIAN SCHULZE, Department of Physics, West Virginia University, ARANKA DERZSI, IHOR KOROLOV, ZOLTAN DONKO, Hungarian Academy of Sciences, EDMUND SCHUENGEL, Department of Physics, West Virginia University — In most PIC simulations of capacitive RF plasmas operated in noble gases only electrons and ions are traced and a constant ion induced secondary electron emission coefficient of \( \gamma_{\text{ion}} = 0.1 \) is used. Here, we demonstrate that tracing fast neutrals that originate from elastic ion-atom collisions in the sheaths, including ionization as well as secondary electron emission induced by these particles, and implementing realistic energy dependent \( \gamma \)-coefficients are essential for obtaining realistic results from such simulations. We find that the ionization caused by fast neutrals strongly enhances the plasma density in simulations of argon discharges driven at 13.56 MHz. This leads to smaller sheaths and limits the maximum driving voltage amplitudes, at which the simulation converges. Both effects are in agreement with experimental findings. Including realistic \( \gamma \)-coefficients also affects the plasma density and other process relevant parameters such as the ion energy and flux at the electrodes. The correct implementation of the energy dependence of secondary electron emission is found to have a drastic effect, if global control parameters used to change the ion bombardment energy in applications are tuned.

10:45AM DT2.00004 Modeling Argon Plasma Excimer Characteristics near a Dielectric Surface in Miniaturized Volumes\textsuperscript{1}. ASHRAF FARAHAT, College of Applied and Supporting Studies, King Fahd University of Petroleum & Minerals (KFUPM), Dhahran 31261, Saudi Arabia — We computationally model plasma -neutral gas dynamics in a miniaturized microthruster encloses Ar and contains a dielectric material sandwiched between two metal plates using a two dimensional plasma model. Spatial and temporal plasma properties are investigated by solving the Poisson equation with the conservation equations of charged and excited neutral plasma species. We find the microthruster properties to depend on small changes in the secondary electron emission coefficient that could result from dielectric erosion and aging. The changes also affect the electrohydrodynamic force produced when we use the microthruster to generate thrust for small spacecrafts. The electrohydrodynamic force is calculated and found to be significant small changes in the secondary electron emission coefficient that could result from dielectric erosion and aging. The changes also affect the electrohydrodynamic momentum exchange is significant in affecting gas flow dynamics and in the formation of excimer species in addition to affecting the UV and visible emission characteristics of the device.

\textsuperscript{1}The authors would like to acknowledge the support provided by the Deanship of Scientific Research (DSR) at the King Fahd University of Petroleum & Minerals (KFUPM) for funding this work through project No. IN111026.
In collaboration with Suzana Zivkovicm, Institute for Biological Research “Sinisa Stankovic,” University of Belgrade; Nenad Selakovíc, Institute of Physics, University of Belgrade; Milica Milutinovic, Jelena Boljevic, Institute for Biological Research “Sinisa Stankovic,” University of Belgrade; and Gordana Malovic, Zoran Lj. Petrovic, Institute of Physics, University of Belgrade.

11:00AM DT2.00005 Study of whole channel discharge characteristics of Hall Thruster under different voltages, DUAN PING, Dalian Maritime University — We used the method of Particle-in-Cell to stimulate the distribution of electron density, ion density and electron temperature with different discharge voltages in a Hall thruster channel. The variation of specific impulse with the discharge voltage was also discussed. It was found that maximum electron and ion densities are gained at the axial 15mm when the discharge voltage is ranging from 250V to 650V and the electron temperature peak emerges near the channel outlet of small axial distance. Under the condition of 700V or higher discharge voltages, highest electron temperature expands in the axial direction and the maximum densities are located in the anode vicinity where the ionization region is limited to. It also revealed that specific impulse increases with the increase of discharge voltage.

11:15AM DT2.00006 A Hybrid PIC/DSMC Model of Breakdown in Triggered Vacuum Spark Gaps, STAN G. MOORE, CHRISTOPHER H. MOORE, JEREMIAH J. BOERNER, Sandia National Laboratories — Triggered vacuum spark gaps (TVSGs) can be used as high voltage, high current switches with a fast switching time and a variable operating voltage, such as in pulsed power applications and crowbar circuits that protect against overvoltage conditions. Hybrid particle-in-cell (PIC) [1] and direct simulation Monte Carlo (DSMC) [2] methods can be used to simulate breakdown in TVSGs. In this talk, we present results of a one-dimensional hybrid PIC/DSMC model and show that changing the density and velocity of injected neutral particles (which can be related to the surface temperature) significantly changes both the time to breakdown and the existence of a short-lived starvation mode in the current waveform.

11:30AM DT2.00007 Testing fluid models of different order on streamer discharges, ARAM MARKOSYAN, University of Michigan, JANNIS TEUNISSEN, CWI, SASHA DUJKO, University of Belgrade, UTE EBERT, CWI — We have compared several fluid models for streamer discharges, namely the recently developed high order fluid model [Dukjo et al., J. Phys. D, 46:5202, 2013], the classical first order model using the local field approximation and the second order fluid model using the local energy approximation with drift-diffusion approximation. Simulation results for planar negative ionization fronts with all three fluid models are presented and compared. As a reference, we use a particle-in-cell/Monte Carlo (PIC/MC) model. All tests are performed for neon and nitrogen at STP for a wide range of reduced electric fields. Our simulation results show large deviations between the models for various properties of negative planar fronts. We discuss the practical and theoretical aspects of applicability of each fluid model.

11:45AM DT2.00008 Investigating the guiding of streamers in nitrogen/oxygen mixtures with 3D simulations1, JANNIS TEUNISSEN, Centrum Wiskunde & Informatica, The Netherlands, SANDER NIJDAM, Eindhoven University of Technology, The Netherlands, EIICHI TAKAHASHI, National Institute of Advanced Industrial Science and Technology, Japan, UTE EBERT, Centrum Wiskunde & Informatica and Eindhoven University of Technology, The Netherlands — Recent experiments by S. Nijdam and E. Takahashi have demonstrated that streamers can be guided by weak pre-ionization in nitrogen/oxygen mixtures, as long as there is not too much oxygen (less than 1%). The pre-ionization was created by a laser beam, and was orders of magnitude lower than the density in a streamer channel. Here, we will study the guiding of streamers with 3D numerical simulations. First, we present simulations that can be compared with the experiments and confirm that the laser pre-ionization does not introduce space charge effects by itself. Then we investigate topics as: the conditions under which guiding can occur; how photoionization reduces the guiding at higher oxygen concentrations and whether guided streamers keep their propagation direction outside the pre-ionization.

11:45AM DT2.00009 Understanding the role of ROS in blood vessel growth, atrophy and differentiation, NEVENA PUAC, Institute of Physics, University of Belgrade — The expansion of the plasma medicine and its demand for in-vivo treatments resulted in fast development of various plasma devices that operate at atmospheric pressure. These sources have to fulfill all demands for application on biological samples. One of the sources that meet all the requirements need for treatment of biological material is plasma needle. Previously, we have used this device for sterilization of planctonic samples of bacteria, MRSA biofilm, for improved differentiation of human periodontal stem cells into osteogenic line and for treatment of plant meristematic cells. It is well known that plasma generates reactive oxygen species (ROS) and reactive nitrogen species (RNS) that strongly affect metabolism of living cells. One of the open issues is to correlate external plasma products (electrons, ions, RNS, ROS, photons, strong fields etc.) with the immediate internal response which triggers or induces effects in the living cell. For that purpose we have studied the kinetics of enzymes which are typical indicators of the identity of reactive species from the plasma created environment that can trigger signal transduction in the cell and ensue cell activity.

In collaboration with Suzana Živkovic, Institute for Biological Research “Sinisa Stankovic,” University of Belgrade; Nenad Selakovic, Institute of Physics, University of Belgrade; Milica Milutinovic, Jelena Boljevic, Institute for Biological Research “Sinisa Stankovic,” University of Belgrade; and Gordana Malovic, Zoran Lj. Petrovic, Institute of Physics, University of Belgrade.

11:45AM DT2.00026 Technical aspects of triggering plasma spark gaps, V. SREBRNIK, R. KAJTAK, Institute of Physics, University of Belgrade — Plasma needle. Previously, we have used this device for sterilization of planctonic samples of bacteria, MRSA biofilm, for improved differentiation of human periodontal stem cells into osteogenic line and for treatment of plant meristematic cells.

11:45AM DT2.00027 Application of atmospheric plasma sources in growth and differentiation of plant and mammalian stem cells1, NEVENA PUAC, Institute of Physics, University of Belgrade — The expansion of the plasma medicine and its demand for in-vivo treatments resulted in fast development of various plasma devices that operate at atmospheric pressure. These sources have to fulfill all demands for application on biological samples. One of the sources that meet all the requirements need for treatment of biological material is plasma needle. Previously, we have used this device for sterilization of planctonic samples of bacteria, MRSA biofilm, for improved differentiation of human periodontal stem cells into osteogenic line and for treatment of plant meristematic cells. It is well known that plasma generates reactive oxygen species (ROS) and reactive nitrogen species (RNS) that strongly affect metabolism of living cells. One of the open issues is to correlate external plasma products (electrons, ions, RNS, ROS, photons, strong fields etc.) with the immediate internal response which triggers or induces effects in the living cell. For that purpose we have studied the kinetics of enzymes which are typical indicators of the identity of reactive species from the plasma created environment that can trigger signal transduction in the cell and ensue cell activity.

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11:45AM DT2.00028 Novel design of atmospheric pressure plasma sources for biophysics and biomedical applications, N. SELAKOVIC, Institute of Physics, University of Belgrade — Plasma needle. Previously, we have used this device for sterilization of planctonic samples of bacteria, MRSA biofilm, for improved differentiation of human periodontal stem cells into osteogenic line and for treatment of plant meristematic cells.

Tuesday, November 4, 2014 10:00AM - 12:00PM –
Session DT3 Effects of Plasmas on Biological Cells — State D - Mounir Laroussi, Old Dominion University

10:00AM DT3.00001 Application of atmospheric plasma sources in growth and differentiation of plant and mammalian stem cells1, NEVENA PUAC, Institute of Physics, University of Belgrade — The expansion of the plasma medicine and its demand for in-vivo treatments resulted in fast development of various plasma devices that operate at atmospheric pressure. These sources have to fulfill all demands for application on biological samples. One of the sources that meet all the requirements need for treatment of biological material is plasma needle. Previously, we have used this device for sterilization of planctonic samples of bacteria, MRSA biofilm, for improved differentiation of human periodontal stem cells into osteogenic line and for treatment of plant meristematic cells. It is well known that plasma generates reactive oxygen species (ROS) and reactive nitrogen species (RNS) that strongly affect metabolism of living cells. One of the open issues is to correlate external plasma products (electrons, ions, RNS, ROS, photons, strong fields etc.) with the immediate internal response which triggers or induces effects in the living cell. For that purpose we have studied the kinetics of enzymes which are typical indicators of the identity of reactive species from the plasma created environment that can trigger signal transduction in the cell and ensue cell activity.

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11:45AM DT2.00026 Technical aspects of triggering plasma spark gaps, V. SREBRNIK, R. KAJTAK, Institute of Physics, University of Belgrade — Plasma needle. Previously, we have used this device for sterilization of planctonic samples of bacteria, MRSA biofilm, for improved differentiation of human periodontal stem cells into osteogenic line and for treatment of plant meristematic cells.

11:45AM DT2.00027 Application of atmospheric plasma sources in growth and differentiation of plant and mammalian stem cells1, NEVENA PUAC, Institute of Physics, University of Belgrade — The expansion of the plasma medicine and its demand for in-vivo treatments resulted in fast development of various plasma devices that operate at atmospheric pressure. These sources have to fulfill all demands for application on biological samples. One of the sources that meet all the requirements need for treatment of biological material is plasma needle. Previously, we have used this device for sterilization of planctonic samples of bacteria, MRSA biofilm, for improved differentiation of human periodontal stem cells into osteogenic line and for treatment of plant meristematic cells. It is well known that plasma generates reactive oxygen species (ROS) and reactive nitrogen species (RNS) that strongly affect metabolism of living cells. One of the open issues is to correlate external plasma products (electrons, ions, RNS, ROS, photons, strong fields etc.) with the immediate internal response which triggers or induces effects in the living cell. For that purpose we have studied the kinetics of enzymes which are typical indicators of the identity of reactive species from the plasma created environment that can trigger signal transduction in the cell and ensue cell activity.

In collaboration with Suzana Živkovic, Institute for Biological Research “Sinisa Stankovic,” University of Belgrade; Nenad Selakovic, Institute of Physics, University of Belgrade; Milica Milutinovic, Jelena Boljevic, Institute for Biological Research “Sinisa Stankovic,” University of Belgrade; and Gordana Malovic, Zoran Lj. Petrovic, Institute of Physics, University of Belgrade.

11:45AM DT2.00028 Novel design of atmospheric pressure plasma sources for biophysics and biomedical applications, N. SELAKOVIC, Institute of Physics, University of Belgrade — Plasma needle. Previously, we have used this device for sterilization of planctonic samples of bacteria, MRSA biofilm, for improved differentiation of human periodontal stem cells into osteogenic line and for treatment of plant meristematic cells.
10:30AM DT3.00002 Minimally-Invasive Gene Transfection by Chemical and Physical Interaction of Atmospheric Pressure Plasma Flow, TOSHIRO KANEKO, Department of Electronic Engineering, Tohoku University — Non-equilibrium atmospheric pressure plasma irradiated to the living-cell is investigated for medical applications such as gene transfection, which is expected to play an important role in molecular biology, gene therapy, and creation of induced pluripotent stem (iPS) cells. However, the conventional gene transfection using the plasma has some problems that the cell viability is low and the genes cannot be transferred into some specific lipid cells, which is attributed to the unknown mechanism of the gene transfection using the plasma. Therefore, the time-controlled atmospheric pressure plasma flow is generated and irradiated to the living-cell suspended solution for clarifying the transfection mechanism toward developing highly-efficient and minimally-invasive gene transfection system. In this experiment, fluorescent dye YOYO-1 is used as the simulated gene and LIVE/DEAD Stain is simultaneously used for cell viability assay. By the fluorescence image, the transfection efficiency is calculated as the ratio of the number of transferred and surviving cells to total cell count. It is clarified that the transfection efficiency is significantly increased by the short-time (<4 sec) and short-distance (<40 mm) plasma irradiation, and the high transfection efficiency of 53% is realized together with the high cell viability (>90%). This result indicates that the physical effects such as the electric field caused by the charged particles arriving at the surface of the cell membrane, and chemical effects associated with plasma-activated products in solution act synergistically to enhance the cell-membrane transport with low-damage.

11:00AM DT3.00003 Impact of plasma induced liquid chemistry and charge on bacteria loaded aerosol droplets, DAVID RUTHERFORD, DAVID MCDOWELL, DAVIDE MARIOTTI, CHARLES MAHONY, University of Ulster, DECLAN DIVER, HUGH POTTTS, EUAN BENNET, University of Glasgow, PAUL MAGUIRE, University of Ulster — The introduction of living organisms, such as bacteria, into atmospheric pressure microplasmas offers a unique opportunity to study the local chemical and electrical effects on cell structure and viability. Individual bacteria, each encapsulated in an aerosol droplet, were successfully transmitted through a non-thermal equilibrium RF coaxial plasma, using a custom-design concentric double gas shroud interface and via adjustment of transit times and plasma parameters, we can control cell viability. Plasma electrical characteristics (n_e ~ 10^14 cm^-3), droplet velocity profiles and aspects of plasma-induced droplet chemistry were determined in order to establish the nature of the bacteria in droplet environment. Plasma-exposed viable E coli cells were subsequently cultured and the growth rate curves (lag and exponential phase gradient) used to explore the effect of radical chemistry and electron bombardment on cell stress. The extent and nature of membrane disruption in viable and non-viable cells were investigated through genomic and protein/membrane lipid content estimation. We will also compare our results with simulations [1] of the effect of bacterial presence on plasma induced droplet charging and evaporation.

11:15AM DT3.00004 Quantitative inactivation-mechanisms of P. digitatum and A. niger spores based on atomic oxygen dose, MASAFUMI ITO, Meijo University, HIROSHI HASHIZUME, Nagoya University, TAKAYUKI OHTA, Meijo University, MASARU HORI, Nagoya University — We have investigated inactivation mechanisms of Penicillium digitatum and Aspergillus niger spores using atmospheric-pressure radical source quantitatively. The radical source was specially developed for supplying only neutral radicals without charged species and UV-light emissions. Reactive oxygen radical densities such as grand-state oxygen atoms, excited-state oxygen molecules and ozone were measured using VUV and UV absorption spectroscopies. The measurements and the treatments of spores were carried out in an Ar-purged chamber for eliminating the influences of OH, NOx and so on. The results revealed that the concentration of reactive oxygen species (ROS) induced inside the cells increased with plasma exposure. On the basis of the dose, we have observed the changes of intracellular organelles and membrane functions using TEM, SEM and confocal-laser fluorescent microscopy. From these results, we discuss the detail inactivation-mechanisms quantitatively based on atomic-oxygen dose.

11:30AM DT3.00005 Treatment of prostate cancer cell lines and primary cells using low temperature plasma, DEBORAH O’CONNELL, ADAM HIRST, York Plasma Institute, Department of Physics, University of York, UK, FIONA F. FRAME, NORMAN J. MAITLAND, YCR Cancer Research Unit, Department of Biology, University of York, UK — The mechanisms of cell death after plasma treatment of both benign and cancerous prostate epithelial cells are investigated. Prostate cancer tissue was obtained with patient consent from targeted needle core biopsies following radical prostatectomy. Primary cells were cultured from cancer tissue and plated onto a chamber slide at a density of 10,000 cells per well in 200 microliter of stem cell media (SCM). The treated sample was previously identified as Gleason grade 7 cancer through tissue histo-pathology. A dielectric barrier discharge (DBD) jet configuration, with helium as a carrier gas, and 0.3% O2 admixture was used for treating the cells. Reactive oxygen and nitrogen species (RONS) produced by the plasma are believed to be the main mediators of the plasma-cell interaction and response. We found the concentration of reactive oxygen species (ROS) induced inside the cells increased with plasma exposure. Exposure to the plasma for >3 minutes showed high levels of DNA damage compared to untreated and hydrogen peroxide controls. Cell viability and cellular recovery are also investigated and will be presented. All findings were common to both cell lines, suggesting the potential of LTP therapy for both benign and malignant disease.

11:45AM DT3.00006 Power source effects of soft plasma jet and the differential response of skin cancer and normal cells, NATHANIEL TAYLOR, Drexel University, DANIL DOBBYNIN, A.J. Drexel Plasma Institute, ALEXANDER FRIDMAN, Drexel University, EUN HA CHOI, Kwangwoon University — The effects of pulsed power direct current energy sources were compared using an indirect discharge plasma jet applied to treat cancerous and normal skin cells. Two power supplies with different voltage and current profiles were compared and optimized through the measurement of physical parameters and evaluated through the treatment of skin cells using an atmospheric pressure nitrogen gas plasma jet. Plasma density and temperature, power output, gas output temperature, and reactive species production were measured. Cell morphology, viability, and ROS generation were investigated using staining. A differential response has been shown between the normal and cancerous cell lines. The cancer cells viability reduced while normal cells did not over the same treatment time.

Tuesday, November 4, 2014 1:30PM - 3:00PM — Session ET1 Plasma Diagnostics and Sources for Biological Applications — State EF - Toshiro Kaneko, Tohoku University
1:30PM ET1.00001 Multi-Modality Pulsed AC Source for Medical Applications of Non-Equilibrium Plasmas, DANIEL FRIEDRICHS, JAMES GILBERT, Coviiden Surgical Solutions — A burgeoning field has developed around the use of non-equilibrium ("cold") plasmas for various medical applications, including sterilization, hemostasis, and tissue ablation. However, regulatory restrictions regarding their safety for use in patient care. Additionally, dedicated capital equipment is difficult for healthcare facilities to justify. We have demonstrated for the first time the generation of non-equilibrium plasma using pulsed AC output from a specially-designed electrosurgical generator. The ability to power novel non-equilibrium plasma devices from a piece of equipment already ubiquitous in operating theatres should significantly reduce the barriers to adoption of plasma devices. We demonstrate the ability of a prototype device, coupled to this source, to reduce bacterial growth in vitro. Such a system could allow a single surgical instrument to provide both non-thermal sterilization and thermal tissue dissection.

Support by the BMBF (FKZ 03Z2DN12) is gratefully acknowledged.

1:45PM ET1.00002 Selective irradiation of radicals for biomedical treatment using vacuum ultraviolet light from an excimer lamp, RYO ONO, YUSUKE TOKUMITSU, SHUNGO ZEN, SEIYA YONEMORI, The University of Tokyo — In plasma medicine, radicals are considered to play important roles. However, the medical effect of each radical, such as OH and O, is unknown. To examine the effect of each radical, selective production of radicals is needed. We developed selective production of radicals for biomedical treatment using a vacuum ultraviolet (VUV) light emitted from an excimer lamp. Selective irradiation of OH radicals can be achieved by irradiating the 172-nm VUV light from a Xe2 excimer lamp to a humid helium flow in a quartz tube. The water molecules are strongly photodissociated by the VUV light to produce OH radicals. A photochemical simulation for the selective OH production is developed based on the VUV density. The calculated OH density is compared with OH density measured using laser-induced fluorescence (LIF). Selective production of other radicals than OH is also discussed.

1:30PM ET1.00003 Diagnostic Challenges in Plasma Medicine, STEPHAN REUTER, HELENA TRESP, ANSGAR SCHMIDT-BLEKER, JOERN WINTER, SYLVAIN ISENI, MARIO DÜNNBIER, KAI MASUR, ANNEMARIE BARTON, MALTE HAMMER, ZIK plasmatis INP Greifswald, THOMAS VON WOEDTKE, KLAUS-DIETER WELTMANN, INP Greifswald — Atmospheric plasmas exhibit large gradients in space and time. A Xe2 excimer lamp is used to generate VUV radiation to excite OH, O and N atoms in helium plasma jet. In vivo measurements of OH, O and N atoms in helium plasma jet for ROS/RNS controlled biomedical processes. OH, O and N atoms are measured using laser-induced fluorescence spectroscopy and ICCD imaging.

2:15PM ET1.00004 Measurement of OH, NO, O and N atoms in helium plasma jet for ROS/RNS controlled biomedical processes, SEIYA YONEMORI, TAKU KAMAKURA, RYO ONO, The University of Tokyo — Atmospheric-pressure plasmas are of emerging interest for new plasma applications such as cancer treatment, cell activation and sterilization. In those biomedical processes, reactive oxygen/nitrogen species (ROS/RNS) are said to play significant roles. To examine the effect of each radical, selective production of radicals is needed. We developed selective production of radicals for biomedical treatment using a vacuum ultraviolet (VUV) light emitted from an excimer lamp. Selective irradiation of OH radicals can be achieved by irradiating the 172-nm VUV light from a Xe2 excimer lamp to a humid helium flow in a quartz tube. The water molecules are strongly photodissociated by the VUV light to produce OH radicals. A photochemical simulation for the selective OH production is developed based on the VUV density. The calculated OH density is compared with OH density measured using laser-induced fluorescence spectroscopy and ICCD imaging.

2:30PM ET1.00005 Vacuum ultraviolet spectroscopic analysis of AC excited non-equilibrium atmospheric pressure Ar plasma jet, KEIGO TAKEDA, KENJI ISHIKAWA, HIROMASA TANAKA, HIROKI KONDO, MAKOTO SEKINE, MASARU HORI, Nagoya University — Plasma biomedical treatments with atmospheric pressure plasma jets (APPJ) have attracted very much. In the treatments, reactive species and high energy photons emitted from APPJ are important factors to realize the performance. Vacuum ultraviolet (VUV) spectroscopy is one of useful techniques to measure quantitative behaviors of atomic radicals and high energy photons. In this study, an AC excited APPJ with Ar gas has been investigated using the spectroscopy. The Ar APPJ was generated under open air condition, and VUV emission spectra was measured by using a Xe2 excimer lamp to a humid helium flow in a quartz tube. The water molecules are strongly photodissociated by the VUV light to produce OH radicals. A photochemical simulation for the selective OH production is developed based on the VUV density. The calculated OH density is compared with OH density measured using laser-induced fluorescence spectroscopy and ICCD imaging.

2:45PM ET1.00006 Non thermal plasma jets interacting with targets and gas flows, ERIC ROBERT, T. DARNY, GREMI/CNRS/Université d’Orleans, D. RIES, CNRS/Université d’Orleans, S. DOZIAS, J-M. POUVESLE, GREMI/CNRS/Université d’Orleans — Non thermal plasma jets at atmospheric pressure have been recently used in an impressive number of works including plasma diagnostics, biomedical treatments and material processing. While the plasma source setups are very simple, it has been evidenced that many parameters may significantly influence the plasma characteristics offering at the same time a large versatility for plasma delivery but also requiring a special attention to match the plasma features for any specific application. In this work, emphasis will be given on two critical topics involved in any plasma jet biomedical applications. The first consists in the influence of the target over which plasma jet impinges. It has been shown that depending on the conductivity of the target, secondary plasma generation occurs, leading to a critical modification of the reactive species generation. The second main issue concerns the strong interplay between the rare gas flow and the plasma species generated during plasma jet ionization wave propagation. Drastic modification of the rare gas flow features have been recently characterized through Schlieren visualization and ICCD imaging.


Work supported by APR “PLASMED” and ANR BLANC “PAMPA” 093003

Tuesday, November 4, 2014 1:30PM - 3:00PM –
Session ET2 Modeling of Plasma Etching State C - Douglas Keil, Lam Research
1:30PM ET2.00001 Profile Control Using Pulsed Power During Plasma Etching in Capacitively Coupled Plasmas 1, SANG-HEON SONG 2, MARK J. KUSHNER, University of Michigan — Profile control during plasma etching is becoming more challenging as feature sizes decrease. Pulsed power in capacitively coupled plasmas (CCPs) is being developed as a means to provide more flexibility in reactive fluxes and ion energy and angular distributions (IEADs) to achieve this profile control. In this talk, we discuss results for profile control in etching of dielectrics from modeling studies of pulsed 2-frequency CCPs sustained in Ar/CF4/O2 mixtures. The simulators include a 2-d plasma hydrodynamics model to produce reactive fluxes and IEADs, and a 2-d Monte Carlo based profile model. IEADs are produced in three formats in pulsed CCPs – when both the low frequency (LF) and high frequency (HF) are on, when only the LF or HF are on, and when both the LF and HF are off. The resulting IEADs are further modified by duty cycle and the size of the blocking capacitor. We found that the side-wall slope of high-aspect-ratio (HAR) features can be controlled by combinations of pulsing the LF and/or HF, and duty cycle. In addition to the feature receiving different IEADs, the ratio of polymerizing to ion fluxes which contributes to control of sidewall slope is also sensitive to these process variables.

1Work supported by DOE Office of Fusion Energy Science, Semiconductor Research Corp. and NSF.

2Now with: Tokyo Electron Ltd., Albany, NY.

1:45PM ET2.00002 Insights into Plasma Etch Profile Evolution with 3D Profile Simulation . SARAWANAPRIYAN SRIRAMAN, ALEX PATerson, Lam Research, YITTING ZHANG, MARK KUSHNER, University of Michigan — Plasma etching is critical for pattern transfer in microelectronics fabrication. For planar devices, efforts in 2D etch profile simulations were sufficient to understand critical etch process mechanisms. In contrast, to understand the complex mechanisms in etching 3D structures of current technology nodes such as FinFETs, 2D profile simulators are inadequate. In this paper, we report on development of a 3D profile simulation platform, the Monte Carlo Feature Profile Model (MCFPM-3D). The MCFPM-3D builds upon the 2D MCFPM platform that includes aspects such as mixing, implantation, and photon assisted processes and addresses reaction mechanisms in surface etching, sputtering, and deposition to predict profile evolution. Model inputs include fluxes of species from plasma derived from the Hybrid Plasma Equipment Model (HPM). Test cases of Si/SiO2 etching in Ar/Cl2 and Ar/CF4/O2 plasmas for representative 2D/3D feature topographies are considered and phenomena such as selectivity and aspect ratio dependent etching will be discussed.

2:00PM ET2.00003 Multi Time-Step Feature Scale Simulations with FPS3D , PAUL MOROZ, Tokyo Electron U.S. Holdings, Inc., DANIEL MOROZ, University of Pennsylvania — Most modern materials processing recipes include many time-steps, each one utilizing different chemistry and plasma parameters, resulting in different composition of fluxes coming to the wafer and different energy and angular distributions of incoming species. The FPS3D feature scale simulator [1-2] is capable of handling varied and complex cases due to its structure and numerical techniques. For this presentation, we selected a set of simulations for processes which are dramatically different from each other. One is the Bosch process, which is a high etch-rate (in the range of 1000 A/s or more) etching for features with dimensions in the range of 1 micron to 100s of microns. The other is the ALE (atomic layer etch), in which etching is done by a single atomic layer per cycle, allowing maximal processing accuracy but with etch rate in the range of one to a few A/min. Both of these processes involve multiple cycles through the etching and passivation (or deposition) steps. FPS3D is well suited for those tasks as it allows consideration of large fluxes and large dimensions of the Bosch process as well as the delicate ALE processing on an atomic level. Results of both 2D and 3D modeling will be presented and the details of the processes will be discussed.


2:15PM ET2.00004 Modeling of plasma-induced damage during the etching of ultimately-scaled transistors in ULSI circuits—A model prediction of damage in three dimensional structures 1, Koji ERIGUCHI, Kyoto University — An increasing demand for high performance field-effect transistors (FETs) leads to the aggressive critical dimension shrinkage and the currently-emerging three dimensional (3D) geometry [1]. Plasma processing is widely used also in the scaled- and 3D FET (e.g. FinFET, STI). In this study, damage creation mechanism during plasma etching—plasma-induced physical damage (PPD)—was investigated in such structures on the basis of the PPD range theory [2], atomistic simulations, and experiments. Compared to PPD in planar FETs (e.g. Si recess [2] [3]), a stochastic modeling and atomistic simulations predicted that, during etching of "fins" in a 3D-FET, the following two mechanisms are responsible for damage creation in addition to an ion impact on the sidewall at an oblique incident angle: 1) incoming ions penetrate into the Si substrate and undergo scattering by Si atoms in the lateral direction even if the incident angle is normal to the surface [4] and 2) some of Si atoms and ions sputtered at the surface being etched impact on the sidewall with energies sufficient to break Si-Si bonds. These straggling and sputtering processes are stochastic and fundamental, thus, result in 3D structure damage ("fin-damage"). The "fin-damage" induced by straggling was modeled by the PPD range theory. Molecular dynamics simulations clarified the mechanisms under the various plasma conditions. Quantum mechanical mechanical calculations showed that created defect structures play the role of a carrier trap site, which was experimentally verified by an electrical measurement. Since they are intrinsic nature of etching, both straggling and sputtering noted here should be implemented to design a low-damage etching process.


1This work was supported in part by Grant-in-Aid for Scientific Research (B) 23360321 from JSPS and STARC project.

2:45PM ET2.00005 Molecular dynamics analysis of silicon chloride ion incidence during Si etching in Cl-based plasmas: Effects of ion incident energy, angle, and neutral radical-to-ion flux ratio , NOBUYA NAKAZAKI, KOJI ERIGUCHI, KOUCHI ONO, Kyoto University — Profile anomalies and surface roughness are critical issues to be resolved in plasma etching of nanometer-scale microelectronic devices, which in turn requires a better understanding of the effects of ion incident energy and angle on surface reaction kinetics. This paper presents a classical molecular dynamics (MD) simulation of Si(100) etching by energetic Cl2+ (x = 1–2) and SiCl3+ (x = 0–4) ion beams with different incident energies Ei = 20–500 eV and angles θi = 0–85°, with and without low-energy neutral CI radicals (neutral-to-ion flux ratios Γn/Γi = 0 and 100). An improved Stillinger-Weber interatomic potential was used for the Si/Cl system. Numerical results indicated that in Cl+1, Cl2+, SiCl3+, and SiCl4+ incidences for θi = 0° and Γn/Γi = 0, the etching occurs in the whole Ei range investigated; on the other hand, in SiCl4+ and SiCl4+ incidences, the deposition occurs at low Ei <300 and 150 eV, respectively, while the etching occurs at further increased Ei [1]. For SiCl3+ and SiCl4+, the transition energies from deposition and etching become lower for Γn/Γi = 100. Numerical results further indicated that in the SiCl4+ incidence for Γn/Γi = 0, the etching occurs in the whole θi range investigated for Ei ≥ 300 eV; on the other hand, for Ei = 100 and 150 eV, the deposition occurs at low θi <60° and 40°, respectively, while the etching occurs at further increased θi; in addition, for Ei ≤ 50 eV, the deposition occurs in the whole θi range investigated.

1:30PM ET3.00001 Recent developments in large-scale ozone generation with dielectric barrier discharges, JOSE L. LOPEZ, Seton Hall University, Department of Physics, South Orange, NJ (USA) — Large-scale ozone generation for industrial applications has been entirely based on the creation of microplasmas or microdischarges created using dielectric barrier discharge (DBD) reactors. Although versions of DBD generated ozone have been in continuous use for over a hundred years especially in water treatment, recent changes in environmental awareness and sustainability have lead to a surge of ozone generating facilities throughout the world. As a result of this enhanced global usage of this environmental cleaning application various new discoveries have emerged in the science and technology of ozone generation. This presentation will describe some of the most recent breakthrough developments in large-scale ozone generation while further addressing some of the current scientific and engineering challenges of this technology.

2:00PM ET3.00002 Ferroelectric-driven atmospheric pressure discharges, MICHAEL JOHNSON, DAVID GO, University of Notre Dame — Typically, dielectric barrier discharges (DBD) operate through a continuous cycle of charging and discharging a dielectric layer. Ferroelectrics are a subset of dielectrics that are inherently polarized due to their non-centrosymmetric crystal structure. The polarization of a ferroelectric has two or more stable conditions, and the polarization state can be switched by applying an electric field that exceeds the coercive field of the crystal. When the dielectric layer in a DBD is replaced with a ferroelectric, this change in polarization can lead to rapid changes in surface potential and be used to manipulate the charge on its surface. More so, these rapid changes in polarization of the crystal can cause strong electric fields at the surface that can lead to electron emission into the discharge. The coercive field of the ferroelectric allows for the occurrence of this emission to be controlled. Because of this, operating conditions of a ferroelectric barrier discharge can be altered to allow for discharges at lower AC voltages and with greater amounts of control. In this work, we investigate the potential advantages of using ferroelectric crystals in place of dielectrics in a barrier discharge while investigating the effects of polarization and polarization shifting on the discharge.

2:15PM ET3.00003 Self-Organization in DBDs on a Single Pulse: Periodic Structures and Diffuse Discharges¹, NATALIA YU. BABAEVA², MARK J. KUSHNER, University of Michigan — Self-organization in dielectric barrier discharges (DBDs) occurs in many forms, from patterns of isolated plasma filaments to more complex arrangements. This self-organization typically develops over many discharge pulses, and is often related to charging of the dielectrics. Another aspect of DBDs is the transition from filamentary to diffuse discharges. The diffuse mode can be achieved at high repetition rate over many pulses, or on a single discharge pulse using over-voltage enabled by a fast-rising applied voltage. In computational studies of DBDs using a 2-dimensional plasma hydrodynamics model, evidence has been found for self-organized-patterns (SOPs) during a single discharge pulse. The conditions are an over-voltaged DBD sustained in humid air with two dielectric layers. We first found a transition between an isolated filament and a more diffuse discharge in raising the applied electric field to approximately 100 kV/cm. The diffuse discharge is sensitive to the surface-ionization-waves (SIWs) that propagate along both dielectrics, and the relative permittivity of those dielectrics. Upon increasing voltage further, SOPs are formed by periodic ionization waves launched into the gap from the edges of the SIWs. The gap-crossing ionization waves may be either positive or negative depending on the relative capacitance of the top and bottom dielectrics.

2:30PM ET3.00004 Charge transfer in surface barrier discharge on µ sec to msec time scales, SERGEY LEONOVI, IGOR ADAMOVICH, VITALY PETRISCHCHEV, The Ohio State University, OSU TEAM — The paper presents experimental results characterizing dynamics of development and kinetics of energy coupling in surface dielectric barrier discharge (SDBD), sustained over dielectric and weakly conducting liquid surfaces, over a wide range of time scales and electrical conductivities. Time-resolved discharge development and mechanisms of coupling with quiescent air are analyzed using nanosecond gate camera imaging, high-sensitivity time-resolved schlieren imaging, surface charge sensor, and Laser Differential Interferometry. It is shown that NS SDBD plasmas generate high-amplitude, broadband, stochastic, point-wise, near-surface perturbations on a long time scale (>100 µs) after the discharge pulse. These perturbations are caused by discharge contraction and originate from the ends of individual streamers where they attach to the surface. It is also demonstrated a significant increase of energy (surface charge) stored on the dielectric surface during the NS discharge pulse, which in this case greatly exceeds energy dissipated as Joule heat (up to a few hundred percent). The present results strongly suggest that surface charge accumulation, along with use of alternating polarity pulse waveform, may significantly improve performance of surface discharge plasma actuators.

3:00PM FT1.00001 Smart material-based radiation sources¹, SCOTT KOVALESKI, University of Missouri — From sensors to power harvesters, the unique properties of smart materials have been exploited in numerous ways to enable new applications and reduce the size of many useful devices. Smart materials are defined as materials whose properties can be changed in a controlled and often reversible fashion by use of external stimuli, such as electric and magnetic fields, temperature, or humidity. Smart materials have been used to make acceleration sensors that are ubiquitous in mobile phones, to make highly accurate frequency standards, to make unprecedentedly small actuators and motors, to seal and reduce friction of rotating shafts, and to generate power by conversion of either kinetic or thermal energy to electrical energy. The number of useful devices enabled by smart materials is large and continues to grow. Smart materials can also be used to generate plasmas and accelerate particles at small scales. The materials discussed in this talk are from non-centrosymmetric crystalline classes including piezoelectric, pyroelectric, and ferroelectric materials, which produce large electric fields in response to external stimuli such as applied electric fields or thermal energy. First, the use of ferroelectric, pyroelectric and piezoelectric materials for plasma generation and particle acceleration will be reviewed. The talk will then focus on the use of piezoelectric materials at the University of Missouri to construct plasma sources and electrostatic accelerators for applications including space propulsion, x-ray imaging, and neutron production. The basic concepts of piezoelectric transformers, which are analogous to conventional magnetic transformers, will be discussed, along with results from experiments over the last decade to produce micro-thrusters for space propulsion and particle accelerators for x-ray and neutron production.

¹Support from ONR, AFOSR, and LANL.
4:00PM FT1.00002 Simulation of the Vapor Shield Effect on Plasma Facing Materials under Tokomak-Like Disruption Conditions. NOUF ALMOUSA, MOHAMED BOURHAM, North Carolina State University. Hard disruptions are expected in large tokamaks, where plasma-facing components (PFCs) receive radiative high heat fluxes resulting in surface melting and evaporation. The boundary layer at the ablating/melting surfaces absorbs a fraction of the heat flux and a vapor shield effect protects the PFCs from further erosion. The energy transmission through the vapor shield $f_{sh}$ is modeled in a 1-D, time dependent code to calculate the erosion under disruption-like conditions of 55 GW/m$^2$ over 150 μs. The $f_{sh}$ value was found to be strongly dependent on materials properties, plasma pressure, and density, but weakly dependent on the plasma internal and kinetic energies. Calculations of $f_{sh}$ at each time step and mesh point are used to predict the ablated mass. The code predictions are used to estimate the erosion rate and erosion thickness for various PFCs. It has been found that high-$Z$ PFCs suffer higher ablation rate as compared to low-$Z$ PFCs. However, the erosion in units of material thickness indicates that the erosion thickness of the highest $Z$ PFCs (tungsten) is less than that of the lowest $Z$ PFCs (beryllium). Detailed comparisons of the erosion behavior and properties of PFCs are presented.

4:15PM FT1.00003 Ion induced electron emission from semiconductors: The effect of conduction band electrons and surface electric fields. DAVID URRABAZO, MATTHEW GOECKNER, LAWRENCE OVERZET, University of Texas at Dallas. A few recent publications point to the possibility of controlling the ion induced electron emission (IIEE) yield from semiconductors in real time through controlling the numbers of electrons in the semiconductor’s conduction band (ne, CB). Of course, ion bombardment induced electron emission also occurs in the plasma processing of semiconductors, and should cause differences between processing n- and p-type wafers if it truly depends upon ne, CB. Hagstrom’s Auger neutralization theory for semiconductors assumes that the IIEE yield should NOT depend upon ne, CB, and as a result most models make the assumption that the IIEE yield is independent of ne, CB (and the position of the Fermi level as well as temperature). To our knowledge, no one has investigated this assumption! Therefore, we have experimentally and theoretically investigated it by using and extending Hagstrom’s theory as well as by measuring the IIEE yield from semiconductor samples versus doping density and type. In addition, we have begun both theoretical and experimental investigations into the effects of a surface E-field on IIEE for semiconductors. We will introduce a device we have designed, modeled, and begun fabricating for measuring the IIEE yield while independently controlling the ion flux and E-field.

4:30PM FT1.00004 A Comparative Study of Polymer and Biomolecule Surface Modifications by an Atmospheric Pressure Plasma Jet and Surface Microdischarge in Controlled Environments. ELLIOT BARTIS, ANDREW KNOLL, PINGSHAN LUAN, CONNOR HART, JOONIL SEOG, GOTTLIEB ÖEHRLIN, University of Maryland, College Park. DAVID GRAYES, University of California, Berkeley, WALTER LEMPERT. The Ohio State University. In this work, polymer- and lipopolysaccharide-coated Si substrates were exposed to a surface microdischarge (SMD) and an atmospheric pressure plasma jet (APPJ) in controlled ambients. We seek to understand how plasma-ambient interactions impact biodeactivation and surface modifications by regulating the ambient gas chemistry and the proximity of the plasma to the ambient. A key difference between the SMD and APPJ is that the APPJ needs an Ar feed gas and the SMD does not. By adding small N$_2$/O$_2$ admixtures to Ar, we find that the O$_2$ admixture in the APPJ is a key factor for both deactivation and surface modification. After plasma treatments, we detected a new chemical species on a variety of surfaces that was identified as NO$_2$. We find that NO$_2$ forms even with no N$_2$ in the feed gas, demonstrating that this species forms due to interactions with ambient N$_2$. Despite a very different discharge mechanism, the SMD modifies surfaces similarly to the APPJ, including NO$_3$ formation. The SMD generates large O$_3$ concentrations, which do not correlate with NO$_3$, suggesting that O$_3$ alone is not involved in the NO$_3$ formation mechanism. The authors gratefully acknowledge financial support by the US Department of Energy (DE-SC0005105 and DE-SC0001939) and National Science Foundation (PHY-1004256).

4:45PM FT1.00005 ABSTRACT HAS BEEN MOVED TO MR2.00004 –

5:00PM FT1.00006 Effect of Cryogenic Cooling for Gallium Nitride Film Placed in Argon Plasma. DAISUKE OGAWA, YOSHITAKA NAKANO, KAJI NAKAMURA, Chubu University. There is no doubt for a gallium nitride (GaN) film to have plasma-induced damage (PID) when exposed in a plasma discharge. Our technique to make in-situ monitoring on a GaN film exposed in argon plasma is valuable toward to reveals the evolution of the damage. We evaluated the PID with photoluminescence (PL) that is excited with a ultra-violet light source. Our preliminary result showed that the PL intensity at the blue luminescence band (BL: 400 – 480 nm) increased while the intensity at yellow luminescence (YL: 480 – 700 nm) decreased as the plasma exposure time increased. Chen et al. previously found that PL spectrum changes due to both PID and substrate temperature. However, BL intensity is independent from the substrate temperature, while BL intensity is dependent on the degree of PID. In this experiment, we performed the plasma exposure to a GaN film under the situation when the substrate temperature was cooled with liquid nitrogen. The substrate temperature is set at -110 degC, and exposed plasma in 15 minutes. In this condition, our BL stayed almost constant. This is an indication that we might be able to avoid the damage in the wavelength shorter than 480 nm. We will show more details from this results and further progresses in this presentation.

5:15PM FT1.00007 Study of the effect of pressure on thermionic emission current. JOHN HAASE, DAVID GO, University of Notre Dame. Thermionic emission is the process in which heating a cathode allows electrons to gain sufficient energy to overcome the material’s work function and be ejected into vacuum. By collecting the emitted electrons at a lower temperature anode and passing them through a load, the thermal energy is directly converted into electrical energy in a process called thermionic energy conversion (TEC). Operating a plasma in the interstitial gap between the cathode and anode produces positive space charge to offset the negative electrons and can improve TEC performance. However, this necessarily requires that the TEC device operates at pressures higher than vacuum. The introduction of a gas between the electrodes of a TEC device can either attenuate, as by measuring the IIEE yield while independently controlling the ion flux and E-field.

Tuesday, November 4, 2014 3:30PM - 5:30PM – Session FT2 Capacitive Discharges - Computational
components [1]. The oxygen model includes, in addition to electrons, the oxygen molecule in the ground state, the oxygen atom in the ground state, the negative ion O⁻, the positive ions O⁺ and O₂⁺, and the metastable states O(1D) and O₂(1A₂). We explore the electron energy distribution function (EEDF), the electron temperature profile, the density profiles of charged particles and electron heating rates for a capacitive coupled oxygen discharge. We explore the influence of the metastables on the plasma parameters and in particular the influence of detachment by the metastable O₂(1A₂) molecule on the electron heating mechanism in the discharge.


4:00PM FT2.00003 Electron beam formation and resonance phenomena in low pressure capacitive rf plasmas, SEBASTIAN WILCZEK, JAN TRIESCHMANN, RALF PETER BRINKMANN, THOMAS MUSSEN BROCK, Ruhr University Bochum, EDMUND SCHÜNGEL, JULIAN SCHULZE, West Virginia University, Morgantown, ARANKA DERZSI, IHOR KOROLOV, ZOLTÁN DONKÓ, Wigner Research Center for Physics, Budapest — In capacitive coupled RF plasmas, the expansion of the modulated plasma sheaths accelerates a fraction of electrons. This consequently leads to various kinds of electron beam formations; one or likely multiple beams are triggered and start propagating. Especially at low pressures, these electrons traverse through the plasma bulk with high kinetic energy and ionize the neutral background gas to sustain the plasma. Under distinct discharge conditions a violation of the quasi-neutrality of the plasma bulk is indicated by a local accumulation of charge density. Consequently, strong electric fields exist even in the center of the discharge. In this work, the electron beam formations are investigated in conjunction with resonance behavior of the discharge by means of 1D Particle-In-Cell simulations. It is shown that the driving frequency or higher harmonics of the driving frequency match the local electron plasma frequency, particularly in the bulk region. This is an indication of local resonance phenomena in conjunction with the establishing of discrete electron beam modes being formed. Moreover, this is connected to a change of the local electric field.

4:15PM FT2.00004 Efficient Modelling of Pulsing CCP Reactors, SCHABNAM NAGGARY, FRANK ATTELN, RALF PETER BRINKMANN, Ruhr-University Bochum, Institute for Theoretical Electrical Engineering, MUSTAFA MEGAHED, ESI Group — Pulsed multi-frequency CCP reactors provide additional means to manipulate the plasma characteristics and in particular the ion energy distribution. The interaction of the plasma with the pulse duty cycle and frequency is not fully understood yet, due to complex excitation and de-excitation of the rf and pulsing signals. Numerical models were demonstrated to accurately capture the transient behavior of the pulsed plasma. The high computational effort, however, makes these models very inaccessible to the community and do not allow for systematic study of the different parameters of interest to system designers. This work presents an efficient model that allows the characterization of the “main” plasma properties including the ion energy distribution functions within seconds. The zero dimensional model allows the analysis of the reactor operation parameter space and it provides the boundary conditions for more detailed, spatially resolved models that are used to fine tune the design including the resolution of wafer edge and wave effects.

3:30PM FT2.00001 Tailoring plasma properties through the non-linear frequency coupling of odd harmonics, ANDREW GIBSON, Centre for Plasma Physics, Queen’s University Belfast, BELFAST, BT7 1NN, ARTHUR GREB, York Plasma Institute, Department of Physics, University of York, YORK, Y01 5DD, WILLIAM GRAHAM, Centre for Plasma Physics, Queen’s University Belfast, BELFAST, BT7 1NN, TIMO GANS, York Plasma Institute, Department of Physics, University of York, YORK, Y01 5DD — Multiple frequency plasma sources are commonplace in plasma-based nano-fabrication. However, the control of plasma properties in these discharges is often limited by a poor understanding of the non-linear coupling between the frequencies. Thus, investigations of this non-linear coupling are crucial for achieving better control of plasma processes and optimizing process outcomes. Presented here is a study of plasma excitation by two coupled odd harmonics (13.56 and 40.68 MHz) using a 1D fluid model of a symmetric capacitively coupled plasma. Non-linear frequency coupling is found to minimise the average plasma potential when both frequencies contribute equally to the voltage waveform. Furthermore, varying the phase between the frequencies can further decrease the average plasma potential, without having a significant effect on the ion density. This effect allows for control of the sheath potential at both electrodes simultaneously, independent of the ion density. As such the use of odd harmonics offers a novel method of plasma control that maintains the symmetry of the discharge. This is in contrast to plasma control techniques utilising the electrical asymmetry effect where the sheath potential is decreased at one electrode by increasing it at the opposing electrode.

3:45PM FT2.00002 Particle-in-cell Monte Carlo collision simulation of a capacitively coupled discharge in oxygen, JON TOMAS GUDMUNDSSON, University of Iceland, MICHAEL A. LIEBERMAN, Department of Electrical Engineering and Computer Sciences, University of California at Berkeley — The oop1 particle-in-cell Monte Carlo collision (PIC-MCC) code is used to simulate a capacitively coupled discharge in oxygen. oop1 is a one-dimensional object-oriented PIC-MCC code in which the model system has one spatial dimension and three velocity components [1]. The oxygen model includes, in addition to electrons, the oxygen molecule in the ground state, the oxygen atom in the ground state, the negative ion O⁻, the positive ions O⁺ and O₂⁺, and the metastable states O(1D) and O₂(1A₂). We explore the electron energy distribution function (EEDF), the electron temperature profile, the density profiles of charged particles and electron heating rates for a capacitive coupled oxygen discharge. We explore the influence of the metastables on the plasma parameters and in particular the influence of detachment by the metastable O₂(1A₂) molecule on the electron heating mechanism in the discharge.

The authors gratefully acknowledge the financial support by the SFB-TR 87 and the ESI Group

4:30PM FT2.00005 Capacitively coupled Plasma Modeling at Low and Moderately High Pressures, KALLOL BERA, Applied Materials, Inc. — Capacitively coupled plasmas have been used in both deposition and etching processes in semiconductor industry. The etching processes are typically performed at low pressure (5-500 mTorr) as directionality and energy of ions are important. The deposition model includes the full set of Maxwell equations in their potential formulation. The equations governing the vector potential are solved in the frequency domain after every cycle for multiple harmonics of the driving frequency. Current sources for the vector potential equations are computed using the plasma characteristics from the previous cycle. The coupled set of equations governing the scalar potential and drift-diffusion equations for all charged species are solved implicitly in time. In the low pressure regime, stochastic heating is important. This effect is considered in the model using modified transport parameters. The model was validating using experimental data. At 13 MHz, secondary electron emission is found to play an important role in enhancing ionization through collisions. At higher frequency, the effect of secondary electron emission is less significant. At very high frequency, the electromagnetic standing wave leads to peak in plasma density at the center of the discharge. In the moderately high pressure regime, secondary electrons are important as they participate in bulk plasma heating. At very high frequency, under moderately high pressure, the electromagnetic effect is also found to be important, with the shape of the plasma profile varying according to the reactor structure. In this paper we will present plasma modeling that adequately represents plasmas at low and moderately high pressures at different frequency.

5:00PM FT2.00006 The effect of ambipolar electric fields on the electron heating in capacitive RF plasmas, JULIAN SCHULZE, West Virginia University, ZOLTÁN DONKÓ, ARANKA DERZSI, IHOR KOROLOV, Hungarian Academy of Sciences, EDMUND SCHUENGEL, Department of Physics, West Virginia University — We investigate the electron heating dynamics in argon and helium capacitively coupled RF discharges driven at 13.56 MHz by Particle in Cell simulations and by an analytical model. Electrons are found to be heated by strong ambipolar electric fields outside the sheath during the phase of sheath expansion in addition to classical sheath expansion heating. Moreover, we find that electrons reflected multiple times from the expanding sheath edge within one RF period are the primary sources of ionization. In fact a synergistic combination of different heating events is required to sustain the plasma. The ambipolar electric field outside the sheath is found to be time modulated due to a time modulation of the electron mean energy caused by the presence of sheath expansion heating only during one half of the RF period at a given electrode. This time modulation results in more heating than cooling on time average. If an electric field reversal is present during sheath collapse, this time modulation will be enhanced. This ambipolar electron heating is found to represent an important heating mechanism, which should be included in models of capacitive RF plasmas.
emitter material in case of a shortage at the tip. Cathode coverage and diffusion in the interior of the electrode, ThO
return of vaporized La by an ion current from the arc plasma to the cathode. Enrichments of La / Th compounds are formed on the cathode surface providing
induced by a transient shortage of La at the cathode tip. The arc attachment moves from the tip to colder areas of the cathode, where a high amount of La
Differences and their influence on the stability of the arc will be presented.

Φ
the work function
JUERGEN MENTEL, PETER AWAKOWICZ, Ruhr-University Bochum — Tungsten cathodes in HID-lamps are commonly doped with rare earth oxides to reduce

3:45PM FT3.00002 Functionalization of plasma synthesized advanced carbons1, EVA KOVACEVIC, GREMI UMR 7344 CNRS and Universite d’Orleans, THIBAULT LABBAYE, JOHANNES BERNDT, GREMI UMR 7344 CNRS et Universite d’Orleans — We report here about experiments concerning the plasma based functionalization of plasma produced carbon nanotubes and free-standing graphenes. The influence of nitrogen and ammonia plasma on the surface properties is investigated, involving the role of the surface temperature on the functionalization procedure. The effect of the plasma treatment on the different carbon materials is analyzed by means of contact angle measurements, near edge x-ray absorption fine spectroscopy (NEXAFS) and XPS. We will discuss the importance of the plasma characteristics for the formation of amino groups and nitrogen incorporation in the material. The important issues concern: the formation of dangling bonds, destructive effects of plasma-surface interactions and recovery of the surfaces

3:45PM FT3.00002 Functionalization of plasma synthesized advanced carbons1, EVA KOVACEVIC, GREMI UMR 7344 CNRS and Universite d’Orleans, THIBAULT LABBAYE, JOHANNES BERNDT, GREMI UMR 7344 CNRS et Universite d’Orleans — We report here about experiments concerning the plasma based functionalization of plasma produced carbon nanotubes and free-standing graphenes. The influence of nitrogen and ammonia plasma on the surface properties is investigated, involving the role of the surface temperature on the functionalization procedure. The effect of the plasma treatment on the different carbon materials is analyzed by means of contact angle measurements, near edge x-ray absorption fine spectroscopy (NEXAFS) and XPS. We will discuss the importance of the plasma characteristics for the formation of amino groups and nitrogen incorporation in the material. The important issues concern: the formation of dangling bonds, destructive effects of plasma-surface interactions and recovery of the surfaces

1 This work was supported by National Science Foundation (NSF Grant No. CBET-1249213).

4:40PM FT3.00005 Flickering of thoriated and lanthanized tungsten cathodes, THOMAS HOEIBING, PATRICK HERMANS, ANDRE BERGNER, CORNELIA RUHRMANN, Ruhr-University Bochum, HANNES TRAXLER, INGRID WESEMANN, Plansee SE, JUERGEN MENTEL, PETER AWAKOWICZ, Ruhr-University Bochum — Tungsten cathodes in HID-lamps are commonly doped with rare earth oxides to reduce the work function Φ. A popular dopant ThO₂ decreases Φ from 4.55 eV to 3.0 eV and, therewith, reduces the cathode temperature. La₂O₃-cathodes seem to represent an alternative, since the reduction of Φ is comparable to that of thoriated cathodes. But a temporally unstable arc attachment can be observed at cathodes doped with La₂O₃. At thoriated cathodes, this flickering can also be detected, but less pronounced. It is attributed to a temporal increase of Φ, induced by a transient shortage of La at the cathode tip. The arc attachment moves from the tip to colder areas of the cathode, where a high amount of La is present. Reasons for a temporal increase of Φ can be attributed to an insufficient transport of oxides from the interior of the cathode and an insufficient return of vaporized La by an ion current from the arc plasma to the cathode. Enrichments of La / Th compounds are formed on the cathode surface providing emitter material in case of a shortage at the tip. Cathode coverage and diffusion in the interior of the electrode, ThO₂- and La₂O₃-electrodes behave differently. Differences and their influence on the stability of the arc will be presented.
4:45PM FT3.00006 Performance and aging effects of automotive HID-Lamps when replacing thorium in the electrodes. ALEXANDER ALEXEJEV, ANDRE BERGNER, THOMAS HOEBING, CORNELIA RUHRMANN, Ruhr University Bochum, PETER FLESCH, OSRAM AG, Berlin, JUERGEN MENTEL, PETER AWAKOWICZ, Ruhr University Bochum, RUHR UNIVERSITY - OSRAM AG COLLABORATION — Tungsten electrodes in automotive HID-Lamps up to now are mostly doped with thorium dioxide (ThO2). The doping decreases the work function $\Phi$ of tungsten from 4.55 eV to 3.0 eV, thus leading to a reduced electrode temperature, resulting in an increased lifetime of the lamp. However, usage of thorium is no longer recommended due to complicated trade relationships and transportation issues. An alternative filling or doping is being searched for, which should replace thorium dioxide without affecting the lamp performance. The fillings/dopants are usually rare earth iodides/oxides respectively. Rare earths have similar physical properties as thorium in terms of electronegativity and adsorption energy. Theoretically, several of them can replace thorium. The resulting lamp performance is, however, greatly affected even by minor changes in the filling/doping. The effect of each new component has therefore to be studied by optical observation and electrode temperature measurements, as well as the aging effects of the investigated lamps.

5:00PM FT3.00007 Optically Pumped Lasing of Ar(4p→4s) Excited in Linear Microplasma Arrays at Atmospheric Pressure1, WILSON RAWLINS, KRISTIN GALBALLY-KINNEY, STEVEN DAVIS, Physical Sciences Inc. Andover MA, ALAN HOSKINSON, JEFFREY HOPWOOD, Electrical and Computer Engineering Department, Tufts University, Medford MA — The optically pumped rare-gas metastable laser is a chemically inert analogue to alkali laser systems. These devices require efficient generation of electronically excited metastable atoms in a continuous-wave electric discharge in flowing gas mixtures at elevated pressure. Linear arrays of microstrip resonators are well suited for this task. We have observed CW optical gain and lasing at 912 nm using linear micro-discharge arrays to generate metastable rare-gas atoms at atmospheric pressure. Ar(4s) metastables are generated in flowing Ar/He mixtures by low-power, CW linear array microplasmas operating near 900 MHz and 1 atm. The metastables are optically excited to selected states in the Ar(4p) manifold by a tunable, CW Ti:S laser. Collisional energy transfer within the manifold produces a population inversion. The Ar(4s) concentration and the optical gain are probed by tunable diode laser spectroscopy.

1Supported by the Air Force Research Laboratory and High Energy Laser Joint Technology Office

5:15PM FT3.00008 Plasma Formation During Operation of a Diode Pumped Alkali Laser (DPAL) in Cs1, NATALIA YU. BABAEVA2, University of Michigan, OLEG ZATSARINNY, KLAUS BARTSCHAT, Drake University, MARK J. KUSHER, University of Michigan — Diode pumped Alkali Lasers (DPALs) produce laser action on the resonant lines of alkali atoms. Diode lasers resonantly pump the $^2P_{3/2}$ state of the alkali atom which is collisionally relaxed to the $^2P_{1/2}$ state which then lases to the ground state $^2S_{1/2}$. The low optical quality of high power semiconductor diode lasers is converted into high optical quality laser radiation from the alkali vapor. The Cs DPAL system using Ar/Cs/C2H6 mixtures has shown promising results. (C2H6 is the collisional relaxant.) In other studies, resonant excitation of alkali vapor by low power lasers has been used to produce highly ionized channels, initiated through associative ionization and superelastic electron heating. The issue then arises if plasma formation occurs during DPAL by similar mechanisms which would be detrimental to laser performance. In this paper, we report on results from a computational study of a DPAL using Cs vapor. The global model addresses quasi-cw pumping of the Ca($^2P_{3/2}$) state by laser diodes, and includes a full accounting of the resulting electron kinetics. To enable this study, the B-spline R-matrix (BSR) with pseudostates method was employed to calculate electron impact cross sections for Cs. We found that for pump rates of many to 10 kW/cm$^2$, plasma densities approaching $10^{13}$ cm$^{-3}$ occur during laser oscillation with higher values in the absence of laser oscillation.

1Supported by DoD High Energy Laser Mult. Res. Initiative and NSF.
2Now with Joint Institute for High Temperatures RAS, Moscow, Russia

5:30PM - 5:30PM –
Session GT1 Poster Session I (17:30-19:30) Exhibit Hall -

GT1.00001 Air mode waveguide cavity with hybrid tunable plasma switching elements for K-band microwaves, BENJAMIN WANG, MARK CAPPPELLI, Stanford University — A tapered holey waveguide with an air mode cavity was designed with plasma switching elements. The propagation of microwaves in this device was investigated experimentally and computationally. Finite difference time domain (FDTD) simulations confirm unique resonance modes for plasma on and plasma off states. Integration of low-pressure plasma elements into this hybrid device allowed for controllable propagation of electromagnetic waves, showing tunable band gaps and resonance states.

GT1.00002 Difference in Rotational Temperatures between Neutral Molecules and Molecular Ions of Low-Pressure Discharge N2-O2 Plasmas, HIROSHI AKATSUKA, HIROKAZU KAWANO, KOICHI NAOI, HAO TAN, ATSUSHI NEZU, HARUAKI MATSUURA, Tokyo Institute of Technology — For a microwave discharge nitrogen plasma with its discharge pressure about 1 Torr, our OES measurement showed that the rotational temperature of N$_2^-$ B state by the first negative system (1NS) is about 1.5 times higher than that of N$_2$ C state by the second positive system (2PS). Meanwhile, it is found that the rotational temperature of O$_2^+$ b state by 1NS is almost the same as that of O$_2$ b state by the atmospheric absorption band, which is quite different from N$_2$ plasma. We consider that the rotational temperature of the ground state O$_2^+$ X ion should be higher than that of O$_2^+$ b state due to difference in the internuclear distance, where that of the O$_2^+$ b state is much larger than that of the ground state O$_2^+$ X. The angular momentum of both X and b states are almost conserved before and after the 13 eV impact excitation due to small mass of an electron. Therefore, the rotational temperature of the X state of O$_2^+$ ion should be estimated to be about 1.3 times that of O$_2^+$ b state. This value gives a similar result with that of nitrogen plasma, where the internuclear distances of B and X states of N$_2$ are almost the same. It is considered that the ground-state molecular ion has higher rotational temperature than neutral molecule.
**GT1.00003 Global Model of a Fast Ionization Wave in Helium**

BENJAMIN YEE, EDWARD BARNAT, Sandia National Laboratories. JOHN FOSTER, University of Michigan — Technical challenges inhibit a complete examination of fast ionization waves via empirical means. The high-voltage pulses used to excite these waves can be on the order of nanoseconds or less. Such short timescales require instruments with exceptional sensitivity and bandwidth, but these may not be available or may not exist. In order to more completely understand the energetics of the fast ionization wave, a global model of a helium discharge was developed. We present the results of the model predictions and a comparison to experimental measurements when possible. The model follows the trajectories of electrons in the plasma and predicts the electron density and temperature as a function of the magnetic field strength in the range 0-300 Gauss. It was established that a rigorous kinetic treatment, which accounts for the plasma ion and electron dynamics, is required for accurate description of the plasma.

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**GT1.00004 Modeling the impact of magnetic field on plasma parameters in an electron beam generated argon plasma**

GEORGE PETROV, DAVID BORIS, TZVETELINA PETROVA, SCOTT WALTON, Naval Research Laboratory — A spatially averaged model of an electron beam generated plasma is developed to model the impact of an externally applied magnetic field on the formation of the electron energy distribution function in an argon background. The model is based on numerical solution of the electron Boltzmann equation that is self-consistently coupled to a set of rate balance equations for electrons and argon ions. The confining effect of the magnetic field is studied theoretically by calculating the electron energy distribution function, electron density and temperature as a function of the magnetic field strength in the range 0-300 Gauss. It was established that a rigorous kinetic treatment, which accounts for the plasma ion and electron dynamics, is required for accurate description of the plasma.

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**GT1.00005 Controlling the Electron Energy Distribution Function Using an Anode**

SCOTT D. BAALRUD, University of Iowa, EDWARD V. BARNAT, MATHEW M. HOPKINS, Sandia National Laboratory — Positively biased electrodes inserted into plasma influence the electron energy distribution function (EEDF) by providing a sink for low energy electrons that would otherwise be trapped by ion sheaths at the chamber walls. We develop a model for the EEDF in a hot filament generated discharge in the presence of positively biased electrodes of various surface areas, and compare the model results with experimental Langmuir probe measurements and particle-in-cell simulations. In the absence of an anode, the EEDF is characterized by a cool trapped population at energies below the sheath energy, and a comparatively warm tail population associated with the filament primaries. Anodes that are small enough to collect a negligible fraction of the electrons exiting the plasma have a little impact on the EEDF, but as the anode area approaches \( \sqrt{m_e/m_i} A_w \), where \( A_w \) is the chamber wall area, the anode collects most of the electrons leaving the plasma. This drastically reduces the density of the otherwise trapped population, causing an effective heating of the electrons and a corresponding density decrease. A global model is developed based on the EEDF model and current balance, which shows the interconnected nature of the electron temperature, density, and plasma potential.

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**GT1.00006 Effect of mass and charge of ionic species on spatio-temporal evolution of transient electric field in CCP discharges**

SARVESHWAR SHARMA, SANJAY KUMAR MISHRA, PREDHIMAN KAW, Institute for Plasma Research, Bhat, Gandhinagar, Gujarat, India, MILES TURNER, Dublin City University, Galnevin, Dublin 9, Ireland, SHANTANU KUMAR KARKARI, Institute for Plasma Research, Bhat, Gandhinagar, Gujarat, India — The formation of capacitive sheath and existence of the transition electric field between sheath edge and bulk plasma in RF-CCP discharge is predicted by Kaganovich (PRL 89, 265006 2002); such structures are sensitive to the plasma composition. On the basis of semi-infinite particle-in-cell (PIC) simulation the effect of charge and mass of ionic species on the spatio-temporal evolution of the transient electric field and phase mixing phenomena in linear and weakly nonlinear regime has been explored. As an important feature, the simulation results predict that the maximum amplitude of the transient electric field decreases while the potential structure approaching to the electrode with increasing ionic mass and charge. The excitation of wave like structures in the transition region and efficient energy transport to the bulk region of CCP discharges in a nonlinear regime has also been predicted.

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**GT1.00007 Tuning of Electron Energy and Density in a Double-Pulsed Argon Plasma**

RICKY TANG, EDWARD BARNAT, PAUL MILLER, Sandia National Laboratories — The ability to tune the properties of a plasma was demonstrated with a double-pulsed positive column discharge. The plasma is generated by the first voltage pulse, which sets the peak electron density. A subsequent voltage pulse is applied during the afterglow to achieve independent tuning of the electron energy. Experiments were conducted over a range of voltage pulse amplitudes. Microwave resonant cavity (MRC) measurements of electron density and temperature demonstrated operating conditions, such as relative pulse amplitudes and pulse width, where the electron temperature can be independently adjusted without affecting the density. Laser absorption measurements of the concentration of the 1S4 metastable states of argon corroborate the MRC measurements, demonstrating an increase in metastable density while the electron density continues its decay after the initial pulse. Electron drift velocity calculation also shows the dependence of the electron energy on the second voltage pulse. Results from the two diagnostics demonstrate the ability to tune the E/N ratio of the plasma, and hence the mean electron energy, independently of the density. This work was supported in part by the Department of Energy Office of Fusion Energy Science Contract DE-SC0001939.

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**GT1.00008 Controlling plasma properties in a dc discharge with two anodes and a cold cathode**

VLADIMIR DEMIDOV, WVU and SPbGU, EVGENY BOGDANOV, SPbGU, MARK KOEPEKE, WVU, ANATOLY KUDRYAVTSEV, SPbGU, IYA KURLYANDSKAYA, SPbU SES, OLGA STEPANOVA, SPbGU — Understanding the interaction between sheath and contacting electrodes is important for predicting plasma kinetics and controlling plasma properties for various applications where the plasma is volumetrically confined. To demonstrate controlling electron temperature in nonlocal plasma, modeling a dc discharge with cold cathode and application of different voltages to the discharge anodes has been performed. The modeling has been conducted in low-pressure argon gas discharge. It has been demonstrated that applied voltage can modify trapping within the device volume the energetic electrons arising from atomic and molecular processes in the plasma and emitted from the cathode due to ion bombarding. This leads to transformation of heat slow electrons by energetic electrons and as a result modifies the electron temperature. This also leads to modification of spatial distribution of densities of charged and excited metastable atom particles and plasma potentials. The above effects have also been experimentally demonstrated in short (without positive column) dc discharges of various constructions.

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1 This work was supported in part by the Department of Energy Office of Fusion Energy Science Contract DE-SC0001939.

2 This work was supported by the NRL 6.1 Base Program.

3 Work supported by the NRL 6.1 Base Program.

4 This work was supported by the Office of Fusion Energy Science at the U.S. Department of Energy under contract DE-AC04-94SL85000, and by the University of Iowa Old Gold Program.

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GT1.00009 Experimental study of low-temperature plasma transport across a magnetic filter

ROMAIN BAUDE, FREDDY GABORIAU, GERMAN HAGELAAR, LAPLACÉ, CNRS and University of Toulouse — Magnetized low-temperature plasmas are widely used in fields like space propulsion, materials processing or neutral beam injection. Charged particle transport in these plasmas is complex and still not fully understood. This paper presents an experimental study of plasma transport across a magnetic barrier as used in various (negative) ion sources. The aim is to obtain experimental data that are sufficiently detailed to provide direct insight into the physical principles of the cross-field transport and to validate numerical simulations. For this purpose we developed a dedicated laboratory set-up featuring an inductive argon discharge connected with a magnetic filter region. A segmented wall probe was used to measure the spatial profiles of the electron and ion current densities across the filter, while the plasma parameters were measured at different positions with a Langmuir probe. Measurements were performed for different gas pressures, magnetic field strengths, and bias voltages. The results clearly demonstrate the transition between a collisional regime where the electron current varies as 1/BZ and a bounded-drift regime with asymmetric electron temperature and 1/B current.

1This work is supported by French National Research Agency (project METRIS ANR-11-JS09-008)

GT1.00010 Breakdown in vapors of alcohols: methanol and ethanol

ZORAN IJ. PETROVIC, JELENA SIVOS, NIKOLA SKORO, DRAGANA MARIC, GORDANA MALOVIC, Institute of Physics, University of Belgrade — Breakdown data for vapors of the two simplest alcohols – methanol and ethanol — are presented. The breakdown is achieved between plan-parallel electrodes, where cathode is made of copper and anode is a thin film of platinum deposited on quartz window. Diameter of electrodes is 5.4 cm and electrode gap 1.1 cm. We compare breakdown voltages (Paschen curves) for methyl and ethyl alcohol in the pressure range 0.1 - 2 Torr. In both vapors, the pressure is kept well below the vapor pressure, to prevent formation of liquid droplets. For each point of Paschen curves corresponding axial profiles of emission are recorded by ICCD camera in visual part of the spectra. Axial intensity distributions reveal important processes of excitation. Both vapors show strong emission peak near the cathode at all pd values covered by measurements, which indicates that excitation by ions and fast neutrals play important role in the discharge. Preliminary spectrally resolved measurements of the discharge structure with optical filters show that dominantly emission comes from CH band at 431 nm. There is a very low intensity of Hα emission detected in ethanol vapor at high E/N, while it is much stronger in methanol even at lower E/N. It is interesting to note that Hα emission in methanol exhibits exponential increase of intensity from the cathode to the anode, so it comes mainly from excitation by electrons, not heavy particles.

1Supported by MESTD projects ON171037 and III41011.

GT1.00011 Electron heating due to coulomb collisions between slow and intermediate electrons in DC glow discharges

STEPAN ELISEEV, ANATOLIY KUDRYAVTSEV, Saint Petersburg State University — As is known, the electrons in the cathode glow discharge plasma (negative glow and Faraday dark space) can be divided into three groups - slow, intermediate and fast electrons. Slow electrons, having maximum density, provide quasi-neutrality. They're locked in a potential well and have Maxwellian energy distribution. Fast electrons gain their energy in the cathode fall and maintain sufficient ionization in discharge. Intermediate electrons originate during ionization by fast electrons and carry current in the discharge. They have energies up to the threshold of inelastic collisions in the gas. At the same time they carry out their energy to the walls of the discharge and spend it on elastic collisions with gas atoms and Coulomb collisions with slow electrons and heat them. The amount of heating depends on the degree of ionization of gas, pressure, discharge tube size etc. The paper presents the results of a study on the impact of the heating on temperature and concentration of slow electrons in glow discharge.

GT1.00012 Investigation of power dependence of electron density for various pressures

JUNE YOUNG KIM, DONG-HWAN KIM, Department of Nanoscale Semiconductor Engineering, Hanyang University, Seoul 133-791, South Korea, JU HO KIM, SANG-BUM JEON, CHIN-WOOK CHUNG, Department of Electrical Engineering, Hanyang University, Seoul 133-791, South Korea — Experimental observation of the electron density variation in inductively coupled plasma with the electron energy probability function was performed at various gas pressures at two RF input powers (25 W, 200 W). The measured electron energy probability functions (EEPFs) at high power discharges (200 W) showed a Maxwellian distribution, while evolution of the EEPFs from a bi-Maxwellian distribution to a Druyvesteyn-like distribution was observed at low RF powers (25 W) with increasing pressure. A discrepancy of the electron density variation between the two RF input powers was observed, and it was explained by the modified collisional loss and the Bohm velocity from the electron energy probability functions of the bi-Maxwellian distribution and the Druyvesteyn-like distribution.

GT1.00013 DBCC Software as Database for Collisional Cross-Sections

DANIEL MOROZ, University of Pennsylvania, PAUL MOROZ, Tokyo Electron U.S. Holdings, Inc. — Interactions of species, such as atoms, radicals, molecules, electrons, and photons, in plasmas used for materials processing could be very complex, and many of them could be described in terms of collisional cross-sections. Researchers involved in plasma simulations must select reasonable cross-sections for collisional processes for implementing them into their simulation codes to be able to correctly simulate plasmas. However, collisional cross-section data are difficult to obtain, and, for some collisional processes, the cross-sections are still not known. Data on collisional cross-sections can be obtained from numerous sources including numerical calculations, experiments, journal articles, conference proceedings, scientific reports, various universities' websites, national labs and centers specifically devoted to collecting data on cross-sections. The cross-sections data received from different sources could be partial, corresponding to limited energy ranges, or could even not be in agreement. The DBCC software package was designed to help researchers in collecting, comparing, and selecting cross-sections, some of which could be constructed from others or chosen as defaults. This is important as different researchers may place trust in different cross-sections or in different sources. We will discuss the details of DBCC and demonstrate how it works and why it is beneficial to researchers working on plasma simulations.

GT1.00014 Anode Sheath and Double Layer Solutions with Ionization

BRETT S. SCHEINER, SCOTT D. BAALRUD, Department of Physics and Astronomy, University of Iowa — When an electrode in a plasma is biased more positive than the plasma potential it attracts electrons and repels ions forming a region of negative space charge (electron sheath). Ballistic electrons moving towards this anode gain energy equal to the difference in electrostatic potential energy, $\Delta \phi = \phi(x) - \phi_{\text{plasma}}$, with a maximum of $\phi_{\text{anode}} - \phi_{\text{plasma}}$. When $\phi_{\text{anode}}$ is large enough, electrons can gain enough energy to ionize neutral atoms through electron impact ionization. This leads to a layer of increased ion density near the anode, which can exceed the local electron density at large enough anode biases forming a double layer. We model the sheath potential profile using Poisson’s equation with a fluid model for the electron density in the case without ionization and formulate an integral equation for the case with ionization where the ion density depends on an integral from $\phi(x)$ to $\phi_{\text{anode}}$. An analytic form of the sheath electric field is obtained for the case without ionization and we demonstrate that it asymptotically agrees with the Child-Langmuir solution. We numerically obtain double layer solutions when including ionization and show that the potential profile expands beyond that of the Child-Langmuir solution.

1This work was supported by the Office of Fusion Science at the U.S. Department of Energy under contract DE-AC04-94SL85000.
GT1.00015 Does the Bohm Criterion have meaning for collisional plasmas?*, GREG SEVERN. University of San Diego, Department of Physics, CHI-SHUNG YIP, SIROUS NOURGOSTAR, NOAH HERSHKOWITZ, University of Wisconsin-Madison, Department of Engineering Physics — Theorists view the Bohm criterion as approximately true, holding only for collisionless plasmas. The question of whether there exists a collisionally modified Bohm Criterion (CMBC) is often answered in the negative, and it is only a question of how the Bohm Criterion fails for the case of finite collisionality. The question is of importance considering that nearly all practical plasma processing applications involve plasmas of finite collisionality. There is, however, very little experimental work to help choose between competing models of how Bohm’s criterion fails. The question of critical importance is this: in plasmas of finite collisionality, do ions reach the Bohm speed at the location where the quasineutral plasma ends and where space charge appears? We have begun to examine the question experimentally in single ion species plasmas, and our goal is to vary the ion-neutral mean free path $\lambda$ within the interval $1 < \lambda/\lambda_D < 10^3$, where $\lambda_D$ is the Debye length, and to present both plasma potential data and ion velocity distribution function profiles, measured by emissive probes and by LIF, respectively, to help us understand and assess the validity of theoretical claims.

1Work supported by NSF grant no. PHY-1206421, CBET-0903783, and CBET-0903832, and U.S. Department of Energy (DOE) Grant Nos. DE-FG02-97ER54437 and DE-FG02-03ER54728

GT1.0016 First steps towards the reaction kinetics of HMDSO in an atmospheric pressure plasma jet in argon*, DETLEF LOFFHAGEN, MARKUS M. BECKER, RÜDIGER FOEST, JAN SCHÄFER, FLORIAN SIGENEGER, INP Greifswald, Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany — Hexamethyldisiloxane (HMDSO) is a silicon-organic compound which is often used as precursor for thin-film deposition by means of plasma polymerization because of its high deposition rate and low toxicity. To improve the physical understanding of the deposition processes, fundamental investigations have been performed to clarify the plasma-chemical reaction pathways of HMDSO and their effect on the composition and structure of the deposited film. The current contribution represents the main primary and secondary plasma-chemical processes and their reaction products in the effluent region of an argon plasma jet at atmospheric pressure. The importance of the different collision processes of electrons and heavy particles are discussed. Results of numerical modelling of the plasma jet and the Ar-HMDSO reaction kinetics indicate that the fragmentation of HMDSO is mainly initiated by collisions with molecular argon ions, while Penning ionization processes play a minor role for the reaction kinetics in the effluent region of the jet.

The work has been supported by the German Research Foundation (DFG) under grant LO 623/3-1.

GT1.00017 Optical emission study of ion composition in an inductively coupled oxygen plasma†, NATHANIEL LY, JOHN B. BOFFARD, CHUN C. LIN, AMY WENDT, University of Wisconsin-Madison, SVETLANA RADOVANOVA, HAROLD PERSING, ALEXANDRE LIKHANSKII, Applied Materials, Silicon Systems Group, Varian Semiconductor Equipment — The success of ion implantation to precisely modify substrate properties requires control of the incident ion energies to achieve the desired depth of the implanted ions. Oxygen plasmas generally contain both O+ and O2+ ions, and in plasma immersion ion implantation (PIII) of oxygen, the two will produce different concentration depth profiles due to their different energy/mass ratios. Predicting the overall profile thus requires knowledge of the relative fluxes of the two ion species. Here we combine experiment and modeling to investigate the feasibility of using non-invasive optical emission spectroscopy (OES) to monitor O+ and O2+ abundances in an oxygen inductively-coupled plasma. Measurements of multiple O, O2, O3+, and O2− emissions were made as a function of pressure (1-30 mTorr) and power (500-2000 W). While the O2− emissions were relatively intense, the O+ emissions were very weak for all conditions examined. Emissions from both ion species were highest at low pressures and at the highest power levels, but the O+ / O2− emission ratio varied little with plasma conditions.

†This work was supported in part by NSF grant PHY-1068670.

GT1.00018 Kinetic study of the NO formation in pulsed air-like low-pressure dc plasmas: measurement and numerical modelling, MARKO HUEBNER, SERGEJ GORCHAKOV, DETLEF LOFFHAGEN, INP Greifswald, Germany, OLIVIER GUIATELLE, LPP, Ecole Polytechnique, France, DANIEL MARINOV, Open University, UK, ANTOINE ROUSSEAU, LPP, Ecole Polytechnique, France, JUERGEN ROEPCKE, INP Greifswald, Germany, INP GREIFSWALD, GERMANY TEAM, LPP, ECOLE POLYTECHNIQUE, FRANCE COLLABORATION — The formation of NO has been studied measuring the temporal evolution of the density of NO, NO2 and NO by high time-resolved quantum cascade laser absorption spectroscopy. The densities of these nitrous oxides have been measured in synthetic air as well as in air with an admixture of 1% of NO and N2O, respectively, at a pressure of 1.33 mbar and mean currents between 50 and 150 mA. The measured time-dependent densities of NO, NO2 and N2O have been compared with those calculated by means of a density functional theory code. The modelling approach includes the coupled solution of the time-dependent electron Boltzmann equation and a system of rate equations for various heavy model particles. In general, measured and calculated results show good qualitative agreement. An important distinction of the NO density evolution during the plasma pulse and the early afterglow are found. The densities of NO2 and N2O decrease exponentially during the plasma pulse and remain almost constant in the afterglow. The admixture of N2O has a remarkable impact on the NO production during the ignition of the plasma. The dominating processes are presented and discussed.

GT1.00019 Surface mechanisms during cryogenic etching of silicon with SF6/O2 inductively coupled plasmas, STEFAN TINCK, University of Antwerp, THOMAS TILLOCHE, Université d’Orléans, ANNEMIE BOGAERTS, University of Antwerp, PLASMANT - GREMI COLLABORATION — A computational and experimental study is performed to obtain better insight in the surface reactions occurring during the etching of silicon with SF6/O2 inductively coupled plasmas at cryogenic conditions. Cryogenic etching is a promising technique to etch ultra-high aspect ratio nanoscale trenches for fabricating microchips. During cryoetching, the substrate (i.e., a silicon wafer) is cooled down to about -100 °C. Cryoetching has some advantages compared to the well-known Bosch process, like no scalloping of sidewalls and no material residues on the reactor walls. A disadvantage of cryoetching is its sensitivity to operating conditions such as substrate temperature and fraction of oxygen in the SF6/O2 mixture. During etching, the sidewalls of the trenches are passivated with a SiF4 layer which prevents lateral etching. When heating the wafer to room temperature, the passivation layer desorbs automatically, leaving a smooth and clean trench. The mechanism of the formation and desorption of this passivation layer at cryogenic temperatures is not well understood and is investigated here. A 2-dimensional hybrid Monte Carlo Fluid plasma model linked with Molecular Dynamics simulations is used for a computational investigation while results are validated by experimentally measured etch rates. The focus is on the reaction mechanisms during cryoetching in comparison with conventional room temperature etching.

GT1.00020 Sum frequency generation spectroscopy of interfacial water molecules influenced by plasma-generated radicals, TAKAHIRO KONDO, TSUYOHITO ITO, Osaka Univ. — We report the effects of radicals generated by plasma on the structure of water molecules in the air/water interfacial region by sum frequency generation (SFG) spectroscopy. SFG spectroscopy gives molecular level information for the interfacial region. We used a visible pulse laser (wavelength: 532 nm) and a tunable IR pulse laser (wavenumber: 2850-4000 cm−1) for SFG spectroscopy. Radicals are generated by a dielectric barrier discharge (DBD) in the air, and supplied to the water surface. We found that the peak at about 3700 cm−1 in the SFG spectrum tends to decrease when the DBD is generated and the radicals are supplied. When the DBD is turned off, the SFG signal recovers. According to previous studies, the SFG peak at about 3700 cm−1 is assigned to the stretch mode of free OH in interfacial water molecules. We believe that the radicals interact with the free OH and disturb the vibration, leading to a decrease of the SFG signal when the DBD is generated. When the DBD is turned off, the SFG signal recovers because there are much less radicals in the air. Details on the experimental results and discussions will be presented at the conference.
GT1.00021 Effects of the Fabrication and Preparation Processes on the SEY of Niobium SRF Cavities, MILOS BASOVIC, Old Dominion University, CAS, ANA SAMOLOV, University of Massachusetts Boston, SVETOZAR POPOVIC, LEPSHA VUSKOVIC, Old Dominion University, CAS — We are reporting progress on effects of the plasma treated surface on the Secondary Electron Yield (SEY) of Niobium (Nb) samples. Fabrication and preparation processes affect intrinsic quality factor (Q factor) to a great extent contributing to multipacting. Multipacting is a resonant phenomenon occurring as an electron buildup and degrading the maximum Q factor achievable by cavity. Apart from the initial impurities of the Nb sheet metal used for cavity fabrication, additional inclusions on the surface of the cavity are added by forming and welding of the components. Operation of the cavities is affected by these inclusions in such a way that it decreases the overall performance of the accelerators. Performance of the cavities can be improved by manipulating the parameters or by mitigating the consequences of the fabrication and preparation processes. We are testing the influence of the electron beam welding and various surface treatments on Nb samples by measuring the SEY of coin-like samples with the surface treated in several different methods. The system is designed to measure energy distribution SEY of the samples under several incident angles. Comparison is being made between non-treated and treated surface, as well as effects of each treatment on SEY of the surface. Our aim is to show which of the surface treatments or combination of them are beneficial to reducing SEY of the cavity surface.

GT1.00022 Laser-induced Fluorescence and Optical Emission Spectroscopy for the Determination of Reactive Species in the Effluent of Atmospheric Pressure Low Temperature Plasma Jets, XUEKAI PEI, HuaZhong University, HAMID RAZAVI, Old Dominion University, XINPEI LU, HuaZhong University, MOUNIR LAROUSSI, Old Dominion University — OH radicals and O atoms are important active species in various applications of room temperature atmospheric pressure plasma jet (RT-APPJ). So the determination of absolute density of OH radicals and O atoms in RT-APPJs is necessary. In this work, the time and spatially resolved OH radicals and O atoms are measured using the laser-induced fluorescence (LIF) technology [1]. In addition, the spatial distribution of the emitting species along the axial direction of the jet is of interest and is measured using optical emission spectroscopy. The absolute OH density of the RT-APPJ is about 2.0 x 10^{13} cm⁻³ at 5 mm away from the plasma jet nozzle and 1 μs after the discharge. The OH density reaches a maximum when H₂O concentration in helium gas flow is about 130ppm. In order to control the OH density, the effect of voltage polarity, applied voltage magnitude, pulse frequency, pulse width on the OH density are also investigated and discussed. O atoms are investigated by TA-LIF. It is demonstrated that the O atoms density reaches a maximum when O₂ percent is about 0.3% in pure He and the lifetime of O atoms in RT-APPJ is much longer (up to dozens of ms) than OH radicals.


GT1.00023 Measurement of Gas Temperature in Negative Hydrogen Ion Source by Wavelength-Modulated Laser Absorption Spectroscopy³, S. NISHIYAMA, K. SASAKI, Hokkaido University, H. NAKANO, M. GOTO, Y. KISAKI, K. TSUMORI, National Institute for Fusion Science, NIFS-NBI TEAM — Measurement of the energy distribution of hydrogen atom is important and essential to understand the production mechanism of its negative ion (H⁻) in cesium-seeded negative ion sources. In this work, we evaluated the temperature of atomic hydrogen in the large-scale arc-discharge negative hydrogen ion source in NIFS by wavelength-modulated laser absorption spectroscopy. The laser beam was passed through the adjacent region to the grid electrode for extracting negative ions. The frequency of the laser was scanned slowly over the whole range of the Doppler width (100 GHz in 1s). A sinusoidal frequency modulation at 600 Hz with a width of 30 GHz was superposed onto the slow modulation. The transmitted laser was detected using a photodiode, and its second harmonic component of the sinusoidal modulation was amplified using a lock-in amplifier. The obtained spectrum was in good agreement with an expected spectrum of the Doppler-broadened Balmer-α line. The estimated temperature of atomic hydrogen was approximately 3000 K. The absorption increased with the arc-discharge power, while the temperature was roughly independent of the power.

³This work is supported by the NIFS Collaboration Research Program NIFS13KLER021.

GT1.00024 Correlating Metastable-Atom Density, Reduced Electric Field, and Electron Energy Distribution in the Early Stages of a 1-Torr Argon Discharge¹, J.B. FRANEK, S.H. NOGAMI, M.E. KOEPKE, V.I. DEMIDOV, W Virginia Univ, E.V. BARNAT, Sandia Nat’l Labs — Temporal measurement of electron density, metastable-atom density, and reduced electric field are used to approximate certain reaction rate constants [1] for electron-atom collision excitation in a 1-Torr positive column of argon plasma. This allows us to relate the observed 420.1nm to 419.8nm line-intensity ratio to plasma parameters by invoking a plausible assumption regarding the shape of the electron energy distribution function (EEDF) throughout the discharge [1]. We show that these reaction rate constants agree well with experimental observations in the late stages of the pulse, but we do not emphasize the late-stage behavior here. Instead, we address discrepancies in the initiation and transient phases of the discharge. We examine three assumptions made in the model to see if the assumptions are violated in these two stages of the discharge: (1) The stepwise excitation from the 1s⁴ and 1s² resonant states is negligible; (2) The numerical model designed for a 5-millitorr plasma is applicable to our 1000-millitorr plasma; and (3) The EEDF is bi-Maxwellian and is modified only slightly due to the presence of electrons or metastable-atoms in the discharge. We conclude that diagnostic signatures for electron density, metastable density, and reduced electric field can be quantitatively interpreted by this correlation at all stages of the discharge. [1] Adams et al. Phys. Plasmas 19, 023510 (2012) *also St. Petersburgh Univ.

¹Work supported by DOE grant DE-SC0001939.

GT1.00025 Optical emission diagnostics for plasma parameters in pulse-modulated argon capacitively-coupled discharges⁵, SHICONG WANG, JOHN B. BOFFARD, CHUN C. LIN, AMY E. WENDT, University of Wisconsin-Madison — Pulsing of discharge power in low pressure rf plasma is a means to improve materials processing outcomes. Plasma-surface interactions depend on the relative fluxes of ions, reactive neutrals and photons, which can be controlled by adjusting pulse frequency and duty cycle, due their effect on plasma properties, particularly the electron energy distribution. We report on an optical emission spectroscopy (OES) based plasma diagnostic to characterize the time evolution of plasma properties within the pulse cycle for two systems: a pulsed capacitively-coupled plasma (CCP), and a pulsed CCP in combination with a continuous-wave (cw) inductively coupled plasma (ICP); Typical conditions: 30 mTorr Ar, 13.56 MHz rf power (400 W peak CCP and 500 W ICP) and 1 kHz pulse frequency. We quantify the trade off between time resolution versus uncertainty in measured OES intensities. Because only a small fraction of CCP rf power contributes to electron heating, the method is limited by relatively low absolute OES intensities for the CCP-only case, and small incremental changes in intensity when the pulsed CCP is combined with the cw ICP. Nevertheless, with sufficient signal averaging, even subtle changes in parameters induced by the CCP in the latter case can be quantified.

⁵This work was supported in part by NSF grant PHY-1068670.
GT1.00026 Diagnostics of nonlocal plasmas: advanced techniques. ALEXANDER MUSTAFAEV, ARTIOMY GRABOVSKYI, ANASTASIYA STRAKHOVA, National University of Mineral Resources “Mining,” Department of General and Technical Physics, VLADIMIR SOUKHOMLINOV, Saint-Petersburg State University, Department of Physics — This talk generalizes our recent results, obtained in different directions of plasma diagnostics. First-method of flat single-sided probe, based on expansion of the electron velocity distribution function (EVD) in series of Legendre polynomials. It will be demonstrated, that flat probe, oriented under different angles with respect to the discharge axis, allow to determine full EVD in nonlocal plasmas. It is found that a cylindrical probe is unable to determine full EVD. We propose the solution of this problem by combined using the kinetic Boltzmann equation and experimental probe data. Second-magnetic diagnostics. This method is implemented in knudsen diode with surface ionization of atoms (KDSI) and based on measurements of the magnetic characteristics of the KDSI in presence of transverse magnetic field. Using magnetic diagnostics we can investigate the wide range of plasma processes: from scattering cross-sections of electrons to plasma-surface interactions. Third-noncontact diagnostics method for direct measurements of EVD in remote plasma objects by combination of the flat single-sided probe technique and magnetic polarization Hanley method.

GT1.00027 Radially resolved spectroscopic analysis of positive streamers under transient luminous events conditions. VACLAV PRUKNER, Institute of Plasma Physics AS CR, v.v.i., Department of Pulse Plasma Systems, Zs Laznokoun 3, 18200 Prague, Czech Republic, TOMAS HODER, Leibniz Institute for Plasma Science and Technology - IAP Greifswald, Felix- Hausdorff-Str. 2, 17489 Greifswald, Germany, MILAN SIMEK, Institute of Plasma Physics AS CR, v.v.i., Department of Pulse Plasma Systems, Zs Laznokoun 3, 18200 Prague, Czech Republic — The Transient Luminous Events (TLE) are huge electrical discharges appearing at the upper atmosphere. Sufficiently spatially and temporally resolved spectroscopy is currently one of the very few methods how to get to closer to the basic TLES parameters. In this study, triggered positive streamers were operated in volume barrier discharge with 4 cm gap fed with synthetic air at pressures between 8.98 and 0.16 torr corresponding to equivalent TLE altitudes ranging from 30 to 60 km, respectively. Time resolved axial and radial emission profiles of streamer channel were collected by scanning the discharge via fast photo-multiplier and spectral band-pass filters. Depending on different streamer velocities, different widths of the streamers were measured. Obtained data were analyzed in order to estimate values of the streamer head electric field with radial resolution.

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GT1.00028 Measuring of the nonlocal EDF of penning electrons by the wall electrode in the plasma afterglow. ANATOLY KUDRYAVTSEV, KIRILL KAPUSTIN, ALMAZ SAYFUTDINOV, St. Petersburg State University — In [1] was patented ionization detector for gas analysis, based on the method of collisional electron spectroscopy (CES), which allows working at high gas pressure. The CES method provides an opportunity to analyze energy of nonlocal electrons released during Penning ionization of atomic or molecular impurities by metastable helium atoms. In this case, the EDF of fast electrons will be narrow peaks that correspond to the energies of their appearance in Penning ionization. To realize the CES method at high (atmospheric) pressure the plasma gap must be small L <0.1 mm. In this condition the traditional Langmuir probe is impossible to use for measuring the EDF. To overcome this difficulty in [1] was proposed to use afterglow plasma and one of the electrodes as a measuring probe for the registration of EDF of fast penning electrons. In this paper we simulate the afterglow of argon discharge between parallel electrodes and show that EDF and electron sources of Penning ionization are determined by the first derivative of the current to the wall electrode with respect to potential. This work was supported by RSCF and SPbSU.


GT1.00029 Time-resolved measurements of energy distributions for mass-identified ions in low pressure plasmas. DAVE SEYMOUR, ALAN REES, TOM RUSSELL, CLAIRE GREENWOOD, Hiden Analytical, HIDDEN TEAM — The direct measurement of energy distributions for mass-identified positive and negative ions arriving at target surfaces in plasma reactors has produced much useful information. The measurements have been, in the great majority of cases, of the time-averaged distributions even when the applied power to the plasma has been pulsed. Time-resolved data particularly during initiation and decay of pulsed plasmas would be advantageous. To facilitate such studies we have incorporated a Multi-Channel Scaler device into the ion detector system of a Hiden EQP instrument. Preliminary data which illustrate the capabilities of the new equipment will be presented. The data were obtained for a number of typical reactor systems. For the first of these the plasma was RF powered, typically at 20 Watts, in nitrous oxide at a pressure of 20 mTorr. The energy distributions for N2O+, NO+ and O+ and O- ions were measured throughout the duration of a pulsing cycle with particular emphasis on the ignition and decay of the plasma. The distributions show considerable detail and clear differences between the behaviour of the different ions which reflect differences in their production and decay mechanisms.

GT1.00030 Analysis of the harmonic currents in floating probes with dielectric films. KYUNG-HYUN KIM, Department of Electrical Engineering, Hanyang University, DONG-HWAN KIM, Department of Nanoscale Semiconductor Engineering, Hanyang University, JIN-YONG KIM, YU-SIN KIM, CHIN-WOOK CHUNG, Department of Electrical Engineering, Hanyang University — Plasma diagnostics using harmonic currents was firstly used to obtain the electron temperatures and ion densities. In this method, the electron temperature is proportional to the ratio of the harmonic currents due to the nonlinearity of the probe sheath. Harmonic currents are affected by input voltage, thus calculation of exact voltage across the sheath is important; the voltage is calculated using phase analysis of the probe current. However, in the case of the dielectric deposited probe, rapid decrease of the second harmonic current than expected is observed. To explain this effect, circuit analysis including non-linear elements is adopted, and the calculations using this analysis are compared with experimental results.

GT1.00031 On harmonic diagnostic method using two frequencies in a floating Langmuir probe. DONG-HWAN KIM, YOUNG-DO KIM, SUNG-WON CHO, YU-SIN KIM, CHIN-WOOK CHUNG, Hanyang University — Plasma diagnostic methods using harmonic currents analysis of floating probes were experimentally investigated. When dual-frequency voltage (ω1, ω2) was applied to a probe, various harmonic currents (ω1, ω2±ω1, ω2±ω2, ω1+ω2) were generated due to the nonlinearity of the probe sheath. The electron temperature can be obtained from the ratio of the two harmonics of the probe currents. According to the combinations of the two harmonics, the sensitivities in measurement of the electron temperature differs and this results in the difference in the electron temperature. From experiments and simulation, it is shown that the difference is caused by the random and systematic noise.

GT1.00032 Tunable external RF choke filter design for single Langmuir probe in RF discharges. SANGBUM JEON, YU-SIN KIM, DONG-HWAN KIM, CHIN-WOOK CHUNG, Hanyang University — The tunable external RF choke circuit was developed to compensate radio frequency (RF) fluctuation in single Langmuir probe measurement. This method consists of series circuit of the harmonic component of the driving frequency, and has high impedance at the resonance frequencies. The measured electron energy probability functions (EPPFs) from the single Langmuir probe with the external RF compensation circuit were obtained under various discharge conditions, such as gas pressures and RF powers. The EPPFs have highly populated low energy electrons with bi-Maxwellian EPPFs at low plasma density regime, compared to results from the uncompensated Langmuir probes. This method can also provide real-time tuning and thus, high quality EPPF measurement is possible even when the rf discharge condition is changed.
GT1.00033 Experimental investigation of plasma parameter profiles on wafer level with discharge gap lengths in an inductively coupled plasma. JU HO KIM, Department of Electrical Engineering, Hanyang University, Seoul, 133-791, Republic of Korea, YOUNG-CHEOL KIM, JUNE YOUNG KIM, Department of Electrical Engineering, Hanyang University, Seoul, 133-791, South Korea, CHIN-WOOK CHUNG, Department of Electrical Engineering, Hanyang University, Seoul, 133-791, Republic of Korea. — Experimental investigation of the gap length effect on plasma parameters was performed in a planar type inductively coupled plasma (ICP) at various conditions. The spatial profile (wafer level, 260 mm) of ion flux, and electron temperature were measured from a 2-D floating probe measurement system. At low pressures, the spatial profile of the ion flux rarely changed; however, at relatively high pressures, the spatial profile of the ion flux dramatically changed with different discharge gap length.

GT1.00034 Inductively-coupled plasmas in pure O₂: measurements of densities of O atoms, electrons and vibrationally excited O molecules. MICKAEL FOUCHER, LPP-CNRS UMR 7648, EMILE CARBONE, CEA grenoble, JEAN-PAUL BOOTH, PASCAL CHABERT, LPP-CNRS UMR 7648, LPP-PLASMAS FROIDS TEAM. — Inductively-coupled plasmas containing O₂ (pure or mixtures) are widely used in materials processing. Various simulations have been developed but experimental validation is still sparse. We present here a comprehensive data set for O₂ plasmas over a wide range of pressure and RF power to address this need. The plasma is excited with a 4-turn planar coil through a dielectric window at 13.56 MHz in an anodized aluminum reactor. The electron density was measured with a microwave resonator hairpin probe. It increases continuously with RF power, but with pressure it passes through a broad maximum around 40 mTorr. Ground-state O atoms densities were determined using Two-Photon Absorption Laser-Induced Fluorescence combined with absolute calibration using Xe TALIF. The atom density increases with gas pressure, but with RF power it remains but progressively saturates to about 20% of the initial (no plasma) gas density. A novel high-sensitivity ultra-broad-band absorption spectroscopy setup allowed O₂ molecules to be detected in high vibrational states (up to v = 18) via the Schumann-Runge bands. Molecular Vibrational temperatures up to 12,000 K were observed, whereas the rotational temperature did not exceed 500 K. This indicates that electron-impact pumping of vibrational levels is important, whereas V-T transfer is slow. These processes must be included to accurately model the O₂ plasma system.

GT1.00035 Study on self-bias effect in floating probe using dual frequency. IL-SEO PARK, HYO-CHANG LEE, YU-SIN KIM, Department of Electrical Engineering, Hanyang University, Seoul, 133-791, Republic of Korea, DONG-HWAN KIM, Department of Nanoscale Semiconductor Engineering, Hanyang University, Seoul, 133-791, Republic of Korea, CHIN-WOOK CHUNG, Department of Electrical Engineering, Hanyang University, Seoul, 133-791, Republic of Korea. — A floating probe is one of the promising electrical probe for plasma diagnostics, which is using small sinusoidal signal to perturb the plasma for obtaining plasma parameters such as ion flux and electron temperature. The ac signal could be selected for the purpose of the plasma condition and its advantages, and single or dual frequency is usually for diagnostics. When one or dual frequency is applied to the probe, a self-bias effect is observed in the capacitor in series to the floating probe. Due to the mobility difference of the ions and electrons, the self-bias effect is presented at the capacitor. In this paper, two consecutive frequencies are applied to the probe with phase differences. The result of the self-bias effect agrees with the floating probe theory, which gives a relation among electron temperature, phase difference and amplitude of the each frequency. The electron temperatures by using the relation can be obtained, and it agree with those of a Langmuir probe.

GT1.00036 Measurement of the surface charge accumulation using anodic aluminum oxide (AAO) structure in an inductively coupled plasma. JI-HWAN PARK, SEUNG-JU OH, HYO-CHANG LEE, YU-SIN KIM, YOUNG-CHEOL KIM, JUNE YOUNG KIM, Hanyang University. CHANG-SEOUNG HA, SEMES, SOON-HO KWON, JUNG-JOONG LEE, Seoul University, CHIN-WOOK CHUNG, Hanyang University. — As the critical dimension of the nano-device shrinks, an undesired etch profile occurs during plasma etch process. One of the reasons is the local electric field due to the surface charge accumulation. To demonstrate the surface charge accumulation, an anodic aluminum oxide (AAO) membrane which has high aspect ratio is used. The potential difference between top electrode and bottom electrode in an anodic aluminum oxide contact structure is measured during inductively coupled plasma exposure. The potential difference is changed with external discharge conditions, such as gas pressure, input power, and gas species and the result is analyzed with the measured plasma parameters.

GT1.00037 The effect of rf plasma fluctuation on floating harmonic probes. JAEWON LEE, KYUNGHYUN KIM, SANGBUM JEON, CHIN-WOOK CHUNG, Hanyang University. — Measurement of electron temperature, plasma density and ion flux with floating harmonic method (FHM) has several advantages for RF plasma diagnosis. In principle, RF oscillation of plasma does not distort the characteristic of the probe at a floating potential. Thus, an active or passive RF compensation is unnecessary. However, in fact, the uncompensated probe results in higher electron temperature than the rf compensated probe especially at low plasma density. Plasma parameters from the FHM and that of Langmuir probe was compared, and it shows that the measured plasma parameter from RF compensated floating probe (FHM) has great agreements with Langmuir probe.

GT1.00038 In-situ measurement method of sheath capacitance in plasmas. JIN-YONG KIM, CHIN-WOOK CHUNG, Hanyang Univ. — In-situ measurement method of sheath capacitance was studied. To measure the sheath capacitance, small dual frequency sinusoidal voltage signals (∼1V) are applied to floating planar probe. The sheath circuit model and capacitance of the dielectric deposition film on the probe are considered in our measurement. The experiment was performed at various discharge conditions and our results are in good agreements with other studies. This study can be helpful for plasma monitoring in industrial processing.

GT1.00039 Two-photon laser-induced fluorescence imaging of atomic oxygen in an atmospheric pressure plasma jet. JACOB SCHMIDT, Spectral Energies, LLC., BRIAN SANDS, UES, Inc., WARUNA KULATILAKA, SUKESH ROY, Spectral Energies, LLC., JAMES SCOFIELD, JAMES GORD, Air Force Research Laboratory. — A femtosecond two-photon absorption laser-induced fluorescence (fs-TALIF) diagnostic is applied to a nanosecond-pulsed, capillary dielectric barrier discharge (CDBD) plasma jet flowing helium with a variable oxygen admixture to produce two-dimensional images of atomic oxygen distributions. The high-peak intensity, low-average energy fs pulses, combined with increased spectral bandwidth, increase the number of photon pairs responsible for the two-photon excitation, resulting in increased TALIF signal. These features enabled imaging of absolute atomic oxygen number densities ranging from 4.07 x 10¹¹ cm⁻³, to the single-shot detection limit of 10¹² cm⁻³. Atomic oxygen imaging results are compared against traditional nanosecond diagnostics employing the same two-photon excitation scheme, including issues of experimental error, signal strengths, and quenching. Xenon calibration is used for quantification of the fluorescence signal. Imaging results show this CDBD capable of remotely generating quasi-steady-state atomic oxygen densities with a spatial distribution that depends on oxygen admixture.
GT1.00040 High sensitivity ultra-broad-band absorption spectroscopy applied to inductively-coupled plasmas in Cl/O, MICKAEL FOUCHER, LPP-CNRS UMR 7648, EMILE CARBONE, CEA gnnoble, JEAN-PAUL BOOTH, PASCAL CHABERT, LPP-CNRS UMR 7648, LPP-PLASMAS FROIDS TEAM — Broad-band absorption spectroscopy is a powerful diagnostic for reactive plasmas, allowing measurement of the absolute densities of numerous atoms, molecules and free radicals in ground and various excited states. Previously Xe arc lamps have been used as the continuum light source, but these suffer from spatiotemporal fluctuations which limit the sensitivity to about $10^{-3}$ in absorption. More recently UV light-emitting diodes have been used, but these only emit over a very limited spectral range. Our new absorption spectroscopy setup uses a laser-driven plasma light source, achromatic optics and an aberration free spectrograph. This light source has ideal characteristics for absorption spectroscopy (high intensity, stability and a wide spectral range (200-1000nm)), overcoming previous limitations. Noise levels as low as $10^{-9}$ can be achieved in single-pass absorption, covering up to 250nm in a single spectrum. Measurements were made in a 13.56 MHz inductively-coupled plasma reactor in O, Cl and Cl/O mixtures. We observed absorption by Cl, O and ClO molecules, and excited state atoms. Whereas the Clvibrational distribution is close to equilibrium with the gas translational temperature, Omolecules show high vibrational excitation (up to $v=18$, $T_{vib}=12000K$). However, high resolution spectra of Oindicated rotational temperatures up to only 500 K. Many oxocarbon molecules were detected in Cl/O mixtures.

GT1.00041 Hairpin resonator probes with frequency domain boxcar operation for time-resolved density measurements in pulsed RF discharges, DAVID PETERSON, THERESA KUMMERER, North Carolina State University, DAVID COUMOU, MKS Instruments, ENI Power Division, Rochester NY, STEVEN SHANNON, North Carolina State University — In this work, microsecond time resolved electron density measurements in pulsed RF discharges are shown using an automated hairpin resonance probe using relatively low cost electronics, on par with normal Langmuir probe boxcar mode operation. A low cost signal generator is used to produce the applied microwave frequency and the reflected waveform is filtered to remove the RF component. The signal is then heterodyned with a simple frequency mixer to produce a dc signal read by an oscilloscope to determine the electron density. The applied microwave frequency is automatically shifted in small increments in a frequency boxcar routine through a LabviewTM program to determine the resonant frequency. A simple dc sheath correction is then easily applied since the probe is fully floating, producing low cost, high fidelity, and highly reproducible electron density measurements. The measurements are made in a capacitively coupled, parallel plate configuration in a 13.56 MHz, 50-200 W RF plasma pulse at 500 Hz, 200 W, 50% duty cycle. The gas input ranged from 50-100mTorr pure Ar or with 5-10% O/He mixtures.

GT1.00042 Experimental Characterization of the Time-Averaged and Oscillatory Behavior of a Hall Plasma Discharge1, CHRISTOPHER YOUNG, ANDREA LUCCA FABRIS, NICOLAS GASCON, MARK CAPPELLI, Stanford University — An extensive experimental campaign characterizes a 70 mm diameter stationary plasma thruster operating on xenon in the 200-500 W power range. This study resolves both time-averaged properties and oscillatory phenomena in the plasma discharge. Specifically, we explore the time variation of the plume ion velocity field referenced to periodic discharge current oscillations using time-synchronized laser induced fluorescence (LIF) measurements. This LIF scheme relies on a triggered signal acquisition gate locked at a given phase of the current oscillation period. The laser is modulated at a characteristic frequency and homodyne detection through a lock-in amplifier extracts the induced fluorescence signal out of the bright background emission.

GT1.00043 Periodic Evolution of a Xe I Population in an Oscillatory Discharge Captured Through Time-Synchronized Laser Induced Fluorescence Techniques1, ANDREA LUCCA FABRIS, CHRISTOPHER YOUNG, MARK CAPPELLI, Stanford University — We track the evolution of the Xe I 6s[1/2] − 6p[3/2] (834.68 nm air) transition lineshape in a plasma discharge oscillating at 60 Hz. Two time-synchronized laser induced fluorescence techniques based on phase sensitive detection of the fluorescence signal are demonstrated, yielding consistent results. One approach used previously involves a sample-and-hold procedure that collects fluorescence signal at a particular phase in the oscillation period and holds the average value until the following sample. The second method is based on fast switching of the fluorescence signal; only the signal collected inside the acquisition gate is sent to a lock-in amplifier for processing. Both methods rely on modulating the exciting laser beam and the latter permits operation at a much higher frequency range with reduced spectral noise density. The maximum observed peak fluorescence intensity occurs at low discharge currents, although the peak intensity drops to zero at zero discharge current. The peak intensity also decreases at the discharge current maximum. Time-varying properties of the xenon neutrals are extracted from a lineshape analysis.

GT1.00044 Theoretical modeling of laser-induced plasmas using the ATOMIC code1, JAMES COLGAN, HEATHER JOHNS, DAVID KILCREASE, ELIZABETH JUDGE, JAMES BAREFIELD II, SAMUEL CLEGG, KYLE HARTIG, Los Alamos National Laboratory — We report on efforts to model the emission spectra generated from laser-induced breakdown spectroscopy (LIBS). LIBS is a popular and powerful method of quickly and accurately characterizing unknown samples in a remote manner. In particular, LIBS is utilized by the ChemCam instrument on the Mars Science Laboratory. We model the LIBS plasma using the Los Alamos suite of atomic physics codes. Since LIBS plasmas generally have temperatures of somewhere between 3000 K and 12000 K, the emission spectra typically result from the neutral and singly ionized stages of the target atoms. We use the Los Alamos atomic structure and collision codes to generate sets of atomic data and use the plasma kinetics code ATOMIC to perform LTE or non-LTE calculations that generate level populations and an emission spectrum for the element of interest. In this presentation we compare the emission spectrum from ATOMIC with an Fe LIBS laboratory-generated plasma as well as spectra from the ChemCam instrument. We also discuss various physics aspects of the modeling of LIBS plasmas that are necessary for accurate characterization of the plasma, such as multi-element target composition effects, radiation transport effects, and accurate line shape treatments.

GT1.00045 RF Models for Plasma-Surface Interactions in VSim1, THOMAS G. JENKINS, D.N. SMITHE, A.Y. PANKIN, C.M. ROARK, C.D. ZHOU, P.H. STOLTZ, S.E. KRUGER, Tech-X Corporation — An overview of ongoing enhancements to the Plasma Discharge (PD) module of Tech-X’s VSim software tool is presented. A sub-grid kinetic sheath model, developed for the accurate computation of sheath potentials near metal and dielectric-coated walls, enables the physical effects of DC and RF sheath physics to be included in macroscopic-scale plasma simulations that need not explicitly resolve sheath scale lengths. Sheath potential evolution, together with particle behavior near the sheath, can thus be simulated in complex geometries. Generalizations of the model to include sputtering, secondary electron emission, effects from multiple ion species and background magnetic fields are summarized; related numerical results are also presented. In addition, improved tools for plasma chemistry and IEDF/EEDF visualization and modeling are discussed, as well as our initial efforts toward the development of hybrid fluid/kinetic transition capabilities within VSim. Ultimately, we aim to establish VSimPD as a robust, efficient computational tool for modeling industrial plasma processes.

1Supported by US DoE SBIR-I/II Award DE-SC0000501.
GT1.00046 Electrical characteristics and energy budget of dielectric barrier discharges in argon at atmospheric pressure\textsuperscript{1}. MARKUS M. BECKER, TOMAS HODER, DETLEF LOFFHAGEN, INP Greifswald — Recently, an asymmetric dielectric barrier discharge ignited in atmospheric pressure argon in a single filament configuration has been analysed by experiments and modelling \textsuperscript{[1,2]}. A special feature of the discharge under consideration is the occurrence of two different discharge modes at different amplitudes of the sinuosiodal voltage supply. At voltages below the critical voltage of 2 kV ordinary filamentary discharges occur, while at higher voltages discharges with striated filaments emerge. In the present contribution the mode transition is investigated with respect to the electrical characteristics as well as the electron energy budget by means of numerical modelling. It is found that the mode transition caused by an increase of the voltage amplitude is accompanied by a non-linear change of the power supply. At voltages below the critical voltage of 2 kV ordinary filamentary discharges occur, while at higher voltages discharges with striated filaments emerge.

1This work was partly supported by the German Research Foundation within the Collaborative Research Centre Transregio 24.

GT1.00047 Modeling of filaments and gas flow in an atmospheric pressure plasma jet\textsuperscript{1}. FLORIAN SIGENEGGER, DETLEF LOFFHAGEN, INP Greifswald, Felix-Hausdorff-Str. 2, 17489 Greifswald, Germany — A non-thermal atmospheric pressure plasma jet is investigated by a combination of different approaches. The jet consists of two concentric capillaries and two ring-shaped electrodes which are twisted around the outer capillary to supply the rf power at 27.12 MHz. One part of the model is devoted to describe one single filament as observed in the active volume between the electrodes. For this purpose a two-dimensional axisymmetric fluid model has been used which comprises continuity equations for electrons and the most important argon species, the electron energy balance equation, Poisson’s equation and an equation for the surface charges at the walls of the capillaries. Furthermore, the heat balance equation is solved to determine the temperature of the gas. The inclusion of contraction mechanisms allows to describe the establishment of a constricted filament and even pronounced striations as observed in the experiments. The second part uses results of the first one to model the gas flow through the jet under the influence of local heating at the position of the filament which leads finally to an azimuthal rotation of the filaments as observed in experiments.

1The work has been supported by the German Research Foundation (DFG) within SFB TRR 24.

GT1.00048 Fast 2D Fluid-Analytical Simulation of IEDs and Plasma Uniformity in Multi-frequency CCPs\textsuperscript{1}. E. KAWAMURA, M.A. LIEBERMAN, D.B. GRAVES, Univ of California - Berkeley — A fast 2D axisymmetric fluid-analytical model using the finite elements tool COMSOL is interfaced with a 1D particle-in-cell (PIC) code to study ion energy distributions (IEDs) in multi-frequency argon capacitively coupled plasmas (CCPs). A bulk fluid plasma model which solves the time-dependent plasma fluid equations is coupled with an analytical sheath model which solves for the sheath parameters. The fluid-analytical results are used as input to a PIC simulation of the sheath region of the discharge to obtain the IEDs at the wafer electrode. Each fluid-analytical-PIC simulation on a moderate 2.2 GHz CPU workstation with 8 GB of memory took about 15–20 minutes. The 2D multi-frequency fluid-analytical model was compared to 1D PIC simulations of a symmetric parallel plate discharge, showing good agreement. Fluid-analytical simulations of a 2/60/162 MHz argon CCP with a typical asymmetric reactor geometry were also conducted. The low 2 MHz frequency controlled the sheath width and voltage while the higher frequencies controlled the plasma production. A standing wave was observable at the highest frequency of 162 MHz. Adding 2 MHz power to a 60 MHz discharge or 162 MHz to a dual frequency 2 MHz/60 MHz discharge enhanced the plasma uniformity.

1This work was supported by the Department of Energy Office of Fusion Energy Science Contract DE-SC000193, and in part by gifts from Lam Research Corporation and Micron Corporation.

GT1.00049 Transport Parameters of $F^{(-)}$ Ions in Mixtures Ar/$BF_3$\textsuperscript{1}. ZELIJA NIKITOVIC, VLADIMIR STOJANOVIC, ZORAN RASPOPOVIC, Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade, JASMINA JOVANOVIĆ, Faculty of Mechanical Engineering, University of Belgrade, Kraljice Marije 16, 11000 Belgrade, Serbia, ZORAN LJ. PETROVIĆ, Institute of Physics, University of Belgrade, Pregrevica 118, 11080 Belgrade — Transport parameters of $F^{(-)}$ ions in mixtures Ar/$BF_3$ in DC fields were calculated by using Monte Carlo simulation technique. The scattering-cross section set for $F^{(-)}$ in $BF_3$ is assembled on the basis of Nanbu’s technique separating elastic from reactive collisions. In this work we present transport coefficients for the conditions of low and moderate reduced electric fields $E/N$ ($E$-electric field, $N$-gas density) accounting for the non-conservative collisions. This mixture is usual in plasma etching applications.

1Results obtained in the Laboratory of Gaseous Electronics Institute of Physics University of Belgrade under the auspices of the Ministry of Education, Science and Technology, Projects No. 171037 and 410011.

GT1.00050 The Influence of Anode Size on Bulk Plasma State: Simulation, Theory, and Experiment\textsuperscript{1}. MATTHEW HOPKINS, BENJAMIN YEE, EDWARD BARNAT, Sandia National Laboratories, SCOTT BAALRUD, University of Iowa — We present recent PIC modeling results in pursuit of identifying the relationship between bulk plasma characteristics and a biased anodic surface. In the limit of small anode size we expect the anode to operate as an ideal probe and exhibit no significant influence on the bulk plasma state. In the other limit of a large anode size we expect the bulk plasma to “lock” onto the anode potential and the plasma state to be heavily influenced by the anode potential. Our investigations include the plasma-anode interface (sheath) structure, plasma potential, and plasma electron energy distribution function modification. The basis for our investigation lies in the plasma-anode interface model from Baalrud, et al.\textsuperscript{[2]} In particular, we target the transition from ion-rich sheaths to electron-rich sheaths at the anode. The theoretical model predicts a transition as a function of the anode-to-wall area ratio, $A_A/A_W$. Comparisons are made between the simulation model, theoretical model, and experimental results. Considerations specific to modeling are also presented.

1This work was supported by the Office of Fusion Energy Science at the U.S. Department of Energy under contract DE-AC04-94SL85000.

2Baalrud, Hershkowitz, Longmier, “Global nonambipolar flow: Plasma confinement where all electrons are lost to one boundary and all positive ions to another boundary,” Phys. Plasmas 14, 014109 (2007).
GT1.00051 A kinetic electron-neutral collision model for particle-in-cell plasma simulation1
TIMOTHY POINTON, KEITH CARTWRIGHT, Sandia National Laboratories — Details of a kinetic electron-neutral collision model for particle-in-cell plasma simulation codes are presented. The model uses an efficient scheme to randomly select collision events – elastic, excitation and ionization – with the appropriate probability [H. Sugawara, et al., J. Comput. Phys. 223, 298 (2007)]. Ionization events create electron-ion pairs, and the secondary electrons can themselves ionize the gas. To maintain a manageable particle count, a particle merger algorithm can be used to periodically replace all particles of a given species in a cell with a new, smaller set that conserves charge, momentum, and energy [D. R. Welch, et al., J. Comput. Phys. 227, 143 (2007)]. Small-scale tests show that results with the merger are in good agreement with non-merged runs. Large simulations can only be done with the merger on, and typically show excellent merger efficiency (>90%).

1Sandia National Laboratories is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin company, for the U.S. DOE's NNSA under contract DE-AC04-94-AL85000.

GT1.00052 Numerical simulation of capacitively coupled RF plasma flowing through a tube for the synthesis of silicon nanocrystals1, ROMAIN LE PICARD, University of Minnesota, SANG-HEON SONG, University of Michigan, DAVID PORTER, Minnesota Supercomputing Institute, MARK KUSHNER, University of Michigan, STEVEN GIRSHICK, University of Minnesota — Silicon nanocrystals (SiNCs) are of interest for applications in the photonics, electronics, and biomedical areas. Nonthermal plasmas offer several potential advantages for synthesizing SiNCs. In this work, we have developed a numerical model of a capacitively coupled RF plasma used for the synthesis of SiNCs. The plasma, consisting of silane diluted in argon at a total pressure of about 2 Torr, flows through a narrow quartz tube with two ring electrodes. The numerical model is 2D, assuming axisymmetry. An aerosol sectional model is added to the Hybrid Plasma Equipment Model developed by Kusher and coworkers. The aerosol module solves for aerosol size distributions and size-dependent charge distributions. A detailed chemical kinetic mechanism considering silicon hydride species containing up to 5 Si atoms is used to model particle nucleation and surface growth. The sectional model calculates coagulation, particle transport by electric force, neutral drag and ion drag, and particle charging using orbital motion limited theory. Simulation results are presented for selected operating conditions, and are compared to experimental results.

1This work was partially supported by the US Dept. of Energy Office of Fusion Energy Science (DE-SC0001939), the US National Science Foundation (CHE-124752), and the Minnesota Supercomputing Institute.

GT1.00053 Numerical optimization of collisional cross sections for plasma simulation by Broyden-Fletcher-Goldfarb-Shanno method , SANG-YOUNG CHUNG, DEUK-CHUL KWON, MI-YOUNG SONG, JUNG-SIK YOON, National Fusion Research Institute — For reliable plasma simulation an accurate full-set data of collision cross sections between each species participated in the plasma is required. However, the full-set of the reaction data is hard to achieve and estimated data have been used for the missing. To achieve reliable reaction data researchers have tuned the estimated reaction data so that the simulation results with the data agree with experimental results. However, as the number of data to be tuned is increased it becomes very hard work for researchers. In this study, we developed a code to optimize the data numerically based on the Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm and adopted with a 0-dimensional global simulator for semiconductor processing plasma. BFGS algorithm is a type of a quasi-Newton method. The second derivatives are used for a next estimation like Newton method but are calculated by iterations from first derivatives and previous second derivatives. So the function is called (i.e. the simulator is executed) much smaller times than Newton method. Parallel algorithm was applied to the code to save time. In the serial code the calculation time for each iteration were proportional to the number of unknown variables but it became independent of the number of the variables in the parallel code.

GT1.00054 Transport Properties of Negative Ions in HBR Plasmas , VLADIMIR STOJANOVIC, Institute of Physics, University of Belgrade, P.O. Box 68, 11080 Belgrade, Serbia, NENAD IVANOVIC, Vinca Institute for Nuclear Science, University of Belgrade, P.O. Box 522, 11000 Belgrade, Serbia, MARIJA RADMILOVIC-RADJENOVIC, ZORAN RASPOPOVIC, ALEKSANDAR BOJAROV, ZORAN PETROVIC, Institute of Physics, University of Belgrade, P.O. Box 68, 11080 Belgrade, Serbia — Low temperature plasma in halogenated gases is standard environment for dry etching of semiconductors. Amount of negative ions in HBR plasmas determines electronegativity so modeling etching devices requires data for anion transport properties. In this work we present cross section set for Br- ions in HBR assembled by using Denpoh-Nanbu theory [1]. The threshold energy values were calculated by known heats of formation. The calculated total cross section accounts for ion-induced-dipole and ion-permanent-dipole interaction by using the local-dipole model. The total cross section was corrected to fit the reduced mobility obtained by SACM (Statistical Adiabatic Channel Model) approximation. Existing cross section measurements [2] were used to scale calculated cross sections. Finally, we used Monte Carlo method to determine transport parameters for Br- as a function of reduced electric fields that can be used in fluid and hybrid plasma models.


GT1.00055 Extended dielectric relaxation scheme for fluid transport simulations of high density plasma discharges1, DEUK-CHUL KWON, MI-YOUNG SONG, JUNG-SIK YOON, Natl Fusion Res Inst — It is well known that the dielectric relaxation scheme (DRS) can efficiently overcome the limitation on the simulation time step for fluid transport simulations of high density plasma discharges. By limiting a realistic and physical shielding process of electric field perturbation, the DRS overcomes the dielectric limitation on time step. However, the electric field was obtained with assuming the drift-diffusion approximation. Although the drift-diffusion expressions are good approximations for both the electrons and ions at high pressure, the inertial term cannot be neglected in the ion momentum equation for low pressure. Therefore, in this work, we developed the extended DRS by introducing an effective electric field. To compare the extended DRS with the previous method, two-dimensional fluid simulations for inductively coupled plasma discharges were performed.

1This work was supported by the Industrial Strategic Technology Development Program (10041637, Development of Dry Etch System for 10nm class SADP Process) funded by the Ministry of Knowledge Economy (MKE, Korea).

GT1.00056 PLASIMO model of micro-plasma jet for biomedical applications , DIANA MIHAIOVA, ANA SOBOTA, WOUTER GRAEF, JAN VAN DIJK, Eindhoven University of Technology, GERJAN HAGELAAR, CNRS, University of Toulouse — Non-equilibrium atmospheric pressure micro-plasma jets are widely studied for use in biotechnology, including treatment of human tissue. The setup under study consists of capillary powered electrode through which helium gas flows and a grounded ring electrode placed a distance of few mm in front of the capillary. The discharge is excited by sinusoidal voltage with amplitude of 2kV and 30kHz repetition rate. The plume emanating from the jet, or the plasma bullets, propagates through a Pyrex tube and the gas phase channel of helium into the surrounding air. Aim of this work is to get insight into the plasma constituents that can affect directly or indirectly living tissue. This includes radicals (OH, NO, O,), ions and electrons, UV radiation, electrical fields. PLASIMO modelling toolkit is used to simulate the capillary plasma-jet in order to quantify the delivery of fluxes and fields to the treated tissue. Verification is made by comparing results obtained with the PLASIMO and MAGMA codes (developed at LAPLACE, Toulouse) for the same input specifications. Both models are validated by comparison with experimental observations at various operating parameters.
GT1.00057 Fluid model of magnetic drifts and instabilities in magnetized low-temperature plasma sources. This paper presents a self-consistent fluid model of low-temperature plasma transport across a magnetic field, designed in particular to describe magnetic drifts and instabilities in the plane perpendicular to the field lines. The model is based on electron and ion continuity equations and full momentum equations and an electron energy equation, without a priori assumptions on the ordering of physical scales (Larmor radii, mean free paths, geometrical dimensions) so that it can cover a wide range of conditions, from non-magnetized collisional plasmas to tokamak edge plasmas. The model is applied to different basic configurations of immediate interest for applications such as ion negative sources. We show that in a typical magnetic filter configuration (e.g. in the ITER negative ion source or Pegases thruster), the magnetic drift is obstructed by the chamber walls which induces an asymmetric electron flux across the filter, scaling as $1/B$.

These results have been confirmed by experimental data from an in-house laboratory set-up. We also present model results on the Cybele ion source featuring a magnetized plasma column, in which the transport is governed by rotating instabilities and very sensitive to the boundary conditions at the end of the column.

GT1.00058 Propagation of a positive streamer discharge along a dielectric rod. Anna Dubinova, UTE Ebert, Jannis Teunissen, Centrum Wiskunde & Informatica — We simulate positive streamer discharges developing in artificial air near dielectric and conductive materials. This research is important, for example, in high voltage technology where surface flashovers are to be avoided. We designed an axially symmetric model in which a positive streamer develops at the tip of the needle electrode (parameterized as a spheroid) and propagates towards and then along a dielectric rod (a cylinder). Our model includes field modification due to the polarization effect, photoionization, charge accumulation on the dielectric surface and photoelectron emission. We describe a numerical method (a generalized Ghost Fluid Method) which allowed us to include dielectric interfaces into our streamer model, in an accurate and fast manner. Finally, we measure the velocity of a positive streamer propagating along the dielectric rod and compare it with experiments. We discuss the importance of the surface photoelectron emission as an intrinsically non-local source of free electrons for streamer propagation.

GT1.00059 Modeling DC-circuit-breakers for long distance electricity transmission. Ashutosh Agnihotri, Centrum Wiskunde & Informatica, Amsterdam, UTE Ebert, Centrum Wiskunde en Informatica, Amsterdam & Eindhoven University of Technology, Eindhoven, Willem Hundsdoerfer, Centrum Wiskunde en Informatica, Amsterdam & Radboud University, Nijmegen. Modeling a circuit-breaker is a multiple timescale problem which involves a cascade of physical processes from avalanche phase to streamer, spark and post discharge phase, with a transition phase between each pair of processes. In particular, Jin Zhang and Bert van Heesch at Eindhoven University of Technology investigate now whether the conventional SF6 can be replaced by supercritical nitrogen. We focus on modeling space charge effects, gas heating and secondary electron emission from cathode. We develop a two-dimensional drift-diffusion model for streamers coupled to the Euler equations for the gas to study the related phenomena. We perform simulations to capture thermal shocks and induced pressure waves caused by the electrical breakdown of the surrounding gas. We include heat exchange mechanisms between the electrons/ions and the surrounding gas.

GT1.00060 2D streamer simulations using the high order fluid model. Aram Markosyan, University of Michigan, Sasha Dukjo, University of Belgrade, UTE Ebert, CWI. In 1D, the recently derived high order fluid model [Dukjo et al. J. Phys. D. 46:5202, 2013] shows promising performance and accuracy compared to the classical first order model using the local field approximation [Markosyan et al., J. Phys. D. 46:5203, 2013]. Here we simulate cylindrically symmetric streamers between two planar electrodes with the high order fluid model. The system is discretized using finite volume spatial discretization (high-resolution scheme) and explicit time stepping. We discuss the results and compare with previous work.

GT1.00061 Simulating the inception of pulsed discharges around needle electrodes. Jannis Teunissen, Centrum Wiskunde & Informatica, The Netherlands, She Chen, Tsinghua University, China, Luuk Heijmans, Eindhoven University of Technology, The Netherlands. When a positive voltage pulse is applied to a sharp electrode, an inception cloud can form around the electrode tip. This is an almost spherically expanding ionized region. As recently demonstrated in experiments by S. Chen, L. Heijmans and S. Nijdam, the properties of these inception clouds depend on the gas mixture and on the voltage pulse. We present a 3D particle model to simulate the initial stage of pulsed discharges near needle electrodes. With this model, we investigate how the properties of inception clouds (growth velocity, maximum size, time of destabilization) depend on the gas mixture and voltage pulse, and we compare with the experiments mentioned above.

GT1.00062 Application of ILDM Technique for Simplifying Complex Plasma Chemistry. Tafizur Rehman, Kim Peerenboom, Efe Kemaneci, Wouter Graef, Jan Vandijk, Eindhoven University of Technology. Complete numerical description of plasma involves solving complex sets of space and time dependent conservation and rate equations. Solution of this large set of equations induces a high computational load on the system. Combustion research is another branch of science that deals with the same issue. To overcome the difficulty, combustion community employs various Chemical Reduction Techniques(CRT). The CRT simply uses the fact that, due to wildly varying time scales, reaction system is not evenly sensitive to all the reactions but some reactions are fast and attain steady state in short interval of time. Hence, fast time scale variation becomes less important and the full description of the system can be given by the slow time scales without any significant loss in chemical kinetics description. The chemical reduction technique we employed is ILDM (Intrinsic Low Dimensional Manifold). This technique finds the low dimensional space inside a complete state space such that after a short interval of time the fast time scales of the system will quickly move onto this low dimensional manifold and the full system description can be given by this lower dimensional manifold. One can use these techniques of combustion research to simplify the complex chemistry in plasma simulation.
GT1.00063 Parametric calculations of plasma jets generated by microdischarges\(^1\), M. FOLETTO, Univ Toulouse, J.P. BOEUF, L.C. PITCHFORD, CNRS and Univ Toulouse — "Guided streamers" or "plasma jets" can be generated in open air by applying rf or impulse voltages to a microdischarge through which there is a flow of helium. For flow conditions such that a helium column surrounded by air extends some distance (centimeters) past the exit of the microdischarge, a plasma jet can be initiated. Previous works have shown that this is essentially a streamer propagating in the easily-ionized helium column and impeded from branching by the surrounding air. For many applications, it is of interest to understand the parameters controlling the properties of the plasma jet. To this end, we present results from a series of parametric calculations using our previously published model \(^1\) to identify the influence of the microdischarge configuration on the generation, propagation, and properties of the plasma jet. We focus mainly on a geometry with hollow, concentric electrodes separated by a dielectric tube corresponding to the experiments of Douat et al \(^2\), and we vary the dimensions and relative off-set of the electrodes, applying an impulse voltage or the experimental waveform to the inner electrode. For the same applied voltage waveform, parameters which influence the electric field and electron density in the plasma jet are the dielectric permittivity, the tube diameter, and the dielectric length.

\(^1\)Support by the French National Research Agency project PAMPA.


GT1.00064 A PLASIMO global model for plasma assisted CO\(_2\) conversion, WOUTER GRAEAF, TAFIZUR REHMAN, DIANA MIHAIOVA, JAN VAN DIJK, Eindhoven University of Technology — Conversion of CO\(_2\) has become a major challenge of our time as it is of interest for the reduction of greenhouse gases in our atmosphere, but also to store energy thereby relieving the supply and demand discrepancy of many alternative forms of energy. Plasma assisted CO\(_2\) conversion is heavily investigated as an efficient method to achieve this goal. Numerical modeling is an important aspect of this investigation, but is difficult due to the complex chemistry. A global model has been constructed to focus on the CO\(_2\) chemistry including its vibrational kinetics. The model has been realized using the global model module of PLASIMO, a highly modular plasma modeling framework. It is based on another model\(^4\) that was constructed using the well-established code Global\(_{kin}\). The aim of the model is therefore twofold. First, to study the chemistry and identify the most important species and reactions and perform parametric studies. The knowledge gained can be applied to other, spatially resolved models. Second, by implementing the same chemistry in the two different global model codes, a cross validation can be performed, a vital scientific process often overlooked in practice.

\[^3\] Tomáš Kozák and Annemie Bogaerts, submitted to Plasma Sources Sci. Tech.

GT1.00065 Magneto-hydrodynamic simulation of hypervelocity neutral plasma jets and their interactions with materials generating extreme conditions, VIVEK SUBRAMANIAM, LAXMINARAYAN RAJA, The University of Texas at Austin, HARI SWARAN SITARAMAN, None — The development of a Magneto-hydrodynamics (MHD) numerical tool to study high density thermal plasma in a co-axial plasma gun is presented. The MHD governing equations are numerically solved using a matrix free implicit scheme in an unstructured grid finite volume framework. The MHD model is used to characterize the high energy jet which emanates from the accelerator. The solver is then used to predict the conditions created at the surface of a flat plate placed at a fixed distance from the exit of the gun. The model parameters are adjusted so that the energy density of the jet impacting the plate is of the same order of magnitude as that of the Edge Localized Mode (ELM) disruptions in thermonuclear fusion reactors. The idea is to use the pressure and temperature on the plate surface to obtain an estimate of the stress created on the plate due to jet impact. The model is used to quantify damage caused by ELM disruptions on the confining material surface.


GT1.00066 Computational modelling of plasma control using electron injection from electrode surfaces, PREMKUMAR PANNEERCHELVAM, LAXMINARAYAN RAJA, The University of Texas at Austin — A common property of gamma-mode discharge is the importance of electron emission from surfaces in establishing the overall discharge structure. The secondary electron emission (SEE) from the cathode surface plays a key role in sustaining direct current glow discharges. Active control of SEE could be used to realize control over discharge properties. Chen and Eden \(^1\) control surface electron emission in a tri-electrode microdischarge to realize gain properties in a plasma transistor device. This work discusses a computational model of a plasma transistor microdischarge device. It includes description of active surface electron emission from one of the electrode surfaces. Gain properties in the plasma by controllable injection of electrons from the surface is shown. The non-linear processes in the plasma that realize rapid increase in the plasma density and current as a function of the electron injection from the electrode is studied using the model.


GT1.00067 Validation of RF CCP Discharge Model against Experimental Data using PIC Method\(^1\), CASEY ICENHOUR, THERESA KUMMERER, North Carolina State University, DAVID L. GREEN, Oak Ridge National Laboratory, DAVID SMITH, Tech-X Corporation, STEVEN SHANNON, North Carolina State University — The particle-in-cell (PIC) simulation method is a well-known standard for the simulation of laboratory plasma discharges. Using parallel computation on the Titan supercomputer at Oak Ridge National Laboratory (ORNL), this research is concerned with validation of a radio-frequency (RF) capacitively-coupled plasma (CCP) discharge PIC model against previously obtained experimental data. The plasma sources under simulation are 10-100 mTorr argon plasmas with a 13 MHz source and 27 MHz source operating at 50-200 W in both pulse and constant power conditions. Plasma parameters of interest in the validation include peak electron density, electron temperature, and RF plasma sheath voltages and thicknesses. The plasma is modeled utilizing the VSim plasma simulation tool, developed by the Tech-X Corporation. The implementation used here is a two-dimensional electromagnetic model, with corresponding external circuit model of the experimental setup. The goal of this study is to develop models for more complex RF plasma systems utilizing highly parallel computing technologies and methodology.

\(^1\) This work is carried out with the support of Oak Ridge National Laboratory and the Tech-X Corporation.
GT1.00068 Particle-In-Cell Simulation and Experimental Characterization of a Cylindrical Cusped Field Plasma Thruster1, ANDREA LUCCA FABRIS, CHRISTOPHER YOUNG, Stanford University, MARCO MANENTE, DANIELE PAVARIN, University of Padova, MARK CAPPELLI, Stanford University — This work aims to provide new insight into the physical mechanisms occurring in the discharge channel and acceleration region of a cusped field plasma thruster through a combined experimental and computational approach. Simulations are performed using the 3D particle-in-cell code F3MPIC, comprised of a PIC core coupled with a finite element electrostatic field solver over an unstructured mesh of tetrahedra. The cusped field structure is also included to resolve magnetized particle dynamics. We perform simulations with two ionization schemes: one where constant particle source rates are assigned to certain regions, and a more rigorous approach based on Monte Carlo collision events. The simulation results reveal correlations between the particle density distributions, electrostatic potential, and magnetic field topology inside the thruster discharge channel that are confirmed through experiments. Laser induced fluorescence measurements have resolved xenon ion velocities at several points near the thruster exit plane. Faraday and floating emissive probe measurements indicate this velocity field is correlated with the measured ion beam current profile and electrostatic potential field.

1This work sponsored by the U.S.A.F. Office of Scientific Research, with Dr. Mitat Birkan as program manager. F3MPIC developed under the European Union FP7 HPH.com project. CVY acknowledges the DOE NNSA SSGF fellowship under Contract DE-FC52-08NA28752.

GT1.00069 Simulation of Neutral Particle Transport During HiPIMS1, JAN TRIECSCHMANN, SARA GAL-LIAN, RALF PETER BRINKMANN, THOMAS MUSSENBROCK, Institute of Theoretical Electrical Engineering, Ruhr University Bochum — In this work the importance of the knowledge of the spatial distribution, its temporal evolution as well as their energy distribution of heavy particles within sputtering processes is discussed. To describe these discharges – typically operated at very low pressures below 1 Pa – specific modeling approaches are required. Our approach comprises a three-dimensional kinetic Lagrangian description of neutral particles. A modified version of the direct simulation Monte Carlo (DSMC) code dsmcFoam [1] is used, with the aim to describe the evolution of background and sputtered particles of a High Power Impulse Magnetron Sputtering (HiPIMS) process in a research reactor. Emphasis is put on the influence of the initial angular distribution of sputtered particles, as well as their energy distribution and its angular dependence. Based on the work of Stepanova and Dew [2] a modified Thompson energy distribution [3] is used. Differently distributed sputtered particles provide densities and fluxes concerning the corresponding film formation.

1This work is supported by the German Research Foundation in the frame of the Collaborative Research Centre TRR 87.

GT1.00070 Numerical simulation of quantum systems using the Particle-In-Cell method1, SVEN DIRKMANN, ZIAID YOUSSEF, TORBEN HEMKE, THOMAS MUSSENBROCK, Ruhr University Bochum — The Particle-In-Cell (PIC) method is a very powerful method for studying the dynamics of plasmas. It has been primarily developed for tracking the charged particle trajectories subject to self-consistent and external electromagnetic fields. Exploiting the power of modern computers, one is able to track the classical paths of tens of millions of particles at the same time. In the late 1980th, it was Dawson (and later Dauget) who had the idea to apply the PIC method to the classical part in the semiclassical approach to quantum systems via path integral methods. One could estimate that if a thousands of classical paths are sufficient to describe the dynamics of one quantum particle, then millions classical paths could describe the dynamics of a quantum particle system. A PIC code in the frame of a semiclassical approach would therefore enable the investigation of a number of quantum phenomena, e.g., optical properties, electrical properties, and, ultimately, chemical reactions. In this contribution we explain the use of the PIC code yapic (developed by the authors) in the frame of the path integral method and discuss the numerical results for simple quantum phenomena, i.e., the quantum harmonic oscillator and quantum tunneling.

1This work is supported by the German Research Foundation in the frame of FOR 2093.

GT1.00071 Simulation of Saddle Coil and Helical Winding Magnetic Field Perturbation in the IR-T1 Tokamak, YOUNES ADLTALAB, PEJMAN KHRSHID, ELHAM ABIZI MOGHADAM, Department of Physics, College of Science, Mashhad Branch, Islamic Azad University, Mashhad, Iran — The magnetic field of a set of saddle coils compared to the magnetic field of the helical winding coil on IR-T1 tokamak in a simulation method. The equation of helical windings that they mounted on vacuum chamber in a spiral modes (L=2, n=1) and (L=3,n=1), where L represents the number of toroidal rounds, and n represents the direction of the poloidal round, using Green function has been calculated, too. The coordinate system defined on a torus and an electric current applied to create a magnetic field and the magnetic field of resonant helical magnetic field disorders of the confinement were calculated in the whole space. In this study, the shape and structure of the Saddle coils has been defined toroidally and then poloidally configuration. The resulting simulation code is used to predict the position and structure of saddle coil that has same magnetic field generation with respect to Helical winding.

GT1.00072 Space – time evolution of low-pressure H2 plasma induced by runaway photoelectrons produced by KrF laser pulse, ALEXEY ZOTOVICH, ANDREY VONYNETS, Moscow State University, Department of Physics, Moscow, Russia, DMITRY LOPAEV, SERGEY ZRYANOV, Nuclear Physics Institute, Moscow State University, Moscow, Russia, DMITRY ASTAKHOV, VLADIMIR KRIVTSUN, KONSTANTIN KOSHELEV, Institute of Spectroscopy RAS (ISAN), RD ISAN, Troitsk, Russia — Extreme Ultraviolet Lithography (EUVL) at 13.5 nm is expected to provide the next generation of ULSI. One of hot EUVL problems is contamination of EUV multilayer optics that compels to search methods of in-situ cleaning. The most promising method is to apply H2 plasma generated over the mirror surface by EUV radiation itself. Therefore investigations of EUV-induced plasma are of great interest for such cleaning technology developing. To model evolution of EUV-induced plasma, the study of H2 plasma induced by photoelectrons extracted from a surface by KrF laser pulse has been done. The experiment was carried out by the space-time resolved probe technique while the analysis was made with using plasma model based on 2D PIC MC code for both electrons and ions. Comparison of experimental and calculated evolution of probe characteristics provides correct applicability of the probe theory and allows one to reveal key mechanisms and parameters which control the evolution of photoelectrons-induced plasma.

GT1.00073 Effect of cathode design on dc gas breakdown, VALERIY LISOVSKIY1, RUSLAN OSMAJEV, VLADIMIR YEGORENKO, Kharkov National University, Svobody Sq.4, Kharkov, 61022 — This paper reports dc breakdown curves we registered between a flat anode and cathodes of various design (a flat one, two types of steps with different height, a cathode possessing a bump or an indentation at its center, cones of different height), the least inter-electrode distance was kept constant. We observed that the minima and the right-hand branches of breakdown curves coincided practically whereas the left-hand ones did not. At lower pressure a divergence of left-hand branches of breakdown curves was registered for cathodes of different height), the least inter-electrode distance was kept constant. We observed that the minima and the right-hand branches of breakdown curves coincided practically whereas the left-hand ones did not. At lower pressure a divergence of left-hand branches of breakdown curves was registered for cathodes of different design. For the step-wise cathodes near to or to the right of the breakdown curve minimum the gas breakdown occurs within the smallest gap between the upper part of the cathode and the flat anode. With the gas pressure lowering the breakdown occurs between the flat anode and the lateral surface of the step-wise cathode, and then its lower flat part. For conical cathodes the breakdown occurs either near its sharp edge or at the lateral surface of the cone at some distance from its edge.

1 and Scientific Center of Physical Technologies, Svobody Sq.6, Kharkov, 61022, Ukraine
GT1.00074 Effect of inter-electrode gap on dc cathode sheath characteristics. VALERY LISOVSKY, EKATERINA ARTUSHENKO, VLADIMIR YEGORENKOV, Kharkov National University, Svobody Sq. 4, Kharkov 61022 — We found in experiment that increasing the inter-electrode distance with the current fixed first leads to the growth of the voltage drop $U$ across the cathode sheath as well as of its thickness $d$. This phenomenon is observed when the anode is located in the negative glow of the dc discharge. With longer distances when the anode is located in the dark Faraday space or positive column, the quantities $U$ and $d$ approach their saturation values and then remain unchanged. The current through the negative glow is supported by fast electrons generated in the cathode sheath where they also gained energy as well as by a diffusion flow. The anode departure from the cathode within the negative glow leads to a decrease of the fast electron flow, therefore a higher voltage $U$ is required to support a fixed current what is accompanied by the cathode sheath thickness $d$ growth. This phenomenon is clearly manifested in argon and nitrogen whereas it is expressed much weaker in electron-nonegene gases (N$_2$O, O$_2$). An analytical model is proposed describing the phenomenon outlined.

GT1.00075 Investigation of a cylindrical transparent cathode discharge. MARK BOWDEN, TOM HARDIMENT, University of Liverpool — The term Transparent Cathode Discharge (TCD) refers to a low-pressure electrical discharge also known as an Inertial Electrostatic Confinement (IEC) plasma. A defining characteristic is that the discharge is generated by a hollow, grid-constructed cathode and an outer, concentrically-arranged anode. Ions and electrons are accelerated by a large potential applied between the grids, with plasma being generated in different parts of the system depending on operating conditions. This project aims to study this device in order to assess its suitability for development as a reactive plasma source. A TCD device with concentric, cylindrical, mesh electrodes was operated in noble and molecular gases, and the discharge observed with a combination of emission imaging, emission spectroscopy and electrical probe diagnostic techniques. Preliminary measurements indicate that the alignment of the apertures in the inner and outer grid electrodes plays key role in determining discharge behaviour.

GT1.00076 Second-harmonic generation in composite of microwave plasma and cm-order metamaterial. AKINORI IWAI, YOSHIHIRO NAKAMURA, OSAMU SAKAI, Kyoto University — Second-harmonic generation was observed by high-power microwave propagation in composite space of plasma and cm-order metamaterial. In principle, high-power electromagnetic waves induce nonlinear polarization and harmonic-wave generation in plasma, because plasma is nonlinear dielectric medium. However, plasma frequency dispersion prevents propagation of fundamental waves; the increase in electron density leads to the evolution of plasma frequency that behaves as a cut-off frequency, and plasma dielectric constant for fundamental waves becomes negative. To remove this difficulty, our setup combines plasma and double-split-ring resonator (DSRR) or another metamaterial, whose negative permeability has been verified theoretically and experimentally [1] in order to cancel out the cutoff property of negative permittivity using negative permeability. Refractive index becomes a real and negative value. By enabling electromagnetic waves to propagate into high-density plasma, intense harmonic generation occurs. Our has reported unique properties of plasma metamaterial [2]. In this study, we experimentally observed second harmonic generation (at 4.9 GHz) in plasma space with DSRR at incident microwave frequency of 2.45 GHz.


GT1.00077 Sustenance of electronegative plasma column in the presence of electron temperature gradient in linear magnetized plasma device. SHANTANU KUMAR KARKARI, MIMANSA SHASTRI, HASMUH KABARIYA, SANJAY MISHRA, Institute for Plasma Research, Bhat Gandhinagar, Gujarat, India, NISHANT SIRSE, Dublin City University, Ireland — Electron-negative plasmas are widely popular in semiconductor processing industries as well as for the production of hydrogen neutral beams for plasma heating in fusion devices. This paper describes about the sustenance of electron-negative oxygen plasma in the presence of electron temperature gradient in magnetized plasma column of the linear plasma device. The electron temperature is self-consistently created in the discharge by the energy filtering of electrons across the magnetic field in conjunction with axial losses of energetic electrons at the grounded end plate. Detail measurements of radial plasma parameters performed using planar Langmuir probe finds substantial decrement in the negative to positive saturation current ratio as observed in the central region of the plasma column, characterized by low electron temperature. The negative ion fraction obtained from these measurements are based on a qualitative model that considers the modified Bohm speed in the presence of negative ions including the attenuation of thermal electron current to the probe due to the presence of external magnetic field.


Wednesday, November 5, 2014 8:00AM - 9:30AM – Session HW1 Non-equilibrium Kinetics and Basic Plasma Physics of Low Temperature Plasmas Ballroom EF - Scott Walton, NRL

8:00AM HW1.00001 Modeling of electron beam-generated plasmas produced in Ar/N2 mixtures. Tzetvetelina Petrova, Evgenia Lock, George Petrov, David Boris, Richard Fersnler, Scott Walton, Naval Research Laboratory — We discuss a non-equilibrium collisional-radiative model coupled with electron kinetics developed to study the population dynamics in electron beam-generated plasmas produced in low pressure Ar/N$_2$ mixtures. Generally, these plasmas are characterized by low electron temperatures (1 eV), low plasma potentials, and plasma densities in the range $10^7$-$10^{11}$ cm$^{-3}$. We have shown both experimentally and theoretically that small admixtures of nitrogen to argon leads to changes in the electron energy distribution function (EEDF) resulting in a lowering of the electron temperature from 1.0 to 0.4 eV. The modeling results show that these changes strongly impact the production of argon excited states via changes in the collisional excitation rates. The contribution of different production and destruction mechanisms of 1s and 2p argon excited states is discussed in detail. The results of the modeling are compared with the experimentally measured EEDF, electron temperature, and the optical emission spectra in 700-850 nm range.

1Work supported by NRL Base 6.1. Program.
8:15AM HW1.00002 Ion instability in Tonks-Langmuir model with collisions  , T.E. SHERIDAN, Ohio Northern University — The Tonks-Langmuir (TL) model describes a discharge with collisionless, kinetic ions and Boltzmann electrons. In the TL model, ions “born” throughout some volume are accelerated to the discharge walls by the self-consistent electric field in both the presheath and the sheath. That is, the TL model solves the Vlasov equation in a bounded geometry, and hence gives the full ion velocity distribution function. In this presentation, we consider the TL model in a one-dimensional planar geometry with a spatially-uniform source of warm ions. Ions are assumed to undergo “charge exchange” collisions with a constant collision frequency. We solve this model using a particle-in-cell (PIC) simulation. Preliminary investigations show that when the ion birth temperature is sufficiently low, and for collision frequencies which are a few percent of the ion plasma frequency, there is an ion instability in the presheath. At the same locations, the time-averaged ion distribution function displays three peaks, one of which may be associated with ions that inverse Landau damping the electron heating.

8:30AM HW1.00003 Mechanism of N_2 Dissociation and Kinetics of N(4S) Atoms in Pure Nitrogen Plasma1 , ANDREY VOLYNETS, Lomonosov Moscow State University, Faculty of Physics, DMITRY LOPAEV, NIKOLAY POPOV, Lomonosov Moscow State University Skobeltsyn Institute of Nuclear Physics — This work deals with kinetics of the ground state nitrogen atoms N(4S) and N_2 dissociation mechanism in pure N_2 plasma. The experiment was carried out in positive column of DC glow discharge for p=5-50Torr, J=20-100mA. N(4S) balance was considered for spatially uniform conditions controlled by only two terms: source (characterized by effective production rate k_{eff}) and loss (characterized by effective loss time τ_{loss}). Analysis of k_{eff} and τ_{loss} gains considerably better understanding of N_2 dissociation. N_2 dissociation rate as function of discharge parameters was obtained using two independent optical methods: actinometry on Ar atoms and N_2→ band emission decay at discharge modulation. With N/N_2 radial profiles N atom surface loss probability γ_N and then τ_{loss} were estimated. γ_N revealed to be dependent on N(4S) concentration and thereby discharge conditions through the sorption balance of physisorbed N atoms. Phenomenological model taking into account basic surface processes provides γ_N data in good agreement with experiment. Finally, k_{eff} was obtained as function of E/N and it was shown that even EEDF calculated with accounting for N_2 vibrational excitation is unable to provide observed values of k_{eff}. Reasons of that fact are discussed in detail.

The work was supported by RFBR (grant #11-02-91063 - CNRS) and by Optec grant

8:45AM HW1.00004 Modeling of vibrational kinetics in CO_2 dielectric barrier discharges  , S. PONDURI, TU Eindhoven, M.M. BECKER, D. LOFFHAGEN, INP Greifswald, S. WELZEL, M.C.M. VAN DE SANDEN, DIFFER, R. ENGELN, TU Eindhoven — CO_2 reduction to CO is considered to improve the prospects of CO_2 recycling which in turn could mitigate the greenhouse effect and serve as energy storage. Non equilibrium plasmas were used in the past to achieve high energy efficiencies in dissociating CO_2. Non equilibrium distribution in asymmetric stretch modes of CO_2, driven by vibrational up-pumping (VV process), has been suggested as key for achieving such high energy efficiencies. In this work, a time-dependent, one dimensional fluid model taking into account balance equations for the densities of all relevant species and electron mean energy is used to investigate the kinetics of VV process in a pure CO_2 dielectric barrier discharge. A Treanor like distribution has been observed in CO_2 asymmetric modes and the rates of dissociation have been obtained from these distributions. The rates thus obtained have proved to be significantly lower than the rates of other dissociating processes such as electron impact dissociation. The effect of power in-coupling, duration of plasma and pressure on the vibrational distributions and CO production rate is also studied.

9:00AM HW1.00005 ABSTRACT WITHDRAWN

9:15AM HW1.00006 Two-Stage Energy Thermalization Mechanism in Nanosecond Pulse Discharges in Air and Hydrogen-Air Mixtures  , IVAN SHKURENkov, SUZANNE LANIER, IGOR ADAMOVICH, WALTER LEMPERT, The Ohio State University — Time-resolved and spatially resolved rotational temperature measurements in air and H2-air, by purely rotational Coherent Anti-Stokes Raman Spectroscopy (CARS), are presented. The experimental results demonstrate high accuracy of pure rotational psec CARS for thermometry measurements at low partial pressures of oxygen in nonequilibrium plasmas. The results are compared with modeling calculations using a state-specific master equation kinetic model of reacting hydrogen-air plasmas, showing good agreement. The results demonstrate that energy thermalization and temperature rise in these plasmas occurs in two stages, (i) “rapid” heating, occurring on the time scale τ_{rapid} ~ 0.1-1 μs atm, caused by collisional quenching of excited electronic states of N_2 molecules by O_2, and (ii) “slow” heating, on the time scale τ_{slow} ~ 10-100 μs atm, caused primarily by N_2 vibrational relaxation by O atoms (in air) and by chemical energy release during partial oxidation of hydrogen (in H2-air). Both energy thermalization mechanisms have major implications for plasma assisted combustion and plasma flow control.

Wednesday, November 5, 2014 8:00AM - 9:30AM — Session HW2 Dusty Plasmas and Negative Ions State C - Masaru Shiratori, Kyushu University

8:00AM HW2.00001 Coulomb Crystals in Cylindrical Dusty Plasmas under Gravity/Microgravity1 , KAZUO TAKAHASHI, Department of Electronics, Kyoto Institute of Technology, HIROO TOTSUJI, SATOSHI ADACHI, Institute of Space and Astronautical Science, Japan Aerospace Exploration Agency — Coulomb crystals of dusty plasmas have been studied under microgravity with utilities boarding on the International Space Station in a joint Russian/German research project. Dynamics of the Coulomb crystals in cylindrical plasmas is investigated with the apparatus of PK-4 being launched till the end of 2014. A science team in Japan studied the cylindrical dusty plasmas to contribute to the project with the PK-4.1 modified original for microgravity experiments of parabolic flights in Japan. In the experiments, the dust particles distributed at the off-centered position close to the bottom in balancing of gravity. Under microgravity, they changed the distribution and formed a Coulomb crystal around the center axis in the plasmas. Several particles arranged in a line parallel to the axis, and the lines piled up to a bundle. Spatial distribution of the dust particles affects on plasma parameters of ion density and electron temperature. Structures of the Coulomb crystals connected to the parameters are discussed.

1The present study were supported by JAXA and Diamond Air Service.

NEGATIVE ION SOURCES

8:15AM HW2.00002 Langmuir probe measurements of the electron energy probability function and laser scattering in nanodusty plasmas1, NARULA BILIK, YUNXIANG QIN, University of Minnesota – Mechanical Engineering, ERAY AYDIL, University of Minnesota – Chemical Engineering and Materials Science, UWE KORTSHAGEN, University of Minnesota – Mechanical Engineering — A Langmuir probe was used to measure real-time electron energy probability distribution function (EEPF) in argon-silane dusty plasma generated by a RF capacitive reactor. The challenge of Langmuir probe measurements in dusty plasma is the coating of the probe surface: A dielectric layer formed by dust particles causes a series resistance and changes the probe work function, leading to inaccuracy in EEPF measurements. We addressed this problem by adding an actuated ceramic shield to the probe. With the actuated shield the probe was exposed to the dusty plasma only when it was measuring and under rapid I-V scan, minimizing the exposure and effectively preventing coating. EEPFs in dusty plasma were captured in 80mtorr and 40W dusty plasma (10sccm argon and 4.7sccm 5% silane in argon flow). Simultaneous measurements of the ion density with a capacitive probe and real-time laser scattering was performed to further characterize the plasma. As particles form in dusty plasma, the electron density dropped but electron temperature increased. The electron density in the dusty plasma dropped much more compared to the ion density due to the attachment of electrons to the growing particles. 1This work was supported by the DOE Plasma Science Center for Predictive Control of Plasma Kinetics.

8:30AM HW2.00003 Correlation between nanoparticle formation and plasma parameters evolution in magnetically confined C2H2/Ar plasma. GEORGES AL MAKDESSI, JOELLE MARGOT, University of Montreal, RICHARD CLERGEREAUX, University of Paul Sabatier — Dusty plasmas are plasmas containing charged nano-sized or even charged micro-sized particles. Known for decades, dusty plasmas have attracted the interest of the scientific community in the early 80s, especially in astrophysics when dusty particles were discovered in the rings of Saturn [1]. Comets and planetary rings are some examples of natural objects formed by dusty plasmas [2]. Dusty particles are also found in laboratories plasmas such as those used for deposition and etching of thin films. In this presentation, we investigate magnetically confined low pressure dusty plasmas in acetylene. The plasma is created by an electromagnetically wave at a frequency of 200 MHz. By performing a parametric study of the influence of the magnetic field on the formation of dust particles and on the plasma properties, we expect to achieve a good understanding of their creation mechanisms, and, ultimately to control their characteristics.


8:45AM HW2.00004 Nanoparticle heating at atmospheric pressures1, NICOLAAS KRAMER, University of Minnesota – Mechanical Engineering, ERAY AYDIL, UWE KORTSHAGEN, University of Minnesota – Chemical Engineering and Materials Science — Plasma growth and crystallization of nanoparticles is an exciting new frontier both for plasma science as well as materials research. To date, the mechanisms of nanoparticle charging and heating in nonthermal plasmas have been studied and understood to some extent for low pressure plasmas. However, particle charging and heating at atmospheric pressures have been little explored. The fundamental processes of nanoparticle charging and heating are significantly different at atmospheric pressure compared to low pressures. Charging is determined through collision enhanced or hydrodynamic, mobility driven collection of ions by the nanoparticles rather than by orbital motion at low pressures. Nanoparticle heating reactions have to compete with nanoparticle cooling through convection/conduction to the neutral gas that is about 100-1000 times faster than at low pressure. Here, we present a Monte Carlo model that stochastically treats nanoparticle heating reactions such as electron-ion recombination and energetic surface reactions. Nanoparticle cooling through conduction/convective is modeled through a continuum model. The model indicates at atmospheric pressure, the nanoparticle temperature on average remains much closer to the gas temperature than at low pressure. 1This work was supported by the DOE Plasma Science Center for Predictive Control of Plasma Kinetics.

9:00AM HW2.00005 Numerical Modeling of a Pulsed Argon-Silane RF Plasma with Biased Substrate for High-Velocity Deposition of Nanoparticles1, STEVEN GIRSHICK, CARLOS LARRIBA-ANDALUZ, Dept. of Mechanical Engineering, University of Minnesota, Minneapolis, MN — It has been hypothesized that deposition of very small silicon nanoparticles during plasma-enhanced chemical vapor deposition of silicon, under conditions where the particle impact velocity is high enough to cause particle melting/amorphization, can lead to epitaxial film growth at low temperature [1]. One way to accomplish this might be by pulsing the RF plasma and applying a positive DC bias during the afterglow of each pulse. The negatively charged particles, trapped in the plasma during the ON phase of each pulse, are accelerated to the substrate during the afterglow. To assess the feasibility of such an approach, we conducted numerical simulations of a pulsed capacitively-coupled RF Ar-silane plasma. We used a modified version of a previously reported 1D model, in which a nanodusty plasma is simulated by self-consistently coupling models for the plasma, chemistry and aerosol [2]. Preliminary results indicate that the approach is feasible, but that parameters such as pulse frequency and duty cycle are important in limiting particle growth and in maximizing fluxes of energetic nanoparticles to the substrate. [1] P. Roca i Cabarrocas, R. Cariou and M. Labrune, J. Non-Cryst. Sol., 358, 2000 (2012). [2] P. Agarwal and S. L. Girshick, Plasma Chem. Plasma Process. 34, 489 (2014).

1Partially supported by US Dept. of Energy Office of Fusion Energy Science (DE-SC0001939) and US National Science Foundation (CHE-124752).

9:15AM HW2.00006 Hydrogen negative-ion surface production on diamond materials in low-pressure H2 plasmas1, GILLES CARTRY, KOSTIANTYN ACHKASOV, CÉDRIC PARDANAUD, JEAN-MARC LAYET, PIIM, Aix Marseille University, CNRS, ALAIN SIMONIN, IRFMP, CEA Cadarache, ALIX GICQUEL, LSPM, CNRS, Paris Nord University, PIIM COLLABORATION, IRFMP COLLABORATION, LSPM COLLABORATION — Negative-ion sources producing H- current density of ~ 200 A/m2 are required for the heating of the fusion plasma of the international project ITER. The only up-to-date solution to reach such a high H- negative-ion current is the use of cesium (Cs). Deposition of Cs on the negative-ion source walls lowers the material work function and allows for high electron-capture efficiency by incident particles and thus, high negative ion yields. However, severe drawbacks to the use of Cs have been identified and its elimination from the fusion negative-ion sources would be highly valuable. Volume production is not efficient enough at low-pressure to reach the high current required. Therefore, we are working on alternative solutions to produce high yield of H- negative-ions on surfaces in Cs-free H2 plasmas. In this communication, we will detail the methodology employed to study negative-ion surface production. In particular we will describe how the negative-ions are extracted from the plasma, and how we can obtain information on surface production mechanisms from the measurement of the H- energy distribution functions. We will present some results obtained on diamond surfaces and show that diamond is a promising candidate as a negative-ion enhancer material in low-pressure H2 plasmas. 1EFDA, FR-FCM, ANR, PACA are acknowledged for their support.

Wednesday, November 5, 2014 8:00AM - 9:30AM – Session HW3 Plasma Interactions with Biological Surfaces State D - Masafumi Ito, Meijo University
8:00AM HW3.00001 Cold flame on Biofilm - Transport of Plasma Chemistry from Gas to Liquid Phase. MICHAEL KONG, Old Dominion University — One of the most active and fastest growing fields in low-temperature plasma science today is biological effects of gas plasmas and their translation in many challenges of societal importance such as healthcare, environment, agriculture, and nanoscale fabrication and synthesis. Using medicine as an example, there are already three FDA-approved plasma-based surgical procedures for tissue ablation and blood coagulation and at least five phase-II clinical trials on plasma-assisted wound healing therapies. A key driver for realizing the immense application potential of near room-temperature ambient pressure gas plasmas, commonly known as cold atmospheric plasmas or CAP, is to build a sizeable interdisciplinary knowledge base with which to unravel, optimize, and indeed design how reactive plasma species interact with cells and their key components such as protein and DNA. Whilst a logical objective, it is a formidable challenge not least since existing knowledge of gas discharges is largely in the gas-phase and therefore not directly applicable to cell-containing matters that are covered by or embedded in liquid (e.g. biofluid). Here, we study plasma inactivation of biofilms, a jelly-like structure that bacteria use to protect themselves and a major source of antimicrobial resistance. As 60-90% of biofilm is made of water, we develop a holistic model incorporating physics and chemistry in the upstream CAP-generating region, a plasma-exit region as a buffer for as-phase transport, and a downstream liquid region bordering the gas buffer region. A special model is developed to account for rapid chemical reactions accompanied the transport of gas-phase plasma species through the gas-liquid interface and for liquid-phase chemical reactions. Numerical simulation is used to illustrate how key reactive oxygen species (ROS) are transported into the liquid, and this is supported with experimental data of both biofilm inactivation using plasmas and electron spin spectroscopy (ESR) measurement of liquid-phase ROS.

8:30AM HW3.00002 Evaluation of the Efficacy of the Plasma Pencil Against Cancer Cells. SOHEILA MOHADES, NAZIR BAREKZI, HAMID RAZAVI, MOUNIR LAROUSSI, Old Dominion University — The plasma pencil generates low temperature and atmospheric pressure plasma. To generate the plasma, high voltage pulses with short width (from nanosecond to microsecond) are applied to a noble gas. The working gas can be helium, argon or a mixture of these with air or oxygen. Generating plasma with helium provides a tolerable temperature for biological cells and tissues. Diagnostic measurements on the plasma plume has revealed the presence of active agents such as reactive oxygen species (ROS) and nitrogen reactive species (RNS), which are known to have biological implications. Recently, low temperature plasma has drawn attention to its potential in cancer therapy. In our lab, the plasma pencil has been used to treat leukemia, prostate and epithelial cancer cells [1]. The cancer cell line used here is the ScaBER (ATCC®HTB3™) cell line originating from a human bladder cancer. The results indicate that specific species induce the molecular mechanisms associated with cell death. The death of cells after plasma treatment will be studied using assays, such as DNA laddering and Caspase-3 activation, to elucidate the mechanism of the apoptotic or necrotic pathways.

1 Work supported by DOE Office of Fusion Energy Science and NSF.

8:45AM HW3.00003 Multiple Pulses from Plasma Jets onto Liquid Covered Tissue1, SETH NORBERG, WEI TIAN, ERIC JOHNSEN, MARK J. KUSHNER, University of Michigan — Atmospheric pressure plasma jets are being studied in the treatment of biological surfaces that are often covered by a thin layer of liquid. The plume of the plasma jet contains neutral radicals and charged species that solvate into the liquid and eventually form terminal species that reach the tissue below. The contribution of neutral and charged species to reactivity in the liquid is sensitive to whether the active plasma plume touches the liquid. In this paper, we discuss results from modeling the production of the aqueous species formed from the interaction of the plume of plasma jets over multiple pulses with the water layer, and the fluxes of the species to the underlying tissue. The model used in this study, nonPDPSIM, solves transport equations for charged and neutral species and electron energy, Poisson’s equation for the electric potential, and Navier-Stokes for neutral flow. The plasma jet transport includes photoionization of O$_2$ and H$_2$O in the gas and liquid phases and photodissociation of H$_2$O$_{aq}$ in the liquid. Multiple pulses when the plasma plume touches and does not touch the liquid will be examined. Two regimes of hydrodynamics will be discussed – low repetition rates where the neutral radicals are blown away before the next discharge pulse, and high repetition rate when the plasma plume interacts with neutral radicals from previous pulses. The density of aqueous ions produced in the liquid layer is strongly dependent on whether the plasma effluent touches or does not touch the water surface.

1 Work supported by the German Research Foundation within PA816.

9:00AM HW3.00004 Atomic oxygen characteristics in a dielectric barrier discharge developed for wound treatment1. SABRINA BALDUS, Institute for Plasma Technology, Ruhr University Bochum, DANIEL SCHROEDER, VOLKER SCHULZ-VON DER GATHE, Institute for Experimental Physics II, Ruhr University Bochum, NIKITA BIBINOV, PETER AWAKOWICZ, Institute for Plasma Technology, Ruhr University Bochum — Nowadays, infected chronic wounds are a major problem of society. Atmospheric pressure plasmas like dielectric barrier discharges (DBDs) have already shown their ability of improving the wound healing process of chronic wounds in clinical trials. Yet, the mechanism of action is poorly understood. A DBD comprising a single driven electrode is a beneficial configuration for wound treatment. The patient itself functions as the counter electrode. Hence, reactive oxygen species (ROS) like ozone or atomic oxygen produced in the plasma reach the wound directly. Some ROS, including superoxide or nitric oxide, are produced by skin cells to repulse invading bacteria. Nevertheless, a very high amount of ROS leads to oxidative stress and can cause cell damage or even cell death. Therefore it is crucial to have a well characterized plasma for effective wound treatment. Plasma parameters are determined using absolutely calibrated optical emission spectroscopy. Density of atomic oxygen is measured applying xenon-calibrated two photon absorption laser induced fluorescence spectroscopy. A simulation of the afterglow chemistry, developed to gain insight in the characteristics of the atomic oxygen and its flux towards the treated surface, is cross-checked with measurement results.

1 Work supported by the German Research Foundation within PA816.

9:15AM HW3.00005 Long Term Effects of Multiple DBD Pulses on Thin Liquid Layers Over Tissue: Reactive Fluences and Electric Fields1, WEI TIAN, MARK J. KUSHNER, University of Michigan — Atmospheric dielectric barrier discharges (DBDs) are used in treatment of tissue, often covered by thin liquid layers. The reactivity reaching the tissue depends on the plasma dose, composition and acidification of the liquid, and the cumulative delivery of electric fields through the liquid. In this paper, we report on a computational investigation of the interaction of DBDs with a thin liquid layer covering tissue over many minutes. We used nonPDPSIM, a 2-d model in which Poisson’s equation, the electron temperature equation, transport equations for charged and neutral species and radiation transport are solved in both the gas and liquid. The liquid layer, 100’s μm thick, is water with dissolved gases [O$_{aq}$ ($aq$ is aqueous), CO$_2$,$aq$], metal ions (Fe$_{aq}$, Fe$_{aq}$), and organics (RH$_{aq}$). Hundreds of pulses at 100 Hz are computed, followed by minutes of afterglow. In the liquid, transient radicals (OH$_{aq}$, H$_{aq}$) are produced during the discharge pulse and are consumed during the interpulse period. Terminal species (H$_2$O$_{aq}$, O$_{aq}$) accumulate and diffuse to the tissue. Ions are dominated by NO$_{aq}$, O$_2$–$aq$ and H$_3O^+$. Production of HNO$_{aq}$ and HOONO$_{aq}$ is assisted by O$_{aq}$ for the first pulses and then O$_{aq}$. Accumulating nitric acid lowers the pH. RH$_{aq}$ consumes most reactive oxygen species in the early plasma treatment leaving RH$_{aq}$. With longer exposure, RH$_{aq}$ can be consumed, enabling more ROS to reach the tissue. The cumulative exposure of electric fields to the tissue depends on the increasing conductivity of the liquid.

1 Work supported by DOE Office of Fusion Energy Science and NSF.
1:30PM KW1.00001 Diagnostics of plasma-surface interactions in plasma processes, KENJI ISHIKAWA, Nagoya University — Low temperature plasma including electrons, ions, radicals and photons can be applied because only high temperature of electron but for background gases. Recently plasma applications in biology and medicine have grown significantly. For complexity of mechanisms, it is needed to understand comprehensively the plasma-surface interactions. To diagnose the interactions comprises of three areas; (1) incident species generated in plasmas toward the surface, (2) surface reactions such as scission and bond of chemical bonds, and (3) products after the reactions. Considered with non-linearity of the chemical reactions as changed by an initial state, we have focused and developed to observe dangling bonds in situ at real time by electron spin resonance (ESR). Moreover, individual contribution and simultaneous irradiation of each species such as radicals and photons have been studied in utilization of light shades and windows in similar manner of the pellets for plasma process evaluation (PAPE) [1]. As exampled, the interaction of polymeric materials [2], fungal spores[3] and edible meats with plasmas were studied on the basis of the real time in situ observations of dangling bonds or surface radicals formation.

1:30PM KW1.00002 Phase-modulated dispersion interferometry for electron-density determination of high-pressure plasma, KEICHIRO URABE, The University of Tokyo, TSUYOSHI AKIYAMA, National Institute for Fusion Science, KAZUO TERAISHIMA, The University of Tokyo — Phase-modulated dispersion interferometry (PMDI) is a laser interferometry technique that was first developed for measurement of electron density in large fusion reactors [1]. PMDI can eliminate the effect of nondispersive components in the refractive-index variation on the measured signals thereby it is mostly free from vibration of optical devices during the measurement. Also, configuration of the laser beam axis in PMDI is simpler than that in heterodyne interferometry. In this paper, we demonstrate the potential of PMDI for the diagnostics of low-temperature plasmas generated at high pressures. Most of the variation of the refractive index induced by the variation of gas density was eliminated by signal processing, and it contributed to accurate electron-density determination in high-pressure plasmas [2]. The measurement results for a pulsed-dc microdischarge in an atmospheric-pressure helium gas flow revealed that the electron density in the microdischarge was in the range between 4x10¹³ and 1.4x10¹⁴ cm⁻³, and our PMDI system had a temporal resolution of 110 µs and a sensitivity of the line-integrated electron density of 7x10¹¹ cm⁻² respectively.

1:30PM KW1.00003 In-situ diagnostics and characterization of etch by-product deposition on chamber walls during halogen etching of silicon, NEEMA RASTGAR, SARAVANAPRIYAN SRIRAMAN, RICKY MARSH, ALEX PATERSON, Lam Research — Plasma etching is a critical technology for nanoelectronics fabrication, but the use of a vacuum chamber limits the number of in-situ, real-time diagnostics measurements that can be performed during an etch process. Byproduct deposition on chamber walls during etching can affect the run-to-run performance of an etch process if there is build-up or change of wall characteristics with time. Knowledge of chamber wall evolution and the composition of wall-deposited films are critical to understanding the performance of plasma etch processes, and an in-situ diagnostics measurement is useful for monitoring the chamber walls in real time. We report the use of attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR) to perform in-situ diagnostics of a vacuum chamber’s walls during plasma etching. Using ATR-FTIR, we are able to monitor the relative thickness and makeup of chamber wall deposits in real time. We then use this information to develop a chamber wall cleaning process in order to maintain reproducible etching conditions from wafer to wafer. In particular, we report mid-IR (4000-650 cm⁻¹) absorption spectra of chamber wall-deposited silicon byproducts formed during halogen etching of silicon wafers.
2:30PM KW1.00004 Accurate characterization of RF antennas for low-temperature plasma discharges with non-uniform magneto-static fields, DAVIDE MELAZZI, University of Padova, Padova, Italy, VITO LANCELLOTTO, Eindhoven University of Technology, Eindhoven, The Netherlands, ALESSANDRO CARDINALLI, ENEA Unità Tecnica Fusione, Rome, Italy, MARCO MANENTE, T4i S.r.l., Padova, Italy, DANIELE PAVARINI, University of Padova, Padova, Italy — The analysis of Radio Frequency Helicon plasma sources appears to have focused on the absorption of electromagnetic energy, but not much on the role played by the antenna driving the plasma discharge. In fact, most approaches assume (i) the induced current density on the antenna a priori, and (ii) a uniform magneto-static field aligned with the plasma column. To determine the antenna current self-consistently and to consider non-uniform magneto-static fields we have developed two codes: ADAMANT and RayWh. The former implements a full-wave approach to evaluate the current distribution on the antenna and the antenna impedance, which is crucial for the design of the feeding network. RayWh solves the 3D Maxwell-Vlasov model equations by a WKB asymptotic expansion, and is capable of predicting the occurrence of mode transitions. We report on a comparative study of various antennas working in the 1-30 MHz range commonly used in Helicon sources. The current distribution on the antenna, power deposition, and wave propagation phenomena have been investigated for various density profiles, magneto-static field configurations, neutral pressure, electron temperature.

2:45PM KW1.00005 Electron Density Measurement of Argon Containing Plasmas by Saturation Spectroscopy1, S. NISHIYAMA, H. WANG, S. TOMIOKA, K. SASAKI, Hokkaido University — Langmuir probes are widely used for electron density measurements in plasmas. However, the use of a conventional probe should be avoided in a plasma which needs high purity because of the possibility of contamination. Optical measurements are suitable for these plasmas. In this work, we applied saturation spectroscopy to the electron density measurement. The peak height of the saturation spectrum is affected by the relaxation frequency of the related energy levels. In the case of the metastable levels of argon, the electron impact quenching process is proportional to the electron temperature, which is the dominant factor. In our experiments, an inductively coupled plasma source and a tunable cw diode laser were used. The frequency of the laser was scanned over the Doppler width of the fs[3/2]2 − fs[3/2]2 (763.51 nm) transition. The experimental saturation spectrum was composed of a sharp Lorentzian peak and a broad base component, which was caused by velocity changing collisions. We deduced a new relationship between the saturation parameter and the measured saturated absorption spectrum with considering velocity changing collisions. We confirmed a linear relationship, which was expected theoretically, between the inverse of the saturation parameter and the electron density.

3:00PM KW1.00006 OH(A,X) radicals in microwave plasma-assisted combustion of methane/air1, WEI WU, CHE FUH, CHUJI WANG, Mississippi State University, LASER SPECTROSCOPY AND PLASMA TEAM — A new microwave plasma-assisted combustion (PAC) system, which consists of a microwave plasma-assisted combustor, a gas flow control manifold, and a set of optical diagnostic systems, was developed as a new test platform to study plasma enhancement of combustion. Using this system, we studied the state-resolved OH(A,X) radicals in the plasma-assisted combustion and ignition of a methane/air mixture. Experimental results identified three reaction zones in the plasma-assisted combustor: the plasma zone, the hybrid plasma-flame zone, and the flame zone. The OH(A) radicals in the three distinct zones were characterized using optical emission spectroscopy (OES). Results showed a surge of OH(A) radicals in the hybrid zone compared to the plasma zone and the flame zone. The OH(X) radicals in the flame zone were measured using cavity ringdown spectroscopy (CRDS), and the absolute number density distribution of OH(X) was quantified in two-dimension. The effect of microwave argon plasma on combustion was studied with two different fuel/oxidizer injection patterns, namely the premixed methane/air injection and the nonpremixed (separate) methane/air injection. Parameters investigated included the flame geometry, the lean flammability limit, the emission spectra, and rotational temperature. State-resolved OH(A,X) radicals in the PAC of both injection patterns were also compared.

3:15PM KW1.00007 Ion Flux and Energy Virtual Sensor for Measuring Ion Flux and Energy Distribution at a RF Biased Electrode in ICP Reactor (RIE-MODE)1, MARIA BOGDANOVA, 1 Skobeltsyn Institute of Nuclear Physics, Moscow State University, SINP MSU, Moscow Russia; 2 Faculty of Physics, Moscow State University, MSU, Moscow, DMITRY LOPAEV, Skobeltsyn Institute of Nuclear Physics, Moscow State University, SINP MSU, Moscow Russia, SERGEY ZYRYANOV, 1 Skobeltsyn Institute of Nuclear Physics, Moscow State University, SINP MSU, Moscow Russia; 2 Faculty of Physics, Moscow State University, MSU, Moscow — The modern technology of micro- and nanoelectronics involves a great number of steps, e.g. pattern transfer, where Reactive Ion Etching (RIE) in rf plasma reactors is widely used. RIE is carried out placing samples on the surface of rf biased electrode, as rule in an asymmetric rf low-pressure discharge. In an effort to control the etching process, ion flux and energy distribution should be controlled precisely as much as possible. However, measurements of them during the process in the real-time operation mode are impossible. Nevertheless, if virtual sensor of ion flux and energy can be developed, such a sensor would allow monitoring ion energy spectrum without direct measurements during plasma processing. This virtual plasma diagnostics should include calculation of ion energy spectrum based on the simple physical model of ion motion in collisionless rf sheath. In addition the modeling has to be fulfilled in the real-time operation mode by using the set of external measurable parameters. This paper is just devoted to creation of such ion energy distribution virtual diagnostics.

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1This work is supported by the National Science Foundation through the grant No. CBET-1066486.

Wednesday, November 5, 2014 1:30PM - 3:00PM – Session KW2 Reactive Microdischarges State C - David Go, University of Notre Dame

1:30PM KW2.00001 Influence of the amount of N2 admixture on the dynamics of atmospheric pressure helium discharges in capillary tubes, ANNE BOURDON, FRANCOIS PECHEREAU, PEDRO VIEGAS, EM2C laboratory, Ecole Centrale Paris — Since a few years, atmospheric pressure helium microplasma jets ignited in thin dielectric tubes have received considerable interest due to their potential for biomedical applications. In particular, the propagation of discharges in long capillary tubes is studied for the development of medical devices for endoscopic applications. In [1], experiments have been carried out to study the influence of various amounts of N2 admixture on the characteristics of a helium discharge in long capillary tubes. In this work, we study with a 2D fluid model the discharge characteristics in conditions close to those used in experiments. Simulation results show that the discharge dynamics and structure depend on the amount of N2 admixture and the applied voltage. In particular, as the amount of N2 admixture increases, the propagation velocity of the discharge in the tube first increases and then decreases, as observed in experiments. To explain these results, a detailed analysis of the kinetic scheme of He-N2 mixtures with various amounts of N2 is presented. The influence of other parameters as the initial preionization level, the tube material and the shape of the applied voltage are also discussed.

State University, Fullerton

5.8 kV) and the inner diameter of the microcapillaries (from 100 to 500 μm) on the discharge dynamics are investigated. Inside the tubes, while the topology of the bullets seems to be strongly dependent on the diameter, their velocity (on the order of 1 to 5x10^7 m/s) is only a function of the applied voltage. In ambient air, the air-plasma bullets propagate at a velocity of 1.25x10^7 m/s. Possible mechanisms for the propagation of air-plasma bullets in ambient air are discussed.

2:45PM KW2.00006 High pressure micro glow discharge: Detailed approach to gas temperature modeling1. MOSTAFA MOBLI, TANVIR FAROUK, Department of Mechanical Engineering, University of South Carolina — High pressure micro plasma discharge has been the center of interest in recent years, unlike low pressure discharges; gas heating is an important factor in these discharges. A Dirichlet temperature boundary condition (iso-thermal) which is the most commonly used, is unable to capture the cathode and anode wall temperature temporal changes, effects of materials thermal characteristics and also forces an artificial cooling of the discharge. To overcome this inadequacy a conjugate heat transfer (CHT) model has been implemented which is found to resolve the gas temperature predictions both in the volume and the electrode surfaces.

1 Supported by the Air Force Research Laboratory and Department of Energy.

Wednesday, November 5, 2014 1:30PM - 3:00PM – Session KW3 Electron-Molecule Collisions and Related Processes  I  State D - Leigh Hargreaves, California State University, Fullerton
1:30PM KW3.00001 Electron attachment to fluorocarbon radicals, NICHOLAS SHUMAN, Air Force Research Laboratory — Most plasma environments contain populations of short-lived species such as radicals, the chemistry of which can have significant effects on the overall chemistry of the system. However, few experimental measurements of the kinetics of electron attachment to radicals exist due to the inherent difficulties of working with transient species. Calculations from first principles have been attempted, but are arduous and, because electron attachment is too sensitive to the specifics of the potential surface, their accuracy has not been established. Electron attachment to small fluorocarbon radicals is particularly important, as the data are needed for predictive modeling of plasma etching of semiconductor materials, a key process in the industrial fabrication of microelectronics. We have recently developed a novel flowing afterglow technique to measure several types of otherwise difficult to study plasma processes, including thermal electron attachment to radicals. Variable Electron and Neutral Density Attachment Mass Spectrometry (VENDAMS) exploits dissociative electron attachment in a weakly ionized plasma as a radical source. Here, we apply VENDAMS to a series of halofluorocarbon precursors in order to measure the kinetics of thermal electron attachment to fluorocarbon radicals. Results are presented for CF₂, CF₃, C₂F₂, C₃F₂, 1-C₄F₂, 2-C₄F₂, and C₅F₅ from 300 K to 900 K. Both the magnitude and the temperature dependences of rate coefficients as well as product branching between associative and dissociative attachment are highly system specific; however, thermal attachment to all species is inefficient, never exceeding 5% of the collision rate. The data are analyzed using a recently developed kinetic modeling approach, which uses extended Vögt-Wannier theory as a starting point, accounts for dynamic effects such as binding between the electron and nuclear motions through empirically validated functional forms, and finally uses statistical theory to determine the fate of the highly excited anion intermediate formed during attachment. The kinetic modeling, along with complimentary data from electron beam measurements, is used to extrapolate the electron attachment rate coefficients to temperature and pressure regimes inaccessible to the experiment, including to non-thermal plasma conditions most relevant to plasma etching.

2:00PM KW3.00002 H₂-Assisted Ternary Recombination of H⁺ with Electrons at 300 K, RAINER JOHNSEN, University of Pittsburgh, PETER DONHALN, PETER RUBOVIC, ABEL KALOSI, MICHAL HEJDUK, RADEK PLASIL, JURAJ GLOSIK, Charles University Prague — Afterglow measurements in ionized He/Ar/H₂ gas mixtures at 300 K show that the recombination of H⁺ ions with electrons is very strongly enhanced in the presence of molecular hydrogen. In the experiments the decay of H⁺ ions was measured by near-infrared (NIR) absorption spectroscopy (SA-CRDS). Rather surprisingly, the H₂-assisted three-body recombination coefficient (K₁₂ = (8.7 ±/− 1.5) × 10⁻²³ cm³ s⁻¹) exceeds by more than two orders of magnitude the corresponding He-assisted coefficient (K₁₂ = (3.3 ±/− 0.7) × 10⁻²⁵ cm³ s⁻¹). We have measured the rate coefficient of faster recombining H₂⁺ cluster ions does not play a significant role at temperature near 300 K. The ternary processes are found to saturate at high He and H₂ densities, suggesting that recombination proceeds by a two-step process, electron capture (with a rate coefficient α₁ = (1.5 ±/− 0.1) × 10⁻⁷ cm³ s⁻¹) into a long-lived Rydberg state with an excited core, followed by collisional stabilization. While these findings provide a plausible explanation for some of the discrepancies between earlier afterglow measurements of H⁺ recombination, the exact nature of these long-lived complexes, and their collisional interactions remain to be elucidated.

1 This work was partly supported by GACR P209/12/0233, GACR 14-14049P, GAUK 692214.

2:15PM KW3.00003 Kinetics of ion-ion mutual neutralization¹, THOMAS M. MILLER, JUSTIN P. WIENS, NICHOLAS S. SHUMAN, ALBERT A. VIGGIANO, Air Force Research Laboratory — We have measured rate coefficients for 87 mutual neutralization reactions between thermal energy anions and cations, a number of them as a function of temperature. In addition, in two cases we have observed a transfer ionization channel in which there is enough energy for the anion reactant to be doubly ionized, yielding a cation product rather than neutralization. We will summarize these results and note correlations, namely: (1) binary neutralization rate coefficients are primarily a function of the chemical nature of the system for atom-atom ionic pairs (with a wide range of rate coefficients), but quickly become dominated by physical aspects (i.e., relative velocity) as the number of atoms in the system increases. (2) Rate coefficients for atom-atom ionic pairs are well fit at 300 K by k = 3 × 10⁻⁴ R²⁻¹.⁶⁻¹, where R is the curve crossing radius given by R = 27.2/ΔE, with ΔE the energy transfer released in the reaction. (ΔE in eV, R in Bohr, and k in cm³/s.) (3) Rate coefficients for systems of more than 4 or 5 atoms are well described by k = 2.7 × 10⁻⁷(T/300⁻¹)⁻⁰.⁹ μ⁻⁰.⁵. (T in K, and the reduced mass μ in amu.) (4) Triatomic systems have rate coefficients smaller than given by the expression in (3).

¹Supported by the Air Force Office of Scientific Research, AFOSR 2303EP

2:30PM KW3.00004 Electron scattering measurements from molecules of technological relevance¹, DARRYL JONES, School of Chemical and Physical Sciences, Flinders University — Biomass represents a significant opportunity to provide renewable and sustainable biofuels [1]. Non-thermal atmospheric pressure plasmas provide an opportunity to efficiently breakdown the naturally-resilient biomass into its useful subunits [2]. Free electrons produced in the plasma may assist in this process by inducing fragmentation though dissociative excitation, ionization or attachment processes [3]. To assist in understanding and refining this process, we have performed electron energy loss experiments from phenol (C₆H₅OH), a key structural building block of biomass. This enables a quantitative assessment of the excited electronic states of phenol. Differential cross sections for the electron-driven excitation of phenol have also been obtained for incident electron energies in the 20-250 eV range and over 3-90° scattering angles.


¹DBJ acknowledges financial support provided by an Australian Research Council DECRA.
3:30PM LW1.00001 Inductively-coupled plasmas in pure Cl, O and mixtures: measurements of atoms, Cl$_2$, O$_2$ and electron densities, MICHAEL FOUCHER, LPP-CNRS UMR 7648, EMILE CARBONE, CEA grenoble, JEAN-PAUL BOETH, PASCAL CHABERT, LPP-CNRS UMR 7648, LPP-PLASMAS FROIDS TEAM — Inductively-coupled plasmas in Cl/O (often with HBr) are widely used in the microelectronics industry for the etching of silicon CMOS gates. Many simulations describing these plasmas (global and 2-dimensional fluid models such as HPEM) have been developed but experimental validation is sparse. This paper addresses this gap with a large quantity of experimental data in plasmas of Cl, O and their mixtures. The plasma is excited by a 4-turn planar coil powered at 13.56 MHz through a dielectric window, and contained in a cylindrical vessel. Electron densities were measured with a microwave hairpin resonator. In all cases the electron density passes through a maximum with pressure. The ground-state O and Cl atom density was measured by Two-Photon Absorption Laser-Induced Fluorescence (TALIF) combined with specific absolute calibration techniques. Broad-band absorption spectroscopy was used to measure the density of Cl and vibrationally excited molecules have been measured in low-pressure plasmas.

3:45PM LW1.00002 Time evolution of spatial RF field profiles in a 100 MHz reactor, BARTON LANE, Tokyo Electron America, IKUO SAWADA, Retired, PETER VENTZEK, COLIN CAMPBELL, Tokyo Electron America, AKIRA KOSHIISHI, Tokyo Electron Miyagi — We report here on time and space resolved magnetic and electric field strength measurements in a 100 MHz reactor. The reactor studied is a test bed reactor with a geometry which approximately mimics commercial reactors for semiconductor manufacturing. The magnetic fields were captured using a B-dot probe fashioned after the work of Miller et al. [1] Time traces at different radial locations are compared using time traces from a fixed pickup probe mounted on the VHF feed in order to obtain magnetic field profiles as a function of radius at different values of the VHF phase. The presence of standing waves and propagating waves are clearly seen. A rapid increase and collapse of the magnetic field at the core of the plasma takes place on a nsec time scale showing the physical origin of the higher harmonic waves seen in previous studies. The profiles show the effect of the non-linear evolution of the wave. The data is presented as an animated sequence of plots of the field strength vs radius. A double dipole probe was also used to measure the vertical component of the VHF field. These measurements confirm the picture given by the B dot probe.

4:00PM LW1.00003 Low pressure characteristics of the multipole resonance probe$^1$, RALF PETER BRINKMANN, JENS OBERRATH, Ruhr-University Bochum — The term "Active plasma resonance spectroscopy" (APRS) denotes a class of related techniques which utilize, for diagnostic purposes, the natural ability of plasmas to resonate on or near the electron plasma frequency $\omega_{pe}$. The basic idea dates back to the early days of discharge physics but has recently found renewed interest as an approach to industry-compatible plasma diagnostics: A radio frequency signal (in the GHz range) is coupled into the plasma via an antenna or probe, the spectral response is recorded (with the same or another antenna or probe), and a mathematical model is used to determine plasma parameters such as the electron density or the electron temperature. When the method is applied to low pressure plasmas (of a few Pa and lower), kinetic effects must be accounted for in the mathematical model. This contribution studies a particular realization of the APRS scheme, the geometrically and electrically symmetric Multipole Resonance Probe (MRP). It is shown that the resonances of the MRP exhibit a residual damping in the limit $\omega \rightarrow 0$ which cannot be explained by Ohmic dissipation but only by kinetic effects.$^1$

4:15PM LW1.00004 Diagnostics of Rotational Temperature and Mean Electron Energy Distribution of DC Glow Discharge Using Spectral Image Processing, DAISUKE SHIMIZU, RYO SASAMOTO, TAKAO MATSUMOTO, YASUJI IWAIWA, KIYOTO NISHIJIMA, Fukuoka University — The non-thermal plasma has been used in various application fields of manufacturing industry such as surface reforming, plasma etching, deposited film forming. The gas temperature and electron energy in non-thermal plasma play a key role of production of active species. Therefore, it is essential to understand the properties of non-thermal plasma for effective plasma applications. In this study, the two-dimensional rotational temperature and mean electron energy distribution of DC glow discharge plasma under various air pressures were observed using spectral image processing. Rotational temperature distribution was estimated from the emission intensity ratio of head and tail of 2nd positive system of $\text{N}_2$ ($2^3 \Sigma^+_o \rightarrow 2^3 \Pi^+_p$, $\lambda = 388.9$ nm) and $\text{N}_2$ ($2^3 \Sigma^+_o \rightarrow 2^1 \Pi^+_p$, $\lambda = 391.4$ nm) under various air pressures. The mean electron energy was estimated from the emission intensity ratio of 2nd positive system band of $\text{N}_2$ ($2^3 \Sigma^+_o \rightarrow 2^1 \Pi^+_p$, $\lambda = 391.4$ nm) and $\text{N}_2$ ($2^3 \Sigma^+_o \rightarrow 2^1 \Pi^+_p$, $\lambda = 391.4$ nm) under various air pressures.

4:30PM LW1.00005 Laser Induced Fluorescence of the Iodine Ion, WILLIAM HARGUS, Air Force Research Laboratory, Edwards AFB, CA — Iodine (I$_2$) has been considered as a potential electrostatic spacecraft thruster propellant for approximately 2 decades, but has only recently been demonstrated. Energy conversion efficiency appears to be on par with xenon without thruster modification. Intriguingly, performance appears to exceed xenon at high acceleration potentials. As part of a continuing program to develop non-intrusive plasma diagnostics for advanced plasma spacecraft propulsion, we have identified the I I 5d$^5$P$^o$ state as metastable, and therefore containing a reservoir of excited state ions suitable for laser probing. The 5d$^5$P$^o$ state transitions at 995 nm, 995 nm, and 995 nm are convenient for diode laser excitation with the 5m$^5$S$^o$ - 6p$^5$P$^o$ transition at 516.12 nm as an ideal candidate for non-resonant fluorescence collection. We have constructed a Penning type iodine microwave discharge lamp optimized for I II production for table-top measurements. This work demonstrates I I laser-induced fluorescence in a representative iodine discharge and will validate our previous theoretical work based on the limited available historical I II spectral data.

4:45PM LW1.00006 Picosecond-TALIF measurements of atomic oxygen in RF driven atmospheric pressure plasma jets$^2$. JEROME BREDIN, JAMES DEDRICK, KARI NIELI, ANDREW WEST, ERIC WAGENAARS, TIMO GANS, DEBORAH O’CONNELL, York Plasma Institute, University of York — Picosecond resolution is required for direct measurements, without assumptions, of radicals under the highly collisional environment of atmospheric pressure. Quenching of two-photon absorption laser induced fluorescence (TALIF) excited states is very efficient and the lifetime of the excited state is on the order of a few tens of ps. On the other hand, mean electron energy was estimated from the emission intensity ratio of 2nd positive system band of $\text{N}_2$ ($2^3 \Sigma^+_o \rightarrow 2^1 \Pi^+_p$, $\lambda = 391.4$ nm) and 1st negative system band of $\text{N}_2$ ($2^3 \Sigma^+_o \rightarrow 2^1 \Pi^+_p$, $\lambda = 391.4$ nm). The each spectral images were taken by an ICCD camera with narrow band-path filters respectively. As a result, the dependence of rotational temperature and mean electron energy distribution in DC glow discharge on ambient pressure are clearly observed using spectral image processing.

$^1$Supported by the German Federal Ministry of Education and Research (BMBF) in the framework of the PhTo project

$^2$The authors acknowledge support by the UK EPSRC EP/H003797/1 and EP/K018388/1
Finally, experimental results are compared to a numerical model which couples transport and reactions within and between the bulk gas and liquid phases. The formation of carbon nanoparticles particles in low pressure magnetized hydrocarbon plasmas is investigated using infrared quantum cascade laser absorption spectroscopy (QCLAS), mass spectrometry (MS) and laser extinction spectroscopy (LES). Results showed that dust formation is correlated to the presence of a large amount of large positively charged hydrocarbon ions. Large negative ions or neutral species were not observed. These results, along with a qualitative comparison of diffusion and reaction characteristic, suggest that a positive ion may contribute to the growth of nanoparticles in hydrocarbon magnetized plasmas. Growth of carbon nanoparticles has been widely studied in RF plasma. Our aim is to complete these studies in different discharge system, in which the growth mechanisms may be different. In particular, we focus our work on dipolar ECR microwave discharge. The magnetic field of the plasma source is likely to trap carbon-containing charged particles and then modify the dust growth kinetics. In the present study the combination of these diagnostics gives us the tools to study the kinetics of plasma processes. In this way both qualitative and quantitative characteristics could be obtained. An outstanding role may be attributed to the positive ions in the monitored magnetized plasmas, whereas usual formation of dust is supposed driven by negative ions. In addition, we focus our work in tungsten nanoparticle in particular with LES, this noninvasive technique provide us the tool to follow the dynamics and concentration dust.

5:15PM LW1.00008 Resonance Frequencies of Curling Probe in Plasma: Surface Wave Analysis, ALI ARSHADI, RALF PETER BRINKMANN, Department for Electrical Engineering and Information Sciences, Ruhr University Bochum — Electron density is a crucial characteristic in reactive plasma sources determining the quality of material processing like etching. A recently invented plasma diagnostic probe called curling probe resonates in distinctive frequencies when it is embedded in the wall of the plasma reactor. The excited frequencies are studied for various electron densities. It has been demonstrated that the high-frequency (HF) volume wave resonances and the low-frequency (LF) surface wave (SW) resonances are predictable considering the wave propagation in plasma when it is diffracted on the curling probe. We consider the three dimensional diffraction of incident plane wave by a slot in an infinitely thin perfectly conducting screen located between dielectric and sheath. Our computations for LF resonances were published recently. The results are in a very good agreement with the FDTD analysis. Here it is demonstrated that the LF resonances are based on the SW propagation. We compare our result with the one comes from SW analysis and we prove that the LF resonances are not dependent on the length of probe. We generalized our study to be able to investigate the effect of sheath thickness and electron-neutral collisions which is not possible in the other theoretical and computational methods.

Wednesday, November 5, 2014 3:30PM - 5:30PM – Session LW2 Plasmas in Liquids State C - Peter Bruggeman, University of Minnesota

3:30PM LW2.00001 Advanced oxidation processes for wastewater treatment using a plasma/ozone combination system, NOZOMI TAKEUCHI, YU KAMIYA, RYO SAEKI, KOSUKE TACHIBANA, KOICHI YASUOKA, Tokyo Institute of Technology — Advanced oxidation process (AOP) using OH radicals is a promising method for the decomposition of persistent organic compounds in wastewater. Although many types of plasma reactors have been developed for the AOP, they are unsuitable for the complete decomposition of highly concentrated organic compounds. The reason for the incomplete decomposition is that OH radicals, particularly at a high density, recombine among themselves to form hydrogen peroxide. We have developed a combination plasma reactor in which ozone gas is fed, so that the generated hydrogen peroxide is re-converted to OH radicals. Pulsed plasmas generated within oxygen bubbles supply only OH radicals but also hydrogen peroxide into wastewater. The total organic carbon (TOC) of the wastewater was more than 1 gTOC/L. The TOC values decreased linearly with time, and the persistent compounds which could not be decomposed by ozone were completely mineralized within 8 h of operation.

3:45PM LW2.00002 Simulation with power circuit by modeling of plasmas within bubble in water, HAYATO OBO, NOZOMI TAKEUCHI, KOICHI YASUOKA, Tokyo Institute of Tech. — Plasma is used in water treatments such as the decomposition of persistent compounds and the generation of chemically active species. We have developed a new plasma reactor with 21 treatment holes and successfully achieved the decomposition of organofluoric compounds by generating 21 plasmas in water. The equivalent circuit model of plasma within bubbles in water consists of plasma and water resistance. A typical plasma model consists of the Zener diode and cannot be used to express the transient state of plasma. In the Zener diode model, therefore, plasma cannot be simulated with a power circuit. In this work, we have developed a new equivalent circuit that consists of an ideal switch, a diode, and water resistance to model the plasma. With the circuit elements used in our model, it is possible to perform simulation of plasmas by modeling the generation as well as the extinction of plasma with a high voltage power circuit. We confirmed that the simulated voltage and current waveforms of the reactor were coincident with the experimental result by applying the variation of a plasma parameter in the plasma model.

4:00PM LW2.00003 Physical and chemical interactions at the interface between atmospheric pressure plasmas and aqueous solutions, ALEXANDER LINDSAY, BRANDON BYRNS, DETLEF KNAPPE, North Carolina State University, DAVID GRAVES, University of California Berkeley, STEVEN SHANNON, North Carolina State University — Transport and reactions of charged species, neutrals, and photons at the interface between plasmas and liquids must be better quantified. The work presented here combines theoretical and experimental investigations of conditions in the gas and liquid phases in proximity to the interface for various discharges. OES is used to determine rotational and vibrational temperatures of OH, NO, and N2; the relationship between these temperatures that characterize the distribution of internal energy states and gas and electron kinetic temperatures is considered. The deviation of OH rotational states from equilibrium under high humidity conditions is also presented. In contradiction with findings of other groups, high energy rotational states appear to become populated with increasing humidity. In the aqueous phase, concentrations of longer-lived species such as nitrate, nitrite, hydrogen peroxide, and ozone are determined using ion chromatography and colorimetric methods. Spin-traps and electron paramagnetic resonance (EPR) are investigated for characterization of short-lived aqueous radicals like OH, O2−, NO, and ONOO−. Finally, experimental results are compared to a numerical model which couples transport and reactions within and between the bulk gas and liquid phases.

4:15PM LW2.00004 ABSTRACT WITHDRAWN
4:30PM LW2.00005 Numerical simulation of plasma-induced electrolysis utilizing dc glow discharge\(^1\). FUMIYOSHI TOCHIKUBO, NAOKI SHIRAI, SATOSHI UCHIDA, Tokyo Metropolitan University, TATSURU SHIRAFUJI, Osaka City University — In this work, we carried out one-dimensional numerical simulation of plasma-induced electrolysis, which consists of atmospheric pressure dc glow discharge and electrolyte solution connected in series. Grounded metal electrode is placed at the bottom of NaCl solution with 1 mm depth while powered electrode is placed at 1 mm above the solution surface. The gap is filled with helium. Continuity equations of charged species both in gas and in liquid were simultaneously calculated with Poisson’s equation. Current continuity is considered at plasma-liquid interface. That is, hydrated electrons equivalent to electron flux from plasma, or \( \text{H}_2 \)\(^+\) ions equivalent to positive ion flux from plasma are supplied in the liquid at plasma-liquid interface. The calculated gas-phase discharge structure is essentially the same as that between two metal electrodes. In front of the metal electrode in liquid, the electric double layer (EDL) with thickness of approximately 10 nm was formed to maintain the electrode reaction. However, the EDL was not formed at the liquid surface in contact with dc glow discharge, because charges are forcibly supplied from plasma to liquid. In other words, plasma-induced electrolysis is controlled at plasma-liquid interface by plasma.

\(^1\)This work was partly supported by KAKENHI (Nos. 21110003 and 21110007).

4:45PM LW2.00006 Control of plasma-liquid interaction of atmospheric DC glow discharge using liquid electrode\(^1\), NAIKO SHIRAI, RYUTA AOKI, AIHITO NITO, TAKUYA AOKI, SATOSHI UCHIDA, FUMIYOSHI TOCHIKUBO, Tokyo Metropolitan University — Atmospheric plasma in contact with liquid have a variety of interesting phenomena and applications. Previously, we investigated the fundamental characteristics of an atmospheric dc glow discharge using a liquid electrode with a miniature helium flow. We tried to control the plasma-liquid interaction by changing the plasma parameter such as gas species, liquid, and applied voltage. Sheath flow system enables another gas (\( \text{N}_2, \text{O}_2, \text{Ar} \)) flow to around the helium core flow. It can control the gas species around the discharge. When liquid (NaCl aq.) cathode DC discharge is generated, Na emission (588 nm) can be observed from liquid surface with increasing discharge current. Na emission strongly depends on the discharge current and liquid temperature. However, when Ar sheath flow is used, the intensity of Na becomes weak. When liquid anode DC discharge is generated, self-organized luminous pattern formation can be observed at the liquid surface. The pattern depends on existence of oxygen gas in gap. By changing the oxygen gas ratio in the gap, variety of pattern formation can be observed. The discharge in contact with liquid also can be used for synthesis of metal nanoparticles at plasma-liquid interface. Size and shape of nanoparticles depend on discharge gases.

\(^1\)This work was supported financially in part by a Grant-in-Aid for Scientific Research on Innovative Areas (No 21110007) from MEXT, Japan.

5:00PM LW2.00007 Characteristics of micro plasma generated on the nanoscale electrode in water. TOMONARI AOYAMA, Department of Electronic Engineering, Tohoku University, HIDEMASA FUJITA, TAKEHIKO SATO, Institute of Fluid Science, Tohoku University, TOSHIRO KANEKO, Department of Electronic Engineering, Tohoku University — Discharges in water are anticipated for various applications such as nano material processing, organic compounds degradation, and bio-medical treatment. Especially, for the bio-medical application, there is a demand to generate micro scale plasma which is smaller than a cell to have an effect only on the selected cell. In this work, the electrodes with curvature radius of less than 1 \( \mu \)m are used and the streamer development from the electrode tip is observed. To characterize the streamers from the electrode tip, the relations among the discharge time, voltage, current, shadowgraph imaging, and optical emission are investigated. The shadowgraph imaging has the maximum time resolution up to 5 ns at resolution of 12 pixel/\( \mu \)m using a high magnification lens and a high speed camera. In the shadowgraph imaging, the streamers are observed at the minimum pulse voltage amplitude of 4 kV. Prior to the streamer development, the precursor of the streamer is formed around the tip of the nanoscale electrode. The maximum size of the precursor region is found to be 20 \( \mu \)m which corresponds to the typical cell size. These results show the feasibility of affecting a specific cell with micro scale discharge.

5:15PM LW2.00008 Plasma Jet (V)UV-Radiation Impact on Biologically Relevant Liquids and Cell Suspension\(^1\). H. TRESP, ZIK plasmat at INP Greifswald, R. BUSSIAHN, INP Greifswald, L. BUNDSCHERER, ZIK plasmat at INP Greifswald, A. MONDEN, ZIK plasmat at INP Greifswald, TU Eindhoven, M.U. HAMMER, K. MASUR, ZIK plasmat at INP Greifswald, K.-D. WELTMANN, TH. V. WOEDTKE, INP Greifswald, S. REUTER, ZIK plasmat at INP Greifswald — In this study the generation of radicals in plasma treated liquids has been investigated. To quantify the contribution of plasma vacuum ultraviolet (VUV) and ultraviolet (UV) radiation on the species investigated, three cases have been studied: UV of plasma jet only, UV and VUV of plasma jet combined, and the plasma effluent including all reactive components. The emitted VUV has been observed by optical emission spectroscopy and its effect on radical formation in liquids has been analyzed by electron spin resonance spectroscopy. Radicals have been determined in ultrapure water (dH\(_2\)O), as well as in more complex, biorelevant solutions like phosphate buffered saline (PBS) solution, and two different cell culture media. Various compositions lead to different reactive species formation, e.g. in PBS superoxide anion and hydroxyl radicals have been detected, in cell suspension also glutathione thiol radicals have been found. This study highlights that UV has no impact on radical generation, whereas VUV is relevant for producing radicals. VUV treatment of dH\(_2\)O generates one third of the radical concentration produced by plasma-effluent treatment. It is relevant for plasma medicine because although plasma sources are operated in open air environment, still VUV can lead to formation of biorelevant radicals.

\(^1\)This work is funded by German Federal Ministry of Education a Research (BMBF) (grant # 03Z2DN12+11).

**Wednesday, November 5, 2014 3:30PM - 5:30PM**

**Session LW3 Electron-Molecule Collisions and Related Processes II**

**State D - Don Madison, Missouri S&T**
3:30PM LW3.00001 Tailoring Bond Cleavage in Gas-Phase Biomolecules by Low Energy Electrons

SYLVIAS PTASINSKA, University of Notre Dame — The high energy quanta of impinging radiation can generate a large number (about 5x10^3) of secondary electrons per 1 MeV of energy deposited. When ejected in condensed phase water, the kinetic energy distribution of these free or quasi-free electrons is peaked below 10 eV. Low energy electrons also dominate in the secondary emission from biomolecular targets exposed to different energies of primary radiation. Due to the mechanism of the radiation-induced processes in the condensed-phase environment, the sensitivity of secondary electrons and induced damage in biomolecules (BM) still need to be investigated. However, based on results from theory and different experiments accumulated within the last decade, it is now possible to determine the fundamental mechanisms that are involved in many chemical reactions induced in isolated gas-phase biomolecules by low energy electrons. The central finding of earlier research was the discovery of the bond- and site-selectivity in the dissociative electron attachment (DEA) process to biomolecules. It has been demonstrated that by tuning the energy of the incoming electron we can gain control over the location of the bond cleavage. These studies showed the selectivity in single bond cleavage reactions leading to the formation of the dehydrogenated closed shell anion (BM-H^-) or the complementary reaction leading to H^-'. The loss of a hydrogen atom or an anion is fast compared with ring cleavage and the excision of heavier fragments and, hence, this reaction can compete efficiently with autodetachment. Moreover, site selectivity has been also observed in the metastable anion formation via the DEA process. Such delayed fragmentation was studied recently for the dehydrogenated closed-shell anion conversion into NCO upon DEA proceeded a few µs after electron attachment, indicating a rather slow unimolecular decomposition. Interestingly, site selectivity was observed in the prompt as well as the metastable NCO^- formation in DEA.

The research described herein was supported by the Division of Chemical Sciences, Geosciences and Biosciences, Basic Energy Sciences, Office of Science, United States Department of Energy through grant number DE-FC02-04ER15533.

4:00PM LW3.00002 Vibrational change by electron collision

STEVEN GUBERMAN, Institute for Scientific Research — The vibrational change in molecular ions due to collisions with electrons can be a fast process. This has not been generally recognized until recently. For a high rate constant, the process requires a resonance state intermediate that is either vibrationally quasi-discrete or continuous. These highly excited states are common at energies just above the neutral ionization potential. The ab initio calculation of vibrational change rate constants is reported for N2^+, i.e. N2^+(v') + e -> N2^+(v') + e. The calculations utilize accurate potential curves, electronic widths, and the MQDT approach for the calculation of cross sections and rate constants. The rate constants are found to be comparable to those for dissociative recombination. Rate constants over a wide electron temperature range for the lowest 5 ion vibrational levels will be reported.

Supported by NSF and NASA.

4:15PM LW3.00003 On Helium Anions in Helium Droplets: Interpreting Recent Experiments

ANDREAS MAURACHER, STEFAN E. HUBER, Leopold-Franzens-Universitaet Innsbruck — Helium droplets provide an ideal environment to study elementary charge transfer reactions. Anions was observed. Furthermore, we give an outlook on the implications of the presence of these anionic species in doped helium droplets with regard to prevent molecule formation at the extremely low temperatures in helium droplets. In contrast, some excited states allow a barrier-free formation of molecular anions.

The research described herein was supported by the Division of Chemical Sciences, Geosciences and Biosciences, Basic Energy Sciences, Office of Science, United States Department of Energy through grant number DE-FC02-04ER15533.

4:30PM LW3.00004 Dynamical Studies of Resonant Electron-Molecule Collisions

DANIEL Slaughter, Lawrence Berkeley National Laboratory — A unique capability of low-energy electrons is to break molecular bonds through low-energy resonant processes. We report a combined experimental and theoretical study on the dynamics following dissociative electron attachment (DEA) at low collision energies that induce ring-breaking in uracil. The experiments employ a DEA reaction microscope [1], consisting of a 3D momentum-imaging negative ion spectrometer, a pulsed low-energy electron gun and an effusive gas target. Building further upon a recently-established technique [2-5], fragment ion kinetic energy and angular distributions resulting from DEA are measured and compared with ab initio scattering calculations to reveal key aspects of the dynamics of the transient anion system. Recent experiments on other related systems will also be presented.


Supported by Chemical Sciences, Geosciences and Biosciences division of BES/DOE

In collaboration with Yosuke Kuriyama, Yu Kawarai, Yoshiro Azuma, Sophia University; Carl Winstead, Vincent McKoy, California Institute of Technology; and Ali Belkacem, Lawrence Berkeley National Laboratory.

5:00PM LW3.00005 Elastic electron scattering from carbon dioxide

ALLAN STAUFFER, York University, TAPASI DAS, RAJESH SRIVASTAVA, Indian Institute of Technology - Roorkee — We have derived a method to obtain the spherically symmetric part of the static interaction between an electron and an arbitrary molecule represented by Gaussian wave functions [1]. Adding polarization-correlation and local exchange potentials provides a total potential that represents electrons scattering from the molecule averaged over all spatial orientations. We will present results for electron scattering from the linear molecule CO2 using such a potential. Since this molecule has no permanent dipole moment, we expect our method to produce accurate results for elastic scattering. We will compare our results with existing experimental and theoretical data for this process to assess the accuracy of the method.

5:15PM LW3.00006  Cross sections and products of electron ionization of m-xylene, p-xylene and o-xylene .  CHARLES JIAO, UES, STEVEN ADAMS, Air Force Research Laboratory — Xylenes are contained in many jet fuels and are one of the components in surrogate mixtures for JP-8. In this study using Fourier-transform mass spectrometry to measure the electron ionization cross sections of m-xylene, p-xylene and o-xylene, it is found that the total cross sections of the three xylene isomers are approximately equal at low energies (<25 eV), and become slightly different at higher energies, reaching maxima of 2.24, 2.10 and 2.05x10^-8 cm^2, respectively, at 80 eV. The electron ionization on these xylenes produces similar products, mainly the parent ion C6H12^+, and fragment species including (C6H5^+ + H), (C6H3^+ + H + H2), (C6H4^+ + C2H4), (C6H4^+ + C2H5), and (C6H5^+ + C2H4). The results indicate that the major by-products of the electron ionization of xylenes are CH3 and H. The latter is believed to play an important role in fuel ignition because it is involved in both chain branching and chain breaking steps, and it triggers the fuel oxidation.

5:30PM - 5:30PM  —  Session MW1 Poster Session II (17:30-19:30)  Exhibit Hall -

MW1.00001 The viscosity cross section for electron scattering from the heavy noble gases .  ALLAN STAUFFER, York University, ROBERT MCEACHRAN, Australian National University — The viscosity cross section is defined in terms of the elastic differential cross section σ(θ) as

\[ \sigma_v = \int_0^\pi (1 - \cos^2 \theta) \sin \theta \sigma(\theta) \, d\theta \]

and appears in the Boltzmann equation for the electron distribution function in velocity space. If this distribution function is expanded in Legendre polynomials, the viscosity cross section arises from the third term. Normally, only the first two terms in this expansion are retained in the solution of the Boltzmann equation. We have recently published results for the elastic and momentum transfer cross section for electron scattering from the heavy noble gases (argon, krypton and xenon) using our complex, relativistic optical potential method which includes the effect of excitation and ionization channels on the elastic cross sections. We also provided simple analytic fits to these cross sections to aid in plasma modelling calculations. We will present similar results for the viscosity cross sections for these gases including fits using similar analytic functions. By including the third term in the expansion of the Boltzmann equation which depends on this cross section, an evaluation of the accuracy of the two-term solution can be made.

MW1.00002 Single and double photoionization of atoms by n-photon absorption at low intensity laser fields: a Generalized Sturmian approach .  JUAN M. RANDAZZO, FLAVIO D. COLAVECCHIA, Centro Atomico Bariloche, Argentina, GUSTAVO GASANEO, Universidad Nacional del Sur, Bahia Blanca, Argentina, DARIO M. MITNIK, IAF, Buenos Aires, Argentina, LORENZO UGO ANCARIANI, Universite de Lorraine, Metz, France — We apply the Generalized Sturmian approach for the study of single and double photoionization of atoms by n-photon absorption at low intensity laser fields. We start with the double photoionization of helium by absorption of a single photon. The three-body wave functions necessary for the calculations (the ground state of the helium atom, and the scattering wave function which contains the post-collisional dynamics after one photon absorption) are both expanded with spherical Generalized Sturmian Functions (GSF) [1]. Very accurate triple differential cross sections for single photon double ionization are obtained helium for 20 and 40 eV. If two or more photons are absorbed, we have to consider the corresponding wave functions which describe the spatial distribution in each stage. We will then consider the scattering solutions for n¿1 analyzing the applicability of an iterative scheme with a focus on the computational requirements for each n.

References:

MW1.00003 Molecular Dynamics simulation of Ru flattening by Gas Cluster Ion Beam .  MASAHI MATSUOKUMA, KAZUYOSHI MATSUZAKI, Tokyo Electronic Limited, KENJI INABA, RYUJI MIURA, AI SUZUKI, NOZOMU HATAKEYAMA, AKIRA MIYAMOTO, Tohoku University — Noble metals such as platinum or ruthenium have been hardly used in the semiconductor devices in spite of their physical and electrical properties, because they were hard to process. High energy monomer ion beams which can cut hard materials may induce structural damages. A gas cluster ion beam (GCIB) consists of a few thousands of atoms or molecules and is accelerated up to several tens keV. GCIB is able to realize localized high energy deposition with low energy per components in the cluster. This means that each component in clusters cannot have enough energy to react with surface. On the other hand, the clusters with tens keV of kinetic energy may make a high reactive field at the hypocenter areas. In consequence it is expected that the GCIB irradiation should achieve the metal processing with low damage. Recently flattening of Ru thin films using GCIB is reported. We conducted molecular dynamics simulation of GCIB incident to Ru surface with the in-house interatomic potential models obtained based on the quantum chemical calculations and found that the internal degree of freedom of a cluster played important roles during the GCIB bombardment.

MW1.00004 Comparison of analytical formulae and quantum calculations for differential cross sections in e-Ar^+ .  J.F.J. JANSSEN, Eindhoven Tech. Univ., O. ZATSARINNY, K. BARTSCHAT, Drake Univ., G.J.M. HAGELAAR, L.C. PITCHFORD, CNRS and Univ. Toulouse — We have previously shown [1] that the fully ab initio, quantum mechanical B-spline R-matrix calculations of Zatsarinny and Bartschat for e-Ar cross sections yield accurate values of swarm parameters (transport and rate coefficients vs. reduced electric field strength, for uniform and constant E/N) when used as input in a Boltzmann solver. These comparisons were made by employing the calculated angle-integrated elastic momentum transfer and total inelastic cross sections (usually sufficient for accurate calculations of swarm parameters). The theory, however, also provides fully differential scattering information, which is now available for argon on the open access website LXCat (www.lxcat.net). In this presentation, we compare predictions from several previously proposed analytical formulae for the angular dependence of the cross sections with the quantum predictions. Such comparisons are of interest, for example, in PIC-MC simulations where, due to lack of information, some approximations about the angular dependence must be made and thus the use of analytical formulae is common.

References:

Work supported, in part, by the United States National Science Foundation (OZ and KB).
MW1.00005 Electron collisions with cesium atoms – benchmark calculations and application to modeling an excimer-pumped alkali laser. OLEG ZATSARINNY, KLAUS BARTSCHAT, Drake University, NATALIA BABAEVA, MARK KUSHNER, University of Michigan — The β-spline R-matrix (BSR) with pseudostate method was employed to describe electron collisions with cesium atoms. Over 300 states were kept in the close-coupling expansion, including a large number of pseudostates to model the effect of the Rydberg spectrum and the ionization continuum on the results for transitions between the discrete physical states of interest. Predictions for elastic scattering, excitation, and ionization for incident energies up to 200 eV are presented and compared to previous results [2,3] and experimental data. Our data were used to model plasma formation in the excimer-pumped alkali laser, XPAL, operating on the Cs and the ionization continuum on the results for transitions between the discrete physical states of interest. Over 300 states were kept in the close-coupling expansion, including a large number of pseudostates to model the effect of the Rydberg spectrum.  

1Work supported by the NSF underPHY-1068140, PHY-1212450, and the XSEDE allocation PHY-090031 (OZ, KB), and by the DoD High Energy Laser Multidisciplinary Research Initiative (NYB, MKJ).

MW1.00006 Electronic excitation of methanol by low-energy electrons. LEIGH HARGREAVES, KEN VARELA, MURTADHA KHAKOO, California State University Fullerton, CARL WINSTEAD, VINCE MCKOY, California Institute of Technology — Differential and integral excitation cross section measurements for the 4 lowest-lying states of states for methanol will be presented, at electron energies between 9 – 20 eV. The data were obtained via electron-energy loss spectroscopy, incorporating a moveable aperture gas source, and applying a least squares data fitting routine to each spectra that separated overlapping contributions from discrete transitions. The results are compared with current theoretical calculations, as well as previously obtained data for water and preliminary results for excitation of ethanol.

MW1.00007 A vortex line for K-shell ionization of a carbon atom by electron impact. S. J. WARD, University of North Texas, J. H. MACEK, University of Tennessee — We obtained using the Coulomb-Born approximation [1] a deep minimum in the TDCS for K-shell ionization of a carbon atom by electron impact for the electron ejected in the scattering plane [2]. The minimum is obtained for the kinematics of the energy of incident electron $E_i = 1801.2$ eV, the scattering angle $\theta_f = 4^\circ$, the energy of the ejected electron $E_k = 5.5$ eV, and the angle for the ejected electron $\theta_k = 239^\circ$. This minimum is due to a vortex in the velocity field. At the position of the vortex, the nodal lines of $\text{Re}[T]$ and $\text{Im}[T]$ intersect. We decomposed the CB1 T-matrix into its multipole components [1] for the kinematics of a vortex, taking the z'-axis parallel to the direction of the momentum transfer vector. The $m = \pm 1$ dipole components are necessary to obtain a vortex. We also considered the electron to be ejected out of the scattering plane and obtained the positions of the vortex for different values of $\phi$-component of momentum of the ejected electron, $\phi_k$. We constructed the vortex line for the kinematics of $E_i = 1801.2$ eV and $\theta_f = 4^\circ$.


MW1.00008 Out-of-plane ($e,e'$) measurements with 150eV incident beam energy on He autoionizing levels. NICHOLAS L.S. MARTIN, Univ of Kentucky, B.A. DEHARAK, Illinois Wesleyan University, K. BARTSCHAT, Drake University — In previous work we reported out-of-scattering-plane ($e,e'$) measurements and calculations for helium 2$^1S^0$ autoionizing levels at 488eV incident electron energy and scattering angle 20.5$^\circ$. The results were presented as (e, 2e) angular distributions energy-integrated over each level and the detailed energy dependence of the recoil/binary peak ratio. We have now begun similar measurements at 150eV electron beam energy and scattering angle 39.2$^\circ$. The geometry is then the same as for the earlier high energy experiments: ejected electrons are detected in a plane that contains the momentum transfer direction and is perpendicular to the scattering plane. The momentum transfer is 2.1 a.u., which is the same as in the earlier experiments. We will present preliminary data and compare the angular distributions with the high energy results.

1Work supported by the National Science Foundation under Grants Nos. PHY-0855040 (NLSM) and PHY-1212450 (KB).

MW1.00009 Experimental and Theoretical Fully differential cross sections for electron impact ionization of phenol molecules. ESAM ALI, Missouri University of Science & Technology, D. JONES, G. SILVA, L. CHIARI, R. NEVES, School of Chemical and Physical Sciences, Flinders University, Australia, M. LOPES, Departamento de Física, UFJF, Juiz de Fora, MG, Brazil, M. BRUNGER, School of Chemical and Physical Sciences, Flinders University, Australia, C. NING, Tsinghua University, Beijing 100084, People’s Republic of China, D. MADISON, Missouri University of Science & Technology — Experimental and theoretical Fully Differential Cross Sections (FDCS) are presented for 250 eV electron impact ionization of the highest and next highest occupied molecular orbitals (HOMO and NHOMO). Theoretical results are compared with experiment for in plane scattering with projectile scattering angles of 5$^\circ$, 10$^\circ$, and 15$^\circ$. Different theoretical models are examined - the molecular 3 body distorted wave (M3DW), and the distorted wave Born approximation (DWBA), with the effects of the post collision interaction (PCI) treated either exactly or with the Ward-Macek approximations. These approximations show good agreement with experimental data for binary peaks. However, for the recoil peak region, experiment finds a noticeable peak while theory predicts no peak. No recoil peak suggests no (or very weak) nuclear scattering, so we have investigated the importance of nuclear scattering by moving the nuclei closer to the center of mass.

1Work supported by NSF and the XSEDE.
MW1.00010 Single electron impact ionization of the methane molecule, MAMMAR BOUAMOUD, University Center of Naama, 45000 Naama, Algeria, MOHAMMED SAHLOALI, Ecole Préparatoire En Sciences Et Technique de Tlemcen, FOUR EL HOUDA BENMAN-SOUR, Laboratoire de Physique Théorique de Tlemcen, ATOMIC AND MOLECULAR COLLISIONS TEAM — Triply differential cross sections (TDCS) results of electron-impact ionization of the inner 2α1 molecular orbital of CH4 are presented in the framework of the Second Born Approximation and compared with the experimental data performed in coplanar asymmetric geometry. The cross sections are averaged on the random orientations of the molecular target for accurate comparison with experiments and are compared also with the theoretical calculations of the Three Coulomb wave (3CW) model. Our results are in good agreement with experiments and 3CW results in the binary peak. In contrast the Second Born Approximation yields a significant higher values compared to the 3CW results for the recoil peak and seems to describe suitably the recoil region where higher order effects can occur with the participation of the recoiling ion in the collision process.

MW1.00011 Single photoionization of many electron atoms and molecules: a Sturmian approach, CARLOS M. GRANADOS CASTRO, LORENZO UGO ANCARANI, Universite de Lorraine, Metz, France, DARIO M. MITNIK, IAFE, Buenos Aires, Argentina, GUSTAVO GASANE, Universidad Nacional del Sur, Bahia Blanca, Argentina — The Sturmian approach, using Generalized Sturmian Functions (GSF), has been applied successfully for the study of several atomic ionization processes [1]. The extension of the method to molecular systems is under development, and is the subject of the present contribution. As a first step, in order to test our methodology, we started with some atomic systems and calculated the photoionization cross section using the one-active electron approximation together with model potentials. We solved the time-independent, first-order perturbative, Schrödinger equation; the scattering wave function is expanded in GSF. Having validated our approach and computer codes, we then studied the photoionization of molecules, such as CH4, using a similar method. After considering initially an angular-averaged model potential, we then used a non-central one leading to a set of angular-coupled equations. The scattering wave function is again expanded in a GSF basis set, but this time with many different angular momenta. In order to take into account the random orientation of the molecule, an angular average over all the possible spatial orientation of the molecule is finally performed. The calculated cross sections are compared with theoretical and experimental data (see [2] and references therein).

MW1.00012 Cross Sections and Transport Properties of Br− Ions in Ar1, JASMINA JOVANOVIĆ, Faculty of Mechanical Engineering, University of Belgrade, VLADIMIR STOJANOVIC, ZORAN RASPOPOVIC, ZORAN PEROVIĆ, Institute of Physics, University of Belgrade — We have used a combination of a simple semi-analytic theory - Momentum Transfer Theory (MTT) and exact Monte Carlo (MC) simulations to develop Br− in Ar momentum transfer cross section based on the available data for reduced mobility at the temperature T = 300 K over the range 10 Td ≤ E/N ≤ 300 Td. At very low energies, we have extrapolated obtained cross sections towards Langevin’s cross section. Also, we have extrapolated data to somewhat higher energies based on behavior of similar ions in similar gases and by the addition of the total detachment cross section that was used from the threshold around 7.7 eV. Relatively complete set was derived which can be used in modeling of plasmas by both hybrid, particle in cell (PIC) and fluid codes. A good agreement between calculated and measured ion mobilities and longitudinal diffusion coefficients is an independent proof of the validity of the cross sections that were derived for the negative ion mobility data. In addition to transport coefficients we have also calculated the net rate coefficients of elastic scattering and detachment.

1 Author acknowledge Ministry of Education, Science and Technology, Proj. Nos 171037 and 410011.

MW1.00013 Limitation of the local approximation for EDF determination on the periphery of the high pressure plasmas, KIRILL KAPUSTIN, MIKHAIL KRASILNIKOV, ANATOLY KUDRAYVTEV, St. Petersburg State University — Local approximation is widely used for the calculation of electron distribution function (EDF). In this approximation, terms which correspond to spatial gradients and ambipolar electric fields in a Boltzmann kinetic equation can be omitted, and EDF can be factorized in a product of electron density, which depends on radius and time and on part of EEDF, which depends on kinetic energy. In this case, EEDF is a function of local parameters such as heating (current-carrying) electric field, gas temperature, density of excited particles etc. These simplifications of calculations of the kinetic equation make this approximation widely used. In this work, physical formation mechanisms of EEDF in a high pressure positive column glow discharge are discussed. It is shown that criterion of applicability of local approximation depends not only on ratio between energy relaxation length and characteristic plasma dimension but also on ratio between heating and ambipolar electric fields. So that, in the gas periphery where ambipolar electric field becomes larger then axial electric field, the local approximation for EEDF is not valid even at a high pressures. This work was supported by RSCF and SPbSU.

MW1.00014 Monte Carlo simulation of electrons in dense gases1, WADE TATTERSALL, Australian National University, GREG BOYLE, DANIEL COCKS, James Cook University, STEPHEN BUCKMAN, Australian National University, RON WHITE, James Cook University — We implement a Monte-Carlo simulation modelling the transport of electrons and positrons in dense gases and liquids, by using a dynamic structure factor that allows us to construct structure-modified effective cross sections. These account for the coherent effects caused by interactions with the relatively dense medium. The dynamic structure factor also allows us to model thermal gases in the same manner, without needing to directly sample the velocities of the neutral particles. We present the results of a series of Monte Carlo simulations that verify and apply this new technique, and make comparisons with macroscopic predictions and Boltzmann equation solutions.

1 Financial support of the Australian Research Council

MW1.00015 Electron swarm transport coefficients in mixtures of H2O with He and Ar: Experiment and Boltzmann equation calculations1, JAIME DE URQUIJO, Universidad Nacional Autónoma de México, E. BASURTO, None, A.M. JUAREZ, Universidad Nacional Autónoma de México, KEVIN NESS, ROBERT ROBSON, James Cook University, MICHAEL BRUNGER, Flinders University, RON WHITE, James Cook University — The drift velocity of electrons in mixtures of gaseous water with helium and argon are measured over the range of reduced electric fields from 0-300Td using a pulsed-Townsend technique. Small admixtures of water to both helium and argon are found to produce negative differential conductivity (NDC), despite NDC being absent from the pure gases. Comparison of the measured drift velocities with those calculated from a multi-term solution of Boltzmann’s equation provides a more discriminative assessment on the accuracy and completeness of electron water vapour cross-sections.

1 Funding acknowledgements: ARC, Mexican govt (PAPIIT IN 111014)
MW1.00016 Transport properties derived from ion-atom collisions: $^6$Li-$^6$Li$^+$ and $^6$Li-$^7$Li$^+$ Cases. MONCEF BOULEDROUA, Faculte de Medecine and Laboratoire de Physique des Rayonnements, Badji Mokhtar University, Annaba, Algeria, FOUZIA BOUCHELAGHEM, Physics Department, Badji Mokhtar University, Annaba, Algeria. LPR TEAM — This investigation treats quantum-mechanically the ion-atom collisions and computes the transport coefficients, such as the coefficients of mobility and diffusion. For the case of lithium, the calculations start by determining the gerade and ungerade potential curves through which ionic lithium approaches ground lithium. Then, by considering the isotopic effects and nuclear spins, the elastic and charge-transfer cross sections are calculated for the case of $^6$Li$^+$ and $^7$Li$^+$ colliding with $^6$Li. Finally, the temperature-dependent diffusion and mobility coefficients are analyzed, and the results are contrasted with those obtained from literature. The main results of this work have been recently published in [Phys. Chem. Chem. Phys. Vol. 16, 18751 (2014)].

3This work has been realized within the frames of the CNEPRU project D01120110036 of the Algerian Ministry of Higher Education.

MW1.00017 Positron cooling by vibrational and rotational excitation of a molecular gas. M.R. NATISIN, J.R. DANIELSON, C.M. SURKO, University of California, San Diego — A better understanding of low energy positron-molecule collisions and thermalization processes will aid in the development of novel experimental techniques and technology. In particular, cryogenic positron plasmas would allow the creation of positron beams with significantly higher energy resolution than currently available, enabling the study of scattering features and annihilation processes not measurable using current techniques. Measurements of positron temperature as a function of time are presented when a positron gas, confined in an electromagnetic trap at an elevated temperature ($\geq 1200$ K), is cooled by interactions with the $300$ K molecular gases CF$_4$, N$_2$ and CO. A simple model describing positron thermalization by coupling to vibrational and rotational modes is also presented and used to make cooling-rate predictions calculated in the Born approximation. Comparisons to the measured positron cooling-rate curves permit estimates of the magnitudes of the relevant cross sections. Positron cooling rates are compared for these gases at $300$ K, and estimates of their effectiveness in cooling positrons to cryogenic temperatures is discussed.

This work is supported by NSF grant PHY 10-68023.


MW1.00018 Two-Electron Systems in Generalized Exponential Cosine Screened Coulomb Potentials. KARINA V. RODRIGUEZ, Universidad Nacional del Sur, Bahia Blanca, Argentina, LORENZO UGO ANCARANI, Université de Lorraine, Metz, France, DARIO M. MITNIK, IAFE, Buenos Aires, Argentina — We look at the ground state of two-electron systems placed in a dense quantum plasma environment where the three interactions between two particles of charges $z_i$ and $z_j$ placed at a distance $r_{ij}$ can be described by exponential-cosine-screened Coulomb potential (ECSCP) [1] $V(r_{ij}) = z_i z_j \exp(-\lambda r_{ij}) \cos(\delta r_{ij})/r_{ij}$ where $\lambda$ and $\delta$ are two positive real screening parameters related to the plasma frequency. The first calculations of the ground and first excited states of H$^-$, He and Li$^+$ where all three interactions between pairs of particles were represented by the same ECSCP, and with $\lambda = \delta$, were recently reported [2,3]. In the present work we show results for two-electron systems for which the interactions are described by generalized ECSCP with unequal parameters. Our calculations are performed with a rather versatile Configuration Interaction approach (see [3] and references therein), with correlated basis functions which explicitly depend on the three interparticle distances and which respect exactly all three cusp conditions.


MW1.00019 A particle-in-cell/Monte Carlo simulation of a dual frequency capacitively coupled chlorine discharge. SHUO HUANG, University of Michigan - Shanghai Jiao Tong University Joint Institute, Shanghai Jiao Tong University, JON TOMAS GUDMUNDSSON, Science Institute, University of Iceland — The effect of the control parameters of both the high and low frequency sources on a dual frequency capacitively coupled chlorine discharge is investigated using a hybrid approach consisting of a particle-in-cell/Monte Carlo simulation and a volume averaged global model. The dependence of the plasma parameters such as particle density, effective electron temperature, electron energy probability function and ion energy and angular distributions for both Cl$^+$ and Cl$^{2+}$ ions, on the discharge pressure, driving frequency, driving current density and secondary electron emission, is systematically investigated. As the low-frequency current density is increased the flux of Cl$^{2+}$ ions to the surface increases almost linearly with increasing low-frequency current, which shows possible independent control of the flux and energy of Cl$^{2+}$ ions by varying the low-frequency current in a dual frequency capacitively coupled chlorine discharge. Besides, as the high frequency current increases, the electron heating is enhanced in the sheath region and diminished in the bulk region, showing a transition of the electron heating from the drift-ambipolar mode to the $\alpha$ mode.

MW1.00020 Generalized Analytical Model for the Radio-Frequency Sheath. UWE CZARNETZKI, Ruhr-University Bochum, Institute for Plasma and Atomic Physics — An analytical model for the planar radio frequency (RF) sheath in capacitive discharges is developed based on the applied RF voltage as the boundary condition. The model applies to all kind of waveforms for the applied RF voltage, includes both sheaths in a discharge of arbitrary symmetry, and allows for an arbitrary degree of ion collisionality in the sheaths (charge-exchange collisions). Further, effects of the finite floating potential during sheath collapse are included. The model can even be extended to electronegative plasmas with low bulk conductivity. The individual sheath voltages, the self-bias, and the RF floating potentials are explicitly calculated by a voltage balance equation using a cubic-charge voltage relation for the sheaths. In particular, the RF-phase as a function of the sheath voltage is determined. This is an input for a single second order non-linear integro-differential equation which is governing the ion flow velocity in the sheath [1]. Fast numerical integration is straight forward and in many cases approximate analytical solutions can be obtained. Based on the solution for the ion flow velocity, densities, electric fields, currents, and charge-voltage relations are calculated. Further, the Child-Langmuir laws for the collisionless sheath as well as the highly collisional case are derived. Very good agreement between model and experiments is obtained.

MW1.00021 Experimental Study of Sheath Voltage Scaling Laws in Asymmetric RF Capacitive Discharges

1. MILKA NIKOLIC, JANARDAN UPADHYAY, LEPSHA VUSKOVIC, SVEZOVAR POPOVIC, Old Dominion University, Physics Department, Center for Accelerator Science — Asymmetric radio frequency (RF) capacitive discharges have been attracting a continuous interest in ongoing research on complex shaped, three dimensional miobium superconducting radio frequency (SRF) cavities. To increase their performance, the SRF cavities can be etched by capacitively coupled RF discharges, a technology already used in semiconductor industry. Since the SRF performance parameters depend highly on plasma properties, we have studied the effects of different pressure and inner and outer electrode area ratio on the sheath voltage scaling laws in the finite length coaxial symmetry RF capacitive discharge, treated originally in [1]. The experimental set up used in this study consists of two finite-length cylindrical coaxial electrodes, the RF powered electrode and the outer grounded electrode. We performed the experiment in Ar and in 15% Cl diluted with Ar mixture at pressure range 0.0375 – 0.46 Torr, and applying the powers from 25 – 200 W. The results are presented in the form of asymmetric sheath voltage scaling law.

[1] Supported by DOE under grant no. DE-SC0007879. JU acknowledges support by JSA/DOE via DE-AC05-06OR23177.

MW1.00022 Ion velocity distribution function measurements in a dual-frequency rf sheath

NATHANIEL MOORE, WALTER GEKELMAN, PATRICK PRIBYL, UCLA Department of Physics, YITING ZHANG, MARK KUSHNER, Electrical Engineering and Computer Science, U. Michigan — Ion dynamics are investigated in a dual-frequency rf sheath above a 300 mm diameter biased silicon wafer in an inductively coupled (440 kHz, 500 W) plasma etch tool. Ion velocity distribution (IVD) function measurements in the argon plasma are taken using laser induced fluorescence (LIF). Planar sheets of laser light enter the chamber both parallel and perpendicular to the surface of the wafer in order to measure both parallel and perpendicular IVDs at thousands of spatial positions. A fast (30 ns exposure) CCD camera measures the resulting fluorescence with a spatial resolution of 0.4 mm. The dual-frequency bias on the wafer is comprised of a 2 MHz low frequency (LF) bias and an adjustable 10-20 MHz high frequency (HF) bias. The bias voltages may be switched on and off (f_{HF}, up to 1 kHz, duty cycle 10-90%). Several different bias and timing combinations were tested. Ion energy distribution function and ion flux measurements for each case are compared. For the case (no HF), the IVD was found to be uniform to within 5% across the wafer. IVDs as a function of phase of the LF bias were also measured. The LF experimental results are compared with simulations specifically designed for this particular plasma tool.

1 Work supported by the NSF and DOE.

MW1.00023 Capacitively coupled dc/rf discharges driven by arbitrary linear circuits

JOHN CARY, University of Colorado and Tech-X Corporation, MING-CHIEH LIN, C. ZHOU, DAVID SMITHE, Tech-X Corporation — We have developed a method for computing the system of an arbitrary linear circuit coupled to a capacitively coupled plasma discharge. The method relies on the known method of separation of the vacuum and plasma generated fields for the discharge. It is time centered and implicit in the circuit quantities, thus guaranteeing second-order accuracy in time. This method has been implemented in the VSim engine (Vorpal). Numerical verification of the order of accuracy will be shown.

MW1.00024 Observation of Transient Electric Fields in Particle-in-Cell Simulation of Capacitively Coupled Discharges

SARVESHWAR SHARMA, SANJAY KUMAR MISHRA, PREDHIMAN KAW, Institute for Plasma Research, Bhat, Gandhinagar, Gujarat, India — The analytical prediction of the presence of transient electric field regions between the bulk plasma and sheath edge in radio frequency capacitively coupled plasma (RF-CCP) discharges has been reported by Kaganovich (PRL 89, 265006 2002). In this paper we have used the semi-infinite particle-in-cell (PIC) simulation technique to verify the theoretical prediction for the existence of transient electric field in the linear regime; it is shown that the PIC simulation results are in good agreement with the results predicted by analytical model in this regime. It is also demonstrated that the linear theory overestimates the transient electric field as one moves from linear to weakly nonlinear regime. The effect of applied RF current density and electron temperature on evolution of transition field and phase mixing regime has been explored.

MW1.00025 Investigation of self-excited plasma series resonance oscillations in multi-frequency capacitive discharges

EDMUND SCHUENEGEL, JULIAN SCHULZE, Department of Physics, West Virginia University, Morgantown, WV 26506, IOR KOROLOV, ARANKA DERZSI, ZOLTÁN DONKÓ, Institute for Solid State Physics and Optics, Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary — The self-excitation of plasma series resonance (PSR) oscillations is a dominant feature in the current of asymmetric capacitively coupled radio-frequency discharges. The asymmetry can be caused by an asymmetry of the chamber geometry and/or that of the applied voltage waveform. We study the self-excitation of the PSR in a geometrically symmetric, electrically asymmetric capacitive argon discharge using PIC/MCC simulations as well as an analytical model. The results show that increasing the number of subsequent harmonics in the driving voltage waveform enhances the asymmetry and, therefore, leads to a significant increase of the current amplitude of higher harmonics, which are generated due to the nonlineairites of the sheaths. These high-frequency resonance oscillations between the capacitive sheaths and the inductive plasma bulk can only be reproduced correctly by the analytical model, if the cubic sheaths charge-voltage relation and the temporal modulation of the bulk length and electron density within the RF period are taken into account. Furthermore, we demonstrate that the nonlinear electron resonance heating (NERH) associated with the presence of PSR oscillations significantly contributes to the total electron heating and causes a spatial asymmetry of the ionization.

MW1.00026 Control of ion energy distributions in capacitive RF discharges using customized voltage waveforms

EDMUND SCHUENEGEL, JULIAN SCHULZE, Department of Physics, West Virginia University, Morgantown, WV 26506, IOR KOROLOV, ARANKA DERZSI, ZOLTÁN DONKÓ, Institute for Solid State Physics and Optics, Wigner Research Centre for Physics, Hungarian Academy of Sciences, Budapest, Hungary — The flux and energy distribution of ions flowing onto the substrate in capacitive radio-frequency discharges is vitally important for the plasma surface interaction. Therefore, controlling and optimizing the shape of the ion flux-energy distribution (IED) allows for an improvement of various plasma surface processing applications. Recently, separate control of the mean energy and the total flux of ions has been achieved via the Electrical Asymmetry Effect. Here, we study the control of the IED shape in capacitively coupled radio-frequency discharges by applying customized voltage waveforms to the powered electrode. Data obtained from PIC/MCC simulations in helium at low pressures show that the dominant features in the shape of the IED result from the energy gain of ions flowing into the sheath and ions created in the sheath (in ion neutral collisions) in the periodically oscillating sheath electric field. The high-energy component of the IED is determined by ions flowing into the sheath, whereas ions created within the sheath lead to peaks in the IED at lower energies. We demonstrate, how the shape of the high-energy component as well as the position (energy) and height (flux) of the peaks can be controlled by varying the phases and amplitudes of the multiple applied frequencies.

MW1.00027 Transition of Plasma Electrons from Anisotropy to Isotropy at Beginning of the Pulsed Discharges

HYO-CHANG LEE, CHIN-WOOK CHUNG, Hanyang University — We present experimental studies on the transition of plasma electrons from anisotropy to isotropy at beginning of the pulsed discharges. The electron energy probability functions (EEPFs) are obtained from the first derivate of the measured I-V curve at planar type Langmuir probes. Strong anisotropy is found depending on the probe direction at the first stage of the low pressure pulsed plasma. The anisotropy of the electrons is transited into isotropy on the EEPF. This paper may provide fundamental understanding of both the electron acceleration via wave-electron interaction and the electron thermal transport in plasma discharges.
MW1.00028 E-H transition and Hysteresis in Radio-Frequency Inductively Coupled Plasmas
HYO-CHANG LEE, CHIN-WOOK CHUNG, Hanyang University — We present both experimental and theoretical studies of E-H transition and hysteresis in radio-frequency inductive discharges. It is found that the hysteresis is significantly affected by nonlinearity of the plasma with the modification of electron energy distribution (EED). This kind of hysteresis is also observed in various plasma discharges with powers, pressures, and magnetic field where EEDs are evolved.

MW1.00029 Comprehensive Plasma Diagnostics of Oxygen ICP
THOMAS WEGNER, CHRISTIAN KÜLLIG, JÜRGEN MEICHSNER, University of Greifswald — A planar inductively coupled 13.56 MHz discharge (ICP) in pure oxygen was studied using comprehensive plasma diagnostics. In particular the 160 GHz Gaussian beam microwave interferometry, the Langmuir probe technique, the phase resolved optical emission and VUV absorption spectroscopy were applied. From the transition from the capacitive (E-) to the inductive (H-) mode all plasma parameter are changed. The E-mode at low electron density and high electron temperature is characterized by high electronegativity. The gas temperature is comparable to room temperature and the molecular oxygen ground state and metastable state (O$_2$(a$^1Σ_g^+$)) density are not significantly changed with increasing RF power in the E-mode. During the transition into the H-mode the electron density increases over two orders of magnitude whereas the electron temperature decreases to about half of the E-mode. The heating mechanisms change from the rf sheath heating and electrical field reversal in the E-mode to two excitation rate patterns in the first and second half of the RF cycle. In the H-mode, the electronegativity is strongly reduced, the gas temperature and the metastable density are increased by a factor of about two.

Funded by the DFG CRC/Transregio 24, project B5.

MW1.00030 Experimental observation of transit time resonance heating through electron energy distribution function measurement in a low pressure inductively coupled plasma
HYUN-JU KANG, CHIN-WOOK CHUNG, Department of Electrical Engineering, Hanyang University — The maximum electron heating by transit time resonance is related to the driving frequency and the skin depth. In this study, electron energy distribution functions (EEDFs) were measured at various frequencies (8MHz, 10MHz, 13.56MHz) and powers in a low-pressure inductively coupled plasma. It was observed that the heated electron energy on the EEDFs is shifted toward lower energy, as the frequency decreases or the power increases.

MW1.00031 Simulation of Plasma Characteristics for Inductively Coupled Argon Plasma Using Dual-Frequency Antennas
XUE-CHUN LI, XIAO-YAN SUN, YOU-NIAN WANG, Dalian University of Technology — A large-area wafer size is necessary for plasma processing in the micro-electronics industry. However, it is one of the most important issues to obtain uniform plasma over a large-area substrate in addition to high-density plasmas for the plasma processing. Recently, the experimental study on the dual-frequency inductively coupled plasma (ICP) has been reported as a mean of improving the plasma uniformity over the large-area substrate [1]. In this work, we develop a self-consistent method combined with the electromagnetic theory and fluid model to simulate the plasma characteristics for dual-frequency inductively coupled argon plasma. In the model, the ICP source consists of two planar-spiral coils. We investigate the plasma uniformity problem by adjusting the parameters of the two coils, such as the RF current, the position of the coils and the RF frequency ratio. It was found that the uniformity of the ion density over the wafer is improved with dual-frequency antennas comparing with a single-frequency antenna. The plasma uniformity increases when the coils are located farther from the centre of the ICP source. It is consistent with the experimental study.


This work was supported by the National Natural Science Foundation of China (No. 11175034, No. 11075029).

MW1.00032 Discharge Characteristic of VHF-DC Superimposed Magnetron Sputtering System
HIROTAKA TOYODA, YUSHI FUKUOKA, TAKASHI FUKUI, NORIHARU TAKADA, KENSUKE SASAI, Nagoya University — Magnetron plasmas are one of the most important tools for sputter deposition of thin films. However, energetic particles from the sputtered target such as backscattered rare gas atoms or oxygen negative ions from oxide targets sometimes induce surface and chemical damages as well as surface roughening to the deposited film surface during the sputtering processes. To suppress kinetic energy of such particles, superposition of RF or VHF power to the DC power has been investigated. In this study, influence of the RF power superposition on the DC target voltage, which is important factor to determine kinetic energy of high energy particles, is investigated. In the study, 40 MHz VHF power was superimposed to an ITO target and decrease in the target DC voltage was measured as well as deposited film deposition properties such as deposition rate or electrical conductivity. From the systematic measurement of the target voltage, it was revealed that the target voltage can be determined by a very simple parameter, i.e., a ratio of VHF power to the total input power (DC and VHF powers) in spite of the DC discharge current.

1Part of this work was supported by ASTEP, JST.

MW1.00033 Carbon Multicharged Ion Generation from Laser Plasma
OGUZHAN BALKI, HANI E. ELSAYED-ALI, Old Dominion Univ — Multicharged ions (MCI) have potential uses in different areas such as microelectronics and medical physics. Carbon MCI therapy for cancer treatment is considered due to its localized energy delivery to hard-to-reach tumors at a minimal damage to surrounding tissues. We use a Q-switched Nd:YAG laser with 40 ns pulse width operated at 1064 nm to ablate a graphite target in ultrahigh vacuum. A time-of-flight energy analyzer followed by a Faraday cup is used to characterize the carbon MCI extracted from the laser plasma. The MCI charge state and energy distribution are obtained. With increase in the laser fluence, the ion charge states and ion energy are increased. Carbon MCI up to C$^{9+}$ are observed along with carbon clusters. When an acceleration voltage is applied between the carbon target and a grounded mesh, ion extraction is observed to increase with the applied voltage.

National Science Foundation

MW1.00034 Energy Distribution of Aluminum Multicharged Ions Generated from Laser Plasma
MD HAIDER SHAIM, ALEXEY BUGAYEV, HANI E. ELSAYED-ALI, Department of Electrical and Computer Engineering and the Applied Research Center, Old Dominion University, Norfolk, Virginia 23529, USA — Multicharged ion sources are an emerging tool for nanofabrication. The higher charge state of multicharged ions has significant potential energy equal to the sum of ionization energies of stripped electrons. Multicharged ion interaction with solids involves the release of this potential energy that causes electronic exchange interaction along with the electronic excitation. We report on measurement of aluminum multicharged ion energy distribution generated by laser ablation of an aluminum target. A Q-switched Nd:YAG laser is used to ablate the aluminum target in an ultrahigh vacuum while an electrostatic time-of-flight spectrometer is used to detect the laser-generated multicharged ions. An increase in the ions’ signal and generation of higher charge state is observed with the increase of laser ablation energy. The energy distribution of ions for increasing laser fluence shows an increase in the ion energy along with narrowing of the distribution. Applying an accelerating voltage to the aluminum target increases the charge extraction and the energy of multicharged ions. Angular distribution of the multicharged ions is dependent on the ion charge state. Multicharged ions up to Al$^{14+}$ are detected.
MW1.00035 Optical Studies of Sputtering in Magnetically Enhanced Helium Discharges\(^1\)

JAMES E. LAWLER, THOMAS J. FEIGENSON, Univ of Wisconsin, Madison, TIMOTHY J. SOMMÈRE\(\text{R}\), DAVID J. SMITH, JASON TROTTER, STEVEN C. ACETO, General Electric Research, Niskayuna, NY — A cold-cathode gas-discharge switch for the electric power grid must operate at the highest possible current density to be competitive. Magnetic enhancement, similar to that of a magnetron sputtering discharge, achieves current densities far above the classic “normal” cold-cathode fall current density. One of two physical mechanisms, power dissipation or sputtering, is likely to limit the ultimate current density of a magnetron-enhanced device. Using forced cooling a power dissipation density of about 1 kW/cm\(^2\) should be achievable. This corresponds to a current density of 5 A/cm\(^2\) assuming a 200 V cathode fall. Sputtering can be much reduced using a light buffer gas such as hydrogen or helium. We are studying the transition to ‘metal mode’ operation in such discharges. Metal mode is often described as a current density at which lines of sputtered metal dominate buffer gas lines in the emission spectrum. Preliminary results in a magnetically enhanced discharge operating in the A/cm\(^2\) range with helium buffer gas over some cathode materials are presented.

\(^1\)The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000298.

MW1.00036 Operation of a high-voltage, high-power gaseous electronics switch for electric grid power conversion\(^1\)

TIMOTHY SOMMÈRE\(\text{R}\), SERGEY ZALUBOVSKY, General Electric Research, Niskayuna, NY — A series of approximations and simple models is used to estimate the properties of a cold-cathode plasma in a high-voltage, high-power gas switch for use in grid-scale electric power conversion. The active volume is a plane-parallel gap \(\sim 1 \text{ cm}\) filled with hydrogen at a pressure \(\sim 0.3 \text{ Torr}\). A magnetic field in the region adjacent to the cathode is used to increase the current density to practical levels \(> 1 \text{ A/cm}^2\). The estimated bulk plasma density is mid-10\(^{12}\) cm\(^{-3}\) and the electron temperature is \(\sim 3 \text{ eV}\), to offset volume recombination. The magnetic field enhances ionization near the cathode and also impedes electron diffusion away from the region, sometimes resulting in a peak of plasma density in an extended presheath region. The switch is opened by applying a positive potential to a grid between the cathode and anode, leading to the formation of an ion matrix sheath around the grid, and an ion-acoustic wave that sweeps out the conducting plasma between the grid and the anode in about 1 \(\mu\text{s}\).

\(^1\)The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000298.

MW1.00037 Modeling of High-Power Gas Switch for Electric Grid System

ALEXANDER V. KHABROV, JOHAN CARLSSON, IGOR D. KAGANOVICH, Princeton Plasma Phys Lab, TIMOTHY SOMMÈRE\(\text{R}\), SERGEY ZALUBOVSKY, GE Research — There has been recent interest in utilizing gas switches in high-power AC/DC conversion for the purpose of power transmission over long distances. These devices would be based on a glow discharge with magnetically insulated cold cathode \([1]\). Their operation is similar to sputtering magnetrons [2,3], but at much higher pressures (0.1 to 1 Torr) in order to achieve high current densities. We present results of numerical (the particle-in-cell code EDPIC 1d3v PIC [4]) and analytical investigation of a gas switch in the conduction phase. The important properties of the high-pressure magnetron discharge are a very narrow cathode sheath and a considerable voltage drop in the magnetized pre-sheath where most of the ionization takes place due to Joule heating. The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000298.


MW1.00038 Experimental and Numerical Investigation of the Dependency of Reaction Dynamics on the Plasma Gas Temperature in He/N\(_2\) Cryoplasmas

HITOSHI MUNEOKA, KEIICHIRO URABE, SVEN STAUSS, KAZUO TERASHIMA, Department of Advanced Materials Science, The University of Tokyo — The plasma gas temperature \(T_g\) is one of the essential parameters in plasma science and technology, but so far, the effect of \(T_g\) on low-temperature high-gas-density plasma chemistry has not been investigated in detail yet. Cryoplasmas, which are defined as plasmas whose \(T_g\) can be controlled below room temperature (RT), have the potential for various applications. In this study, we investigate the effect of \(T_g\) on the reaction dynamics in He/N\(_2\) cryoplasmas, we developed a new 0D reaction model and also investigated the cryoplasmas by time-resolved laser absorption spectroscopy (LAS) and optical emission spectroscopy (OES). LAS measurements in He cryoplasmas at the same gas density as at RT and 1 atm, showed a longer lifetime (>50 times) of metastable helium atom \((\text{He}^m)\) at cryogenic temperature (CT) compared to those at RT. OES revealed a time delay of the N\(_2^+\) emission peak relative to the He emission peak of a few microseconds, and the delay decreased with increasing \(T_g\). The simulation using our reaction model suggested that the long lifetime of \(\text{He}^m\) at CT are due to the change of the reaction dynamics related to \(\text{He}^m\) as a function of \(T_g\).

MW1.00039 Electron avalanche and spark evolution along laser path in resonant laser-induced ignition

STEVEN ADAMS, Air Force Research Laboratory, Wright-Patterson AFB, BOYD TOLSON, AMBER HENSLEY, UES, Inc. — A multi-photon ionization scheme is studied that could provide laser-induced ignition within a high-voltage gap across an aircraft combustion chamber. The multi-photon resonant enhanced multiphoton ionization (REMPI) technique could potentially be applied as a laser trigger from a compact low power laser source leading to breakdown and ignition of an aircraft air-fuel flow. In this experiment, an ultraviolet laser is passed through an aperture in the anode and into the flow chamber. The REMPI process forms an ionized channel between the electrodes and, with an applied electric field, eventually leads to breakdown precisely along the laser path. A delay time of 200 to 1000 ns between the laser pulse and breakdown event is typical for our range of conditions. High speed imaging and spectroscopic data reveal evidence of space charge regions and local field distortion within the interelectrode space during the delay time and a model is applied to simulate the electron avalanche process. Spatially resolved spectroscopic analysis identifies various regions and degrees of laser photionization, electron impact ionization, radical species and gas heating during the delay time.

MW1.00040 Preliminary investigation of an atmospheric microplasma using Raman and Thomson laser scattering

BRADLEY SOMMERS, STEVEN ADAMS, Air Force Research Laboratory, Wright-Patterson AFB — A triple grating spectrometer system has been coupled with an ultraviolet laser at 266 nm for the purpose of investigating Rayleigh, Raman, and Thomson scattering within atmospheric plasma sources. Such laser interactions present a non-invasive diagnostic to investigate small scale atmospheric plasma sources, which have recently garnered interest for applications in remote optical sensing, materials processing, and environmental decontamination. In this work, the laser scatter and temperature relationship were calibrated with a heated nitrogen cell held at atmospheric pressure while subsequent scattering measurements were made in atmospheric discharges composed of nitrogen and air. An adjustable electrode configuration and dc circuit were assembled to produce a microdischarge operating in normal glow mode, thus providing a non-thermal plasma in which the translational, rotational, vibrational and electron temperatures are not in equilibrium. Preliminary results include measurements of these temperatures, which were calculated by fitting simulated scattering spectra to the experimental data obtained using the triple grating spectrometer. Measured temperatures were also compared with those obtained using standard optical emission spectroscopy methods.

\(^3\)Special thanks to the NRC Research Associateship Program
MW1.00041 Numerical Investigations of Positive Surface Streamer Discharges For High-Pressure Large Gap Arc Breakdown, ASHISH SHARMA, LAXMINARAYAN RAJA, Dept. of Aerospace Engineering and Engineering Mechanics, The University of Texas at Austin — Streamers are thin conducting channels which are formed by application of fast high-voltage pulses at the electrode surface. Surface streamers are used in a flash-lamp approach to initiate an arc breakdown in a large electrode gap at atmospheric and higher pressures. In this study, high-fidelity simulations are performed to study the propagation of cathode directed surface streamers into high pressure argon medium. The streamer model employed is based on the self-consistent multispecies and continuum description of the plasma. The model predicts transient dynamics of a surface streamer. Of particular interest is the conductivity of the streamer channel as a function of the electron density in the trail of the streamer head. The spatially continuous conductive streamer successfully bridges the gap between two electrodes from which an arc column can develop. The model predicts the conductivity of the streamer column as a function of gas properties, applied voltages on the electrodes and wall losses. The Model results compare favorably with accompanying experimental results for a flash-lamp based approach for large gap arc breakdown.

MW1.00042 Atomic oxygen production scaling in a nanosecond-pulsed externally grounded dielectric barrier plasma jet, BRIAN SANDS, UES, Inc. (AFRL), JACOB SCHMIDT, Spectral Energies, LLC. (AFRL), BISWA GANGULY, UES, Inc. (AFRL), JAMES SCOFIELD, Air Force Research Laboratory — Atomic oxygen production is studied in a capillary dielectric barrier plasma jet that is externally grounded and driven with a 20-ns risetime positive unipolar pulsed voltage at pulse repetition rates up to 25 kHz. The power coupled to the discharge can be easily increased by increasing the pulse repetition rate. At a critical turnover frequency, determined by the net energy density coupled to the discharge, the plasma chemistry abruptly changes. This is indicated by increased plasma conductance and a transition in reactive oxygen species production from an ozone-dominated production regime below the turnover frequency to atomic-oxygen-dominated production at higher pulse rates. Here, we characterize atomic oxygen production scaling using spatially- and temporally-resolved two-photon absorption laser-induced-fluorescence (TALIF). Quantitative results are obtained via calibration with xenon using a similar laser excitation and collection system. These results are compared with quantitative ozone and discharge power measurements using a helium gas flow with oxygen admixtures up to 3%.

MW1.00043 Characterization of combined power plasma jet using AC high voltage and nanosecond pulse for reactive species composition control, KEISUKE TAKASHIMA, HIDEAKI KONISHI, TOSHIKATO KATO, TOSHIRO KANEKO, Department of Electronic Engineering, Tohoku University — In the application studies for both bio-medical and agricultural applications, the roles of the reactive oxide and nitride species generated in the plasma has been reported as a key to control the effects and their effects on the living organisms. The total O$_2$ production in an atmospheric pressure plasma jet and the sterilization threshold on Botrytis cinerea is presented. With the increase of the OH radical exposure to the Botrytis cinerea, the probability of sterilization is increased. In this study, to resolve the roles of reactive species including OH radicals, a combined power plasma jet using nanosecond pulses and low-frequency sinusoidal AC high voltage (a few kHz) is studied for controlling the composition of the reactive species. The nanosecond pulses are superimposed on the AC voltage which is in synchronization with the AC phase. The underlying work to characterize the combined power discharge with electric charge and voltage cycle on the plasma jet will also be presented to discuss the discharge characteristics to control the composition of the reactive species.

MW1.00044 Modeling of non-equilibrium and non-thermal plasma discharge in air: Three temperature modeling approach, RAJIB MAHAMUD, TANVIR FAROUK, Department of Mechanical Engineering, University of South Carolina — The rapid progress in atmospheric pressure non-thermal plasma discharge has made air to be a preferable choice for feed gas. Despite the ease of operation of such discharges in air, the preference of air provides added complexity to modeling and simulations in terms of kinetics and different temperature modes. The diatomic nature of both N$_2$ and O$_2$ contributes to this complexity. In this work we report simulation results from a one-dimensional multi-physics model. A dc driven air plasma discharge operating at atmospheric and higher pressure is simulated. The model considers 50 species and 200 elementary reactions. The reaction scheme considers electron introduced and heavy particle reactions for N$_2$ and O$_2$ as well as interactions between nitrogen and oxygen. In addition to the species conservation equations, poisson’s equation three different temperature’s are resolved - electron, vibrational and translational. A special focus has been the coupling between the different temperatures to accurately resolve the energy cascade. The predictions from the model are found to be in good qualitative agreement against experimental measurements available in the literature.

MW1.00045 Comparison of Fabrication Techniques for Micro-Scale Spark Gap Plasma Switches, MATTHEW BURNETTE, DAVID STAACK, None — Microplasma spark gaps with 2D geometries were fabricated by two techniques on alumina, first using photolithography and metal sputtering with thicknesses of hundreds of nanometers, and second using thermal-spray several microns thick, but with lower feature resolution. Several high temperature metals were tested as electrode material for the microplasma device, including tungsten and chromium; however the chromium samples were not robust enough, eroding away too quickly for extensive testing. Scanning electron microscope (SEM) images were taken before and after testing to determine the wear on the samples. The sputtered tungsten thin films and thermal-spray deposited nickel films on alumina were compared after testing in 1 atm of helium running for one hour at a current of 1 mA. Slight wear and discoloration were noted on the anodes, yet significant erosion occurred on the cathodes; no wear was noted on the alumina. The thermally-sprayed nickel sample had the least wear, while the thin tungsten sample had the most wear. Discoloration was also seen on the nearby floating-voltage electrodes despite not being a part of the circuit, most likely due to heating. As the electrodes eroded, the plasma attachment point moved unpredictably.

MW1.00046 On cathode spot motion in magnetically driven high-pressure arcs, VALERIAN NEMCHINSKY, Keiser University, Fort Lauderdale, Florida USA, VLADIMIR KOLOBOV, ROBERT ARSLANBEKOV, CFD Research Corporation — High-pressure magnetically driven arcs are used in many industrial applications. In this paper, the arc is forced to rotate by axial magnetic fields along tubular electrodes to reduce electrode erosion. Many questions about the nature cathode and anode spot motion and electrode erosion remain unclear. We develop computational tool for simulations of electrode erosion in high pressure moving arcs. In gas phase, we assume that the operation of cathode spot operation in the high-pressure arc has many features of the vacuum arc (so called cold cathode mode) modified by the high pressure gas environment under high current density on the level of 10$^7$A/m$^2$ and temperature exceeding melting point. The gas-dynamic interaction of the cathode vapor jet with background gas defines the erosion rate. We study the arc column attachment to the cathode. The arc column motion by the Lorentz force produces a tilt near the cathode due to time lag of electrode heating processes. It is suggested that the tilt of the arc column leads to asymmetry of the cathode voltage drop: it is larger at the leading end of the cathode attachment and lower at the opposite (trailing) end. The asymmetry of the cathode voltage drop causes asymmetry of the heat transfer to the cathode: it is shifted ahead of the cathode temperature distribution. As a result, the cathode spot moves catching up running away heat flux. The proposed model allows to connecting the tilt angle of the arc column with the speed of the arc rotation and current density at the cathode.
MW1.00047 Optical emission in a sonoplasma production system with the help of a punching metal plate, K. SASAKI, Y. IWATA, S. TOMIOKA, S. NISHIYAMA, Hokkaido University, N. TAKADA, Nagoya University — Sonoplasmas are liquid-phase plasmas produced by ultrasonic power. We have reported an efficient method for producing standing sonoplasmas (Y. Iwata, et al., Appl. Phys. Express 6 (2013), 127301). This method employs a punching metal plate which is inserted just below the water surface with the irradiation of ultrasonic wave. In this work, we examined spatiotemporal variations of optical emission (sonoluminescence) intensities from sonoplasmas. The optical emission images were captured at various phases using an ICCD camera. The region with the strong optical emission intensity coincided with the region with cavitation bubbles. In addition, the optical emission intensity was observed in the shrink phase of cavitation bubbles. These experimental observations indicate that the optical emission is caused by sonoplasmas which are produced at the collapses of cavitation bubbles. Optical emissions were also observed at different positions and different phases, but the distributions of these optical emission intensities were broader than that observed at the shrink phase of cavitation bubbles. The distribution of the optical emission intensities can be utilized as a hint for understanding the spatiotemporal distribution of the ultrasonic power.

MW1.00048 Oxide nanoparticles synthesis via laser-induced plasma in liquid, TAKU GOTO, HANSEL WEIHS, Osaka University, MITSUHIRO HONDA, SERGEI KULINICH, Tokai University, YOSHIKI SHIMIZU, AIST, TSUYOHITO ITO, Osaka University — Laser ablation in fluids has recently attracted a lot of attention as one of synthetic techniques to prepare new attractive nanomaterials, with the ability to control both product chemistry and morphology in many systems. In this study, we generated laser-induced plasma in H$_2$O – ethanol mixtures, while ablating metal targets to produce oxide nanoparticles and to study the effect of the medium on their properties. The ablated targets used in this study were Zn or Sn plates. A nanosecond Nd:YAG laser with the wavelength of 532 nm (10 Hz, 20-30 mJ/pulse) was applied to irradiate the targets. The liquid media were maintained at 0.1 to 30 MPa to study the effect of pressure. We found that the H$_2$O/ethanol ratio (at atmospheric pressure) can control the properties of the produced ZnO nanoparticles, such as defects and oxidation degree. The properties were examined by photoluminescence (PL) spectroscopy, X-ray diffraction, electron microscopies, and so on. More details will be presented at the symposium.

MW1.00049 Comparison of temporal variation in emission intensity of OH(A) in after-glow period of Ar/H$_2$O and He/H$_2$O gas-mixture plasmas in water$^1$, TATSURU SHIRAFUJI, Osaka City University — Previously, we have reported quite long duration (approx. 500 ns) of optical emission intensity of OH(A) in an after glow period of Ar plasma in water.$^6$ Numerical simulation has revealed that this phenomenon can be explained in terms of production of OH(A) through the reaction of H$_2$O$^+$ excited and low temperature electrons. We can perform similar plasma processing using He plasma in water with almost the same process performance in the case of decomposition of methylene blue molecules in aqueous solution. Thus, we have expected that the long duration of OH(A) optical emission can be observed also in He plasma in water. However, such long duration of OH(A) optical emission has not been observed in the case of He plasma in water. To understand this difference, we have performed numerical simulation of Ar/H$_2$O and He/H$_2$O plasmas, and discuss differences in major reaction pathways to produce OH(A) in Ar/H$_2$O and He/H$_2$O plasmas.

$^1$This work has been partly supported by the Grant-in-Aid for Scientific Research on Priority Area “Frontier science of interactions between plasmas and nano-interfaces” from MEXT, Japan, and a Grant-in-Aid for Scientific Research (C) from JSPS.


MW1.00050 A two-phase multi-physics model for simulating plasma discharge in liquids, ALI CHARCHI, TANVIR FAROUK, Department of Mechanical Engineering, University of South Carolina — Plasma discharge in liquids has been a topic of interest in recent years both in terms of fundamental science as well as practical applications. Even though there has been a large amount of experimental work reported in the literature, modeling and simulation studies on plasma discharges in liquids is limited. To obtain a more detailed model for plasma discharge in liquid phase a two-phase multiphysics model has been developed. The model resolves both the liquid and gas phase and solves the mass and momentum conservation of the averaged species in both the phases. The fluid motion equation considers surface tension, electric field force as well as gravitational force. To calculate the electric force, the charge conservation equations for positive and negative ions and also for the electrons are solved. The Possion’s equation is solved in each time step for obtaining a self consistent electric field. The obtained electric field and charge distribution is used to calculate the electric body force exerted on the fluid. Simulation show that the coupled effect of plasma, surface and gravity results in a time-evolving bubble shape. The influence of different plasma parameters on the bubble dynamics is studied.

MW1.00051 Exploration of Underwater Laser Breakdown Using Two Synchronized Gated Cameras, LUTZ HUWEL, CLAYTON BAUMGART, SUSANNAH BETTS, THOMAS J. MORGAN, Wesleyan University, WILLIAM C. GRAHAM, Queen’s University Belfast — Using two synchronized intensified CCD cameras, we have studied spatial and temporal characteristics of optical breakdown in water created by a focused 10 ns pulsed Nd:YAG laser operating at 1064 nm. For three water samples with different impurity content (ultrapure, distilled, and tap water), the plasma evolution was monitored up to 1 ms after breakdown. Images taken by the two cameras, systematically delayed relative to each other, reveal that the center of emission intensity does not remain at a fixed location. In single plasma events, the center first moves, on average, toward the incoming laser beam. Then, at about 100 to 200 ns, the apparent direction of motion reverses and the center returns towards the focal point. On the other hand, in repetitive breakdown the time averaged center moves steadily downstream with each subsequent pulse. Details of this behavior depend on repetition frequency. We will also present shadowgraphy results revealing time resolved speeds of both shockwave and bubble expansion.

MW1.00052 Modulation frequency dependence of bispectrum of laser light scattering intensity from nanoparticles formed in reactive plasmas$^1$, TEPEPE ITO, DAISUKE YAMASHITA, HYUNWOOG SEO, KUNIHIRO KAMATAKI, NAHO ITAGAKI, KAZUNORI KOGA, MASAHARU SHIRATANI, Kyushu University — Interactions between plasmas and nano-interface are one of the most important issues in plasma processing. We have studied effects of plasma fluctuation on growth of nanoparticles in reactive dusty plasmas with amplitude modulation (AM) and have clarified that plasma fluctuation leads to generation of a large amount of nanoparticles with small size$^1$. Here we report results of bispectrum analysis of time evolution of laser light scattering intensity from nanoparticles in reactive plasmas. Experiments were carried out using a capacitively-coupled discharge reactor. We employed Ar+DM-DMOS discharge plasmas to generate nanoparticles. We found higher harmonics and sub-harmonics in spectra of laser light scattering intensity, suggesting nonlinear coupling between plasma parameters and nanoparticle growth rate. We will report modulation frequency dependence of bispectrum of laser light scattering intensity.


$^1$Work supported by MEXT.
MW1.00053 Iodine as propellant for electric space propulsion, PASCALINE GRONDEIN, PASCAL CHABERT, ANE AANESLAND, Laboratoire de Physique des Plasmas — In PEGASES (an electric grided thruster) both positive and negative ions are expelled after extraction from an ion-atom plasma formed downstream a localized magnetic field placed a few centimeters from the ionization region. For this thruster concept, we believe that iodine is the best candidate. Its advantages are multiple: high and therefore good for high thrust, low ionization threshold and high electronegativity (the latter crucial for PEGASES) leading to high iondensities and low RF power, at solid state at STP with a high vapor, and finally inexpensive. Iodine is also diatomic and therefore energy loss in dissociation processes are reduced compared to SF6. We present here a dedicated experimental set-up intended for iodine experiments to study their effect on the plasma parameters. The gas electron ionization cross-sections of an evaporator chamber with temperature controlled gas lines and vacuum chamber to control condensation. A global model of the iodine electronbeams plasma will be developed to compare and predict the plasma behavior and composition inside the thruster. The main challenge in this model is to reproduce the conditions of a strongly segregated plasma with two regions: one with rather high electron temperature and low electronegativity and the other an ion-atom plasma with low temperature.

MW1.00054 Computational modeling of nanoparticle charging mechanism in a hydrocarbon flame, PARTH SHAH, ALEXEI SAVELIEV, North Carolina State University — A model that describes the charging mechanism of a 20 nm nanoparticle introduced in a methane-air counterflow laminar diffusion flame was developed and analyzed. The detailed kinetic model considers the production of ions and electrons in a methane-air flame due to chemi-ionization, thermal ionization and charging due to diffusion. The chemi-ionization model considers a one-step reaction that produces ions and electrons in a flame in addition to the detailed neutral reaction mechanism. The model is analyzed to study the effects of temperature, total nanoparticle concentration and chemi-ionization on charge formation in nanoparticles as well as on ions and electrons. The results show that thermal ionization is more dominant at high temperatures whereas diffusion charging is important at low temperatures. High concentration of nanoparticles influences the gas-phase ion and electron concentration to a very significant level whereas low concentration has a negligible effect on the same.

MW1.00055 Negative ion surface production on carbon materials in hydrogen plasma: a thermodesorption analysis of carbon surface states, GILLES CARTRY, KOSTIANTYN ACHKASOV, CEDRIC PARDAUD, JEAN-MARC LAYET, PIIM, Aix Marseille University, CNRS, ALAIN SIMONIN, IRFM, CEA Cadarache, ALIX GICQUEL, LSPM, CNRS, Paris-Nord University, OTHMEN SAIDI, RÉGIS BISSON, THIERRY ANGOT, PIIM, Aix Marseille University, CNRS, PIIM COLLABORATION, IRFM COLLABORATION, LSPM COLLABORATION — Negative ion surface production in plasmas has been studied in the context of fusion where H- surface production in cesium-seeded plasmas is of a primary interest for neutral beam injection devices. The observed improvements have included a lowering of the onset temperature at which the catalytic discharge is effective, and an increase in the over-all efficiency of the process. A number of diagnostic methods have been employed to study the synergistic behaviour of plasmas and heated catalysts, the technique adopted often being specific to the monitoring of a particular reaction product. The work described here is aimed at demonstrating the versatility of mass-spectrometric methods in following the behaviour of typical plasma-assisted catalytic processes.

MW1.00056 Mass-spectrometric Observations of Plasma-assisted Catalysis, DAVE SEYMOUR, ALAN REES, DAVID LUNDIE, Hiden Analytical, HIDDEN TEAM — Plasma discharges are known to facilitate the catalysis of reactive gas mixtures. A variety of plasmas, including surface barrier discharges, have been demonstrated to enhance the efficiency of the catalysts such as nickel/alumina or silver/alumina, used in conventional thermally-activated reactors. The observed improvements have included a lowering of the onset temperature at which the catalytic discharge is effective, and an increase in the over-all efficiency of the process. A number of diagnostic methods have been employed to study the synergistic behaviour of plasmas and heated catalysts, the technique adopted often being specific to the monitoring of a particular reaction product. The work described here is aimed at demonstrating the versatility of mass-spectrometric methods in following the behaviour of typical plasma-assisted catalytic processes.

MW1.00057 Structure and Characteristics of a Spherical Plasma Focus: Theory and Simulation, YASAR AY, North Carolina State University, Department of Nuclear Engineering, Raleigh, NC 27695, USA, MOHAMED A. ABDAL-HALIM, Benha University, Faculty of Science, Department of Physics, 13518 Benha, Egypt, MOHAMED BOURHAM, North Carolina State University, Department of Nuclear Engineering, Raleigh, NC 27695, USA — Most studies of dense plasma focus devices use cylindrical coaxial shapes, however, a spherical shape is investigated herein. Snow plow model and shock wave equations are coupled with the circuit equations to model the spherical plasma focus. Of interest in spherical plasma is to have both sheath expansion and the magnetic pressure changing rate for the rundown phase instead of the constant sheath only for the cylindrical case. The developed model is compared to published experimental results for validation and good agreement was obtained. Hydrogen and its isotopes were separately used for investigating the effect of the different molecular weights on plasma parameters. The gas pressure and discharge voltage were varied for these gases. To study the effect on the plasma parameters. The study predicts a peak discharge current of 1.5MA for tritium with 0.92MA dip discharge current, and less for deuterium and hydrogen. The current drop for tritium indicates focus action. It indicates that the sheath thickness for heavy gases is lower than lighter gases. Predicted maximum temperature variation is about 11.1eV for hydrogen, 14.6eV for deuterium, 15.9eV for DT mixture and 17eV for pure tritium; which are high enough to study their effect on the plasma parameters. Predicted maximum temperature variation is about 11.1eV for hydrogen, 14.6eV for deuterium, 15.9eV for DT mixture and 17eV for pure tritium; which are high enough to study their effect on the plasma parameters.

MW1.00058 Study of an EEDF Driven Rare Gas Metastable Laser, GUY PARSEY, Michigan State University, YAMAN GUCLU, Max-Planck Institute, JOHN VERBONCOEUR, ANDREW CHRISTIE, Michigan State University — Following advancements in dipole-pumped alkali vapor lasers (DPAL), it has been shown that metastable rare gas atoms exhibit similar spectral properties with an inherently less reactive gain medium. Rare gas lasers (RGL) use an electric discharge to maintain the metastable species densities analogous to heating for the alkali vapor, both of which focus on optical pumping to induce lasing with a three-level scheme. We propose using a modified electron energy distribution function (EEDF) to either modify RGL efficiency characteristics or to drive the optical gain process. Using our general-purpose kinetic global modeling framework (KGMF), we present a study on the effect of the EEDF on the RGL reaction kinetics with an emphasis on determining if lasing can be achieved without optical pumping. Considering the classical optically driven RGL as a baseline, we focus on the EEDF as a pumping mechanism. A pure Ar model is used along with models of Ar, Kr, Xe using He to drive collisional relaxation of the upper level.

MW1.00059 Characterization of Plasma Generated in a Commercial Grade Plasma Etching system, GABRIELLA BESSINGER, DERETH DRAKE, Valdosta State University, SVETOZAR POPOVIC, LEPOSAVA VUSKOVIC, Old Dominion University — The use of plasma for etching and cleaning of many types of metal surfaces is becoming more prominent in industry. This is primarily due to the fact that plasma etching can reduce the amount of time necessary to clean/etch the surface and does not require large amounts of environmentally hazardous chemicals. Most plasma etching systems are designed and built in academic institutions. These systems provide reasonable etching rates and easy accessibility for monitoring plasma parameters. The downside is the cost is typically high. Recently a number of commercial grade plasma etchers have been introduced on the market. These etching systems cost near a fraction of the price, making them a more economical choice for researchers in the field. However, very few academics use these devices because their effectiveness has not yet been adequately verified in the current literature. We will present the results from experiments performed in a commercial grade plasma etching system, including analysis of the pulse characteristics observed by a photo diode and the plasma parameters obtained with optical emission spectroscopy.
MW1.00060 Ion densities of CH$_4$F$^+$ and CHF$_3^+$ generated by dissociative ionization of charge exchange collisions in Ar or Kr diluted CH$_2$F$_2$ Plasmas, MAKOTO SEKINE, YUSUKE KONDO, YUDAI MIYAWAKI, KENJI ISHIKAWA, TOSHIRO HAYASHI, KEIGO TAKEDA, HIROKI KONDO, MASARU HORI, Nagoya University, PLASMA NANOTECHNOLOGY TEAM — Hydro-fluorocarbon gas, CH$_2$F$_2$, is used for SiO$_2$ and Si$_3$N$_4$ etching, where the reduction of F in molecule leads high selectively. High selectively were reported as using hydro-fluorocarbon gases having more molecular mass such as C$_2$HF$_7$ [1]. H reacts to N and removes it from Si$_3$N$_4$. Therefore H works as an etchant of Si$_3$N$_4$. By using CH$_2$F$_2$ gas as an addition of conventional process, high selectively was obtained [2]. In order to understand the etch mechanism for the CH$_2$F$_2$ containing plasma, we investigate the gas phase species and reaction to produce etchants. In many cases, multiple fragmentation of the parent gas is suppressed by dilution of large amount of rare gas (M). Besides, dissociative ionization of charge exchange collisions, CH$_2$F$_2$ + M$^+$ $\rightarrow$ C$_2$HF$_-$ + F$^-$+ M$^*$ and CHF$_3$ + H$^+$ + M$^*$ (M=Ar, Kr) has not been clarified yet. Here we show the CH$_2$F$_2^+$ ion was dominant in the Ar-diluted plasma, because the channel of resonant dissociative ionization between Ar$^+$ (ca. 15.8 eV) and C-F bonding cleavage (ca. 15.6 eV) became dominant. In contrast, for the Kr-diluted plasma, similar exchange between Kr$^+$ (ca. 14.0 eV) and C-H bond cleavage (ca. 13.9 eV) generated dominantly CHF$_3^+$ ion. This behavior in the fraction of ion densities in the CH$_2$F$_2$ plasma affects significantly to the selectivity.


MW1.00061 Roughness formation on photoresist during etching examined by HBr plasma-beam, MAKOTO SEKINE, YAN ZHANG, KENJI ISHIKAWA, KEIGO TAKEDA, HIROKI KONDO, MASARU HORI, Nagoya University, PLASMA NANOTECHNOLOGY TEAM — For highly precise patterning in device fabrication, it is required to suppress roughness formations on photoresist (PR) polymers during plasma etching. HBr plasma treatment called “plasma cure” was proposed to reduce the roughness [1]. By using a beam irradiation, we reported the PR roughness formation in fluorocarbon plasma [2], and the effect of HBr cure. We report the roughness formation mechanism by surface analyses and power spectral density (PSD) of the roughness. Average slope and roll-off frequency of PSD are characterized by frequency components, the high-frequency roughness. We treated the data for six samples: a) pristine, b) after Ar plasma irradiation, c) after Ar plasma followed by HBr cure, d) after HBr plasma, e) after HBr followed by Ar plasma beam, and f) after HBr followed by H$_2$ and Ar plasma beam irradiations. The PSD slopes were changed by each process. Based on the results, we speculated that the Ar-plasma beam formed a crust layer on the PR surface with unrelied stress and HBr cure may soften the bulk PR to relieve the stress and cause agglomeration of polymers at the size over 10 nm.


MW1.00062 N-doped TiO$_2$ Prepared by RF DBD Plasma, ZHI-GUANG SUN, JING-LIN LIU, XIAO-SONG LI, ZHAO-JUN ZHAI, AI-MIN ZHU, Dalian University of Technology, LABORATORY OF PLASMA PHYSICAL CHEMISTRY TEAM — TiO$_2$ is the most promising photocatalyst because of its chemical stable, non-toxic, low-cost, high photocatalytic activity and other attractive properties. Anatase has the highest photocatalytic activity among the three crystal forms of TiO$_2$. However, the 3.2 eV bandgap of anatase TiO$_2$ makes it can only utilize the ultraviolet part of solar spectrum. Nitrogen doping is an effective method to extend the absorption range of anatase to visible light. N-doped TiO$_2$ preparation methods, such as heat treatment under NH$_3$ flow, the hydrolytic precipitation and the sol-gel process, have been reported. In this work, preparation of N-doped TiO$_2$ was explored by radio-frequency (RF) dielectric barrier discharge (DBD) plasma using Ar as discharge gas. TiCl$_4$, O$_2$ and N$_2$ were used as Ti, O and N precursors, respectively. In addition, H$_2$ was added to the plasma. X-ray photoelectron spectra (XPS) showed nitrogen was successfully doped into the as-prepared TiO$_2$. Further investigations on structure, composition and optical property of the as-prepared TiO$_2$ samples were conducted by X-ray diffraction (XRD), Fourier-transform infrared (FT-IR) and UV-Vis absorption spectra techniques.

MW1.00063 Cluster Incorporation Control by Hydrogen Silane Mixture in Multi Hollow Discharge Plasma CVD, SUSUMU TOKO, YOSHIIRO TORIGOE, YOSHINORI KANEMITU, HUNWOO SEO, KAZUNORI KOGA, MASA-HARU SHIRATANI, Kyushu University — Light-induced degradation has been one of the most important issues for hydrogenated amorphous silicon (a-Si:H) solar cells. In SiH$_4$ discharges employed for a-Si:H deposition, there coexist SiH$_3$ radicals and clusters. Our previous results show that incorporation of amorphous silicon clusters is responsible for the light-induced degradation. Therefore, it is important to control the incorporation of clusters into films. We have developed multi-hollow discharge plasma CVD method, by which clusters are driven toward the downstream region and high quality a-Si:H films can be deposited in the upstream region. In this study, we report that the generation rate of clusters and the amount of clusters incorporated into films can be controlled by hydrogen silane mixture. The generation rate of clusters correlates with electron temperature, which information was obtained by the optical emission intensity ratio ISi*/ISiH*. The amount of cluster incorporation was measured with quartz crystal microbalances (QCMs) [1]. With decreasing hydrogen gas flow rate the amount of cluster incorporation decreases.


1Work supported by NEDO and PVTEC.

MW1.00064 Effect of oxygen atoms dissociated by non-equilibrium plasma on flame of methane oxygen and argon pre-mixture gas, HARUAKI AKASHI, TOMOKAZU YOSHINAGA, National Defense Academy, KOICHI SASAKI, Hokkaido Univ. — For more efficient way of combustion, plasma-assisted combustion has been investigated by many researchers. But it is very difficult to clarify the effect of plasma on the flame of methane. Because there are many complex chemical reactions in combustion system. Sasaki et al [1] and Hase et al [1] reported that the emission of high energy electrons which are accelerated by the microwave. The high energy electrons also dissociate oxygen molecules easily and oxygen atom would have some effects on the flame. But the dissociation ratio of oxygen molecules by the non-equilibrium plasma is significantly low, compared to that in the combustion reaction. To clarify the effect of dissociated oxygen atoms on the flame, dependence of dissociation ratio of oxygen on the flame has been examined using CHEMKIN. It is found that in the case of low dissociation ratio of 10$^{-6}$, the ignition of the flame becomes slightly earlier. But it is also found that in the case of high dissociation ratio of 10$^{-6}$, the ignition time becomes significantly earlier by almost half.


3This work was supported by KAKENHI(22340170).
MW1.00065 Multiplex coherent anti-Stokes Raman scattering microspectroscopy for monitoring molecular structural change in biological samples, TAKAYUKI OHTA, Meijo University, HIROSHI HASHIZUME, KEIGO TAKEDA, KENJI ISHIKAWA, Nagoya University, MASAFUMI TTO, Meijo University, MASARU HORI, Nagoya University — Biological applications employing non-equilibrium plasma processing has been attracted much attention. It is essential to monitor the changes in an intracellular structure of the cell during the plasma exposure. In this study, we have analyzed the molecular structure of biological samples using multiplex coherent anti-Stokes Raman scattering (CARS) microspectroscopy. Two picosecond pulse lasers with fundamental (1064 nm) or the supercontinuum (460-2200nm) were employed as a pump and Stokes beams of multiplex CARS microspectroscopy, respectively. The pump and the Stokes laser beams were collinearly overlapped and tightly focused into a sample using an objective lens of high numerical aperture. The CARS signal was collected by another microscope objective lens which is placed facing the first one. After passing through a short pass filter, the signal was dispersed by a polychromator, and was detected by a charge-coupled device camera. The sample was sandwiched by a coverslip and a glass bottom dish for the measurements and was placed on a piezo stage. The CARS signals of the quinhydrone crystal at 1635, 1584, 1237 and 1161 cm⁻¹ were assigned to the C-C, C=O stretching, O-H and C=O stretching vibrational modes, respectively.

MW1.00066 Inactivation of the biofilm by the air plasma containing water, RYOTA SUGANUMA, KOICHI YASUOKA, Tokyo Inst of Tech - Tokyo, YASUOKA TAKEUCHI LAB TEAM — Biofilms are caused by environmental degradation in food factory and medical facilities. Inactivation of biofilm has the method of making it react to chemicals including chlorine, hydrogen peroxide, and ozone. Although inactivation by chemicals has the problem that hazardous property of a residual substance and hydrogen peroxide have slow reaction velocity. We achieved advanced oxidation process (AOP) with air plasma. Hydrogen peroxide and ozone, which were used for the formation of OH radicals in our experiment, were able to be generated selectively by adjusting the amount of water supplied to the plasma. We inactivated Pseudomonas aeruginosa biofilm in five minutes with OH radicals generated by using hydrogen peroxide and ozone.

MW1.00067 VUV-Photoionization CES-Detector of Volatile Bio-Marker Molecules, ALEXANDER MUSTAFAEV, National Mineral Resources University, St.-Petersburg, Russia, NATALIYA LUNEVA, St.-Petersburg State University, Faculty of Dentistry and Medical Technologies, Russia, GEORGE PANASYUK, UES Inc., Dayton OH 45432, USA, NIKOLAY TIMOFEEV, St.-Petersburg State University, Faculty of Physics, Russia, ALEXANDER TSYGANOV, Spectrum-Micro LLC, St.-Petersburg, 191036 Russia — Energy spectra of characteristic electrons released via photoionization by vacuum ultraviolet (VUV) radiation of admixture molecules in the atmospheric air, not using traditional evacuated energy analyzers, can be determined by Collisional Electron Spectroscopy (CES) method [1]. Some details of CES-photoionization sensor were described in [2]. Our further developments are devoted to application of CES-detectors for a mobile continuous bio-chemical diagnostics. It is known that “on breathing” it is possible to find out volatile bio-marker molecules of a lot of diseases (lung cancer, tuberculosis, COPD, asthma, diabetes, kidney disease, mammary cancer, Crohn’s disease, ulcerative colitis, etc.). But today’s lightweight and expensive laboratory equipment (like GC MS) provides observation of these bio-markers only during patients’ visits to a doctor. In this way we study pocket-size CES-sensor with micro-plasma krypton resonance radiation source (10.6 eV photons) for the photoionization detection of metabolic ammonia, ethanol, acetone and pentane molecules directly in atmospheric air.


MW1.00069 Diagnostics of AC excited Atmospheric Pressure Plasma Jet with He for Biomedical Applications, MASARU HORI, TAKUMI KUMAKURA, KENJI ISHIKAWA, HIROMASA TANAKA, HIROKI KONDO, MAKOTO SEKINE, Nagoya University, YOSHIHIRO NAKAI, NU Global — Atmospheric pressure plasma jets (APPJ) are frequently used for biomedical applications. Reactive species generated by the APPJ play important roles for treatments of biomedical samples. Therefore, high density APPJ sources are required to realize the high performance. Our group has developed AC excited Ar APPJ with electron density as high as 10¹⁵ cm⁻³ and electron density of the APPJ were measured by optical emission spectroscopy. From theoretical fitting of 2nd positive system of N, electron density and temperature was estimated to be 299 K and 3.4 x 10¹⁵ cm⁻³. The AC excited He APPJ has a potential to realize the high performance. Our group has developed AC excited Ar APPJ with electron density as high as 10¹⁵ cm⁻³ and realized the selective killing of cancer cells and the inactivate spores of Penicillium digitatum. Recently, a new spot-size AC excited APPJ with He gas have been developed. In this study, the He APPJ was characterized by using spectroscopy. The plasma was discharged at a He flow rate of 5 slm and a discharge voltage of AC 9 kV. Gas temperature and electron density of the APPJ were measured by optical emission spectroscopy. From theoretical fitting of 2nd positive system of N₂ emission (380.4 nm) and Stark broadening of Balmer β line of H atom (486.1 nm), the gas temperature and the electron density was estimated to be 299 K and 3.4 x 10¹⁵ cm⁻³. The AC excited He APPJ has a potential to realize high temperature with room temperature and become a very powerful tool for biomedical applications.

MW1.00070 Comparison of plasma generated nitrogen fertilizer to conventional fertilizers ammonium nitrate and sodium nitrate for pre-emergent and seedling growth, A. ANDHAVARAPU, W. KING, A. LINDSAY, B. BYRNS, D. KNAPPE, W. FENTON, S. SHANNON, North Carolina State University — Plasma source generated nitrogen fertilizer is compared to conventional nitrogen fertilizers in water for plant growth. Root, shoot sizes, and weights are used to examine differences between plant treatment groups. With a simple coaxial structure creating a large-volume atmospheric glow discharge, a 162 MHz generator drives the air plasma. The VHF plasma source emits a steady state glow; the high drive frequency is believed to inhibit the glow-to-arc transition for non-thermal discharge generation. To create the plasma activated water (PAW) solutions used for plant treatment, the discharge is held over distilled water until a 100 ppm nitrogen aqueous concentration is achieved. The discharge is used to incorporate nitrogen species into aqueous solution, which is used to fertilize radishes, marigolds, and tomatoes. In a four week experiment, these plants are watered with four different solutions: tap water, dissolved ammonium nitrate DI water, dissolved sodium nitrate DI water, and PAW. Ammonium nitrate solution has the same amount of total nitrogen as PAW, sodium nitrate solution has the same amount of nitrate as PAW. T-tests are used to determine statistical significance in plant group growth differences. PAW fertilization chemical mechanisms are presented.
Numerical Simulation of Acceleration and Deceleration of Weakly-Ionized Rarefied Arc-Jet along Diverging Magnetic Field

HIROSHI AKATSUKA, SATOSHI TSUNO, AMPAN LAOSUNTHARA, ATSUSHI NEZU, HARUAKI MATSUURA, Tokyo Institute of Technology — We are studying supersonic helium plasma jet along a diverging magnetic field with low-ionization degree and low electron density. It had been experimentally found that the ion Mach number had its maximum about 3 at 1 cm downstream after passing the magnetic nozzle, and after that, the ion Mach number turned to decrease, and the plasma potential dropped. We numerically simulated the expanding plasma along the open magnetic field. Considering dimensionless numbers of the plasma flow, we chose hybrid scheme, i.e., Direct Simulation Monte Carlo (DSMC) method for neutral particles and ions, and fluid method for electrons. Residual molecules in the vacuum chamber were also included as particles. Consequently, we find the velocity increase just after passing the open field line, followed by deceleration due to collisions with residual molecules with temperature increase. In this acceleration-deceleration phenomenon, the velocity difference between neutrals and charged species are found, which also affects the space potential. We discuss the mechanisms of potential formation by the pressure difference and the friction force between the charged particles and neutral species. The numerical results are, at least qualitatively, consistent with our previous experimental results.

ABSTRACT WITHDRAWN

Kinetic Modeling of Martians Atmospheric Aerobraking Plasma

DERETH DRAKE, EVAN SMITHWICK, Valdosta State University — During Martian atmospheric aerobraking the plasma that forms around a spacecraft can be considered a high-volume plasma reactor that is sustained by the dissipation of the spacecraft's kinetic energy. At altitudes below 100 km, it has been shown that the plasma parameters vary considerably depending on the spacecraft's trajectory. However, in the range which is applicable to aerobraking, 100 km < h < 200 km, little of this work has been completed. We have evaluated a simple kinetic model to determine a probable range of plasma parameters for altitudes between 100 and 200 km using existing Martian atmospheric data and available probe trajectories.

Study of Unsteady Flow Actuation Produced by Surface Plasma Actuator on 2-D Airfoil

MINH KHANG PHAN, JICHUL SHIN, University of Ulsan — Effect of flow actuation driven by low current continuous or pulsed DC surface glow discharge plasma actuator is studied. Schlieren image of induced flow on flat plate taken at a high repetition rate reveals that the actuation is mostly initiated near the cathode. Assuming that the actuation is mostly achieved by ions in the cathode sheath region, numerical model for the source of flow actuation is obtained by analytical estimation of ion pressure force created in DC plasma sheath near the cathode and added in momentum equation as a body force term. Modeled plasma flow actuator is simulated with NACA0012 airfoil oscillating over a certain range of angle of attack (AoA) at specific reduced frequencies of airfoil. By changing actuation authority according to the change in AoA, stabilization of unsteady flow field is improved and hence steady aerodynamic performance can be maintained. Computational result shows that plasma actuation is only effective in modifying aerodynamic characteristics of separated flow. It turns out that plasma pulse frequency should be tuned for optimal performance depending on phase angle and rotating speed. The actuation authority can be parameterized by a ratio between plasma pulse frequency and reduced frequency.

Self-assembled Ag nano-patterns forming in downflow of ammonia-Ar atmospheric pressure microplasmas

NAOYA KIHARA, ELLA BLANQUET, OSAMU SAKAI, Kyoto University — Fractal-like Ag nano-patterns were observed after drying silver nitrate solution in downflow of ammonia-Ar atmospheric pressure microplasmas. These atmospheric-pressure plasma microplasmas generated hydrazine, and this hydrazine density in their downflow region was in the order of 10^{15} cm^{-3} [1]. As hydrazine is a very strong reducing agent, Ag nano-particles were extracted from the silver nitrate solution. The Ag nano-structures were fractal-like patterns, with fractal dimension range of 1.6-1.9. The network structures in these patterns with several mm diameter showed good electric conductivity and extraordinary optical responses, which will be favorable for future low-cost optical metamaterials.


Interactions between plasma-treated carbon nanotubes and electrically neutral materials

DAISUKE OGAWA, KEIJI NAKAMURA, Chubu University — A plasma treatment can create dangling bonds on the surface of carbon nanotubes (CNTs). The dangling bonds are so reactive that the bonds possibly interact with other neutral species even out of the plasma if the lifetime of the bonds is effectively long. In order to have good understandings with the interactions, we placed multi-wall CNTs (MWCNTs) in atmospheric dielectric barrier discharge that was created in a closed environment with the voltage at 5 kV. We set 50 W for the operating power and 15 minutes for the process time for this plasma treatment. Our preliminary results showed that the reaction between dangling bonds and neutrals likely occurred in the situation when CNTs were treated with argon plasma, and then exposed in a nitrogen-rich dry box. We did Fourier transform infrared (FTIR) spectroscopy after the treatments. The measurement showed that the spectrum with plasma-treated CNTs was different from pristine CNTs. This is an indication that the plasma-treated CNTs have reactive cites on the surface even after the discharge (~ minutes), and then the CNTs likely reacted with the neutral species that causes the different spectrum. In this poster, we will show more details from our results and further progresses from this research.

Optimizing Natural Gas Networks through Dynamic Manifold Theory and a Decentralized Algorithm: Belgium Case Study

CALEB KOCH, LEIGH WINFREY, Virginia Tech — Natural Gas is a major energy source in Europe, yet political instabilities have the potential to disrupt access and supply. Energy resilience is an increasingly essential construct and begins with transmission network design. This study proposes a new way of thinking about modelling natural gas flow. Rather than relying on classical economic models, this problem is cast into a time-dependent Hamiltonian dynamics discussion. Traditional Natural Gas constraints, including inelastic demand and maximum/minimum pipe flows, are portrayed as energy functions and built into the dynamics of each pipe. Doing so allows the constraints to be built into the dynamics of each pipeline. As time progresses in the model, natural gas flow rates find the minimum energy, thus the optimal gas flow rates. The most important result of this study is using dynamical principles to ensure the output of natural gas at demand nodes remains constant, which is important for country to country natural gas transmission. Another important step in this study is building the dynamics of each flow in a decentralized algorithm format. Decentralized regulation has solved congestion problems for internet data flow, traffic flow, epidemiology, and as demonstrated in this study can solve the problem of Natural Gas congestion. A mathematical description is provided for how decentralized regulation leads to globally optimized network flow. Furthermore, the dynamical principles and decentralized algorithm are applied to a case study of the Fluxys Belgium Natural Gas Network.

Plasma Modeling of Electrosurgery

SCOTT JENSEN, DANIEL FRIEDRICHS, JAMES GILBERT, WOUN-JHANG PARK, DRAGAN MAKSIMOVIC, University of Colorado-Boulder — Electrosurgery is the use of high frequency alternating current (AC) to illicit a clinical response in tissue, such as cutting or cauterization. Power electronics converters have been demonstrated to generate the necessary output voltage and current for electrosurgery. The design goal of the converter is to regulate output power while supplying high frequency AC. The design is complicated by fast current and voltage transients that occur when the current travels through air in the form of an arc. To assist in designing a converter that maintains the desired output power during these transients, we have used the COMSOL Plasma Module to determine the output voltage and current characteristics during an arc. This plasma model, used in conjunction with linear circuit elements, allows the full electrosurgical system to be validated. Two models have been tested with the COMSOL Plasma Module. One is a four-species, four-reaction model based on the local field approximation technique. The second simulates the underlying air chemistry using 30 species, 151 chemical reactions, and a coupled electron energy distribution function. Experimental output voltage and current samples have been collected and compared to both models.
MW1.00079 POSTDEADLINE —

MW1.00080 Solutions of the low-frequency plasma sheath circuit equations , MIRKO VUKOVIC, Tokyo Electron, US Holdings, Inc. — We derive a relation between the time derivatives of the current and voltage of the low-frequency plasma sheath. This relation is used to derive a first order differential equation for the electrical current in a driven series resistor, capacitor, and sheath circuit. Analytic and semi-numeric solutions are obtained for pulse and periodic excitations. We use these solutions to analyze the Langmuir probe response in some common diagnostic applications: the pulse excitation (Samara et al, 2012) and AC Bias (Van Nieuwenhove & Van Oost, 1985) methods.

1Samara et al. A dc-pulsed capacitively coupled planar Langmuir probe for plasma process diagnostics and monitoring, Plasma Sources Sci. Technol. 21 (2012) 065004

MW1.00081 Atomic Layer Etching of Silicon to Solve ARDE-Selectivity-Profile-Uniformity Trade-Offs , MINGMEI WANG, ALOK RANJAN, TEL Technology Center, America, LLC, PETER VENTZEK , Tokyo Electron America, Inc., AKIRA KOSHIISHI, Tokyo Electron Miyagi Ltd. — With shrinking critical dimensions, dry etch faces more and more challenges. Minimizing each of aspect ratio dependent etching (ARDE), bowing, undercut, selectivity, and within die uniformly across a wafer are met by trading off one requirement against another. At the root of the problem is that roles radial flux, ion flux and ion energy play may be both good and bad. Increasing one parameter helps meeting one requirement but hinders meeting the other. Self-limiting processes like atomic layer etching (ALE) promise a way to escape the problem of balancing trade-offs. ALE [1] was realized in the mid-1990s but the industrial implementation has been slow. In recent years interest in ALE has revived. We present how ARDE, bowing/selectivity trade-offs may be overcome by varying radical/ion ratio, byproduct re-deposition. We overcome many of the practical implementation issues associated with ALE by precise passivation process control. The Monte Carlo Feature Profile Model (MCFPM) is used to illustrate realistic scenarios built around an Ar/C2H2 chemistry driven etch of Si masked by SiO2. We demonstrate that ALE can achieve zero ARDE and infinite selectivity. Profile control depends on careful management of the ion energies and angles. For ALE to be realized in production environment, tight control of IAD is a necessary. Experimental results are compared with simulation results to provide context to the work. [1] Athavale et al., J. Vac. Sci. Technol. B, 14, 3702 (1996).

MW1.00082 Interfacial instability of wormlike micellar solutions sheared in a Taylor-Couette cell , HADI MOHAMMADIGOUSHKI, SUSAN J. MULLER, Chemical and Biomolecular Engineering-UC Berkeley — We report experiments on wormlike micellar solutions sheared in a custom-made Taylor-Couette (TC) cell. The computer controlled TC cell allows us to rotate both cylinders independently. Wormlike micellar solutions containing water, CTAB, and NaNo3 with different compositions are highly elastic and exhibit shear banding within a range of shear rate. We visualized the flow field in the $\theta$-$z$ as well as $r$-$z$ planes, using multiple cameras. When subject to low shear rates, the flow is stable and azimuthal, but becomes unstable above a certain threshold shear rate. This shear rate coincides with the onset of shear banding. Visualizing the $\theta$-$z$ plane shows that this instability is characterized by stationary bands equally spaced in the z direction. Increasing the shear rate results to larger wave lengths. Above a critical shear rate, experiments reveal a chaotic behavior reminiscent of elastic turbulence. We also studied the effect of ramp speed on the onset of instability and report an acceleration below which the critical Weissenberg number for onset of instability is unaffected. Moreover, visualizations in the $r$-$z$ direction reveals that the interface between the two bands undulates. The shear band evolves towards the outer cylinder upon increasing the shear rate, regardless of which cylinder is rotating.

MW1.00083 Inelastic processes of electron interactions with halouracils – cancer therapy agents , CHETAN LIMBACHIYA, The M.S. University of Baroda, Vadodara, India, MINAXI VINODKUMAR, V.P. Science College, Vallabh Vidyanagar, India, MOHIT SWADIA, P.S. Science College, Kadi, India — We report electron impact total inelastic cross sections for important cancer treatment agents, 5-fluorouracil (5FU), 5-chlorouracil (5ClU) and 5-bromouracil (5BrU) from ionization threshold through 5000 eV. We have employed Spherical Complex Optical Potential [1, 2] method to compute total inelastic cross sections $Q_{inel}$ and Complex Scattering Potential – ionization contribution (CSP-ic) formalism, to calculate total ionization cross sections $Q_{ion}$. Electron driven ionization cross sections for these important compounds of therapeutic interest are reported for the first time in this work. In absence of any ionization study for these cancer therapy agents, we have compared the data with their parent molecule Uracil. Present cross sections may serve as a reference estimates for experimental work.

2Chetan Limbachiya et al., Molecular Physics, 112(1), 101 (2014)

MW1.00084 Study of striations in a spherically symmetric hydrogen discharge , LOWELL MORGAN, Kinema Research & Software, LLC, MONTY CHILDS, MICHAEL CLARAGE, PAUL ANDERSON, Aurtas International, Inc. — We have observed, in experiments similar to those of [1, 2], multi spherically symmetric striations or double-layers in a hydrogen discharge, sometimes containing a small amount of helium having a total gas pressure in the range 0.7 - 5 Torr. The discharge is a positive corona around a 6mm diameter steel anode driven by a 600V, max 3 Amp DC power supply. Using mass spectrometry we have found that sometimes as much as 10% of the H2 is dissociated into atomic hydrogen. The dominant positive ion is $H_3^+$. We have performed UV, visible, and near-IR spectroscopy of the plasma looking at line ratios and Stark broadening in order to obtain an estimate of electron temperature and density. We have also performed Abel transforms on images of the striations in order to find the true relative broad band emissivity from the optically thin plasma as a function of radius out from the anode finding that, typically, it peaks several anode radii out into the plasma striations. Some modeling and simulation of the plasma chemistry and transport will also be presented. Research supported by the International Science Foundation.


MW1.00085 Investigation of the rates of surface and bulk ROS-generating reactions using indigo dye as an indicator , CARLY ANDERSON, DOUGLAS CLARK, DAVID GRAVES, University of California, Berkeley — We present evidence for the existence of two distinct processes that contribute to the generation of reactive oxygen and nitrogen species (RONS) in liquids exposed to cold atmospheric plasma (CAP) in air. At the plasma-liquid interface, there exists a fast surface reaction zone where RONS from the gas phase interact with species in the liquid. RONS can also be produced by “slow” chemical reactions in the bulk liquid, even long after plasma exposure. To separate the effects of these processes, we used indigo dye as an indicator of ROS production; specifically generation of hydroxyl radical. The rate of indigo decolorization while in direct contact with CAP was compared with the expected rate of hydroxyl radical generation at the liquid surface. When added to aqueous solutions after CAP exposure, indigo dye reacts on a time scale consistent with the production of peroxynitrous acid, ONOOH, which is known to decompose to hydroxyl radical below a pH of 6.8. In this study, the CAP used was a air corona discharge plasma run in a positive streamer mode.
MW1.00086 A Global Enhanced Vibrational Kinetic Model for Investigation of Negative Hydrogen Ion Sources, SERGEY AVERKIN, NIKOLAOS GATSONIS, Worcester Polytechnic Institute — A new Global Enhanced Vibrational Kinetic Model (GEVKM) is developed for modeling low pressure hydrogen ion production and extraction processes in low (mTorr level) to high pressure (Torr level) ion sources. GEVKM couples steady-state space averaged continuity equations for ground-state neutral H\textsubscript{2}, H\textsubscript{2}+, H\textsubscript{3}+, negative ions H\textsuperscript{−}, electronically excited hydrogen atoms H(n\textsubscript{e}=2-3), and electrons with electron energy and total energy equations. Compared to previous global models GEVKM includes a full vibrational kinetics treatment, a self-consistent evaluation of heavy particle temperature and spatial variation of species densities in estimation of wall fluxes. The input parameters to GEVKM are ion source geometry, inlet hydrogen flow rate and absorbed power and outputs include concentration and temperature of all species. The GEVKM is verified and validated by comparisons with previous experimental and computational results for a low pressure (100-100 mTorr) volume negative ion source and a high pressure (10-100 Torr) microwave generated hydrogen plasma reactor. The GEVKM is also used for a parametric investigation of a new high pressure negative hydrogen ion source that includes the RF discharge chamber and a nozzle.

MW1.00087 Electron density and temperature diagnostics for atmospheric pressure plasmas using continuum radiation, SANGHOO PARK, Korea Advanced Institute of Science and Technology, SE YOUN MOON, Chonbuk National University, WONHO CHOE, Korea Advanced Institute of Science and Technology — Information on electrons is particularly valuable because most of the important plasma reactions are governed by electron kinetics. However, diagnostics of electron density (n\textsubscript{e}) and temperature (T\textsubscript{e}) of low temperature atmospheric pressure plasmas is still challenging although there are some advanced diagnostics available such as laser Thomson scattering or optical emission spectroscopy combined with complex plasma equilibrium models. In this work, we report a simple spectroscopic diagnostic method with high temporal and spatial resolution based on continuum radiation in the UV and visible range for n\textsubscript{e} and T\textsubscript{e}. Together with the basic principle for the diagnostics including electron-atom bremsstrahlung (or neutral bremsstrahlung) and hydrogen radiative dissociation continuum, some experimental results in several argon and helium atmospheric pressure plasmas will be presented. In a typical argon 13.56 MHz parallel plate capacitive discharge, the measured values are T\textsubscript{e}=2.5 eV and n\textsubscript{e}=0.7-1.1×10\textsuperscript{12} cm\textsuperscript{-3} at P\textsubscript{rf}=110-200 W. Two-dimensional T\textsubscript{e} profile of an Ar pulsed plasma jet using a DSLR camera and this diagnostics will also be shown.

MW1.00088 High-energy tail formation in an ion energy distribution function in the cylindrical Hall thruster plasma, YOUBONG LIM, HOLAK KIM, JAEJUNG PARK, Korea Advanced Institute of Science and Technology, JONGHO SEON, Kyung Hee University, WONHO CHOE, Korea Advanced Institute of Science and Technology — Ion energy distribution functions (IEDFs) of individual ion species having different charge states (i.e. Xe\textsuperscript{+}, Xe\textsuperscript{2+}, Xe\textsuperscript{3+}, etc.) in the Hall thruster plasma are obtained from the measured E × B probe spectrum by a novel inversion technique using the iterative Tikhonov regularization method. The obtained IEDFs show the existence of a high-energy tail in the cylindrical Hall thruster plasma that is mainly due to Xe\textsuperscript{+} ions despite the presence of Xe\textsuperscript{2+} and Xe\textsuperscript{3+} ions with a large fraction. Ion dynamics inside the plasma was numerically investigated to demonstrate that the high-energy tail is due to nonlinear ion acceleration in the plasma oscillating at typically 100 to 500 kHz. We found that this oscillation driven by transit-time instability is responsible for the shift of the IEDF of the Xe\textsuperscript{+} ions toward the high-energy side, showing the formation of high-energy tail in the overall IEDF. It was also found that the Xe flow rate raised from 4 to 10 s cc/min increases the oscillation strength at the same frequency of 360 kHz, which can be applied to control of the shape of the IEDF.

MW1.00089 Ion beam and performance characteristics in the presence of multiply charged ions in annular and cylindrical type Hall thruster plasmas\textsuperscript{1}, HOLAK KIM, YOUBONG LIM, JONGHO SEON, WONHO CHOE, Korea Advanced Institute of Science and Technology (KAIST), KOREA ADVANCED INSTITUTE OF SCIENCE AND TECHNOLOGY (KAIST) COLLABORATION, KYUNG HEE UNIVERSITY COLLABORATION — Operation performance and ion beam characteristics in the presence of multiply charged ions in cylindrical Hall thruster (CHT) and annular Hall thruster (AHT) plasmas are compared under identical conditions such as channel diameter, channel depth, and propellant flow rate. According to our previous results, the propellant utilization of the 200 W class CHT will exceed unity [J. Lee et al., Appl. Phys. Lett. 99, 131505 (2011); M. Seo et al., Phys. Plasmas 20, 023507 (2013)] and the papers suggest that this may be related to the presence of multiply charged ions. In this work, we report the large fractions of Xe2\textsuperscript{+} and Xe3\textsuperscript{+} ions measured in the CHT plasma, which are about 16-26% and 6-7%, respectively. The measured values of specific impulse and thrust are higher by 1.4 times in CHT than in AHT at 300 V of the anode voltage, and it is found that the high fraction of multiply charged ions is responsible for the higher values of specific impulse and thrust. The details of the comparison of the overall performance and beam characteristics associated with multiply charged ions in AHT and CHT will be presented.

\textsuperscript{1}This work was partly supported by the Space Core Technology Program (Grant No. 2014MA1A3A3A02034510) and the Korea Institute of Materials Science (KIMS) (Grant No. 10043470).

Thursday, November 6, 2014 8:00AM - 9:15AM –
Session MR2 Plasma Interactions with Liquid  State C -
8:00AM MR2.00001 Detection of solvated electrons at a plasma-liquid interface, DAVID B. GO, PAUL RUMBAUGH, DAVID BARTELS, University of Notre Dame, R. MOHAN SANKARAN, Case Western Reserve University — We have recently shown that charge can be transferred from a DC microplasma jet into an aqueous solution to promote electrolytic reduction reactions [1,2]. However, the precise nature of these charge transfer reactions remains poorly understood—in particular, it is not known if plasma electrons solvate and solvated electrons are responsible for the reduction of solution species. To address these questions, we have designed and built an optical absorption spectroscopy system to directly detect solvated electrons at a plasma-liquid interface, which only have a lifetime of ~ 1 μs. Our preliminary results reveal that plasma electrons do indeed solvate, and survive up to depths of approximately 0.5 nm beneath the plasma-liquid interface. Adding electron scavengers such as nitrite and nitrate salts to the solution causes a decrease in optical absorption, indicating a decrease in the average lifetime of the solvated electrons, further confirming their existence. Measuring optical absorption as a function of scavenger concentration, we extrapolate rate constants that agree well with prior radiolysis experiments. These preliminary findings are consistent with the hypothesis that free electrons from atmospheric pressure plasmas solvate in aqueous solutions, and open potential applications of plasmas for solvated electron chemistry.

8:20AM MR2.00002 Comparison of Plasma Activation of Thin Water Layers by Direct and Remote Plasma Sources

MARK KUSHNER, University of Michigan — Plasma activation of liquids is now being investigated for a variety of biomedical applications. The plasma sources used for this activation can be generally classified as direct (the plasma is in contact with the surface of the liquid) or remote (the plasma does not directly touch the liquid). The direct plasma source may be a dielectric barrier discharge (DBD) where the surface of the liquid is a floating electrode or a plasma jet in which the ionization wave forming the plasma plume reaches the liquid. The remote plasma source may be a DBD with electrodes electrically isolated from the liquid or a plasma jet in which the ionization wave in the plume does not reach the liquid. In this paper, a comparison of activation of thin water layers on top of tissue, as might be encountered in wound healing, will be discussed using results from numerical investigations. We used the modeling platform nonPDPSIM to simulate direct plasma activation of thin water layers using DBDs and remote activation using plasma jets using up to hundreds of pulses. The DBDs are sustained in humid air while the plasma jets consist of He/O2 mixtures flowed into humid air. For similar number of pulses and energy deposition, the direct DBD plasma sources produce more acidification and higher production of nitrates/nitrites in the liquid. This is due to the accumulation of NOxOy plasma jets, the convective flow removes many of these species prior to their diffusing into the water or reacting to form higher nitrogen oxides. This latter effect is sensitive to the repetition rate which determines whether reactive species formed during prior pulses overlap with newly produced reactive species in the gas phase. In the plasma jets, the convective flow removes many of these species prior to their diffusing into the water or reacting to form higher nitrogen oxides. This latter effect is sensitive to the repetition rate which determines whether reactive species formed during prior pulses overlap with newly produced reactive species.

1Work supported by National Science Foundation and Department of Energy.

8:40AM MR2.00003 Interaction of non-equilibrium plasma jets with liquids: chemistry, transport and biological interactions.

PETER BRUGGERMAN, —

9:00AM MR2.00004 Non-thermal equilibrium plasma-liquid interactions with femtolitre droplets

PAUL MAGUIRE, CHARLES MAHONY, ANDREW BINGHAM, JENISH PATEL, DAVID RUTHERFORD, DAVID MCDOWELL, DAVIDE MARIOTTI, University of Ulster, EUAN BENNET, HUGH POTTIS, DECLAN DIVER, University of Glasgow — Plasma-induced non-equilibrium liquid chemistry is little understood. It depends on a complex interplay of interface and near surface processes, many involving energy-dependent electron-induced reactions and the transport of transient species such as hydrated electrons [1]. Femtolitre liquid droplets, with an ultra-high ratio of surface area to volume, were transported through a low-temperature atmospheric pressure RF microplasma with transit times of 1 – 10 ms. Under a range of plasma operating conditions, we observe a number of non-equilibrium chemical processes that are dominated by energetic electron bombardment. Gas temperature and plasma parameters (ne ~ 1011 cm−3, T_e <4eV) were determined while size and droplet velocity profiles were obtained using a microscope coupled to a fast ICCD camera under low light conditions. Laminar mixed-phase droplet flow is achieved and the plasma is seen to significantly deplete only the slower, smaller droplet component due possibly to the interplay between evaporation, Rayleigh instabilities and charge emission [2].


8:00AM MR3.00001 Challenges in Understanding and Predictive Modeling of Plasma Assisted Combustion

IGOR V. ADAMOVICH WALTER R. LEMPERT, The Ohio State University, Columbus, —

8:20AM MR3.00002 Plasma-Based Mixing in Compressible Flow

SERGEY LENONOV, The Ohio State University —

8:40AM MR3.00003 Plasma Assisted Combustion Mechanism for Small Hydrocarbons

ANDREY STARIKOVSKIIY, Princeton University —

9:00AM MR3.00004 Laser-Induced Plasma in Reactive Flows for Ignition and Measurements

HYUNGROK DO CAMPBELL D. CARTER, University of Notre Dame; Air Force Research Laboratory —

Thursday, November 6, 2014 8:00AM - 9:20AM –
Session MR3 Plasma Enhanced Chemically Reactive Flows

8:00AM MR3.00001 Challenges in Understanding and Predictive Modeling of Plasma Assisted Combustion

IGOR V. ADAMOVICH WALTER R. LEMPERT, The Ohio State University, Columbus, —

8:20AM MR3.00002 Plasma-Based Mixing in Compressible Flow

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9:00AM MR3.00004 Laser-Induced Plasma in Reactive Flows for Ignition and Measurements

HYUNGROK DO CAMPBELL D. CARTER, University of Notre Dame; Air Force Research Laboratory —

Thursday, November 6, 2014 10:00AM - 12:00PM –
Session NR1 Plasma Boundaries, Sheaths, and Basic Plasma Physics II

10:00AM NR1.00001 Modeling Sheaths in DC Discharges

SCOTT ROBERTSON, University of Colorado - Boulder —

Textbook presentations on sheaths are often limited to a discussion of Bohm’s criterion because more detailed analysis results in equations that can be solved only by numerical methods. There are both fluid and kinetic models for sheaths that can be solved by packaged numerical integration routines in a mathematical spreadsheet such as Mathematica, Matlab, or Mathcad. The potential profiles and the currents for sheaths at boundaries usually have monotonic profiles that are easily modeled using a Boltzmann distribution for electrons and for ions using the fluid momentum equation and the continuity equation with a source term describing plasma production. Additional ion species and bi-Maxwellian electron distributions are easily included. Virtual cathodes may form above emissive surfaces which divide the distribution function of emitted electrons into a passing population and a reflected population that can be modeled only by a kinetic approach. For sheaths at inserted objects such as probes and dust particles, it is customary to prescribe the plasma characteristics at infinity, to ignore creation of new plasma by ionization, and to solve for the radial variation of the density near the object and for the current collected by the object. A kinetic model is required for sheaths at inserted objects because the distribution function must be divided into passing particles and collected particles.
10:30AM NR1.00002 Electric field profiles in obstructed helium discharge, PETER FENDEL, Thorlabs, BIJWA GANGULY, PETER BLETZINGER, Air Force Research Laboratory — Axial and radial variations of electric field have been measured in dielectric shielded 25 mm diameter parallel plate electrode for 2 mA, 2250 V helium dc discharge at 1.75 Torr with 6.5 mm gap. The axial and radial electric field profiles have been measured from the polarization dependent Stark splitting of 2S → 11 P transition through collision induced fluorescence from 4D → 2P. The electric field values showed a strong radial variation peaking up to 5 kV/cm near the cathode radial boundary, and decreasing to about 1 kV/cm near the anode, suggesting the formation of an obstructed discharge for this low Pd condition. Also, the on-axis electric field was nearly constant across the gap indicating a radially non-uniform current density. In order to obtain information about the space charge distribution in this obstructed discharge, it was modeled using the 2-d axisymmetric Poisson solver with COMSOL finite element modeling program. The model discharge dimensions were selected to match the experimental dimensions. The best fit to the measured electric field distribution was obtained with a space charge variation of ρ(r) = ρ0(r/r0)^3, where ρ(r) is the local space charge density, ρ0 is the maximum space-charge density, r the local radial value and r0 the radius of the electrode.

10:45AM NR1.00003 Electric field measurements in a nanosecond pulse discharge by picosecond CARS / 4-wave mixing, BEN GOLDBERG, IVAN SHKURENKOV, IGOR ADAMOVICH, VALERY GODYAK, WALTER LEMPERT, The Ohio State University — Time-resolved electric field measurements in hydrogen by picosecond CARS / 4-wave mixing are presented. Measurements are carried out in a high voltage nanosecond pulse discharge in hydrogen in plane-to-plane geometry, at pressures of up to several hundred Torr, and with a time resolution of 0.2 ns. Absolute calibration of the diagnostics is done using a sub-breakdown high voltage pulse of 12kV/cm. A diffuse discharge is obtained by applying a peak high voltage pulse of 40 kV/cm between the electrodes. It is found that breakdown occurs at a lower field, 15-20 kV/cm, after which the field in the plasma is reduced rapidly due to plasma self shielding. The experimental results are compared with kinetic modeling calculations, showing good agreement between the measured and the predicted electric field.

11:00AM NR1.00004 EEDF and Plasma Parameters of an Argon Positive Column, VALERY GODYAK, BENJAMIN ALEXANDROVICH, Retired, GEORGE PETROV, Naval Research Laboratory — The existing experimental data base on plasma properties of the positive column in noble gases was obtained during the past century with optical spectroscopy and Langmuir probe technique. The latter is based on the assumption of a Maxwellian electron distribution function (EEDF). However, numerous calculations for EEDFs and experiments in Ramsauer-type gases, such as Ne, Ar, Kr and Xe, have shown Druyvesteyn-like distributions in the elastic energy range, unless strong e-e collisions at large plasma density were able to Maxwellize the EEDF. Another source of error in Langmuir probe diagnostics in Ramsauer gases is a large uncertainty in determining the plasma potential that may result in significant error in estimation of the plasma density. It has been shown [1] that the only reliable way to find basic plasma parameters in such plasmas is the EEDF measurement with plasma parameters determined as appropriate integrals of the measured EEDF. In the present work, we carried out EEDF measurements in Ar and found plasma parameters as EEDF integrals in wide ranges of pressure (1 mTorr – 1 Torr) and discharge current (3mA – 3A) in a positive column in DC discharge. The experimental results were compared with simulations based on solution of the one-dimensional electron Boltzmann equation [2] coupled with a set of equations for the plasma density and plasma potential [3]. The problems associated with EEDF measurements in DC plasmas prone to different kind of instabilities, as well as the area of the model applicability are discussed in this presentation. [1] V. Godyak, et al, J. Appl. Phys. 73, 3657 (1993). [2] D. Uhrlandt and R. Winkler, J. Phys. D 29, 115 (1996). [3] U. Kortshagen et al, Plasma Sources Sci. Tech. 5, 1 (1996).

11:15AM NR1.00005 A self-consistent view on plasma-neutral interaction near a wall: plasma acceleration by momentum removal and heating by cold walls, GERARD VAN ROOIJ, NIEK DEN HARDER, TEOFIL MINEA, AMY SHUMACK, H. DE BLANK, FOM Institute DIFFER, PLASMA PHYSICS TEAM — In plasma physics, material walls are generally regarded as perfect sinks for charged particles and their energy. A special case arises when the wall efficiently neutralizes plasma particles (with a significant portion of their kinetic energy) and at the same time the upstream plasma is of sufficiently high density to yield strong neutral-ion coupling (i.e. reflected energy and momentum will not escape from the plasma). Under these conditions, plasma-surface interaction will feedback to the upstream plasma and a self-consistent view on the coupling between plasma and neutrals is required for correct prediction of plasma conditions and plasma-surface interaction. Here, an analytical and numerical study of the fluid equations is combined with experiments (in hydrogen and argon) to construct such a self-consistent view. It shows how plasma momentum removal builds up upstream pressure and causes plasma acceleration towards the wall. It also shows how energy reflection causes plasma heating, which recycles part of the reflected power to the wall and induces additional flow acceleration due to local sound speed increase. The findings are relevant as generic textbook example and are at play in the boundary plasma of fusion devices.

11:30AM NR1.00006 Effects of Emitted Electron Temperature on the Sheath, J.P. SHEEHAM, University of Michigan - Ann Arbor — It has long been known that electron emission from a surface significantly affects the sheath surrounding that surface, reducing the sheath potential and electric field. Typical fluid theory of a planar sheath with emitted electrons assumes that the plasma electrons follow the Boltzmann relation and the emitted electrons are emitted with zero energy, predicting a potential drop of Te across the sheath when the surface is allowed to float. A one-dimensional kinetic theory of sheaths surrounding planar, electron-emitting surfaces is presented which accounts for plasma electrons lost to the surface and the temperature of the emitted electrons. It is shown that ratio of plasma electron temperature to emitted electron temperature significantly affects the sheath potential when the plasma electron temperature is within an order of magnitude of the emitted electron temperature. The sheath potential goes to zero as the plasma electron temperature equals the emitted electron temperature, which can occur in the afterglow of an rf plasma and some low-temperature plasma sources. These results were validated by particle-in-cell simulations. The theory was tested by making measurements of the sheath surrounding a thermionically emitting cathode in the afterglow of an rf plasma. The measured sheath potential shrunk to zero as the plasma electron temperature cooled to the emitted electron temperature, as predicted by the theory.

Thursday, November 6, 2014 10:00AM - 12:00PM
Session NR2 Magnetically Enhanced Plasmas State C - Jon Gudmundsson, University of Iceland

10:00AM NR2.00001 Effects of anomalous transport on magnetic filter effect, YEVGENY RAITSES, IGOR KAGANOVI ¯C, Princeton Plasma Phys Lab, ANDREI SMOLYAKOV, WINSTON FRIAS, University of Saskatchewan, Canada — The application of the magnetic field in a low pressure plasma can cause a spatial separation of cold and hot electron groups. This so-called magnetic filter effect is not well understood and the subject of on-going studies. In this work, we investigate electron and ion velocity distribution functions in a low pressure plasma discharge with crossed electric and magnetic field. Previous experimental studies showed that the increase of the magnetic field leads to a more uniform profile of the electron temperature across the magnetic field. This surprising result indicates the importance of anomalous electron transport that causes mixing of hot and cold electrons. High-speed imaging revealed a coherent rotating structure with frequency of a few kHz. Theory describing coherent rotating structures and resulting anomalous transport has been developed and points to ionization and electrostatic instabilities as their possible cause [1-3]. The rotating structure affects perturbations of the plasma and model in both azimuthal and axial direction of the plasma pinch. Preliminary results of Particle-in-Cell simulations and Laser-Induced-Fluorescence measurements showed these perturbations alter the ion velocity distribution function.

10:15AM NR2.00002 Optical diagnostics of sputtering in magnetically enhanced high-current discharges1, DAVID SMITH, STEVEN ACETO, JASON TROTTER, TIMOTHY SOMMERER, GE Research, Niskayuna, NY, JAMES LAWLER, University of Wisconsin-Madison, Madison, WI — We have investigated a gallium-based liquid cathode for use in a high-voltage, high-current plasma source for grid-scale electric power conversion. The cathode requirements include conduction of high current density (1-10 A cm−2), preferably at low voltage, along with minimal loss by evaporation and/or sputtering. The approach to satisfy these criteria has been to operate with a modified commercial magnetron system at high pressure where the choice of working comprises the light elements, such as hydrogen or helium. A separate anode is used to form a plane-parallel geometry. We have demonstrated pulsed operation with current densities exceeding 2 A cm−2 and voltages below 200 V, over a pressure range of 50-800 mTorr. The sputtering rate on gallium and other cathode materials has been estimated for various plasma conditions using a line ratio emission spectroscopy diagnostic based on analysis of the radiation trapping.

The information, data, or work presented herein was funded in part by the Advanced Research Projects Agency-Energy (ARPA-E), U.S. Department of Energy, under Award Number DE-AR0000298.

10:30AM NR2.00003 Fluctuations, instabilities and transport in Hall plasma devices, ANDREI SMOLYAKOV, University of Saskatchewan — Devices with stationary, externally applied, electric field which is perpendicular to a moderate amplitude magnetic field B0, are common in magnetically controlled plasmas. High interest applications involve Penning type plasma sources, magnetrons and magnetic filters, and electric space propulsion such as Hall thrusters. The electric field produces a stationary current due to the E0 × B0 electron drift, while ions do not feel the magnetic field due to their large Larmor radius. Standard drift modes do not exist in such plasma but the ExB electron drift in inhomogeneous plasma and inertial (non-magnetized) ion response result in the so called anti-drift mode. The equilibrium electron flow destabilizes this mode and additional destabilization may come from the gradient of the magnetic field. The electron flow also result in instabilities of negative energy ion sound modes destabilized by dissipation due to collisions and sheath impedance. Sheath impedance is a result of fluctuating electric current into the sheath and further taken over by the current in the dielectric wall. Sheath impedance provide boundary conditions for ion sound wave at the boundaries of a finite length plasma. The quantitative characteristics of these instabilities and its potential ramifications for Hall devices are described.

11:00AM NR2.00004 Magnatron Deposition Systems, JOHN FORSTER, Applied Materials —

11:30AM NR2.00005 Achievement of high atomic hydrogen densities in cylindrical rf plasmas with magnetic field, URSFL FANTZ, STEFAN BRIEFER, Max-Planck-Institut fuer Plasmaphysik — Cylindrical rf plasmas in hydrogen with and without an axial magnetic field of up to 120 G are investigated in the pressure range of 0.3 to 10 Pa. The atomic hydrogen density is determined with optical emission spectroscopy, analyzing the Balmer lines and the molecular radiation (Fulcher band). The results obtained by using different coil geometries (4 to 6 turn windings and Nagoya type antenna) as well as different diameters (10 cm and 25 cm) of a quartz, aluminum oxide or aluminum nitride cylinder are compared. RF powers of up to 600 W at a frequency of 13.56 MHz are available for the 10 cm configuration, whereas up to 70 kW power at 1 MHz are used for the 25 cm cylinder. Density ratios of atoms to molecules of up to 0.3 are achieved in both configurations, whereby the achievement in the high power setup is limited by neutral depletion. The influence of the wall material on the atomic densities, and thus the recombination coefficient, will be pointed out.

11:45AM NR2.00006 ABSTRACT WITHDRAWN —

Thursday, November 6, 2014 10:00AM - 12:00PM —
Session NR3 Heavy Particle Collisions State D - Michael Schulz, Missouri S&T

10:00AM NR3.00001 Antimatter-matter scattering including rearrangement1, ALISHER KADYROV, ARC Centre for Antimatter-Matter Studies, Curtin University, Perth, Australia — Two distinct versions of the convergent close coupling (CCC) approach to ion-atom and ion-molecule collisions have been developed in the impact parameter representation. The first method starts from the exact three-body Schrödinger equation for the total scattering wave function and leads to coupled-channel Lippmann-Schwinger type integral equations for the transition amplitudes, with the relative motion of the heavy particles treated fully quantum mechanically. The second approach utilises a traditional semi-classical approximation. It is based on the time-dependent Schrödinger equation for the electronic part of the scattering wave function and leads to a system of coupled differential equations. This allows one to test the quality of approximations used in standard approaches to the problem. Both methods are applied to calculate antiproton collisions with inert gases and simple molecular targets in the energy range from 1 keV to 1 MeV. The methods are also applied to proton collisions including rearrangement channels. Interplay of direct ionisation and electron capture to continuum in target breakup is investigated. The first CCC calculations of the antiproton and proton stopping power in atomic and molecular hydrogen are presented.

The work was supported by the Australian Research Council

10:30AM NR3.00002 Fully Differential Study of Projectile Coherence Effects in Ionization of H21, THUSITHA ARTHANAYAKA, SACHIN SHARMA, BASU LAMICHHANE, AHAMAD HASAN, JUAN REMOLINA, SUSMITHA AKULA, DON MADISON, MICHAEL SCHULZ, Missouri Univ of Sci & Tech — In recent years, the important role of the projectile coherence properties in ionization of H2 has been demonstrated in measured double differential cross sections (DDCS). Here, we report the first fully differential study of such effects. The additional kinematic information was used to further “clean” the data from any background which may have survived the coincidence condition and the results show that the observed coherence effects are not just due to an experimental artifact. Furthermore, interference effects could be studied in unprecedented detail by comparing fully differential cross sections (FDCS) for a coherent and an incoherent projectile beam. For relatively small ejected electron energies we observe pronounced single-center interference, for which the molecular structure of the target is not of primary importance. Rather, this type of interference is due to a coherent superposition of different transition amplitudes leading to the same final state. However, for larger electron energies (corresponding to a speed close to the projectile speed) clear signatures of molecular two-center interference are observed in addition to single-center interference.

1This work has been supported by NSF.
This method was extended to calculate detachment rates in air and other O
formation of vibrationally excited temporary O
ions. The reason is that the effect of resonant charge transfer in collisions between O
− ions has been theoretically studied in oxygen and O
2−N
2 mixtures. It was shown that, for a given value of the reduced electric field, the
−vacancy production, but is not sufficient to explain the data. Replacing the IEM by an independent-event model for one of the contributing
excitation-ionization processes and also taking a shake-off process into account improves the comparison with the measurements significantly.

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1This work is supported by NSERC, Canada and by OTKA, Hungary.

11:00AM NR3.00004 Signatures of the electron saddle swaps mechanism in the photon spectra following charge-exchange collisions, SEBASTIAN OTRANTO, IFISUR and Departamento de Física Universidad Nacional del Sur, Av. Alem 1253, 8000 Bahía Blanca, Argentina — During the last few years, several experimental and theoretical studies have focused on state selective charge exchange processes between charged ions and alkali metals. These data are of particular importance for the tokamak nuclear fusion reactor program, since diagnostics on the plasma usually rely on charge-exchange spectroscopy. In this sense, alkali metals, have been proposed as potential alternatives to excited hydrogen/deuterium for which laboratory experiments are not feasible at present. In this talk, we present our recent work involving ion collisions with alkali metals. Oscillatory structures in the angular differential charge-exchange cross sections obtained using the MOTRIMS technique are correctly described by classical trajectory Monte Carlo Simulations. These oscillations are found to originate from the number of swaps the electron undergoes around the projectile-target potential saddle before capture takes place and are very prominent at impact energies below 10 keV/amu. Moreover, cross sections of higher order of differentiability also indicate that the swaps leave distinctive signatures in the (n,l)-state selective cross sections and in the photon line emission cross sections. Oscillatory structures for the x-ray hardness ratio parameter are also predicted.

In collaboration with Ronnie Hoekstra, Zernike Institute for Advanced Materials, University of Groningen and Ronald Olson, Department of Physics, Missouri University of Science and Technology.

11:30AM NR3.00005 Development of Ultra-Accelerated Quantum Chemical Molecular Dynamics Method for Gaseous Electronics Applications, AKIRA MIYAMOTO, KENJI INABA, RYUJI MIURA, AI SUZUKI, NOZOMU HATAKEYAMA, Tohoku University, MASAAMI MATSUKUMA, KAZUYOSHI MATSUZAKI, Tokyo Electron Limited, TOHOKU UNIVERSITY COLLABORATION, TOKYO ELECTRON LIMITED COLLABORATION — Much attention has been given to the computational design of complex chemical dynamic processes including various solid surface reactions including gaseous electronics. For this purpose we have developed novel quantum chemical molecular dynamics method called ultra-accelerated quantum-chemical molecular dynamics (UA-QCMD) method which is around 10,000,000 times faster than the conventional first principles molecular dynamics method. In the present study we demonstrated that the quantum chemical calculation in UA-QCMD, that is Colors, has high accuracy in comparison with DFT and thermodynamic data. On the basis of high speed and high accuracy calculation of the UA-QCMD method we have confirmed that the method is effective for investigating dynamic mechanism of a variety of gaseous electronics processes including oxidation process of Si crystal with O
2, H
2O and O radical, oxidation process of Ge crystal with O radical and planarization process of Ru with the gas cluster ion beam (GCCIB). The calculated results have been demonstrated to agree well with experimental results and give detailed mechanism of these gaseous electronics reaction processes.

11:45AM NR3.00006 Electron detachment from O
2− ions in oxygen and air in a strong electric field, ALEXANDR PONOMAREV, SSC Keldysh Research Centre, Moscow, Russia, NICKOLAY ALEKSANDROV, Moscow Institute of Physics and Technology, Dolgoprudy, 141700, Russia — Electron detachment from O
2− ions have been theoretically studied in oxygen and O
2−N
2 mixtures when the ions are heated in a strong external electric field. Properties of the ions were studied by a Monte Carlo simulation technique. Collisional cross sections for ion-molecule scattering was calculated on the basis of the statistical approach for the vibrational transfer and relaxation in collisions between O
2− ions and O
2 molecules. To validate the statistical approach used, we calculated ion mobility and diffusion coefficients under conditions under which experiments are available and obtained good agreement with measurements in pure oxygen. The detachment rate was determined under the assumption that electron detachment proceeds via the shake-off process and also taking a shake-off process into account improves the comparison with the measurements significantly.

We gratefully acknowledge the support by “Deutsche Forschungsgemeinschaft” in the frame of Research Unit FOR1123 ‘Physics of Microplasmas’ and by the Research Department “Plasma with Complex Interactions”
1:45PM PR1.00002 The formation of a turbulent front in a time modulated argon APPJ1. SHIQIANG ZHANG, EDDIE VAN VELDHUIZEN, Department of Applied Physics, Eindhoven University of Technology, the Netherlands. PETER BRUGGEMAN, University of Minnesota, Department of Mechanical Engineering, 111 Church Street SE, Minneapolis, MN 55455, U.S.A., ANA SOBOTA, Department of Applied Physics, Eindhoven University of Technology, the Netherlands — Cold atmospheric pressure plasma jets (APPJ) are promising tools for biomedical applications such as wound healing, disinfection, decontamination, and material processing. The jet effluent is blown in an open air environment which leads to air diffusion and argon-air mixtures in the effluent flow. Since the reactive species carried by the flow are important in such kinds of applications, knowledge of the characteristics of the flow are crucial for understanding the distribution, evolution, transport, and chemical reactions of these reactive species. The flow dynamics of an non equilibrium argon-based atmospheric pressure plasma jet (APPJ) is investigated in this work. Shadowgraphy results show that turbulent front appears when the plasma is switched on and off and the laminar length of the flow during the plasma on phase is shorter than that during the plasma off phase. Time resolved gas temperature profiles obtained by Rayleigh scattering are used to explain the formation of the turbulent front when the plasma is switched on and off and the reduction of the length of the laminar flow.

1The funding is partly from STW

2:00PM PR1.00003 Dynamics of a Microwave Excited Microplasma Flowing into Very Low Pressures1, PENG TIAN, University of Michigan, MARC DENNING, RANDALL URDAHL, Agilent Technologies, MARK J. KUSHNER, University of Michigan — Capacitively coupled microplasmas in dielectric cavities have a range of applications from VUV sources for surface treatment to radical production. Due to the small size of these devices, pd (pressure x size) scaling requires that they operate at high pressure. When the output of the microplasma is needed at low pressure, a plume of radicals and ions flows from the higher pressure microdischarge cavity into the lower pressure workspace. These conditions affect both the delivery of the radicals, ions and photons in the plume, and the dynamics of the microdischarge. In this paper, we discuss results from a computational investigation of a microwave excited microplasma operating at a pressure of several Torr of a rare gas with powers of 2-10s of Watts at 2.5 GHz. The plume from the microdischarge cavity flows into pressures as low as a few mTorr. A 2-d plasma hydrodynamics model with radiation and electron energy transport addressed using Monte Carlo techniques has been modified to enable the plume to flow into near vacuum. Plasma dynamics and reactive fluxes from the cavity will be discussed for different flow boundary conditions, as a function of power, pressure and gas mixtures.

1Work supported by Agilent Technologies, DOE Office of Fusion Energy Science and NSF.

2:15PM PR1.00004 Interaction of High-Frequency Electromagnetic Waves with Pre-Breakdown Atmospheric Pressure Micro-Discharge Region1, ABBAS SEMNNANI, DIMITRIS PEROULIS, Purdue University — The properties of a micro-scale gap at atmospheric pressure are completely different in pre- and post-breakdown conditions. Unlike the quasi-neutral region formed after breakdown, the ion number density is orders of magnitude higher than the electron density in pre-breakdown conditions. Consequently, ions may also contribute on the discharge conductivity even though they are much heavier than electrons. In this work, we study the interaction of high frequency electromagnetic waves with the discharge region before and after breakdown. The study is done at room temperature and atmospheric pressure conditions with gaps in the order of hundreds of nanometers up to a few micrometers. Gas discharge simulations are performed by using the PIC/MCC technique while the finite difference time domain (FDTD) method is used for electromagnetic simulations. The species are imported into EM simulations by a conduction current term in Ampere’s law. The validity of conventional wisdom of ignoring the ions’ contribution is examined for different cases.

1This paper is based upon work supported by the National Science Foundation under Grant No. ECCS-1202095.

2:30PM PR1.00005 Fluid modeling of operating modes in a field emission driven alternating current (FEDAC) microdischarge, AYYASWAMY VENKATRAMAN, ARGHAVAN ALAMATSAZ, THERAZHUNDUR RAMESH SHIVAPRASAD, Univ of California - Merced — The recent interest in electrostatic microscale devices has lead to a great emphasis on electrical breakdown of gases in microgaps. The breakdown process has been shown to be significantly different from its counterpart in macrogaps with field emission of electrons from the cathode playing a major role. This work aims to build on prior work dealing with pre-breakdown and post-breakdown operating modes in direct current field emission driven (FED) microdischarges. Specifically, charged particle dynamics in microscale gaps that are driven by time-varying fields are studied using an in-house two-fluid code with appropriate cathode boundary conditions including field emission. The model includes continuity and energy equations for both electrons and ions to account for the significant non-equilibrium and is augmented by the Poisson’s equation for electrostatic potential. The frequency dependence of breakdown behavior as well as pre-breakdown and post-breakdown current-voltage characteristics is determined for a wide range of frequencies from low radio frequency (RF) to microwave and contrasted with existing results for direct current FED microdischarges. The results are also used to explain trends recently observed in an evanescent-mode cavity resonator operating in the microwave regime.

2:45PM PR1.00006 Quantum Simulation of Field Emission in Microscale Gas Discharges1, YINGJIE LI, DAVID GO, University of Notre Dame — Field emission can be a critical cathode process in microscale gas discharges, especially for electrode gaps less than 10 μm. In this work, ion-enhanced field emission is determined by solving the one-dimensional Schrödinger’s equation. In most prior work, a linear approximation for the ion potential has been coupled with the Fowler-Nordheim equation, but this does not realistically account for the form of potential barrier, and underestimates the impact of the ion’s potential well. Here, the tunneling behavior is more accurately represented by determining the wave function of the electrons inside and outside of the cathode in order to predict the emission current. Using this approach, microscale breakdown theory is revisited, in order to understand the deviation from classic breakdown theory at microscale dimensions.

1This material is based upon work supported by the Air Force Office of Scientific Research under AFOSR Award No. FA9550-11-1-0020.

Thursday, November 6, 2014 1:30PM - 3:30PM –
Session PR2 Plasma Deposition and Nanoparticle Generation
State C - Kazuo Takahashi, Kyoto Institute of Technology
1:30PM PR2.00001 Surface modifications by plasma produced nanoparticles\textsuperscript{1}. JOHANNES BERNDT, PASCAL BRAULT, GREMI UMR 7344 CNRS & Université d’Orléans — Low temperature plasmas with their distinct non equilibrium character are a versatile tool for the production and subsequent deposition of nanoparticles. This contribution will focus on two aspects: on strategies to control the formation of nanoparticles in reactive low temperature plasmas and on the production and functionalization of nanoparticle-deposits. The importance of such nanoparticle-deposits will be discussed on the basis of two examples: the production of surfaces with switchable wetting properties and the decoration of surfaces with nanoparticles for fuel cell applications.

\textsuperscript{1}The financial support of the European Commission under the FP7 Fuel Cells and Hydrogen Joint Technology Initiative grant agreement FP7-2012-JTI-FCH-325327 for the SMARTCat project is gratefully acknowledged.

1:45PM PR2.00002 Nickel Nanoparticles Production using Pulsed Laser Ablation under Pressurized CO\textsubscript{2}. MARDISANGHY MARDIS, NORIHARU TAKADA, Nagoya University, SITI MACHMUDAH, Sepuluh Nopember Institute of Technology, WAHYU DIONO, HIDEKI KANDA, Nagoya University, KOICHI SASAKI, Hokkaido University, MOTONOBU GOTO, Nagoya University — We used nickel (Ni) plate as a target and irradiated pulse laser ablation with a fundamental wavelength of 1064 nm under pressurized CO\textsubscript{2}. The Ni plate was ablated at various pressure (5–15 MPa), temperature (15–80\textdegree C), and irradiation time (3–30 min). The method successfully generated Ni nanoparticles in various shape and size. Generated Ni nanoparticles collected on a Si wafer and the ablated Ni plate were analyzed by Field Emission Scanning Electron Microscope (FE-SEM). With changing pressure and temperature, the structures of Ni nanoparticles also changed. The shape of generated particles is sphere-like structure with diameter around 10-100 nm. Also it was observed that a network structure of smaller particles was fabricated. The mechanism of nanoparticle fabrication could be explained as follows. Ablated nickel plate melted during the ablation process and larger particles formed, then ejected smaller spherical nanoparticles, which formed nanoclusters attached on the large particles. This morphology of particles was also observed for gold and silver nanoparticles with same condition. Further, the optical emission intensity from ablation plasma and the volume of the ablated craters were also examined under pressurized CO\textsubscript{2}.

2:00PM PR2.00003 Plasmas for controlling the synthesis of semiconductor nanocrystals. REBECCA ANTHONY, Department of Mechanical Engineering, Michigan State University — Recently, nonthermal plasma synthesis of opto-electronically active semiconductor nanoparticles has attracted interest. The plasma reactor is especially attractive for synthesis of some earth-abundant and nontoxic semiconductor nanocrystals (NCS), such as silicon and gallium nitride. These materials, with high melting temperatures, are more challenging to grow using the liquid-phase techniques that are successful for other materials, such as II-VI NCS. Here, plasma synthesis of high-quality NCS from these materials will be discussed, including investigations on controlling the NCS’ light emission properties via physical changes in the NCS brought about by altering the plasma parameters. For example, if the pressure of the gas mixture around the NCS and the temperature of the substrate is increased, the emission wavelength of the NCS blue shifts. This is due to the increased rate of diffusion and outgrowth of the NCS. In addition, the formation of NCS clusters can be controlled by changing the plasma parameters and the pressure of the feed gases. The plasma reactor can be used to grow high-quality NCS with controlled properties. These properties are crucial for the development of opto-electronic devices.

2:30PM PR2.00004 Novel method of Ge crystalline thin film deposition on SiO\textsubscript{2} by sputtering. MASAHARU SHIRATANI, DAIKI ICHIDA, HYUNWOONG SEO, NAHO ITAGAKI, KAZUNORI KOGA, Kyushu University — We are developing a novel method of Ge crystalline thin film deposition on SiO\textsubscript{2} by sputtering. For the method, very thin Au films were deposited on SiO\textsubscript{2} substrates and then Ge atoms were irradiated to the Au films by sputtering. By EDX and SEM measurements, we found two kinds of Ge film growth: one is Ge film formation on Au films for a high flux irradiation of Ge, and the other is Ge film formed between Au films and SiO\textsubscript{2} substrates for a relatively low flux irradiation of Ge. The latter film formation is useful to create fine Ge crystalline films on various kinds of substrate with aligned crystal orientation and a large grain size. XRD and Raman measurements show the films are Ge crystal and the better crystallinity for the higher substrate temperature. Surface morphology depends on the substrate temperature. At 180-250C Ge islands of 50 nm in diameter are formed on surface. Smooth Au films are obtained at 320C. Au aggregates of 100 nm in diameter are formed on surface at 400C. The Ge films show a high absorption coefficient for a wide light wavelength range from 400 nm to 1100 nm and photo generated current in the same wavelength range.

3:00PM PR2.00005 Surface modification due to atmospheric pressure plasma treatment during film growth of silicon dioxide like and amorphous hydrogenated carbon material. KATJA RUEGNER, RUEDIKER REUTER, ACHIM VON KEUDELL, JAN BENEDIKT, Ruhr-Uni Bochum, RD Plasmas with Complex Interactions — Plasma deposition of silicon dioxide (SiO\textsubscript{2}) or amorphous hydrogenated carbon (a-C:H) at atmospheric pressure is a promising tool for industrial applications. SiO\textsubscript{2} is used as scratch resistant layers, as protection against corrosion or as a diffusion barrier layer. a-C:H is of special interest due to its optical, electrical, biocompatible and mechanical properties, which are tunable, depending on the bonding state of carbon. Besides the deposition of material, atmospheric pressure plasma jets (APJJ) can be used to modify the surface of the deposited films during their growth. Deposition and the treatment are realized in the same chamber, were both jets face a rotating substrate. Therefore, deposition and treatment of the same trace can be performed in an alternating manner. Further, in-situ FTIR is applied. For the deposition an APPJ with two parallel electrodes is used, operating with either He/HMDSO in the case of SiO\textsubscript{2} deposition or He/H\textsubscript{2}/H\textsubscript{2}O in the case of a-C:H deposition. For the treatment either the APPJ or a coaxial jet with different gas mixtures is used. For the deposition of SiO\textsubscript{2}-like films the treatment with a H\textsubscript{2}O/2, a H\textsubscript{2}/N\textsubscript{2}, and an Ar plasma during the film growth have shown significant changes in the film structure. The influence of treatments on a-C:H film is currently under investigation.

3:30PM PR2.00006 Comparison of sticking probabilities of metal atoms in magnetron sputtering deposition of CuZnSnS films. K. SASAKI, S. KIKUCHI, Hokkaido University — In this work, we compared the sticking probabilities of Cu, Zn, and Sn atoms in magnetron sputtering deposition of CZTS films. The evaluations of the sticking probabilities were based on the temporal decays of the Cu, Zn, and Sn densities in the afterglow, which were measured by laser-induced fluorescence spectroscopy. Linear relationships were found between the discharge pressure and the lifetimes of the atom densities. According to Chantry (P. J. Chantry, J. Appl. Phys. 62, 1141 (1987)), the sticking probability is evaluated from the extrapolated lifetime at the zero pressure, which is given by \( \tau = \frac{1}{\alpha n} \) with \( \alpha \), \( n \), and \( \bar{\bar{n}} \) being the sticking probability, the ratio between the volume and the surface area of the chamber, and the mean velocity, respectively. The ratio of the extrapolated lifetimes observed experimentally was \( \tau_{Cu} : \tau_{Zn} : \tau_{Sn} = 1 : 1.3 : 1 \). This ratio coincides with the ratio of the reciprocals of their mean velocities (1/\( \tau_{Cu} \) : 1/\( \tau_{Zn} \) : 1/\( \tau_{Sn} \) = 1.00 : 1.37 : 1.01). Therefore, the present reflection result suggests that the sticking probabilities of Cu, Sn, and Zn are roughly the same.

\textsuperscript{1}Work supported by JSPS.

\textsuperscript{2}The project is supported by the German Research Foundation (DFG) in the research group FOR 1123.

\textsuperscript{3}Supported by JSPS.
Advances in plasma technology and electrochemical applications

Wednesday, November 5, 2014 1:30PM - 3:00PM
Session PR3 Coronal and HV Discharges

2:00PM PR3.00003 The role of oxygen and nitrogen metastable states in the electrical breakdown of air

John Lowke, CSIRO Materials Science and Engineering — For the initial formation of an electrical discharge in air, an electric field of approximately 25 kV/cm is required at a pressure of 1 bar, corresponding to a value of E/N of ~100 Td. E is the electric field strength and N the gas number density. Below 100 Td, there are two typical regimes: the corona breakdown and the breakdown associated with electron attachment. In the corona breakdown, negative ions are formed, which can lead to the formation of negative glow and streamers. In the breakdown associated with electron attachment, positive ions are formed, which can lead to the formation of positive column and avalanches. In both regimes, the electron density increases due to the production of electrons from the ionization of molecules.

2:15PM PR3.00004 Back corona enhanced organic film deposition inside an Atmospheric Pressure Weakly Ionized Plasma reactor

Rokibul Islam, Shuzheng Xie, Karl En gland, Patrick Pedrow, Washington State University — A grounded screen with short needle-like protrusions has been designed to generate back corona in an Atmospheric Pressure Weakly Ionized Plasma (APWIP) reactor. The grounded screen with protrusions is placed downstream at a variable gap length from an array of needles that is energized with 60 Hz high voltage. The excitation voltage is in the range 0-10kV RMS and the feed gas mixture consists of argon and acetylene. A Lecroy 9350AL 500 MHz digital oscilloscope is used to monitor the reactor voltage and current using a resistive voltage divider and a current viewing resistor, respectively. The current signal contains many positive and negative current pulses associated with corona discharge. Analysis of the current signal shows asymmetry between positive and negative corona discharge currents. Photographs show substantial back corona generated near the tips of the protrusions situated at the grounded screen. The back corona activates via bond scission acetylene radicals that are transported downstream to form a plasma-polymerized film on a substrate positioned downstream from the grounded screen. The oscilloscopes will be used to generate corona mode maps that show the nature of the corona discharge as a function of gap spacing, applied voltage and many other reactor parameters.

2:45PM PR3.00005 Fast-imaging and spectroscopic analysis of atmospheric argon streamers for large gap arc breakdown

Michael Pachulio, Francis Stefani, Roger Bengtson, Laxminarayan Raja, Univ of Texas, Austin — A non-equilibrium plasma source has been developed to assist in the low-voltage arc breakdown of large electrode gaps. The source consists of a dielectric embedded wire helically wound around a confining cylindrical quartz chamber. Annular electrodes cap the ends of the quartz chamber. An argon feed gas is used to provide a uniform environment and exhausts to ambient atmospheric conditions. A negative polarity 50 kV trigger pulse is applied to the embedded trigger wire to initiate the arc breakdown. Application of the trigger pulse produces a localized corona discharge along the inner surface of the quartz tube. The corona provides seed electrons through which streamers propagate from one of the main discharge electrode along the quartz surface until it reaches the opposite electrode to bridge the gap. Once the gap is bridged a spark over occurs and robust arc discharge is formed in the chamber volume. Fast imaging of the streamer propagation establishes its velocity in the range of ~100 km/s. Spectroscopy of the streamer discharge in atmospheric argon has been conducted and electron temperature and number density estimated from a collision radiative model. Argon spectrum is dominated by neutral argon lines in the 650-950 nm range, and singly ionized argon lines are observed in the ultra-violet to near UV (300-400 nm).

3:15PM PR2.00007 RF Magnetron Sputtering Deposited W/Ti Thin Film For Smart Window Applications

Lutfi Oksuz, Melek Kiristi, Ferhat Bozduman, Aysegul Uygun Oksuz, Suleyman Demirel University — Electrochromic (EC) devices can change reversible and persistent their optical properties in the visible region (400–800 nm) upon charge insertion/extraction according to the applied voltage. A complementary type EC is a device containing two electrochromic layers, one of which is anodically colored such as vanadium oxide (V2O5) while the other cathodically colored such as tungsten oxide (WO3) which is separated by an ionic conduction layer (electrolyte). The use of a solid electrolyte such as NaFon eliminates the need for containment of the liquid electrolyte, which simplifies the cell design, as well as improves safety and durability. In this work, the EC device was fabricated on a ITO/glass slide. The WO3–TiO2 thin film was deposited by reactive RF magnetron sputtering using a 2-in W/Ti (9:1 wt%) target with purity of 99.9% in a mixture gas of argon and oxygen. As a counter electrode layer, V2O5 film was deposited on an ITO/glass substrate using V2O5 target with the same conditions of reactive RF magnetron sputtering. Modified NaFon was used as an electrolyte to complete EC device. The transmittance spectra of the complementary EC device was measured by optical spectrophotometry when a voltage of ±3 V was applied to the EC device by computer controlled system. The surface morphology of the films was characterized by scanning electron microscopy (SEM) and atomic force microscopy (AFM) (Fig 2). The cyclic voltammetry (CV) for EC device was performed by sweeping the potential between ±3 V at a scan rate of 50 mV/s.

Thursday, November 6, 2014 1:30PM - 3:00PM
Session PR3 Coronal and HV Discharges

1:30PM PR3.00001 Temporal evolution of the electron density produced by nanosecond repetitively pulsed discharges in water vapor at atmospheric pressure

Florent Saint-C, Deanna Lacoste, EM2C laboratory, Michael Kirkpatrick, Emmanuel Odic, Supelce-E3S, Christophe Laux, EM2C laboratory — A study of plasma discharges produced by nanosecond repetitive pulses (NRP) in water vapor at 450 K and 1 atm has been performed. The plasma was generated between two point electrodes with 20-nS duration, high-voltage (0-20 kV) pulses, repeated at a frequency of 10 kHz, in the spark regime (2 mA/pulse). Atomic lines measured by optical emission spectroscopy were used to determine the electron number density in this non-equilibrium water-vapor plasma. The broadenings and shifts of the Hα line were used to determine an ionization level of about 10%. This ionization level is two orders of magnitude higher than the one obtained for similar NRP discharges in air at atmospheric pressure.

1:45PM PR3.00002 Fast-imaging and spectroscopic analysis of atmospheric argon streamers for large gap arc breakdown

Michael Pachulio, Francis Stefani, Roger Bengtson, Laxminarayan Raja, Univ of Texas, Austin — A non-equilibrium plasma source has been developed to assist in the low-voltage arc breakdown of large electrode gaps. The source consists of a dielectric embedded wire helically wound around a confining cylindrical quartz chamber. Annular electrodes cap the ends of the quartz chamber. An argon feed gas is used to provide a uniform environment and exhausts to ambient atmospheric conditions. A negative polarity 50 kV trigger pulse is applied to the embedded trigger wire to initiate the arc breakdown. Application of the trigger pulse produces a localized corona discharge along the inner surface of the quartz tube. The corona provides seed electrons through which streamers propagate from one of the main discharge electrode along the quartz surface until it reaches the opposite electrode to bridge the gap. Once the gap is bridged a spark over occurs and robust arc discharge is formed in the chamber volume. Fast imaging of the streamer propagation establishes its velocity in the range of ~100 km/s. Spectroscopy of the streamer discharge in atmospheric argon has been conducted and electron temperature and number density estimated from a collision radiative model. Argon spectrum is dominated by neutral argon lines in the 650-950 nm range, and singly ionized argon lines are observed in the ultra-violet to near UV (300-400 nm).

3Research was performed in connection with AFOSR contract FA9550-11-1-0062.
2:30PM PR3.00005 Plasma decay in O₂-containing mixtures after high-voltage nanosecond discharge, NICKOLAY ALEKSANDROV, EUGENY ANOKHIN, SVETLANA KINDYSHEVA, Moscow Institute of Physics and Technology, Dolgoprudny, Russia, ANDREY STARIKOVSKIY, Princeton University, Princeton, USA — Plasma decay after a high-voltage nanosecond discharge has been studied experimentally and numerically in O₂:Ar, O₂:CO₂ and some other mixtures for room gas temperature and pressures between 1 and 10 Torr. Time-resolved electron density history was measured by a microwave interferometer for initial electron densities in the range (1-3) × 10¹² cm⁻³ and the effective electron-ion recombination coefficient was determined. A numerical simulation was carried out to describe the temporal evolution of the densities of charged particles under the conditions considered. The balance equations for these particles were solved simultaneously with the equation for electron effective temperature. It was shown that the loss of electrons in this case is determined by dissociative and three-body electron recombination with O²⁺ ions. The rate coefficient of three-body electron recombination was determined for these molecular ions. When changing gaseous mixture composition, the frequency of electron energy relaxation was varied by many orders of magnitude. This allowed extracting the values of three-body electron-ion recombination for both thermalized and heated electrons.

2:45PM PR3.00006 NO density and gas temperature measurements in atmospheric pressure nanosecond repetitively pulsed (NRP) discharges by Mid-IR QCLAS¹, MARIEN SIMENI SIMENI, GABI-DANIEL STANCU, CHRISTOPHE LAUX, Laboratory EM2C, Ecole Centrale Paris — Nitric oxide is a key species for many processes: in combustion, in human skin physiology... Recently, NO-ground state absolute density measurements produced by atmospheric pressure NRP discharges were carried out in air as a function of the discharge parameters, using Quantum Cascade Laser Absorption Spectroscopy. These measurements were space averaged and performed in the post-discharge region in a large gas volume. Here we present radial profiles of NO density and temperature measured directly in the discharge for different configurations. Small plasma volume and species densities, high temperature and EM noise environment make the absorption diagnostic challenging. For this purpose the QCLAS sensitivity was improved using a two-detector system. We conducted lateral absorbance measurements with a spatial resolution of 300µm for two absorption features at 1900.076 and 1900.517 cm⁻¹. The radial temperature and NO density distributions were obtained from the Abel inverted lateral measurements. Time averaged NO densities of about 1.16 cm⁻³ and gas temperature of about 1000K were obtained in the center of the discharge.

¹PLASMAFLAME project (Grant No ANR-11-BS09-0025 )

Thursday, November 6, 2014 3:30PM - 5:30PM –
Session QR1 Plasma Modeling and Simulations II

3:30PM QR1.00001 RF plasma conductivity in the CERN Linac4 H⁻ ion source, comparison of simulations and measurements, STEFANO MATTEI, CERN, 1211 Geneva 23, Switzerland, SHINTARO MOCHIZUKI, KENJIRO NISHIDA, TAKANORI SHIBATA, Graduate school of Science and Technology, Keio University, 3-14-1 Hiyoshi, Kouhoku-ku, Yokohama 223-8522, Japan, JACQUES LETTRY, CERN, 1211 Geneva 23, Switzerland, AKIYOSHI HAYASHI, Graduate school of Science and Technology, Keio University, 3-14-1 Hiyoshi, Kouhoku-ku, Yokohama 223-8522, Japan, MINH QUANG TRAN, Centre de Recherches en Physique des Plasmas, Ecole Polytechnique Federale de Lausanne, CH-1015 Lausanne, Switzerland — CERN Linac 4 H⁻ ion source is a Radio Frequency Inductively Coupled Plasma (RF-ICP) ion source. A solenoid antenna of 4 to 6 turns heats the plasma at a frequency of 2 MHz, in pulses of 0.5 ms and with a repetition rate of 0.8 to 2 Hz. In order to investigate the underlying plasma physics we have developed a Particle-In-Cell Monte Carlo Collision (PIC-MCC) code with the long-term goal to optimize the ion source operational parameters and geometry. This paper presents the determination of the complex plasma conductivity based on the PIC-MCC simulations. The resistive and reactive components of the plasma conductivity are computed as the proportionality factor between the RF electric field and the resulting plasma current. We present a parametric investigation as a function of the antenna current, gas pressure and antenna geometry. The simulation results, corresponding to the Linac 4 ion source, are compared to the time-resolved optical emission photometry measurements of the Balmer lines obtained on a dedicated ion source test stand.

3:45PM QR1.00002 A Fast Four Fluid Model of Electronegative Plasmas Including Non-Isothermal Neutrals¹, ANDREW HURLBATT, TIMO GANS, DEBORAH O'CONNELL, York Plasma Institute, Department of Physics, University of York, Heslington, York, YO10 5DD — A novel semi-analytical fluid model has been developed of a four component plasma consisting of positive ions, negative ions, non-maxwellian electrons and non-thermal neutrals. The four dominant interspecies reactions are considered, as well as elastic collisions between charged and neutral species. The model is based on an idealised RF discharge with an infinite planar geometry, and provides time averaged spatial profiles of species densities and fluxes, as well as neutral gas temperature, within the plasma bulk and presheath. Due to the combination of boundary conditions and normalisations, only the mean electron energy and the relative electron density are required as input parameters. The pressure length product of the system is given as an output, meaning the model can be scaled to any plasma discharge sharing geometrical characteristics. Despite the increased complexity and reduced assumptions compared with other similar electronegative models, analyticity is maintained until the point of spatial integration. This means the computation time is on the order of seconds, allowing the detailed investigation of discharge properties on phenomena such as Neutral Gas Depletion and electronegative to electropositive transitions over large regions of parameter space.

¹EPSRC EP/K018838/1

4:00PM QR1.00003 Uncertainty and error in complex plasma chemistry models, MILES TURNER, Dublin City University — Plasma chemistry models commonly contain hundreds if not thousands of parameters, in the way of rate constants and other related coefficients. None of these parameters is exactly known. Moreover, in modern models, the parameters have often been transmitted from the primary data sources by complex and error prone routes. Consequently, typical plasma chemistry models embody unavoidable uncertainty, because of inexact knowledge of the parameters, and some margin of avoidable error, because of faulty transmission. This paper discusses a model for helium/oxygen mixtures (a moderately complex model with some 350 reactions), in which all the the rate constants have been traced to primary sources, with the initial aim of determining the uncertainty associated with each parameter. This data is then used in a Monte Carlo procedure to investigate the resulting uncertainty in the model predictions. Uncertainty is found to be unequally distributed across the model outputs, but for some results it is a factor of several or more. This certainly needs to be considered when comparing model calculations with experiments, or deciding whether conclusions drawn from the model predictions are robust. The process of tracing the sources for the rate constants shows that some of them have been polluted by various types of error. Some examples will be discussed.
4:15PM QR1.00004 Development, Verification and Validation of VizArc: a General-Purpose Thermal Plasma Simulation Tool. SHANKAR MAHADEVAN, DOUG BREDEN, Esgee Technologies Inc., LAXMINARAYAN RAJA, The University of Texas at Austin — This work describes a recently developed general-purpose simulation tool (VizArc) for computational modeling of thermal plasmas. These plasmas typically exist in systems where the pressures range from 0.1-10 atm and with temperatures ranging from about 1000 K to ~10,000 K. VizArc solves a coupled set of non-linear governing equations that describe physical and chemical phenomena in multi-species, single-temperature, quasi-neutral plasma. Governing equations for the flow and electromagnetic quantities in the gas and heat transfer in solids are included. Applications include the modeling of spark discharges, HID lamps, circuit breakers and welding/spray coating. Verification and validation, which are essential aspects of computational code development, are discussed. The simulation model is validated with the results of recent experimental measurements of power coupling to the plasma inside the bottle and thus the electromagnetic wave propagation along the plasmaline. In this contribution, we present a detailed dispersion analysis based on an analytical approach. We study how modes of guided waves are propagating under different conditions (if at all). The analytical results are supported by a series of self-consistent numerical simulations of the plasmaline and the plasma.

4:30PM QR1.00005 An Analytical Study of the Mode Propagation along the Plasmaline. DANIEL SZELEMELY, RALF PETER BRINKMANN, THOMAS MUSSENBROCK, DENIS EREMIN, None, THEORETICAL ELECTRICAL ENGINEERING TEAM — The market shows in recent years a growing demand for bottles made of polyethylene terephthalate (PET). Therefore, fast and efficient sterilization processes as well as barrier coatings to decrease gas permeation are required. A specialized microwave plasma source — referred to as the plasmaline — has been developed to allow for treatment of the inner surface of such PET bottles. The plasmaline is a coaxial waveguide combined with a gas-inlet which is inserted into the empty bottle and initiates a reactive plasma. To optimize and control the different surface processes, it is essential to fully understand the microwave power coupling to the plasma inside the bottle and thus the electromagnetic wave propagation along the plasmaline. In this contribution, we present a detailed dispersion analysis based on an analytical approach. We study how modes of guided waves are propagating under different conditions (if at all). The analytical results are supported by a series of self-consistent numerical simulations of the plasmaline and the plasma.

5:00PM QR1.00007 Electron acceleration due to the two-stream instability of ion and electron beams propagating in background plasma. IGOR KAGANOVICH, Princeton Plasma Phys Lab, DMYTRO SYDORENKO, Department of Physics, University of Alberta, Canada — Intense electron or ion beams propagating in plasmas are subject to the two-stream instability, which leads to a slowing down of the beam particles, acceleration of the plasma particles, and transfer of the beam energy to the plasma particles and wave excitations. Making use of the particle-in-cell codes EDIPIC and LSP, we have simulated two-stream instability interactions over a wide range of beam and plasma parameters. Typically, the instability saturates due to nonlinear wave-trapping effects of either the beam particles or plasma electrons. The saturation due to nonlinear wave-trapping effects limits the “mixing” in phase-space and may produce coherent structures in the electron velocity distribution function. For the case of an electron beam, simulations show that the two-stream instability is intermittent, with quiet and active periods. During the active periods of the two-stream instability, the beam interacts with the plasma most intensively at locations where the global frequency of the instability matches the local electron plasma frequency. These intense localized plasma oscillations produce peaks in the velocity distribution function similar to the ones measured in the experiment [1].

5:15PM QR1.00008 Transport and radiation in complex LTE mixtures. JESPER JANSSEN, Eindhoven University of Technology, KIM PEERENBOOM, Université libre de Bruxelles, JOS SUUKER, Philips Lighting, MYKHAIOLO GNYBIDA, Eaton European Innovation Center, JAN VAN DIJK, Eindhoven University of Technology — Complex LTE mixtures are for example encountered in re-entry, welding, spraying and lighting. These mixtures typically contain a rich chemistry in combination with large temperature gradients. LTE conditions are also interesting because they can aid in the validation of NLTE algorithms. An example is the calculation of transport properties. In this work a mercury free high intensity discharge lamp is considered. The investigation focusses on using salts like Inl or Snl as a buffer species. By using these species a dominant background gas like mercury is no longer present. As a consequence the diffusion algorithms based on Fick’s law are no longer applicable and the Stefan-Maxwell equations must be solved. This system of equations is modified with conservation rules to set a coldspot pressure for saturated species and enforce the mass dosage for unsaturated species. The radiative energy transport is taken into account by raytracing. Quantum mechanical simulations have been used to calculate the potential curves and the transition dipole moments for indium with iodine and tin with iodine. The results of these calculations have been used to predict the quasistatic broadening by iodine.

Thursday, November 6, 2014 3:30PM - 5:00PM –
Session QR2 Plasma Applications in Accelerator Technology
State C - Keith Cartwright, Sandia National Laboratory

3:30PM QR2.00001 The Grand Challenges for Engineering in the 21st. THOMAS KATSOLLEAS, Dean, Duke Pratt School of Engineering — The Grand Challenges for Engineering in the 21st century identified by the NAE re-frame the engineering profession in human facing terms rather than in terms of disciplines or devices. Nevertheless, plasmas will play a major role in solving many of these challenges. The challenges involve making the world more sustainable, more healthful, more secure and more joyful. From the challenge of Provide Clean Water (to nearly a billion people who lack regular access to it), to Provide Energy from Fusion and Engineer the Tools of Scientific Discovery, plasmas will play an essential role. This talk highlights progress on the NAE Grand Challenges and the role that plasmas are playing in addressing them. Particular attention will be given to plasma-based particle accelerators and the question of whether they really offer a path to smaller, cheaper accelerators that could impact human health through cancer therapies or enable new discoveries at the high energy frontier.
4:00PM QR2.00002 Gaseous Electronics Phenomena in Particle Accelerators\textsuperscript{1}, SVETOZAR POPOVIC, Old Dominion University, Physics Department, Center for Accelerator Science — The work is motivated by the development of new compact superconducting RF (SRF) accelerating structures that are capable of producing gradients in excess of 100 MV/m. Compact accelerators and accelerator-based light sources are currently expected to have numerous applications ranging from use in medicine to high-energy physics. However, they require more compact accelerating cavities and components for beam control. Developing and operation of compact particle accelerators involve a multitude of concepts that are analogue to those developed in the traditional disciplines of gaseous electronics. Non-planar, asymmetric superconductor surface treatment using radiofrequency discharges applies techniques that are analogue to those used in the development of planar micro- and nano-electronic devices, although performed on much larger and curved surfaces. During operation, compact particle accelerators behave as pulsed power devices. Just as in the pulsed power devices, it has been reported that all compact concepts are inclined to support the field emission and the multipactor effects that, in turn, limit their range of operation. Multipactor discharge presents a major boulder in the development of compact accelerators and light sources. Multipactor is a resonant discharge generated by the RF field where the growth in the electron density is sustained by secondary emission from cavity walls driven by the RF power that is used for particle acceleration. If more than one electron is emitted for each primary electron, the rate of electron density growth could become high enough to dissipate a significant fraction of the RF power inside the cavity before the saturation due to space-charge or other effects sets in. Using the archived data collection on the performance tests of SRF accelerator components, we identify the relevant gaseous electronics phenomena and their mechanisms. We also review the efforts on mitigation of detrimental effects.

\textsuperscript{1}Supported by DOE under grant No. DE-SC0007879.

4:30PM QR2.00003 Uniform Plasma Etching of Complex Shaped Three Dimensional Niobium Structures for Particle Accelerators\textsuperscript{1}, JANARDAN UPADHYAY, DO IM, JEREMY PESHLE, SVETOZAR POPOVIC, LEPSHA VUSKOVIC, Old Dominion University, LARRY PHILLIPS, ANNE-MARIE VALENTE-FELLICIANO, Jefferson Lab — Complex shaped three dimensional niobium structures are used in particle accelerators as superconductive structures to conduct radio frequency (SRF) cavities. The inner surfaces of these structures have to be chemically etched for better performance, as SRF performance parameters are very sensitive to their properties. Plasma etching of inner surface of three dimensional niobium structures has not been reported even though plasma etching of niobium has been reported earlier for Josephson junction and other applications. We are proposing an RF capacitively coupled coaxial (ccp) plasma etching method for nano machining of niobium structures for SRF applications. We are using gas mixture of Argon and Chlorine. We report the effects of the pressure, RF power, gas concentration, shape and size of the inner electrode, temperature of the structure, DC bias voltage and residence time on the etch rate of the niobium. We also show the method to reduce the asymmetry effect in coaxial ccp by changing the shape of the inner electrode in cylindrical structure, as well as a method to overcome the severe loading effect in etching of 3D structures for uniform mass removal purpose.

\textsuperscript{1}Supported by DOE under grant no. DE-SC0007879. JU acknowledges support by JSA/DOE via DE-AC05-06OR23177.

4:45PM QR2.00004 ABSTRACT WITHDRAWN –

Thursday, November 6, 2014 3:30PM - 5:30PM –
Session QR3 Collisions Involving Antimatter Particles and Atoms State D - Ugo Ancarani, Universite de Lorraine

3:30PM QR3.00001 Positron Annihilation as a Probe of Intramolecular Vibrational Energy Redistribution (IVR)\textsuperscript{1}, J.R. DANIELSON\textsuperscript{2}, University of California, San Diego — Experiments at incident energies in the range of the molecular vibrations show that positrons can attach to molecules via vibrational Feshbach resonances.\textsuperscript{\textsuperscript{3}} While attached, the positron has an increased probability of annihilation, leading to an enhancement of the measured annihilation rate. This enhancement is limited because the vibrational auto-detachment rate is typically much faster than the annihilation time, meaning that most positrons escape before annihilating. However, in many molecules, intramolecular vibrational energy redistribution (IVR) couples the entrance mode energy into nearly isoenergetic multimode states. This process leads to either suppression or enhancement of the annihilation depending on whether the auto-detachment rate of the coupled vibrations is faster or slower than that of the entrance mode. These effects have recently been combined into a simplified rate-equation model which describes the effect of IVR on the measured annihilation rates.\textsuperscript{\textsuperscript{4}} With certain approximations, the primary unknown in the model is the IVR coupling rate. This model will be described and used to show how observations of annihilation enhancement or suppression can be used to extract an estimate of the IVR coupling rate for selected modes in several small molecules.

\textsuperscript{1}This work was supported by NSF grant PHY 10-68023.

\textsuperscript{2}In collaboration with M. R. Natisin, A. C. L. Jones, and C. M. Surko.

\textsuperscript{3}G. F. Grilakin, et al., Rev. Mod. Phys. 82, 2557 (2010).


4:00PM QR3.00002 Total cross sections for positron scattering from the noble gases\textsuperscript{1}, ROBERT MCEACHRAN, Australian National University, ALLAN STAUFFER, York University — Our complex, relativistic optical potential method for the elastic scattering of electrons and positrons from atoms includes the effects of excitation and ionization of the target and thus produces elastic cross sections more accurately than using a purely real potential. We have used this method to calculate differential and integrated cross sections for scattering of electrons and positrons from the noble gases. Recently, we have included a simplified form of positronium formation in our formulation, resulting in very good agreement with experimental cross sections for positron scattering from the heavy noble gases at energies where positronium formation is important.\textsuperscript{1} Since our method now produces results for total scattering cross sections (i.e. including contributions from elastic, excitation and ionization scattering as well as positronium formation) we can compare the results from our calculations with recent measurements of this quantity. Detailed comparisons will be made at energies above the positronium formation threshold which is the inelastic channel with the lowest energy threshold in positron scattering from the noble gases.

4:15PM QR3.00003 Collisions and Transport in Antihydrogen Physics. MICHAEL CHARLTON, Swansea University — It has been possible for more than a decade to form antihydrogen atoms by the controlled mixing of antiprotons and positrons held in arrangements of charged particle traps [1]. More recently, magnetic minimum neutral atom traps have been superimposed upon the anti-atom production region, promoting the trapping of a small quantity of the antihydrogen yield [2-4] and first facilitating experiments [5]. We will describe some of the collision and plasma/transport physics that underpin these achievements, including a discussion of topical issues.


4:45PM QR3.00004 B-spline R-matrix with pseudostates calculations for electron collisions with atomic nitrogen1, YANG WANG, Harbin Institute of Technology, OLEG ZATSARINNY, KLAUS BARTSCHAT, Drake University — The B-spline R-matrix (BSR) with pseudostates method [1] is employed to treat electron collisions with nitrogen atoms. Predictions for elastic scattering, excitation, and ionization are presented for incident energies between threshold and about 100 eV. The largest scattering model included 690 coupled states, most of which were pseudostates that simulate the effect of the high-lying Rydberg spectrum and, most importantly, the ionization continuum on the results for transitions between the discrete physical states of interest. Similar to our recent work on e-C collisions [2], this effect is particularly strong at “intermediate” incident energies of a few times the ionization threshold. Predictions from a number of collision models will be compared with each other and the very limited information currently available in the literature. Estimates for ionization cross sections will also be provided.


This work was supported by the China Scholarship Council (Y.W.) and the United States National Science Foundation under grants PHY-1068140, PHY-1212450, and the XSEDE allocation PHY-090031 (OZ and KB).

5:00PM QR3.00005 Calculation of the polarization fraction and electron-impact excitation cross section for the Cd$^+$ (5p)$^2$P$_{3/2}$ state1, CHRISTOPHER J. BOSTOCK, DMITRY V. FURSA, IGOR BRAY, Curtin University, KLAUS BARTSCHAT, Drake University — We present fully relativistic convergent close-coupling and semirelativistic Breit-Pauli -matrix calculations of the integrated cross section and the polarization fraction for electron-impact excitation of the (5s)$^2$S$_{1/2}$ $\rightarrow$ (5p)$^2$P$_{3/2}$ transition in Cd$^+$. Above 30 eV, the polarization fraction results are in agreement with earlier RDW calculations [1], but in disagreement with measurements [2], particularly above 60 eV. Cascade contributions and hyperfine depolarization are found to have a negligible effect on the polarization fraction but have a significant effect on the predicted cross section. We also find that the cross section over the entire energy range scales in proportion to the optical oscillator strength of the target model. This is an important generalization of Kim’s f-scaling idea [3], since it does not require an ad-hoc shift of plane-wave Born results in the intermediate energy regime.


Work supported by the Australian Research Council and the United States National Science Foundation.

5:15PM QR3.00006 Effect of Charge Distribution in Out-of-Plane Structure for Excitation-Ionization Collisions. A.L. HARRIS, T.P. ESPOSITO, Illinois State University — We present fully differential cross sections (FDCS) for electron-impact excitation-ionization of helium when the ionized electron is found outside of the scattering plane. Using our 4-Body Distorted Wave and First Born Approximation models, we show that the shape of the FDCS is largely due to the charge distribution of the He$^+$ ion in the final state. We also examine the effects of electron correlation in the target helium atom, and the effects of the projectile interactions with the target.

Friday, November 7, 2014 8:30AM - 10:30AM — Session SF1 Plasma Sources — State EF - Julian Schulze, West Virginia University

8:30AM SF1.00001 EED$^f$ and IED$^f$ of the non-ambipolar e$^-$-beam plasma and their effects on etch. LEE CHEN, Tokyo Electron America, Inc. — The control of electron shading is crucial in achieving the super-high aspect ratio contact (HARC); precise ion-energy control is essential in the selective etching of lamella diblock copolymers to develop the nano-lines for Direct Self Assembly (DSA). The plasma EED$^f$ not only determines the chemistry but also dictates the shading level of the features. The above processes are presented as examples to illustrate the effects of EED$^f$ and the surgical surface-excitation by a controlled IED$^f$. In addition to demonstrating the methods of achieving a prescribed IED$^f$ through external bias, the properties of the non-ambipolar electron plasma (NEP) will be presented. NEP is heated by the non-ambipolar beam-current density in the range of 10s Acm$^{-2}$ through beam-plasma instabilities. Its IED$^f$ has a Maxwellian bulk followed by a broad energy-continuum connecting to the most energetic group with energies above the beam-energy and such EED$^f$ seems consistent with that required for deep-contact etching. The remnant of the injected electron-beam power terminates at the NEP end-boundary (i.e., wafer) could set up a controllable DC sheath potential resulting in mono-energetic surface excitation by the charge-neutral plasma beam without the application of external bias.

In collaboration with Zhiying Chen, Tokyo Electron America, Inc., Austin, TX 78741.

9:00AM SF1.00002 ABSTRACT WITHDRAWN —
9:15AM SF1.00003 Prevention of ion flux inhomogeneities in large area capacitively coupled discharges via the Electrical Asymmetry Effect, EDMUND SCHUENGEL, JULIAN SCHULZE, Department of Physics, West Virginia University, Morgantown, WV 26506, SEBASTIAN MOHR, UWE CZARNETZKI, Institute for Plasma and Atomic Physics, Ruhr-University Bochum, Germany. For large area processing applications of capacitively coupled radio frequency (CCRF) discharges, the lateral uniformity of the plasma surface interaction is crucially important. The benefit of an increase in the plasma density and, therefore, in the overall deposition rate by driving the discharge at higher frequencies is accompanied with inhomogeneities caused by the presence of electromagnetic effects. Here, we propose a method based on the Electrical Asymmetry Effect (EAE) to prevent such inhomogeneities. Spatially resolved measurements of the ion flux onto the grounded electrode of a CCRF discharge operated in hydrogen show a standing wave pattern in a 81.36 MHz single-frequency discharge, strongly reducing the ion flux uniformity. However, applying a dual-frequency voltage waveform consisting of 40.68 MHz + 81.36 MHz, the lateral distribution of the ion flux can be controlled via the phase angle between the two applied harmonics. Using the EAE, a phase angle dependent DC self-bias develops in the geometrically symmetric discharge. Tuning the phase angle allows for the compensation of ion flux inhomogeneities due to the standing wave effect. Thus, a high and laterally uniform ion flux can be generated in electrically asymmetric high frequency plasmas.

1Funding by the German Federal Ministry for the Environment, Nature conservation, and Nuclear Safety (0325210B) is gratefully acknowledged.

9:30AM SF1.00004 Transient response of pulsed multi-source RF CCP discharges, THERESA KUMMERER, DAVID PETERSON, North Carolina State University; DAVID COUMOU, MKS Instruments, STEVEN SHANNON, North Carolina State University. The electrical response of a pulsed RF CCP discharge with a second CW power source is studied within the kHz timescale of a typical pulsed system. This response is compared to plasma parameters such as sheath thickness, electron density, electron temperature, and optical emission to elucidate trends with respect to operating condition. Several regions within the pulse cycle with characteristic decay constants and saturation points have been identified using voltage, current, and phase measurements from the CW powered electrode. These trends are compared to global plasma parameters measured using Langmuir probe, hairpin resonators, spectroscopy, and high time resolution in-line RF metrology. These observed transient regions have a dependence on pressure, relative power levels, pulse frequency, and gas composition. Data was taken using argon and argon-oxygen plasmas with pulsing plurality of frequency configurations where one generator is pulsed while the other maintains constant power output. The goal of this study is to parameterize conditions for active power delivery control in advanced multi-source RF systems that utilize pulsing on one or more of their power supplies.

9:45AM SF1.00005 Etching of photoresist with an atmospheric pressure plasma jet, ANDREW WEST, York Plasma Institute, University of York, UK; MARC VAN DER SCHANS, Eindhoven University of Technology, The Netherlands; CIGANG XU, Oxford Instruments Plasma Technology, UK; ERIK WAGENAARS, York Plasma Institute, University of York, UK. Low-pressure oxygen plasmas are commonly used in semiconductor industry for removing photoresist from the surface of processed wafers; a process known as plasma ashing or plasma stripping. The possible use of atmospheric-pressure plasmas instead of low-pressure ones for plasma ashing is attractive from the point of view of reduction in equipment costs and processing time. We present experiments to study residence time effects on the etching of photoresist using a plasma jet (APPJ) in helium gas with oxygen admixtures driven by radio-frequency power. In these experiments, the neutral, radical rich effluent of the APPJ is used for etching, avoiding direct contact between the active plasma and the sensitive wafer, while maintaining a high etch rate. Photoresist etch rates and etch quality are measured for a range of plasma operating parameters such as power input, driving frequency, flow rate and wafer temperature. Etch rates of up to 10 micron/min were achieved with modest input power (45 W) and gas flow rate (10 slm). Fourier Transform Infrared (FTIR) spectroscopy showed that the quality of the photoresist removal was comparable to traditional plasma ashing techniques.

1This work was supported through the UK Engineering and Physical Sciences Research Council grant EP/K018388/1.

10:00AM SF1.00006 Development and characterization of a fast neutral beam source for damage-free etching, MARK BOWDEN, University of Liverpool, DANII MARINOV, ADETOKUNBO AYILARAN, NICHOLAS BRAITHWAITE, The Open University. ΖIAD EL OTELL, IMEC — Etching with energetic neutral beams is a promising technology for next generation sub-10 nm device fabrication. In this study a fast neutral beam has been produced by accelerating, extracting and neutralizing positive and negative ions from different phases of a pulsed discharge. A cylindrical, inductively coupled plasma (ICP) was excited between two planar disk-electrodes in mixtures of SF6 and O2 at about 20 mTorr. The discharge was pulsed at 2 kHz and 50% duty cycle. The extraction electrode was a 10 mm thick carbon plate (or a 0.8 mm steel plate) with an array of 1 mm holes, held at ground potential. Ions grazing the sides of the extraction holes incidence have a high probability (70-95%) of neutralization. The electrically asymmetric high frequency plasma surface interaction is crucially important. The benefit of an increase in the plasma density and, therefore, in the overall deposition rate by driving the discharge at higher frequencies is accompanied with inhomogeneities caused by the presence of electromagnetic effects. Here, we propose a method based on the Electrical Asymmetry Effect (EAE) to prevent such inhomogeneities. Spatially resolved measurements of the ion flux onto the grounded electrode of a CCRF discharge operated in hydrogen show a standing wave pattern in a 81.36 MHz single-frequency discharge, strongly reducing the ion flux uniformity. However, applying a dual-frequency voltage waveform consisting of 40.68 MHz + 81.36 MHz, the lateral distribution of the ion flux can be controlled via the phase angle between the two applied harmonics. Using the EAE, a phase angle dependent DC self-bias develops in the geometrically symmetric discharge. Tuning the phase angle allows for the compensation of ion flux inhomogeneities due to the standing wave effect. Thus, a high and laterally uniform ion flux can be generated in electrically asymmetric high frequency plasmas.

1Funding by the German Federal Ministry for the Environment, Nature conservation, and Nuclear Safety (0325210B) is gratefully acknowledged.

10:15AM SF1.00007 Hysteresis in Radio-Frequency Inductively Coupled Plasmas, HYO-CHANG LEE, CHIN-WOOK CHUNG, Hanyang University. We present both experimental and theoretical studies of hysteresis in radio-frequency inductive discharges. It is found that the hysteresis is significantly affected by nonlinearity of the plasma with the modification of electron energy distribution (EED). This kind of hysteresis is also observed in various plasma discharges with powers, pressures, and magnetic field where EEDs are evolved.
Experimental Characterization of Magnetogasdynamic Phenomena in Ultra-High Velocity Pulsed Plasma Jets

KEITH LOEBNER, BENJAMIN WANG, MARK CAPPPELLI, Stanford University

The formation and propagation of high velocity plasma jets in a pulsed, coaxial, deflagration-type discharge is examined experimentally. A sensitive, miniaturized, immersed probe array is used to map out magnetic flux density and associated radial current density as a function of time and axial position. This array is also used to probe the magnetic field gradient across the exit of the accelerator and in the jet formation region. Sensitive interferometry via a continuous-wave helium-neon laser source is used to probe the structure of the plasma jet over multiple chords and axial locations. A two-dimensional plasma density gradient profile at an instant in time during jet formation is compiled via Shack-Hartmann wavefront sensor analysis. The qualitative characteristics of rarefaction and/or shock wave formation as a function of chamber back-pressure is examined via fast-framing ICCD imaging. These measurements are compared to existing results of MHD simulations of the coaxial deflagration accelerator and the ensuing rarefaction jet that is expelled from the electrode assembly. The physical mechanisms governing the behavior of the discharge and the formation of these high energy density plasma jets are proposed and validated against both theoretical models and numerically simulated behavior.

This research was conducted with Government support under and awarded by DoD, Air Force Office of Scientific Research, National Defense Science and Engineering Graduate (NDSEG) Fellowship, 32 CFR 168a

Plasma diagnostics of non-equilibrium atmospheric plasma jets

ALEXEY SHASHURIN, DAVID SCOTT, MICHAEL KEIDAR, The George Washington University, MIKHAIL SHNEIDER, Princeton University

Intensive development and biomedical application of non-equilibrium atmospheric plasma jet (NEAPJ) facilitates rapid growth of the plasma medicine field. The NEAPJ facility utilized at the George Washington University (GWU) demonstrated efficacy for treatment of various cancer types (lung, bladder, breast, head, neck, brain and skin). In this work we review advances of the research conducted at GWU concerned with the development of NEAPJ diagnostics including Rayleigh Microwave Scattering setup, method of streamer scattering on DC potential, Rogowski coils, ICCD camera and optical emission spectroscopy. These tools allow conducting temporally-resolved measurements of plasma density, electrical potential, charge and size of the streamer head, electrical currents flowing through the jet, ionization front propagation speed etc. Transient dynamics of plasma and discharge parameters will be considered and physical processes involved in the discharge will be analyzed including streamer breakdown, coupling of the streamer tip with discharge electrodes, factors determining NEAPJ length, cross-sectional shape and propagation path etc.

Dynamic Contraction of the Positive Column of a Self-Sustained Glow Discharge in Molecular Gas Flow

MIKHAIL SHNEIDER, Princeton University

Contraction of the positive column of a self-sustained glow discharge in molecular gas, Physica of Plasmas 19, 033512 (2012)


Pulsed laser measurement of temperature and conductivity of a decaying arc channel

PATRICK STOLLER, EMMANOULI PANOUSIS, JAN CARSTENSEN, VALERIA TEPPATI, ABB Switzerland Ltd.

When a high voltage circuit breaker interrupts alternating current, the arc established between its contacts is axially blown by a transonic gas flow until it is extinguished at a current-zero crossing. Improvement of circuit breaker design to achieve higher short circuit current ratings or more compact equipment relies on an understanding of the processes involved in cooling and interruption of the arc. At present, current, voltage, and pressure measurements together with CFD simulations give only limited insight into how the arc is cooled—mainly via convection and radiation—and finally is interrupted via turbulent mixing. Measurement of the density, temperature, and conductivity of the arc embedded in a gas flow would permit validation of the CFD simulations and allow direct quantitative determination of important parameters such as the arc and boundary layer width and temperature. We have developed a Speckle imaging technique that permits determination of these parameters via measurement of the refractive index. A pulsed, nanosecond laser is used to interrogate the arc and surrounding flow. The short pulse length permits visualization of turbulent flow features and prevents smearing of time varying features of the flow and the arc that may occur if a continuous wave laser is used. We present and compare to CFD simulations measurements of the temperature, density, and conductivity of axially blown arcs. Based on these results we examine the dependence of the arc width on blowing conditions.

Pseudo-continuous meter-scale microwave plasma production under atmospheric pressure

HIROTAKA TOYODA, HARUKA SUZUKI, SUGURU NAKANO, Nagoya University, HITOSHI ITOH, Tokyo Electron Ltd., MAKOTO SEKINE, MASARU HORI, Nagoya University

Atmospheric pressure plasmas (APP) have been given much attention because of its cost benefit and a variety of possibilities for industrial applications such as large area processing. We have been studying production of a pseudo-continuous meter-scale 2.45 GHz microwave APP source which consists of a loop-structure waveguide antenna and a circulator. Plasma is produced inside a meter-length slot of the waveguide and pseudo-continuous plasma is realized by fast movement of small (a few mm in length) plasmas along the slot. In this study, plasma behavior is investigated by a high-speed camera and an ICCD camera to give insight into the mechanism of the plasma movement. In emission intensity profile along the slot from a single plasma, asymmetric structure and higher emission intensity was observed in the vicinity of the plasma edge of the microwave downstream side, suggesting the plasma movement was induced by the asymmetric ionization rate in the single plasma. Origin of such asymmetric structure was investigated using a simulation of three-dimensional electromagnetic field.
10:00 AM SF2.00006 CO\textsubscript{2} dissociation in vortex-stabilised microwave plasmas. S. WELZEL\textsuperscript{1}, W.A. BONGERS, M.F. GRASWINCKEL, M.C.M. VAN DE SANDEN\textsuperscript{2}, FOM Institute DIFFER, Edisonbaan 14, 3439 MN Nieuwegein — Plasma-assisted gas conversion techniques are widely considered as efficient building blocks in a future energy infrastructure which will be based on intermittent, renewable electricity sources. CO\textsubscript{2} dissociation in high-frequency plasmas is of particular interest in carbon capture and utilisation process chains for the production of CO\textsubscript{2}-neutral fuels. In order to achieve efficient plasma processes of high throughput specifically designed gas flow and power injection regimes are required. In this contribution vortex-stabilised microwave plasmas in undiluted CO\textsubscript{2} were studied in a pressure range from 170 to 1000 mbar at up to 1 kW (forward) injected power, respectively. The CO\textsubscript{2} depletion was measured downstream, e.g. by means of mass spectrometry. Although the system configuration was entirely not optimized, energy efficiencies of nearly 40\%, i.e. close to the thermal dissociation limit, and conversion efficiencies of up to 23% were achieved. Additionally, spatially-resolved emission spectroscopy was applied to map the axial and radial distribution of excited atomic (C, O) and molecular (CO, C\textsubscript{2}) species along with their rotational temperatures.

\textsuperscript{1}Eindhoven University of Technology, Postbox 513, 5600 MB Eindhoven
\textsuperscript{2}Eindhoven University of Technology, Postbox 513, 5600 MB Eindhoven

10:15 AM SF2.00007 Experimental observation of electron density bifurcation in plasma-metamaterial composites in microwave range. OSAMU SAKAI, YOSHIHIRO NAKAMURA, AKINORI IWAI, Kyoto University — Metamaterials, which are composed of designed microstructures and show extraordinary electromagnetic responses, match plasmas so well, and high-power microwave induce bifurcation phenomena in this plasma-metamaterial composite. Since dielectric constant or permittivity of plasmas varies from positive to negative values at microwave frequencies, the composite with negative permeability becomes a reconfigurable negative refractive index material \cite{1}. Furthermore, as indicated by our recent report \cite{2}, this composite shows strong nonlinear properties. Bifurcation of permittivity (or electron density) was predicted by a theory \cite{2}, and we have verified it in our recent experiments; using double split ring resonators whose array showed negative permeability at 2.45 GHz, clear bifurcation with hysteresis was observed in electron density evolutions with input power <300 W. This result implies that this composite is a nonlinear microwave metamaterial.

\begin{thebibliography}{99}
\bibitem{1} O. Sakai et al., Plasma Sources Sci. Technol. 13, 013001 (2013).
\end{thebibliography}

Friday, November 7, 2014 8:30 AM - 10:30 AM —
Session SF3 Electron Collisions with Atoms and Molecules — State D - Allan Stauffer, York University

8:30 AM SF3.00001 Angular distributions for ionization from excited states of atoms\textsuperscript{1}. JAMES COLGAN, Los Alamos National Laboratory — We present recent theoretical work examining cross sections for electron-impact ionization of excited states of atoms. Our work is motivated by recent measurements of the angular differential cross sections from electron-impact single ionization of Mg atoms in the 3s3p excited state \cite{1}, which were prepared by laser excitation of the Mg target. We use the time-dependent close-coupling approach to electron-ion impact ionization \cite{2} and explore the angular distributions from excited state Na and Mg, building on recent work by us in which we examined the angular distributions from the ground states of Na and Mg \cite{3}. We examine the differences between the angular distributions resulting from ionization of the ground and excited states. Our calculations are also compared to the recent measurements \cite{1}, and we highlight where further work would be desirable in this area.

\begin{thebibliography}{99}
\end{thebibliography}

1\textsuperscript{The Los Alamos National Laboratory is operated by Los Alamos National Security, LLC for the National Nuclear Security Administration of the U.S. Department of Energy under Contract No. DE-AC5206NA25396.}

9:00 AM SF3.00002 Theoretical and experimental results for electron-impact ionization of the 3p state of Mg that has been laser aligned\textsuperscript{1}. SADEK AMAMI, DON MADISON, Missouri Univ of Sci & Tech, KATE NIXON, ANDREW MURRAY, University of Manchester, United Kingdom, JAMES COLGAN, Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA — Low energy theoretical and experimental quadruple differential cross sections (QDCS) will be presented for electron impact ionization of magnesium atoms that have been aligned by lasers. The incident projectile electron has an energy of 43.31 eV, the scattered and ejected electrons were detected with equal energies (E_1=E_2=20 eV), one of the final state electrons was detected at a fixed scattering angle of 30 degrees, and the other final state electron is detected at angles ranging between 0 degrees and 180 degrees. The Mg atoms are excited to the 3p state using a laser that produces a standing wave aligned perpendicular to the laser beam direction. Theoretical results will be compared with the experimental data for several different alignment angles both in the scattering plane as well as in the plane perpendicular to the incident beam direction.

\textsuperscript{1}This work is supported by the US National Science Foundation under Grant No.PHY-1068237.

9:15 AM SF3.00003 Quasi-Sturmian basis functions for two- and three-body scattering problems. JESSICA A. DEL PUNTA, LORENZO UGO ANCARANI, Université de Lorraine, Metz, France, GUSTAVO GASANEO, Universidad Nacional del Sur, Bahia Blanca, Argentina — For quantum three-body scattering processes, one important theoretical issue is how to impose to the wave function the correct asymptotic behavior. In many methods the problem is solved using basis functions that generally do not possess the correct behavior at large distances. One exception is given by the Generalized Sturmian Functions (GSF) \cite{1} which are defined taking into account the interactions of the problem under consideration, thus making them an efficient basis set. We present in this work an alternative set of basis functions, named Quasi Sturmian Functions (QSF). Starting with the two-body case \cite{2}, QSF satisfy a non-homogeneous differential equation, and may be constructed with a selected asymptotic behavior (e.g. outgoing). Contrary to GSF, these basis functions have analytical closed form for the case of a Coulomb potential. Moreover, we showed that the QSF provide a superior convergence rate when solving a two-body scattering problem. For the three-body case, we propose a representation using hyperspherical coordinates. While the angular variables are treated in a parametric way, the hyperradial coordinate can be imposed.

\begin{thebibliography}{99}
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9:30 AM SF3.00004 Low energy electron-molecule scattering using the R-matrix method

JIMENA GORFINKIEL, The Open University — The study of electron-molecule collisions continues to attract significant interest stimulated, in no small part, by the need for collisional data to model a number of physical environments and applied processes (e.g. the modelling of focused electron beam induced deposition and the description of the interaction of radiation with biological matter). This need for electron scattering data (cross sections but also information on the temporary negative ions, TNI, that can be formed) has motivated the renewed development of theoretical methodology and their computational implementation. I will present the latest developments in the study of low energy electron scattering from molecules and molecular clusters using the R-matrix method. Recent calculations on electron collisions with biologically relevant molecules have shed light on the formation of core-excited TNI these larger targets. The picture that emerges is much more complex than previously thought. I will discuss some examples as well as current and future developments of the methodology and software in order to provide more accurate collisional data (in particular cross sections) for bigger targets.

In collaboration with Zdenek Masin, The Open University.

This work was partially supported by EPSRC.

10:00 AM SF3.00005 Theoretical and Experimental Triple Differential Cross Sections for Electron Impact Ionization of SF$_6$

HARI CHALUVADI, Missouri University of Science and Technology, KATE NIXON, ANDREW MURRAY, University of Manchester, CHUANGANG NING, Tsinghua University, JAMES COLGAN, Los Alamos National Laboratory, DON MADISON, Missouri University of Science and Technology — Experimental and theoretical Triply Differential Cross Sections (TDCS) will be presented for electron-impact ionization of sulfur hexafluoride (SF$_6$) for the molecular orbital 1t$_{1g}$. M3DW (molecular 3-body distorted wave) results will be compared with experiment for coplanar geometry and for perpendicular plane geometry (a plane which is perpendicular to the incident beam direction). In both cases, the final state electron energies and observation angles are symmetric and the final state electron energies range from 5eV to 40eV. It will be shown that there is a large difference between using the OAMO (orientation averaged molecular orbital) approximation and the proper average over all orientations and also that the proper averaged results are in much better agreement with experiment.

Work supported by NSF under grant number PHY-1068237. Computational work was performed with Institutional resources made available through Los Alamos National Laboratory.

10:15 AM SF3.00006 Importance of projectile-target interactions in the triple differential cross sections for Low energy (e,2e) ionization of aligned H$_2$

ESAM ALI, DON MADISON, Missouri Univ of Sci & Tech, X. REN, A. DORN, Max-Plank-Institute for Nuclear Physics, CHUANGANG NING, Tsinghua University, Beijing, China — Experimental and theoretical Triple Differential Cross Sections (TDCS) are presented for electron impact ionization-excitation of the 2$s\sigma_g$ state of H$_2$ in the perpendicular plane. The excited 2$s\sigma_g$ state immediately dissociates and the alignment of the molecule is determined by detecting one of the fragments. Results are presented for three different alignments in the xy-plane (scattering plane is xy) - alignment along y-axis, x-axis, and 45° between the x- and y-axes for incident electron energies of 4, 10, and 25 eV and different scattered electron angles of 20° and 30° in the perpendicular plane. Theoretical M4DW (molecular 4-body distorted wave) results are compared to experimental data, and overall we found reasonably good agreement between experiment and theory. The Results show that (e,2e) cross sections for excitation-ionization depend strongly on the orientation of the H$_2$ molecule.