DOE Center for
Predictive Control of Plasma Kinetics:
Multi-Phase and Bounded Systems

6th Annual Meeting

June 10-11, 2015
University of Maryland, College Park, MD
We gratefully acknowledge the funding from

The U.S. Department of Energy Office of Science

Fusion Energy Sciences Program

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## Schedule

**Wednesday, June 10, 2015**

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2 Benjamin Goldberg (Ohio State University)
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5 Santosh Kumar Kondeti (University of Minnesota)
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6 Carlos Larriba-Andaluz (University of Minnesota)
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7 Romain Le Picard (University of Minnesota)
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1 Amanda Lietz (University of Michigan)
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2 Alexander Lindsay (University of California-Berkeley)
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3 Pingshan Luan (University of Maryland)
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4 Dominik Metzler (University of Maryland)
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5 Marlene Patino (PPPL)

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Abstracts: Oral Presentations

Introduction to the Annual Meeting:
Progress in the Extension Year, the Path Forward and the Role of LTPs in the National Assessment of Plasma Physics

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Electrical Engineering and Computer Science, Ann Arbor, MI 48109-2122 (mjkush@umich.edu)

The Department of Energy Center for the Predictive Control of Plasma Kinetics: Multi-Phase and Bounded Systems was established in the Fall of 2009 in response to recommendations of the National Research Council Plasma 2010 Decadal Study. The Plasma 2010 study emphasized the importance of low temperature plasmas (LTPs) to the economic well-being and national security of the United States, and the high level of the fundamental science challenges facing the LTP field. The Center selected as its unifying theme the control of plasma kinetics as being the optimum approach to address both fundamental science issues and providing improved understanding that rapidly leads to technological advances.

Since the Center proposal was originally written, there has been a significant shift in emphasis field of LTPs from lower pressures to higher pressures, with motivating applications now including biotechnology. During the 6th year of the Center, the extension year, research was reoriented to address the higher pressure regime. The Center continues to perform world-leading research in this new pressure regime. This transition in the field of LTPs is occurring at a time when the field of plasma physics in the United States is undergoing a strategic planning process in which the science challenges and societal benefit of the field are being assessed.

In this talk, a brief overview of the Center will be provided from these perspectives. The status of the 6th Year progress in this new parameter space will be briefly summarized and how that progress will be built upon if the Center is renewed for an additional 2 years. The role of LTPs in the national assessment of plasma physics will be discussed.
Nanodusty Plasmas

Romain Le Picard\textsuperscript{(a)}, Nicolaas Kramer\textsuperscript{(a)}, Narula Bilik\textsuperscript{(a)}, Carlos Larriba-Andaluz\textsuperscript{(a)}, Eray Aydil\textsuperscript{(b)}, Uwe Kortshagen\textsuperscript{(a)} and Steven Girshick\textsuperscript{(a)}

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Under PSC support, we have conducted joint experimental and modeling studies of nanodusty plasmas, and have made significant progress in the understanding of fundamental mechanisms of plasma-nanoparticle interactions. In recent papers, we explored the non-equilibrium between plasma and nanoparticle species, deriving conditions under which nanoparticles are heated to temperatures high enough to produce high quality nanocrystals \cite{1,2}. We pointed out the significant differences between plasma synthesis at low pressures and atmospheric pressure \cite{3}. Most recently, we succeeded in obtaining the first reliable Langmuir probe measurements of electron distribution functions in nanodusty plasmas \cite{4} (Fig. 1), shedding new light on electron kinetics in these plasmas. In a collaboration between the University of Minnesota and the University of Michigan, we have developed numerical models of several types of nanodusty plasmas, with a focus on synthesis of silicon nanoparticles in silane-containing plasmas. Systems modeled include a parallel-plate capacitively-coupled RF system in both continuous \cite{5,6} and pulsed mode (Fig. 2), and the flow-through cylindrical tube with RF ring electrodes used in several of the experimental studies cited above. This presentation will review the recent progress in our understanding of nanodusty plasmas and discuss a vision for the future of the field of plasma-nanomaterials physics.

\begin{itemize}
\item \textbf{Fig. 1} – Measured temporal evolution of EEPF in 80-mTorr argon-silane dusty plasma \cite{4}.
\item \textbf{Fig. 2} – Particle size distribution across electrode gap, 0.4 ms into the afterglow phase of a pulse. White lines indicate average particle charge. Pulse frequency = 50 Hz, duty cycle = 50%. Applied positive DC bias attracts particles to lower electrode.
\end{itemize}

References

Diagnostics of Dynamic and Structured Plasma Discharges

E. V. Barnat\textsuperscript{(a)}, B. R. Weatherford\textsuperscript{(a,d)}, B. T. Yee\textsuperscript{(b,a)}, J. E. Foster\textsuperscript{(b)}, J. Franek\textsuperscript{(c)}, S. Nogami\textsuperscript{(c)}, M. Koepke\textsuperscript{(c)} and V. Demidov\textsuperscript{(c)}

\textsuperscript{(a)} Sandia National Laboratories (evbarna@sandia.gov),
\textsuperscript{(b)} University of Michigan
\textsuperscript{(c)} West Virginia University
\textsuperscript{(d)} L3 Communications

In this presentation, a survey of collaborative studies that have been facilitated or enabled through the DOE-PLSC will be described. While each study had independent objectives and utilized very different plasma operating regimes, we emphasize common themes that unite the various studies. Specifically, we emphasize the development and application of diagnostics and plasma generating techniques that are employed for interrogation and characterizing of temporally varying and structurally rich plasma systems to assess the role electron kinetics play these discharges.

For example, a two-dimensional, time resolved diagnostic platform based on laser-collision induced fluorescence has been developed and employed for the study of dynamic plasma systems of interest to members of the low-temperature plasma community. The talk will describe both development and application of the diagnostic in both helium and more recently argon discharges.

As illustrated in Figure 1, the LCIF technique is applied to helium (upper plot) and argon (lower plot) discharges formed above magnetized electrodes. For the helium case, the electrode is biased positive and electrons are drawn to the electrode. On the other hand, for the argon case, the electrode is biased negative and electrons are pushed from the cathode. Both illustrate the ability of the LCIF technique to interrogate challenging plasma environments [1-2].

Finally, discussion is offered on current efforts to extend the LCIF platform to the study of higher pressure plasma systems. Discussed will be the experimental platform and approach utilized to assess limits placed on the technique by competition by other (neutral) collision events.

References
Towards Predictive Control of Electron Kinetics in Plasma Applications

I. D. Kaganovich\(^{(a)}\), D. Sydorenko\(^{(b)}\), A.V. Khrabrov\(^{(a)}\), Y. Raitses\(^{(a)}\), P. Ventzek\(^{(c)}\), L. Chen\(^{(c)}\), V.I. Demidov\(^{(d)}\), A.S. Mustafaev\(^{(e)}\),

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\(^{(e)}\) National Mineral Resources University, St. Petersburg 199106, Russia (alexmustafaev@yandex.ru)

The purpose of the talk is to give an overview of accomplishments in predictive control of electron kinetics in low-pressure plasmas enabled by the DOE Center for Control of Plasma Kinetics. Low-pressure discharges are widely used in industry as the main plasma sources for many applications including plasma processing, discharge lighting, plasma propulsion, particle beam sources and nanotechnology. Being partially-ionized, bounded, and weakly-collisional, the plasmas in these discharges demonstrate nonlocal electron kinetic effects, nonlinear processes in the sheaths, beam-plasma interaction, collisionless electron heating, etc.\(^{[1]}\). Such plasmas often have a non-Maxwellian electron velocity distribution function. We report on recent advances in nonlocal electron kinetics in low-pressure plasmas where a non-Maxwellian electron velocity distribution function was “designed” for a specific application: in dc discharges with auxiliary biased electrodes for plasma control\(^{[2]}\), hybrid DC/RF unmagnetized\(^{[3]}\) and magnetized plasma sources\(^{[4]}\), and Hall thruster discharges\(^{[5]}\).

We show using specific examples that this progress was made possible by synergy between full-scale particle-in-cell simulations, analytical models, and experiments. Initial “academic” studies paved the way to understanding of modern plasma devices that are being developed for future plasma technology. Our studies of collective interaction of electron beam with the plasma\(^{[3]}\) aides understanding and optimization of this device\(^{[6]}\). Another example is modeling of high power plasma switch for electric grid system recently being proposed by General Electric\(^{[7]}\). Developed analytical and simulation tools are now being used to provide optimization strategy for the device.

In summary, the Center funding allowed us to develop set of valuable analytical and simulation tools that are now being used in industry to increase US competitiveness.

References

Low-temperature Plasma Surface Interactions for Treatment of Polymers, Biomolecules and Atomic Layer Etching

E. A. J. Bartis(a), D. Metzler(a), A. Knoll(a), C. Li(a), P. Luan(a), N. Fox-Lyon(a), D. B. Graves(b), V. Godyak(c), J. Franek(d), M. Koepke(d), V. Demidov(d), and G. S. Oehrlein(a)

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(d) West Virginia University, Morgantown (koepke@wvu.edu)

Control of plasma-surface interactions is essential for successful application of low temperature plasma to materials processing. Our initial work in this project was focused on the understanding of H2/D2/Ar plasmas interacting with carbon-based films. This work led to important insights on plasma distribution functions, etching behavior and applications for surface modifications, including biological deactivation of biomolecules. These insights were a basis for two evolutions of this project: 1) understanding the interaction of small plasma sources operated at atmospheric pressure with biomolecules and polymers; 2) atomic layer etching of materials.

Cold atmospheric plasma (CAP) sources can be important sources of reactive chemical species that can deactivate bacteria and biomolecules or modify surfaces under mild conditions. In this work, we evaluated the interaction of two different CAP sources, a surface microdischarge (SMD) that operates with N2/O2 mixtures and an atmospheric pressure plasma jet (APPJ) that operates with low molecular gas admixtures to Ar, with model polymers and toxic biomolecules such as lipopolysaccharide (LPS) and peptidoglycan. These sources were mounted inside vacuum chambers that can be evacuated and then refilled with a controlled environment. These chambers allow for post treatment transfer under vacuum to a UHV surface analysis system and in situ ellipsometric monitoring of film properties. LPS biological activity was investigated by an enzyme-linked immunosorbent assay. Electrical and optical characterizations of the CAP sources were performed along with post treatment attenuated total reflectance Fourier transform infrared spectroscopy. One selected insight concerns surface bound NO3. We find that surface bound NO3 after CAP treatment is generic to a variety of CAP sources and substrates, and that it originates from gas-phase species. Studying model polymers with various side groups suggests that alcohol (-OH) groups are the most susceptible to NO3 formation while ester (C=O) groups resist it. We also propose a possible correlation between surface-bound NO3 and biodeactivation of selected biomolecules.

Low temperature plasma with carefully controlled fluxes to surfaces can be used for controlled etching of Angstrom thin layers of SiO2 and Si. Self-limited etching is based on deposition of thin (~5 Å) reactive fluorocarbon (FC) layers on SiO2 and/or Si using pulsed C4F8, CHF3, and C4F6 gas flows. Subsequent low energy (20 to 30 eV) Ar+ ion bombardment removes the FC layer along with thin layers of SiO2 or Si from the surface. Etching of the SiO2 stops once the reactive supply has been exhausted. Low Ar+ ion energies are essential to achieve self-limited etching rates. The SiO2 and Si etching behavior for the cyclic approach has also been compared to continuous precursor addition. For this, SiO2 and Si etching and the selectivity of SiO2 over Si was investigated as a function of FC surface coverage, ion energy (20 to 30 eV), and etch step length using in situ ellipsometry. Key requisites to achieve high SiO2/Si etching selectivity are the control of reactive precursor surface coverage and the maximum energy of Ar+ ion bombardment.

The authors gratefully acknowledge financial support from the National Science Foundation (PHY-1004256, PHY-1415353 and CBET-1134273) and US Department of Energy (DE-SC0005105 and DE-SC0001939).
Advances in Low Temperature Plasmas from 1 mTorr to 1 atm

Vincent M. Donnelly and Demetre J. Economou

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New and traditional plasma diagnostics, coupled with simulations, have produced new knowledge on the behavior of non-equilibrium plasmas and their interactions with surfaces, at both low and atmospheric pressure. This presentation will highlight some of the most important findings.

(a) Nearly mono-energetic ion energy distributions (IEDs) were obtained by using a pulsed plasma, and applying a synchronous DC bias voltage on a boundary electrode in contact with the plasma during a time window in the afterglow. The ion energy was set by the value of the applied DC voltage. Particle-In-Cell (PIC) simulations and semi-analytical models were employed to identify voltage waveforms that, when applied to a substrate electrode, yield custom IEDs.

(b) The ability to generate nearly mono-energetic ion fluxes to a substrate allowed the study of etching silicon with ion energy below the threshold for ion-assisted etching (~ 16 eV for chlorine). Above a threshold, the etching rate depended on the square root of ion energy (Fig. 1). Below that threshold, the etching rate was independent of ion energy. A number of judicious experiments showed that this subthreshold etching was mainly due to VUV radiation generated by the plasma.

(c) Features as small as 3 nm were written in Si by Nanopantography with the self-space-charge-neutralized ion beam extracted from the pulsed plasma.

(d) In-plasma photo-assisted etching was used to transfer nanopatterns defined by Nanopantography in Si. Due to the very high selectivity of photo-assisted etching, the ~ 2nm Si native oxide was used as a mask. High aspect ratio (5:1) sub-10 nm patterns were generated in a massively parallel manner.

(e) A plasma reactor incorporating dual tandem inductively coupled plasma sources (main and auxiliary ICP source), separated by a grid, was developed to manipulate the electron energy distribution (EED). By pulsing the main plasma source, while maintaining the auxiliary source in continuous wave (cw) mode, a low electron temperature (~1 eV) at high plasma density was realized. A hybrid (fluid-kinetic) simulation predicted the measured trends in the evolution of the EED.

(f) Plasma ignition delays were observed in the pulsed main ICP in electronegative gases. In chlorine plasmas, ignition delay occurred for duty cycles greater than 60%. In contrast to expectations, the ignition delay was longer with increasing duty cycle up to ~99.6%.

(g) A combined experimental-simulation study of atmospheric pressure plasma jets (APPJ) interacting with surfaces is under way. We are developing a new optical emission spectroscopy diagnostic to be able to probe the last several 100 nm of gas near a surface. This is based on recording spectra as a function of angle using a semi-cylindrical prism. Past the critical angle, only evanescent wave coupled emission is detected from the region within less than one wavelength of the surface. At the same time, we are employing a plasma transport and reaction fluid model to predict the spatiotemporal profiles of plasma species and electric field. The fluxes of important species (e.g., O atoms in the case of He plasma gas in an O2 ambient) on the surface are predicted for both insulating and conducting surfaces, to be compared with data.

Figure 1. Si etching rates in different Cl- and Br-containing plasmas.
Modeling and Simulation of Low Temperature Plasma Discharges

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We have used global, fluid and kinetic particle-in-cell (PIC) simulations to study applications in semiconductor processing, plasma propulsion and bio-medicine, as well as address basic plasma physics issues such as instabilities, waves and electron heating. We have developed a fast 2D hybrid fluid-analytical code for plasma reactors which includes both capacitive and inductive coupling of source coils to plasma, electron and ion sheath heating, and multiple drive frequencies. We have also developed fast global codes to simulate atmospheric pressure micro-discharges which are of interest in the bio-medical field.

Using our 2D hybrid fluid-analytical code, we were able to perform simulations of electronegative (EN) transformer coupled plasmas (TCPs) in both stable and unstable regimes, showing good agreement with available experiments and our analytical models. The 2D fluid-analytical code was also used to study ion plasma uniformity and ion energy distributions (IEDs) in multi-frequency capacitively-coupled plasmas (CCPs). We interfaced the 2D hybrid code with a 1D PIC model of the sheath region in order to obtain the IEDs at the wafer electrode.

A fast numerical-analytical global code for atmospheric pressure inert gas (e.g., He) discharges with trace elements of reactive gases (e.g., N\textsubscript{2} or O\textsubscript{2}) was developed to simulate bio-medical plasma jet devices. Using 1D PIC simulations of atmospheric pressure He/N\textsubscript{2} as a guide, we improved the global model in the high power regime by including a hot electron population and electron multiplication in the sheaths. The improved global code was used to simulate chemically complex, atmospheric pressure He/H\textsubscript{2}O gases.

We conducted 1D PIC simulations of a voltage-driven 1 mm width atmospheric pressure He/(2\% H\textsubscript{2}O) plasma discharge in series with an 0.5 mm width liquid H\textsubscript{2}O layer and a 1 mm width quartz dielectric layer. The H\textsubscript{2}O and dielectric layers are modeled as a capacitor with $C_T \approx 3.46 \times 10^{-12}$ F, equal to the series combination of $C_{H2O} = \kappa_{H2O} \epsilon_0 A/d_{H2O}$ and $C_D = \kappa_D \epsilon_0 A/d_D$, where $\kappa_{H2O} = 80$, $d_{H2O} = 0.5$ mm, $\kappa_D = 4$, $d_D = 1$ mm, and electrode area $A = 1$ cm\textsuperscript{2}. The global model was used to determine the most important species and collisional reactions to use in the PIC simulations. A series of simulations were conducted at 27 MHz with $V_{rf} = 350-600$ V. As shown, in Fig. 1a, we find that the H\textsubscript{2}O rotational and vibrational excitation losses are so high that electrons reach the walls at thermal temperatures. We also simulated a lower frequency case of 50 KHz with $V_{rf} = 10$ KV. In this case, the discharge runs in a pure time-varying $\gamma$-mode, and as shown in Fig. 1b.

Figure 1 – Results for 1mm wide, 760 Torr He/(2\% H\textsubscript{2}O) discharge showing (a) Electron energy distribution at walls for 450V@27MHz, and (b) Average Density vs. time for 10KV@50KHz.
Electric Field Vector Measurements in Transient Ionization Wave Discharges

I. V. Adamovich and W. R. Lempert
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This work presents the results of time-resolved electric field measurements (i) in a nanosecond discharge between two plane electrodes covered by dielectric plates, and (ii) time-resolved electric field vector measurements in a ns pulse, surface ionization wave discharge in hydrogen, both using a picosecond four-wave mixing technique. The results in a plane-to-plane discharge are compared to kinetic modeling predictions, showing good agreement, including non-zero electric field offset before the main high voltage pulse, breakdown moment, and reduction of electric field in the plasma after breakdown. The difference between the experimental results and model predictions is likely due to non-one-dimensional structure of the discharge. Comparison with the kinetic modeling predictions shows that electric field in the nanosecond pulse discharge is controlled primarily by electron impact excitation and charge accumulation on the dielectric surfaces. Electric field vector components in the near surface discharge are measured separately, using pump and Stokes beams linearly polarized in the horizontal and vertical planes, and a polarizer placed in front of the infrared detector. Time-resolved electric field vector is measured at three different locations across the discharge gap, at three different heights above the alumina ceramic dielectric surface, ~100 μm, 600 μm, and 1100 μm (total of nine different locations). The results show that after breakdown, the discharge develops as an ionization wave propagating along the dielectric surface at an average speed of 1 mm/ns. The surface ionization wave forms near the high voltage electrode, close to the dielectric surface (~100 μm). The wave front is characterized by significant overshoot of both vertical and horizontal electric field vector components. Behind the wave front, the vertical field component is rapidly reduced. As the wave propagates along the dielectric surface, it also extends further away from the dielectric surface, up to ~1 mm near the grounded electrode. The horizontal field component behind the wave front remains quite significant, to sustain the electron current toward the high voltage electrode. After the wave reaches the grounded electrode, the horizontal field component experiences a secondary rise in the quasi-DC discharge, where it sustains the current along the near-surface plasma sheet. The measurement results indicate presence of a cathode layer formed near the grounded electrode with significant cathode voltage fall, ≈3 kV, due to high current number density in the discharge. The present results provide the most extensive data set available on electric field distribution in a surface ionization wave discharge, which can be used for validation of kinetic models and assessing their predictive capability.
Cold atmospheric plasma (CAP) in contact with water influence each other. Water evaporation and evaporative cooling alter the near-interfacial composition and temperature of the plasma and can strongly alter rates of chemical kinetics. Other species from the liquid phase can enter the plasma. The water layer acts as a bounding surface for the plasma so the water electrical properties affect the plasma. When the liquid surface acts as a cathode, secondary electron emission following positive ion and photon impact of the surface will strongly alter plasma properties. Furthermore, surface charge coupled with solvation and ion kinetics on and near the water surface will affect the flow of current from the plasma to the surface. Liquid convection can be induced by plasma at the interface and this can greatly alter the transport of species within the liquid phase.

The research conducted this year has focused on several aspects of this complex problem. In one study, a thoroughly characterized argon based atmospheric pressure plasma jet (APPJ) operated in open-air lab environment has been used to assess chemical reaction mechanisms. In a second study, coupled plasma/gas and liquid neutral transport and reaction were modeled. Finally, a self-consistent model of the water/electrolyte structure in the presence of plasma has been developed.

APPJ plasma chemistry can be altered by admixing O₂, H₂O and air in an RF Ar CAP jet. This allows changing between dominating NOₓ species and reactive oxygen species. The change in chemistry has a huge impact in the H₂O₂ production in the liquid being treated. H₂O₂ is an extremely important compound that often dominates the reduction of mammalian cell viability. A distinctive case has been found for Ar–O₂ mixtures leading to a 100% cell viability reduction while the amount of H₂O₂ produced is at the level of the detection limit. The strong distance effect and the necessary presence of Cl⁻ anions in the liquid to obtain the effect eliminates O₃ as the main active component. Based on the analysis of the detailed gas phase chemistry, the biological effect may be initiated by the exceptional high O density in excess of 10²² m⁻³ near the jet nozzle for this plasma condition (see figure 1). The proposed mechanism involves the reaction of O with Cl⁻ in liquid forming OCl⁻ that is known to impact cell viability at larger concentrations.

A second study examined the role of plasma/gas convection on convective transport and reaction of neutral species in water. Very sharp gradients of highly reactive species such as OH and ONOO⁻ were observed. Water evaporation and evaporative cooling were seen to be significant in the near-interfacial region.

A third study examined the water electrolyte double layer region at the plasma-water interface. One of the key unresolved questions has to do with the proper way to model the finite rate solvation and reaction kinetics of charged species (electrons and ions) that impact the water surface. This is also an issue for interfacial electrons that may solvate and alter interfacial chemistry and physics.
Understanding Reactivity, Transport, and Fluid Dynamical Processes at the Plasma Liquid Interface Using a 2-D Bubble Apparatus

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New and emerging atmospheric pressure plasma applications such as plasma medicine and plasma-based water purification rely on the interaction of plasma with liquid water. The source of physical and chemical reactivity induced by the plasma occurs at the interface between the plasma and the liquid. Indeed, the source function includes processes taking place at the interface driven by the diffusion of gas phase products into the liquid and by the direct production of radicals at the interface. In particular, the plasma interaction at the interface can also drive fluid dynamical processes that can lead to transport via convection for example.[1] These processes drive observed reactivity in the bulk solution far removed from the discharge. The nature of these processes remains poorly understood. Such an understanding enables one to predict induced chemistry as well as to optimize the plasma applicator for a variety of plasma-in-liquid applications. One major impediment to understanding the nature of physical processes taking place at the interface and ultimately in the bulk liquid is the lack of suitable diagnostics to probe this region. The intervening liquid shields the interfacial region from direct interrogation, e.g. laser absorption. In order to interrogate the interfacial region, the Plasma Science and Technology Laboratory is currently investigating a two dimensional bubble apparatus that essentially eliminates the optical depth associated with intervening liquid, making imaging and spectroscopy relatively straightforward. In this work, we use a variant of a Hele-Shaw cell which is traditionally used to study two dimensional flows.[2] Here a bubble is injected into a thin layer of water which fills the gap between two closely spaced plates. The liquid-gas interface is essentially inviscid. Fluid dynamical effects at the interface driven by the streamer discharge such as oscillations, chemical transport gradients and interfacial reactivity are therefore constrained to two dimensions in the cell and are thus readily assessable to imaging and spectroscopy studies.

Presented here are recent findings associated with the imaging of a discharge produced in the bubble driven by a nanosecond pulser. Observed streamer induced surface waves at the interface is discussed. Chemical transport gradients are also observed using chemical probes that track not only spatial pH changes in time but also inferred OH activity. Peroxide formation and transport is also studied. Interfacial perturbations that could potentially drive convection cells are also discussed. Nonlocal effects such as the observed formation of microbubbles far removed from the primary bubble discharge were also observed. The apparatus is also amenable to the direct study of streamer bubble hopping. Streamer bubble hopping experiments are also discussed. Future experiments and the inferred implications for actual plasma devices are also discussed.

References
An Update on Studies of Atmospheric Pressure Plasma Treatment of Liquid over Tissue: Jets and DBDs

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Atmospheric pressure plasma jets (APPJs) and dielectric barrier discharges (DBDs) are the typically applied plasma sources for the treatment of liquids and liquid covered tissue. Optimizing those plasma sources is challenging on at least four levels. The first is the large operational parameter space, particularly for APPJs, which includes repetition rate, gas mixture, voltage waveform and flow rate. The second is the interaction of plasma produced species with the ambient air which then becomes sensitive to environmental factors such as humidity and convection. The third challenge is the conversion of gas phase plasma activated species to liquid-resident reactive species. The fourth is the intrinsic variability of the plasma sources which is particularly problematic for DBDs.

In this paper, we provide an update on computational investigations of plasma treatment of liquid layers over tissue by APPJs and DBDs. The model used in this investigation, \textit{nonPDPSIM}, is a 2-dimensional plasma-hydrodynamics simulation which addresses gas phase plasma sources in contact with liquid. In addition to solution of Poisson’s equation and plasma transport, neutral flow, radiation transport and surface kinetics are also addressed. The following studies will be discussed:

\textit{Multiple pulsed APPJ into humid air:} The first step in APPJ treatment of surfaces is the propagation of the plasma jet into humid air. Methods to control the production of RONS (reactive oxygen and nitrogen species) in the effluent of He/O\(_2\) plasma jets were investigated while varying flow rate, repetition rate, O\(_2\) fraction and voltage. We found a synergistic effect where combinations of flow rate and repetition rate enabled multiple gas phase reactions to occur that preferentially produced, for example, nitric-acids.

\textit{Multiple pulsed APPJ onto thin water layers:} The APPJ in the first study was directed onto a thin water layer while varying similar system parameters. We found the ability to produce activated species in the liquid were similarly sensitive to residence time effects that enabled higher order species to be produced.

\textit{Multiple pulsed DBD onto thin water layers:} The emphasis of this study was the intrinsic variability of DBDs with respect to streamer locations. There are fast- and slow-reacting species that transport from the gas phase into the liquid. For example, OH penetrates only a short distance into the water layer. The end result is that plasma produce OH\(_{aq}\) will react with other plasma produced aqueous species, such as NO\(_{aq}\) dominantly in locations where the OH enters the liquid from the gas phase or where OH\(_{aq}\) is produced by the plasma by, for example, photo-dissociation. The placement of the streamer and the repetition rate of the streamers are then important to the transport of species deeper into the liquid.
Scaling of Rotating Plasma Structures and Anomalous Electron Cross-Field Transport in Low Temperature Magnetized Plasmas

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Plasmas in cross-field discharge devices exhibit complex nonlinear behavior resulting in variety of turbulent fluctuations and structures that critically affect operation and performance of these devices. \(E \times B\) rotating structures or so-called rotating spoke oscillations have been observed in a variety of plasma devices with magnetized electrons and non-magnetized or weakly magnetized ions such as Penning discharges, sputtering magnetrons, and Hall thrusters [1,2]. These oscillations are usually low mode number with a characteristic frequency of \(\Omega_{ce} \ll \omega \leq \Omega_{ci}\), where \(\Omega_{ce}\) and \(\Omega_{ci}\) are gyrofrequency of electrons and ions, respectively. Recent experiments of Penning discharges demonstrated that low frequency (1-10’s kHz) spoke oscillations are responsible for anomalous electron cross-field transport that limits the maximum achievable electric field and increases power losses in these devices. In the past year, using a set of Langmuir probes, high speed imaging diagnostics and a newly constructed time-resolving laser-induced fluorescence (LIF) diagnostic [3], we conducted a comprehensive characterization of the rotating plasma structures in a low temperature magnetized plasma of the Penning discharge for different operating parameters. In particular, our measurements revealed a strong dependence of spoke oscillations on the input discharge parameters, including gas, gas pressure, the magnetic field, and the electron injection from the cathode. The spoke frequency follows the scaling of \((B/M)^{0.5}\), where \(B\) is the magnetic field and \(M\) is the atom mass. The increase of the gas pressure above \(10^{-4}-10^{-3}\) torr leads to the suppression of the spoke oscillations. The spoke suppression was also achieved with the increase of electron injection from the cathode and by applying a feedback control of the segmented anode electrodes. Existing theories of rotating plasma structures, including collisionless modified Simon-Hoh instability, cannot explain the measured scaling of the rotating frequency. Recent theory and simulations describing these rotating structures, and also LIF measurements, point to the important role of electrostatic ion trapping in the formation of these structures. These results and methods of spoke suppression can be important for many plasma applications, including nanoscale level plasma processing of materials and plasma propulsion.

References
Recent experiments have shown that the discharge oscillation of a Hall effect thruster (HET) is associated with the plasma oscillation inside the discharge channel. In order to model such discharge plasma oscillation, a hybrid-direct kinetic (DK) simulation is developed. A fluid model is used for electrons and the ions are solved using DK simulation, in which kinetic equations are solved directly in discretized phase space to obtain the velocity distribution functions (VDFs). In comparison to existing particle methods, there are two main advantages of using the DK simulation: (1) time averaging technique is not used since there is no statistical noise that arises due to the use of macro-particles; and (2) ionization events are captured every time step on every phase space bin whereas the particle methods cannot capture the ionization in detail due to memory restriction. An example of a typical discharge oscillation obtained from a hybrid-DK simulation is shown in Figure 1.

The mode transition of the discharge oscillation in HETs between oscillatory and stable modes has been analyzed and comparison made to experiments. It is found that the stabilization of the oscillation mode is associated with reduced electron transport that suppresses the ionization process. The balance between Joule heating and the other energy loss mechanisms is also likely to excite and stabilize the plasma oscillation and hence the discharge current oscillation.

In addition, a perturbation theory is developed to investigate the ionization oscillations in HETs. Oscillation modes are found as an unstable root of the linear perturbation from the ion and neutral atom continuity, ion momentum, and electron energy equations. The ionization oscillation mode is unconditionally stable when the perturbation of the electron energy is neglected but an ionization instability mode is found for large electron convection and small wall heat flux. Theoretical prediction supports the observations from the hybrid-DK simulation.

We also plan to discuss some on-going work including construction of a hybrid modular fluid-DK simulation technique for modeling of high-pressure plasma that contain localized regions of nonequilibrium, such as encountered by streamers interacting with aerosols, and a two-dimensional plasma simulation of HET discharge plasmas.

References

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A fundamental understanding of dusty plasma physics is important for the optimization of plasma-aided manufacturing processes. Determination of the electron energy probability function (EEPF) using Langmuir probes is particularly valuable in studying electron-dust interactions. However, Langmuir probe measurements in dusty plasmas are a challenge because particle deposition on the probe leads to contamination and distortion of the measured EEPF. We here present reliable EEPF measurements in a capacitively coupled argon-silane dusty plasma using a shielded Langmuir probe. A solenoid-actuated shield covered the probe which was exposed to the plasma only for short periods of time (less than 6 seconds) when the current-voltage characteristics were recorded during rapid voltage scans. This approach minimized probe contamination.

The evolution of the EEPF in a dusty plasma obtained using this method is shown in Fig. 1. In the presence of dust, the electron density decreased and the electron temperature increased in comparison to a pristine argon plasma. While the population of lower energy electrons decreased in the presence of dust, the high energy tail regions overlapped throughout the experiment.

Langmuir probe measurements were complemented with ion density measurements using a capacitive probe [1] and ex situ examination of particles using electron microscopy. While the ion density decreased only slightly in the dusty plasma, the electron depletion was significant due to attachment loss to the nanoparticles. Using the ion-electron density difference and the analytical model of particle charging [2], we found that the particle charge was approximately given by one elementary charge per nanometer of particle diameter, and the particle density was on the order of $10^7$ cm$^{-3}$, which was about two orders of magnitude lower than the electron and ion densities in the dusty plasma. Using this technique, we hope to achieve a detailed understanding of the physics of plasma-nanoparticle interactions in dusty plasmas.

References
Electric Field Measurements in Dielectric Barrier and Surface Ionization Wave Nanosecond Pulse Discharges

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The poster presents the results of time-resolved electric field measurements in a nanosecond pulse discharge between two plane electrodes covered by dielectric plates, using picosecond four-wave mixing diagnostics. For absolute calibration, the IR signal was measured in hydrogen at a pressure of 440 Torr, for electrostatic electric field ranging from 0 to 8 kV/cm. By measuring the intensities of the pump, Stokes, and IR signal beam for each laser shot during the time sweep across the high-voltage pulse, temporal evolution of the electric field in the nanosecond pulse discharge was determined with sub-nanosecond time resolution. The results are compared to kinetic modeling predictions, showing good agreement, including non-zero electric field offset before the main high voltage pulse, breakdown moment, and reduction of electric field in the plasma after breakdown. Comparison with the kinetic modeling predictions shows that electric field in the nanosecond pulse discharge is controlled primarily by electron impact excitation and charge accumulation on the dielectric surfaces.

Results of electric field vector measurements in nanosecond pulse surface ionization wave discharge between two electrodes on an alumina ceramic surface are also presented. Vertical and horizontal electric field components were measured using a polarizer placed in front of the IR detector. Temporal evolution of vertical and horizontal electric field components was determined at several axial locations (near the high voltage electrode, midway between the electrodes, and near the grounded electrode), at several heights above the dielectric surface. Approximately 100 µm above the dielectric plate, the vertical field component was shown to increase significantly as the wave front passed the measurement location, and then fall rapidly (within several nanoseconds). The horizontal component was shown to have a gradual increase until the wave front passed, followed by a rapid drop. However, the horizontal field component did not fall to zero until the end of the applied voltage pulse, due to a conduction current path formed between the electrodes once the wave front reached the grounded electrode. Additional measurements were done 500 and 1000 µm above the dielectric dielectric surface.
Atmospheric pressure plasma jets (APPJ) are sources of a variety of reactive chemical species which can be used for a variety of potential industrial and medical applications. In this study, we investigate the etching mechanism by APPJ treatments of a poly(methyl methacrylate)-based 193 nm photoresist polymer (PR193) and a polystyrene-based 248 nm photoresist polymer (PR248) using in situ ellipsometry to monitor film thickness and refractive index in real time. The kilohertz-driven, two-ring electrode APPJ used in this work was operated with low admixtures of O₂ and N₂ to Ar feedgas [1]. Voltage and current waveforms were collected to characterize electrically the APPJ and measure power dissipation. Additional characterization was also done by attenuated total reflection Fourier transform infrared spectroscopy (ATR-FTIR).

We observe etching of the photoresist polymers using an APPJ with pure argon feed gas when the visible plume is not in direct contact with the polymer surface. This etching rate is sensitive to the Ar gas flow rate and local gas environment. No etching was seen without direct line of sight from source to sample. The etching was shown to be line-of-sight by placing a grounded mesh directly over the sample during treatment which showed etching only where the holes exposed the sample to the plasma. This led to the investigation of high energy photons on polymer etching using an optical filter approach. The results of these experiments are shown in Figure 1. When a MgF₂ filter with a 114 nm cutoff wavelength is placed directly over the sample, reduced etching still occurs. When a sapphire filter with cutoff wavelength of 142 nm is used, no etching is seen at all. This demonstrates that vacuum-ultraviolet (VUV) radiation reaches the surface at atmospheric pressure, which may have significant implications, e.g. for use of these devices in the medical field.

VUV-induced etching is further supported by experiments that show that etching increases in nitrogen environments compared to oxygen environments as the oxygen more effectively absorbs VUV radiation. The etch rate increases with increasing argon gas flow rate. This suggests that the ability of the VUV to reach the surface is dependent on the lifetime of Ar₂⁺ species that emit VUV radiation around 125 nm. ATR-FTIR analysis of the polymers post treatment show a reduction of C=O bonding which is characteristic of VUV interactions with these photoresist materials. This study will be continued by investigating the effects of H₂O admixtures to the feedgas on surface modifications and comparison to other atmospheric pressure plasma sources.

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References
Magnetically Insulated Baffled Probe for Plasma Potential Measurements in a Penning Discharge

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A baffled probe is a magnetically insulated probe capable of measuring electron temperature, ion temperature, and plasma potential.[1,2] A ceramic baffle shields a cylindrical tungsten electrode from the magnetized plasma on two sides. The baffle is much larger than the electron gyroradius and smaller than the ion gyroradius. Rotating the baffle perpendicular to the magnetic field isolates the probe from electrons and allows only ion flux to reach the floating electrode. A 90-degree rotation opens the probe completely to field lines, allowing electrons to reach the electrode. In this configuration, the electrode functions as a floating Langmuir probe. An intermediate rotation of the baffle allows a small fraction of the total electron flux to reach the probe. It is anticipated that by equalizing the fluxes of both plasma species to the electrode, the probe sheath is greatly reduced and the probe floats at a potential near the plasma potential.

We present results of measurements of the plasma potential using the baffled probe in a low-temperature magnetized plasma produced in an E×B Penning discharge. Results of these measurements are compared with plasma potential measurements taken with traditional emissive probes and Langmuir probes. In addition, we use the baffled probe to resolve fluctuation of plasma potential induced by short-timescale oscillations, which are commonly observed in various magnetized discharges and associated with rotating plasma structures such as spoke oscillations.[2]

References
Induced Interfacial Fluid Dynamics during the Impingement of an
Atmospheric Pressure Plasma Jet onto Water

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Atmospheric pressure plasma jets are widely used in studies involving the interaction of plasmas with living matter [1]. As most living cells are kept in a liquid medium for *in vitro* studies, plasma treatment involves the impingement of plasma jet on the liquid surface of the reservoir in which the cells are suspended. The interfacial liquid dynamics can strongly influence the transport of reactive species from gaseous phase to liquid phase and directly impact the plasma induced liquid phase chemistry responsible for the biological interactions. The impingement of gas jets on liquids has been studied in considerable detail (see for example [2]). Nonetheless, as the plasma has been shown to have a strong impact on the gas flow dynamics [3], similar impact is expected on the liquid interfacial dynamics.

In this study, penetration depth of an RF plasma jet and the associated dynamics of the liquid interface was studied by a Photron fast framing camera. The measurements have been performed in a container filled with 40 ml of distilled water. The RF jet is described in detail in [3, 4]. Figure 1 compares the jet penetration for the plasma on and off case for two different distances from the jet nozzle to the water surface: 2.54 and 15.24 mm. At the shortest distance, plasma is in electrical contact with the liquid and at the largest distance, no electrical contact between plasma and liquid occurs. As the penetration depth is oscillating in time, both the maximum and minimum penetration depth is shown.

The amplitude of the oscillations and maximum penetration depth is found to be higher when the plasma is on compared to the plasma off case. We still observe this effect at the largest distance between nozzle and water surface when no significant amount of charge is transferred to the liquid. This suggests that gas heating drastically changes the gas flow and consequently the induced liquid interfacial dynamics. The oscillation frequency is found to be lower compared to only gas flow at small distances and higher at the largest distance. This shows that additional disturbances occur at the liquid interface due to the interaction of the plasma filament with the liquid and/or charge injection from the plasma to the liquid. The gas flow rate, container size and plasma power also strongly influences the jet penetration as expected.

**References**

Controlled Deposition of Silicon Nanoparticles Using a Pulsed RF Argon-Silane Plasma

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Previous researchers have hypothesized that monocrystalline silicon films could be grown using an RF nanodusty plasma under conditions in which the impact energy of the nanoparticles on a (100)-Si substrate was enough to melt or amorphize the nanoparticles without causing film damage.[1] To explore this hypothesis, we have conducted numerical simulations in which an RF silane-containing plasma is pulsed while a positive DC bias (50-150V) is applied during the OFF phase in order to collect the nanoparticles that nucleate and become negatively charged and trapped in the plasma during the ON phase. By controlling pulse frequency, pressure, duty cycle and bias voltage, one could potentially control the fluence, size and impact energy (eV/atom) of the collected nanoparticles.

To investigate this scenario we utilized a previously developed 1-D numerical model of a capacitively-coupled RF argon-silane plasma in which nanoparticles nucleate and grow, modified to consider chemistry, plasma pulsing and applied substrate bias.[2] This model self-consistently solves for the coupled behavior of plasma, chemistry, and aerosol. Conditions include 13.56-MHz frequency, 100-200-V RF voltage amplitude, 100-200 mTorr pressure, 30:1 Ar-SiH4 with an inlet velocity at the top electrode of 27 cm/s, and 4-cm electrode gap.

Spatial profiles of electron and ion densities, electron temperature, plasma potential, and electric field are determined using a continuum formulation assuming that the electron energy distribution function is Maxwellian. The chemistry module considers silicon hydride neutral and ionic species containing up to two Si atoms. The rate of formation of anions containing three Si atoms is taken as a surrogate for the particle nucleation rate. The evolution of the particle size and charge distributions.[3] Phenomena considered include particle surface growth by chemical vapor deposition, size- and charge-dependent coagulation (accounting for the effect of image potentials for interactions between charged and neutral nanoparticles), charging by electron and ion attachment based on Orbital Motion Limited theory, and nanoparticle transport by electric force, neutral drag, ion drag and Brownian diffusion.

References
Modeling of 2D Capacitively Coupled RF Plasmas for the Synthesis of Silicon Nanocrystals

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Silicon nanocrystals are of high interest due to applications in light emission, photovoltaics, nanoelectronics, and biomedicine. We have developed a numerical model of a 2D capacitively-coupled RF plasma for the synthesis silicon nanocrystals. A description of the experimental set-up can be found in Ref [1]. The reactor is a narrow quartz tube (0.5 cm inner diameter) through which flows a mixture of argon, helium, and silane. The top electrode is powered at \(~15W\)—only \(~30\%\) is coupled to the plasma—and the bottom electrode is grounded. Typical plasma conditions are 2 Torr, 100 sccm Ar and 15 sccm He/SiH\textsubscript{4} with 5\% SiH\textsubscript{4}, and the gas temperature range is 400-600 K. Under these conditions, the nanoparticle residence time is 1-2 ms in the dense plasma region around the electrodes. It is possible to tailor particle size in the 3-5 nm diameter range by varying flow rates.

In this work, Girshick’s aerosol-plasma model [2] is incorporated into the Hybrid Plasma Equipment Model (HPEM) of Kushner’s group. The model solves Poisson’s equation for the electric field along with population balance, momentum, and energy equations for all gas species. The EEDF is calculated through a Boltzmann solver. An aerosol sectional model is used [4] to solve population balance equations, momentum equations, particle surface growth and coagulation, and particle charging. Nucleation and surface growth rates are self-consistently calculated based on the silicon hydride chemistry implemented. For each particle size, the charge distribution is self-consistently calculated knowing electron and ion fluxes to particles. The nanoparticle cloud is fully coupled to the plasma. Figure 1 shows total nanoparticle density in the tube and the nanoparticle size distribution along the center line. The nanoparticle concentration is greatest along the centerline. Under these conditions, nanoparticles are mostly negatively charged. Since the wall potential is lower than the plasma potential, particles are repulsed from the wall and pushed to the centerline. Nucleation becomes significant around 2 cm above the powered electrode. Surface growth rates peak between the two electrodes. The electron density is high up to 1 cm below the grounded electrode, as observed experimentally [1]. Similarly, the predicted H density corresponds to experimental observations, \(\sim10^{13}\text{ cm}^3\) [1].

References
Atmospheric pressure plasma jets (APPJs) have been shown to produce a therapeutic response in tissues, with benefits such as induced death of cancer cells [1]. One of the goals in designing APPJs is to control the propagation of the plasma ionization wave beyond the end of the tube and into the ambient air where reactive oxygen and nitrogen species (RONS) are produced. Since the parameter space for designing APPJs is large, it is critical to understand how design and operational parameters inter-relate and impact the discharge dynamics. In this paper we discuss results of a computational investigation of the dynamics of APPJs having two ring electrodes, and how these dynamics are affected by the placement of the rings and ground planes. A two-dimensional plasma hydrodynamic model, nonPDPSIM, was used for this investigation [2].

A typical geometry is shown in Fig. 1. In this case, the helium at 2 slm is flowed through a tube 1 mm in diameter with oxygen at impurity levels, 10 ppm. The powered electrode is at -20 kV for a pulse duration of 80 ns. When the lower electrode is powered the ionization wave (IW) primarily propagates in one direction, toward the grounded electrode ring. The IW is attenuated as it passes the grounded ring as much of the electron density goes to negative charge buildup on the dielectric surface to charge the capacitance of the ring-wall stack. The result is a high plasma density within the tube between the two rings with less intense propagation beyond the end of the tube. When the upper electrode is powered, the IW propagates in both directions, resulting in more rapid propagation out of the tube, and a slightly lower plasma density within the tube between the two electrodes.

References
Momentum, Heat, and Neutral Species Transport in Convective Atmospheric Plasma-Liquid Systems

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Interactions of atmospheric plasmas with liquids are important for a variety of applications including biomedicine, degradation of biological and chemical contaminants in waste-water, and agriculture. While progress has been made in realizing application technologies, there are still fundamental scientific questions that need to be answered in order to optimize these processes. In plasma medicine, for instance, the mechanism by which plasma reactivity is conveyed to subcutaneous cells is an active area of research. Works like [1] and [2] have shed some light on the matter, but more work remains, especially for convective atmospheric systems. In this work we investigate the transport of momentum, heat, and neutral species for a point-to-plane geometry common in pulsed coronas but also analogous to a gas jet impinging on a water surface. A fluid model is used and the governing equations are discretized using the finite element method implemented in the commercial multi-physics package COMSOL. [3]

The most prominent result obtained from the model is the existence of large gradients in reactive species concentrations at the gas-liquid interface. OH and ONOOH concentrations decrease by as much as 9 and 4 orders of magnitude respectively within 50 microns of the liquid surface. This result suggests that the majority of plasma reactivity is contained within a small interfacial layer. Moreover, in plasma medicine, cells submerged under water or tissue layers likely receive a small percentage of the reactivity that a target at the surface would receive. In addition to the interfacial concentration gradients, the model reveals a notable difference between bulk gas and liquid temperatures that arises from convective cooling and water evaporation. When the effect of convection on temperature is considered, terminal aqueous species concentrations change by up to factors of two because of changes in rate coefficients.

References
Effect of Humidity on the Surface Modification of Lipopolysaccharide (LPS) by Cold Atmospheric Pressure Plasmas

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The cold temperature surface micro-discharge (SMD), due to its scalable large area and relatively uniform discharge, has received much attention in the past five years \cite{1}. The SMD normally works under ambient air condition that contains not only N\textsubscript{2} and O\textsubscript{2} but also water vapor which usually has a big impact on both the plasma gas chemistry and surface reactions. In this study, the effect of humidity on efficacy of SMD-treatment of lipopolysaccharide (LPS) surfaces in various N\textsubscript{2}/O\textsubscript{2} mixture ambient was examined. We find that all SMD-treated LPS surfaces show oxygen uptake and NO\textsubscript{3} formation, while the amount of these modifications is strongly dependent on the gas environment. By comparing X-ray photoelectron spectroscopy (XPS) of wet-treated (50\% relative humidity at 20 °C) surfaces with their dry counterparts, as shown in figure 1, we find that the water vapor reduces surface modification, and the difference between wet- and dry-treated surface decreases with the increasing fraction of ambient N\textsubscript{2}. Among all the dry- and wet-gas conditions, the dry 5\% of N\textsubscript{2} ambient shows the greatest modification.

Furthermore, electrical and optical characterizations of the SMD source were also performed. We find that the additional water vapor results in extra power dissipation, even though it does not change the discharge current profile significantly. Optical emission spectrum (OES) of selected ambient conditions showed that the general emission intensity decreased with the extra water vapor. To our surprise, none of the wet environments show observable OH (A-X) emission for the SMD treatments.

We also evaluated the biological deactivation efficiency of SMD on LPS in both the dry and wet gases using enzyme-linked immunosorbent assay (ELISA). We find that the bio-deactivation rate of dry gases is much higher than that of their wet counterparts, except the synthetic air condition which shows comparable amount as in the XPS.

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References
Fluorocarbon Assisted Atomic Layer Etching of SiO₂ and Si Using a Cyclic Ar/C₄F₈ Plasma

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There is great interest in establishing directional etching methods capable of atomic scale resolution for fabrication of highly scaled electronic devices. Recently, controlled etching of SiO₂ at the Angstrom-level based on steady-state Ar plasma, periodic injection of a defined number of C₄F₈ molecules, and synchronized plasma-based Ar⁺ ion bombardment has been demonstrated.[1] Controlled etching is based on deposition of a thin (~ several Å) reactive fluorocarbon (FC) layer on SiO₂ and/or Si enabled by precise precursor injection, e.g. C₄F₈, CHF₃, and C₄F₆. For low energy Ar⁺ ion bombardment conditions, the physical sputter rate of SiO₂ vanishes, whereas SiO₂ can be etched when FC reactants are present at the surface. The physical sputter threshold of Si is lower than SiO₂, posing an additional challenge for selective etching. This cyclic approach was used to investigate the transition from SiO₂ to Si etching employing SiO₂-Si-SiO₂ layers. The etch behavior during the cyclic approach is compared to continuous precursor addition etching of SiO₂ and Si. Si etching and the selectivity of SiO₂ over Si is investigated as a function of FC surface coverage, ion energy (20 to 30 eV), and etch step length using in situ ellipsometry. Time-dependent etch and deposition rates are compared for Si and SiO₂. A key to high selectivity lies in the surface coverage and surface chemistry. Polymer deposition and etch behaviors on SiO₂ and Si substrates are therefore crucial and compared in detail. X-ray photoelectron spectroscopy is used to investigate surface chemistry at various stages of the cyclic etching. Additionally, the choice of precursor can have a significant impact on the surface chemistry and therefore the chemically enhanced etching. The nature of the thin FC films deposited in a cyclic fashion differs from the steady-state layer produced with conventional continuous precursor addition.

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References:

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Self-consistent modeling of plasma discharges requires a complete understanding of the plasma-wall interactions. Electrons emitted from materials (termed secondary electrons) due to bombardment by electrons, can have a significant impact on the sheath and overall behavior of plasmas [1]. The importance of plasma-material interactions in the presence of SEE, have prompted previous investigations of SEE properties of materials especially with applications to magnetic fusion, plasma thrusters, and high power microwave devices. In this work, we present results of measurements of SEE properties of graphite and lithium materials relevant to magnetic fusion devices and plasma thrusters applications [2, 3]. The total SEE yield, defined as the number of emitted secondary electrons per incident primary electron, has been measured for graphite and lithium for primary energies from 2-5000 eV and 20-900 eV, respectively [4-10]. This work builds on previous work by extending yield measurements for lithium up to 5 keV and by providing energy distributions of secondary electrons emitted from graphite and lithium.

Experiments are conducted in two vacuum facilities (i.e., 10^-10 Torr and 10^-8 Torr) at the Princeton Plasma Physics Laboratory. A device utilizing 4-grid optics for LEED/AES (low energy electron diffraction/Auger electron spectroscopy), which has an integral electron gun, is used to produce a mono-energetic electron beam. Measurements of SEE yield are made by measuring the primary electron beam incident on the sample and the flux of secondary electrons [12]. Additionally, the energy distribution of emitted electrons is measured by applying a retarding electric potential to semitransparent grids and measuring the current on a final screen from electrons with sufficient energy to overcome the applied potential. The spectrum of Auger electrons is used to determine surface composition during measurements. Temperature program desorption is used to determine lithium film thickness.

References
Surface Charge Dynamics and OH and H Number Density Distributions in Near-surface Nanosecond Pulse Discharges at a Liquid / Vapor Interface

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The poster presents results of an experimental study of surface charge dynamics and kinetics of radical species reactions in nanosecond pulse discharges sustained at a liquid-vapor interface, above distilled water surface. The near-surface plasma is sustained using two different discharge configurations, a surface ionization wave discharge between two exposed metal electrodes and a double dielectric barrier discharge. At low discharge pulse repetition rates (~100 Hz), residual surface charge deposition after the discharge pulse is a minor effect. At high pulse repetition rates (~10 kHz), significant negative surface charge accumulation over multiple discharge pulses is detected, both during alternating polarity and negative polarity pulse trains. Laser Induced Fluorescence (LIF) and Two-Photon Absorption LIF (TALIF) line imaging are used for in situ measurements of spatial distributions of absolute OH and H atom number density distributions in near-surface, repetitive nanosecond pulse discharge plasmas.

Both in a surface ionization wave discharge and in a double dielectric barrier discharge, peak measured H atom number density, \([H]\) is much higher compared to peak OH number density, due to more rapid OH decay in the afterglow between the discharge pulses. Higher OH number density was measured near the regions with higher plasma emission intensity. Both OH and especially H atoms diffuse out of the surface ionization wave plasma volume, up to several mm from the liquid surface. Kinetic modeling calculations using a quasi-zero-dimensional H\(_2\)O vapor / Ar plasma model are in qualitative agreement with the experimental data. The results demonstrate experimental capability of in situ radical species number density distribution measurements in liquid-vapor interface plasmas, in simple canonical geometry that lends itself for validation of kinetic models.
Controlling VUV Photon Fluxes in Inductively Coupled Plasmas

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Low pressure, non-equilibrium inductively coupled plasmas (ICPs) are widely used for materials processing in microelectronics fabrication. In these materials processing applications, there has been considerable effort to control the fluxes of radicals and ions, and the distribution of ion energies to the substrate, in order to optimize the surface properties. Less attention has been paid to the fluxes of vacuum-ultraviolet (VUV) photons produced by these low pressure plasmas and the consequences of those fluxes on materials properties.

VUV photons are increasingly recognized as being important reactants in ICPs, and have been found to have both negative and synergistic effects in microelectronics processing. VUV fluxes are a source of damage to ultralow dielectric constant films, such as porous SiOCH, during plasma etching.[1] Coincident with ion fluxes, VUV photons can change the roughening characteristics of photo-resist as a function of temperature,[2] or produce etching when the energies of the ion fluxes are below the accepted thresholds for ion initiated etching in halogen-containing ICPs.[3] These observations motivate the development of methods to independently control VUV photon fluxes or to control the ratio of VUV fluxes to ion fluxes in ICPs used for materials processing.

In this work, we discuss results from a computational investigation of VUV fluxes produced in low-pressure (up to tens of mTorr) continuous wave (CW) ICPs sustained in Ar, Ar/Xe and He/Ar gas mixtures. The goal of this investigation is to characterize the VUV fluxes and propose methods to control the absolute value of VUV fluxes, their spectra and the ratio of VUV fluxes to ion fluxes. The model used in this investigation is the Hybrid Plasma Equipment Model (HPEM), which is a 2-dimensional hydrodynamics model with radiation transport addressed by a spectrally resolved Monte Carlo simulation. We found that in CW ICPs with Ar, VUV fluxes are a function of gas pressure (see Fig. 1) with a dependence on reactor geometry. Some coarse tunability of the VUV emission is also possible by use of rare-gas mixtures.

References
## List of Participants

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</table>
Stamp Student Union

**Basement**
1 – Art & Learning Center (B0107)
2 – Activities Room (B0108)
3 – TerpZone–Bowling/Billiards/TV Lounge (B0106)
4 – Subway (B0106)
5 – Food Co-op (B0203)
6 – University Book Center
7 – Facilities Office (B0226)
P – Public Phones
R – Restrooms
E – Elevator
GROUND FLOOR

Ground Floor
7 – Hoff Theater (0126)
8 – Stamp Ticket Office (0124)
9 – Baltimore Room (0240)
10 – Campus Programs – Student Engagement/
     Leadership/Community Service Learning (0110)
11 – Food Court (0496)
12 – McDonald’s (0215)
13 – Saladworks (0214)
14 – Moby Dick
15 – Sbarros (0212)
16 – Chick-Fil-A (0118)
17 – Sushi by Panda (0117)
18 – Taco Bell (0113)
19 – Auntie Anne’s (Coming soon)
20 – Panda Express (0112)
21 – Capital One Bank (0105)
22 – Terrapin Shipping and Mailing (0211)
23 – University Book Center (Terp Shop)
24 – Student Involvement Suite (0207, 0208, 0209)
25 – Union Shop (0210)
26 – Copy Services (0232)
27 – SEE – Student Entertainment Events (0221)
28 – Terrapin Technology Store (0203)
P – Public Phones
FR – Family Restroom
R – Restroom
E – Elevator
First Floor
28 – Coffee Bar (1203)
29 – Multicultural Involvement & Community Advocacy (1120)
30 – Adele's (1240)
31 – Graduate Student Suite (1121)
32 – Event Services/Marketing
33 – North Court (1482)
34 – Undergraduate/Graduate Legal Aid (1235)
35 – Nanticoke Room (1238)
36 – Marketing Asst. (1236)
37 – Stamp Gallery (1220)
38 – Atrium (1107)
39 – Off Campus Housing (1110)
40 – Information Desk (1201)
41 – Prince George's Room (1210)
42 – Grand Ballroom Lounge (1209)
43 – Grand Ballroom (1206)
44 – Reading Room (1105)
45 – Office of Fraternity & Sorority Life (1110)
R – Restrooms
E – Elevator
SECOND FLOOR

Second Floor
47 – Technology Services - IT Help/
Audio Visual Services (2220)
48 – Thurgood Marshall Room (2113)
49 – Margaret Brent Room (2112)
50 – Colony Ballroom (2203)
51 – Harriet Tubman (2110)
52 – Pyon Su Room (2108)
53 – Edgar Allen Poe Room
54 – Calvert Room
55 – Crossland Room
56 – Juan Ramon Jimenez Room
57 – Benjamin Banneker Room
58 – Charles Carroll Room
R – Restrooms
E – Elevator