Plasma Science and Technology
Room: 305 - Session PS1-FrM

Plasma Sources
Moderator: Steven Vitale, MIT Lincoln Laboratory

8:20am **PS1-FrM1 Small High Density Plasma Sources for Focussed Ion Beam Applications**, ***Rod Boswell***, Australian National University, Australia **INVITED**

Oregon Physics has developed the HyperionTM system of high brightness plasma ion sources which are now being used on Focused Ion Beams and TOF-SIMS around the world. These plasma sources are ten times brighter than present sources and reduce the time necessary for analysis from days to hours. They are also more reliable and can be focused down to smaller spots. The development of these sources, especially the optimization of the rf antenna design and extraction geometry will be described. Extraction of positive ions is used for reverse engineering on the nano-metre scale and negative ions are used for Time of Flight Secondary Ion Mass Scectroscopy (TOFSIMS).

SIMS uses beam of primary ions (typically O-) focused onto a target. Sputtered secondary ions are measured by mass spectrometer which can detect elements and their isotopes in the low parts per billion (10-9 or ng/g) range. Particles as small as a few 100 nanometres can be analysed.

Time of Flight (TOF)SIMS measures the time of arrival of the secondary ions at the detector, which depends on their mass yielding an extremely good high mass resolution. It can detect: cocaine in urine, benzodiazepines (eg. valium) in hair and gunshot residues in fingerprints even after strenuous washing! Additionally, TOF-SIMS can simultaneously detect cocaine in the presence of other drugs (i.e. flurazepam (a benzodiazepine hypnotic) and chlorpromazine (used for psychosis and heroin withdrawal) in urine. It is possible to relate the TOF-SIMS fingerprints to the evidence found at the crime scene, which can be considered as examination of forensic evidence transfer. Elemental composition of anthrax spores using TOF-SIMS has been carried out by Weber et. al. at LLNL. This is of use in assessing the origin of bio-weapons.

9:00am **PS1-FrM3 A Remote Microwave Plasma Source for Reactive Gas Generation**, ***Xing Chen***, *I. Pokidov, K. Wenzel, C.X. Ji*, MKS Instruments, Inc.

A remote microwave plasma source has been developed for generation of activated gases, such as O, H, N and F. The plasma source comprises a dielectric tube surrounded by a conductive coil that serves as microwave antenna and cooling structure. A waveguide is coupled to a microwave cavity to guide the microwave energy into the plasma discharge tube. The electric field of the microwave energy is oriented such that microwave propagates along the conductive coil and deposits energy uniformly in the plasma tube. The plasma discharge tube can be made of quartz, sapphire, aluminum nitride or other dielectric materials to accommodate various gas chemistries. This paper characterizes the plasma source and its operation with O_2, N_2, H_2, H_2O, NH_3, H_2/N_2 and H_2/He gasses. Experimental measurements of plasma density and atomic gas flux of O, N, and H, using Langmuir probes, recombination probes and calorimetry, are presented. Typical plasma density is on the order of 10^{12} cm^{-3}. The plasma source operates in a broad range of power and gas flow conditions. The use of microwave plasma generation, combined with crystalline plasma tube materials, significantly reduces tube erosion and associated chemical and particle contaminations.

9:20am **PS1-FrM4 Mechanisms for Plasma Density Distribution Control using a Large Diameter Radial Line Slot Antenna Microwave Plasma Source**, ***Toshihiko Iwao***, *T. Hirano, A. Suzuki*, Tokyo Electron Limited, Japan, *P. Ventzek*, Tokyo Electron America, *K. Ishibashi*, Tokyo Electron Limited, Japan

Microwave plasmas are frequently employed for etch, thin film deposition and surface activation for semiconductor or flat panel manufacturing. A major advantage of microwave driven plasma sources operating in the overdense regime or surface wave regime is that the plasmas in the high density source and lower density substrate contacting region may be well separated. This separation is useful for damage free or highly selective plasma process applications. The radial line slot antenna is an efficient microwave applicator for these process applications. Microwaves are radiated from a metal plate with a slot pattern adjacent to the dielectric top window. The electromagnetic field distribution and plasma density are controlled by optimizing the pattern. [1] Uniform plasma processes with the radial line slot antenna source have been demonstrated; however, it is challenging to overcome the tendency of the substrate-contacting plasma to become center-dense in large volume reactors under the action of ambipolar diffusion at low pressure. In this presentation, we present the results of an investigation of the effect of antenna size on the plasma density distribution for a wide gap reactor. A concurrent experimental and simulation study reveal the importance of controlling the transport parameters in the downstream wafer-contacting region to overcome ambipolar diffusion. [2] In particular, we show how the source region plasma generation impacts the electron energy distribution function in the downstream region. Anisotropic features in the electron energy distribution function plays a critical roll in controlling the plasma uniformity which we demonstrate through plasma absorption probe measurements and simulations of plasma structure.

[1] Y.Yasaka, et al., Phys.Plasmas 9, 1029(2002)

[2] J.Yoshikawa, et al., J. Vac. Sci. Technol. A 31, 031306(2013)

9:40am **PS1-FrM5 The NEPTUNE Bipolar Source: A New Instrument for Surface Treatment Applications**, ***Dmytro Rafalskyi***, *A. Aanesland*, LPP, CNRS - Ecole Polytechnique, France

In this work we present a recently patented and developed source of oppositely charged particles called "Neptune". The source accelerates simultaneously positive ions and electrons extracted from an ICP discharge. The produced broad beam is quasi-neutral with high directionality of all emitted charged particles, and as a result a dedicated neutralizer is redundant in this system. The source can be operated using any kind of working gas, such as Ar, SF_6, CF_4 etc. The simultaneous ion-electron extraction is realized using the RF self-bias effect in low-pressure plasmas. A double-grid ion optical system is RF-powered ensuring both efficient ion extraction and acceleration, and electron injection. In the extraction system ions are continuously accelerated in the RF sheath between the first (plasma/screen) and second grids, while the electrons are extracted periodically when the sheath collapses. Due to the fact that the extraction system is RF-powered via a capacitor, a DC current cannot flow between the extraction grids, and the total amount of ions and electrons escaping the plasma is the same. The first proof-of-concept of the Neptune source is demonstrated. First results of the beam measurements are reported, particularly in comparison with a traditional 2-grid ion source equipped with an external neutralizer. We show here that the Neptune source can be efficiently used for low-ARDE processes, as well as for other applications where the accelerated flows with high directionality of both kinds of charged species are required. It is demonstrated that the independent control of the ion flux and energy allows achieving bipolar beams generation in wide range of parameters. It is shown that the proposed ion-electron extraction technique reduces charging effects on the substrate. This work was supported by a Marie Curie International Incoming Fellowships within the 7th European Community Framework (NEPTUNE PIIF-GA-2012-326054) and by ANR under grant number ANR-2011-BS09-40.

10:00am **PS1-FrM6 Process Optimization by Phase Control in Multi-Frequency Capacitive RF Plasmas**, ***Julian Schulze***, *E. Schuengel*, West Virginia University, *A. Derzsi, I. Korolov, Z. Donko*, Hungarian Academy of Science, Hungary

An overview of a novel method to control process relevant plasma parameters and particle flux-energy distribution functions in multi-frequency capacitive radio frequency (CCRF) plasmas is presented. Based on experimental, simulation, and modeling studies in different gases (Ar, H_2, SiH_4, CF_4) we demonstrate that the ion flux-energy distribution function at the substrate can be controlled separately from the ion flux by adjusting the harmonics' phases and amplitudes in a CCRF discharge driven by multiple consecutive harmonics based on the Electrical Asymmetry Effect. The quality of this separate control is significantly better compared to classical dual-frequency plasmas driven by two largely different frequencies. Adding more harmonics enlarges the control range. Tuning the ion energy by phase control in H_2-SiH_4 plasmas allows to control the morphology of deposited Si:H thin films. In large area CCRF plasmas radial inhomogeneities of the ion flux due to standing wave effects can be prevented by customizing the driving voltage waveform.

These optimizations of process control are based on a detailed scientific understanding of the non-local particle heating mechanisms in technological plasmas. Such mechanisms are complex and strongly depend on global control parameters such as the gas mixture, pressure, and voltage amplitudes. Differences of the electron heating mechanisms in electropositive and electronegative plasmas and their effects on process control will be discussed. In electronegative and/or dusty plasmas, e.g. operated in CF_4 or SiH_4, a novel heating mode, the Ω-mode, and novel coupling mechanisms between the driving frequencies are present and strongly affect process relevant plasma parameters. Moreover, resonance phenomena such as the Plasma Series Resonance play a major role in multi-frequency CCRF plasmas driven by customized voltage waveforms at low pressures of a few Pa.

Existing processing reactors can be easily upgraded to use the method of phase control in multi-frequency plasmas by modifying the external RF supply only. No modifications of the reactor itself is required, but a detailed understanding of the plasma physics is needed to optimize plasma-surface interactions.

10:40am **PS1-FrM8 Controlling the Flux of Reactive Species in Electron Beam Generated Plasmas**, ***Scott Walton****, D.R. Boris, E.H. Lock, S.C. Hernandez, Tz.B. Petrova, G.M. Petrov*, Naval Research Laboratory

Electron beam generated plasmas are characterized by high plasma densities (> 10^{9} cm^{-3}) and very low electron temperatures (< 1 eV), making them well-suited for next-generation processing techniques where high fluxes of low energy ions are desirable. In this work, we focus on controlling the flux of reactive species incident to substrates located adjacent to magnetically collimated electron beam generated plasmas. In particular, we discuss strategies for regulating both the type and energy of the ions at the substrate surface. We use a suite of diagnostics including Langmuir and RF impedance probes along with a mass-resolved ion energy analyzer to show how various operating parameters can be changed to control both the bulk plasma properties and the ion flux at the surface. This work is supported by the Naval Research Laboratory Base Program.

11:00am **PS1-FrM9 Ignition Delay in Electronegative Pulsed Dual Source Tandem Plasmas**, ***Shyam Sridhar****, L. Liu, D.J. Economou, V.M. Donnelly*, University of Houston

Control of the ion energy distribution (IED) is of utmost importance in semiconductor manufacturing. Pulsed plasmas can produce IEDs with small energy spread, necessary to enhance etching selectivity and minimize damage. However, the IED is broadened during the power-on period by capacitive-coupling, imposing an RF potential on the DC plasma potential. This can be eliminated with a Faraday shield but, with electronegative gases, it is not possible to ignite pulsed ICPs, since electron density rapidly decays when power is off, and re-ignition requires large electric fields produced by high-voltage capacitive coupling. Motivated by this problem, we have explored a "tandem" plasma system, where a continuous (auxiliary) ICP is injected through a grid into a pulsed (main) ICP. Using such a system, an ignition delay was observed in pulsed (period 1 ms) Cl_2 plasmas with a duty ratio (DR) ~ 60%. The ignition delay monotonically increased with DR to reach a maximum of 500 ms at DR ~99%. It was also observed that, for a given DR, the ignition delay increased by increasing the main ICP power or by decreasing the auxiliary ICP power. The ignition delay may be attributed to the low electron density in the main ICP, which decays to a value less than the density when the auxiliary ICP were operating alone. At low electron densities, power transfer efficiency is poor. The flux of seed electrons from the auxiliary ICP then acts to restore the electron density, thereby improving the power transfer in the main ICP and allowing plasma re-ignition. Similar results were also observed using other electronegative gases such as SF_6 and CF_4/O_2 mixtures.

11:20am **PS1-FrM10 A Global Model for Ignition Delay of Pulsed Electronegative Plasmas**, ***Lei Liu****, S. Sridhar, D.J. Economou, V.M. Donnelly*, University of Houston

A Faraday shield can be employed to minimize capacitive coupling in inductively coupled plasmas (ICP), to obtain ion energy distributions with a tight energy spread. However, in the presence of a Faraday shield, it is challenging to operate a pulsed electronegative plasma with a long afterglow duration, as most of the electrons are lost, and re-ignition requires large electric fields produced by high-voltage capacitive coupling. Our experimental studies have shown that by using a dual plasma source, consisting of a main pulsed ICP in tandem with an auxiliary continuous wave ICP, Faraday-shielded pulsed plasmas in electronegative gases can be produced even with long afterglow duration (1000 μs). However, an ignition delay was observed with duty cycles >60%. A global (spatially averaged) model with chlorine chemistry was developed to describe the mechanism of ignition delay. The flux of charged species from the auxiliary ICP was included in both particle and energy balance equations. Predicted results of ignition delay for different duty cycles, auxiliary ICP powers and main ICP powers agreed with experimental observations. The observed ignition delay increasing with increasing duty cycle is counter-intuitive. One would expect that, as the duty cycle increases, and the afterglow time correspondingly decreases (for constant pulse period), the electron density at the end of the afterglow would be higher, making it easier to re-ignite the plasma, i.e., shorter delay time, in contrast to observation. Once the lower plasma power is off for > ~5μs it appears that there is a critical electron density in the lower plasma (n_{cr}), equal to or below the electron density when the upper (cw) plasma is operating alone (no power in the lower plasma). When both plasmas are powered, the afterglow of the lower plasma keeps decaying for as long as the electron density is above n_{cr}. This is because the rate of plasma production is then lower than the rate of plasma loss. As soon as the electron density falls below n_{cr}, the rate of plasma production starts exceeding the rate of plasma loss, and the electron density starts increasing, eventually re-igniting the ICP. Now, the higher the duty cycle, the higher the electron density at the end of the afterglow, and the longer it takes for that electron density to decay to n_{cr}, resulting in longer delay times.

11:40am **PS1-FrM11 Ion Energy Distribution Control Using Phase Locked Harmonic Drive**, *A. Zafar,* North Carolina State University*, Y. Zhang,* University of Michigan*, T. Kummerer,* North Carolina State University*, D.H. Clark,* Plasmatherm Inc.*, M.J. Kushner,* University of Michigan*, D. Coumou,* MKS Instruments*,* ***Steven Shannon***, North Carolina State University

Dual frequency RF power delivery has demonstrated the capability to increase the operating range of industrial plasmas including independent control of electron density and sheath bias and control of ion energy distribution function (IEDF) width. In this talk, we focus on the later demonstration and present a method for enhanced control of IEDF shape by utilizing a dual frequency drive where harmonic frequencies are employed and the relative phase of these two applied waveforms is controlled. We will show that by controlling both current ratio and phase angle, not only can the width of the distribution be controlled, the higher order moments (specifically distribution skew) can also be controlled, providing distribution functions that are either skewed toward the low energy peak of a typical bimodal RF driven IEDF or skewed toward the high energy peak. Experimental and simulated results will be presented for both dual frequency and three frequency configurations.

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