Plasma Science and Technology
Room: 304 - Session PS1-ThA

Plasma Diagnostics, Sensors, and Control II
Moderator: V.M. Donnelly, University of Houston

2:00pm **PS1-ThA1 Spatial Density Distribution of Low-energy Electrons in a 2f-CCP by Laser Absorption and Optical Emission Spectroscopy**, ***T. Ohba***, KEIO University, Japan, *T. Kitajima,* National Defense Academy of Japan, *T. Makabe*, KEIO University, Japan

Optical emission spectroscopy (OES) is widely used as the tool of plasma diagnostics and plasma characteristics. The OES is restricted to the phenomena caused by higher energy electrons over the threshold of the electronic excitation of the target molecule mostly greater than ~10 eV, while the mean energy of electrons in a low-temperature radio frequency plasma is typically 3-5 eV in the bulk plasma, A simple in-situ method to determine spatiotemporally resolved transport of low energy electrons in a two-frequency capacitively coupled plasma (2f-CCP) is presented by using OES and laser absorption spectroscopy in pure Ar.[1] The method employs the long-lived metastable atom Ar($1s_5$) and short-lived excited Ar($2p_9$). Due to the large cross section of metastable atoms with electrons,[2] the net excitation rate of Ar($2p_9$) obtained by OES is expressed as a function of the electron density at the peak energy ~3.3 eV and the metastable density. The spatiotemporal measurement of the electron density distribution with energy of ~3 eV is demonstrated in a typical condition in a 2f-CCP, driven at 100 MHz and biased at 500 kHz in pure Ar at 25, 50 and 100 mTorr. The density shows almost no dependence on time in the bulk plasma and has a sharp peak in the sheath in front of the bias electrode at higher pressure. The influence of photon reabsorption will be further discussed.

[1]M. Ishimaru, T. Ohba, T. Ohmori, T. Yagisawa, T. Kitajima and T. Makabe, Diagnostics for low-energy electrons in a two-frequency capacitively coupled plasma in Ar , Appl. Phys. Lett. 92, 071501 (2008)

[2]A. A. Mityureva and V. V. Smirnov, Opt. Spectrosc. 97, 508 (2004).

2:20pm **PS1-ThA2 Time-Resolved Absorption Spectroscopy with LEDs as Light Source: Application to Etching Plasma Monitoring**, ***G. Cunge***, *D. Vempaire, M. Touzeau, N. Sadeghi*, LTM-CNRS, France

Broad band absorption spectroscopy is widely used to measure the concentration of radicals, which is important to understand the physical chemistry of many plasmas. We show that it is possible to increase significantly the sensitivity of this technique and to perform time-resolved measurement by using Light Emitting Diodes (LEDs) as a light source. This is obtained thanks to the high stability of the LED intensity. By modulating the LED current and using a lock-in amplifier for light detection, it is possible to get rid of the plasma emission, which greatly enhances the reliability of the absorption spectroscopy technique in reactive plasmas. In particular, wavelength dependent absorption cross section can be measured without any distortion, inherent to baseline fluctuations when using other light sources such as Xe arcs. This is particularly important when the species absorbs over a broad band continuum. Finally, we show that it is possible to achieve time resolved measurements of radical density decay in the afterglow of pulsed discharges, giving insight into the gas phase and surface loss processes of these radicals. The method is applied to study radical loss kinetics in BCl3 and SiCl4 based high density plasmas. We concluded that UV absorption with LED is a new and powerful plasma diagnostics, which allows detecting several radicals with a small and low cost equipment, and which may be used for real time process monitoring applications.

2:40pm **PS1-ThA3 Spatio-temporally Resolved Optical Emission Spectroscopy for Investigating rf Plasmas and Micro-Discharges**, ***D. O'Connell***, Queen's University Belfast, Northern Ireland **INVITED**

Non-thermal low temperature plasmas are widely used for technological applications. Increased demands on plasma technology have resulted in the development of various discharge concepts based on different power coupling mechanisms. Despite this, power dissipation mechanisms in these discharges are not yet fully understood. Of particular interest are low pressure radio-frequency (rf) discharges and also more recently developed micro-discharges at elevated pressure. Optical measurements are a powerful diagnostic tool offering high spatial and temporal resolution. Improved advances in technology and modern diagnostics now allow much better temporal resolution and deeper insight into fundamental mechanisms. In low pressure rf discharges insight into the electron dynamics within the rf cycle can yield vital information. The optical emission from these discharges exhibits temporal variations within the rf cycle, requiring high temporal resolution on a nano-second time scale. These variations are particularly strong, in for example capacitively coupled plasmas (CCPs), but also easily observable in inductively coupled plasmas (ICPs), and can be exploited for insight into power dissipation. Interesting kinetic and non-linear coupling effects are revealed in capacitive systems. In the relatively simple case of an asymmetric rf CCP the complexity of the power dissipation is exposed and various mode transitions (gamma-, alpha-mode and wave-particle interactions) can be clearly observed and investigated. Multi-frequency plasmas, provide additional process control for technological applications. Through investigating the excitation dynamics in such discharges the limitations of functional separation is observed. Recently developed micro-plasmas provide reactive plasma environments for processing applications without the need for expensive vacuum systems. On the one hand they allow extremely localised treatment, e.g. localised surgery. On the other hand they can provide the opportunity for controlled and scalable large area treatment using array devices of thousands or millions of micro-plasmas. However, fundamental understanding of the important mechanisms in particular coupling effects between individual discharge devices is to date poorly understood. Time and space resolved optical emission spectroscopy reveal details of these mechanisms.

3:20pm **PS1-ThA5 Time Resolved Studies of Ion Dynamics in an RF-Biased Plasma Reactor**, ***B. Jacobs***, *W. Gekelman*, University of California - Los Angeles, *M. Barnes,* Intevac Corporation, *P. Pribyl*, University of California - Los Angeles

Plasma reactors used in semiconductor processing require precise control over both ion bombardment energy and ion flux to the substrate surface; furthermore these parameters must be uniform over the entire substrate. We report on Laser-Induced Fluorescence (LIF) measurements of the vertical and radial argon ion velocity distributions in a vertical plane above the wafer in an Inductively Coupled Plasma (ICP) Plasma Reactor with a 700 kHz ICP source and a 2 MHz capacitively coupled bias to a 300 mm silicon wafer substrate. The ICP source is capable of pulsed operation with periods of 1 - 100 ms and variable duty cycles. The LIF diagnostic measures ion velocities at over 30,000 points simultaneously in a 10 cm x 8 cm region with a 500 µm spatial and 10 ns temporal resolution. The laser can be phase-locked to either the ICP or capacitive substrate bias source. In this manner, two-dimensional ion distribution functions are investigated as a function of the RF phase of the capacitively coupled substrate bias as well different phases of the ICP pulse period. By combining the LIF data with Langmuir probe and microwave interferometer measurements, we obtain previously unavailable data in relation to the ion dynamics over a 300mm substrate - including ion energy and angular distributions, ion drifts and heat flux, and their spatial variations.

4:00pm **PS1-ThA7 A New Diagnostic Based on Fast Atom-Atom Ionization to Measure the Energy Distribution of a Fast Neutral Beam**, ***A. Ranjan***, *V.M. Donnelly, D.J. Economou*, University of Houston

A new diagnostic was developed to measure the energy distribution of a fast (10s to100s eV) neutral beam. Fast neutrals were allowed to collide with slow (thermal) neutrals in a chamber of controlled background pressure (e.g., 10^{-4} Torr). A fraction of the fast neutrals was ionized as a result of the atom-atom collisions. The ionized species current was measured as a function of energy with a gridded energy analyzer and off-axis channel electron multiplier, housed in a differentially pumped chamber. The energy distribution of the fast neutral beam was determined from the known cross section of the atom-atom ionization collision as a function of energy. The method was applied to measure the energy distribution of a fast neutral beam formed by surface neutralization of ions, extracted through a grid with high aspect ratio holes (neutralization grid). A pulsed-plasma technique was implemented to achieve an ion beam with a tight energy spread. Ion energy was controlled by a DC bias, applied on an electrode in contact with the plasma, during part of the afterglow period. The electron temperature decays rapidly in the afterglow, which yields a nearly uniform space potential, resulting in an ion beam with tight energy spread. The peak of the NED was ~7% lower than that of the parent ion energy distribution (IED), compared to a ~3% expected energy loss, based on specular reflection. The neutral energy distribution (NED) had a larger energy spread as compared to the parent IED. For example, the FWHM of a NED and the corresponding parent IED were 32 eV and 10 eV, respectively. To study the effect of surface roughness of the neutralization grid, results for a metal grid with a "rough" surface (roughness ~ 10s of nm) will be compared with those of a "smooth" (0.15 nm RMS roughness) silicon grid.

4:20pm **PS1-ThA8 Metastable Probe in Remote Helium Plasma**, ***N. Miura***, *J. Hopwood*, Tufts University

An electrostatic probe for measuring helium metastable density was designed and tested in low-pressure, remote helium plasmas. The measured spatial distribution of helium metastable atoms was then compared with a numerical flow simulation of the plasma. The probe measures secondary electron emission due to helium metastable fluxes at a clean stainless steel surface. The probe consists of a small, planar surface surrounded by an outer guard ring. The outer ring was biased positively to reject plasma ions and the inner part was biased negatively to reject the remaining electrons. In this manner only neutral atoms reach the inner surface, and the inner probe current is due to metastable-induced secondary electrons. Energetic photons generated in the upstream plasma source region were screened from the probe, avoiding photoelectron emission. The experimental gas pressure was 5.5 - 7.5 mTorr inside a 15-cm diameter chamber located downstream from an ICP. Three metastable probes were positioned at different distances downstream from the ICP source and simultaneously swept in the radial direction to obtain spatially-resolved metastable densities. In comparing these measurements to models, the diffusive flow approximation was not completely valid since the mean free path of the metastable atoms was not negligible relative to the chamber dimensions.[1] Therefore, the metastable flow was simulated by both the continuous fluid model and the Monte Carlo method. The results are compared and discussed. The conventional method to measure metastable density is optical absorption, which is well-established and non-invasive.[2,3] That technique gives the density integrated along the optical path and lacks spatial resolution unless Abel inversion is applied. The probe method described here has good spatial resolution, but it is invasive and the secondary electron emission yield is very sensitive to the probe's surface cleanliness.[4] The probe also relies on electrostatic screening due to the biases applied to its surfaces, so the method is only practical in regions of low electron density such as remote plasmas (~10^8 cm^{-3}).

[1] P.J. Chantry, J. Appl. Phys. 62, 1141 (1987).
[2] A.V. Phelps, Phys. Rev. 99, 1307 (1955).
[3] K.E. Greenberg and G.A. Hebner, J. Appl. Phys. 73, 8126 (1993).
[4] T.A. Delchar, D.A. McLennan, and A.M. Landers, J. Chem. Phys. 50, 1779 (1969).

4:40pm **PS1-ThA9 Etch Process Control with a Deposition-Tolerant Planar Electrostatic Probe**, ***J.P. Booth***, *D. Keil, C. Thorgrimsson, M. Nagai, J. Kim, L. Albarade*, Lam Research Corporation

We have implemented the deposition-tolerant ion flux probe described by Braithwaite et al.[1] as an in-situ process monitoring sensor on a commercial dielectric etch tool. The probe head is integrated into the upper (grounded) electrode and is made of the same material, and has been shown to have negligible process impact. With the use of an embedded digital signal processor to analyze the current-voltage characteristics in real-time, this sensor delivers high-precision time-resolved measurements (at 10 Hz) of the ion flux, electron temperature and probe floating potential. In addition, if there are thin films deposited on the probe, the film thickness and conductivity can be determined. This gives unprecedented insight into the power delivery, gas composition and surface state of the reactor during wafer processing. This talk will explore how this information can be used to improve the yield, throughput and cost-of-ownership of production etch tools.

[1] N. St.J. Braithwaite, J.P. Booth, and G. Cunge, Plasma Sources, Science and Technol., 5, 677, (1996).

5:00pm **PS1-ThA10 A New Diagnostic Tool of Radio-Frequency Etching Plasma Produced in Insulated Vessels**, ***H. Shindo***, *K. Kusaba*, Tokai University, Japan

A new method to measure electron temperature and electron energy distribution function by an emissive probe has been proposed.[1] The method is based on measurement of the functional relationship between the floating potential and the heating voltage of emissive probe. From the measured data of the floating potential change as a function of the heating voltage, the electron temperature could be determined by comparing with the theoretical curve obtained under the assumption of Maxwellian distribution. The overall characteristic of the floating potential change could be explained as a function of the heating voltage. The electron temperatures obtained by the present method were consistent with those measured by the rf-compensated Langmuir probe within the error. These experimental verifications were made in the electron density range of $2.6x10^{11}$–$2.8x10^{12}$ cm^{-3} in an inductively coupled plasma of Ar. In this study, a prototype of the diagnostic tool based on the present method was developed in a computer-aided fashion. The method was also applied to a SF_6 etching plasma which was produced in ceramic discharge tubes by surface-wave with the frequencies of 13.56 and 60 MHz. In this experiment, the Renium filament was employed, and the erectron energy as well as the potentials were measured in SF_6 plasma. These data were found to be consistent with the Si ecth rate obtained in the SF_6 plasma. It was stressed that the present method was advantageous in that the probe is operated in a floating condition, hence applicable to plasmas produced in an insulated container. The electron energy distribution function was also obtained in. SF_6 etching plasma which was produced in ceramic discharge tubes by surface-wave.

[1] K. Kusaba and H. Shindo, Review of Scientific Instruments, 78,123503(2007).

5:20pm **PS1-ThA11 Near-Real-Time Two-Dimensional Wafer Surface Measurements for Process Optimization and Control**, *C.T. Gabriel*, Spansion, Inc., ***G. Roche***, KLA-Tencor

Optimizing and monitoring plasma etching processes has always relied on one-dimensional data provided by the plasma tool (reflected power, Vdc, optical emission intensity, etc.) or by post-etch measurements such as critical dimensions or film thickness changes. It has long been desired to monitor the plasma condition across the wafer surface in real time. Wafer-level sensors have been developed to measure the temperature of the wafer surface in near real time, and now sensors are being developed to monitor other plasma parameters in a similar way. Here we present measurements of Vrf, a parameter related to the plasma potential, taken from a two-dimensional array of sensors across the surface of a 300 mm wafer processed in a multi-frequency, capacitively coupled industrial plasma for dielectric etching. We show the relationship between Vrf and several process parameters, including RF power, pressure, and CO flow rate. The one-dimensional electrostatic chuck voltage, Vesc, does not respond to these parameters in the same way. Some plasma transients were detected by Vrf that were not detected by Vesc or by optical emission intensity. Vrf appears to correlate with plasma density, and because it is an array of detectors, it proved useful in identifying degraded plasma uniformity at lower CO flows. Such wafer-level Vrf measurements may be valuable for applications such as plasma monitoring, chamber matching, and process optimization to minimize plasma process induced damage.

Authors Index

Bold page numbers indicate the presenter