Plasma Science and Technology
Room 311 - Session PS2-ThM

Plasma Diagnostics II

Moderator: E.A. Edelberg, Lam Research Corporation

8:20am **PS2-ThM1 Advanced Actinometry of Inductively Coupled Cl@sub 2@-Ar Plasmas For Plasma Etching***, **N.C.M. Fuller**, I.P. Herman,* Columbia University*; V.M. Donnelly,* Bell Laboratories, Lucent Technologies

The exact composition of Cl@sub 2@-Ar plasmas can influence the overall mechanism and rates of adlayer formation and removal (ion-induced sputtering) during the etching of various materials; therefore, the mixture composition can be altered to improve the overall plasma chemical etching process. To this end, optical emission spectroscopy (OES) and Langmuir probe analysis have been used to measure the electron temperature, T@sub e@ and the absolute species densities in a high-density inductively coupled (ICP) chlorine-argon plasma at 18 mTorr as function of the 13.56 MHz radio frequency (rf) power and argon fraction. In the H (bright) mode, the electron temperature, T@sub e@, measured by trace rare gases optical emission spectroscopy (TRG-OES), increases from 3 eV at 350 W to ~ 6 eV at 770 W for a chlorine plasma (1% Ar). At 600 W (10.6 Wcm@super -2@), T@sub e@ increases from 5.0 eV to ~ 6.5 eV as the argon fraction increases from 0.01 to 0.73. In the E mode at 200 W, the fraction of Cl@sub 2@ that dissociates to form Cl increases from ~10% to ~ 40% as the argon fraction increases from 0.01 to 0.73. In the H mode at 600 W, this dissociation fraction increases from 82% to 96% over the same range. In the H mode and for all argon fractions, the electron density, calculated by a global model, increases by at least an order of magnitude from 300 W to ~ 750 W, and at 600 W it decreases from 1.0 x 10@super 12@ cm@super -3@ to 5.5 x 10@super 10@ cm@super -3@ as the argon fraction increases from 0.01 to 0.73. OES is also used to estimate the peak value of the electron impact excitation cross section for the dissociative excitation of Cl@sub 2@ to the Cl (4p@super 2@ D@super 0@ J@super '@ = 3/2, 5/2) excited state with subsequent emission at 822.2 nm. This peak value is 1.7±0.3 x 10@super -19@ cm@super 2@. The changes in the surface adlayer when the mixture composition is varied will also be discussed.

8:40am **PS2-ThM2 Diagnostics of Inductively Coupled Chlorine Plasmas: Measurements of the Neutral Gas Temperature***, **V.M. Donnelly**, M.V. Malyshev,* Bell Laboratories, Lucent Technologies

We report measurements of the bulk, neutral gas temperature in a chlorine inductively coupled (ICP), or transformer-coupled plasma (TCP). A trace amount (2-5%) of N@sub 2@ was added to the discharge and the rotational temperature of the C-state was determined from the C->B emission in the ultraviolet. This temperature has been shown by others to be equal the rotational temperature of ground state N@sub 2@, which is the thermally equilibrated (translational and rotational) gas temperature (T@sub g@). The gas temperature 3 cm above the wafer is equal to, or only slightly above the wall temperature (300 K) throughout the low-power, capacitively-coupled regime (

9:00am **PS2-ThM3 A New Diagnostic Method for Monitoring Plasma Reactor Walls: Multiple Total Internal Reflection Infrared Surface Probe***, **A.R. Godfrey**, S.J. Ullal, E.S. Aydil,* University of California, Santa Barbara*; E.A. Edelberg, L.B. Braly, V. Vahedi,* Lam Research Corporation

One of the major concerns in plasma etching of thin films with high density inductively coupled plasma (ICP) reactors is wafer-to-wafer etch rate reproducibility. Inductively coupled plasma reactors are typically operated at low pressures where the mean free path of species in the plasma is on the order of the reactor dimensions. As a result, reactive radicals collide with the chamber walls as often as they do with each other in the gas phase and the walls play a crucial role in determining the plasma properties and etching behavior. Thus, it is critical to monitor the wall conditions and the nature of the films and adsorbates that are deposited on the walls. We have developed a surface probe based on in situ multiple total internal reflection Fourier transform infrared (MTIR-FTIR) spectroscopy that can be used as a diagnostic technique to monitor the films and adsorbates on the walls of both plasma etching and deposition reactors. A small (5 cm x 1 cm x 0.1 cm) trapezoidal shaped infrared transparent crystal with 45° beveled edges is placed flush with the reactor walls with the beveled edges facing small IR transparent windows. Infrared beam from a spectrometer is focused onto one of the beveled edges and made to undergo multiple total internal reflection through the crystal before exiting it from the opposite beveled edge. The films deposited on the crystal surface are sampled by the infrared beam which is collected and detected using an IR detector. This diagnostic method enables in situ monitoring of the deposits on the reactor walls during plasma processing. The MTIR-FTIR surface probe and its applications to monitoring reactor walls during plasma etching and deposition processes will be described in detail. Specifically, this talk with emphasize application of the MTIR-FTIR probe to monitoring the walls of a Lam ICP reactor during etching of Si with Cl@sub 2@/O@sub 2@ gases and subsequent cleaning in between etched wafers with a F containing discharge.

9:20am **PS2-ThM4 Laser-Aided Diagnostics of Discharge Plasmas***, **K. Muraoka**, K. Uchino, M. Bowden, M. Maeda,* Kyushu University, Japan **INVITED**

In order to understand, and ultimately optimize discharge plasmas for various purposes, we have to know spatio-temporal distributions of (1) electric fields, (2) electron density and temperature (or EEDF itself if it is away from Maxwellian), and (3) reaction products. The authors have extensively explored potentials of laser-aided plasma diagnostics (LAPD) for this purpose and applied it to various discharges. These are developments and applications of laser optogalvanic spectroscopy (LOG) and laser-induced fluorescence (LIF) to detect Stark effect for (1), Thomson scattering to measure electron density and temperature/EEDF for (2), and LIF, Raman scattering, Rayleigh scattering, and ultra-violet absorption to measure density and temperature of atoms and molecules for (3). Each of these is described, with a special emphasis being placed on (2).

10:00am **PS2-ThM6 Energy Distributions of Incident Ions to a RF-Biased Substratep***, **H. Kawada**, N. Tsumaki,* Hitachi Ltd., Japan

Energy distributions of incident ions and molecules to a substrate exposed to a plasma generated in fluorocarbon gas was obtained by a Quadrupole Mass Spectrometer equipped with an energy filter which was operated with time modulation. The incident ions a nd molecules which entered into an orifice opened in the substrate surface were analyzed by the QMS mounted under the orifice. An 800-kHz radio frequency (rf) voltage was applied to the substrate, as it is commonly done in order to enhance dry etching rea ction on wafers mounted on the substrate. Because of the alternating voltage in the rf, an electrical potential of the substrate is also alternating and not constant. On the other hand, the reference potential used for the QMS optics is not always equal t o the potential of the substrate because the QMS optics must be electrically insulated and kept stable for normal operation. Therefore, post-acceleration of the ions would occur by the unstable potential difference between the substrate and the QMS optics, after the incident ions has received kinetic energy in acceleration between the plasma and the substrate. Such the post-acceleration causes a large error in measuring the kinetic energy that is essential of the incident energy. In order to obtain real energy distributions by minimizing the post-acceleration, time modulation was carried out in our detection setup, that is, the incident energy was measured only at the moment when the rf voltage of the substrate was equal to the reference potential in the QMS optics. Furthermore, by varying the reference potential, the incident energy could be measured at a specific phase of the rf voltage of the substrate. We also measured relative densities of radicals caused in the plasma by using Infrared Laser Absorption Spectroscopy. The energy distributions of the incident ions at a specific bias phase, and its correlation to the radical densities will be shown and discussed.

10:20am **PS2-ThM7 Energy and Angular Distribution of Ions Effusing from a Hole in Contact with a High Density Plasma***, **D. Kim**, C.-K. Kim, D.J. Economou,* University of Houston

The energy and angular distribution of ions extracted from a hole in contact with a low- temperature plasma have been investigated both computationally and experimentally. A single hole is thought to be a well-defined system for understanding the interaction of a plasma with a biased grid. Such plasma-grid interaction finds applications in neutral beam etching, ion sources, satellite thrusters, etc. The plasma parameters (Debye length), hole diameter and thickness determine the characteristics of the ions (and fast neutrals) extracted through the hole. We have developed a Monte Carlo simulation to follow the trajectories of ions and fast neutrals from the bulk plasma through the sheath and out the hole. Collisions with gas phase species and the walls of the hole are taken into account. We have also measured the energy and angular distribution of ions effusing from a hole on a wall in contact with a high density plasma. A hemispherical sectioned electrode is used as the detector. The hole diameter is varied from 25 to 1000 microns and the hole aspect ratio (depth to diameter) is varied from 0.25 to 10. The energy and angular distributions in both experimental data and simulations reflect the strong disturbance of the sheath when the hole size exceeds the local Debye length.

10:40am **PS2-ThM8 Electron Temperature and Ion Energy Measurements with A High-resolution, Sub-micron, Retarding Field Analyzer**, ***M.J. Sowa**, M.G. Blain, R.L. Jarecki, J.E. Stevens,* Sandia National Laboratories

A silicon wafer-based, submicron, high-resolution, retarding field analyzer (RFA)@footnote 1@ was used to measure ion energy and infer electron temperature (Te) in an inductively coupled plasma. RFA ion energy measurements are expected to have a resolution of < 0.1 eV based on simulations. By monitoring the flux of ions to the collector of the RFA while allowing the shield to float, we are able to measure the local difference between the plasma and floating potentials. From this difference, the electron temperature can be calculated directly from sheath theory. Experimental conditions include 10, 20, and 40 mTorr Ar at 100, 200, and 300 W of plasma source power at axial positions of 42-217 mm from the source dielectric window. RFA Te values were compared to those obtained with single and double probes. Excellent agreement was observed between the single probe and RFA over all conditions. Double probe measurements matched the other measurement techniques at 20 and 40 mTorr, and gave 5-30% higher Te values at 10 mTorr. The ion energy spreads measured with the RFA are close to Gaussian with standard deviations from 1.8-2.2 eV. The ion energy spread increased weakly with pressure but showed little dependence on the position or the measured Te value, which ranged from 1.3 - 2.7 eV.@footnote 2@ @FootnoteText@ @footnote 1@ M.G. Blain, J.E. Stevens, J.R. Woodworth, Appl. Phys. Lett., v.75, n.25, p.3923, 1999. @footnote 2@ Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

11:00am **PS2-ThM9 Mass Resolved Ion Energy Distribution Measurements in an Inductively Coupled H@sub 2@/Ar Plasma with a Highly Collisional Presheath**, ***S. Agarwal**, D. Maroudas, E.S. Aydil,* University of California, Santa Barbara

Ion energy distributions (IEDs) in a plasma are determined by the spatio-temporal variation of the potential in the sheath and the presheath. In practice, it is not possible to directly measure the electric field in these regions as they are very thin and easily perturbed by a probe. However, in cases were the preseheath/sheath is collisional and/or the transit time through the sheath is comparable to the rf cycle, structured ion energy distributions are obtained which may be used to compute the electric field in the plasma near a surface. Mass-resolved IED measurements were made using a QMS equipped with a Bessel box energy analyzer in a H2/Ar plasma. The ions were sampled through an aperture on the grounded electrode in a helical resonator plasma reactor through a 2.8 degrees solid angle to detect mostly those ions that have been created by inelastic collisions. These ions preserve information about the electric fields in the sheath and the presheath. The ionic species detected were H+, H2+, H3+, Ar+, and ArH+. The IEDs for H+, H2+ and H3+ showed multiple peaks (as many as 20) superimposed on a saddle structure whereas the IEDs for Ar+ and ArH+ showed only a single peak approximately centered at the time averaged plasma potential. The saddle shaped IED arises because the transit time through the sheath for the lighter ions is less than the rf cycle and the multiple peaks arise due to charge exchange or proton transfer reactions or electron impact ionization in the quasi-neutral presheath region. If there are collisions in the sheath, the peaks appear at an energy lower than the saddle shaped curve. However, in the present measurements, the peaks were superimposed on the saddle curve itself, which means that they arise from collisions in the presheath and subsequent splitting of this multi-peaked distribution in the thin collisionless sheath region. The number and position of the peaks can be used in principle to reconstruct the electric field in the plasma.

11:20am **PS2-ThM10 Langmuir Probe Analysis for High Density Plasmas**, ***F.F. Chen**,* University of California, Los Angeles

The theory of Langmuir probes has been reexamined for use in high-density plasma tools with plasmas in the N = 10@super 11-13@ cm@super -3@ range. The most accurate computations for collisionless plasmas have been done by Laframboise,@footnote 1@ but the results are difficult to apply to data because of the normalized units used. Up to now, for densities in the 10@super 9-11@ cm@-3@ range, the simpler Orbital Motion Limited (OML) theory has sufficed. The two theories agree at low densities. To make the Laframboise curves accessible for real-time I - V analysis of probe data at higher N, we have found analytic approximations to the curves by a double parametrization technique. Furthermore, an iterative procedure permits separating the ion and electron currents in their overlap region, thus yielding an accurate fit to the shape of the ion characteristic and hence accurate values of N and KT@sub e@ regardless of the density range. Comparison with experiment, however, gives surprising results. For N such that the ratio of probe radius to Debye length exceeds 3 (thin sheaths), the OML theory is expected to fail, but it fits the SHAPE of the ion characteristics better than the Laframboise theory, which gives N values 2-3 times higher. The latter seems to agree better with independent measurements of N using microwaves or plasma oscillation probes. We have also parametrized an intermediate theory, that of Allen, Boyd, and Reynolds,@footnote 2@ but this gives unreasonably low N values. A possible cause of the paradox is the effect of charge-exchange collisions. @FootnoteText@ @Footnote 1@ Laframboise, J.G., Univ. Toronto Inst. Aerospace Studies Rept. 100 (June, 1966). @Footnote 2@ Allen, J.E., Boyd, R.L.F., and Reynolds, P., Proc. Phys. Soc. (London) B70, 297 (1957).

11:40am **PS2-ThM11 Single Photon Ionization as a Probe of Radicals in Hot-Wire and Plasma Processing**, *H.L. Duan, **S.F. Bent**,* Stanford University

Gas phase radicals produced in both plasma and hot-wire sources for etching or deposition can influence reaction pathways, reaction rates, and product distributions. Identifying and monitoring the concentrations of free radicals during processing is generally difficult due to the short radical lifetime and low radical concentrations relative to the background. Here we describe the use of a single-photon vacuum ultraviolet (VUV) photoionization technique for the detection of free radicals during thin film growth. In this technique, VUV radiation at 118 nm is generated by frequency mixing of the output of a pulsed Nd:YAG laser to obtain the ninth harmonic. Photons at 10.5 eV contain sufficient energy to ionize many radicals of interest; the laser-ionized ra dicals are then detected by time of flight mass spectrometry. The potential of SPI as a radical probe in electronic materials processing will be demonstrated in studies of two chemical vapor deposition systems using hot-wire activation (HW-CVD): growth o f amorphous hydrogenated silicon (a-Si:H) thin films using silane and growth of amorphous silicon carbon alloys from methylsilane precursor gases. The SPI probe allows for simultaneous detection of Si, SiH@sub x@, Si@sub 2@H@sub y@, and CH@sub 3@ radicals present in the gas phase. It is shown that, other than H atoms, Si atoms are the dominant radicals produced by the hot tungsten filament in the presence of silane. Hydrogen dilution is found to change the gas phase silyl radical distribution. In the case of methylsilane decomposition on the hot wire, methyl radicals are produced in addition to Si-containing radicals. Studies as a function of filament temperature, filament aging, and hydrogen dilution demonstrate the strength of this technique for monitoring reactive radicals in situ with both spatial and temporal resolution. The use of the SPI method for radical detection in plasma processing will also be discussed.

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