Plasma Science and Technology Division
Room 318/319/320 - Session PS-ThA

Diagnostics II

Moderator: G.L. Bell, Sematech

2:00pm **PS-ThA1 In Situ Surface Diagnostics in Plasma Processing: Present Status and Future Challenges***, **E.S. Aydil,*** University of California, Santa Barbara **INVITED**

Understanding and controlling plasma-surface interactions in plasma etching and deposition is a prerequisite for achieving process goals. Towards that end, the last decade has witnessed a steady growth of research activity both in developing new plasma and in situ surface diagnostic methods and using them to address key problems in plasma processing.@footnote 1@ In this talk, we will review the recent progress in diagnostic methods with emphasis on in situ surface diagnostic techniques, their current limitations, and challenges for the next decade. Specifically, we will describe applications of techniques such as multiple internal reflection Fourier transform infrared spectroscopy,@footnote 2@ spectroscopic ellipsometry, and laser induced thermal desorption@footnote 3@ to problems in plasma etching and deposition. Simultaneous use of in situ surface diagnostics in conjunction with ex situ surface characterization methods such as X-Ray photoelectron spectroscopy and plasma gas phase diagnostic techniques such as optical emission spectroscopy has led to improved understanding of plasma etching and deposition processes. Examples from plasma etching of Si and SiO@sub 2@ and plasma deposition of hydrogenated amorphous silicon, fluorinated SiO@sub 2@ and silicon nitride will be reviewed. Despite the recent successes, major challenges remain both in advancing the capabilities of the existing surface diagnostics and applying the knowledge acquired to date to develop simple predictive models of surface processes. While some of the sophisticated surface diagnostic methods provide valuable information on surface reactions and species during process development, their use in manufacturing for real time process control is almost impossible due to their complexity. Inventing robust sensors and diagnostic tools for use in manufacturing remains a major challenge for the next decade. @FootnoteText@ @footnote 1@G. S. Oehrlein, Surf. Sci. 386, 222 (1997). @footnote 2@E. S. Aydil and R. A. Gottscho, Solid State Technol. 10, 181 (October 1997). @footnote 3@I. P. Herman, V. M. Donnelly, C. C. Cheng, K. V. Guinn, Jpn. J. Appl. Phys. 35, 2410 (1996).

2:40pm **PS-ThA3 Comparison of Surface Wave Plasma with ICP used in Oxide Etching***, H. Kokura, S. Yoneda, K. Nakamura,* Nagoya University, Japan*; N. Matsumoto,* Sumitomo Metal In., Ltd., Japan*; M. Nakamura,* Fujitsu Ltd., Japan*; **H. Sugai,*** Nagoya University, Japan

High-density large-diameter SWP (surface wave plasma) is produced by microwave discharge at 2.45 GHz, without magnetic field. With application to SiO@sub 2@ etching in mind, comparison of SWP to ICP (inductively coupled plasma) at 13.56 MHz is made in such a way as to replace the antenna on the quartz plate from a slot type (SWP) to a single loop (ICP) in the identical plasma vessel where the discharge electron density, pumping speed and wall temperatures are kept at the same values. In order to set the electron density at the same value, a novel probe technique is developed, which enables reliable measurement of electron density even when the probe surface is contaminated by polymer deposition. First, impurity (CO@sub 2@, SiF@sub 2@) monitoring shows considerable sputtering of quartz window in case of ICP due to electrostatic antenna-plasma coupling. Second, a degree of dissociation of source gas (10% C@sub 4@F@sub 8@ + 90% Ar) at the same electron density is higher in ICP than in SWP. Third, the neutral radical densities (CF@sub 3@, CF, F) at the same electron density are ten times higher in SWP than in ICP. Fourth, as for the ionic composition, ICP contains CF@super +@ more than 90% while SWP has less CF@super +@ and more CF@sub 3@@super +@, C@sub 2@F@sub 4@@super +@ and C@sub 3@F@sub 5@@super +@. As a consequence, ICP is more highly dissociated than SWP at the same electron density. The origin of this difference is tentatively attributed to the high-energy electron population :optical emission spectroscopy of ArI line suggested 1.5 - 2 times more high-energy electron in ICP than SWP. The physical process leading to a difference in the electron energy distribution functions between ICP and SWP will be discussed, together with etching results. Finally, a radical composition of plasmas produced by an alternative etching gas, C@sub 3@HF@sub 7@O (HFE227), for environmental issue is measured in comparison to conventional gas C@sub 4@F@sub 8@.

3:00pm **PS-ThA4 An ICP Source Design with Improved Azimuthal Symmetry@footnote 1@***, **M.H. Khater**[1], L.J. Overzet,* University of Texas, Dallas*; B.E. Cherrington,* University of Dayton

The geometry of an inductively coupled plasma (ICP) source impacts the plasma and processing uniformity. A reasonably uniform source design does not always guarantee uniform plasma, however, because transmission line effects also impact its performance.@footnote 2@ These cause the current to vary along the coil length producing azimuthal asymmetries in the RF fields of planar sources, a non-uniform power deposition in the plasma and non-uniform processing rates. The azimuthal uniformity for planar coils can be improved somewhat but with significant drawbacks. A source geometry that is inherently uniform and is not adversely impacted by transmission line effects would be preferred. We will present what we think is just such an ICP source design. The geometry is three dimensional rather than planar and consists of two (or more) layers of full and semicircular loops with the RF current generally flowing in opposite directions. Typically, the "bottom" layer consists of full circular loops, while the "top" layer consists of semicircular loops. The length of the new source is greater than that of a similarly sized planar coil, nevertheless, both have inductances near 3 µH. We have measured the free space magnetic fields produced by one of these sources in the (r,@theta@) plane using a B-dot probe. It generated fields of higher azimuthal symmetry than the planar coil despite a larger current variation (I@sub out@/I@sub in@) along the source length. The average value of the peak azimuthal electric field for the new source was E@sub theta@/I@sub out@=0.24 V/(cm A) with a standard deviation of @sigma@=0.0085. The planar coil produced 0.32 V/(cm A) with @sigma@=0.027. The new source has been used to produce high density (10@super 11@-10@super 12@ cm@super -3@) Ar and SF@sub 6@ discharges at low pressures (5-20 mTorr) and to etch poly silicon. @FootnoteText@ @footnote 1@ This material is based upon work supported by Beta Squared Inc. under Grant No. UTD96-56 and by the State of Texas Advanced Research Program under Grant No. 009741-043. @footnote 2@ M. Kushner, et al., J. Appl. Phys. 80, 1337 (1996).

3:20pm **PS-ThA5 Characterization of 100 MHz Inductively Coupled Plasma (ICP) by Comparison with 13.56 MHz ICP***, **H. Nakagawa**, S. Morishita, S. Noda, M. Okigawa, M. Inoue, M. Sekine,* Association of Super-Advanced Electronics Technologies (ASET), Japan

The effect of the excitation frequency on gas dissociation was investigated using a multi-spiral coil in inductively coupled plasma (ICP). The same apparatus except for wave generators and matching circuits was used in the 100 MHz@footnote 1@ and 13.56 MHz excitation wavelength experiments. The electron density (Ne) and electron temperature (Te) in the Ar plasma were measured using a Langmuir probe. In both cases, the value of the Ne was around 2 e+11 cm@super -3@ at the excitation power of 2 kW in 3 Pa (Ar = 400 sccm). Although the Ne in 13.56 MHz plasma is a little higher than that in the 100 MHz plasma, Te (~3) in the 13.56 MHz plasma is higher than that (~2) in the 100 MHz plasma. From the dependence of the radial distribution of the Ne on the ICP source power, it was found that the 13.56 MHz-ICP was produced in a space under the coil area, and that the 100 MHz-ICP was generated throughout the reactor. This is because of the strong capacitive coupling in the 13.56 MHz-ICP, and because the inductive coupling in the 100 MHz-ICP is stronger than that in the 13.56 MHz-ICP. In the C@sub 4@F@sub 8@ / Ar plasma, CF@sub X@ (x=1, 2, 3) radical densities in the reactor wall were measured by appearance mass spectrometry (AMS),@footnote 2@ and the F radical density was evaluated using actinometry through optical emission spectroscopy of Ar (750.4 nm) and F (703.7 nm).@footnote 3@ The degree of dissociation of C@sub 4@F@sub 8@ in the 100 MHz-ICP was higher than that in the 13.56 MHz-ICP, but the CF@sub 2@ / F density ratio in the 100 MHz-ICP was 3 ~ 5 times as large as that in the 13.56 MHz-ICP. This result indicates that the dissociation of a high order (ex. CF@sub 2@ + e --> CF + F + e) in the 13.56 MHz-ICP is larger than that in the 100 MHz-ICP. Thus, it was demonstrated that the 100 MHz-ICP has a greater ability to suppress F radical generation than the 13.56 MHz-ICP. @FootnoteText@ This work was supported by NEDO. @footnote 1@H. Nakagawa et al.: Proc. 14th Symp. on Plasma Processing,136 (Hamamatsu, 1998). @footnote 2@M. Goto et al.: Jpn. J. Appl. Phys. 33 (1994) 3602. @footnote 3@J. S. Jenq et al.: Plasma Source Sci. Technol. 3 (1994) 154.

[1] **PSTD Coburn-Winters Student Award Finalist**

3:40pm **PS-ThA6 Multi-Frequency Operation of RIE and ICP Sources@footnote 1@***, S. Rauf, M.J. Kushner,* University of Illinois, Urbana-Champaign

In both inductively and capacitively coupled rf discharges, the source frequency strongly influences the plasma and electrical properties. Multiple sources at different frequencies are often simultaneously used to combine their attractive features. For example, the goal of dual-frequency RIE plasmas is to separately optimize the magnitude and energy of ion fluxes to the substrate. If the source frequencies are significantly different from each other, the resulting plasma properties can generally be characterized in terms of the separate contributions of the individual sources. However, when the frequencies are close to each other (e.g., 6.78 MHz and 13.56 MHz), the sources interact through the nonlinear plasma medium, thereby complicating this additive relationship. The dynamics of rf plasma processing reactors with multi-frequency sources have been investigated using a coupled plasma equipment-circuit model. In capacitively coupled Ar and Ar/CF@sub 4@ discharges, the addition of a high frequency source (27.12 MHz) on the opposing electrode decreases the magnitude of the dc bias at the substrate (13.56 MHz) due to nonlinear interaction between the separately powered sheaths and a reapportionment of current. In ICP reactors, the dc bias on the substrate has a strong dependence on the rf bias frequency (becoming more negative at higher frequencies) due to the differences in sheath impedance at the powered substrate and the grounded walls. This relationship can be altered by repositioning the antenna which, in turn, reapportions the current collected on biased and grounded surfaces. It was also found that by adding rf sources at remote locations from the substrate in ICP reactors, such as small areas of the wall, one can control the dc bias at the substrate without appreciably changing the ion flux or electron temperature. @FootnoteText@ @footnote 1@Work supported by AFOSR/DARPA, SRC and NSF.

4:00pm **PS-ThA7 Diagnostics in a Novel Capacitively Shielded, Inductively Coupled Plasma Source***, **V.A. Shamamian**, J.E. Butler, D. Leonhardt,* Naval Research Laboratory*; J.L. Giuliani,* Naval Research Laboratory, US

An electrostatic shield in the form of a slotted metal cylinder is often placed between the exciting coil and the dielectric discharge tube of an inductively coupled plasma system in order to screen the electric field generated by the coil. Such fields can, under some circumstances, have a deleterious effect on the process for which the plasma is being used. For very high power systems, the dielectric discharge tube can be replaced by a thick-walled, water-cooled, slotted metal cylinder (i.e., a cold crucible). It is not generally realized that the electrostatic shield can also lead to a significant reduction of the r.f. magnetic fields inside the tube as well as altering its axial distribution. This effect needs to be considered in detailed modeling of inductively coupled plasma systems and is of practical importance in determining the impedance the plasma presents to the r.f. generator. In this combined experimental and theoretical work, we have employed induction probes to study the effect by measuring the r.f. magnetic field inside hydrogen discharges. We interrogated the level to which the plasma screens the field as a function of pressure and coupled power. In addition, we have employed optical emission imaging techniques and a radiation transport model to extract the axial and radial dependence of the electron and neutral temperatures, and plasma spatial extent in the axial direction. We have found that the electron temperature is constant in the axial direction but strongly dependent in the radial dimension, and the plasma extent is self-similar with respect to the value of power divided by pressure. Finally, we have developed electromagnetic models that give good agreement with the plasma induction probe observations. We are currently developing a global 2D model which incorporates electromagnetics, gas phase chemistry and transport, and surface recombination. Work supported by IST/BMDO, DARPA, and ONR.

4:20pm **PS-ThA8 Volume/Surface Effects on Dissociation Processes in Ar/C@sub 4@F@sub 8@ Plasma***, **K. Kinoshita,*** Association of Super-Advanced Electronics Technologies (ASET), Japan*; S. Morishita, S. Noda, M. Okigawa, M. Inoue, M. Sekine,* ASET, Japan

We clarified that the control of multistage dissociation in Ar diluted C@sub 4@F@sub 8@ plasma via the total number of collisions, @tau@ N@sub e@ <@sigma@v>,@footnote 1@ is essential in establishing a high-performance SiO@sub 2@ etch process in a narrow-gap parallel plate reactor. For the scaling of the reactor to a larger wafer size in the near future, a wider gap space will be required to assure uniformity of the gas supply and exhaust. Changing the gap space (i.e, volume/surface ratio) must affect the gas dissociation process by changing total number of collisions. Here, @tau@ and N@sub e@ can be controlled by the pumping speed and source power. Therefore, we examined the change in <@sigma@v> on the gap space and its effect on the dissociation process. Two kinds of UHF (500 MHz) plasma sources were used. One source had a spoke antenna coupled with plasma through a quartz top plate and the other had a carbon top plate antenna with a magnetic field of ECR condition. In both systems, when the gap space was widened, the N@sub e@ increased and <@sigma@v> for the C@sub 4@F@sub 8@ dissociation decreased, when @tau@ was constant. <@sigma@v> for excitation for ArI emission also decreased with increasing gap space. Kinetic analysis through rate equations indicated that the reaction rate constant <@sigma@v> for the F generation reaction decreased with increase in gap space in both plasma sources. These results suggest that changing the electron energy distribution by changing the gap space significantly influences the reaction rate constant of the dissociation reactions in the Ar/C@sub 4@F@sub 8@ plasma. @FootnoteText@ This work was supported by NEDO. @footnote 1@ T. Tatsumi et al., Jpn. J. Appl. Phys., 37 (1998) to be published

4:40pm **PS-ThA9 Investigation of the Gasphase of Expanding Ar/C@sub x@H@sub y@ Plasmas***, A. de Graaf, M.F.A.M. van Hest, **K.G.Y. Letourneur**, M.C.M. van de Sanden, D.C. Schram,* Eindhoven University of Technology, The Netherlands

An expanding argon plasma into which several C@sub x@H@sub y@ precursors are injected was used for the deposition of diamond-like carbon films. The argon plasma is created in a cascaded arc and expands into a low-pressure vessel, where precursor gases, such as CH@sub 4@, C@sub 2@H@sub 2@, C@sub 2@H@sub 4@ and C@sub 2@H@sub 6@ are injected into the beam. The gasphase of these plasmas was investigated by means of Fourier Transform Infrared (FTIR) absorption spectroscopy and Mass Spectrometry (MS). The consumption of the different precursor gases was derived from both FTIR and MS measurements for several arc currents, pressures and flows. The results from the two techniques are compared in order to eliminate the effect of temperature and to distinguish whether reaction products are formed in the background or in the plasma beam. By correlating the depletion measurements with the growth rate measured in situ by ellipsometry, information is obtained on the reactions taking place inside the plasma and during deposition. Assuming that only argon ions are contributing to the dissociation of the C@sub x@H@sub y@, the electron energy being too low (typically 0.2 eV in these plasmas), the ionization degree of the arc can be deduced as function of arc current and argon flow. The measurements also prove that other stable monomers are produced in the plasma phase, i.e. polymerization is taking place. The possible polymerization reactions, occurring either in the gasphase or at the reactor walls, will be discussed for the different precursor gases.

5:00pm **PS-ThA10 Electrical Control of Spatial Uniformity of Chamber-Cleaning Plasmas Investigated using Planar Laser-Induced Fluorescence***, **K.L. Steffens**, M.A. Sobolewski,* National Institute of Standards and Technology

Fluorocarbon plasmas are widely used by the semiconductor industry for in situ cleaning of PECVD chambers. Control and optimization of chamber-cleaning processes are critical for reduction of both the emission of greenhouse gases and chamber-cleaning time. Also the spatial distribution of chemically reactive species in the plasma should be tailored to maximize the cleaning rate at appropriate surfaces. Previous studies in parallel-plate reactors have indicated that reactive species density distributions, plasma emission, and cleaning rates are correlated to the rf current measured at the upper, grounded electrode. In this study, the current at the upper electrode was varied by adjusting the impedance between the upper electrode and ground, and the resulting changes in plasma uniformity were investigated using optical techniques. Measurements were made in O@sub 2@/CF@sub 4@ and O@sub 2@/C@sub 2@F@sub 6@ plasmas in the capacitively-coupled Gaseous Electronics Conference Reference Cell at pressures from 0.1 to 1 Torr. The 2-dimensional density distribution of the reactive radical, CF@sub 2@, was measured using planar laser-induced fluorescence (PLIF), and the regions where reactive species were generated were determined using spatially-resolved, broadband optical emission. As the current at the upper electrode was varied, changes were observed in the axial symmetry of the broadband emission and in the radial uniformity of the CF@sub 2@ PLIF. These results suggest that electrical control of the current paths through the plasma could be used to control the spatial distribution of reactive chemical species, aiding in the optimization of chamber-cleaning plasmas and other fluorocarbon plasmas.

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