Tuesday Morning, October 29, 2013

Plasma Science and Technology
Room: 102 B - Session PS1-TuM

Plasma Sources
Moderator: S. Shannon, North Carolina State University

8:00am **PS1-TuM1 Non-ambipolar Electron Plasma and its Physical Properties**, ***L. Chen***, *Z.Y. Chen, M. Funk*, Tokyo Electron America, Inc.

This report discloses a new type of plasma source: the Non-ambipolar Electron Plasma (NEP). Although, it is basically heated by electron beam, its power coupling and plasma physical property differentiate itself from the generic e^-–beam plasmas. Such differences open up potential applications that could have been difficult with the generic plasmas. The NEP system consists of two plasmas separated by a dielectric charged-species injector. Plasma-1 is the ground-referenced electron-source plasma (e.g., Ar) and it is an inductively coupled source (ICP) in this study for convenience reason. Plasma-2 is the NEP itself whose majority plasma-boundary is the DC-conductive accelerator with the remaining minority plasma-boundary being dielectric. NEP is typically molecular (e.g., N_2) in the pressure range of 1-3 mtorr and its accelerator voltage varied from V_A=+80 to V_A=+600V. The NEP plasma potential (V_P) is boundary-driven. Therefore, NEP V_P tracks the accelerator voltage with its value just very slightly above V_A. The current across the dielectric charged-species injector is non-ambipolar: only electrons are transported from ICP to NEP and only positive-ions are transported from NEP to ICP. The non-ambipolar electron-current injected into NEP is in the range of 10s Acm^{-2} with beam-energy ~ eV_A and it heats NEP through beam-plasma instabilities. Its EED*f* has a Maxwellian bulk followed by a broad energy-continuum connecting to the most energetic group with energies above the beam-energy. The remnant of the injected electron-beam power terminates at the NEP end-boundary floating-surface setting up sheath potentials from V_S=80 to V_S=580V in response to the applied values of V_A. The floating-surface is bombarded by a space-charge neutral plasma-beam whose IED*f* is near mono-energetic. When the injected electron-beam power is adequately damped by NEP, its end-boundary floating-surface V_S can be linearly controlled at almost 1:1 ratio by V_A. NEP does not have an electron-free sheath; its "sheath" is a widen presheath that consists of a thermal presheath followed by an "anisotropic" presheath, leading up to the end-boundary floating-surface. Its ion-current of the plasma-beam is much higher than what a conventional thermal presheath can supply. If the NEP parameters cannot damp the electron beam power sufficiently, V_S will collapse and becomes irresponsive to V_A.

8:20am **PS1-TuM2 Ion Energy-Angular Distributions in Dual Frequency Capacitively Coupled Plasmas Using Phase Control**, ***Y. Zhang***, *M.J. Kushner*, University of Michigan

Dual frequency capacitively coupled plasmas (CCPs) provide the microelectronics fabrication industry with flexible control for high selectivity and uniformity. For a given low frequency (LF) bias, the, magnitude and wavelength of the high frequency (HF) bias will affect the electron density, electron temperature, sheath thickness and so ion transit time through the sheath. These variations ultimately affect the ion energy and angular distributions (IEADs) to the substrate. For example, with higher HF power, the electron density and ion fluxes will increase, which will increase the etch rate. However, the higher HF power will also reduce the sheath thickness and reduce the ion transit time. This will produce more structure in the IEADs. One potential control mechanism for the IEADs is the relative phase of the LF and HF biases. In this paper, results from a two-dimensional computational investigation of Ar and $Ar/C_4F_8/O_2$ plasma properties in an industrial CCP reactor are discussed. The resulting IEADs are used as inputs to a feature profile model to assess etch profiles. In this reactor, both the LF (2 MHz) and HF (up to 60 MHz) are applied to the lower electrode. The phase between the LF and HF is controlled.

To separately control rates of ionization and the shape of IEADs, the HF should be significantly higher than the LF. Under these conditions, there are many HF cycles per LF cycle. Although there are clear changes in the IEADs when varying the phase between the HF and LF, these changes are modulations to the IEADs whose shape is dominated by the LF. By sweeping the phase difference between the LF and HF, these modulations can be used to smooth and sculpt the IEADs. As the difference between the HF and LF becomes smaller, the IEADs become more sensitive to the phase differences between the HF and LF. These phase differences also affect the dc bias, an affect often call the electrical-asymmetry-effect when the frequencies are equal. Profile simulations are used to demonstrate possible control schemes for over-etch through phase control.

*Work supported by the Semiconductor Research Corp., DOE Office of Fusion Energy Science and the National Science Foundation.

8:40am **PS1-TuM3 Investigation of Photo-Assisted Etching in Different Halogen-Containing Plasmas and Synergetic Effects of a Tandem Plasma System**, ***W. Zhu****, *L. Liu, S. Sridhar, V.M. Donnelly, D.J. Economou*, University of Houston

Photo-assisted etching (PAE) of p-type Si in halogen-containing plasmas was discovered at sub-threshold ion energy in a Faraday-shielded, inductively coupled plasma (ICP). Halogen-containing feed gases (Br_2, HBr, Br_2/Cl_2 and HBr/Cl_2) were explored and the strong dependence of PAE on different etchant gases was investigated. Sub-threshold etching rates in 50% halogen /50% Ar cw ICPs were ordered as 25% HBr/ 25% Cl_2 > 25% Br_2/ 25% Cl_2 > 50% Cl_2 > 50%HBr > 50% Br_2. H-atoms also caused isotropic etching in HBr plasmas; sub-threshold etching of patterned p-Si in other gases was anisotropic. PAE was much less important for Br_2, with an etching rate 4 times slower than that for Cl_2, under similar conditions. The dependence of PAE on incident photon energy was characterized by filtering incident photons with different wavelength to the sample surface. Vacuum UV was much more important than UV or visible light in inducing PAE. PAE is expected to cause substantial complications for processes that require low ion energies to achieve high selectivity and low damage, such as atomic layer etching. To address this issue, a tandem plasma system was developed to inject one plasma (upper plasma) into another plasma (lower plasma) separated by a grid. A "boundary electrode" (BE) in contact with the upper plasma could be biased to influence the plasma potential. The goal was to manipulate the electron energy distribution functions (EEDF), and possibly enhance ion-assisted etching compared to PAE. Plasma parameters and EEDFs were measured with a Langmuir probe over a wide range of power, pressure and position in cw Ar plasmas. With both plasmas powered (100 W lower plasma/ 500W upper plasma) at 10 mTorr, low energy electrons were depleted in the lower plasma when the BE was grounded. However, with 60 V bias on the BE, low energy electron depletion did not occur, and the high energy tail was enhanced. The reverse behavior was found in the upper plasma under the same conditions. Pulsed lower plasma with cw upper plasma injection was also explored. High plasma density of 2×10^{11} cm^{-3} with selectable, nearly-constant T_e (e.g. 0.8 eV) was achieved in the afterglow of the lower plasma at 10 mTorr.

9:00am **PS1-TuM4 Control of Energy Distributions in Inductively Coupled Plasmas using Tandem Power Sources**, ***M.D. Logue***, University of Michigan, *W. Zhu, H. Shin, L. Liu, S. Sridhar, V.M. Donnelly, D.J. Economou*, University of Houston, *M.J. Kushner*, University of Michigan

In plasma materials processing, finer control of the electron energy distribution, *f(ε)*, enables better selectivity of generating reactants produced by electron impact excitation and dissociation. This is particularly important in low pressure, inductively coupled plasmas (ICPs) where dissociation products often react with surfaces before interacting with other gas phase species. Under these conditions, fluxes to surfaces are more directly a function of electron impact rate coefficients than gas phase chemistry. Externally sustained discharges are able to control *f(ε)* by, for example, augmenting ionization independent of the *f(ε)* of the bulk plasma so that *f(ε)* can be better matched to lower threshold processes. In this case, the tail the *f(ε)* is lowered. Following the same logic, introducing additional losses by external means will produce an increase in the tail of *f(ε)*. To achieve this control, a tandem (dual) ICP source has been developed. In this device, the primary (lower) source is coupled to the secondary (upper) source through a biasable grid to control the transfer of species between the two sources with the intent of controlling *f(ε)* in the primary source. A boundary electrode (BE) at the top of the system, along with the grid, can be dc biased to shift the plasma potential. This controls the energy of charged species passing into the primary source as well as ion energy distributions (IEDs) to surfaces.

Results will be discussed from a computational investigation of the control of and IEDs, in a tandem source ICP system at pressures of tens of mTorr. The model used in this study is the Hybrid Plasma Equipment Model (HPEM) with which *f(ε)* and IEADs as a function of position and time are obtained using a Monte Carlo simulation. *f(ε)* and IEDs will be discussed while varying the relative power in the primary and secondary sources, and dc biases (BE and grids) in continuous and pulsed formats. Results from the model will be compared to experimental data of *f(ε)* and IED obtained using a Langmuir probe and a gridded retarding field ion energy analyzer.

* Work supported by the DOE Office of Fusion Energy Science, Semiconductor Research Corp. and the National Science Foundation.

*** Coburn & Winters Student Award Finalist**

9:20am **PS1-TuM5 Si-Gate Etching in Radial Line Slot Antenna Plasmas: Control of Selectivity, Anisotropy and Loading**, ***S. Voronin**, A. Ranjan, H. Kintaka, K. Kumar, P. Biolsi*, TEL Technology Center, America, LLC

Shrinkage of transistors as dictated by Moore's law is required to make smaller, faster and less power-consuming devices at lower cost. 3-D gate transistors at 22nm technology node and beyond are needed to continue Moore's law. To obtain all these advantages of 3-D transistors, their fabrication has stringent requirements to the etch process such as high anisotropy, high selectivity to Fin and Gate mask films and minimum loading between isolated and nested lines. In addition, precise control over the gate profile from a vertical to a slightly negative angle is important for integration purposes. In this work we present highly selective 3D gate etching in halogen-based Radial Line Slot Antenna plasma. Having spatially separated plasma generation and plasma processing regions, RLSA™ etchers benefit of a very low electron temperature (T_e~1eV) processing plasma discharge compared to conventional sources. Low electron temperature in the process plasma provides low dissociation rates of by-product and precursor gas, and ion bombardment of the structure at very low energies resulting in small iso-nested loading and very high process selectivity respectively. The ability of RLSA™ plasma sources to operate in a very wide range of the pressures allows the etch process well above 100mT. This leads to further decrease of the electron temperature in the bulk and the ion energy, providing notch-free etching of the structure. Changing by-product re-deposition rate by O_2 flow, etching times and bias power modulation regimes we can effectively control the gate profile from slightly tapered to slightly inversed tapered. Iso-nested delta can be minimized (and even reversed) by adjusting the process chemistry, bias power and pressure. Being very selective, RLSA™ plasma process allows very long over-etching times without damaging the mask. This makes the process universal, minimizes wafer-to-wafer profile variation and effective for etching the structures where Si layer thickness varies across the wafer. It is shown that artificial increase of the plasma electron temperature in the chamber to ~2eV (an analog of a conventional plasma etcher) results in dramatic decrease of process selectivity to the oxide.

9:40am **PS1-TuM6 Vacuum-Ultraviolet Emission Spectra of Plasma-Processing Reactors**, ***K. Mavrakakis**, M. Nichols, W. Li, K. Katz,* University of Wisconsin-Madison*, J. McVittie, A. Hazeghi,* Stanford University*, S. Banna,* Applied Materials Inc.*, Y. Nishi,* Stanford University*, J.L. Shohet*, University of Wisconsin-Madison

Plasma processing is an essential part of modern integrated circuit fabrication. The unique ability of plasmas to etch various materials in an anisotropic way and also to deposit thin films (PE-CVD) has made plasma processing the dominant method of processing modern IC circuits. One of the key problems with plasma exposure of low-k dielectric materials is that processing damage from vacuum ultraviolet emission (VUV) can take place. In order to further investigate the radiation-induced damage to dielectric films, it is important to determine whether different plasma reactors produce significant variations in their generated VUV spectra. In this work, we examine the VUV spectra generated by four unique plasma reactors using argon as the fill gas. They are: electron cyclotron resonance, capacitively coupled, neutral loop/ICP and microwave slot-plane antenna reactors. A McPherson Model 234 VUV monochromator was used for all measurements. The monochromator was fit to each reactor through a sequence of port aligners and collimation systems so that plasma light was well focused on the input slits. The output of the monochromator was focused on a sodium salicylate coating that scintillates in the visible portion of the spectrum and that light was detected by a photomultiplier. It was expected that the emission intensity varied with pressure and microwave power. However, depending on the reactor involved, this is not always the case. The resulting data shows that the emission intensity increases with the decrease of pressure and the increase of microwave power. The interesting result that we obtain is that argon does not always follow that trend over the same pressure and power ranges. As a result, it is important to optimize the processing conditions to minimize the VUV output whenever possible.

This work has been supported by the Semiconductor Research Corporation under Contract No. 2012-KJ-2359 and by the National Science Foundation under Grant CBET-1066231.

10:40am **PS1-TuM9 Counteractions to Plasma Chamber Corrosions by Earthquake**, ***T. Moriya***, Tokyo Electron, Japan **INVITED**

At the Japan's big earthquake in 2011, the plasma etching tools have received the big damages from the earthquake. Most of the etching tools were not able to be used normally. Many particles were contaminated to the wafers during etching process because the chambers were corroded by the outgassed acids during shutdown for several days. Just when the big earthquake attacked to the plant, some etching tools were on maintenance (doing wet cleaning). Because the technicians had to escape out of the clean room with leaving the tools as it is, some halogen gasses (fluorine, chlorine, bromine and so on) were outgassed from the process chambers. These gasses were combined with humidity in the room and became kinds of acids. In the process modules, the metal components were mostly corroded by the halogen-outgas related acids. Especially, as the gas feeding lines were contaminated, a lot of defects were created by the particles. In fact, a lot of particles were counted on wafers because of the corrosion related particle contaminations. By wet wiping of the process chambers, there were some good effects to the particle reduction but it was NOT completed. So, we checked and replaced many parts such as gas feeding line with using some special techniques. After that, the particle level was recovered to normal. The surface particle monitor was used to check the *in situ* particle level and worked effective. For checking the particles in the gas line, we suggest new method to observe the particles by using a wafer and creating a shockwave in the gas line. Since we already had the reference data which was obtained before the earthquake, we could compare between the normal condition and the current condition from the viewpoint of chamber contamination.There is another serious problem such as RF reflection alarms. This alarm means that the RF power cannot be supplied to the tool appropriately. As we changed some chamber parts, polished contacting areas and also changed the software parameters, and then, the RF reflection alarms were eliminated completely. The static chamber impedance measurement was also done to check the electric property. We also recorded the normal condition of the plasma chamber before the earthquake. So, we could compare between the normal condition and the current condition from the viewpoint of chamber electricity. If we want to manage the risks of corrosion by the earthquake, not only the surface particle count but also the static chamber impedance and the conditions of metal parts should be recorded periodically during the normal situation.

11:20am **PS1-TuM11 An Improved Cathodic Arc Plasma Source for Large Area Coatings**, *J. Kolbeck, **A. Anders***, Lawrence Berkeley National Laboratory

Cathodic arc plasmas are widely used in the hard coatings industry to produce binary and ternary metal nitrides and oxynitrides, some of them exhibiting superhardness (> 40 GPa) and high oxidation resistance at elevated temperature. High deposition rates (10-100 nm/min) and self-ion-assistance to film growth are attractive features of the arc deposition process. However, microscopic droplets or "macroparticles" produced at cathode spots have prevented broader application of this technology, for example to optical coatings or to thin films used in the electronics industry. Here we report on the development of a linear cathodic arc plasma source that can be coupled to a linear macroparticle filter. We aim to develop a plasma source suitable for high-rate, large-area coatings, where films are essentially free of macroparticles. Operation and performance of the improved source will be demonstrated with metal and metal oxide films.

Specifically, we deposited aluminum-doped zinc oxide (AZO), a transparent conducing oxide which is non-toxic and made from abundant materials, a prime candidate for replacing the more expensive indium tin oxide (ITO) in some applications. AZO deposited on glass by filtered cathodic arc plasma exhibit very high electron mobility (some samples exceeding 50 cm^2/Vs) for moderately high carrier concentrations (~ 10^{20} cm^{-3}), high transmittance in the visible and solar infrared (80-85%), with sheet resistance as low as 10 Ohms per square for relatively thick (~ 1 µm) films. AZO was also deposited on polycarbonate plastic at room temperature, with properties of interest to flexible electronics.

11:40am **PS1-TuM12 High Density Narrow Tube Ozonizer by Increased Barrier Discharge Frequency**, ***J. Tsujino**, T. Kitajima, T. Nakano*, National Defense Academy of Japan

Atmospheric plasmas are being general tool for various surface treatment applications, such as cleaning, sterilization, hydrophilic property control, etc. Among these applications, oxygen related radicals are the key species to influence the surface chemistry of the target. For the transport of the radical, spraying plasma processed gases to the object is commonly applied among these uses. There are certain reasons to develop high density atmospheric plasma source which is compact and able to be introduced or " retrofit " to the current chemical processing systems. In the current study, we are developing the high frequency atmospheric ozonizer plasma source in general 1/4 inch O.D. tube which gives high density ozone.

High frequency barrier discharge at 280 kHz consists of the alumina tube, the cupper grounded electrode, and the aluminum drive electrode. (shown in fig . 1) The aim of MF range of frequency is to shift power deposition target to electrons from ions, and to increase the barrier discharge frequency. High voltage for the barrier discharge (0.5 mm gap) is produced by the LC resonance circuit (fig . 2).

Comparison of ozone density between 50 Hz (0.8 g /Nm^3, 40 kVpp) and 280 kHz (30 g/Nm^3, 6.5 kVpp) shows the production rate is increased 40 times for realistic voltage range (fig . 3).

V-I characteristic of 280 kHz (fig . 4) shows the discharge current and power is increased steeply around 6 kVpp that corresponds to the rapid increase of ozone production rate.

The increase of power with voltage is explained by the change of waveform (fig . 5). Small change of the voltage leads to the forwarding of the current phase and increase of barrier discharge frequency.

The power efficiency of the ozonizer is 19 g /kWh which is comparable to the commercial small scale unit.

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