# Tuesday Morning, November 3, 1998

## Plasma Science and Technology Division
## Room 314/315 - Session PS1-TuM

### Pulsed Plasmas

**Moderator:** N. Hershkowitz, University of Wisconsin, Madison

8:20am **PS1-TuM1 Simulation of a Pulsed-Power Inductively Coupled Chlorine Plasma**, ***V. Midha***[1], *D.J. Economou,* University of Houston

Low pressure high density plasmas are widely used for the fabrication of sub-micron semiconductor devices. Recently, pulsed power operation has emerged as a promising technique for reducing charge induced damage and etch profile distortion (e.g., notching) associated with conventional continuous wave discharges. This paper reports results of a fluid simulation of a pulsed-power inductively-coupled chlorine plasma. The mass, energy, and full momentum equations for the charged species are solved simultaneously with the Poisson equation and the Helmholtz equation for the electromagnetic power deposition profiles. A p-version, least-squares finite-element formulation of the glow discharge equations was developed which is capable of capturing sharp fronts in the sheath region without numerical diffusion. Also, this method is unconditionally stable circumventing the extremely short dielectric relaxation time constant of the system. Simulation results show spontaneous separation of the plasma into an ion-ion core and an electron-ion periphery, depending on the negative ion to electron density ratio. These results are in agreement with a semi-analytic model of the system. The influence of the rf bias frequency on the sheath dynamics and the ion flux and energy to the driven electrode during the afterglow was also examined. Significant oscillations of the ion flux were observed when the ion transit time through the sheath was about equal to the period of the applied field. Finally, the transition to a fully developed ion-ion plasma state and the dynamics of this new kind of plasma were studied.

8:40am **PS1-TuM2 Fluorocarbon Film Composition and Reactor Effluent from Pulsed PECVD of Difluoromethane, 1,1,2,2-Tetrafluoroethane, and Hexafluoropropylene Oxide**, ***C.B. Labelle***[2], *K.K. Gleason,* Massachusetts Institute of Technology

Low dielectric constant (< 2.5) fluorocarbon thin films were deposited from three precursors with relatively low global warming potentials: difluoromethane (CH@sub 2@F@sub 2@), 1,1,2,2-tetrafluoroethane (C@sub 2@H@sub 2@F@sub 4@), and hexafluoropropylene oxide (HFPO, C@sub 3@F@sub 6@O). For each feed gas, reactor effluent and film composition were determined as a function of pulsed plasma excitation on and off timing cycles. Fourier Transform Infrared Spectroscopy (FTIR) confirms only partial decomposition of the feed gas occurs in pulsed PECVD, and only a relatively small number of additional gas-phase effluent species are produced in significant concentration. A minimum reaction set has been proposed for each precursor to account for the major effluent species. Most notable for CH@sub 2@F@sub 2@ and C@sub 2@H@sub 2@F@sub 4@ pulsed plasmas is the competition between CF@sub 2@-producing reactions and HF elimination reactions. HFPO pulsed plasmas, due their lack of H, do not have this competition, but the presence of oxygen in the precursor is significant. Support for these reaction sets is also found from a comparison of film composition. In each case, the CF@sub x@ distribution, as well as the presence or absence of hydrogen in the film, can be explained by the proposed reaction sets. Most notably, the role of the competition between CF@sub 2@-producing reactions and HF elimination reactions is reflected in the CF@sub 2@ vs. quaternary carbon concentrations as determined by carbon-1s x-ray photoelectron spectroscopy. Precursors with dominant CF@sub 2@-producing reactions lead to films with larger CF@sub 2@ concentrations, whereas precursors with dominant HF elimination reactions lead to films with larger quaternary carbon concentrations. In the case of the HFPO films, the high CF@sub 2@ fractions are easily explained by the dominant decomposition of HFPO into CF@sub 2@ and trifluoroacetyl fluoride (CFOCF@sub 3@). More significantly, however, the absence of significant oxygen in the films can be traced to the formation of several very stable oxygen species in the pulsed plasma which exit the reactor without being further broken apart and incorporated into the film. Finally, the global warming impact of the pulsed plasma effluents, and thus, of each film deposition process, has been determined.

9:00am **PS1-TuM3 Surface Composition and Reactivities of Fluorocarbon Radicals from Pulsed Fluorocarbon Plasmas**, *N.M. Mackie,* Colorado State University*; J. Bard,* Butler University*; N.E. Capps,* ***E.R. Fisher***, Colorado State University

Pulsed fluorocarbon plasmas are becoming an increasingly popular method to deposit materials with high fluorine content for a variety of thin film applications and to reduce the adverse charging effects during dry etching. Despite the enormous bod y of work on continuous wave (CW) fluorocarbon plasmas, the underlying deposition and etching mechanisms in pulsed and CW plasmas are still controversial. Pulsed hexafluoropropylene oxide (HFPO) plasmas have been postulated to deposit films from surface reactions of CF@sub 2@ radicals even though the sticking coefficient of CF@sub 2@ is known to be low. We have performed a critical comparison of fluorocarbon films deposited from variable duty cycle pulsed and equivalently powered CW HFPO plasmas. We have determined the duty cycle dependence of CF@sub 2@ reactivities and relative gas phase densities from CW and pulsed HFPO plasmas using our Imaging of Radicals Interacting with Surfaces (IRIS) method, which combines spatially resolved laser-induced fluore scence (LIF) with molecular beam techniques.. Preliminary results show that CF@sub 2@ radicals indeed have a low reactivity in a 5% pulsed HFPO plasma with R = -0.1 ± 0.07 and that there is some surface production of CF@sub 2@ during pulsed plasma processing. In addition, time resolved optical emision spectroscopy (OES) has been used to track excited state atoms and radicals throughout the pulse cycle. Insights into the deposition mechanism of HFPO pulsed and CW plasmas will be discussed.

9:20am **PS1-TuM4 Pitting-Free Gate Etching by Lowering Bias Frequency in Pulsed ECR Plasma with a Divergent Magnetic Field**, ***H. Morioka***, *A. Hasegawa, D. Matsunaga, N. Abe,* Fujitsu Ltd., Japan

In the fabrication of ULSI beyond quarter micron design rule, very high selectivity to gate oxide is one of the essential issues for gate electrode etch process such as poly-Si etching. The reason for this is not only that the gate oxide is getting thinner as the device generation changes, but also that the gate oxide along gate electrodes in a dense pattern region is easily pitted like spikes during overetch (microtrenching), even though the selectivity to the oxide is high enough in the open space. Therefore, excessively high selectivity is required to suppress the pitting in most cases. There are roughly two approaches to achieve high selectivity. one is lowering ion energy by decreasing bias power, and the other is changing chemistry. However, these approaches have disadvantages, that is, lowering ion energy often causes profile distortion such as notching, and the chemistry of high selectivity is sometimes followed by etching residue, strong proximity effect, and "particle" problem because this kind of chemistry tends to enhance polymer deposition on the wafer and chamber wall. Therefore, we have studied effects of bias frequency and pulsed plasma, to suppress the pitting in an alternative way. Our experiments were performed on an ECR plasma etch tool with a divergent magnetic field. Several bias frequencies between 13.56 MHz and 400 KHz with CW and pulsed ECR plasma sources were used to examine their effect to µ-loading of the selectivity and sub-trench depth of half-etch profile. In this experiment, by using pulsed plasma, having a cycle of 100 µs and 25% - 50% duty, and lower bias frequency than 2 MHz, we found that the selectivity µ-loading and the sub-trench depth were decreased, and consequently, we have achieved vertical etched profile without the pitting of the thin gate oxide (2.5 nm). These results imply that the lowering bias frequency (and pulsed plasma) has the efficiency to suppress topography dependent variation of selectivity and etched profile.

9:40am **PS1-TuM5 Pulse-Power Hollow Cathode**, *A. Belkind,* ***J. Cai***, Stevens Institute of Technology*; R. Scholl,* Advanced Energy Industries

An oxygen plasma generated by a linear multiorifice hollow cathode (LMHC) is used for oil removal from metal strips. To operate the source with a DC power the cathode is constructed from stainless steel. The source has a power limit that determined by cathode overheating and consequential appearance of arcs that destroy the cathode. Stainless steel replacement by aluminum would substantially improve cathode cooling and increase the power limit. Unfortunately DC discharge in oxygen with an aluminum cathode is accompanied with arcing. One way to avoid arcing in to use pulse-power. In this work, pulse-power hollow cathode discharge is investigated. Pulse durations and frequency influences on an oxygen plasma generated in various hollow cathodes are studied. Implementation of pulse-powered aluminum hollow cathode for oil removal is discussed.

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

10:00am **PS1-TuM6 Diagnostics of Pulsed Plasmas, and the Use of Pulsed Plasmas as a Diagnostic Tool**, ***M.V. Malyshev***, *V.M. Donnelly,* Bell Laboratories, Lucent Technologies

Pulsed plasma (PP) experiments were carried out in a transformer coupled plasma (TCP) reactor in argon and chlorine plasmas. Time resolved electron temperatures (T@sub e@), electron energy distribution functions (EEDF), electron densities (n@sub e@), positive ion densities (n@sub i@ @super +@), and negative ion densities ~(n@sub i@ @super +@ - n@sub e@) were measured with combinations of trace rare gases optical emission spectroscopy (TRG-OES), Langmuir probe, and microwave interferometry (MWI). These plasma parameters were studied as a function of pressure and power and compared with CW plasma operation. Time resolved number densities of metastable states of rare gases (1s@sub 3@ and 1s@sub 5@) were determined from a model that computes TRG-OES intensities. As the RF power is switched on at the beginning of the 100 us pulse period in a 10 mTorr Cl@sub 2@ plasma, n@sub e@ is near zero and starts increasing slowly, while T@sub e@ rises rapidly to 8 eV and falls to 4 eV in 5 us and to 1.9 eV in 20 us. We also designed a series of PP experiments to circumvent an impediment (the lack and inconsistency of published cross sections for electron impact excitation out of metastable states) in our TRG-OES model. Time resolved OES signals and n@sub e@ (from MWI) were recorded and compared. The rise of optical emission excited from the ground state (e.g. Ar 750.4 nm) coincides with the rise of n@sub e@ during the plasma-ON period, while the emission that comes mainly from excitation out of metastables (e.g. Xe 881.9 nm) increases more rapidly. Assuming the ground state cross sections are correct, we used this comparison to scale cross sections for excitation out of the metastables. Recent theoretical calculations agree with our pulsed-plasma-corrected cross sections.

10:20am **PS1-TuM7 Pulsed Plasma Processing with Helicons**, ***C. Charles***, Australian National University, Australia **INVITED**

High density, low pressure plasma sources utilizing modulated power have been attracting much attention recently. By modulating the power it is possible to further optimize and control the performance of processing plasmas by changing the pulse frequency and the duty ratio. Pulsing is also of interest for studies of basic plasma physics and pulsed argon discharges are useful benchmarks for a better understanding of the more complex mechanisms involved in pulsed plasma processing with electronegative discharges. Experimental and analytical analyses of helicon discharges in continuous and pulsed excitation using various gases (argon, oxygen) are used to present the main features of pulsed plasma processing. Three phases can be distinguished in a pulsed discharge, the breakdown phase, the steady-state phase and the post-discharge, which affect the processing in various ways as a result of temporal changes in the ion energy distribution function, plasma potential, plasma density and electron temperature. Details on the pulsed deposition of silicon dioxide using silane/oxygen mixtures are given to illustrate the effect of those temporal changes on the quality of the deposited films.

11:00am **PS1-TuM9 Very High Density Helicon Mode Operation in WOMBAT**, ***R.W. Boswell***, *A. Degeling,* Australian National University, Australia

A Helicon Wave mode which exhibits a peak downstream density of greater than 10@super 12@ cm@super -3@ in argon (so called the "blue mode" because of bright ArII emission along the axis) has been oberved. The experimental conditions are : argon gas pressure of 3 mtorr, dc magnetic field of 100g and rf power input of 2 to 3 kW at 13.56MHz into a source region of 18 cm radius and 50 cm length using a double half - turn antenna. The nominal plasma density is about 10@super 11@cm@super -3@ when tuned for the normal Helicon wave mode under these conditions, and the blue mode appears sporadically for intervals of about 2 ms every few seconds. By pulsing the rf power for a duration of a few milliseconds it was found that the blue mode could be tuned to and operated more consistently, however the duration of the mode never exceeded a few milliseconds until the power level was increased above 4kW (where the blue mode operated continuously). B-dot probe measurements indicate that the wave phase velocity while the blue mode operates is about 3x10@super 6@ m/s, which has been shown previously to be the optimum velocity for resonant wave heating of plasma electrons to increase the ionisation rate.The instability of the mode on time scales of a few milliseconds may be due to a neutral pressure decrease in the source caused by ion pumping while the blue mode is operating. Once the blue mode is quenched the ion pumping stops and the pressure increases in the source, allowing the blue mode to return in a few milliseconds.

11:20am **PS1-TuM10 An Overview of Ion-Ion Plasmas for Semiconductor Processing@footnote 1@**, ***L.J. Overzet***, University of Texas, Dallas; *D.J. Economou,* University of Houston; *J.L. Kleber, S.K. Kanakasabapathy,* University of Texas, Dallas; *B.A. Smith,* Texas Instruments Inc. **INVITED**

Negative ions form in almost all discharges used in semiconductor etching and deposition. In addition, the presence of negative ions can impact nearly every aspect of the discharge: from the discharge chemistry and the formation of particulates to the discharge structure and the transfer of energy from the source to electrons. The presence of negative ions forces the question: Can negative ions be used effectively in plasma processing? Recently, several groups have been investigating whether or not negative ions can be used to process semiconductors and the results thus far have been encouraging. We have found that time resolved measurements of pulsed discharges can provide information on how negative ions can be used for surface processing. Negative ions are ordinarily trapped inside the plasma volume, but, pulsed plasmas allow for efficient negative ion extraction during the afterglow period because the negative ion to electron concentration ratio (electronegativity) can increase dramatically. Plasmas with very large electronegativities are often called "ion-ion plasmas." Ion-ion plasmas have such small electron densities, that the sheaths one ordinarily expects to form no longer form in the same fashion and negative ions can more freely reach processing surfaces. This change in the sheath structure during the transition to an ion-ion plasma should be detectable and a proposed "plasma four point probe" for detecting this transition will be presented as well. Finally, high density plasmas can facilitate negative ion extraction because the high densities make the sheaths thin and the plasma source is sometimes positioned far from the processing wafer allowing the electron average energy to be smaller near the wafer. @FootnoteText@ @footnote 1@ This material is based upon work supported by the National Science Foundation under Grant Nos. ECS-9257383 and CTS-9713262 and by the State of Texas Advanced Research Program under Grant No. 009741-043.

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