Plasma Science and Technology
Room: B2 - Session PS2-ThA

Plasma Diagnostics, Sensors, and Control II
Moderator: C.A. Wolden, Colorado School of Mines

2:00pm **PS2-ThA1 Absorption Spectroscopy Diagnostics of a Dual-Frequency Capacitive Dielectric Etch Tool using Ultraviolet Light-Emitting Diodes**, ***J.-P. Booth***, CNRS/Ecole Polytechnique, France, *J. Bredin,* LPP, France, *G.A. Curley*, LPN/CNRS, France

Dual–frequency capacitively-coupled etch reactors using Ar/fluorocarbon/O_2 mixtures are widely employed for etching of dielectric films for integrated circuit manufacture. CF_x free radicals play an important role in the gas-phase and surface chemistry controlling etching and polymer deposition. The CF_2 radical is the most abundant, and its density can be measured by UV absorption via the A-X band (230-270 nm). Previously Xe arc lamps have been used for the absorption light source, but these sources are rather unstable, limiting the sensitivity of the technique, as well as being cumbersome and relatively expensive. We have successfully replaced the Xe arc with UV light-emitting diodes. The baseline stability is of the order $2x10^{-4}$, compared to $1x10^{-3}$ with an arc lamp. We determined the variation of the CF_2 density as a function of gas composition and power in a modified 2 + 27MHz commercial etch reactor operating in $Ar/C_4F_8/O_2$. As expected, the CF_2 density decreases rapidly as the O2/C4F8 ratio is increased. The CF_2 density increases with RF power at both frequencies, but is most affected by 27 MHz power. There is speculation that CF_2 may play an important role in either or both the creation and destruction of F- negative ions. However, we did not find any simple correlation between CF_2 density and electronegativity (as determined from electron density and ion flux measurements).

We also attempted to measure the F^- negative ion density by the continuum absorption below 365 nm. However in this case we observed a broad but structured absorption when the O2/C4F8 ratio is small. This absorption is too intense to be attributed to F^-, and we speculate that it is due to unsaturated CxFy oligomerisation products.

We wish to thank the Lam Foundation for financial support.

2:20pm **PS2-ThA2 On-wafer Monitoring for UV/VUV Photon Irradiation during Plasma Processes**, ***B. Jinnai***, *S. Fukuda, H. Ohtake,* Tohoku University, Japan, *E.A. Hudson,* Lam Research Corp., *S. Samukawa*, Tohoku University, Japan

Plasma processes are indispensable for the fabrication of ULSI devices. In plasma, there are many activated species, such as charged particles, radicals, and photons. By using these species, etching and film deposition can be achieved. UV/VUV photon irradiation from plasma can cause serious problems because UV/VUV photons can be absorbed in films and generate defects, which may cause degradations of device characteristics. In order to overcome this issue, it is important to understand characteristics of UV/VUV photon irradiation from plasma, such as UV/VUV spectrum and its absolute intensity (photon flux). To investigate these characteristics of UV/VUV photon irradiation from plasma, a VUV spectrograph can be used. A VUV spectrograph is, however, generally expensive and large system, so it is difficult to install. Also, spectra data obtained from a spectrograph is not always corresponding to the information of UV/VUV photon irradiation incident to wafers, due to the different field of view. In this study, we measured plasma properties on a commercial capacitively-coupled dielectric etch reactor using a VUV spectrograph and our developed on-wafer monitoring technique. The on-wafer measurement is based upon plasma-induced current in SiO2 and SiNx thin films. Furthermore, we develop the neural network (NN) modeling method based on the data from our developed on-wafer monitoring technique. By using this method, we could successfully predict the profiles of the UV/VUV spectrum. From the current measured by the on-wafer monitoring technique, we calculated the absolute intensity of UV/VUV photons. The on-wafer monitoring technique has many advantages for the investigation of UV/VUV photon irradiation during plasma processes, and can be applied to the prediction of device damages induced by UV/VUV photon irradiation from plasma.

2:40pm **PS2-ThA3 Influence of Argon Metastables on the Rotational Temperature of Nitrogen in Inductively Coupled Ar/N_2 Plasmas**, ***J.-S. Poirier***, *J. Margot, L. Stafford, P.-M. Berube,* Universite de Montreal, Canada, *M. Chaker*, INRS-EMT, Canada

In low-pressure discharges commonly used for materials processing, neutral gas temperature are routinely determined from the rovibronic structure of N_2 inserted as a tracer. This is realized by comparing the measured emission intensities of the bandhead and the violet-degraded tail of the second positive system of N_2 ($C^3\Pi_u$ v' -> $B^3\Pi_g$ v'') to the prediction of a model with the rotational temperature, T_{rot}, as the adjustable parameter. Such measurements are usually performed using the most intense (v',v'')=(0,0) and (0,2) bands at 337.1 and 380.5 nm. However, in argon-containing plasmas, these bands typically yield temperatures larger than those obtained from other methods such as Doppler-shifted laser-induced fluorescence (D-LIF). Hypotheses for such discrepancy vary; either the emitting $C^3\Pi_u$n'=0 level (11.026 eV above the ground state) could be populated by the $^3P_0$ and $^3P_2$ argon metastables (11.723 and 11.548 eV above the ground state) or the spatial non-uniformity of the plasma could skew D-LIF measurements. In this work, we examined the influence of Ar metastables on the rotational temperature of N_2. We compared T_{rot} values obtained from different N_2 bands, notably (0,0), (0,2), (1,0), and (4,2) to a less conventional plasma sampling mass spectrometry (PSMS) technique in which the Ar plasma on-to-plasma off signal intensity ratio is linked to the gas temperature. These measurements were performed in an inductively coupled 98%Ar/2%N_2 plasma as a function of pressure and absorbed power. We show that N_2 bands with v'≤2 generated much higher T_{rot} values than the (4,2) band or the PSMS. For example, for a 20 mTorr, 1000 W Ar plasma, the (0,0), (0,2), (1,0), (4,2), and PSMS yielded temperatures of 973, 715, 920, 485, and 415 K, respectively. We then computed the reaction rates for excitation of the $C^3\Pi_u$ v'=0 level by collisions with Ar metastables, R-Ar^m, and by electron-impact, R-e, from the ground state. The densities required as inputs for those calculations were measured by Langmuir probe for electrons and, for the metastables, were determined from a global model. We found that that the ratio of the temperatures obtained from the (0,0) and (1,0) bands to that of the (4,2) band increased quasi-linearly with the R-Ar^m-R-e ratio, going from 1.5 to 2 as the Ar metastable-to-electronic excitation rate ratio increased from 0.01 to 0.1. Since Ar metastables can have a strong influence on rotational temperatures even for R-Ar^m-R-e ratio as low as 0.01, accurate gas temperature measurements in mostly Ar plasmas thus require analysis of bands for which v'≥3 as these levels (e.g. 11.74 eV for $C^3\Pi_u$ v'=4) are above the $^3P_0$ Ar metastable level.

3:00pm **PS2-ThA4 Electron Temperatures and Electron Energy Distribution Functions in Dual Frequency Capacitively-Coupled CF_4/O_2 Plasmas, Measured with Trace Rare Gases-Optical Emission Spectroscopy (TRG-OES)**, ***Z.Y. Chen***, *V.M. Donnelly, D.J. Economou,* University of Houston, *L. Chen, M. Funk, R. Sundararajan*, Tokyo Electron America

Dual-frequency capacitively coupled plasmas (2f-CCP) used in the fabrication of modern integrated circuits may provide quasi-independent control of ion flux and energy. The accurate determinations of the electron temperature (T_e) and the electron energy distribution function (EEDF) are important for understanding plasma behavior and optimizing plasma processes in 2f-CCPs. In this study, measurements of T_es and EEDFs in CF_4/O_2 plasmas generated in a 2f-CCP etcher were performed as a function of pressure, applied RF power, and O_2 feed gas content by using trace rare gases-optical emission spectroscopy (TRG-OES). The parallel plate etcher was powered by a high frequency (60 MHz) "source" top electrode, and a low frequency (13.56 MHz) "substrate" bottom electrode. 80%CF_4+20%O_2 or 90%CF_4+10%O_2 plasmas were ignited at pressures ranging from 4 to 200 mTorr, top RF powers of 500 and 1000 W, four different bottom RF powers (0, 100, 300 and 500 W), and three different wafers (Si, Al and anodized Al). T_e was measured across the plasma at a height of 5 mm above the lower electrode. For Si substrates, T_e increased with increasing pressure between 4 and 20 mTorr (typically from 5 to 6.5 eV). The dependence of plasma electronegativity on pressure may be responsible for this behavior. T_e decreased rapidly with increasing pressure in the 20-60 mTorr range, and then slowly decreased with further increases in pressure to 200 mTorr, where T_e = 2.4 to 2.7 eV. Increasing the applied bottom RF power resulted in higher T_e, caused by enhanced stochastic heating of electrons with increasing low frequency voltage. Over the entire pressure range investigated, T_es in 90%CF_4+10%O_2 plasmas were similar to those in 80%CF_4+20%O_2 plasmas. The EEDFs exhibited bi-Maxwellian characteristics with an enhanced high energy tail, especially at pressures >20 mTorr. Different dependences of T_e on pressure and applied top and bottom RF powers were observed for Al and anodized Al wafers.

3:40pm **PS2-ThA6 Laser and LED based Optical Diagnostic Techniques Applied in Industrial Plasma Etch Reactors**, ***N. Sadeghi***, Université Joseph Fourier de Grenoble and CNRS-UJF-INPG, France, *G. Cunge, D. Vempaire, M. Touzeau, R. Ramos*, CNRS-UJF-INPG, France **INVITED**

External cavity tunable diode lasers (DL) and Light Emitting Diodes (LEDs) are cost effective and easy to use tools that can be easily

implemented for the diagnostics of process plasmas. We have used these techniques to characterize plasmas produced in several industrial etch reactors (Applied Materials and LAM Research) and to better understand the interaction mechanisms of the plasma with surfaces present: wafers or/and reactor walls.

Using near infrared DLs, we deduce the gas temperature in different silicon etch plasmas (Cl_2, CF_4, SF_6,..) from the Doppler width of absorption lines from argon metastable atoms when traces of argon is added to the process gas [1]. Absorption and Laser Induced Fluorescence experiments with a blue DL permits to map up the angular dependent velocity distribution function of aluminum atoms sputtered from a RF biased Aluminum wafer under argon ion bombardment [2].

We have shown that the sensitivity of Broad Band Absorption Spectroscopy (BBAS) can be enhanced by at least one order of magnitude when a LED is used as a light source [3]. Thanks to the high stability of the LEDs, it is also possible to perform time-resolved measurements of radicals densities in pulsed plasmas [4]. With a 350 nm LED, the time variation of Cl_2 density down to 3 mTorr can be measured with a time resolution of about 10 millisecond [3]. With a 275 nm LED, we have measured the decay time in the afterglow of the BCl radical produced in BCl_3/Cl_2 plasmas. It has been shown that the main loss mechanism of BCl radical is its gas phase reaction with Cl_2 to form BCl_2 molecule [4].

[1] G. Cunge, R. Ramos, D. Vempaire, M. Touzeau, M. Nejbauer, and N. Sadeghi, JVST A **27**, 471 (**2009**)

[2] R. Ramos, G. Cunge, M. Touzeau, and N. Sadeghi, J. Phys. D: Appl. Phys. **41,** 152003 (**2008**)

[3] G.Cunge, D.Vempaire, M.Touzeau and N.Sadeghi, Appl. Phys. Letters **91**, 231503 (**2007**)

[4] D.Vempaire and G.Cunge, Appl. Phys. Letters **94,** 21504 (**2009**)

4:20pm **PS2-ThA8 Monitoring of Atomic H and Cl Surface Loss Kinetics by Time-Resolved Optical Emission Spectroscopy in an ICP Reactor used for Etching III-V Materials**, ***G.A. Curley****, L. Gatilova, S. Guilet, S. Bouchoule*, LPN-CNRS Upr20, France

A study is undertaken of the loss mechanisms of H and Cl atoms in an inductively coupled plasma used for the etching of III-V materials for photonic device fabrication. A better understanding of these mechanisms may allow us to refine our previous kinetic models of Cl2/H2-based plasma used to anisotropically etch InP-based devices [1], and be useful for monitoring the reactor walls state. The study is also of interest for Cl2/HBr-based plasma chemistries.

The plasma phase is diagnosed using a time-resolved optical emission spectroscopy technique often referred to as pulsed induced fluorescence (PIF). In previous PIF studies, the plasma is pulsed with a standard TTL signal and a short probing pulse (0.05 to 1 ms) is added to scan the afterglow. In our case we extract the fluorescence signal directly from the rising edge of the plasma ignition and therefore only standard pulse operation of the RF generator is required.

In principle the evolution of various radical densities in the afterglow could be followed with the PIF technique by varying the duration of the interval between two successive pulses (the off time). In this study we monitor the evolution of hydrogen and chlorine radicals to deduce their surface recombination coefficients. The plasma is pulsed with an off-time ranging from 200 µs to 100 ms. The on-time is chosen for steady state conditions to be reached. The targeted pressure value lies in the range of 0.5 mTorr to 10 mTorr.

In the case of hydrogen, comparing the increase rate of H2 to the decay rate of H allows us to estimate if surface recombination mechanisms other than H(g) + H(s) -> H2 have to be considered. We therefore monitored both the H-alpha (656.3 nm) the Fulcher-alpha (602nm) line of H2. By pulsing the plasma with long off-times we can verify that emission from dissociative excitation of H2 is negligible under our experimental conditions.

The typical recombination coefficient of H in our reactor, with SiOAlCl passivated walls, has been found to be around 0.01. More interestingly the growth rate of H2 is at least two times higher than the decay rate of H. We will therefore discuss two possibilities that may explain this experimental observation:

1) the existence of a competing loss mechanism for H2;

2) the existence of another loss mechanism for H-atoms. This possibility was proposed in a study of the side-wall passivation of InP etched with Cl2/H2 chemistry [1], where H(g) + Cl(s) -> HCl was assumed to favor the removal of Cl from the passivation layer.

Finally, the PIF technique is evaluated for the first time in chlorine plasmas to deduce the surface loss coefficient of chlorine atoms.

[1] L. Gatilova et al, JVST A 27 (2009) 262

4:40pm **PS2-ThA9 Real Time Control of an Inductively Coupled Plasma Simulation**, ***B.J. Keville****, M.M. Turner*, Dublin City University, Ireland

Process yield in many plasma assisted processes may be improved significantly by real time, closed loop control of certain plasma species. This paper describes the closed loop control of a low pressure, inductively coupled plasma simulation. The plasma simulation consists of a global model of the plasma chemistry coupled to an equivalent circuit. The equivalent circuit incorporates an impedance matching box and an model of power coupling from the antenna into the plasma which has been derived from the wave equation and the two term solution to the Boltzmann equation. In addition, mass flow controller models and gas flow transport delays are included in the simulation. The design of effective, real time, closed loop control algorithms is facilitated by simple, control-oriented, dynamical models of the relationship between actuators (inputs) and the process quantities to be controlled. The paper will indicate how the parameters of a control algorithm may be determined from the process model (model-based control) in order to guarantee a robustly stable closed loop response. In general, process measurements are noisy and may not provide direct estimates of process quantities to be controlled. For example, estimates of atomic oxygen density obtained from optical emission spectroscopy are ambiguous due to dissociative excitation. Furthermore, many process parameters such as wall sticking coefficients are extremely difficult to estimate and may change due to chamber seasoning. The paper will indicate how an optimal state estimator may be used to improve estimates obtained from optical emission spectroscopy and how such estimates may be used to adapt the control algorithm in real time in order to guarantee process stability despite changes in process parameters.

5:00pm **PS2-ThA10 Wafer Temperature Response During Plasma Etching and Applications to Chamber Matching**, ***J. Shields****, C. Gabriel*, Spansion, Inc.

As dimensions shrink, wafer temperature plays an increasingly important role in plasma etch process control. Temperature, however, is usually only monitored indirectly by measuring the chuck temperature or the coolant temperature during processing. To address these issues, we have employed the wireless KLA SensArray Integral wafer to measure the actual wafer temperature at 65 locations during wafer processing in a dielectric etch chamber with three different RF frequencies available. The Integral wafer records the temperature up to several times per second on internal memory, which is then downloaded to a computer after processing is completed. We conducted tests with no RF power, to determine effect of upper electrode and lower electrode temperatures on the wafer. We then measured the temperature response under variable RF excitation conditions for three different process chemistries utilized for dielectric and organic etching. For each process chemistry, comparisions between different excitation frequencies and combinations of frequencies were performed. The dependence of wafer temperature average and uniformity on backside helium cooling was determined, including a series of tests with no backside helium to isolate the effect of just RF delivered power. Finally, the promising application of this technique to chamber matching activities was analyzed.

5:20pm **PS2-ThA11 Plasma Etch Chamber Wall Deposits – Impact on Etch Species Density and Evaluation of Cleaning Procedures**, ***D. Dictus****, D. Shamiryan, V. Paraschiv, S. Degendt, W. Boullart, M.R. Baklanov*, IMEC, Belgium*, C. Vinckier*, KU Leuven, Belgium

During the last ten years there has been a growing awareness about the impact of the plasma etch chamber wall condition on the density of reactive species in the etch chamber. This is especially the case for ICP chambers at low pressure (5-80mTorr) where gas phase diffusion and recombination at the reactor wall can be a dominant loss mechanism for reactive species. The majority of the studies are carried out for reaction chambers, coated with SiOCl or CF_x -based polymers.

In this paper we expanded the study to metal deposits such as titanium and tantalum which are frequently used for metal gate application in front-end-of-line, or as hard mask material for low-k etching in back-end-of-line. Additionally we made an evaluation of the cleaning procedures to remove these metals from the reactor walls.

CF_x-based polymers where deposited by igniting a polymerizing plasma, while Si, Ti and Ta were deposited by etching Si, TiN and TaN, respectively, in $Cl_2/HBr/O_2$ plasmas. The composition of the chamber wall deposits was investigated by XPS analysis of so-called 'floating samples'. Relative density variation of reactive species (Cl, Br, O and F) in "contaminated" chambers was analyzed by actinometry. For the actinometry experiments we added 5% Ar to respectively Cl_2, HBr, O_2 and SF_6 plasmas and we related the peak intensities to the Ar 750nm peak. Our results indicate that the effect of the metal deposits is very similar to the CF_x-based deposits. We can summarize this as a lowering of all tested

species densities when the chamber walls contain metal(oxide) traces. By comparing our data with previously published results we can also estimate a recombination probability.

Next to the study on density variations of reactive species we investigated how these metals are best cleaned from the chamber walls. This is again done with actinometry, by comparing the data of 'clean' and 'coated' chamber walls. For CF_x based coatings and SiOCl coated chambers the cleaning procedure is well known and is mostly done with O_2 and SF_6 based plasmas respectively. For the metals however we found that titanium should be cleaned with Cl_2 plasma and for Ta we observed that none of the tested chemistries was able to quickly remove it. Since our XPS data indicate that the Ti and Ta on the walls is partially in the form of TiO_2 and Ta_2O_5 this is not a surprising result. Finally, we did observed that it's possible to clean both metals with BCl_3 or $SiCl_x$ containing plasmas but this is beyond the scope of this work.

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