Tuesday Morning, October 30, 2012

Plasma Science and Technology
Room: 24 - Session PS1-TuM

Plasma Diagnostics, Sensors and Control 1
Moderator: V. Nagorny, Mattson Technology

8:00am **PS1-TuM1 Monitoring Plasma Etch Processes with Wave Cut-Off, Langmuir, and Radio-Frequency Probes**, ***M.A. Sobolewski***, National Institute of Standards and Technology (NIST) **INVITED**

In industrial plasma etching processes, etch rates, profiles, and the critical dimensions of etched features may depend very sensitively on ion current density and other plasma parameters. The reproducibility of plasma conditions is thus an important concern, but the many mechanisms that can cause plasma properties to vary during processing have not been much studied. Here, such mechanisms were investigated using a wave cut-off probe and a Langmuir probe, in tetrafluoromethane/argon plasmas in an rf-biased, inductively coupled plasma reactor. The wave cut-off probe provided measurements of plasma electron density every few seconds. Because it is based on a frequency measurement, it can precisely measure small changes in electron density, often as small as 1 %. Internal resonances in the cut-off probe, however, can degrade this precision. The Langmuir probe provided measurements of the ion current density, electron and ion densities, and electron energy distribution function, with a time resolution of tens of seconds.

Several different phenomena were investigated. First, we investigated the changes in plasma electron density that occur when the rf bias is turned on or off. Analysis shows that such changes can be explained by the stochastic heating of electrons by rf bias power, the interaction of the rf bias and the inductive source, and perturbations in gas composition caused by etch products. Second, we investigated the changes in all plasma parameters that occur when etches of silicon dioxide films on silicon substrates reach endpoint. Analysis shows that the changes observed at etch endpoint were primarily due to changes in gas composition, rather than changes in electron emission from the wafer surface. Third, we also observed nonidealities in the inductive source that affect its ability to maintain constant plasma parameters.

Simultaneous with these measurements, the rf current and voltage were measured outside the reactor, in the rf bias and inductive source circuitry. These external measurements were strongly correlated to — and explained by — the wave cut-off and Langmuir probe data. These results strongly suggest that nearly all of the phenomena observed here can be monitored equally well by external rf measurements, instead of invasive probes.

8:40am **PS1-TuM3 Impact of Self-Absorption on Emission Spectral Lines for Non-Equilibrium Plasma Source**, ***E. Gudimenko***, *V. Milosavljevic, S. Daniels*, Dublin City University, Ireland

Precise optical measuring techniques of spectral lines are necessary for low pressure plasma semiconductor manufacturing analysis. Problems which add to the inaccuracy of the optical measuring techniques include spectral line broadening mechanisms such as self-absorption.

Self-absorption has been widely neglected or its importance overlooked for plasma diagnostics.

In this study several different techniques are used to examine the impact of self-absorption on emission spectral lines from a reactive ion etch (RIE) plasma chamber, measured using a high resolution optical spectrometer. The experiments are performed in an Oxford Instruments plasma lab 100 RIE chamber which operates at a standard single frequency (GEC) 13.56 MHz with maximum RF power of 600 W. The OES spectrums were taken with a Horiba Jobin Yvon Czerny-Turner design Auto MicroHR spectrometer with focal length of 140 mm and spectral resolution of 0.25 nm at 400 nm wavelength.

One technique which is used is to check line intensity ratios within multiplets which abide by so-called LS-coupling rules. The time or spatial fluctuation in the observed intensity of the strongest or metastable line within the multiplet, in respect to the weakest spectral line in the same multiplet shows that self-absorption is present. Another technique which is examined is to change the optical path length by measuring the plasma from different points or different viewports on the plasma chamber. If the increase in signal intensity changes corresponding to optical path length, there is no self-absorption.

A Design of Experiments (DOE) has been used to cover the multidimensional external parameter space e.g. power, pressure, flow rate and chemistry. The results from the techniques are compared to each other for accuracy and the impact of self-absorption is then quantified. In this work the influence of self-absorption of neutral Argon and Oxygen spectral lines for a range of parameters in an RIE plasma chamber has been studied. Almost all the measured spectral lines have been affected, up to some level, by self-absorption. Some spectral lines shapes are changed by self-absorption up to 60%. One of the most widely used actinometry spectral lines for plasma diagnostics, Argon 750 nm, has its intensity affected by self-absorption by up to 40%.

Correction of self-absorption is a necessary step for OES based plasma diagnostics. In the case of Actinometry calculation correction of self-absorption could change the final result up to 20%.

This material is based upon works supported by Science Foundation Ireland under grant No.08/SRC/I1411

9:00am **PS1-TuM4 Real-Time Plasma Deposition Thickness Control using *In Situ* Optical Emission Interferometry**, *D.J. Johnson,* ***K.D. Mackenzie****, C.W. Johnson, L. Martinez*, Plasma-Therm LLC

Measurement of the thickness of a growing film as it is deposited can provide real advantages in a production environment. Consistent film thickness is achieved despite long term process drifts and machine to machine variations in deposition rate. Also the time lost due to system re-qualification after routine cleans and maintenance procedures can be reduced significantly.

In this work film thickness is measured in situ in a PECVD system by reflectance techniques, using the plasma emission as a light source (Optical Emission Interferometry, OEI). A parallel plate deposition **system** is described in which the plasma emission reflected from the substrate is monitored through one of the gas introduction holes in the upper electrode. During the deposition of silicon dioxide and silicon nitride films, the emission bands from molecular nitrogen in the 300 – 400nm region are used for measurement purposes. As the film thickness increases the reflected intensity undergoes a cyclical variation due to interference effects. The film thickness change for one complete cycle is known from the values of the wavelength and the refractive index of the film at that wavelength. The number of interference cycles, including fractional cycles is counted and the film thickness calculated in real time as the film is deposited. The process is terminated when the desired film thickness is reached. An example is shown where the long term variation in film thickness is significantly reduced as compared to running a process terminated by time alone.

For thin films (eg < 100nm) a series of interference cycles is not generated, so the "peak counting" approach cannot be used. Instead, multiple wavelengths (multiple nitrogen bands) are monitored, generating more data points which permits a more accurate determination of the film thickness. This approach is applied to the deposition of a 50nm silicon nitride film.

The above approaches strictly measure change in film thickness, not absolute film thickness. It is shown that by monitoring the complete spectrum and calculating the spectrum change with time, the result is equivalent to the differential of the film's reflectance spectrum. From this the absolute film thickness is calculated. This is particularly useful for the deposition of thicker films where a final film thickness is required, despite a variable or unknown starting film thickness. Although not discussed here, the same approach can be used when etching thick films down to a final required thickness.

9:20am **PS1-TuM5 Subsequent Temporal Change of Gaseous H and N Radical Density in Plasma after Different Processes**, ***T. Suzuki****, A. Malinowski, K. Takeda, H. Kondo, K. Ishikawa*, Nagoya University, Japan, *Y. Setsuhara*, Osaka University, Japan, *M. Shiratani*, Kyushu University, Japan, *M. Sekine, M. Hori*, Nagoya University, Japan

A precise shape control at less than 1 nm scale is demanded in large-scaled-integrated-circuits (LSI) fabrication of the 10-nm half pitch and beyond. In realization of super-fine plasma etching process, surface reactions of ions and radicals play important role because they determine etched feature [1]. Thus control of actual plasma parameters such as substrate temperature, radical density, and electron density is required. It has been proved that the radical density is changed as a result of emission into bulk plasma both of etching products and adsorbed species on chamber wall. However, investigation of influence of inner wall condition on bulk radical density has not been studied yet. Thus, in this study we focused on gaseous radical density in H_2/N_2 plasmas, and investigated temporal changes subsequently after different kind of plasmas where inner wall condition could be changed.

Measurements of gaseous radical densities have been carried out by the Vacuum Ultra Violet Absorption Spectroscopy (VUVAS) equipped with a micro-discharge hollow cathode lamp (MHCL) [2]. In this case we measured transition lines for Lyman α at 121.6 nm for H atoms and $^{4}P_{5/2}$-$^{4}S^{0}_{3/2}$, $^{4}P_{3/2}$-

$^4S^0_{3/2}$ and $^4P_{1/2}$-$^4S^0_{3/2}$ at 120.0 nm for N atoms. H_2/N_2 plasma was generated in a 100-MHz capacitively coupled plasma (CCP) reactor with H_2/N_2 gas mixture ratio of 75/25. Applied power was 400W (100 MHz) for upper electrode, and 200W (2 MHz) for bottom electrode respectively. The gaseous radical densities for the H_2/N_2 plasmas were monitored subsequently after different plasmas, (a) seasoning condition of H_2/N_2 plasma, (b) O_2 plasma, and (c) air exposure.

First, temporal changes for N radical density in the H_2/N_2 plasma subsequently, after the various plasma exposures were compared. In case of (a) seasoning, the N density was stable. On the other hand, the N radical densities were much varied after (b) O_2 plasma, and (c) air exposure. Notably, the density just after H_2/N_2 plasma ignition reached value which is more than twice higher when compared to stabilized value for (a) seasoning. Interpretation can be given as etched products or process gases were adsorbed on inner wall surface at the previous process, and then those species were desorbed from the wall into bulk plasmas in the subsequent processes. In accordance with organic *low-k* etching using H_2/N_2 plasmas, when a ratio of H radical and N radical (H/(H+N)) was changed more than 15% against an optimal original value, a shape of etched feature is resulted in modifications with scales of 10 nm [1].

[1] M. C. Sung *et al*, J. Appl. Phys. **107**, 113310 (2010).

[2] S. Takashima *et al*, J. Vac. Sci. Technol. A **19**, 599 (2001).

10:40am **PS1-TuM9 Experimental Implementation of Real-time Multivariable Control of a Capacitively Coupled Plasma**, ***Y. Zhang**, B.J. Keville, C. Gaman, A. Holohan, M. Turner, S. Daniels*, Dublin City University, Ireland

The ever-increasing demand for higher device density in integrated-circuit fabrication has resulted in stringent requirements in respect of quality, reliability and precision of all fabrication processes in semiconductor manufacturing. *Reactive Ion Etching* (RIE) is a critical technology used at many stages of the manufacturing process. At present, most semiconductor manufacturing equipment is operated in open loop mode. Consequently, key plasma parameters such as ion flux and radical densities at the substrate surface are sensitive to drift in tool subsystems, changes in wall condition and wafer loading, for example. Such disturbances may affect process metrics such as etch depth and anisotropy and result in a significant degradation in device yield and performance.

In this presentation, we describe the implementation of a multi-variable *Linear Quadratic Gaussian/Loop Transfer Recovery* (LQG/LTR) controller to regulate key plasma parameters in an updated Mini-lab RIE 80 capacitively coupled chamber. The custom designed, real-time data-acquisition and control system has been implemented in Labview on a National Instrument CompactRIO real-time controller, which has been interfaced to a hairpin resonance probe and an optical emission spectrometer, the Ocean Optics USB4000. Experimental results are presented which compare the performance of the multivariable LQG/LTR controller to that of a suite of decentralised *single-input-single-output* (SISO) controllers.

This research forms part of program to implement multivariable closed-loop control on an industrial *Electron Cyclotron Resonance* (ECR) plasma etch chamber. The presentation concludes by describing progress in this part of the program.

11:00am **PS1-TuM10 Multivariable Control of a Capacitively Coupled Plasma**, ***B.J. Keville**, Y. Zhang, M. Turner*, Dublin City University, Ireland

Present practice in reactive ion etching specifies etch recipes in terms of inputs such as gas flow rates, RF power and pressure. However, ostensibly identical chambers running identical recipes may produce very different results. Extensive ‘chamber matching’, i.e. initial iterative, empirical tuning of the process recipe, which entails time-consuming, ex situ statistical analysis of etch metrics, is required to ensure that an etch chamber produces acceptable results. Once matched, etchers are run ‘open loop’ and are thus sensitive to disturbances such as actuator drift, wall seasoning and substrate loading, which may have deleterious effects on process metrics such etch depth, uniformity, anisotropy and selectivity,. An alternative approach, which would reduce sensitivity to disturbances of the plasma generating process, would be to specify a recipe in terms of plasma quantities such as radical densities, and to regulate these in real time by adjusting the inputs with a suitable multivariable control algorithm.

Multivariable closed loop control of an $SF_6/O_2/Ar$ plasma in an Electron Cyclon Resonance (ECR) etcher is the focus of a major research program in the National Centre for Plasma Science and Technology (NCPST) in Dublin City University (DCU). As an intermediate step, a multivariable LQG/LTR control algorithm has been implemented on a capacitively coupled plasma using the same gas mixture. This presentation describes the design of the algorithm, and its efficacy is demonstrated via simulation with a variety of disturbances. The performance of the multivariable algorithm is compared to that of a suite of decentralised single-input-single-output (SISO) controllers.

11:20am **PS1-TuM11 Single and Multi-Point Ion Energy Distributions in a VHF+RF Commercial Reactor Measured by Novel In-Wafer Ion Energy Analyzer**, ***B.G. Lane**, M. Funk, L. Chen, R. Sundararajan, J. Zhao*, Tokyo Electron America

The energy distribution of the ions impacting the wafer is a key determinant of process results. A novel, all silicon, minimally perturbing, non-contaminating, in-wafer, 2 and 3 layer ion energy analyzer described elsewhere in this conference is used to measure ion energy distributions for a variety of realistic processing conditions in a commercial VHF + 13.56 MHZ RF reactor with no modifications to its basic geometry or RF delivery system. Spectra with energies as high 1 keV are measured with resolution on the order of 1%. Total ion transmitted flux as well as the floating potential of the plasma exposed 1st grid relative to ground are measured in addition allowing estimates of the plasma potential at the sheath edge. Measured energy spectra are compared to particle simulations aiding in the interpretation of the spectral features. We show data and discuss the splitting of the high energy peaks due to finite ion sheath crossing time effects and how this splitting scales with frequency, power and pressure. We discuss how such splitting can be used to estimate the ion density at the sheath edge. We discuss the origin and scaling of charge exchange peaks. We use the identification of atomic and molecular oxygen ion peaks to estimate the resolution of the diagnostic . The use of VHF to obtain narrow ion energy distributions at moderate ion energies will be highlighted. Spectra using a multi-point, 2 layer variant of the ion energy analyzer design were obtained at 4 radial locations for a variety of conditions in argon and oxygen plasmas. These spectra quantify center to edge variations and reveal unique spectral features due to pre-existing modifications to the test reactor's upper counter electrode surface. We believe that these may be the first reported measurements of ion energy distribution functions for some of the more extreme conditions investigated and some of the first reported multi-point ion energy spectra for a commercial plasma reactor.

11:40am **PS1-TuM12 Characterizing Electron Beam Generated Plasmas for Plasma Processing Applications**, ***D.R. Boris**, R. Fernsler, S.G. Walton*, Naval Research Laboratory

Electron beam generated plasmas have a variety of unique features that make them distinctive plasma sources for materials processing. They are characterized by high plasma density, very low electron temperature, and unique gas phase chemistries that distinguish them discharge based plasmas. This work presents frequency probe and Langmuir probe measurements (where applicable) of plasma density over a range of 10^9 to 10^{12} cm^{-3} in a variety of processing plasma chemistries. This work also features the effect of varying gas chemistry on energy distribution function measurements as well as OES (optical emission spectroscopy) and mass spectrometry measurements.

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