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

Plasma Diagnostics, Sensors and Control 2
Moderator: R. Ramos, LTM, France

2:00pm **PS1-WeA1 ECR Plasma Etching Characterization using a Retarding Field Energy Analyzer**, ***B. Dolinaj***, Dublin City University, Ireland, *V. Milosavljevic*, Dublin City University, *D. Gahan*, Impedans Ltd., *N. MacGearailt*, Intel Corporation, *M.B. Hopkins*, Impedans Ltd., *S. Daniels*, Dublin City University

Dry etching technology was introduced to integrated circuit manufacturing due to its unique ability to do anisotropic removal of material to create high aspect ratio structures. Dry etching tools in the semiconductor industry use plasma to generate electrons, bombarding ions and free radicals. These radicals are chemically reactive and highly efficient at removing material from substrate surfaces, so the etch profiles depend on ion density and ion energy.

Electron cyclotron resonance (ECR) plasma etching reactors are widely used in wafer production. They use a low pressure, high density plasma source that has resonant magnetic field coils and two independently controlled microwave and radio frequency (RF) sources. ECR plasma etching is a very complex process and most of the progress with ECR etching tools up to this time has been accomplished empirically. Introducing new and adapted plasma diagnostic techniques is essential for further characterization and better understanding of plasma and etching processes.

In previous work we presented electrical measurements obtained using a retarding field energy analyzer (RFEA) installed in an commercial ECR etching reactor. RFEAs are generally used for charged particle flux and energy distribution measurements at electrically grounded surfaces. We demonstrated that an electrically isolated RFEA can be successfully used for measuring ion energy distribution functions (IEDFs) at the surface of RF driven electrodes in the presence of strong DC magnetic fields.

In this work we present further achievements in plasma diagnostics and ECR etching characterization. The original experimental setup is expanded for additional diagnostic tools. Phase resolved optical emission spectroscopy (PROES) measurements are taken at three different discharge locations simultaneously with RFEA measurements. Electrical and optical measurements show strong correlation in comparable aspects which proves their validity and together they provide more information about plasma in complementary aspects. The RFEA has also been used to measure the electron energy distribution function (EEDF) with the aim of electron temperature and density estimation in the bulk plasma. For validating EEDFs obtained with the RFEA, we performed similar measurements of EEDFs in a capacitively coupled plasma (CCP) reactor using the RFEA and the Langmuir probe. Results of this validation and estimations made from EEDFs are presented and discussed. Experimental and theoretical plasma etching characterization has been done through the analysis of spatially resolved data sets obtained from RFEA and spectroscopic ellipsometry at various radial locations.

2:20pm **PS1-WeA2 Time Resolved Ion Flux Measurement in Pulsed ICP Plasmas**, ***G. Cunge***, *M. Darnon*, LTM-CNRS, France, *N.St. Braithwaite*, The Open University, UK, *E. Despiau-Pujo, P. Bodart, M. Brihoum, M. Haass, O. Joubert*, LTM-CNRS, France

Pulsed ICP plasmas are a promising solution to several technological issues related to IC circuit fabrication. Recent results are indicating that pulsing the inductively coupled power and/or the RF biasing power allows to increase the etch selectivity and to reduce plasma induced damages in ultrathin layer. However, the reasons for these improvements remain unclear. In particular, the impact of plasma pulsing on the ion flux (and ion energy) in electronegative gases used for IC circuit fabrication has not been studied in details. In this work, we have used a capacitively-coupled planar ion flux probe to monitor the time variations of the ions flux in various plasmas (CF4, SF6, Cl2, HBr…etc) operated in an industrial etch reactor from AMAT. We will discuss in detail the experimental set-up that we have designed to carry out time resolved measurement and the issues associated with this measurement. Results will be presented from both electropositive (Ar, He) and electronegative (Cl2, BCl3, SiCl4, SF6) plasmas. We will first present the impact of the ICP source pulsing frequency and duty cycle on the ion flux. These results will be compared to those obtained from a global model. We will then discuss the impact of the RF biasing power on the ion flux in pulsed plasmas. Both the ICP source power and the RF bias power can be independently or synchronously pulsed. In the latter case different duty cycles and a phase delay can be used. During synchronized pulsing with a delay between the ICP and the rf bias pulses, some interesting instabilities (ion flux oscillations) are observed. They are related to the generation of ion acoustic waves by the rapid expansion (or collapse) of the sheath in front of the wafer when the RF bias pulse is applied to the chuck. These results will be eventually compared to IEDF measurements in pulsed plasmas and the consequences on pulsed plasma etch process design will be discussed.

2:40pm **PS1-WeA3 *In Situ* Monitoring of Electron Density and Dielectric Layer on the Wall with Curling Probe**, ***A. Pandey***, *Y. Liang, S. Ikezawa, K. Nakamura, H. Sugai*, Chubu University, Japan

A new type of microwave resonator probe, *curling prob*e, has recently been proposed [1] which employs mono-pole excitation of spiral slot antenna. This probe enables direct measurement of electron density in reactive plasmas, based on a quarter-wavelength resonance at the frequency $f=b(c/4L)[2/(e_{\mathrm{in}}+e_{\mathrm{out}})]^{1/2}$. Here, b is the finite-size correction factor, L is the antenna length, e_{in} and e_{out} are the relative permittivities of two dielectrics inside and outside the slot antenna, respectively. When the probe is inserted into plasma, the outer dielectric constant e_{out} is expressed as $e_{\mathrm{p}} =1-(f_{\mathrm{p}}/f)^2$ with the electron plasma frequency $f_{\mathrm{p}}=(e^2n/me_0)^{1/2}$. Thus, measuring the resonance frequency of curling probe, one can determine f_{p}, and hence the electron density n. The finite-difference time-domain (FDTD) simulation of 11-mm-diam curling probe of 35-mm antenna length shows a sharp resonance at the frequency from 1 GHz to 6 GHz uniquely determined by the electron density. The sheath formed in front of the probe surface was modeled as a vacuum layer of ~$5l_{\mathrm{D}}$ in thickness. The resonance frequency was hardly influenced by the sheath at the density higher than 10^{11} cm^{-3}. Basic experiments of electron density measurement by the curling probe were performed in an argon (1~20 Pa) low-power (<2 kW) discharge in ICP device for 300-mm-wafer process. The power dependence of the resonance frequency observed by the curling probe was explained well by the FDTD simulation result as well as the analytical formula. The radial distribution of electron density was measured by a movable curling probe.

When a polymer layer (permittivity e_{d}) is deposited on the probe surface, the resonance frequency decreases with the increasing layer thickness. Using this probe characteristic, one can *in situ* monitor the thickness of dielectric layer deposited onto a wall of plasma vessel, where the curling probe is positioned to just the same surface of inner wall. The FDTD simulation shows ~10 MHz shift in the resonance frequency for 15-mm-thick deposition of polymer (e_{d} =3.2), in good agreement with the experimental observation. Thus, the wall deposition layer during chamber cleaning or CVD process can be monitored by the curling probe. In fact, amorphous carbon layer formed on the vessel wall was *in situ* monitored by the curling probe in a 1-kW surface-wave plasma in CH_4/Ar *deposition* discharge and in O_2/Ar *cleaning* discharge. This model experiment successfully demonstrated an applicability of curling probe to monitoring the dielectric layer deposited on the plasma vessel wall.

[1] I. Liang, K. Nakamura, and H. Sugai, Appl. Phys. Express 4, 066101 (2011).

4:00pm **PS1-WeA7 Time Resolved Laser Induced Fluorescence for Probing the Excitation Kinetics of a Low Temperature Argon Discharge**, ***J.M. Palomares Linares***, *E.A.D. Carbone, S. Hübner, W.A.A.D. Graef, J.J.A.M. van der Mullen*, Eindhoven University of Technology, the Netherlands **INVITED**

In this contribution we report a series of experiments based on time resolved laser induced fluorescence (tr-LIF) on low temperature discharges. This technique is used, in combination with Thomson scattering (TS) measurements, to get insight in the excitation kinetics of the discharge.

This method is used to pump different levels within the 4p and 5p groups of the Ar excitation space, from the Ar metastable level $1s_5$. Measuring the tr-LIF decay times in combination with the TS measurements of electron density provides simultaneously total destruction rates by electron and heavy particle collision of the pumped levels. These effective excitation rates are of great importance for the development of models, and are scarce in the case of high excited argon levels.

Similarly, the time response of the collisional induced fluorescence signals (tr-LCIF) emitted by other excited levels is used to study the interaction between levels. In the particular case of Ar this method is used to obtain the "depopulation rates" of metastable 4s levels. When other gasses are introduced in the discharge tr-LCIF signals are obtained from the emission of different excited species of those gasses. These experiments enable us to probe in details the excitation exchange between different species. The use of a high rep-rate system is fundamental for the LCIF measurements, where the low intensity of the signals demands measurement times up to 30 minutes.

The experiments are done in a range of intermediate pressures (0.65 mbar – 40 mbar), on a surfatron microwave induced plasma, working with pure Ar, and mixtures of Ar with H_2, O_2, and N_2. The tr-LIF diagnostic is performed with a 5KHz high rep-rate Nd:YAG laser in combination with a Dye laser system. This setup allows to record tr-LIF signals 500 times more intense than with the common 10 Hz systems. Two equivalent systems are used to pump different wavelengths, a tripled frequency Nd:YAG (@355 nm) in combination with a Coumarine-2 Dye laser (430 nm - 460 nm), and a doubled frequency Nd:YAG (@532 nm) with a Pyridine-1 Dye laser (670 nm – 720 nm). The Thomson scattering measurements are performed with an independent Nd:YAG (532 nm) system and a triple grating spectrograph for the detection of the scattered photons.

4:40pm **PS1-WeA9 Analysis of Run-to-Run Variability in the Bosch Process using rf Probe and Emission Spectroscopy Measurements**, ***M. Fradet***, *L. Stafford,* Université de Montréal, Canada, *C. Coïa*, Teledyne Dalsa, Canada

Deep silicon etching is a crucial step for several emerging and evolving technologies, including micro-electromechanical systems (MEMS) and CMOS image sensors. Among etching methods available, the Bosch process is widely used because it allows fast etching rates together with high aspect ratios. This process relies on rapidswitches between isotropic etching in SF_6-containing plasmas and polymer deposition for sidewall passivation in C_4F_8-containing plasmas. As a result of reactor wall conditioning, run-to-run variability in etching rates and uniformity is commonly observed. In order to understand the origin of such drifts and thus to develop new strategies to reduce these effects, we have started investigations of the temporal evolution of the properties of SF_6 and C_4F_8 plasmas in the Bosch process on an industrial, inductively-coupled plasma reactor (ICP) at Teledyne Dalsa. In this context, a rf probe was installed on the transmission line connecting the generator to the substrate holder. This system measures the amplitude of the current and voltage as well as the phase between them, allowing determination of the real and imaginary parts of the impedance. During one etch cycle in Ar/SF_6 (total duration of 10s), the absolute value of the reactance, |X|, decreased sharply within the first second and then reached a plateau. For one sample exposed to many etch and deposition cycles, the cycle-averaged value of |X| slowly decreased between the first and the 70th cycle. For many samples etched in the same chamber with a 2 minutes O_2 plasma clean between each run, the run-averaged value of |X| decreased with the sample number. Over this whole range of experimental conditions, the resistance remained fairly constant. From optical profilometry measurements, the etching rate was found to decrease from 340 to 300 nm/s between run #1 and #5. This decrease matched relatively well the observed decrease of |X|, suggesting that the reactance determined from rf probe measurements is a good parameter to examine in a non-intrusive way run-to-run variability in deep silicon etching. More recently, preliminary analysis of the plasma emission in the Ar/SF_6 plasma revealed that the F (703.7 nm)-to-Ar (750.4 nm) line-intensity ratio (related to the F density) remained constant within the first few seconds and then decreased mid-way in the etch cycle due to strong F uptake. Future experiments will attempt to determine whether the observed decrease of the Si etching rate due to wall conditioning can be attributed to a reduction of the fluorine concentration during the etch cycle or to a higher density of fluorocarbon radicals during the passivation cycle.

5:00pm **PS1-WeA10 Spatially-resolved Optical Emissions Spectroscopy of Capacitively Coupled Discharges**, ***G. Franz***, *I. Krstev, F. Schamberger*, Hochschule München, Germany

Optical emission spectroscopy has evolved a mighty tool for evaluating the high-energy tail of the electron energy distribution function EEDF [1]. Since it is a non-evading technique, a spatially-resolved measurement cannot be performed, which limits its general applicability, especially for inhomogeneous plasmas, in particular capacitively-coupled discharges with their thick plasma sheaths and large rf electric fields, and microwave-driven plasmas which exhibit a very high plasma density in front of the microwave window which prevents the penetration of the microwave into deeper regions of the reactor. A spatially averaging technique therefore overdraws the region close to the window leading to erroneous results and conclusions.

To overcome these limitations, a cyclindrical parallel-plate reactor was equipped with a magnifying double lens system with different focal lengths halfway between the two "electrodes" to resolve radially dependent spectroscopic data obtained with the two actinometric gases Kr and Xe [2]. From these data, the electron temperature of the high-energy tail of the EEDF of capacitively coupled discharges through argon and the weakly electronegative gas mixture CF_4/O_2 can be calculated [3].

These data are modeled with ray tracing programs to evaluate the degree of magnification. Compared with an experimental setup with a plane window instead of a converging lens and only one focusing lens for the glass fiber, we can enhance the S/N ratio by a factor of at least 100 yielding a radial resolution of about 1 – 2 mm which is in the same range of Langmuir probes.

Compared with measurements obtained with Langmuir probes in the plasma bulk, electron temperatures show in fact the expected behaviour of definitely hotter temperatures.

[1] V.M. Donnelly, J. Phys. D: Appl. Phys. **37**, R217 (2004)

[2] G. Franz, I. Krstev, F. Schamberger, Plasma Sci. Techn. **14**(8), to be published 2012

[3] M.V. Malyshev and V.M. Donnelly, J. Vac. Sci. Technol. **A15**, 550 (1997)

5:20pm **PS1-WeA11 Model-based Ion Energy Control in ICP Etcher**, ***M. Klick***, Plasmetrex, Germany, *H.P. Maucher*, United Monolithic Semiconductors

In particular for III-V semiconductors, plasma processes close to active zones of surface-sensitive devices are critical, demanding low damage through ion bombardment and so an excellent process understanding and control. In order to get the ion energy into the right range, the bias power is switched off working then a downstream-like mode. A complete model of the entire system with this special setup is presented and validated. It demonstrates that the bias matchbox capacitances are excellent control elements for the ion energy. We can also show that the Vp measurement is not representing the ion energy here. The ion energy is estimated by the sheath voltage from the model and shows a reasonable correlation to the etch rate observed.

This paper focuses on a general method to characterize equipment and plasma by a combination of off-line and real-time measurements. The first major goal of this paper is to show how reduced models of plasma equipment can be used to estimated important plasma parameters as to understand how the plasma process works. The equivalent circuit i only a tools to explain the over all plasma physical picture, it does mean that an equivalent circuit is always the right tool to describe a plasma. This resulting, reduced and so also not self-consistent model must be verified and then used for the ion energy control in an ICP etcher.

The model is based on an combined plasma and RF model in the special case of an existing bias matchbox but zero bias power. The control elements are the capacitance in the bias matchbox. We show the tune capacitance to be an excellent control element, but we can also demonstrate that – at least in this case – an RF peak voltage measurement is not representing the ion energy and alone not very useful.

Trikon/Aviza Omega 201 ICP etcher was used. A 100 mm electrode, a cylindrical coil around a ceramic chamber wall, and a Al chamber lid are main parts of the chamber.

Usually two generators are running at 13.56 MHz as master and slave with an adjustable phase shift between source and bias generator. In our case the bias generator is switched off in order to achieve a very low ion energy and thus almost no damage at the wafer. First investigations have shown that the position of load and tune capacitance in the bias matchbox to be very important for etch rate and wafer damage. Therefore a model was built to understand and finally to utilize these effects for process control.

5:40pm **PS1-WeA12 High Energy IED Measurements with MEMs based Si Grid Technology Inside a 300mm Si Wafer**, ***M. Funk***, *B.G. Lane, L. Chen, J. Zhao, R. Sundararajan,* Tokyo Electron America, *Y. Yamazawa*, Tokyo Electron Limited, Japan

The measurement of ion energy at the wafer surface at conditions that are realistic for commercial equipment and process development without extensive modification of the reactor geometry has been an industry challenge. High energy, wide frequency range, process gases tolerant, minimally perturbing, contamination free and accurate ion energy measurements are the base requirements. In this work we will report on the complete system developed to achieve the base requirements, including the safe and easy use by engineers. The system includes: a reusable silicon ion energy analyzer (IEA) wafer, signal feed through, RF confinement, and high voltage measurement and control.

The commercial manufacturing of an IEA system at a reasonable cost involves many disciplines, but can be achieved through the use of commercial methods and suppliers. Design aspects will be presented, including MEMs silicon etch technology that enables features in the sensor design that overcomes challenges in high voltage RF potentials while minimizing ion neutralization. The IEA wafer detail design required careful understanding of the relationships between the plasma Debye length, the number of grids, intergrid charge exchange (spacing), capacitive coupling, materials, and dielectric flash over constraints. RF confinement with measurement transparency was addressed so as not to disturb the chamber plasma, wafer sheath and DC self-bias as well as to achieve spectral accuracy. For commercial plasma etch reactors the wafer is floating at several kV relative to the outside ground and often the plasma wetted DC ground area is small and not well defined. To overcome the difference between the wafer surface and the outside environment a non-perturbing measurement system was developed that can be isolated and floated by several thousands of volts, while making accurate ion energy current and voltage measurements.The experimental results reported were collected using a commercial parallel plate etcher powered by a dual frequency (VHF + LF) bottom electrode; with various power combinations. Various process gases were tested and variations by pressure were tested to confirm the robustness and sensitivity of the physical design and measurement circuit and methods.

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