Plasma Science and Technology Division
Room: 22 - Session PS-ThM

Plasma Sources
Moderators: Rebecca Anthony, Michigan State University, David Ruzic, University of Illinois at Urbana-Champaign

8:00am **PS-ThM1 New Plasma Source Generating High Radical Flux With Low Ion and Photon Flux**, *Y. Pilloux, **David Lishan**, M. Segers*, Plasma-Therm LLC

Substrate cleaning of organics utilizes a range of technologies that includes wet processing, barrel ashers, and microwave driven downstream plasmas. In this work, we introduce a unique inductively coupled downstream source configuration to generate high density radical concentrations (>1.1E+17 cm^{-3}) but without high ion and photon fluxes typically found in conventional inductively coupled plasmas. Although the plasma discharge tubes are isolated from the treatment chamber, they deliver a large concentration of free radicals. The low ion and photon exposure significantly reduces the opportunity for damage to sensitive layers. This inductive plasma arrangement prevents local heating and charging on the wafer, and behaves similarly as a microwave downstream plasma. However, a higher oxygen radical flux promotes more efficient organic layer cleaning and/or removal of photoresists even when low thermal budgets are a constraint.

This work will first describe the High Density Radical Flux (HDRF) source and characterize its behavior in generating high radicals flow and low ions in local downstream, on the wafer surface. Second, several applications using the HDRF technology will be discussed. These applications will include cleaning of 30:1 aspect ratio (AR) silicon vias, removal of sacrificial layers in MEMS structures, low temperature photoresist removal, and surface smoothing of Bosch generated sidewalls using micro-isotropic etching. With a low local electrical potential, due to the limited ions present in the process chamber, the HDRF is particular efficient with 3D structures on the wafer (e.g. MEMS and other high AR features) where preventing ion shielding effects is important.

8:20am **PS-ThM2 Towards Plug-and-Play Tailored Voltage Waveform Plasma Sources: Progress in Matching and Calibration**, ***Erik V. Johnson***, LPICM, Ecole Polytechnique, France, *K. Yamaki*, LPP-CNRS, *J.-P. Booth*, LPP-CNRS, Ecole Polytechnique, France

The use of non-sinusoidal Tailored Voltage Waveforms (TVWs) to excite a plasma process has proven to be a rich field. Performing deposition or etching using such TVWs been shown to provide (1) a greater degree of control over outcomes, (2) more understanding of those processes, and even (3) processes unachievable by any other means, such as electrode-selective deposition.

The dream design for a Tailored Voltage Waveform plasma source is one that can ensure that an exact version of a given waveform appears on the RF electrode, but without increasing the complexity and cost of the source far beyond that of a single frequency RF source (including matchbox). These requirements are challenging due to the multi-harmonic nature of TVW's; the matching network must simultaneously provide efficient impedance matching at multiple frequencies, and as the phase between harmonics matters, for certain systems the waveform appearing at the RF feedthrough will not be a scaled version of the one on the electrode.

We address these two challenges directly. For the multi-frequency impedance matching challenge, we present progress on the design and fabrication of a high-power multi-frequency matchbox. This system allows the semi-independent tuning of the matching condition at each harmonic. For the second challenge involving uncertainty in the waveform appearing at the electrode, we present results using the plasma properties themselves to eliminate potential sources of error in the waveform. This technique avoids the need for probes located within the vacuum chamber, optical access to the plasma, or limiting the waveforms to lower frequencies.

8:40am **PS-ThM3 Selective Radical Production in Remote Plasma Sources**, ***Shuo Huang***, University of Michigan, *V. Volynets, S. Lee, S. Nam, S. Lu*, Samsung Electronics Co. Ltd., Republic of Korea, *M.J. Kushner*, University of Michigan

Remote plasma sources (RPS) are being used to achieve isotropic etching with high selectivity by avoiding charging, energetic ion bombardment and UV/VUV radiation using long distance and discriminating barriers between the RPS and the substrate. By using multiple plasma sources or multiple gas inlets at different locations, the reaction pathway can be optimized for producing desirable process radicals. NF_3 and HBr are frequently used sources of F and Br atoms, the main etchants of silicon-containing materials, by electron impact dissociative attachment and excitation. NF_x (x = 1 – 3) and HBr can exothermically react with other neutral species to produce F, Br and OH radicals, which also enables customizing the reaction pathway by flowing gases downstream of the RPS.

In this paper, we report on results from a computational investigation of an inductively coupled RPS having multiple gas inlets with the goal of determining strategies for selectively producing reactive fluxes. The investigation was performed using the plug flow mode of 0-dimensional model, Global_Kin and in 2-dimensions using the Hybrid Plasma Equipment Model (HPEM). With $NF_3/N_2/O_2$ mixtures flowed through the RPS from an upstream inlet, the dominant radicals flowing downstream are F and O formed through dissociative excitation and attachment of NF_3 and O_2. NO molecules were formed through endothermic reactions among N_2, N, O_2 and O species. With HBr injected downstream of the plasma source, mixing with the plasma produced radicals enable another level of selectivity. Due to lack of electrons and low gas temperature (~ 350 K) downstream, HBr reacts with F and O through exothermic reactions (HBr + F > HF + Br, HBr + O > OH + Br and HBr + OH > H_2O + Br) and the dominant downstream radicals transition from F and O to Br and HF. Vibrationally excited HF(v), a highly polar molecule, may be formed through reactions having a larger exothermicity than the vibrational quanta, and so may produce a significant flux of activation energy to the wafer

Work was supported by Samsung Electronics, DOE Office of Fusion Energy Science and the National Science Foundation.

9:00am **PS-ThM4 On Electron Heating in Magnetron Sputtering Discharges**, ***Jon Tomas Gudmundsson***, University of Iceland, *D. Lundin*, Université Paris-Sud, France, *M.A. Raadu*, KTH-Royal Institute of Technology, Sweden, *T.M. Minea*, Université Paris-Sud, France, *N. Brenning*, KTH-Royal Institute of Technology, Sweden

The magnetron sputtering discharge has been applied successfully in various industrial functions for over four decades. Sustaining a plasma in a magnetron sputtering discharge requires energy transfer to the plasma electrons. In the past, the magnetron sputtering discharge has been assumed to be maintained by cathode sheath acceleration of secondary electrons emitted from the target, upon ion impact. These highly energetic electrons then either ionize the atoms of the working gas directly or transfer energy to the local lower energy electron population that subsequently ionizes the working gas atoms. This is the essence of the well-known Thornton equation, which in its original form [1] is formulated to give the minimum required voltage to sustain the discharge. However, recently we have demonstrated that Ohmic heating of electrons outside the cathode sheath is typically of the same order as heating due to acceleration across the sheath in dc magnetron sputtering (dcMS) discharges [2]. The secondary electron emission yield γ_{see} is identified as the key parameter determining the relative importance of the two processes. In the case of dcMS Ohmic heating is found to be more important than sheath acceleration for secondary electron emission yields below around 0.1. For the high power impulse magnetron sputtering (HiPIMS) discharge we find that direct Ohmic heating of the plasma electrons is found to dominate over sheath acceleration by typically an order of magnitude, or in the range of 87 – 99 % of the total electron heating. A potential drop of roughly 80 - 150 V, or 15 - 25% of the discharge voltage, always falls across the plasma outside the cathode sheath [3]. We also discuss the influence of the magnetic field strength on the discharge properties.

[1] J A Thornton, J. Vac. Sci. Technol. 15 (1978) 171

[2] N. Brenning et al., Plasma Sources Sci. Technol. 25 (2016) 065024

[3] C Huo et al., Plasma Sources Sci. Technol. 22 (2013) 045005

9:20am **PS-ThM5 High-Density Plasma Generation in Low-Pressure Metamaterial Space**, ***Osamu Sakai***, The University of Shiga Prefecture, Japan **INVITED**

Generation of high-density plasmas have been one of the main topics in science and technology of low-temperature plasma since high throughputs in material processing such as dry etching and thin-film deposition are achieved by high electron density which enhances chemical and physical processes in weakly-ionized plasma. When we use microwaves in plasma generation, there have been several methods proposed so far for high-density plasma, like electron-cyclotron-resonance plasma and surface-wave plasma.

Here we propose another scheme in which a magnetic metamaterial makes magnetic permeability in discharge space negative. Microwave propagation in simple discharge space with no objects and no external magnetic field is limited by cutoff density where electric permittivity or dielectric constant is down to zero. When magnetic metamaterial who has negative permeability is installed in the space, microwave propagation is possible beyond the cutoff density, with negative refractive index state with negative permittivity that indicates high electron density. Experimental observation confirmed existence of this scheme, and electron density was much higher than the cutoff density (approximately $7x10^{10}$ cm^{-3} when microwave frequency is 2.45 GHz) [1]. The value of electron density has no limitation with smooth microwave propagation with large negative values of refractive index.

In addition to these advantages on generation of high-electron-density plasma, recent experimental studies have revealed that this scheme of plasma generation has roles of high energy storage and an efficient energy converter. From the estimations based on monitored electron density and temperature, the existing energy density in the plasma generation space with the metamaterial is by 3 orders of magnitude larger than that in microwave propagation in the free space. Such stored energy is efficiently converted into the second harmonic wave via nonlinear and asymmetry effects between plasma and metamaterial [2], as well as into chemical energy via enhanced dissociation of gas molecules. These facts indicate that this plasma source will contribute to novel functions that can be hardly established using other plasma generation schemes as well as the general function as a high-density plasma source for material processing.

[1] O. Sakai, Y. Nakamura, A. Iwai and S. Iio, Plasma Sources Sci. Technol. 25 (2016) 055019.

[2] A. Iwai, Y. Nakamura and O. Sakai, Phys. Rev. E 92 (2015) 033105.

11:00am **PS-ThM10 Optical Emission Spectroscopy of a Spark-coupled Laser Aluminum Plasma for Multicharged Ion Generation**, ***Md Mahmudur Rahman***, *O. Balki*, *M. Shaim*, *H.E. Ali*, Old Dominion University

A spark-coupled laser plasma is used to generate multicharged ions. A Q-switched Nd:YAG laser (λ = 1064 nm, , τ = 8 ns, pulse energy ≤ 100 mJ, repetition rate 1 Hz) ablates an aluminum target creating a laser ion source, while the spark discharge further enhances ion generation. A high-voltage pulse-forming network produces up to 12 kV, ~1 µs pulse across the spark electrodes. Line emission from neutrals and ions are probed by optical emission spectroscopy. These spectral lines are used to obtain time-integrated, spatially-resolved electron temperature (T_e) from the Boltzmann plot and electron density (n_e) from Stark broadening. The pulse forming network is triggered with a thyratron through a delay in order to optimize the timing between the laser pulse and the spark discharge for best spark energy coupling to the laser plasma. A delay of 100 ns is found to produce the best coupling of the spark energy to the laser plasma. For a spark energy of 1.5 J, the intensity of the Al IV 372.6 nm and Al III 361.2 nm lines increases by a factor of ~10 and ~ 6, respectively compared to that from the laser plasma alone. The effective ion temperature (T_{ieff}) associated with translational motion along the plume axis is calculated from the ion time-of-flight (TOF) signal and compared with T_e. The results show that T_{ieff} is much larger than T_e, although the plasma is considered to be in local thermodynamic equilibrium. This result is explained in view of the different regions of the plasma probed by ion TOF and optical spectroscopy.

11:40am **PS-ThM12 Effect of Secondary Electrons on the Ionization Dynamics and Control of Ion Properties in Electronegative Capacitive Discharges**, ***Aranka Derzsi***, Wigner Research Centre for Physics, Hungarian Academy of Sciences, Hungary **INVITED**

The realization of the separate control of the ion flux and ion energy distribution at the substrate in capacitively coupled radio frequency (RF) discharges is an important issue for various applications of plasma processing, ranging from plasma based etching and deposition procedures in the semiconductor industry to plasma assisted surface treatment of medical interest. In order to attain such independent control of the ion properties, the application of non-sinusoidal voltage waveforms (pulse-like, or saw-tooth-type, for instance), known as „tailored“ or „customized“ RF voltage waveforms for the excitation of capacitive RF discharges, has recently been introduced. Such waveforms differ from the conventionally applied sinusoidal voltages by exhibiting different absolute values of their positive and negative extrema. This control method is based on the electrically asymmetric plasma response, known as the Electrical Asymmtery Effect, observed when non-sinusoidal exciting voltage waveforms are applied, leading to the generation of a dc self-bias voltage in a geometrically symmetric discharge cell. The applications of tailored voltage waveforms, generated by using multiple harmonics of a base frequency (multi-frequency excitation), offer new possibilities for controlling plasma properties. Most of the systematic studies on capacitive RF plasmas excited by tailored voltage waveforms have been conducted so far in electropositive capacitive RF discharges. However, the applications usually require complex mixtures of reactive gases. For instance, oxygen is widely used in etching and thin film deposition techniques, CF_4 is also frequently applied to etch silicon and silicon-dioxide in microelectronics.

Secondary electrons generated at the electrodes are known to influence the ionization dynamics and induce transitions of the discharge operation mode from the α-mode to the γ-mode in electropositive discharges at high driving voltage amplitudes and/or pressures. In electropositive discharges these γ-electrons influence the quality of the separate control of ion properties. Here, we report our systematic simulation studies of the effect of secondary electrons on the electron power absorption and ionization dynamics and on the quality of the separate control of ion properties at the electrodes in low-pressure capacitively coupled RF discharges operated in reactive, electronegative gases excited by tailored voltage waveforms.

Authors Index
Bold page numbers indicate the presenter