## Plasma Science and Technology Division
## Room 104A - Session PS-ThM

### Plasma Sources

**Moderators:** TaeSeung Cho, Applied Materials, Geunyoung Yeom, Sungkyunkwan University, Republic of Korea

8:00am **PS-ThM-1 Model of a Radio-Frequency Low Electron Temperature Plasma Source*, Shahid Rauf,*** *L Dorf, K Collins,* Applied Materials

The time-averaged plasma potential in a partially ionized plasma is directly linked to the electron temperature ($T_e$). Plasmas with low $T_e$ or plasma potential are attractive for applications that require low ion energy at surfaces. One of the most promising such applications is atomic layer etching. Reactive ion etching relies on reaction of energetic ions and chemically reactive radicals on surfaces for material removal. Ion energy in radio-frequency (RF) plasmas is typically 10s of eV or higher. Since such energetic ions can damage and modify the near-surface material, film etching with atomic precision becomes impractical using low pressure RF plasmas. On the other hand, if the plasma potential is low and capability exists to control the ion energy at the substrate using RF or DC biasing, one can etch material with Å-scale fidelity [1]. Even conventional plasma processes can benefit from low $T_e$ as plasma potential determines the energy of ions bombarding the chamber surfaces.

This paper describes a radio frequency (RF) driven low $T_e$ plasma source. This source utilizes two RF supplies, a higher frequency source (60 MHz) for plasma production and a lower frequency source (2 MHz) for controlling the ion energy. The plasma source is divided into two regions separated by a perforated plate. A high density (> $10^{17}$ $m^{-3}$) plasma is generated in the primary region next to the RF powered electrode. The DC bias on the powered electrode is high (~ 2000 V) leading to energetic ion bombardment on it. These ions produce secondary electrons that, under the low-pressure condition under consideration, enter the plasma as a beam of energetic electrons and many of them reach the perforated plate. It is demonstrated that the slits in the perforated plate can be designed to prevent the RF primary plasma from leaking into the secondary region while still allowing the beam electrons to pass through. The plasma produced by the beam electrons has moderate density (~ $10^{16}$ $m^{-3}$) and $T_e$ < 0.5 eV. The influence of slit dimensions on the characteristics of the plasma in the secondary discharge region is examined in the paper.

[1] L. Dorf, J. C. Wang, S. Rauf, G. A. Monroy, Y. Zhang, A. Agarwal, J. Kenney, K. Ramaswamy and K. Collins, J. Phys. D 50, 274003 (2017).

8:20am **PS-ThM-2 Electron-beam Sustained Plasma with Unique Characteristic of Low Electron Temperature at Very Low Pressure*, Zhiying Chen,*** Tokyo Electron America, Inc.*; K Nagaseki,* Tokyo Electron Miyagi, Ltd., Japan*; J Blakeney, M Doppel, P Ventzek,* Tokyo Electron America, Inc.*; A Ranjan,* TEL Technology Center, America, LLC.

Low electron temperature plasmas have recent interest because of their potential applications in atomic layer etching, etch of non-volatile materials and polymer processing. Electron-beam sustained plasmas (ESP) are primarily sustained by an electron beam. In this presentation we describe one kind of ESP system consisting of two plasmas separated by a dielectric injector. The electron-source plasma is generated by an inductively coupled source (ICP), on the boundary walls of which a negative DC voltage is applied. The main plasma is the ESP itself, which is generated by the electron beam extracted from ICP through a dielectric injector by an accelerator located inside the ICP. The electron temperature and electron energy distribution functions (EED*f*) are measured by Langmuir Probe. We show the ESP plasma is characterized by a low electron temperature (less than 1eV) at very low pressure (1-10mT) measured. This unique characteristic is unavailable to conventional plasmas, in which pulsing or high pressure is required to obtain low electron temperature. The plasma also illustrates the controllable EED*f* especially when superposed on an additional plasma such as a simple ICP source. The electron temperature of the ICP source can be significantly dropped with the addition of an ESP. The presentation includes a discussion regarding the uniformity and scalability of the ESP system. In particular, the generation of a sheet electron beam without the aid of a magnetic field and the impact of externally coupled capacitive power are discussed.

8:40am **PS-ThM-3 Hydrid Plasma Source with Inductive and Capacitive Fields: Fundamental Understanding and Nano-applications*, Hyo-Chang Lee,*** Korea Research Institute of Standards and Science (KRISS), Republic of Korea **INVITED**

Hybrid plasma source with inductive and capacitive fields, which is often called RF-biased inductively coupled plasma (ICP) or reactive ion etcher, has been widely used in semiconductor, display, and solar-cell etching processes [1]. The original concept for the hybrid plasma source is an expectation that the antenna coil of the ICP controls the plasma density while the RF bias controls the ion energy independently. However, the RF bias can act as plasma source like an asymmetric capacitively coupled plasma (CCP) and directly affect plasma parameters such as electron temperature, plasma density, and electron energy distribution. In this talk, I will present effects of inductive and capacitive fields of the hybrid plasma source on the plasma parameters, electron heating, and processing result [2-9]. This invited talk will find the fundamental understanding of the hybrid plasma source and give open possibilities for applications to various applied fields to find novel control knob and optimizing processing conditions for improvement of the device quality and processing results.

[1] H.C. Lee, Appl. Phys. Rev. 5, 011108 (2018).

[2] Lee et al., Appl. Phys. Letts. 96, 071501 (2010).

[3] Lee et al., Phys. Rev. E 81, 046402 (2010).

[4] Lee et al., Thin Solid Films 519 7009 (2011).

[5] Lee et al., Appl. Phys. Letts. 101, 244104 (2012).

[6] Lee et al., J. Appl. Phys. 111, 093301 (2012).

[7] Lee et al., Plasma Sources Sci. Technol. 21 035003 (2012).

[8] Lee et al., Plasma Sources Sci. Technol. 22 032002 (2013).

[9] Lee et al., Plasma Sources Sci. Technol. 24 0240 (2015).

9:20am **PS-ThM-5 Improving RF Power Delivery for Pulsed Operation***, J Brandon, C Smith, K Ford,* North Carolina State University*; S Nam,* Samsung Electronics*; **Steven Shannon**,* North Carolina State University

The increased reliance on pulsed RF power delivery for manufacturing applications has greatly expanded the process window and performance capability of state-of-the-art process equipment. Power delivery under pulsed conditions rely mainly on static impedance matching conditions, delivered power compensation, or optimization algorithms that minimize power reflection due to impedance mismatch over multiple pulse cycles. On time scales within the RF pulse, power delivery can significantly impact process performance, particularly as devices approach the sub 10nm regime, as it can impact electron temperature spikes at ignition and the formation of electric potentials in and around the plasma and substrate. Options to improve power delivery efficiency within the pulse can provide mechanisms to control or mitigate these conditions for process optimization, but have practical limitations due to the ms time scale response needed to capture electrical transients under pulsed conditions.

Using standard match topologies found in pulsed RF systems, methodologies for impedance matching optimization for plasma transient control are presented. Using a simple global plasma model with equivalent circuit module for capturing power delivery circuitry and a cylindrical ICP reactor, the interaction between power coupling (specifically impedance matching) and plasma conditions during the power-on transient of a pulsed ICP system are studied. Control of electron temperature spiking at the power onset as well as rate of rise of plasma density are demonstrated using a static p-type match topology. The impact of dissipative losses in the matching network are also explored, and suggest that the standard insertion loss, or “equivalent series resistance” characterization of impedance match power dissipation may present an incomplete picture of match performance under transient conditions and that dissipation in the shunt elements play a significant role with regard to the transient plasma conditions during the power on cycle of a pulsed RF system, and may provide a pathway for improving the efficiency of power delivery during pulsed operation. Finally, a synergistic approach where match topology, source antenna design, and plasma load are considered can provide pathways for within-pulse impedance matching and power delivery control. We will present examples where this approach may enable within-pulse active tuning of pulsed RF systems with existing technologies. This work is supported by the Samsung Mechatronics R&D Center.

9:40am **PS-ThM-6 Optimizing Transients Using Low-High Pulsed Power in Inductively Coupled Plasmas**, ***Chenhui Qu***, *S Lanham,* University of Michigan*; T Ma, T List, P Arora, V Donnelly,* University of Houston*; M Kushner,* University of Michigan

Pulsed inductively coupled plasmas (ICPs) are widely used for etching in semiconductor device fabrication. Pulse repetition frequencies (PRFs) of up to 10s kHz are commonly used for the high power density provided during the pulse-on period and the unique chemistry during the pulse-off period. The use of highly attaching halogen gases produces low electron densities during the pulse-off period, which can produce instabilities, E-H transitions and ignition delays when applying power. To mitigate these issues, a low-level power could be maintained during "pulse-off" to limit the minimum plasma density, therefore reducing ignition delays and enhancing plasma stability.

In this work, ICPs sustained by 1-5 kHz pulsed power using $Ar/Cl_2$ mixtures at tens of mTorr were computationally and experimentally studied. The computations were performed with the 2-D Hybrid Plasma Equipment Model. The experiments include measurements of electron density ($n_e$), temperature ($T_e$) and electron energy distributions. The power is modulated during the pulse-off period and the transient behavior of the ICP was studied.

The computed $T_e$ reaches a quasi-steady state for both high and low power excitation. Some experimental results agree well with the predictions from the model while others show a reproducible delay in plasma ignition. The model predicts that within the skin-depth, $T_e$ spikes to a high value during the low-to-high power modulation and a low value during a high-to-low power modulation. Due to some averaging and energy loss that occurs during transit from the skin depth, both measurements and model results show little modulation in $T_e$ a few cm above the substrate. The influence of the power, pressure, PRF and duty cycle of the pulse profile on the bulk plasma properties will be discussed.

* Work supported by Samsung Electronics Co. Ltd., National Science Foundation and the DOE Office of Fusion Energy Sciences.

11:00am **PS-ThM-10 Silicon Nitride Film Formations Using Magnetic-Mirror Confined New Plasma Source**, ***Tetsuya Goto,*** Tohoku University, Japan*; S Kobayashi,* Kotec Company, Ltd., Japan*; S Sugawa,* Tohoku University, Japan

Realization of high-quality silicon nitride film formation at low temperature was strongly required for various fields such as the Si CMOS devices, the solar cells, as well as the micro electro mechanical systems (MEMS). In this study, a magnetic-mirror confined electron cyclotron resonance plasma source for low-damage plasma processings was newly developed, and applied to the silicon nitride film formations. The mirror-confined plasma is the well known concept in a field of fusion plasmas where high-density and high-temperature plasmas are produced by confining plasmas using the magnetic field. We applied this concept to plasma enhanced chemical vapor depositions. In a magnetically confined plasma, neutral reactive species produced by the plasma can escape from the confined plasma without the restriction of motion by the magnetic field, contrary to the confined charged particles of ions and electrons. Thus, when the substrate is placed at the neighborhood of the confined plasma, a large amount of reactive species will be supplied to the substrate with low irradiation of ion flux, suggesting the realization of low-damage and high-quality processes. It was found that the magnetic mirror confinement method worked well to excite the high-density plasma larger than $10^{11}$ $cm^{-3}$ with low plasma excitation power of 10 W or less. SiN films were deposited by exciting $Ar/SiH_4/N_2/H_2$ plasmas. It was found that, in the optimized condition, an impurity concentration of oxygen in the film could be suppressed less than 1%, which was even smaller than that in the controlled low-pressure chemical-vapor deposited film at 750◦C, suggesting the realization of high-quality nitridation process. Next, wet etching stability was investigated by dipping the films into the 5% HF solution. For the 400◦C-deposited film, the etching rate was approximately 3 nm/min which was the same level to that of 750◦C-LPCVD film. Although the etching rate of the 200◦C-deposited film increased to approximately 10 nm/min, this rate was much smaller than that of thermally-grown $SiO_2$ film (approximately 40 nm/min).

It was also confirmed that the excellent step coverage could be obtained for the 0.5 micron trench pattern.

The developed plasma source has a potential to realize high-quality film deposition processes of the plasma CVD, the plasma ALD, and the reactive sputtering.

Acknowledgement

The deposition process was carried out in Fluctuation-Free-Facility in Tohoku University.

1. T. Goto, K. Sato, Y. Yabuta and S. Sugawa, Rev. Sci. Instrum. vol. 87 (2017) 123508.

2. T. Goto, K. Sato, Y. Yabuta, S. Hara and S. Sugawa, Journal of the Electron Devices Society, vol. 6, (2018) 512.

11:20am **PS-ThM-11 Resonant Element Microwave Plasma Source**, ***Barton Lane***, *P Ventzek, A Bhakta,* Tokyo Electron, America, Inc.*; K Nagaseki,* Tokyo Electron Miyagi, Ltd., Japan*; A Ranjan,* Tokyo Technology Center America

We report here the use of resonant elements for plasma generation. The resonant elements are realized as metal structures embedded in alumina using a metal printing and lamination process. The embedded structures present a flat featureless alumina face to the plasma which is optimal for reducing particle generation. The structures are chosen to be resonant in the microwave frequency range and thus have geometric sizes of approximately 10 mm, although this can be chosen for the particular application. The structures can be viewed as LC circuits which have a number of resonances in the microwave band each with a corresponding spatial electric field eigenmode. The geometry of the structures reported here positions the inductive portion near to the plasma and in one eigenmode produces inductively generated circular mirror currents in the plasma which have a spatial dimension of 10 mm. The LC structures which we report on have a quadrupole symmetry in order to minimize the coupling to surface waves which tend to propagate away from the launch structure and are difficult to control. The fields responsible for plasma generation are the near fields of the resonant structure and these die away quickly from the structure giving a localized plasma generation region. The alumina blocks in which the resonant element structures are embedded are pierced by cylindrical holes through which gas is injected into the generated plasma. For one eigenmode of this system at low pressures ( ~ 10 mTorr) the electric fields are such that the plasma concentrates in the supersonic gas jet and has a size of approximately 1 mm. The structures can also be used to sustain a plasma in a high pressure cavity which then serves as a source of radicals through jet outlets. In this case the cavity pressures are in the several Torr or higher range. With the addition of small permanent magnets operation in the 0.1 mTorr regime is possible by exploiting the electron cyclotron phenomenon. The resonant elements can be arranged in an array. We report on a linear array which is coupled by TEM parallel plate transmission lines embedded in the alumina. Because the presence of plasma tends to detune the structures from resonance there is a natural negative feedback which helps to balance the multiple elements producing a reasonably uniform "curtain" of plasma. The ability to extend such an array to cover the entire upper electrode of a semiconductor reactor has been noted as well as the ability to control the spatial distribution by choosing different natural resonances for different regions of the reactor.

11:40am **PS-ThM-12 Microwave Plasma Enabling Efficient Power-To-X Conversion**, ***Gerard van Rooij,*** DIFFER, The Netherlands, Netherlands **INVITED**

Sustainable energy generation by means of wind or from solar radiation through photovoltaics or concentrated solar power will continue to increase its share of the energy mix. Intermittency due to e.g. day/night cycle, regional variation in availability, and penetration of sustainable energy into sectors other than electricity such as the chemical industry necessitates means of storage, transport and energy conversion on a large scale. A promising option is the synthesis of chemicals and artificial fuels using sustainable energy. A truly circular economy requires that the raw materials are the thermodynamically most stable ones such as $CO_2$ and $N_2$. In this contribution it will be highlighted how plasma chemistry can potentially combine compatibility with e.g. intermittency and localized production to activate these molecules with maximum energy efficiency, essentially due to preferential vibrational excitation (causing inherently strong out-of-equilibrium processing conditions that achieve selectivity in the reaction processes). Examples will be discussed of research carried out at DIFFER to ultimately enable a scale up to chemical industrial applications.

A common microwave reactor approach is evaluated experimentally with laser Rayleigh and Raman scattering (to assess gas and vibrational temperatures) and Fourier transform infrared spectroscopy (yielding conversion and efficiency). For example, 50% energy efficiency was observed in pure $CO_2$ (forming CO and $O_2$) in a thermodynamic equilibrium conversion regime governed by gas temperatures of ~3500 K. These results are interpreted on basis of Boltzmann solver based plasma dynamics estimates, indicating that intrinsic electron energies are higher than what is favourable for preferential vibrational excitation. Pulsed experiments (1-5 kHz) in which gas temperature dynamics are revealed confirm this picture. In pure $N_2$, vibrational temperatures are observed in excess of 10000K and up to five times higher than the gas temperature. The signature of the Treanor effect (overpopulation of higher levels) is confirmed. These observations are promising in view of economic localized production of fertilizer. Finally, an outlook is given to novel reactor approaches that tailor the plasma dynamics to optimally promote vibrational excitation and to achieve the desired non-equilibrium.

# Author Index

## Bold page numbers indicate presenter


— A —
Arora, P: PS-ThM-6, 2
— B —
Bhakta, A: PS-ThM-11, 2
Blakeney, J: PS-ThM-2, 1
Brandon, J: PS-ThM-5, 1
— C —
Chen, Z: PS-ThM-2, **1**
Collins, K: PS-ThM-1, 1
— D —
Donnelly, V: PS-ThM-6, 2
Doppel, M: PS-ThM-2, 1
Dorf, L: PS-ThM-1, 1
— F —
Ford, K: PS-ThM-5, 1
— G —
Goto, T: PS-ThM-10, **2**
— K —
Kobayashi, S: PS-ThM-10, 2
Kushner, M: PS-ThM-6, 2
— L —
Lane, B: PS-ThM-11, **2**
Lanham, S: PS-ThM-6, 2
Lee, H: PS-ThM-3, **1**
List, T: PS-ThM-6, 2
— M —
Ma, T: PS-ThM-6, 2
— N —
Nagaseki, K: PS-ThM-11, 2; PS-ThM-2, 1
Nam, S: PS-ThM-5, 1
— Q —
Qu, C: PS-ThM-6, **2**
— R —
Ranjan, A: PS-ThM-11, 2; PS-ThM-2, 1
Rauf, S: PS-ThM-1, **1**
— S —
Shannon, S: PS-ThM-5, **1**
Smith, C: PS-ThM-5, 1
Sugawa, S: PS-ThM-10, 2
— V —
van Rooij, G: PS-ThM-12, **2**
Ventzek, P: PS-ThM-11, 2; PS-ThM-2, 1