Plasma Science and Technology
Room 315 - Session PS1-ThM

Advanced Ion and Reactant Control I

Moderators: Dr. Sebastian Engelmann, IBM T. J. Watson Research Center, **Prof. Dr. Christophe Vallee**, UAlbany

8:00am **PS1-ThM-1 Plasma Prize Talk: Drilling Really Tiny Holes in Glass: The Role of Ion Energy Control in Nano-Fabrication***, **Steven Shannon**,* North Carolina State University **INVITED**

You would be amazed at how reliant our high technology economy relies on a process that at first glance sounds very straight forward... drilling holes in glass. Of course, this description simplifies things. These holes are as small as several hundred atoms in diameter and are as much as 200 times deeper than they are wide, and they are one of the most critical components in advanced interconnect layers for logic devices and the backbone of advanced memory devices.

Plasma assisted etching is used to fabricate these tiny holes. By combining the non-equilibrium chemistries and directed energetic ions formed in plasma systems, highly anisotropic holes can be cut into dielectric layers. This talk will focus on one aspect of these processes, the energetic ions that strike the surface. The role of these ions in anisotropic etching of these features and efforts to control and measure the direction and energy of these ions to further extend the capabilities of these processes will be discussed. Mechanisms for approximating and measuring the energy of ions that drive these processes will be discussed. Finally, current and future research paths for further extending the capabilities of these critical ion driven processes will be presented.

8:30am **PS1-ThM-3 Time-Domain RF Matching and Ion Energy Control in Pulsed Bias Capacitively Coupled Plasmas***, **Yeon Geun Yook**,* University of Michigan*; Hyunjae Lee,* Samsung Electronics, Republic of Korea*; Mark J. Kushner,* University of Michigan

Pulsed-bias capacitively coupled plasmas (CCPs) are widely used in advanced semiconductor plasma etching processes to control ion energy, surface charging, and etch profiles. In practical RF systems, the voltage waveform produced by the generator is not necessarily delivered directly to the wafer electrode due to intervening impedances, including the match-box. Even when the impedance of the plasma reactor is well matched to the power supply though the match-box with continuous-wave (CW) excitation or late during the power-on phase of pulsing, a mismatch can occur during the power-on and power-off transitions. This mismatch is due to the finite transient response of the matching network, stored energy in circuit components, blocking-capacitor charge dynamics, and time-varying plasma impedance. These effects can distort the electrode voltage and self-bias waveform, thereby modifying the ion energy distribution delivered to the wafer.

In this work, the effects of time-domain RF matching transients on ion-energy control in pulsed-bias dual-frequency CCPs sustained in Ar/HF mixtures were computationally investigated using the Hybrid Plasma Equipment Model (HPEM). The bottom electrode is modeled with a π-type matching network and blocking capacitor through which the bias power is applied. First, the matching capacitors are tuned to minimize reflected power for long pulsed biases which have achieve a quasi-steady state. The effects of generator rise/fall times, pulse period, and blocking-capacitor value on plasma properties are analyzed, including time-dependent reflected power, network loss, stored energy, plasma absorbed power, and self-bias voltage.

The consequences of pulse power delivery on phase-resolved ion energy and angular distributions (IEADs) to the wafer during the rise, top-flat, fall, and off phases were investigated. Waveform compensation was explored as a possible strategy to mitigate matching-induced waveform distortion and improve ion-energy control. The plasma properties obtained from the HPEM were used as input to the Monte Carlo Feature Profile Model (MCFPM) to evaluate the impact of RF matching transients on etch profiles during cryogenic etching.

8:45am **PS1-ThM-4 Tailored Voltage Waveforms in Capacitively Coupled Plasmas: Effect of Voltage Transition Slope on Ion and Electron Dynamics in Argon Discharges***, **Syed Zulqarnain**, Basak Bagci,* North Carolina State University*; Harutyun Melikyan, Ebony Mays,* Micron Technology*; Steven Shannon, Amanda Lietz,* North Carolina State University

Capacitively coupled plasmas (CCPs) are extensively employed in selective and anisotropic etching of semiconductor materials and deposition of thin films. Tailored voltage waveforms offer a promising approach to independently control ion energy and flux at the electrode surface, providing an additional degree of freedom for tuning the ion energy distribution function (IEDF). A square-shaped bias waveform is particularly attractive because its flat negative plateau maintains a near-constant sheath voltage, allowing ions to arrive at the substrate with narrow, well-defined energy. The negative phase must exceed the ion transit time across the sheath to ensure acceleration under a near-static potential, while the longer positive phase allows complete charge neutralization before the next pulse. This asymmetry makes the duty cycle a physically meaningful design parameter. At each polarity transition, the sheath boundary rapidly expands or collapses, transferring energy into electrons. The slew rate (dV/dt) sets the sheath expansion velocity, governing the intensity of this heating burst and the sheath potential during the transition. Ions crossing the sheath in this window experience a time-varying potential, shaping the tail of the IEDF. The slew rate is thus a fundamental control variable that simultaneously couples waveform shape to sheath dynamics, electron power absorption, and ion bombardment. In this study, a dual-frequency CCP discharge in pure argon at 10 mTorr is investigated using the Monte Carlo collisions-based particle-in-cell code, EDIPIC[1]. A 60 MHz sinusoidal waveform on the upper electrode sustains the discharge and controls plasma density, while a 400 kHz asymmetric square voltage waveform on the lower electrode controls ion bombardment. The waveform uses a short negative phase (~0.5 μs) sufficient for ion transit and a longer positive phase (~2.0 μs) for full charge neutralization before each pulse. As the transition slope varies from near-instantaneous to gradual, its influence on sheath dynamics, electron heating, and power deposition is explored through time-resolved analysis over a single low-frequency cycle. The simulated IEDFs are compared against experimentally obtained IEDFs via retarding field energy analyzer, alongside comparisons of plasma density and sheath width. This investigation elucidates the interplay among the dual-frequency drive, waveform transition dynamics, and plasma response, providing insight into how square-wave tailored waveforms can control plasma dynamics in low-pressure CCP discharges*, with extensions to O_2 admixtures.*

1.https://pcrf.princeton.edu/capabilities/modeling-tools-and-computer-codes/edipic-code/

9:00am **PS1-ThM-5 Studies of Rf-ICP Source with a High Voltage Nanosecond-Tailored Voltage Waveform Biased Substrate***, **Yerbolat Ussenov**, Yevgeny Raitses,* Princeton Plasma Physics Laboratory

High-voltage substrate pulsing is a promising technique for tailoring peak ion energies and narrowing ion energy distribution functions (IEDFs) in high-aspect-ratio (HAR) plasma etching [1,2]. By utilizing a non-sinusoidal asymmetric bias (100–600 kHz) characterized by short positive pulses (~hundreds of ns) and extended negative phases, surface charge neutralization can be achieved while maintaining precise control over ion bombardment. In this study, we investigate the impact of pulsed substrate biasing [3] on a cylindrical inductively coupled plasma (ICP) source. Time-averaged axial distributions of plasma parameters and electron energy distribution functions (EEDFs) were characterized via Langmuir probe diagnostics and compared against steady-state (pristine) plasma conditions. To capture the transient discharge physics, time-resolved dynamics were analyzed through instantaneous floating potential measurements at different substrate to probe distance. Furthermore, the spatio-temporal evolution of optical emissions near the substrate was evaluated using phase-resolved optical emission spectroscopy (PROES) equipped with an ICCD camera and light emission filter. Also, the Doppler shift laser induced fluorescence (LIF) implemented to test the possibility of time resolved IEDF measurements. Our preliminary results demonstrate that the pulsing significantly alters the local plasma properties near the substrate. The underlying physical drivers are discussed.

This work was conducted at the Princeton Collaborative Research Facility (PCRF), which is supported by the U.S. DOE under Contract No. DE-AC02-09CH11466. The authors are grateful to Prof. Vince Donnelly for sharing ICP design, and Eagle Harbor Technologies, Inc. for providing their pulser.

1. S.-B. Wang, A. E. Wendt, J. Appl. Phys. 88, 643–646 (2000)

2. S. Rauf, P. Tian, J. Kenney, and L. Dorf, J. Vac. Sci. Technol. B 40, 032202 (2022)
3. J. Prager, T. Ziemba, P. Melnik, J. Perry, C. Bowman, AVS 70th International Symposium & Exhibition, 2025

9:15am **PS1-ThM-6 Experimental Investigation of Tailored Voltage Waveforms in Dual-Frequency Ar/O_2 Capacitively Coupled Plasmas**, ***Basak Bagci***, *Syed M. Zulqarnain, Amanda M. Lietz, Steven C. Shannon,* North Carolina State University

Tailored voltage waveforms in capacitively coupled plasmas (CCPs) provide a powerful approach for controlling ion energy distributions and electron heating in semiconductor plasma processing. In low-pressure CCP discharges, waveform asymmetry and transition dynamics strongly influence sheath evolution, plasma potential, and ion acceleration, making waveform tailoring particularly attractive for applications requiring independent control of ion energy and ion flux. While these effects have been extensively investigated in noble gas plasmas, significantly less attention has been given to electronegative gas mixtures relevant to semiconductor manufacturing.

In this work, experimental measurements are performed in a dual-frequency and single-frequency CCP reactor operating in argon/oxygen mixtures at pressures near 10 mTorr. A 60 MHz sinusoidal waveform applied to the upper electrode sustains the plasma, while a low-frequency asymmetric pulsed waveform applied to the lower electrode controls ion bombardment dynamics. The influence of oxygen admixture and waveform transition characteristics on plasma behavior is investigated using synchronized plasma diagnostics. Ion energy distribution functions (IEDFs) are measured using a retarding field energy analyzer (RFEA), while electron density is obtained using a hairpin resonance probe. Simultaneous voltage measurements are acquired using VI probes to correlate plasma response with applied waveform dynamics.

The addition of oxygen significantly modifies the discharge through electronegativity-driven changes in electron density, sheath structure, and ion transport. Variations in waveform transition slope and duty cycle alter sheath expansion dynamics and electron heating during polarity transitions, producing measurable changes in the IEDF shape, energy spread, and high-energy ion population. Comparisons between pure argon and Ar/O_2 mixtures reveal how electronegative chemistry couples with tailored voltage waveforms to influence plasma stability and ion bombardment characteristics.

These measurements provide experimental insight into waveform-controlled plasma dynamics in electronegative CCP discharges and contribute to the development of advanced plasma control strategies for semiconductor processing applications.

9:30am **PS1-ThM-7 Passive Antenna Control of Ion Energy in Inductively Coupled Plasmas: Mechanism Study via Antenna Design Variation**, ***Minsu Choi,*** Department of Physics, Chungnam National University, Republic of Korea; *Chulhee Cho,* Institute of Quantum Systems (IQS), Chungnam National University, Republic of Korea; *Inho Seong, Wonnyoung Jeong, Byeongyeop Choi, Seonghyun Seo, Isak Lee,* Department of Physics, Chungnam National University, Republic of Korea; *Youngseok Lee,* TEK R&D center, Tokyo Electron Korea; *Shinjae You,* Department of Physics, Chungnam National University, Republic of Korea

Ion energy is a critical parameter in plasma etching processes, governing etch rate, selectivity, and profile control. Conventional ion energy control requires an additional RF bias power source, which increases system complexity and cost. Passive antenna technology has recently been proposed as a bias-free alternative for ion energy modulation in inductively coupled plasmas (ICP), where ion energy is tuned through changes in the plasma potential. However, the mechanism by which a passive antenna modifies the plasma potential remains poorly understood.

In this work, we elucidate this mechanism through a systematic comparison of three antenna configurations: a closed-loop antenna, an open-ended antenna, and an open-ended antenna with an anodized surface. These designs were chosen to selectively suppress the two candidate pathways for plasma potential control —conduction current to the antenna and voltage generation at the antenna terminals. Plasma parameters, including electron density, electron temperature, and plasma potential, were measured using a Langmuir probe. Our results reveal two key contributions to passive antenna–driven ion energy control: (1) the collection of plasma electrons by the passive antenna, and (2) the voltage that develops at the open end of the antenna. Both effects act in concert to elevate the plasma potential and thereby increase ion energy at the substrate.

9:45am **PS1-ThM-8 Effects of Ar/O2 Gas Mixture Ratios on Ion Energy Distribution Functions in a Dual-Frequency CCP**, ***Tanjina Akter***, *Syed Zulqarnain, David Kanfer, Basak Bagci, Duncan Trosan,* North Carolina State University; *Chenyao Huang, Mark J. Kushner,* University of Michigan; *Amanda Lietz, Steven Shannon,* North Carolina State University

The investigation of ion energy distribution functions (IEDFs) formed by a powered sheath above a cathode can help optimize etching processes during the micro and nano fabrication. Capacitively coupled plasmas (CCP) have been routinely used to fabricate these structures. The coupling of ion flux and ion energy in a single-frequency CCP configuration limits its application for large-scale production. Hence, an independent control of ion flux and mean energy is required, which can be obtained by a multiple-frequency RF power configuration. Dual-frequency CCP can provide decoupled ion flux and ion energy, where the high-frequency component of the discharge produces charged particles and sustains the plasma, and the low-frequency component accelerates the ions to the surface [1]. A dual-frequency CCP configuration, with 60 MHz for the high-frequency (HF) and 13.56 MHz for low-frequency (LF), has been used in this experiment to observe the IEDF by placing a Retarding Field Energy Analyzer (RFEA) on the LF electrode. Bimodal IEDFs were found by the RFEA for the pressure range of 1-50 mTorr, electron densities of 10^9-10^{11} cm^{-3}, the sheath potential of 50-100 V, and the sheath thickness of 0.5-0.1 cm in the dual-frequency CCP using argon and argon-oxygen gas mixtures. The variations of IEDFs, electron density, and sheath thickness with different argon–oxygen gas mixture ratios were examined under constant HF and LF power conditions. The independent control of density and sheath voltage using a dual frequency configuration was also used to study the role of gas mixing under identical density and voltage conditions that primarily dictate the IEDF to better understand the impact of molecular and electronegative effects on the evolution of IEDF's in these CCP reactors. A Particle-In-Cell (PIC) simulation has been performed to validate the experimental results.

This work is supported by the Department of Energy (DOE) grant DE-SC0024545.

Reference:

[1] Zhen-hua Bi, Yong-xin Liu, Wei Jiang, Xiang Xu, and You-nian Wang. A brief review of dual-frequency capacitively coupled discharges. Current Applied Physics, 11(5):S2–S8, 2011.

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