Plasma Science and Technology
Room 315 - Session PS1-MoA

Plasma Diagnostics

Moderators: Prof. Dr. Sumit Agarwal, Colorado School of Mines, USA, **Dr. John Arnold**, IBM

1:30pm **PS1-MoA-1 Plasma Diagnostics for Industry: Restrictions, Reluctance, and Reward**, ***James Ellis***, *Ben Harris, Montu Bhuva, Jordyn Polito, Geoffrey Hassall,* Oxford Instruments Plasma Technology, UK **INVITED**

The compound semiconductor industry continues to push the boundaries of device performance across markets such as power electronics and data communications; however, this success has increased the emphasis on precision in plasma processing. For a capital equipment manufacturer, it is imperative that a pragmatic approach is taken when using plasma diagnostics to bridge the gap between plasma physics and high-volume manufacturing. This presentation will explore the restrictions, reluctance, and rewards of deploying plasma diagnostics within this sector.

There are significant restrictions when using plasma diagnostics within an industrial setting. For example, commercial systems are often limited by their optical access for complex diagnostics. Furthermore, any integrated diagnostic (or sensor) must meet rigorous standards for robustness, cost, and usability to ensure they remain relevant for industrial applications. This presentation will give an overview of these restrictions in contrast to academic constraints.

The semiconductor sector takes a conservative stance against risk due to the high costs involved with change; this understandably gives a 'process-first' mentality that must be considered when using diagnostics. Any diagnostic that risks contaminating the chamber or may cause drift in an already qualified process is a liability. This presentation will discuss how diagnostics need to be tested to ensure that they do not impact the process, with a specific case study on the curling probe.

Whilst the complexities of using diagnostics in industrial settings are apparent, the reward certainly justifies the effort. Integrating diagnostics enables the acceleration of hardware development and provides the ground truth necessary to validate complex plasma models. This can narrow the process optimisation envelope, enabling a faster transition from process development to the satisfaction of a performance specification. Finally, we highlight the role of external academic partnerships in this journey. For example, by utilising more complex laser-based diagnostics we can build greater confidence in the simplified diagnostic approaches used internally and the complex chemistry models that they validate.

2:00pm **PS1-MoA-3 Use of the OES Signal as an Indicator of Si Etch-Rate Uniformity During Fluorocarbon Plasma Etching**, ***Nobuyuki Kuboi***, *Takashi Yagisawa, Yasufumi Miyoshi, Akiko Kawamoto, Shoji Kobayashi, Yoshiya Hagimoto,* Sony Semiconductor Solutions Corporation, Japan*; Hiroshi Akatsuka,* Institute of Science Tokyo, Japan

During the plasma etching of complex structures with high aspect ratios such as advanced CMOS devices and image sensors, the quantitative prediction and accurate control of the etch rate and uniformity is essential to realize process stability and high yield in mass production. However, variations in these properties are almost impossible to detect during plasma etching in mass production, and their real-time monitoring has been limited to optical emission spectroscopy (OES) analysis. Therefore, the OES signal must be used to address this issue.

The authors previously investigated SiN etch-rate variations during $CF_4/Ar/H_2$ plasma etching using the OES signal of the H Balmer line and found that this variation could be tracked[1]. In this work, to better understand the relationship between Si etch-rate uniformity and the OES signal, the authors experimentally measured variations in Si etch-rate uniformities for 75 process conditions using an ICP reactor with $C_4F_8/SF_6/Ar$ plasma. Analysis of the results using PCA and PLS regression suggests that variations in Si etch-rates at the wafer center and in edge regions depend on variations in the OES signals originating from de-excitation on F with a wavelength of 780 nm and de-excitation on CF (240 nm) and CF_2 (246 nm), respectively. This result indicates that these OES signals can be used as indicators of Si etch-rate uniformity.

To confirm the validity of the analysis, we used a collisional-radiative model to model the emissions of F (780 nm), CF (240 nm), and CF_2 (246 nm) considering gas diffusion and wall sticking as loss processes with electron density (N_e), electron temperature (T_e), and ground-state gas density as input parameters. The simulation results showed that the F (780 nm) intensity is large when N_e and T_e are large, which corresponds to the wafer center region in the ICP reactor, whereas the CF (240 nm) and CF_2 (246 nm) intensities have inverse trends in the F intensity. Therefore, these OES signals can be indicators of Si etch-rate uniformity during fluorocarbon plasma etching.

Combining an inverse analysis of the experimental OES signals [2] with our emission models, distributions of N_e, T_e, and ion/radical densities can be quantitatively derived. Using these values as inputs for our voxel-slab model [3], the uniformities of feature profiles and plasma-induced damage can be predicted, reflecting real-time chamber conditions. This future work will be introduced in our presentation.

[1] N. Kuboi *et al*., Jpn. J. Appl. Phys. **49**, 08JD01 (2010).

[2] Y. Yamashita *et al*., J. Vac. Sci. Technol. A**42**, 023003 (2024).

[3] N. Kuboi *et al*., J. Vac. Sci. Technol. A**33**, 061308 (2015).

2:15pm **PS1-MoA-4 Non-Invasive Viewport Plasma Resonance Sensor for in-Situ Monitoring of Plasma Etching via Electron Density Measurement**, ***InYong Park***, *GeonWoong Eom, SangHo Lee, Min Hur, WooSeok Kang, Dae-Woong Kim,* Korea Institute of Machinery and Materials, Korea (Democratic People's Republic of)

In semiconductor plasma etching, process reproducibility is a critical requirement. However, the nonlinear nature of plasma can produce different outcomes under nominally identical recipes. Small variations at the etch endpoint can damage the wafer and the underlying interconnect layers, requiring precise in-situ monitoring. Optical emission spectroscopy (OES) is widely used for end-point detection (EPD), owing to its non-invasive nature and its sensitivity to changes in the plasma emission spectrum at the etch endpoint. However, the OES emission intensity depends on multiple coupled parameters: electron density, electron temperature, and emitting-species concentration. As a result, a single emission line cannot uniquely identify the plasma state. As the critical dimensions of semiconductor devices shrink, the open area exposed to the etchant decreases, reducing the flux of reaction byproducts and degrading the signal-to-noise ratio of EPD. Moreover, OES alone, without supplementary calibration, does not directly yield quantitative plasma parameters, which limits its ability to resolve subtle variations in plasma state.

A microwave probe directly measures the electron density by detecting microwave resonances of the plasma. The electron density, in turn, tracks the etch rate through the ion flux at the wafer surface under controlled plasma chemistry, pressure, and bias. However, conventional microwave probes must be inserted into the chamber, which is an invasive configuration that perturbs the plasma and restricts their use in production-grade equipment.

To overcome this limitation, we developed a viewport plasma resonance (VPR) sensor that measures the electron density non-invasively through a dielectric viewport, with the sensor positioned outside the chamber. To our best knowledge, this is the first viewport-coupled microwave resonance diagnostic for in-situ electron-density measurement during plasma etching. Electron densities measured by the VPR sensor were benchmarked against a conventional invasive microwave probe, and the correlations among etch rate, electron density, and OES intensity were quantitatively analyzed through simultaneous measurement. The resulting multi-sensor framework separates density-driven plasma variations from chemistry-driven emission changes, providing a route to non-invasive, quantitative monitoring of plasma etching for improved process reproducibility.

2:30pm **PS1-MoA-5 Non-Invasive Detection of RF Plasma Arcing by View-Port-Type Radio Emission Spectrometry**, ***Geon Woong Eom***, *SangHo Lee, In Yong Park, Woo Seok Kang, Min Hur, Dae-Woong Kim,* Korea Institute of Machinery and Materials, Republic of Korea

Arcing in radio-frequency (RF) plasma is a transient, localized discharge that can be triggered by field enhancement near cracks, protrusions, particles, or locally heated surfaces. Because such events can damage the process chamber, generate particles, and degrade wafer yield, real-time detection of arcing is essential for plasma process monitoring. In this work, we propose a non-invasive arcing detection method based on view-port-type radio emission spectrometry (VP-RES), which senses RF electromagnetic emission from the plasma through an optical/electrical access port without direct insertion into the discharge region.

Artificial arcing was generated in a capacitively coupled plasma reactor using an arcing-inducing metal structure. The VP-RES response was compared with voltage and current waveforms measured by a conventional

voltage–current probe. To resolve transient RF signatures, the measured signals were analyzed in the time–frequency domain using wavelet transform analysis, allowing normal plasma operation and arcing events to be distinguished by their spectral and temporal features. In parallel, three-dimensional electromagnetic simulations of the field distribution inside the reactor were used to guide the sensor geometry and viewport location, with the design goal of maximizing signal coupling to arc-induced emission and spatial sensitivity within the discharge volume.

The results suggest that VP-RES can provide a practical, non-invasive diagnostic route for real-time arcing detection in RF plasma systems. By combining view-port-based RF emission sensing with time–frequency analysis, the proposed method offers a potential alternative or complementary approach to conventional electrical monitoring, particularly where direct probe installation is constrained or where localized transient detection is required.

2:45pm **PS1-MoA-6 High Sensitivity Detection of Subtle Electron Density Variations Using a Cutoff Probe***, **Jang Jinhyeok**,* Applied Physics lab for Plasma Engineering (APPLE), Department of Physics, Chungnam National University, Korea (Democratic People's Republic of)*; Cho Chulhee,* Institute of Quantum Systems (IQS), Chungnam National University, Korea (Democratic People's Republic of)*; Seong Inho, Jeong Wonnyoung, Choi Byeongyeop, Seo Seonghyun, Lee Isak,* Applied Physics lab for Plasma Engineering (APPLE), Department of Physics, Chungnam National University, Korea (Democratic People's Republic of)*; You Shinjae,* Applied Physics lab for Plasma Engineering (APPLE), Department of Physics & Institute of Quantum Systems (IQS), Chungnam National University, Republic of Korea

The electron density is one of the key plasma parameters that affect process reproducibility in plasma processing, and even small variations in the electron density can influence the process outcome. Accurately detecting such subtle variations critically depends on the sensitivity of the diagnostic instrument employed, and therefore a comparative evaluation of different diagnostic methods is required.

In this study, we demonstrate the high sensitivity of a cutoff probe for detecting subtle electron density variations. Small variations in the electron density were introduced by slightly varying the RF power, and the resulting changes were simultaneously measured by a cutoff probe and a Langmuir probe to compare their detection performance.

The results showed that the cutoff probe clearly resolved the subtle electron density variations in a stepwise manner, whereas the Langmuir probe could not distinguish the same variations because they were comparable to its measurement scatter.

In conclusion, the cutoff probe was confirmed to detect subtle electron density variations more effectively than the Langmuir probe. These findings can contribute to the selection of appropriate diagnostic methods in environments where the detection of small electron density variations is required

3:00pm **PS1-MoA-7 Young Investigator Awardee Talk: Spatially Resolved Probes for the Measurement of Hydrogen, Oxygen, Nitrogen, Chlorine, and Fluorine Radicals***, **Dren Qerimi**,* University of Illinois **INVITED**

Accurate measurement of reactive radical species in low-temperature plasmas is critical for understanding plasma chemistry, plasma-surface interactions, and semiconductor processing. Conventional optical diagnostics generally provide line-of-sight or volume-averaged measurements and often lack the spatial resolution necessary to resolve localized plasma behavior. In this work, we present spatially resolved catalytic radical probes capable of measuring H, O, N, and F radicals in plasma sources, with ongoing efforts extending the technique to chlorine-containing plasmas. The diagnostic platform utilizes catalytic probe surfaces that convert radical recombination or reactive loss into a measurable thermal response. Arrays of probes with different catalytic materials enable discrimination between multiple reactive species while maintaining sub-centimeter spatial resolution. Measurements of H, O, and N radicals were performed in a helicon plasma source over powers from 300–1100 W and pressures from 10–100 mTorr. Radical densities on the order of 10^{12}–10^{14}cm^{-3} were measured, while electron densities ranged from 10^{10}–10^{12}cm^{-3} and electron temperatures from ~2–8 eV. Radical densities increased with both pressure and power and followed trends consistent with independently measured plasma parameters. The probe framework was further extended to fluorine radical measurements relevant to plasma etching applications. Because fluorine plasmas present chemically aggressive environments, a non-equilibrium radical probe technique was developed in which radical-induced tungsten etching serves as the sensing mechanism. Experiments in NF_3 and SF_6 plasmas demonstrated a linear correlation between probe response and fluorine density up to 10^{21}m^{-3}. Calibration in a research-scale etcher enabled quantitative spatial fluorine density measurements and comparison with actinometry. Spatially resolved measurements revealed substantial radial nonuniformities in fluorine density above the wafer surface that are not captured by conventional optical diagnostics, improving interpretation of silicon etch kinetics and etch probability measurements. Current work focuses on extending these diagnostics to chlorine radical measurements for halogen-based plasma processing chemistries. These results demonstrate that catalytic radical probes provide a versatile diagnostic platform for spatially resolved measurements of reactive species in plasma environments relevant to both fundamental plasma studies and advanced semiconductor manufacturing.

3:30pm **PS1-MoA-9 Operando Plasma-XPS: Platform Development, Capabilities, and Metrology Challenges***, **Andrei Kolmakov**,* NIST

Plasma-driven processes are central to technologies spanning semiconductor manufacturing, advanced materials synthesis, energy systems, aerospace engineering, catalysis, environmental remediation, and biomedicine. Although conventional ultra-high vacuum (UHV) X-ray photoelectron spectroscopy (XPS) is a powerful tool for surface chemical analysis, its inability to operate at plasma-processing pressures has created a major metrological gap for operando measurements. Recent advances in ambient-pressure XPS (AP-XPS) instrumentation open new opportunities for direct studies of plasma-solid, plasma-liquid, and plasma-gas interactions. Here, we report on the hardware development and pilot testing of a plasma-compatible AP-XPS (plasma-XPS) platform for operando characterization of plasma-assisted processes and reactive environments [1]. We demonstrate conditions under which XPS spectra can be collected directly during plasma operation, enabling simultaneous monitoring of transient surface chemistry, gas-phase species, and mass- and optical spectra. We observed plasma-induced oxidation/reduction reactions, metastable surface species, and the importance of plasma-chamber wall reactions on local plasma chemistry [2]. Wealso observed RF/AC plasma-induced shifts in binding energy, XPS peak broadening, and splitting associated with surface charging and neutralization, particularly in poorly conducting materials. Gas-phase XPS spectra acquired during these plasma conditions also exhibit plasma-dependent binding-energy shifts and satellite structures, offering additional opportunities for real-time plasma diagnostics [3]. Overall, plasma-XPS emerges as a potentially versatile operando metrology platform for real-time diagnostics, process monitoring, and mechanistic studies across a broad spectrum of plasma-enabled technologies.

References

[1] J.T. Diulus, A.E. Naclerio, J.A. Boscoboinik, A.R. Head, E. Strelcov, P.R. Kidambi, A. Kolmakov, The Journal of Physical Chemistry C, 128 (2024) 7591-7600.

[2] J. T. Diulus, A. R. Head, J. A. Boscoboinik, and A. Kolmakov, J. Vac. Sci. Technol. A 43, 040401, (2025)

[3] J. T. Diulus, A. R. Head, J. A. Boscoboinik, C. Corbella, A. Tselev, and A. Kolmakov, J. Vac. Sci. Technol. A 44, 020405 (2026)

Author Index

Bold page numbers indicate presenter