Plasma Science and Technology
Room 315 - Session PS2-TuM
High Aspect Ratio and Cryogenic Etching II

Moderators: Dr. Hisataka Hayashi, Daikin Industries, Ltd., **Dr. Pingshan Luan**, TEL Technology Center America

11:00am **PS2-TuM-13 Plasma-Material Interactions in Cryogenic Hydrogen-Fluoride Plasma Etching***, **Shih-Nan Hsiao**, Yusuke Imai, Makoto Sekine,* Nagoya University, Japan*; Ryutaro Suda, Yoshihide Kihara,* Tokyo Electron Miyagi Limited, Japan*; Masaru Hori,* Nagoya University, Japan **INVITED**

For more than half a century, reactive ion etching (RIE) has served as a cornerstone of semiconductor manufacturing, facilitating the high-throughput production of silicon wafers. Its success is fundamentally rooted in the ion-neutral synergy—the collaborative interaction between reactive chemical species and high-energy ions—which has been pivotal to the evolution of microelectronics [1]. However, as device architectures transition toward sub-nanometer scales and complex high-aspect-ratio (HAR) 3D structures, conventional RIE processes encounter significant physical and chemical bottlenecks. Specifically, the degradation of traditional ion-chemical synergy in these advanced regimes often leads to diminished etching efficiency and reduced production yields. To address these limitations, cryogenic plasma etching utilizing hydrogen fluoride (HF)-based chemistries has emerged as a sophisticated alternative [2]. This approach exploits a distinct interplay between incident ions, physisorbed surface layers, and the substrate. Despite its potential, the underlying etching mechanisms of cryogenic HF plasma remain partially obscured [3-5]. In this work, we elucidate the plasma-material interactions during the cryogenic etching of dielectric materials. By employing in-situ diagnostics, including spectroscopic ellipsometry and attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR), we systematically characterize the influence of bias voltage, substrate temperature, and HF partial pressure on the etching behavior of SiO_2 and SiN. Based on our findings, we propose a comprehensive mechanistic framework for dielectric etching in cryogenic HF plasmas. Furthermore, we extend this discussion to the synergistic interactions governing plasma-assisted atomic layer processes using HF chemistries for nanofabrication.

References

[1] J. W. Coburn and H. F. Winters, J. Appl. Phys. 50, 3189 (1979)

[2] Y. Kihara et al., VLSI symposium T3-2 (2023).

[3] S. N. Hsiao et al., Small Methods, 8, 2400090 (2024).

[4] S. N. Hsiao et al., Chem. Eng. J., 522, 167517 (2025)

[5] S. N. Hsiao et al., Small Methods, 10, e01744 (2026).

11:30am **PS2-TuM-15 Investigation of Surface Reactions of SiO_2 and SiN Films Under Cryogenic Etching Process via in-Line/Situ Analysis***, **Hiroyuki Fukumizu,*** Kioxia Corporation, Japan **INVITED**

This study explores cryogenic etching processes for SiO_2 and SiN films, which are essential for high aspect ratio hole etching in 3D Flash Memory. The blanket SiO_2 films were etched by $H_2/F_2/Ar$ gas mixture plasma over a temperature range from 25 to −200 °C, examining the mechanisms involved in cryogenic conditions via in-situ FT-IR analysis. The etch rate at −100 °C is about 3.2 times higher than at 25 °C due to co-adsorption of H_2O and HF. However, below −100 °C, the solidification of H_2O decreases etching efficiency. In addition to SiO_2, the study addresses the etching behavior of SiN films, where cryogenic etching using HF/PF_3 gas mixtures was investigated. To clarify the factors influencing SiN etch rates, we employed a plasma beam irradiation apparatus equipped with low-temperature in-line XPS analysis to examine surface reactions in detail. Additionally, findings show that the ammonium salt NH_4F forms on the SiN surface under cryogenic conditions, enhancing etch rates. The introduction of PF_3 promotes the formation of NH_4PF_6, which can be decomposed by energetic ion irradiation to further boost etching efficiency. These insights contribute significantly to optimizing cryogenic etching processes.

12:00pm **PS2-TuM-17 Dynamics of Charge Conduction in Water Layers Formed During Cryogenic Etching of HAR SiO_2 Features***, **Chenyao Huang**, Yeon Geun Yook, Yifan Gui,* University of Michigan*; Steven Shannon,* North Carolina State University*; Mark J. Kushner,* University of Michigan

During the fluorocarbon plasma etching of dielectric materials, differential charging within features arises from the disparity between the arrival onto the wafer of energetic ions with narrow angular spread and low-energy electrons with broad angular distributions. The resulting intra-feature electric fields can deflect particle trajectories, leading to defect formation and reduced etch rates. Cryogenic plasma etching (CPE) is being investigated as an alternative due to its high etch rate and attractive sidewall profile control for high aspect ratio (HAR) features. During cryogenic etching of dielectrics using HF containing gas mixtures, water layers containing solvated HF form along the feature sidewalls in addition to charge deposition from incident charged particle fluxes. These liquid layers may have significant conductivity due to the ionic solute concentrations (e.g., H_3O^+ and F- when solvating HF in water). This conductivity can alter the potential distributions within the feature by conducting externally deposited charges and facilitating self-polarization.

In this work, we computationally investigated charging dynamics including conductive layers for pre-formed SiO_2 features, and during plasma etching of HAR SiO_2 features using Ar/HF gas mixtures in multi-frequency capacitively coupled plasmas. Feature evolution is modeled and using the 3D voxel-based Monte Carlo Feature Profile Model (MCFPM). Fluxes and energy angular distributions (EADs) of incident species are produced by the reactor-scale Hybrid Plasma Equipment Model (HPEM). The MCFPM samples incident fluxes to statistically launch pseudoparticles representing charged and neutral species, which are tracked until they interact with solid materials. We have developed and integrated modules into the MCFPM to account for charge conduction and redistribution within conductive water layers during etching. Our results indicate that these highly conductive, thin layers transform local maxima of electric potential into a broadened profile with lower peak potentials within the features. During SiO_2 etching, the water layer counteracts externally deposited charges through the redistribution of external and intrinsic charges, resulting in a reduced electric potential that correlates inversely with the intrinsic charge densities represented by the dissolved ions.

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