Plasma Science and Technology
Room 315 - Session PS1-WeM

Plasmas for 3D Integration

Moderators: Hiroyuki Fukumizu, KIOXIA, **Dr. Jeffrey Shearer**, TEL Technology Center, America, LLC

8:00am **PS1-WeM-1 Challenges in Plasma Etching for 3D Interconnect Technology**, ***Violeta Georgieva***, *Jeongsoo Kim, Eoin Jackman, Quyang Lin, Katia Devriendt,* IMEC, Belgium **INVITED**

Three-dimensional (3D) interconnect technology based on die vertical stacking has been attracting increasing attention recently as a key approach to extend system-level performance beyond conventional scaling limits [1]. Through-silicon vias (TSVs), through-dielectric vias (TDVs), and nano-TSVs (nTSVs) used in backside power delivery networks enable high-density vertical electrical signal or power transport in heterogeneous 3D integration.

3D interconnect performance depends not only on interconnect structures but also on upstream processes such as plasma dicing, which ensure die integrity and bonding yield. Reducing wafer thickness and downsizing dies have revealed the limitations of conventional mechanical and laser dicing methods, while plasma dicing offers precise and clean die singulation [2].

This work focuses on the challenges faced by the plasma etching community in delivering high-aspect-ratio processes with tight control of anisotropy at both the macroscale (TSV, TDV, and plasma dicing) and the nanoscale (nTSVs). In addition to profile performance, other important parameters such as high selectivity to photoresist (PR) and hard mask (HM), as well as endpoint detection in very small open areas with dense layouts, are addressed.

TSVs and nTSVs are both affected by etch-rate suppression and profile distortion due to aspect-ratio-dependent etching [3, 4]. For nTSVs, these challenges are exacerbated by the need for nanoscale precision, especially in TSV-last schemes, where extremely high silicon-to-oxide selectivity is required to preserve thin oxide liners [4].

TDVs introduce additional complexity due to the need to etch multilayer back-end-of-line dielectric stacks while maintaining uniformity and protecting underlying metallization [5]. Furthermore, intrinsically low dielectric-to-PR selectivity and limited HM options remain critical constraints.

Plasma dicing combines many of these challenges, requiring precise etching of silicon, dielectric, and polymer layers within a single process [6].

This presentation reviews current process solutions and innovations addressing these issues and highlights remaining gaps and future directions in plasma etching for advanced 3D interconnect integration.

References

[1] SJ. Koester, et al, IBM J Res Dev **52**, 583–597 (2008).

[2] N. Matsubara, et al., 2012 4th ESTC, Amsterdam, Netherlands.

[3] WW. Shen, KN. Chen, *Nanoscale Res Lett* **12**, 56 (2017).

[4] T. Shigetoshi, et al, VLSI 2026, Honolulu, Hawaii, accepted.

[5] Y. Morikawa and W. Chen, *2024 IEEE 74th ECTC*, Denver, CO, USA.

[6] V. Georgieva, et al, 2024 SSDM, Himeji, Japan.

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8:30am **PS1-WeM-3 Low Global Warming Potential (GWP) Gases for Deep Si Etch for Through-Silicon Via (TSV) Applications**, ***Richa Agrawal***, *Gloria Fraczak, Nathan Marchack,* IBM Research*; Yohei Takakura,* DAIKIN INDUSTRIES, LTD.*; Teodor Todorov, Martin M. Frank, Jaylynn Sheppard, Jose Daboin, Brian Pham,* IBM Research*; Kazunori Horiguchi,* DAIKIN INDUSTRIES, LTD.*; Yasuhiro Nojiri, Hisataka HAYASHI,* DAIKIN INDUSTRIES, LTD., Japan*; ERIC JOSEPH, ROBERT L. BRUCE,* IBM Research

Through-silicon vias (TSVs) are crucial components for three-dimensional (3D) integration technologies. Conventional Bosch processes typically rely on fluorinated gases such as c-C_4F_8 and SF_6, which exhibit high global warming potentials (GWPs) and are increasingly subject to environmental regulations. Given the criticality of deep-Si etch processes for packaging applications, it is of great interest to investigate alternative plasma chemistries to focus on sustainability for future technological node development.

In this work, the applicability of alternative with much lower GWPs for TSV applications at aspect ratios >10:1 with different integration routes, is investigated. The alternative gases show comparable etch profiles to the conventional C_4F_8-SF_6 processes – key performance indices including critical dimensions (CD), anisotropy, etch rates, mask selectivity are compared. Optical emission spectroscopy (OES) is used to assess gas phase species and compare plasma characteristics. Electrical characterization of the integrated TSVs shows similar resistance scaling for C_4F_8-SF_6 processes and alternative gases, with performance governed by TSV geometry, CD, and liner material properties. Exhaust sampling analysis using Fourier Transform Infrared Spectroscopy (FTIR) showed a two to three orders of magnitude reduction in high-GWP emission byproducts with the usage of alternative gases compared to C_4F_8 and SF_6. These results demonstrate a viable alternative pathway to reducing environmental impact while maintaining etch and electrical performance integrity for TSV fabrication.

8:45am **PS1-WeM-4 Multiscale Modeling Approach for Bosch Silicon Etching Process Coupled to Machine Learning, Toward a Fast Etching Process Optimization**, *Rim Ettouri,* Nantes Université, CNRS, Institut des Matériaux de Nantes Jean Rouxel (IMN), France*; Fatima-Zahrae Hilal, Valeria Borodin,* IMT Atlantique, CNRS, Nantes Laboratory of Digital Sciences, LS2N, France*;* ***Ahmed RHALLABI,*** Nantes University, CNRS, Institut des Materiaux de Nantes Jean Rouxel, IMN, France

Deep silicon etching is a major challenge for the development of many electronic devices, such as DRAM memories, integrated 3D capacitors, and MEMS. Developing deep silicon etching processes with minimal morphological defects and a high degree of anisotropy, while avoiding empirical trial-and-error approaches, remains a significant scientific and technological challenge requiring substantial time and resources.

The Bosch process, based on an alternating discharge including an etching phase and a deposition phase, appears to be a particularly suitable solution for meeting these requirements depending on the targeted applications. However, its optimization generally requires long and costly experimental campaigns.

In this context, the development of etching simulators based on a multi-scale approach represents a promising alternative. Such tools could contribute in the understanding of plasma–surface interaction mechanisms and the optimization of the etching processes in a faster time.

In this context, we developed a multiscale approach for a deep silicon etching using the Bosch process with alternating discharges SF_6 for the etching step and C_4F_8 for the deposition step.The model is composed of three modules: a global kinetic model of SF_6 and C_4F_8 ICP plasmas, a sheath model based on the Monte Carlo method, and a 2D etching model based on the cellular Monte Carlo method.The simulator allows the prediction of the temporal evolution of the etched profiles, the surface chemical composition, and the etching rate.Well-known phenomena in the Bosch process, such as scalloping and undercut, are clearly demonstrated.

One of the disadvantages of our multi-physics models is its very long run time.Using machine learning to predict the evolution of silicon etch profiles as a function of the operating conditions (RF power, pressure, gas flow rates, ...) is a good way to significantly reduce the simulation times.The simulations from our multiscale approach serve as training data for the machine learning. This enables to move towards an AI approach that contributes to Bosch process optimization.

The data-driven analysis identified the relative importance of each parameter and their interactions for instance, quantifying how pressure and power jointly affect polymer deposition and SiF_x by-product formation.

9:00am **PS1-WeM-5 Feature-Scale Model of Si Plasma Etching in $SF_6/O_2/SiF_4$ Mixtures**, ***Maryam Khaji***, University of Michigan, Ann Arbor*; Fatima Jenina Arellano, Kouta Kawahara, Noboru Yamaguchi, Taichi Suzuki, Tadamasa Kobayashi, Kenta Doi,* Ulvac Technologies, Inc., Japan*; Mark J. Kushner,* University of Michigan, Ann Arbor

High aspect ratio plasma etching of Si for TSV (through-silicon vias) and packaging applications is primarily performed in fluorine-containing plasmas with feedstock gases containing CF_4, NF_3 and SF_6 [1]. Si etching by F atoms is an isotropic process. Adding gases such as O_2 and SiF_4 produces sidewall passivation which, with moderate substrate biases, enables anisotropy. For comparable F-atom fluxes to the wafer, several studies have reported significantly higher Si etch rates in SF_6-containing plasmas compared to other F-containing plasmas [2]. This enhancement has been attributed to the possible catalytic role of S-containing species, surface sulfidization, which increases the efficiency of fluorination and increases etch yields [1,3]. In this work, results will be discussed from feature-scale

modeling of Si HAR etching in an inductively coupled plasma (ICP) source sustained in $SF_6/O_2/SiF_4$ gas mixtures. With the goal of distinguishing the unique aspects of plasma etching in gas mixtures containing SF_6, the surface reaction mechanism includes fluorination, sulfidization, oxidation, and ion sputtering. Reaction probabilities were calibrated against experimental results obtained for different ICP powers, RF bias powers, gas compositions, and pressures. Reactor-scale simulations were performed with the Hybrid Plasma Equipment Model (HPEM), and feature-profile evolution was evaluated using the Monte Carlo Feature Profile Model (MCFPM) [4]. The consequences of plasma properties on feature evolution will be discussed. A brief update on the gas phase reaction mechanism for SF_6 containing plasmas will be provided.

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References

1. P. Arora et al., J. Vac. Sci. Technol. A **37**, 061303 (2019).
2. V. M. Donnelly et al., J. Vac. Sci. Technol. A **35**, 05C202 (2017).
3. P. Y. Tessier et al., Nucl. Instrum. Methods Phys. Res. B **155,** 280 (1999).
4. C. Huard et al., J. Vac. Sci. Tech. A **35**, 05C301 (2017).

9:15am **PS1-WeM-6 Transport Gradient Model of Oxygen and Fluorine Flux Ratio in High-Aspect-Ratio Silicon Etching**, ***Kenji Ishikawa**, Shuto Tsuchioka, Trung Nguyen Tran, Kenichi Inoue, Takayoshi Tsutsumi,* Nagoya University, Japan*; Thi-Thuy-Nga Nguyen,* nagoya University, Japan

This study presents a quantitative investigation of the bowing mechanism observed in high-aspect-ratio (HAR) silicon etching using SF6/O2 inductively coupled plasmas through a multi-scale simulation framework. By integrating reactor-scale plasma modeling with feature-scale profile evolution analysis, we examine the dynamic balance of reactive radicals at the etch front and its role in profile formation. In contrast to previous studies relying on qualitative interpretations based on optical emission intensity ratios, this work provides numerical validation of the transport gradient model.

The model demonstrates that the localized oxygen-to-fluorine (O/F) flux ratio, rather than the global gas composition, governs sidewall passivation and etch stability. The local flux ratio incorporates transport physics, including Knudsen diffusion and surface sticking probabilities, which significantly modify reactant distributions. Consequently, gradients in radical flux develop along trench depth, producing spatially varying surface reactions.

Parametric simulations identify a critical threshold in the local O/F flux ratio between 3.5% and 3.6%. Above this threshold, oxygen-rich coverage enables passivation and anisotropic etching. Below it, fluorine-dominant coverage induces a nonlinear increase in etch rate, causing rapid lateral etching and bowing.

This insight explains why a 30% O2 condition maintains verticality at shallow depths, whereas 20% O2 causes immediate bowing as the local O/F ratio falls below the threshold. These findings highlight the importance of transport-limited effects in HAR structures and provide a theoretical basis for optimizing radical flux control in advanced plasma etching processes.

9:30am **PS1-WeM-7 Effects of Discharge Frequency and Precursor Molecule on the Deposition Rate, Film Density, and Residual Stress of a-C:H Hard Masks**, ***Kazunori Koga**, Shunpei Ohara, Soichiro Yoshida, Ryosuke Kinnami, Shinjiro Ono, Takamasa Okumura, Kunihiro Kamataki, Naho Itagaki, Masaharu Shiratani,* Kyushu University, Japan

Hydrogenated amorphous carbon (a-C:H) films are essential materials for hard masks in high-aspect-ratio (HAR) etching in semiconductor manufacturing. High-speed deposition of high-density and low-stress a-C:H films is strongly demanded for superior plasma etching resistance. Here, a-C:H films were deposited via plasma chemical vapor deposition (plasma CVD) where methane, acetylene, and cumene (C_9H_{12}) were used as precursor gases to evaluate their deposition rate, density, and stress. A parallel-plate plasma CVD system was used with 1 cm^2 Si substrates under Ar-diluted precursors. An RF voltage of 13.56 MHz or 400 kHz was applied. For 400 kHz, the concentration, flow rate, pressure, and Vpp were 5%, 100 sccm, 0.02 Torr, and 1600–2400 V. For 13.56 MHz, the flow rate was 100 sccm, concentration 5–50%, pressure 0.02–0.3 Torr, and Vpp 100 V or 250 V. At 13.56 MHz, acetylene and cumene yielded higher deposition rates than methane. Cumene achieved a 20 nm/min higher rate than acetylene with comparable density and stress (~1.0 GPa). Stress increased with density, reaching 3.8 GPa at 2 g/cm^3. Conversely, 400 kHz conditions—providing higher self-bias and incident ion energy—yielded high density (~2 g/cm^3) and low stress (~1.0 GPa), keeping stress constant independent of density. At 400 kHz, cumene deposited 10 nm/min faster than acetylene. Factors determining density were examined. Raman spectroscopy showed that hydrogen content and density are inversely correlated, independent of discharge conditions or precursors. To clarify ion energy effects, an ion energy index was defined as |Vdc|/pressure/Nc, where |Vdc| is self-bias voltage and Nc is the number of carbon atoms per molecule. Using this index, density peaked at ~5 regardless of precursors or frequencies. This indicates that the sub-plantation model, where incident ion energy is distributed among carbon atoms within a molecule to determine density, holds true even for high-carbon-number cumene. The Raman D/G peak ratio (sp^2/sp^3 bonding ratio) correlated well with density in the low-ion-energy region (13.56 MHz) but deviated in the high-ion-energy region (400 kHz). This deviation suggests a structural difference under high ion energy, explaining why stress remained decoupled from density. Etching measurements confirmed that higher density decreased the etching rate, proving that density governs etching resistance regardless of precursors or deposition conditions.

9:45am **PS1-WeM-8 Impact of HBr/H2 Gas Mixture on Etching of GeSexTe1-x Chalcogenide Thin Films for Reconfigurable and Nonlinear Photonics**, ***Giovanni BEDOUI,*** CEA-LETI, France*; Aurélien TAVERNIER, Yoann BRULE, Jean-Baptiste DORY, Pierre MEILLEUR, Jules LAGRAVE, Clémence JAMIN-MORNET, Pierre NOE,* CEA-Leti, France

Chalcogenide materials are alloys composed of one or multiple chalcogen elements (S, Se, Te) and one or multiple alloying elements (Ge, As, ...). They demonstrate a wide transparency window and high linear and non-linear (NL) indices in the near and mid infrared. Some of them exhibit phase-change properties, transitioning reversibly from an amorphous to a crystalline state, with an unusual contrast between the electrical and optical properties of these two states [1,2]. As their properties makes them interesting for micro and nano-photonics applications, one issue impeding their widespread integration is the ability to pattern them without altering their optical properties.[3]

To address this issue, a plasma etching process with minimal impact over morphology and stoichiometry is needed for $GeSe_xTe_{1-x}$ destined to reconfigurable (1.55µm) and NL (2µm) applications. A focus will be made on HBr/H_2 etching gases and H_2/Ar Post-Etching Treatment (PET), expecting low impact on surface roughness (Rq), stoichiometry alteration and non-volatile compound (NVC) formation.[4]

This work involves unpatterned $Ge_{50}Te_{50}$ and $Ge_{50}Se_{50}$ thin film etching with HBr and HBr/H_2 both with and without PET in an ICP chamber. Characterization methods such as 2D Atomic Force Microscopy (AFM) for Rq and X-Ray Photoelectron Spectroscopy (XPS) for atomic composition were used. Figure 1 shows AFM measurement of Rq for both alloys at each gas composition. HBr/H_2 mix induces the lowest Rq and PET decreases Rq for both alloys. Figure 2 shows XPS measurement of both alloys with each gas composition. HBr and H_2 cause stoichiometric shifts by forming volatile GeH_x and NVC $GeBr_x$ in both alloys. For GeTe, PET seems to limit both NVC and volatile by-products. For GeSe, PET induces volatile SeH_x by-products generation.[5] We can conclude that HBr/H_2 + PET etching mix seems the most promising.

To go further, the impact of HBr/H_2 + PET mix over unpatterned and patterned $GeSe_xTe_{1-x}$ thin films will be studied. Characterizations techniques as 3D and 2D AFM for sidewall roughness and Rq measurement, XPS for atomic composition and Scanning Electron Microscopy (SEM) for sidewall angle analysis will be used. The addition of CH_4 gas into the etching mixture could be studied to improve sidewall angle control.[6]

[1] A. Albanese, Physica Rapid Research Ltrs 2400129 (2024)

[2] P. Noé, Semicond. Sci. Technol. **33**, 1 (2017)

[3] B. J. Eggleton, *Nature Photon*, vol. 5, no. 3, pp. 141–148, Mar. 2011

[4] B. Fontaine, 'Mechanism of residues formation on Ge-rich GST after plasma etching'

[5] D. R. Lide, "Handbook of Chemistry and Physics"

[6] K. T. Vu *JVST: Vacuum, Surfaces, and Films*, vol. 29, no. 1, Art. no. 1, Jan. 2011

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