Plasma Science and Technology
Room 315 - Session PS+AP-MoM

Plasma Processes for Advanced Interconnects
Moderators: Dr. John Arnold, IBM, **Takeshi Ohmori**, Hitachi

10:00am **PS+AP-MoM-1 Interconnect for 7A and Beyond***, **Scott Allen,*** IBM Research Division, Albany, NY **INVITED**

BEOL scaling continues to challenge the limits of plasma etch process capability. Conventional approaches have shown to have limited extendibility for next generation devices. Challenges with the traditional damascene integration and superior resistance scaling with alternate conductors make transition to subtractive patterning more attractive. Capacitance control using new dielectric materials or schemes requires innovation and examination. Additionally, High-NA EUV and other new patterning techniques provide pathways forward but require significant development. Advances in etch tooling and stack materials are providing options to meet these challenges. Novel use of known techniques can be integrated with these new tools and materials to enable semiconductor technology at 7A and beyond.

10:30am **PS+AP-MoM-3 Epitaxial conductors to replace Cu in advanced interconnect metallization***, **Jean-Philippe Soulie**, François Chancerel, Steven Brems, Chen Wu, Johan Swerts, Seongho Park, Christoph Adelmann,* IMEC, Belgium **INVITED**

Cu interconnects face a steep resistance and reliability penalty when line widths approach dimension of 10nm: electron scattering at surfaces and grain boundaries amplifies the resistivity, while diffusion barriers and liners consume an increasing fraction of the available cross–section and are increasingly difficult to scale[1]. In this context, epitaxial conductors offer a fundamentally different route to sustain conductivity at nanoscale dimensions by eliminating large–angle grain boundaries, reducing microstructural variability, and improving pattern–transfer fidelity during direct metal etch. Here, we summarize our recent progress on epitaxial conductors aimed at replacing Cu in advanced BEOL metallization, with a focus on CMOS–compatible epitaxial Ru and metallic delafossite $PtCoO_2$.

For Ru, we demonstrate honeycomb epitaxy on AlN(0001)/Si(111) using standard PVD at a BEOL–relevant thermal budget, scalable to 300–mm wafers[2]. Structural characterization confirms coherent epitaxial alignment and low mosaicity. Electrical transport measurements reveal bulk–like resistivity (7.8µΩcm at 30nm), resulting in a markedly weaker thickness–dependent resistivity increase than polycrystalline Ru and Cu in the ultrathin regime. These findings highlight the advantage of suppressing grain–boundary scattering through epitaxy.

Beyond elemental metals, we show that metallic delafossite $PtCoO_2$ can deliver even lower resistivity at nanoscale thicknesses when epitaxy is stabilized. Using a multilayer PVD approach combined with repeated oxidation anneals, epitaxial $PtCoO_2$ is stabilized down to 4 nm and exhibits an unusual thickness–independent resistivity of 4.8µΩcm over the 8 to17nm range[3]. This behaviour is enabled by solid–phase epitaxial regrowth, film densification, and defect annihilation, underscoring the critical role of interface chemistry and oxygen control in complex oxide conductors.

Looking forward, the integration of epitaxial conductors into realistic interconnect architectures will require scalable strategies compatible with amorphous BEOL dielectrics. Layer–transfer approaches, such as wafer-to-wafer bonding followed by substrate removal, emerge as a universally applicable pathway for epitaxial conductor integration, enabling the decoupling of epitaxial growth from backend processing. Continued progress in epitaxial growth, interface engineering, and transfer integration positions epitaxial Ru and delafossite oxides as strong contenders for future liner–light or linerless interconnect technologies beyond Cu.

[1]J-Ph. Soulié,J. Appl. Phys.136(17)171101(2024).[2]C. Adelmann,2026 ECTC(2026),Orlando(USA).[3]J-Ph. Soulié,2026 IEEE IITC(2026),San Jose (USA)

11:00am **PS+AP-MoM-5 Reactive High Power Impulse Magnetron Sputtering with Positive Cathode Reversal Using a Rotary Magnetron***, **Nicholas Connolly**, Collin Jeckell,* University of Illinois Urbana-Champaign*; Rajib Paul, Brian Jurczyk,* Starfire Industries, LLC*; David Ruzic,* University of Illinois Urbana-Champaign

This work investigates the novel sputtering technology of HiPIMS with positive cathode reversal (Positive Kick™), herein referred to as HiPIMS+CR, on rotary magnetrons for reactive sputtering. As compared to DC, HiPIMS provides the advantage of higher ion fractions at the target[1] and at the substrate[2]. As compared to standard HiPIMS, positive cathode reversal allows for control of the ion energy at the substrate, allowing for tuning of film properties such as stress as well as increased deposition rate overall[3]. In this work, the deposited film is aluminum nitride (AlN), which has applications in resonator devices, piezoelectric devices, and as a thermal spreader for heat management[4]. Many large-area industrial coating processes utilize rotary magnetrons instead of planar magnetrons, as they offer increased target utilization and higher power throughput due to better heat removal. It has been shown with DC that rotary magnetrons offer some benefits and differing deposition physics when compared to planar targets because of the target shape and rotation[5]. This work characterizes HiPIMS+CR applied to a rotary magnetron with target length of 430mm and target outer diameter of 145mm, identifying where the rotary configuration may offer benefit through a research-scale system.

HiPIMS+CR AlN reactive sputtering in the rotary magnetron configuration is characterized by both plasma diagnostics and film characteristics. To characterize the plasma, a Hiden Analytical PSM probe was used to gather time and energy resolved spectra of each ion species at the substrate location versus various plasma parameters. Whether the target was rotating or not rotating affected both the Al^+ and N^+ ion counts without changing the Ar^+ and N_2^+ counts (see Figures 1 and 2), where the N^+/Al^+ ratio increased by over 50% by simply rotating the target and keeping all other process parameters constant. This indicates target rotation does affect the system and adds another variable to adjust film properties such as stoichiometry. Hysteresis curves were generated at various target rotation speeds to understand how the poisoning point was affected by rotation speed in HiPIMS+CR.

AlN film characterization will be presented across varying HiPIMS+CR process recipe parameters, as well as target rotation speed, for the critical characteristics of the applications of AlN. Characteristics measured include film stoichiometry (including oxygen contamination), crystal structure and orientation measured with X-ray diffraction (XRD), and film density measured with X-ray reflectivity (XRR). Thermal conductivity measurements are also made using time-domain thermoreflectance (TDTR).

11:15am **PS+AP-MoM-6 Two-Step Etching for Suppressing Etch-Depth Variation in Tin Etch-Back***, **Yudai Mashiko**, Makoto Satake, Taku Iwase, Naoyuki Kofuji, Yasushi Sonoda,* Hitachi, Ltd., Japan

In the fabrication of advanced semiconductor devices, uniform TiN etch-back—in which TiN is filled into deep trenches—is essential for contact-plug formation. However, seams are unintentionally formed during the filling process. Consequently, the local etching rate increases due to seam widening, resulting in etch-depth variation between the area around the seam and the surrounding region [1].

In our previous study [2, 3], we reported that radical etching was superior to plasma etching because, in the latter, energetic ions accelerated by self-bias voltage exacerbated seam widening. However, even with conventional radical etching, it remains difficult to suppress the direct exposure of radicals to the seam region. Therefore, we propose a two-step etching process that employs a deposition-film formation step prior to etching. In this method, a deposition film is first formed to serve as a mediating layer, after which TiN is etched by radicals while maintaining this film. This approach is designed to prevent the direct exposure of radicals to the seam.

The mechanism underlying seam-widening suppression was investigated using etch-profile simulations. The deposition film on the TiN surface significantly shortens the effective mean free path of the radicals, thereby preventing their direct exposure to the TiN surface. Consequently, the radical flux reaching the seam interior is markedly reduced, shifting the etching process from a reaction-limited to a supply-limited regime. This transition ensures that etching is governed by the arrival rate of radicals rather than their reactivity, which the simulations confirmed effectively suppresses seam widening compared with conventional radical etching.

Based on these findings, the two-step process was experimentally demonstrated. A $SiCl_x$ deposition film was formed using $Cl_2/SiCl_4$-based plasma, followed by TiN etching with Cl_2-based plasma. Cross-sectional observations confirmed that the standard deviation of the etch-depth variation was significantly reduced from 3.8 nm (conventional) to 1.5 nm. These results demonstrate that the proposed two-step etching is an effective approach for achieving uniform TiN etch-back.

[1] G. Vereecke et al., Microelectron Eng. 200 (2018).

[2] Y. Mashiko, et al., DPS 45th international symposium (2024)

[3] T. Iwase, et al., Proc. SPIE PC13429 (2025)

11:30am **PS+AP-MoM-7 Roughness Generation Mechanisms in Ru Etching Using O_2/Cl_2-Based Plasma for Advanced Interconnects***, Miyako Matsui,* *Tomoyasu Shohjoh, Taiga Kasai,* Hitachi Ltd., Japan*; Kiyohiko Sato, Makoto Miura,* Hitachi High-Tech Corporation, Japan*; Kenichi Kuwahara,* Hitachi High-Tech Corporation, Jamaica **INVITED**

Continued device miniaturization necessitates further reduction of metal pitch through advanced patterning technologies such as extreme ultraviolet lithography. As metal pitches shrink, alternative metal interconnects are required to replace Cu in order to achieve tighter pitches in the back end of line. Ru is a candidate for alternative interconnects at metal pitches of 20 nm and below, because Ru interconnects are expected to exhibit lower effective resistance than Cu interconnects at such small dimensions. In addition, Ru can be etched directly, enabling new scaling boosters such as semi–damascene patterning. To realize such patterning technologies, Ru patterns must be etched vertically with high selectivity to hard masks, while roughness and other forms of damage must be suppressed to reduce interconnect resistance.

In this work, we investigated the mechanisms of roughness generation during Ru etching and achieved low–roughness etching of fine Ru patterns using an O_2/Cl_2–based plasma generated by a microwave electron cyclotron resonance etching system. The roughness of Ru line patterns is primarily governed by the transfer of mask pattern roughness, as well as by micromasking effects caused by non–volatile byproducts formed on the sidewalls and by the Ru grain structure.

To analyze the mechanisms of roughness generation in Ru etching, the line edge roughness (LER) of Ru lines and Si_3N_4 masks was evaluated before and after Ru etching using a high–voltage CD–SEM, which simultaneously evaluates Si_3N_4 mask roughness from secondary-electron images and Ru line roughness from backscattered-electron images. Ru etching was performed on 32 nm-pitch Ru patterns with Si_3N_4 mask line widths varied from 23 nm to 10 nm. We found that Ru line roughness is influenced not only by Si_3N_4 mask roughness but also by non–volatile RuO_x and $RuCl_x$ species non–uniformly formed on the Ru sidewalls. In addition, Ru sidewall etching tends to proceed preferentially along grain boundaries. The roughness of Ru sidewalls depends on the balance between ion flux, which generates non–volatile RuO_x and $RuCl_x$ on the sidewalls, and radical flux, which isotropically etches Ru.

To reduce the LER of Ru lines, we proposed adding a passivation gas to the O_2/Cl_2 plasma to form a uniform protective layer on the pattern sidewalls. This uniform protection layer enables stable etching of fine patterns even when the balance between ion flux and radical flux penetrating into the trenches varies to some extent with changes in aspect ratio during Ru etching.

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