Wednesday Morning, July 1, 2026

ALD Applications
Room Ybor Salons I-IV - Session AA1-WeM

ALD for Memory I

Moderators: Han-Bo-Ram Lee, Incheon National University, **Seung Wook Ryu**, SK hynix

8:00am **AA1-WeM-1 Atomic Layer Deposition in Conventional and Emerging DRAM Devices***, **Kyooho Jung**, Jungkyun Kim, Kyung Mee Song, Sunghyun Kim, Donghyun Kim, Sangjun Lee, Jeonggyu Song, Sangwook Kim,* Samsung Advanced Institute of Technology, Republic of Korea **INVITED**

Atomic Layer Deposition (ALD) has become an indispensable technology in the semiconductor industry due to its excellent conformality, step coverage, film quality, and precise thickness control. This presentation introduces ALD process developments and device characterizations conducted at Samsung for both conventional and emerging DRAM technologies.

In conventional DRAM, capacitors represent one of the most critical application areas for ALD. The primary objectives for capacitors include achieving a high dielectric constant, low bulk and interfacial defect densities, excellent step coverage, and reduced mechanical stress-induced failures. These requirements can be addressed through careful optimization of the ALD process and thin-film stack design. This talk will present several approaches we have employed to improve dielectric constant, leakage current characteristics, and mechanical stress in DRAM capacitors.

For emerging DRAM devices, we will introduce our recent work on oxide semiconductor vertical channel transistors (VCTs), 1TnF DRAM, and 1T ferroelectric FETs (3D FEFETs). ALD plays a key role in these technologies owing to its superior thickness uniformity, precise interface and layer control, and compatibility with complex 3D structures. This presentation will discuss both the device performance and material properties of ALD-based films implemented in these emrging DRAM devices.

8:30am **AA1-WeM-3 Sacrificial Atomic Layer Deposition for Nanostructured Chalcogenide Materials***, **Chanyoung Yoo**,* Hongik University, Republic of Korea

Atomic layer deposition (ALD) offers unique advantages for conformal and thickness-controlled growth of functional materials. However, extending ALD to chalcogenide materials remains fundamentally challenging due to severe surface oxidation, limited precursor compatibility, and the tendency toward island growth and phase separation. These issues become more pronounced when targeting low-dimensional, metastable, or superlattice chalcogenide structures required for next-generation memory and neuromorphic devices.

In this presentation, we introduce sacrificial atomic layer deposition (S-ALD) as a general and scalable growth paradigm for nanostructured chalcogenide materials. The key concept of S-ALD is the deliberate incorporation of a sacrificial layer that temporarily mediates metal–chalcogen bonding during ALD cycles and is selectively removed in a subsequent step [1]. This sacrificial process effectively suppresses parasitic oxidation, mitigates ligand incompatibility, and enables controlled chalcogen rearrangement, thereby facilitating the deposition of highly uniform, fully substrate-covering crystalline chalcogenide films with growth behavior approaching layer-by-layer deposition.

By applying S-ALD, we demonstrate several representative chalcogenide systems that are difficult to realize using conventional approaches. These include top-to-bottom local epitaxial growth of two-dimensional Sb_2Te_3 enabled by controlled sacrificial layer removal [1], melt-quenching-free Sb_2Te_3/GeTe superlattice phase-change films with well-defined interfaces [2], and ultrathin monatomic antimony [3] and tellurium films with atomic-level thickness control. Structural and spectroscopic analyses reveal that S-ALD promotes uniform, layer-by-layer growth even at reduced deposition temperatures. The versatility of S-ALD highlights its potential as a unified platform for engineering low-dimensional and three-dimensional chalcogenide architectures. This approach provides new opportunities for conformal integration of phase-change materials, ferroelectric–chalcogenide heterostructures, and emerging nanoelectronic devices, where precise control over phase, thickness, and crystallinity is essential.

[1] C. Yoo et al., *Chem. Mater.*, 35, 17, 7311 (2023)
[2] C. Yoo et al., *Adv. Mater.*, 34, 50, 2207143 (2022)
[3] G. Jeon et al., Adv. Mater., e19924 (2025)

8:45am **AA1-WeM-4 Enhancing Dielectric Properties of ALD Al-Doped HfO_2 Films for Memory Applications: The Role of Homogeneous Aluminum Distribution***, **Son Hoang**, Larry Chen, Charlene Chen, Randall Higuchi, Vijay Narasimhan, Liana Alves,* EMD Electronics*; Zeyuan Ni,* STDC, Tokyo Electron Technology Solutions Ltd, Japan*; Atsushi Kubo,* STDC, Tokyo Electron Technology Solutions Ltd., Japan

The stabilization of non-monoclinic phases including tetragonal and orthorhombic of HfO2 in ultrathin films (<6 nm) is essential for enhancing permittivity and ferroelectricity, which are critical for DRAM capacitors and emerging non-volatile memory technologies such as ferroelectric tunnel junctions (FTJs) and ferroelectric field-effect transistors (FeFETs). Previous studies have shown that incorporating Al dopant can effectively stabilize these non-monoclinic phases [1,2,3]. The ALD investigations typically employed an atomic layer deposition (ALD) supercycle of HfO2 and Al2O3 with varying HfO2/Al2O3 cycle ratios to modulate the Al concentration in the Al-doped HfO2 films. However, a 6 nm Al-doped HfO2 film generally requires only 1 or 2 Al2O3 cycles to achieve the narrow optimal Al concentration window of 3-5 atomic percent, resulting in highly localized Al distribution. This presents a critical gap in understanding the effects of Al dopants in ALD compared to physical vapor deposition (PVD) or theoretical studies, which assume homogeneous Al distribution in HfO2 films [3].

In this work, we demonstrate that achieving a homogeneous distribution of Al in ALD Al-doped HfO2 thin films (<60 Å) is crucial for optimizing performance in advanced memory applications. We employed a Hf-Al-Oxidant (Hf-Al-O) ALD method, wherein the Al precursors selectively adsorb onto unoccupied sites left after hafnium precursor exposure. This selective adsorption leads to a three-fold dilution of Al incorporation into HfO2, resulting in a more uniform Al dopant depth profile while preventing the formation of continuous Al2O3 layers that can hinder crystallization, as often seen in conventional HfO2/Al2O3 supercycle approaches. The Hf-Al-O method produced Al-doped HfO2 films with 100% non-monoclinic phases, compared to only 50% in HfO2/Al2O3 supercycle processes. Furthermore, metal-insulator-metal capacitors fabricated with these films exhibited a dielectric constant increase from 19 to 27, a reduction in leakage current by 1.5 orders of magnitude relative to pure HfO2 films, and excellent ferroelectric properties with 2Pr window of 15–20 $\mu C/cm^2$.

1. *H. Park, J. Jeong, H. W. Kim, E. Hong, N.Kim, S. Jeon, Y. Kim, H. Choi, and J. Woo. Effect of the number and distribution of Al2O3 atomic layer deposition cycles within HfO2 layer on ferroelectric characteristics. Appl. Phys. Lett. 2024 124, 132102*
2. *L. Feng; Y.-Ch. Li ; T. Huang ; H.-L. Lu and D. W. Zhang . Effects of Al doping concentration and top electrode on the ferroelectricity of Al-doped HfO2 thin films. AIP Advances, 2014, 14, 015105*
3. *M. H. Park, T. Schenk, C. M. Fancher, E. D. Grimley,c C. Zhou,d C. Richter, J. M. LeBeau, J. L. Jones, T. Mikolajick and U. Schroeder. A comprehensive study on the structural evolution of HfO2 thin films doped with various dopants. J. Mater. Chem. C, 2017, 5, 4677*

9:00am **AA1-WeM-5 Germanium Doping for Electrical Modulation of Ferroelectric HZO Using Atomic Layer Deposition***, **Jared McWilliams**,* EMD Electronics, USA

Since its first discovery, ferroelectricity in hafnia-based oxides has seen significant improvement using the large-scale, manufacturing-friendly atomic layer deposition (ALD) method, making them the most promising candidate for advancing non-volatile memory technology. Among all compositions, the 1:1 ratio alloy $HfZrO_2$ (HZO) is the most studied compound due to the low thermal budget required to achieve satisfactory electrical performance. However, the high operating voltage of HZO,resulting in high energy dissipation and device early failure, hinders its further technical adoption. Significant efforts have been invested in understanding switching mechanisms and predicting potential dopant candidates to reduce the coercive voltage of HZO.

This work demonstrates, for the first time, the experimental validation of Germanium-doped HZO since the theoretical prediction by Chae *et al.* [1]. Electrical behaviors such as polarization switching, leakage, and voltage-dependent capacitance are taken into account along with physical characterizations to elucidate the mechanisms behind the ferroelectric switching and the reduction in the coercive field of Ge-doped HZO. Different doping strategies to achieve desirable ferroelectric characteristics are also presented, highlighting the importance of dopant concentration and the location of dopant atoms within the device stack. The advantage of using precursors with wide ALD windows is also discussed to emphasize

further the role of precursor choices in maintaining a low thermal budget for the fabrication process of doped HZO.

9:15am **AA1-WeM-6 ALD 2026 Young Investigator Award Finalist: Design of Interface Formation Process for Superior Ferroelectricity and Enhanced Fatigue Resistance in $Hf_xZr_{1-x}O_2$-Based Ferroelectric Devices**,
***Takashi Onaya**, Toshihide Nabatame, Takahiro Nagata, Kazuhito Tsukagoshi,* National Institute for Materials Science, Japan

Ferroelectric $Hf_xZr_{1-x}O_2$ (HZO) has been extensively studied due to the maturity of its atomic layer deposition (ALD) process and its low thermal budget below 400°C. However, fatigue, which is degradation of switching polarization (P_{sw}) during field cycling, remains a critical issue for practical applications. We previously reported that the primary origin of fatigue is the electric-field-induced interface reaction between the HZO film and the TiN electrode, which leads to the formation of additional oxygen vacancies in the HZO film [1]. To suppress this interface reaction, we focused on interface formation processes of inserting an oxygen blocking interfacial layer (IL) at the HZO/TiN interface. In this work, we investigated the ferroelectricity and fatigue properties of HZO films by inserting ILs.

First, the TiN/HZO/TiN capacitor with the surface-oxidized TiN bottom-electrode (w/ Oxid.-BE-TiN) was fabricated by O_2 plasma treatment of the BE-TiN surface in the ALD chamber, following by continuous deposition of the ALD-HZO film without vacuum break. The oxygen-rich TiO_xN_y-IL was formed for the w/ Oxid.-BE-TiN capacitor at the HZO/BE-TiN interface evaluated by XPS analysis. For the endurance properties, no significant difference in P_{sw} in the pristine state was observed between the capacitors without (w/o) and w/ Oxid.-BE-TiN due to almost the same crystal structure of both HZO films evaluated by XRD patterns. In the fatigue state, on the other hand, the P_{sw} degradation of the w/ Oxid.-BE-TiN capacitor was suppressed by ~14% compared to that of the w/o capacitor. This could be because the oxygen-rich TiO_xN_y-IL plays a critical role as an oxygen blocking IL, which suppresses the interface reaction at the HZO/BE-TiN interface.

Next, ALD-ZrO_2 nucleation layers (NLs), which promote the ferroelectric orthorhombic (O) phase formation in HZO films [2], were employed as oxygen blocking ILs. The HZO film for TiN/ZrO_2/HZO/ZrO_2/TiN (w/ ZrO_2-NL) capacitor formed more O phase compared to the TiN/HZO/TiN (w/o) capacitor, resulted in 2.3 times higher P_{sw} in the pristine state. For the fatigue state, furthermore, the w/ ZrO_2-NL capacitor exhibited less P_{sw}degradation (~33%) compared to the w/o capacitor (~52%). Therefore, it was found that the ALD-ZrO_2-NLs are effective not only in enhancing P_{sw} but also in suppressing fatigue by acting as an oxygen-blocking IL.

These experimental results indicate that careful design of the HZO/electrode interface is crucial for achieving high P_{sw} and high fatigue resistance simultaneously in HZO-based ferroelectric devices.

[1] T. Onaya et al., Solid-State Electron. 210, 108801 (2023).

[2] T. Onaya et al., APL Mater. 7, 061107 (2019).

9:30am **AA1-WeM-7 Low-Temperature ALD HfO_2 for Magneto-Ionic Applications**,
Alessandro Cataldo, Politecnico di Milano, Italy*; Sabina Spiga,* Consiglio Nazionale delle Ricerche (CNR-IMM), Italy*; Himadry Nandan Mohanty, Alan Durnez,* Centre de Nanosciences et de Nanotechnologies (C2N), France*; Andrea Li Bassi,* Politecnico di Milano, Italy*; Seyed Ariana Mirshokraee,* Consiglio Nazionale delle Ricerche (CNR-IMM), Iran (Islamic Republic of)*; Liza Herrera Diez,* Centre de Nanosciences et de Nanotechnologies (C2N), France*; **Alessio Lamperti**,* Consiglio Nazionale delle Ricerche (CNR-IMM), Italy

Voltage-controlled magneto-ionic devices rely on oxide-based functional layers capable of enabling low-power operation, reversible mechanisms, cyclability, and stable interfacial coupling with ferromagnetic (FM) materials. In this framework, hafnium dioxide (HfO_2) has emerged as a key enabling material to control the channel gating in metaplastic spintronic synapses and to sustain the electric field for the ion migration [1-2]. Among the deposition techniques, atomic layer deposition (ALD) offers precise thickness control, conformality, and atomic-level tunability, making it a privileged approach for synthesizing HfO_2 films [3]. However, the integration of oxides with FM materials for such applications requires low-temperature (low-T) processing to avoid interfacial and magnetic properties degradation [4-5]. Moreover, the functionality of these devices is linked with the content and mobility of ions which migrate towards the ferromagnet via gating applications. Therefore, a controlled defectivity through an engineered ALD growth is fundamental. In this work, we investigate the growth of HfO_2 via ALD using TEMAHf and H_2O over a temperature range from 200 °C to 80 °C, focusing on engineering the H_2O semi-cycle to tailor the defectivity, and on the correlation between growth process and physical, chemical and electric properties.

A progressive reduction of the deposition temperature leads to a marked increase in the growth-per-cycle (GPC) from 0.82 Å/cy at 200 °C to 1.34 Å/cy at 80 °C. XPS measurements confirm a consistent Hf^{4+} chemical state, while the O/Hf atomic ratio evolves from 1.98 at 200°C to a minimum of 1.8 at 80°C. Furthermore, OH- content is seen to increase significantly for growth temperatures below 100°C. ToF-SIMS profiling confirms an increment of OH- species and highlights an almost constant concentration of carbon-related contaminants, indicating a selective incorporation of functional OH- groups. C-V measurements on MIM devices report a dielectric constant $k \approx 17 \pm 1$ independently on the growth temperature of the integrated HfO_2, proving the high quality despite the thermal budget reduction. However, breakdown voltage analysis shows that a reduced growth temperature deeply affects the sub-conductive behaviour of the grown oxide as well as the dielectric breakdown, showing a E_{BD} shift from 3 MV/cm to 4.5 MV/cm for V^+.

The results demonstrate that engineered low-T ALD HfO_2 can achieve the combination of high dielectric performance, controlled ionic content, and interface compatibility required for magneto-ionic devices such as spintronic synapses for advanced computing architectures.

References

1. B.E. Mokhtari et al., Appl. Phys. Lett., 2025
2. R. Pachat et al., Adv. Mat. Interfaces, 2022
3. E. Kessels et al., Nature Reviews Methods Primers, 2025
4. U. Bauer et al., Nature Materials, 2015
5. M. Nichterwitz et al., APL Materials, 2021

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9:45am **AA1-WeM-8 High-mobility Atomically Ordered IGZO Transistors Deposited by Thermal Atomic-Layer-Deposition**,
***Min-Seo Kim**, Seong-Hwan Ryu,* Hanyang University, Korea*; Yoon-Seo Kim,* IMEC, Belgium, Republic of Korea*; Jin-Seong Park,* Hanyang University, Korea

As silicon-based devices approach fundamental scaling and integration limits, oxide semiconductors have attracted increasing attention as channel materials for next-generation memory and logic technologies requiring three-dimensional architectures and back-end-of-line (BEOL) compatibility. In advanced DRAM systems, high-mobility channels are essential to secure sufficient driving current and sensing margin, while in logic and monolithic three-dimensional (M3D) integration, minimizing the mobility mismatch between silicon and oxide transistors is critical to suppress bandwidth bottlenecks during inter-tier communication. Although amorphous InGaZnO (IGZO) offers excellent processability and uniformity, its carrier transport is inherently limited by disordered bonding networks, motivating structural strategies to overcome the mobility ceiling of amorphous oxides. Atomic layer deposition (ALD) provides a powerful platform for such structural engineering owing to its angstrom-level thickness control and precise regulation of interfacial reactions. In oxide nanolaminate systems, confining carrier transport within In_2O_3-dominant layers and inducing two-dimensional electron gas (2DEG)-like conduction at oxide–oxide interfaces has been proposed as an effective route toward mobility enhancement. However, realizing electronically active interfaces in amorphous systems critically requires atomically controlled layer stacking and chemically complete reactions during growth.

In this study, we demonstrate thermal atomic-layer-deposited atomically ordered IGZO (AO-IGZO) thin films exhibiting ultra-high mobility through 2DEG-like interfacial conduction. By systematically varying the deposition temperature, we identify 250 ℃ as an optimal growth condition where impurity suppression and interfacial ordering are simultaneously achieved. X-ray reflectivity and diffraction analyses reveal the formation of an amorphous yet atomically ordered superlattice-like structure composed of periodically modulated In_2O_3-rich conducting layers and GaZnO barrier layers. Such ordering is absent at lower temperatures due to incomplete precursor reactions and is degraded at higher temperatures where nanolaminate periodicity is disrupted. Top-gate thin-film transistors incorporating the 250 ℃ AO-IGZO channels exhibit a field-effect mobility of approximately 113 cm^2/Vs, far exceeding that of conventional amorphous IGZO devices. This enhanced transport is attributed to carrier confinement at the In_2O_3/GZO interface, which promotes 2DEG-like conduction and effectively circumvents bulk amorphous scattering. These results establish thermal ALD as a viable route for realizing atomically ordered amorphous oxide semiconductors with exceptional mobility, offering a scalable pathway

toward high-performance oxide transistors for advanced semiconductor integration.

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