ALD Applications
Room Ybor Salons I-IV - Session AA-MoA

Quantum ALD Applications

Moderators: Robert Clark, TEL Technology Center, America, LLC, **Arpita Saha**, Oxford Instruments

4:00pm **AA-MoA-11 Two Level Systems Mitigation by Atomic Layer Deposition for Quantum Application***, **Thomas Proslier**, Yasmine Kalboussi, Théo Dejob, Fabien Eozenou, Gregoire Jullien,* CEA Saclay, France*; sandrine Tusseau-nenez,* Ecole Polytechnique - CNRS, France*; Nathalie Brun, Michael Walls,* Université Paris-Saclay, France*; frédéric miserque, Maurice Luc,* CEA Saclay, France **INVITED**

Superconducting quantum bits (qubits) are regarded as one of the key technological building blocks for future quantum computers and sensors. One of the primary obstacles to extending qubit performance and in particular their coherence times is the presence of photon-absorbing defects, commonly modeled as two-level systems (TLS). Microscopic sources of TLS—such as oxygen vacancies, hydroxyl groups, and amorphized structures—have been identified in dielectric surfaces, interfaces, and Josephson junctions. Thanks to its atomic-scale control of composition and thickness, atomic layer deposition (ALD) offers a powerful approach to address this challenge and mitigate some of these defects mechanisms. ALD is also fully compatible with standard microelectronic fabrication processes and can be readily integrated into the production of two-dimensional superconducting films.

Niobium (Nb) superconducting cavities, widely used in particle accelerators, provide a simpler type of resonator compared to qubits, with the advantage of involving only a single interface—Nb and vacuum. This makes them ideal platforms for investigating how the structure, chemical composition, and thickness of various oxide capping layers affect resonator performance and TLS properties.

I will present performance measurements from Nb superconducting resonators coated via ALD with amorphous as well as crystalline films with thicknesses between 2 and 10 nm. Following thermal treatments, these coatings were found to enhance quality factors and coherence times relative to bare niobium with its native oxide. TLS-model fits of RF measurements, combined with surface characterization techniques such as XPS and TEM, enable the extraction of TLS properties—including dielectric losses and defect concentrations—in the various capping layers.

These findings offer valuable insight for future technological developments of superconducting resonators operating in the quantum regime, including qubit architectures.

4:30pm **AA-MoA-13 Atomic Layer Deposition Based Dopant Engineering of Er-Doped CeO$_2$ Thin Films for Scalable Quantum Materials***, **Terrick McNealy-James,*** University of Central Florida*; Emily Miura-Stempel, Ratul Mangalr,* University of Washington*; Justin Moore, Diego Javier-Jimenez, Titel Jurca,* University of Central Florida*; Brandi Cossairt,* University of Washington*; Parag Banerjee,* University of Central Florida

Quantum information technology has the potential to transform sensing, communication, and computing by exploiting intrinsic spin-photon interfaces of rare-earth-ions (REIs). These spin-photon interfaces stem from the shielded 4f-shell electrons of REI's, which give rise to long-lived electron spin states and long coherence times. When combined with the compatibility of solid-state dielectric host materials with established silicon-based integration and fabrication technologies, REI's can become a promising pathway towards developing scalable solid-state quantum platforms.

Among the candidates for host materials, cerium oxide (CeO$_2$) is an attractive option with its crystalline morphology, wide band gap (3.19 eV) and low concentration of nuclear spins, all of which contribute to reduced magnetic noise and a theoretically predicted coherence times of up to 47 ms. Building on these characteristics, erbium-doped cerium oxide (Er:CeO$_2$) has become a compelling solid-state material for spin-based quantum information processing. Studies of Er:CeO$_2$ nanoparticles have demonstrated long electron spin coherence times in the microsecond range. However, the morphology and particulate nature of nanoparticles present a significant challenge for large scale integration into solid-state device architectures.

In this work, we address these challenges by developing Er:CeO$_2$ thin films via atomic layer deposition (ALD), a gas phase, wafer scale technique capable of angstrom-level thickness control, conformal coating, and precise dopant incorporation. Two distinct ALD based doping strategies are investigated and compared. The first approach uses a super cycle method, in which Er$_2$O$_3$ cycles are periodically inserted into CeO$_2$ growth sequence to control dopant concentration through cycle ratio adaptations. The second, less-explored approach utilizes co-dosing of erbium and cerium precursors in the same ALD cycle with the goal of achieving a more spatially dispersed dopant distribution.

To establish an understanding of each doping strategy dual and tandem techniques of *in situ* quadrupole mass spectrometry (QMS) and spectroscopic ellipsometry (SE) are used to monitor film growth behavior and gas-phase reaction chemistry during deposition. *Ex situ* techniques including x-ray photoelectron spectroscopy (XPS), x-ray diffraction (XRD), and Raman spectroscopy are used to correlate dopant incorporation pathways with structure-property relationships. Additionally, pump-probe spectroscopic techniques will measure the lifetimes of the spin polarized electrons in Er:CeO$_2$ and benchmark their performance to state-of-art, spin-photon systems.

4:45pm **AA-MoA-14 Superconducting Nitrides by Fast Remote Plasma ALD for Quantum Applications***, **Harm Knoops**, Arpita Saha, Dmytro Besprozvannyy, Nick Chittock,* Oxford Instruments Plasma Technology, UK*; Silke Peeters, W.M.M. (Erwin) Kessels,* Eindhoven University of Technology, Netherlands*; Ciaran Lennon,* Oxford Instruments Plasma Technology, UK*; Nidhi Choudhary, Robert Hadfield,* University of Glasgow, UK*; Iliya Shiravand, Davood Shahrjerdi,* New York University*; Christos Zachariadis, Alessandro Bruno,* QuantWare B.V., Netherlands

Superconducting films ranging from a few to hundreds of nanometers are at the basis of a wide range of quantum devices and are therefore key in advancing quantum technology to an era of widespread utility. The further development of quantum technologies hinges on improvements in materials and their interfaces using scalable processing. With its atomic-scale growth control and wafer-scale uniformity, plasma-enhanced ALD (PEALD) could become an enabling technique for the growth of superconducting thin films with high-quality interfaces. High-throughput processes would facilitate the growth of films beyond the few tens of nanometers, broadening the application perspective for ALD of superconducting films.

We demonstrate PEALD including substrate biasing for a variety of superconducting nitride films ranging from 5 to 100 nm thickness, with a high throughput of up to > 50 nm/houron the PlasmaPro ASP system. The nitrides TiN, NbN, NbTiN, and TaCN are deposited and investigated through a range of collaborations with the intent to show their utility for quantum device applications.

Extensive material analysis shows how NbN, TiN, and NbTiN have useful film properties and remain superconducting down to low thicknesses.[1,2] Substrate biasing during PEALD enables tuning of the materials properties either by reducing contaminants in the film and improving crystallinity to achieve low resistivities, or by increasing disorder for applications such as microwave kinetic inductance detectors. For Nb and Ta compounds the presence of carbon is interesting in that it can be present in the form of superconducting carbonitrides (shown for Nb and Ta compounds).[2,3] Furthermore, these carbonitride films were found to support high internal quality factors exceeding 10^5 at 50 mK in the single-photon regime.[3]

The wide parameter space enabled by PEALD was also found to allow for high-quality planar TiN films. As an example, two samples achieved a T_c of 4.583 ± 0.005 K and 4.700 ± 0.005 K respectively with a narrow transition width of 0.007 ± 0.003 K indicating high material quality with minimal contamination. Further collaboration with partners is ongoing to showcase the utility of these films in 3D structures as through-silicon vias. Here several mA of critical current was found per via in preliminary work. These and other results indicate the promise of superconducting nitrides by fast remote plasma ALD for quantum applications.

1. Peeters et al., *AVS Quantum Sci.* **7**, 026801 (2025)
2. Choudhary et al., *APL Mater.* **13**, 111104 (2025)
3. Shiravand et al., *Appl. Phys. Lett.* **127**, 192603 (2025)

5:00pm **AA-MoA-15 Wafer-Scale Thermal ALD of Superconducting TiN: A Scalable Process with Room-Temperature Predictive Mapping***, **Sanaz Zarabi**, John Rönn, Otto Laitinen,* Beneq Oy, Finland

Superconducting thin films are at the heart of next-generation technologies, from quantum computing to ultra-sensitive detectors, but their integration into scalable microfabrication remains a bottleneck. Titanium nitride (TiN), with its tunable superconducting properties and compatibility with CMOS processes, stands out as a key material candidate (1-2). In this work, we report a fully thermal ALD process for TiN deposition on 200 mm wafers using $TiCl_4$ and NH_3 at **480 °C** with **TFS200** reactor, achieving homogeneous films with a superconducting critical temperature (Tc) of **3.65 K** with an average thickness of **45.23 nm,** shown in Figure 1. Importantly, the process is directly scalable to a batch process without degradation in superconducting performance, maintaining a thickness non-uniformity (σ/avg) of **4.34 %**.

To tackle the longstanding limitation of cryogenic, localized T_c measurements, we introduce a non-destructive room-temperature metrology strategy for the first time that correlates **refractive index and extinction coefficient** (measured via **spectroscopic ellipsometry**) with superconducting behavior. This enables rapid, full-wafer assessment of superconductivity without using cryogenic equipment, providing a powerful tool for both process monitoring and device screening. Using this method, we quantify superconductivity non-uniformity (σ/avg) across a 200 mm wafer with 5 mm edge exclusion to be **1.87%** for single-wafer deposition and **1.21%** in batch processing, validating the approach as a powerful tool for scaling superconducting materials into manufacturable device platforms.

Furthermore, we present comprehensive structural and compositional characterization using **TEM**, **XRD**, and **ToF-ERDA** to probe grain structure, crystallinity, stoichiometry, and impurity content. These insights directly link film quality to superconducting behavior, deepening our understanding of how to optimize ALD-grown TiN for quantum and cryogenic applications.

Together, these results establish a scalable, high-performance route to superconducting TiN, backed by both advanced characterization and a practical, predictive metrology framework tailored for real-world manufacturing.

References:

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2. Grigoras, Kestutis, N. Yurttagül, J-P. Kaikkonen, Elsa T. Mannila, Patrik Eskelinen, D. P. Lozano, H-X. Li et al. "Qubit-compatible substrates with superconducting through-silicon vias." *IEEE Transactions on Quantum Engineering* 3 (2022).

5:15pm **AA-MoA-16 ALD Outstanding Presentation Award Finalist: Growth of Superconducting Trilayer NbN/AlN/NbN Structures for Photonics and Quantum Computing Applications***, **Ciaran Lennon,*** Oxford Instruments Plasma Technology, UK*; Nidhi Choudhary,* University of Glasgow, UK*; Dmytro Besprozvanny,* Oxford Instruments Plasma Technology, UK*; Valentino Seferai,* University of Glasgow, UK*; Arpita Saha,* Oxford Instruments Plasma Technology, UK*; Harm Knoops,* Oxford Instruments Plasma Technology, Netherlands*; Harriet van der Vliet,* Oxford Instruments Plasma Technology, UK*; Robert Hadfield, Martin Weides,* University of Glasgow, UK

Superconducting materials are the building blocks for many nascent quantum technologies that underpin the quantum revolution of the 21st century. Reliable and reproducible growth of superconducting materials, particularly thin films, is paramount for the ongoing progress of the field [1,2]. Plasma-enhanced atomic layer deposition (PEALD) has recently been demonstrated as a promising candidate for superconducting thin film growth, offering superior uniformity, conformality and thickness control to conventional physical vapor deposition techniques, such as sputtering, while exhibiting superior film quality (T_c and J_c) and more compositional variety than thermal ALD [3]. Critically, the role of RF substrate biasing in PEALD of superconducting thin films, allowing for greater ion energy control, has also been shown to improve the superconducting properties and provide more tunability for specific device applications [4,5].

Owing to the sub-nm thickness control and compositional diversity of PEALD, allowing for growth of relatively complex heterostructures, we have identified it as the ideal technique for the growth of superconducting multilayer structures for both superconducting nanowire single-photon detectors (SNSPDs) and Josephson junctions (JJs) [6]. Our work presents a study of the growth of NbN/AlN/NbN trilayer structures using PEALD with RF substrate biasing, with 5 nm NbN layers (SNSPDs) and 30 nm NbN layers (JJs), detailing their structure, morphology, composition and superconducting properties. We report $T_c > 6$ K for 5 nm NbN layers and $T_c >$ 12 K for 30 nm layers. We then present the fabrication of both multilayer SNSPD and JJ structures using electron beam lithography and reactive ion etching. For the multilayer SNSPDs, we present device characterization from 1.5 µm up to 4 µm wavelengths, examining the device performance in the mid-IR. For the JJ structures we present preliminary results detailing the electrical properties, including the critical current density (J_c), of devices tested at millikelvin temperatures.

Overall, this work presents significant progress in the development of a PEALD toolbox for the growth of high-quality superconducting multilayer structures for the development of a variety of superconducting quantum device modalities.

[1] Morozov D. V., et al., Contemp Phys **62** 69–91

[2]de Leon N. P., et al., Science **372** 253

[3]Peeters S. A., et al., Appl Phys Lett **123** 132603

[4]Lennon C. T., et al., Materials for Quantum Technology **3** 045401

[5] Wang D., et al., Nature Materials https://doi.org/10.1038/s41563-025-02448-

[6]Alam S., et al., Coatings **13** 278

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

ALD Interconnect Applications

Moderators: Scott Clendenning, Intel Corporation, **Jin-Seong Park**, Hanyang University

8:00am **AA1-TuM-1 Molybdenum Deposition Chemistry for Advanced Interconnects*, Kyle Blakeney,*** Lam Research Corporation **INVITED**

Molybdenum (Mo) stands out among advanced interconnect materials due to its intrinsically low resistivity, strong adhesion, and ability to be integrated without liners or diffusion barriers—features that maximize conductive cross–section as device dimensions continue to shrink. In contrast to tungsten, Mo offers superior resistivity scaling, improved adhesion behavior, and broad compatibility with advanced device architectures. Despite this promise, there are few published Mo ALD reports as most research laboratories cannot readily handle the unique process chemistry and reactor conditions.

The ALD/CVD Metals Product Group at Lam Research has developed Mo deposition technologies targeting interconnect scaling across NAND Flash, DRAM, and logic applications. This presentation will first outline the research strategies that enabled these advances, from modular coupon reactors for rapid pathfinding, to decades of leadership in tungsten ALD.

The second part of the talk will examine Mo precursor surface chemistry, comparing halide–based and metalorganic (MO) approaches. Although metalorganic precursors are commonly used for depositing non–conductor films—including SiO_2, SiN, TiN, and Al_2O_3—they have not matched the performance of chloride–based precursors for depositing high–purity metallic Mo. But the low vapor pressure solid Mo chloride precursors place demands on hardware design to exploit the complex surface chemistry for both conformal and selective deposition, creating new opportunities for barrier–less and bottom–up Mo integration in advanced interconnects.

8:30am **AA1-TuM-3 Thermal Atomic Layer Deposition of Transition Metal Phosphide Thin Films for Interconnects***, John D. Hues, **Nolan Olaso**, Wesley Jen,* Micron School of Materials Science and Engineering, Boise State University*; Mehedi Hasan Prince, Sadiq Shahriyar Nishat,* Department of Materials Science and Engineering, Rensselaer Polytechnic Institute*; Steven M. Hues,* Micron School of Materials Science and Engineering, Boise State University, Boise*; Daniel Gall,* Department of Materials Science and Engineering, Rensselaer Polytechnic Institute*; Elton Graugnard,* Micron School of Materials Science and Engineering, Boise State University, Boise

The aggressive scaling of semiconductor technology nodes has pushed copper interconnects to their limit, as the technology approaches its minimum viable dimensions. Further scaling results in unacceptable levels of interconnect resistance due to interface and grain boundary scattering, which degrades device performance and power consumption metrics. The proliferation of generative artificial intelligence and cloud computing threatens to strain this relationship further as demand for high-performance logic and memory devices rises sharply. To better meet this demand, alternative interconnect materials must be investigated. One family of materials being explored is topological metals, which are predicted to have favorable resistivity scaling largely due to their topologically protected surface states, which suppress electron scattering in nanoscale films. We report on novel thermal atomic layer deposition (ALD) chemistries for various phosphide-based topological metals, specifically molybdenum phosphide (MoP) and niobium phosphide (NbP) using molybdenum(V) chloride (MoCl5), niobium(V) chloride (NbCl5) and tris(dimethylamino)phosphine (TDMAP) between at 325 to 400 °C. The resulting films were characterized using ex-situ X-ray photoelectron spectroscopy (XPS), atomic force microscopy (AFM), scanning electron microscopy (SEM), and four-point probe measurements. Film composition was confirmed through XPS chemical state analysis to be near-stoichiometric (1:1). Four-point probe measurements of the as-deposited films indicated non-ideal electrical performance, which was subsequently improved through post-deposition annealing. While additional work is required to further improve the electrical performance of these materials, these new ALD chemistries may provide a scalable, BEOL-compatible method for the deposition of next-generation interconnect materials.

8:45am **AA1-TuM-4 Low Resistivity Metallic Films by Thermal Atomic Layer Deposition Enabling Next Generation Interconnects*, Sara Harris,*** Forge Nano*; Thomas P. Moffat,* NIST*; Matthew S. Weimer, Dane Lindblad,* Forge Nano*; Daniel Josell,* NIST*; Arreliane Dameron,* Forge Nano

Device miniaturization continues to push technological boundaries, requiring constant evolution in transistor material systems, architecture, and manufacturing processes. To fully actualize bleeding edge (two to three nanometer) transistor capabilities, integrated circuit (IC) manufacturing must keep pace. Back end of line (BOEL) fabrication poses several challenges to chip scaling: most notoriously the copper bottleneck in which thick barrier layers and resistance capacitance (RC) delays limit functional interconnect pitch to 21 nanometers [1]. To overcome this critical barrier, low resistivity, conformal metal films have been studied for hybrid metallization; decreasing interconnect resistance and reducing barrier layer thicknesses. As interconnect pitch decreases traditional PVD copper barrier/seed layers are limited by line of sight and experience pinch off and void formation [2]. Expanding on the ruthenium (Ru) ALD copper seed layers presented last year, this work explores the use of low resistivity thermal ALD iridium (Ir) to enable next generation interconnects. Thermal ALD Ir and Ru deposited at 250 °C both demonstrate conformal deposition on 10:1 aspect ratio through glass vias (TGVs) and show void free copper fill using a cyclic pulsed electrochemical deposition (ECD) process. As expected, the primary difference between the Ir and Ru is electrical resistivity. Seed film resistivity as deposited on TGVs was measured using four-point probe; 10 nm of Ru measured 41 $\mu\Omega \cdot cm$ and 10 nm of Ir measured 16 $\mu\Omega \cdot cm$. Successful copper ECD was demonstrated with 10 nm of Ir (resistivity 16 $\mu\Omega \cdot cm$) and 20 nm of Ru (resistivity 22 $\mu\Omega \cdot cm$). The full layer stack for these films and conformal TGV Cu fill is shown in *Figure 1*. Reduction in required layer thickness combined with improved electrical properties and demonstrated conformality could serve as crucial steps forward for advanced interconnects and BEOL architecture. Additionally, this work compares Ir film quality as deposited at 250 °C and 300 °C. Ir deposited at 300 °C exhibits improved environmental stability when compared to 250 °C Ir as measured with 4-point probe after aging in atmosphere over several months. 300 °C Ir also shows a shortened nucleation delay, and optical constants (n and k) more closely aligned to bulk Ir values, as measured with spectroscopic ellipsometry. Ir film characterization for both temperatures including XPS, XRR, XRD and AFM is ongoing, and will be presented.

9:00am **AA1-TuM-5 Investigating TaN-Doped Ru Film Using ALD and Pulsed CVD Process for Enhanced BEOL Interconnects Performance in Logic Device*, Juhyeon Lee,*** *Hyun Cho, Jungmin Lee, Wonhyuk Hong, Hyeonseok Do, Jongkwan Lee, Jihwan Lee, Yoonsuk Kim, Eunji Jung,* Samsung Electronics Co., Republic of Korea

As BEOL interconnect dimensions continue to scale, aggressive reduction of barrier and liner thickness is critical for enabling Cu fill scalability. Conventional TaN-based schemes require an additional liner layer with a minimum thickness to ensure stable Cu reflow, which fundamentally limits total barrier thickness scaling and motivates the development of alternative, highly scalable barrier materials.

In this work, a Ru-rich TaN-doped diffusion barrier was designed and optimized through simulation, with a particular focus on the Ru/Ta composition ratio. Three key parameters were systematically investigated as a function of Ru content: (1) relative energy mapping of Cu diffusion pathways, (2) stability of residual Cu atoms within the barrier structure, and (3) formation-energy differences between crystalline and amorphous phases. Based on these analyses, an optimized Ru/Ta ratio predicted to form an amorphous and continuous TaN-doped Ru barrier film was identified.

To validate these findings, the optimized composition was deposited using a hybrid process combining atomic layer deposition (ALD) and pulsed chemical vapor deposition (CVD). To overcome the nucleation challenges and island growth typically associated with CVD-type Ru precursors, a pulsed injection scheme was employed to promote high-density nucleation and ensure superior film continuity at the ultrathin regime. The film composition and sub-20 Å thickness were confirmed by XPS and XRF, respectively, enabling precise evaluation of composition-dependent properties.

Reliability evaluations demonstrated that the TaN-doped Ru films provide a robust diffusion barrier. The films exhibited significantly enhanced time-dependent dielectric breakdown (TDDB) characteristics and electromigration (EM) lifetimes exceeding 10 years. These results demonstrate that the TaN-doped Ru diffusion barrier deposited by ALD and pulse CVD provides an effective and scalable solution for ultrathin BEOL interconnects, making it a promising candidate for advanced logic technology nodes.

9:15am **AA1-TuM-6 Low-Resistivity Ruthenium Thin Films with Enhanced Surface Morphology via High-Temperature 6-Step Atomic Layer Deposition for Advanced Interconnect Applications***, **Dahyeon Park**, Jeongha Kim, Soohyun Kim,* Ulsan National Institute of Science and Technology (UNIST), Republic of Korea

As semiconductor devices continue to scale, the increase in interconnect resistance has emerged as a major bottleneck limiting device performance. Ruthenium (Ru) is attracting attention as a promising candidate to replace conventional copper (Cu) and tungsten (W) interconnects due to its low bulk resistivity and superior resistance to electromigration. Meanwhile, the electrical properties of Ru thin films are reported to depend heavily on microstructural factors such as crystallinity and impurity distribution, and relatively high deposition temperatures are known to be advantageous for improving these properties. However, high-temperature atomic layer deposition (ALD) requires both thermal stability of the precursor and precise control of surface reactions, which has acted as a significant technical constraint in conventional Ru ALD processes.

The recently reported Ru precursor, [Ru(trimethylenemethane (TMM))(*p*-cymene)], exhibits excellent thermal stability up to approximately 400 °C, offering the advantage of applicability in high-temperature processes. However, when the process temperature increases beyond a certain level, the resistivity of the thin film actually increases due to enhanced electron scattering caused by increased surface roughness. This suggests the need for a process design capable of effectively controlling surface morphology while maintaining the benefits of high-temperature processing.

In this study, we propose a high-quality Ru thin film deposition process via a 6-step ALD utilizing a [Ru(TMM))(*p*-cymene)] precursor and a sequential H_2–O_2 injection strategy. The Ru thin films deposited using the optimized 6-step process exhibited a resistivity of 15.5 μΩ·cm at a thickness of approximately 20 nm, a significant improvement compared to the 18.2 μΩ·cm of the conventional 4-step process. This reduction in resistivity is attributed to the mitigation of electron scattering resulting from the improvement in surface roughness.

Furthermore, the optimized process achieved 100% step coverage with uniform thickness distribution even in nanoscale trench patterns. These results demonstrate the potential of the 6-step ALD process to mitigate the limitations posed by next-generation interconnect scaling while maintaining low resistivity characteristics.

References

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Acknowledgements

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9:30am **AA1-TuM-7 Atomic Layer Modulation for Compositionally Controlled Ruzno Films as Diffusion Barriers for Cu Interconnects***, **Yeseul Son**,* Ulsan National Institute of Science and Technology, UNIST, Republic of Korea*; Soo-Hyun Kim,* Ulsan National Instititute of Science and Technology, UNIST, Republic of Korea*; Jeongha Kim, Minwoo Kim, Sang Bok Kim,* Ulsan National Institute of Science and Technology, UNIST, Republic of Korea

Atomic layer modulation (ALM) was employed as an ALD-based process strategy to enable compound thin-film formation with precise compositional control. In ALM, multiple metal precursors are sequentially introduced within a single ALD cycle, followed by a common reactant step, allowing atomic-scale mixing of multi-component systems while retaining the precise thickness control, excellent uniformity, and cycle-to-cycle reproducibility characteristic of ALD processes. Based on this capability, RuZnO thin films were synthesized and investigated as diffusion barrier layers for Cu interconnects. RuZnO was selected to combine the favorable properties of Ru, such as thermal stability and a short electron mean free path, with the ability of ZnO to enhance adhesion at dielectric interfaces through zinc silicate formation, thereby integrating diffusion suppression and interfacial stability within a single layer. RuZnO films were deposited using tricarbonyl(trimethylenemethane)ruthenium [Ru(TMM)$(CO)_3$] and diethylzinc (DEZ) as precursors, and O_2 as a reactant. The Ru–Zn–O composition was systematically varied by controlling the ALM process's various parameters. The structural properties, thickness uniformity, and compositional distribution of the ALM-grown films were analyzed using XRD, XRR, RBS, and TEM. The results confirm the formation of homogeneous RuZnO layers over a range of compositions, indicating effective atomic-scale mixing achieved within the ALM cycle. Based on these results, compositionally controlled RuZnO films grown by ALM are discussed as diffusion barrier layers for Cu interconnects, and the detailed results will be presented at the conference.

9:45am **AA1-TuM-8 A 2-step Platinum Atomic Layer Deposition Process for Suppressing Interfacial Oxidation in Advanced Interconnect Applications***, **Jeongha Kim**, Yeseul Son, Soo-Hyun Kim,* Ulsan National Institute of Science and Technology, Republic of Korea

The continuous scaling of copper (Cu) interconnects has resulted in a sharp increase in resistivity due to enhanced surface and grainboundary scattering, highlighting the need for alternative metals for next-generation interconnects [1]. According to the Fuchs–Sondheimer (FS) and Mayadas–Shatzkes (MS) model, larger grain sizes reduce grainboundary scattering, thereby enabling lower resistivity [2]. Among various candidate metals, platinum (Pt)offers an advantage over othernoble metals such as ruthenium (Ru) in that its lower melting temperature allows the formation of larger grains at the same atomic layer deposition (ALD) process temperature [3]. However, while O_2-based metal ALD processes can achieve low resistivity films, they can induce interfacial oxidation of the underlying layers. In contrast, H_2-based metal ALD effectively suppresses interfacial oxidation but typically results in relatively high resistivity [4].

To overcome this trade-off, we propose a 2-step Pt ALD process consisting of an H_2-based nucleation step followed by an O_2-based Pt deposition step. Experimental results show that the H_2 process effectively suppresses interfacial oxidation while maintaining the quality of Pt films. Although the as-deposition films exhibit relatively high resistivity, post-deposition annealing reduces the resistivity by approximately 52%. The proposed 2-step Pt ALD process enables the formation of low-resistivity Pt films while minimizing interfacial oxidation and is experimentally demonstrated to be effective in mitigating scaling effects. Compared to the process using only an O_2 reactant, the proposed approach achieves lower resistivity in thinner Pt films, highlighting its potential as a promising process for next-generation interconnect technology.

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Acknowledgements

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ALD Applications
Room Ybor Salons I-IV - Session AA2-TuM
ALD Dielectric Applications

Moderators: Olasehinde Owoseni, Intel, **Seung-Yeul Yang**, Samsung

10:45am **AA2-TuM-12 Sub-5 nm Indium Oxynitride Channel in Top-gated FETs Fabricated by PEALD for High-Performance 3D Transistor***, **Doo San Kim**, Minjong Lee, Soham Shirodkar,* The University of Texas at Dallas*; Min Gyeong Jo,* Hanyang University, Republic of Korea*; Thi Thu Huong Chu, Dushyant Narayan, Dan Le,* The University of Texas at Dallas*; Youngbae Ahn, Ja-Yong Kim, Seung Wook Ryu,* SK hynix, Republic of Korea*; Jiyoung Kim,* The University of Texas at Dallas

As silicon scaling approaches its physical limits, indium-based oxide semiconductors have emerged as promising channel materials because they maintain high carrier mobility and drive current even at channel thickness below 5 nm, enabling superior scalability. Among them, In_2O_3 exhibits excellent drive current; however, hydrogen incorporation leads to hydroxyl (OH) formation, resulting in device instability and threshold voltage shifts. Incorporating nitrogen to form indium oxynitride (InON) is expected to enhance mobility while effectively suppressing the formation of hydrogen induced OH bonds, thereby improving device stability.

Despite these advantages, direct deposition of InON via atomic layer deposition (ALD) is challenging because the bonding dissociation energy of In-O (~346 kJ/mol) is significantly stronger than that of In-N (~186 kJ/mol), making it difficult to incorporate sufficient nitrogen during the simultaneous supply of oxygen and nitrogen reactants.[1,2] In this work, we propose a two-step channel formation strategy: the initial deposition of an indium nitride (InN) thin film followed by an oxidation process to convert it into an InON channel layer.

In this presentation, we report the deposition of sub-5 nm conformal InN films via Hollow-Cathode Plasma (HCP)-enhanced ALD at 240 °C. To improve the structural and electrical stability of the channel, an annealing-based oxidation process was applied, converting InN into the more robust InON and evaluating their integration into top-gated (TG) thin-film transistor (TFT) devices. We investigated the influence of process parameters such as plasma power, process pressure, and deposition temperature for the film characteristics. The 5 nm InON layer was deposited at 240 °C, followed by the deposition of a 5 nm hafnium zirconium oxide (HZO) dielectric layer, and finally a TG-FET was demonstrated using Ni metal contacts. We presented InON TG-FET results, including transfer and output characteristics, temperature dependence, and channel length scaling. Our findings demonstrate that InON-based TFTs with a 100nm channel length achieve an on-current of ~1.2mA/μm at V_D = 1 V, an I_{on}/I_{off} ratio exceeding 10^9, and a contact resistivitywith Ni of $4 \times 10^{-8} \Omega\cdot cm^2$. In addition, the $\triangle V_{th}$ under positive and negative bias stress is 90 and 15 mV, at $V_{ov} = \pm 1$ V.

This work was supported by SK hynix Inc.

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11:00am **AA2-TuM-13 V_{Fb} Control Technique of SiO_2/Dipole/$HfZrO_2$ Stack Structure Using New LaTiO and AlTiO Dipoles***, **Tomomi Sawada**, Toshihide Nabatame, Hiromi Miura, Manami Miyamoto, Takashi Onaya, Kazuhito Tsukagoshi, Naoki Fukata, Wipakorn Jevasuwan,* National Institute for Materials Science (NIMS), Japan*; Shinji Migita,* National Institute of Advanced Industrial Science and Technology (AIST), Japan

Dipole technique has been widely investigated to control the threshold voltage (V_{th}) of metal/High-k CMOS with GAA gate stack in 50 mV increments. La_2O_3 and Al_2O_3 are generally employed as n- and p-type dipoles. However, it remains a big issue of a large V_{th} shift in the sub-nm region of the dipole layer. In this paper, we investigated flatband voltage (V_{fb}) shift for SiO_2/dipole/$HfZrO_2$ stack structure using new LaTiO and AlTiO as n- and p-type dipoles.

p-Si/SiO_2/dipole/$HfZrO_2$/Au capacitor was fabricated at a maximum process temperature of 400 °C as follows: La_2O_3, TiO_2 and Al_2O_3 dipole layers were deposited on p-Si/SiO_2 (3.6 nm) by ALD at 250 °C with H_2O and La(iPrCp)$_3$, TDMAT, and TMA, respectively. LaTiO and AlTiO dipoles were also prepared by changing each ALD cycle of La_2O_3 and TiO_2, and Al_2O_3 and TiO_2 by ALD at 250 °C with H_2O, respectively. Next, an $HfZrO_2$ (2 nm) film was deposited on dipole layer by ALD at 250 °C using TEMA(Hf/Zr)(Hf/Zr = 1/1) cocktail and H_2O. Au gate electrode was deposited on $HfZrO_2$ film to form capacitor. Finally, forming gas annealing was carried out at 400 °C in 3%H_2.

The La_2O_3 and Al_2O_3 dipole capacitors exhibited negative and positive V_{fb} shifts as the La_2O_3 and Al_2O_3 dipole thickness increased, respectively. The V_{fb} shifts for the La_2O_3 and Al_2O_3 dipole capacitors were almost saturated, showing -0.35 and +0.32 V, respectively, when the dipole thickness was 0.8 nm. On the other hand, the TiO_2 dipole capacitor exhibited a V_{fb} shift of nearly 0 V regardless of the dipole thickness. This is due to differences in the strength and direction of the dipoles of La_2O_3, Al_2O_3 and TiO_2 at the SiO_2/dipole interface. The LaTiO (La = 0.46) dipole capacitors reduced the negative V_{fb} shift from -0.29 to -0.11 V compared to the La_2O_3 dipole capacitors when the dipole thickness was 0.2 nm. With a 0.2 nm thick dipole, the AlTiO (Al = 0.62) dipole capacitors also reduced the positive V_{fb} shift by approximately 25% compared to the Al_2O_3 dipole capacitors. This indicates that the dipole strength of La_2O_3 and Al_2O_3 can be effectively reduced by adding TiO_2 without dipole effect. In the LaTiO and AlTiO dipole capacitors, La and Ti atoms, and Al and Ti atoms, respectively, were piled up at the SiO_2/$HfZrO_2$ interface using STEM and EDS analysis. By employing new LaTiO and AlTiO dipoles in addition to La_2O_3 and Al_2O_3, V_{fb} controllability could be enhanced in the sub-nm region of the dipole layer. This is because TiO_2 without the dipole effect was added. This presentation is partially based on the results of the post-5G project (JPNP20017), entrusted to LSTC, commissioned by NEDO.

11:15am **AA2-TuM-14 Low-Temperature High-Pressure Deuterium Annealing for Defect Passivation in ALD-Deposited HfO_2 High-k Film***, **Ji-Yeon Park**, Seok-Won Lim, Gi-Beom Park, Chang-Kyun Park, Jin-Seong Park,* Hanyang University, Korea

Atomic layer deposition (ALD) is a key process technology for integrating high-k gate dielectrics into advanced semiconductor devices, providing excellent thickness control, compositional uniformity, and conformality. As conventional SiO_2 gate dielectrics reach their physical scaling limits due to increased direct tunneling leakage, high-k materials such as HfO_2 have been widely adopted [1]. Although ALD enables the formation of high-quality HfO_2 thin films, device performance is strongly influenced by defect states formed at the HfO_2/Si interface [2].In this study, ALD-deposited HfO_2 thin films grown using a Cp-Hf/O_3 process were investigated with a focus on the correlation between HfO_2/Si interfacial defect and electrical characteristics. Post-deposition deuterium treatment was employed not to modify the intrinsic quality of the ALD film, but as a post-ALD interface engineering and analytical tool to evaluate and improve defect states located at or near the interface. Electrical characterization using C–V and J–E measurements showed reductions in interface trap density, improved flat-band voltage stability, decreased leakage current density, and enhanced breakdown field after deuterium treatment, suggesting effective passivation of interface-related defects. Secondary ion mass spectrometry (SIMS) and X-ray photoelectron spectroscopy (XPS) analyses were conducted to examine deuterium incorporation behavior and changes in chemical bonding states, and their relationship to the observed electrical improvements was analyzed. These results indicate that the electrical performance of ALD-grown HfO_2 high-k dielectrics is governed primarily by interface quality rather than bulk film limitations. This work highlights the importance of post-ALD interface engineering and provides insight into ALD-compatible strategies for achieving reliable high-k/Si interfaces in next-generation semiconductor devices.Reference1) Wilk, Glen D., Robert M. Wallace, and JáM Anthony. "High-κ gate dielectrics: Current status and materials properties considerations." Journal of applied physics 89.10 (2001): 5243-5275. 2) E. P. Gusev,et al " Ultrathin high-k gate stacks for advanced CMOS devices," Microelectronic Engineering 69 (2003): 145-151.

11:30am **AA2-TuM-15 Infiltration of Porous SiOCH Thin Films by High-k Materials: Toward Nanocomposites with Enhanced Dielectric Properties***, **Julie Chaussard**, Stéphane Cadot, Marc Veillerot, Hélène Coudert-Alteirac, Nicolas Gauthier, Nicolas Bernier, Chloé Guérin, Aude Lefèvre,* CEA/LETI-University Grenoble Alpes, France*; Patrice Gonon,* Université Grenoble Alpes, CNRS, France*; Vincent Jousseaume,* CEA/LETI-University Grenoble Alpes, France

Dielectric materials, especially insulating polymers, are crucial for various technological applications due to their high breakdown voltage and low cost [1]. However, they generally exhibit low dielectric constant and thermal stability, limiting their use in field as power electronics.

To enhance their dielectric constant, recent studies have explored the elaboration of nanocomposites by adding alumina nanoparticles into a polymer matrix, resulting in significant improvements in dielectric constant and breakdown voltage even at low concentrations [2]. Despite these promising results, the elaboration methods used were incompatible with standard microelectronic processes.

This work studies the elaboration of nanocomposite thin films using microelectronic materials stable up to 400°C, deposited by vacuum deposition techniques. To this end, 100 nm porous SiOCH were deposited by PE-CVD on Si wafers using a porogen approach [3]. Then high-k material was infiltrated into this porous thin film using ALD. The filling process for different materials and precursors was characterized using physicochemical methods (XRF, ellipsometry, XRR, ToF-SIMS, FTIR, TEM). Then, the electrical properties were studied (dielectric constant, dielectric losses, breakdown voltage). In the case of trimethylaluminum/O_3, the results highlight that the filling of the nanometric pores of the porous SiOCH occurs in the first ALD cycles (<5). Using an optimized recipe, a maximum filling of ≈50% of the porosity was obtained. As the number of cycles increases, high-k growth continues on the surface at a rate similar to that observed on Si. FTIR analysis reveals the formation of -OH groups in the first cycles, which increases dielectric constant and dielectric losses. A similar behavior is observed when using H_2O as oxidant. However, after 25 ALD cycles, the disappearance of -OH groups is observed for the TMA/O_3 process. One hypothesis is that the alumina layer formed on top of the porous structure becomes thick enough to limit H_2O adsorption into the matrix. This leads to the elaboration of composites with a dielectric constant 42% higher than that of the porous matrix while maintaining low dielectric losses. Finally, infiltration of porous SiOCH with HfO_2 and $HfZrO_2$ (from chlorinated precursors and water), which have higher dielectric constant than Al_2O_3, also enables enhanced dielectric properties without the presence of -OH groups. But in this case the filling rate is slightly lower than that observed with alumina.

In conclusion, this work demonstrates an easy approach for the elaboration of nanocomposites using standard microelectronic materials to achieve a broader range of electrical properties.

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11:45am **AA2-TuM-16 Electrical Characterization of High-k ALD TiO_2 on AlGaN/GaN HEMT Structures**

Neeraj Nepal, *James G. Champlain, Vikrant J. Gokhale, Peter M Litwin, Brian P Downey, Virginia D Wheeler,* U.S. Naval Research Laboratory

Transport and breakdown field characteristics of GaN-based HEMT technologies are limited by high and non-uniform peak electric fields at the drain-edge of the gate. The non-uniform peak field causes premature electric field induced breakdown limiting the device performance [1]. These deleterious effects can be mitigated by integrating films with high dielectric constants (high-k, >20), such as TiO_2 [2-4]. For HEMTs, increased k leads to increased power handling capability without significant reduction in operation frequency. Thus, the goal is to integrate the highest k material possible. ALD provides flexibility in device design, integration and back-end-of line compatibility, making it a promising route for these high-k films. However, ALD high-k dielectrics with ideal interfaces and reduced trapping on AlGaN/GaN HEMTs have not been reported. In this talk, we report on the optimization and electrical characterization of the ALD TiO_2 interface with AlGaN-barrier HEMT structures.

Previously optimized deposition parameters [3] served as the baseline to further optimize electrical performance by pretreating the dielectric-barrier interface of $Al_{0.25}Ga_{0.75}N$/GaN HEMT structures. *Ex-situ* pretreatments including NH_4OH, UV O_3+BOE, piranha and O_2 plasma descum were studied. Similarly, *in-situ* UHV annealing, plasma treatments and their combinations were also studied. The optimum interface was found to be a combination of *ex-situ* O_2-plasma descum and *in-situ* H_2 and N_2 plasma treatments. Initial results using this preparation, a 20nm TiO_2 film demonstrated a reduction in gate leakage by 10^5 compared to a Schottky gate,zero CV hysteresis, a dielectric constant ≥ 50, and no significant change in 2DEG density. Even though the ALD TiO_2 has a narrower bandgap than AlGaN-barrier material, its large dielectric constant provides a pathway forward for dielectric permittivity engineering within the device structure. This engineering approach can improve breakdown voltage, lowers gate leakage and minimizes non-ideality over the state-of-the-art.

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Tuesday Afternoon, June 30, 2026

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

ALD for Catalysts and Fuel Cells

Moderators: Hao Van Bui, Phenikaa University, **Nathanaelle Schneider**, CNRS-IPVF

1:30pm **AA1-TuA-1 Copper's Cosy Blanket: A Comparison of Non-Selective and Area-Selective ZnO deposition on Catalyst Stability***, **Kalani Ostermeijer**, Ruud van Ommen, Evgeny Pidko,* Delft University of Technology, Netherlands

In the past few decades, valorizing CO_2 has drawn significant interest as it offers a more carbon neutral pathway to chemicals and fuels. However, CO_2 reduction has proven to be problematic due to its thermodynamic and kinetic constraints. Heterogeneous thermo-catalysts can improve the kinetics, thus play a critical role in the push for the industrialization of sustainable chemicals and fuels. Methanol is considered a promising product thanks to being a key chemical building block. Currently, the commercial $Cu/ZnO/Al_2O_3$ catalyst requires harsh conditions (50-100 bar H_2 and 200-300 °C). After prolonged exposure to temperatures above 200 °C, sintering of the dispersed active phase is observed. This was shown to worsen in the presence of water vapor, which is produced in high amounts during the hydrogenation process. Therefore, protecting Cu nanoparticles from thermal and hydrothermal sintering is key to enhancing the operating productivity and efficiency of the methanol production process.

In this work we aim to protect Cu nanoparticles by forming a ZnO overlayer on top of a Cu/SiO_2 catalyst using both non-selective and area-selective atomic layer deposition. ZnO was deposited using diethyl zinc and ethanol under atmospheric pressure in a fluidized bed reactor at 100 °C. To induce area-selectivity, the Cu/SiO2 catalyst was treated with trimethoxypropylsilanes using air-free wet synthesis techniques, passivating surface silanol groups. All catalysts were characterized using temperature programmed desorption, elemental analysis, electron microscopy (focused ion beam scanning electron microscopy and transmission electron microscopy), and x-ray photoelectron spectroscopy, and their stability was assessed in a fixed-bed reactor under industrially relevant conditions (250 °C and 50 bar). Herein, we explore how tailoring the metal oxide interface using targeted ZnO deposition can alter the stability of Cu/ZnO based methanol hydrogenation catalysts, improving the rational design of catalysts via ALD.

This work is part of the Advanced Research Center for Chemical Building Blocks, ARC CBBC, which is co-founded and co-financed by the Dutch Research Council (NWO) and the Netherlands Ministry of Economic Affairs and Climate Policy

1:45pm **AA1-TuA-2 Effect of Buffer Layers on Cobalt-Based Thin-Film Catalysts for Fischer–Tropsch Synthesis***, **Muhammad Hamid Raza**, Avela Kunene,* Helmholtz-Zentrum Berlin (HZB), Germany*; Lucia M. Toscani,* Department of Interface Design, HZB, Germany*; Alexander Steigert,* Helmholtz-Zentrum Berlin (HZB), Germany*; Athanasios Skaltsogiannis,* Department of Interface Design, HZB, Germany*; Ali Shan Malik,* Helmholtz-Zentrum Berlin (HZB), Germany*; Catalina E. Jiménez,* Department Interface Design, HZB, Germany*; Marcus Bär,* Department of Interface Design and Energy Materials In-Situ Laboratory Berlin (EMIL), HZB, Berlin. Helmholtz-Institute Erlangen-Nürnberg for Renewable Energy (HI ERN), Berlin. Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Erlangen., Germany*; Rutger Schlatmann, Daniel Amkreutz,* Helmholtz-Zentrum Berlin (HZB), Germany

In Fischer-Tropsch synthesis, *hcp*-Co^0 nanoparticles show higher CO dissociation activity and enhanced C_{5+} selectivity than the *fcc*-Co^0 nanoparticles due to the presence of more numerous and more active B_5 sites.[1] As such, thin film catalysis offers opportunities to tailor catalysts properties by design that are pre-adapted to specific crystallographic morphology for their targeted application. Fischer-Tropsch synthesis (FTS) benefits from thin film catalysts, by selectively tailoring the catalytically most active phase *i.e., hcp*-Co^0. This streamlined catalyst design enhances catalytic activity and selectivity toward the desired end products.[2] Varying deposition conditions and metal-support interactions affect the reducibility and crystallographic morphology of the FTS active phase. Herein, cobalt-based thin film FT catalysts are synthesized with varying chemical structures and crystallographic phases, including metallic and metal oxides phases, onto various supports and buffer layers (Al_2O_3, SiO_2, ZrO_2, CeO_2, Si_xN_y, Si_xC_y, TiO_2). Key properties such as film morphology and stability, as well as metal/metal oxide–support interactions (MSI) in terms of support-induced reducibility and morphological evolution of the cobalt films are investigated in thin films catalyst systems. Phase changes are systematically studied under *in-situ* FTS-relevant oxidation–reduction conditions using synchrotron grazing incident X-ray diffraction. Indeed, as-deposited metallic cobalt shows higher stability than its oxide counterpart, the *spinel*-Co_3O_4, under FT-relevant reduction conditions. A semi-quantitative analysis of the diffraction data indicates that the relative *fcc*-to-*hcp* ratio depends on the nature of the buffer layer, with samples supported on CeO_2, TiO_2 and Al_2O_3 - SiO_2 exhibiting the lowest apparent *fcc*/*hcp* ratio. These well-defined cobalt-based (Co, Co_xO_y) thin film catalysts offer a promising alternative for enhancing FT performance. Clear structure–property correlations will be presented to guide the rational design of advanced FT catalyst systems.

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2 Kunene, A. *et al.* Thin-Film Catalysis Innovations in Fischer–Tropsch Synthesis for Enhanced Activity. *Industrial & Engineering Chemistry Research* **64**, 22939-22948 (2025).

2:00pm **AA1-TuA-3 Preparing Well-defined CO_2-Conversion Catalysts using Atomic Layer Deposition***, **Doga Özerk**, Evgeny Pidko, J. Ruud van Ommen,* TU Delft, Netherlands

CO_2 hydrogenation to methanol is attractive, as methanol serves both as a base chemical and an energy carrier. However, due to the thermodynamic stability and low reactivity of CO_2, its conversion remains highly challenging and requires the use of efficient catalysts. Conventional catalyst synthesis methods, such as wet chemistry, often lack control over the structural and morphological properties of the materials, typically yielding catalysts with broad particle size distributions and mixed compositions. In contrast, ALD provides atomic-level precision in catalyst design, enabling the synthesis of catalysts with well-defined compositions, controlled particle sizes, and tailored active sites. This work focuses on the development of Cu and Pd-based catalysts via ALD for CO_2hydrogenation. Copper-based catalysts have been widely studied for this reaction due to their excellent hydrogen dissociation capability and cost-effectiveness compared to noble metals. However, Cu-based catalysts often suffer from nanoparticle sintering under reaction conditions, leading to catalyst deactivation through the loss of active sites and disruption of the synergistic interactions between Cu and other components in the catalyst. Pd-based catalysts have been traditionally used as Reverse Water Gas Shift catalysts, however their full potential for methanol synthesis remains underexplored. Recent studies report high methanol selectivities, yet no comprehensive mechanistic investigation has revealed the origin of this performance or established clear structure-activity relationships, due to inadequate control over Pd dispersion in conventional synthesis methods. The goal of this study is to achieve precise control over Cu and Pd dispersion and particle size at the atomic level to enhance activity and selectivity.

Cu and Pd-ALD catalysts are synthesized using $Cu(hfac)_2$ + H_2O and $Pd(hfac)_2$ + CH_2O as precursors in an atmospheric-pressure fluidized bed ALD system operating at 250 °C, with N_2 as the carrier gas. Pulse and purge times, as well as the number of ALD cycles, are varied to tune the catalyst properties. TiO_2, Al_2O_3, and CeO_2 nanoparticles (particle size: ~25 nm) are used as supports.

We will report the Cu and Pd particle size distributions on various metal oxide supports and their correlations with ALD parameters. The effect of particle size on catalytic activity and selectivity for methanol synthesis will be evaluated. The ALD-prepared catalysts will be compared to counterparts synthesized via wet impregnation. Differences in morphology, particle size, surface area and crystallinity will be discussed to elucidate structure-performance relationships.

2:15pm **AA1-TuA-4 Palladium Nanostructures by ALD for Electrocatalysis: From Single Atoms to Nanoparticles***, Raul Zazpe, Jhonatan Rodriguez-Pereira, **Jan Macak**,* Uni Pardubice, Czechia

This presentation is focused on the ALD growth of Pd nanostructures – from single atoms, through atomic clusters up to nanoparticles – that are deposited on various substrates and demonstrate an excellent electrocatalytic performance [1-3] for the hydrogen evolution reaction (HER).

In fact, Platinum group metals such as Pt, Ru, Pd, Ir, etc., have superior performance for various catalytic applications [4]. Due to their scarcity, efforts were being made to reduce or replace these noble metals. Atomic Layer Deposition (ALD) is one among the best technique to facilitate lowering of loading mass on a support of interest [5-7].

Due to the governing surface energy variations between noble metals and support surfaces, the growth initiates as single atoms, continues through atomic clusters to nanoparticles (NP) and with a further increase in ALD cycles the agglomeration among NP's dominates over the individual NP size increase, thus developing thin films of relatively higher thickness.

For electrocatalytic applications, it is important to choose the right substrates. Among the available ones, carbon papers (CP) and titania nanotube (TNT) layers are best choices considering their physio-chemical properties, availability, vast literature, and low costs incurred using these as support substrates in electrocatalysis and photocatalysis.

The presentation will introduce and describe the synthesis of Palladium nanostructures – starting from single atoms, through NPs to solid films by ALD on CP substrates [1] and TNT layers with high aspect ratios [2] and QCM crystals [3]. It will also includethe corresponding physical and electrochemical characterization and encouraging results obtained in electrocatalysis.

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2:30pm **AA1-TuA-5 Controlling the Wettability and Durability of PEM Electrolysers with Plasma-Enhanced ALD of Niobium Nitride***, **Athina Tzavara-Roussi**, Volkert van Steijn, Ruud van Ommen,* Delft University of Technology, Netherlands

Green hydrogen has emerged as an effective energy storage medium, capable of buffering excess electricity generated from intermittent renewable sources. Proton exchange membrane (PEM) water electrolysers is a key technology for green hydrogen production as they offer higher efficiency, compact design and rapid response to fluctuating energy input. However, their large-scale deployment requires reducing reliance on critical raw materials while maintaining their durability.

The porous transport layer (PTL) plays a crucial role on the anodic side of PEM electrolysers. This titanium-based layer is responsible for the transport of water to the catalytic sites and the discharge of oxygen gas to the flow plates, as well as providing an electrically conductive pathway for electrons. However, the PTL faces two critical challenges that impact the performance and cost. The first challenge is the progressive growth of an oxide layer on the surface of titanium, which significantly reduces its electrical conductivity. Commercially the platinization of the titanium substrate is commonly applied to mitigate this issue, but further increases the manufacturing costs. The second challenge lies in the counter-current transport of liquid water and oxygen as dissolved gas and bubbles. This leads to the accumulation of oxygen gas within the pores of the PTL, which increases mass transport losses. This limitation becomes more pronounced at higher current densities due to higher gas production, which is otherwise advantageous for lowering the unit cost of hydrogen production.

In this work, we demonstrate the plasma-enhanced atomic layer deposition (PE-ALD) of niobium nitrides to fabricate a functional coating on the PTL surface. Niobium is an attractive candidate to replace noble metals and as nitride it can promote electron transfer to reduce ohmic losses by protecting the titanium substrate from oxidation and simultaneously being highly conductive itself. The niobium nitride coating additionally provides hydrophilicity to facilitate the water imbibition throughout the PTL, while accelerating the removal of oxygen bubbles to decrease mass transport losses. We investigate how the elemental composition, the morphology and the thickness of the niobium nitride coating influence its conductivity and hydrophilicity. Ultimately, the impact of the PTL coating on the performance and stability of a 4cm^2 PEM cell is evaluated.

This project receives a Dutch National Growth Fund contribution from the programme NXTGEN HIGHTECH.

2:45pm **AA1-TuA-6 ALD Imparts Efficiency Improvements in Proton Exchange Membrane Water Electrolyzers***, **Arrelaine Dameron**, Sara Harris, Dane Lindblad,* Forge Nano*; Alexandra Oliveira,* Mott Corporation*; JingJing Jin, Lucas Cohen, Zhexi Lin,* Columbia University*; Alexander Papandrew,* Mott Corporation*; Daniel Esposito,* Columbia University*; Matthew Weimer,* Forge Nano

Green hydrogen (H_2) offers a pathway to decarbonizing ammonia, methanol, and other chemical manufacturing processes, but widespread adoption requires achieving cost parity with hydrogen produced via steam methane reforming. Improving the electrical efficiency and achievable current density of proton–exchange membrane water electrolyzers (PEMWEs) is therefore essential for lowering the cost of green hydrogen. In this work, we use atomic layer deposition (ALD) to engineer two critical PEMWE stack components, enabling high–current–density operation at elevated cell potentials to directly enhance system efficiency and reduce cost.

A major limitation to high–efficiency PEMWE operation is the significant ohmic loss across the Nafion membrane, which becomes dominant at current densities above ~2 A cm^{-2}. Nafion is also a per– and polyfluoroalkyl substance (PFAS), raising environmental and regulatory concerns. To address these challenges, we developed zero–gap electrolyzers that employ PFAS–free, proton–conducting silicon oxide membranes fabricated via ALD. Although pristine SiO_2 exhibits proton conductivity 2–3 orders of magnitude lower than Nafion, phosphorus doping substantially enhances H^+ transport. As a result, thin (<50 nm) PO_x–doped SiO_2 membranes achieve area–specific resistances more than 10× lower than Nafion–117, while their dense structure simultaneously suppresses hydrogen crossover to acceptable levels at pressures up to ~100 bar.

A second barrier to efficient operation is the corrosion and passivation of titanium porous transport layers (PTLs) under high–potential, acidic conditions. This degradation increases interfacial contact resistance and drives voltage decay. Conventional mitigation relies on micrometer–thick noble–metal coatings (Au, Ir, Pt) applied by electrodeposition or PVD, which significantly increases system cost. Here, we investigate ultrathin ALD–deposited iridium coatings (10–20 nm) on titanium sinter PTLs. These ALD Ir coatings exhibit lower interfacial contact resistance than comparable Pt layers due to their high conductivity in both metallic and oxide states. When implemented in PEMWE cells, they support stable operation at 3 A cm^{-2} and <1.9 V for 1000 hours with no detectable voltage degradation.

3:00pm **AA1-TuA-7 Atomic Layer Deposition of Tantalum Oxide for enhanced stability of CNTs during Photoelectrochemical Water Splitting***, **Muhammad Awais Khan**,* Luxembourg Institute of Science and Technology (LIST), Luxembourg*; Diego Martinez Martinez,* luxembourg Institute of Science and Technology (LIST), Luxembourg*; Amr Nada, Nicolas Boscher,* Luxembourg Institute of Science and Technology (LIST), Luxembourg

To mitigate climate change, the global energy landscape is shifting towards hydrogen, with demand reaching 100 Mt in 2024 [1]. Photoelectrochemical (PEC) water splitting has emerged as a vital pathway for sustainable green H2 production. However, widespread implementation is hindered by thermodynamic bandgap mismatches, sluggish kinetics, and stability issues of the photo-electrocatalyst. Carbon nanotubes (CNTs) provide an ideal conductive scaffold due to their exceptional axial charge transport and high effective surface area. Despite these advantages, it has been observed that the high curvature of the graphene lattice renders CNTs susceptible to structural degradation in oxidative PEC environments [3]. Fig In particular, bare CNT electrodes exhibit severe structural degradation after 1 h chronoamperometry (CA) stability testing under illumination in 1 M KOH, as illustrated in Fig. 1. To preserve the structural integrity of CNTs, we used Atomic Layer Deposition (ALD) to deposit a protective Tantalum Oxide (Ta2O5) shell on CNTs (see Fig 2). ALD was chosen considering its sub-nanometric precision, which allows the deposition of conformal, pinhole-free films on high aspect ratio CNTs packed in a complicated forest, and the restricted carrier diffusion length in tantalum-based compounds (~50-100 nm), which demands a controlled thickness (Fig. 1). The ALD deposition process was carried out utilizing pentakis-(dimethyl-amino)-tantalum (PDMAT) and H2O as co-reactant, yielding an optimized growth per cycle (GPC) of 0.5 Å/cycle, as monitored by in-situ spectroscopy ellipsometry. X-ray diffraction (XRD) and X-ray reflectometry (XRR) confirmed the growth of dense (~6.4 g/cm3), high-purity Ta2O5 amorphous films, while X-ray photoelectron spectroscopy (XPS) verified a Ta/O ratio of 2.8 with negligible carbon contamination. Transmission Electron Microscopy (TEM) and Energy Dispersive Spectroscopy (EDS) mapping demonstrated ultra-conformal coating of Ta2O5 along the entire CNT length, ensuring complete surface passivation (cf. Fig 2). PEC performance was evaluated using cyclic voltammetry (CV), linear sweep voltammetry (LSV), electrochemical impedance spectroscopy (EIS), and chronoamperometry (CA). The Ta2O5 film significantly reduced charge-transfer resistance and effectively suppressed the morphological collapse observed in bare CNTs during stability tests (cf. Fig 1). Moreover, CA measurements under chopped illumination revealed a distinct photo-response associated with the Ta2O5 bandgap, confirming the shell's active role in the PEC process. While Ta2O5 successfully stabilizes the conductive core, its wide bandgap limits visible-light harvesting. Consequently, this work establishes a robust baseline for transitioning toward nitrogen-doped Tantalum Oxynitride (Ta-O-N) to optimize bandgap alignment (~2.1 eV), thereby targeting theoretical solar-to-hydrogen (STH) efficiencies of up to 15.25 % with photocurrent densities of 8.1 mA cm-2 [4].

3:15pm **AA1-TuA-8 Atomic Layer Deposited AZO on Lithium Niobate: A Scalable Platform for RF Energy Harvesting and Frequency Mixing**, ***Hamed Atashbar***, University of Central Fllorida*; Hakhamanesh Mansoorzare, Terrick McNealy-James, Parag Banerjee, Reza Abdolvand,* University of Central Florida

Radio frequency (RF) signal processing and energy harvesting are critical functionalities for emerging wireless technologies. These capabilities can be effectively realized via the acoustoelectric (AE) effect, where the interaction of propagating surface acoustic waves (SAW) and electrons in thin resistive films convert acoustic energy into a DC signal or facilitate wave mixing. While previous literature has explored these effects using graphene [1] or III-V semiconductors (e.g., InGaAs) [2], these films often suffer from manufacturing scalability challenges or limited sheet resistivity control.

This work investigates the integration of atomic layer deposited (ALD) Al-doped ZnO (AZO) films with lithium niobate (LN) SAW delay lines as a robust, scalable platform for both RF-to-DC conversion and nonlinear frequency mixing. ALD AZO of 25 nm thickness were deposited on SAW devices with 100 nm thick interdigitated lines (Fig. 1). A FIJI Gen2 System from VEECO was used for the deposition, using trimethyl aluminum and diethyl zinc as Al and Zn sources and water as an oxidant. A dopant level of 2 at% was maintained while thicknesses of 20 to 30 nm were attempted on the SAW devices.

Experimental results demonstrate a linear response with a dynamic range exceeding 30 dB. Further, the devices can handle RF input powers as high as 20 dBm, generating an open-circuit voltage of 342 mV and a short-circuit current of 3 µA, measured for a device with SAW wavelength of 8 µm (FP=4 µm, 540 MHz), while the lower conversion range is masked by DC readout noise floor (Fig. 2). The device metrics enabled by ALD AZO surpass those of standard electronic rectifiers, in general, and particularly improve the conversion efficiency by more than 5.1 times relative to graphene-based counterparts.

Beyond passive detection, the platform leverages the inherent nonlinearity of the AE interaction to enable wave mixing applications. As shown in Fig. 3, fabricated AE mixers support the generation of sum and difference SAW frequencies through multi-wave mixing. This capability allows the platform to perform signal processing tasks, such as frequency conversion, entirely within the micro-acoustic domain. Crucially, the use of ALD AZO provides a commercially viable pathway for these advanced nonlinear functions, offering a distinct advantage over non-scalable III-V or graphene alternatives. These results position the AZO-on-LN platform as a versatile solution for next-generation RF sensing, harvesting, and signal processing.

ALD Applications
Room Ybor Salons I-IV - Session AA2-TuA

ALD for Batteries and Energy Storage

Moderators: Rong Chen, Huazhong University of Science and Technology, **Neil Dasgupta**, University of Michigan

4:00pm **AA2-TuA-11 Fabricating Artificial Electrode Electrolyte Interfaces for Lithium Batteries**, *Sara Pakseresht, Princess Stephanie Llanos, Filipp Obrezkov, Ville Mikkulainen,* ***Tanja Kallio,*** Aalto University, Finland **INVITED**

With the growing need to increase the energy density of lithium batteries (LIBs), numerous studies have focused on developing high-capacity electrodes capable for operation at a wide potential range. Yet, extending the potential range often compromises the cycling stability because of accelerated mechanochemical ageing of the electrode active materials. Here, various coatings are applied via ALD or MLD on lithium battery electrodes to mitigate premature capacity fade. Focus is on investigating their attributes and effect of the coatings on the performance of high voltage positive electrode materials, particularly $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (NMC811), and lithium negative electrode. Additionally, some light is shed on the synthesis of the coatings.

Such coatings as lithium titanate, titanium terephthalate and lithium fluoride are investigated on NMC811 to understand attributes of coatings, or artificial cathode electrolyte interfaces, with different chemical and physicochemical features. Due to the complex interplay of the degradation mechanisms at the crystal structure, particle, and electrode levels, *operando* XRD and dilatometry are combined with ex-situ characterization techniques to have an in-depth understanding of the mechanism of enhancement received by these coatings. The multiscale analyses show that electrodes with coated NMC811 experience more reversible variations and the applied coating improves the cycle life by suppressing various ageing processes.

As for the negative electrodes, highly reactive metallic lithium offering high capacity and most negative lithium redox potential is considered. Electrochemical measurements complemented with o*perando* dilatometry and optical measurements enable optimizing coating thicknesses to achieve a tradeoff between mechanical and chemical durability.

The reaction mechanism during ALD is studied by in-situ near atmospheric pressure XPS. Different reaction mechanisms between the NMC811 substrate and the utilized organometallic precursors are revealed. These measurements also yield information on the active role of lithium metal during the evolution of the coating.

4:30pm **AA2-TuA-13 Beyond Conventional ALD: Investigating Standalone Chemical Vapor Transformation Precursors for Battery Cathode Functionalization**, ***Donghyeon Kang***, *Jeffrey Elam,* Argonne National Laboratory

Atomic layer deposition (ALD) is a cornerstone technique for stabilizing battery interfaces, typically involving the sequential application of a metal precursor and a co-reactant to grow protective thin films. However, the inherent reactivity of battery cathode surfaces—often covered by native impurities like lithium carbonate (Li2CO3)—presents an opportunity to bypass traditional binary cycles. This study investigates the use of standalone vapor-phase precursors as a direct functionalization strategy, eliminating the need for a secondary pulse while achieving superior interfacial control.

We explore a series of aluminum (Al), phosphorus (P), and boron (B) precursors to determine their efficacy as "transforming" agents. Unlike standard ALD growth, these precursors react directly with the surface layer, converting detrimental impurities into beneficial, lithium-conducting interphases. This process effectively "cleans" the cathode surface while simultaneously depositing a sub-nanometer protective skin in a single, self-limiting step.

The reaction mechanisms are elucidated through **in situ FTIR spectroscopy**, which provides real-time evidence of carbonate consumption and the simultaneous emergence of Al-O, P-O, or B-O vibrational modes. These surface-sensitive insights are corroborated by **XPS** depth profiling and **ab initio calculation**, confirming the transformation of the cathode-electrolyte interface (CEI). Our findings demonstrate that standalone precursor exposure is a scalable and efficient alternative to conventional ALD, offering a streamlined pathway for the surface engineering of high-capacity battery materials.

4:45pm **AA2-TuA-14 Tackling Issues of Transition Metal Oxide Cathodes Using Sulfide Coatings**, ***Xiangbo Meng***, *Kevin Velasquez Carballo, Taohedul Islam,* University of Arkansas

Transition metal oxides (e.g., layered $LiNi_xMn_yCo_zO_2$) are among the most promising cathodes for next-generation lithium-ion batteries (LIBs) and beyond, but suffer from a series of structural and interfacial issues. In addressing these issues, surface modification has been proved being facile and effective. In this regard, atomic layer deposition (ALD) has emerged and offered some unrivaled benefits in coating quality and process.[1-3] In the past years, we have been investigating various coating materials [4-7] while recently, we first discovered that sulfides are very unique as coatings materials.[8-10] They can react with oxygen released from lattices of transition metal oxide cathodes, transform into sulfates, and thereby protect electrolytes from oxidation. Furthermore, the resultant sulfates as coatings still play multiple important roles in enhancing cathode performance: (1) strengtheners to maintain mechanical integrity and reduce microcracking of cathodes; (2) robust interfaces to mitigate undesirable interfacial reactions and alleviate the formation of cathode electrolyte interphase (CEI); (3) protective layers to hinder transition metal ions from dissolution, (4) structural stabilizers to suppress unfavorable phase transformation; and (5) physical barriers to inhibit crosstalk between the cathodes and anodes and to protect anodes from degradation. As a consequence, we demonstrated that sulfides are excellent surface coatings, which could dramatically improve the performance of transition metal oxide cathodes. Thus, our studies have greatly widened the search of surface coatings and provided new solutions for next-generation LIBs and beyond.

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5:00pm **AA2-TuA-15 Atomic Layer Deposition Tuned Surface Chemistry for Advanced Lithium and Manganese Rich Cathodes***, **Jahnavi Manikantan Sudharma**, Kyobin Park, Sungjoon Kim, Subhadip Mallick, Jason Croy, Donghyeon Kang, Jeffrey Elam,* Argonne National Laboratory, USA

The growing deployment of renewable energy and the rapid expansion of artificial intelligence and machine learning infrastructures place increasingly dynamic demands on modern electrical grids, requiring the need for high-performance, renewable energy-storage technologies. While nickel (Ni)-rich layered oxides remain the state-of-the-art materials for lithium-ion battery cathodes, their reliance on costly and supply-constrained Ni and cobalt (Co), motivates the development of alternative materials. Lithium- and manganese (Mn)-rich (LMR) cathodes offer a compelling solution due to their high energy density and reversible capacities enabled by anionic redox. However, oxygen loss associated with this redox process induces severe surface and interfacial degradation, including electrolyte decomposition, transition-metal migration, and Mn dissolution, which hinder long-term cycling stability of these cathodes. Suppressing Mn dissolution at the surface is still a key challenge. Advancing surface engineering, structural tuning, and electrolyte optimization is therefore critical to unlocking the full potential of LMR cathodes for next-generation energy-storage systems. Atomic layer deposition (ALD) being a self-limiting thin film growth method characterized by the sequential exposure of chemical species, offers a promising strategy to stabilize the interfaces by depositing tailored ultrathin, uniform and conformal coating layers on the surface and thereby mitigating the surface degradation of the cathode. Surface coatings applied through atomic layer deposition (ALD) offer a highly controlled route to stabilize these interfaces; however, the fundamental mechanisms governing how different ALD chemistries interact with LMR surfaces remain poorly understood. In this presentation, I will discuss our recent study combining in situ measurements of ALD chemistries, ex situ thin film characterization, and electrochemical testing of prototype batteries. By systematically investigating ALD coating chemistries including lithium phosphate (Li_3PO_4) and lithium borate ($LiBO_x$), we elucidated how ALD surface reactions govern coating composition, structure, and protective functionality and how this functionality affects cycling performance. These insights will inform rational interface-engineering strategies, enabling the practical deployment of high-energy, cobalt-lean Mn-rich cathodes for next-generation lithium-ion batteries.

5:15pm **AA2-TuA-16 Comparing Al-phosphate ALD on $LiMn_2O_4$ and SiO_2***, **Lowie Henderick**, Christophe Detavernier, Jolien Dendooven,* Ghent University, Belgium

Although lithium ion batteries (LIB) have already significantly improved, undesirable side-reactions at the electrode-electrolyte interface hamper further performance gains. Atomic layer deposition (ALD) is a promising route to improve performance via deposition of a protective coating, where materials ranging from inert (e.g. Al_2O_3 and Al-phosphate) to more conductive coatings (e.g. TiO_2 or LiPON) are being explored. ALD processes for protective coatings are typically characterized on standard native SiO_2/Si substrates and then blindly copied to the LIB electrode material. However, in situ studies have shown that the surface reactions during initial ALD cycles on battery electrodes can differ markedly from those observed on native SiO_2/Si substrates. For instance, it was shown that Al_2O_3 deposition leads to Al doping at the electrode surface[1], altering its performance. Such effects should be more properly addressed and understood if one aims to fully optimize the LIB electrode. In this work, the deposition of Al-phosphate on a $LiMn_2O_4$ (LMO) electrode is studied with in-vacuo XPS and EDX using two different ALD processes. Both processes are well understood on SiO_2, but their initial growth on a LIB electrode has not yet been addressed. On the one hand, a plasma enhanced ALD process is used consisting of TMP plasma–O_2 plasma–TMA. For this process, a 5 times higher growth rate is observed on LMO during 30 cycles compared to SiO_2. It was found that, while there is saturating growth on SiO_2, continuous polymerisation takes place on LMO due to the reactivity of the electrode surface, forming a thick phosphate-rich layer with an equivalent thickness growing beyond 15 nm after prolonged exposure (fig. 1). This highlights a significant process difference, where CVD is observed on LMO even though ALD was expected based on the process characterization on SiO_2. On the other hand, a TMP vapour–O_2 plasma–TMA–O_2 plasma process is used for which more ALD-like (self-limiting) growth can be observed on LMO. Nevertheless, based on in-vacuo XPS, it can be seen that the peak areas of the coating are approximately 70% higher during the initial cycles on LMO compared to SiO_2 (fig.2), suggesting substrate specific growth. Next to this, the P-to-Al concentration ratio also significantly differs (fig.3), further indicating a clear substrate dependency. This work highlights the importance of proper LIB interface engineering. Only by studying the deposition directly on the relevant battery electrode material, the initial growth can be fully characterized and the interface can be engineered towards next generation LIB performance. [1] Chen,L. et al., Chem, 2418 – 2435 (2018)

5:30pm **AA2-TuA-17 Unravelling the Mechanism of Al_2O_3 Atomic Layer Deposition on Li_6PS_5Cl for All-Solid-State Batteries***, Kyobin Park, Donghyeon Kang, Taewoo Kim, Vepa Rozyyev, Anil Mane, Hacksung Kim, Francisco Vargas, Zachary Hood, Peter Zapol, Justin Connell, **Jeffrey Elam**,* Argonne National Laboratory

Sulfide superionic conductors with the argyrodite structure (e.g., Li_6PS_5Cl, LPSCl) are extremely promising for all solid-state batteries, but poor atmospheric stability and high interfacial reactivity limit their widespread adoption. Coating LPSCl powders with ultrathin, metal oxide coatings using atomic layer deposition (ALD) mitigates these problems, protecting LPSCl against atmospheric degradation[1] and reducing reactivity with Li metal, yielding more stable cycling[2]. Despite significant promise, the ALD mechanism is unknown, hampering the development of new coating chemistries.

In this study, we elucidate the mechanism for Al_2O_3 ALD on LPSCl using trimethyl aluminum (TMA) and H_2O by combining *in situ* Fourier transform infrared spectroscopy measurements and *ex situ* solid-state magic angle spinning nuclear magnetic resonance, UV Raman spectroscopy, and X-ray photoelectron spectroscopy measurements with density functional theory calculations. We determine that ALD Al_2O_3 nucleates promptly via TMA reaction with native -OH, -SH, and PS_3-OH groups to form transient C-Al-O(S) species that are rapidly hydrolyzed during the subsequent H_2O exposure. This reversible transformation maintains surface nucleophilicity and prevents sulfide decomposition. The resulting layer-by-layer growth leads to highly conformal Al_2O_3 coatings on LPSCl.

This detailed understanding of ALD surface reactions provides critical insights guiding the selection of future ALD chemistries with greater enhancement in cycling performance.

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ALD Applications
Room Tampa Bay Salons 5-9 - Session AA-TuP
ALD Applications Poster Session

AA-TuP-1 Improving the Thermoelectric Properties of ALD Synthesized Thermoelectric Thin Films Sb_2Te_3 by Cr+ and Ar+Ion Implantation*, **Sadiya Tahsin**, Helmut Baumgart,* Old Dominion University

Atomic layer deposition (ALD) provides atomic-scale thickness control and excellent conformality, enabling the integration of thermoelectric materials onto complex, high–aspect ratio architectures. In this study, Sb_2Te_3 thin films were deposited by ALD on planar and porous silicon substrates and subsequently modified through ion implantation to independently tune electrical and thermal transport. Chromium (Cr^+) and argon (Ar^+) ions were employed to decouple chemical doping from structural disorders. Cr^+ implantation was used to adjust carrier concentration through electrically active doping, while Ar^+ implantation introduced lattice defects and disorder without chemical substitution. Post-implantation annealing at 225 °C enabled partial defect recovery and dopant activation. Hall effect measurements reveal a substantial increase in carrier concentration and electrical conductivity in annealed, implanted films compared to pristine as-deposited samples. This enhancement is accompanied by reduced carrier mobility, consistent with increased carrier scattering from implantation-induced defects. These results demonstrate that combining ALD-enabled conformal growth with controlled ion-beam defect engineering offers a scalable pathway for optimizing Sb_2Te_3 thermoelectric thin films through independent control of electronic and phononic transport.

AA-TuP-2 A New Sn-based Precursor as Dry Photoresist for Extreme Ultraviolet Lithography Process*, **Junsok Choi**, Shijin Song, Youngwon Kim, Juhyung Lee, Ahreum Kim, Seonghan Kim, Dae Won Ryu,* Hansol Chemical, Republic of Korea

Extreme Ultraviolet Lithography (EUVL) has become essential process for reduction in device dimension. Recently, in EUVL, Dry-deposition & Dry-development approaches have attracted considerable attention because of their capability of preventing pattern collapse, relaxing Resolution-Line edge roughness-Sensitivity (RLS) trade-off, and reducing environment effect. As Photoresists (PR) for Dry EUVL, Sn-based precursors with EUV-sensitive ligands have been widely researched due to high absorption coefficient of Sn towards EUV light.

In this study, we developed a new Sn precursor as a dry PR for EUVL. The thin PR films of 25 nm were deposited through chemical vapor deposition (CVD). Then, 5X5 μm^2 patterns and 1:1 line/space (L/S) patterns were formed through E-beam lithography process for measurement of sensitivity resolution and line-edge roughness (LER) of the developed dry PR.

The sensitivity of the dry PR was evaluated with E-beam dose when thickness after development reaches maximum with increasing the dose for 5X5 μm^2 patterns. The thickness of those patterns after development were measured through optical microscopy. D_{100} (Dose at maximum thickness) of the PR was 399 $\mu C/cm^2$ at the voltage of 100 kV.

1:1 L/S patterns with half pitch = 50, 40, 30, 20, and 10 nm were observed with scanning electron microscopy (SEM). From hp = 50 nm to hp = 20 nm, no major defects (pattern collapse, bridging and line pinching) was observed. LER at hp =20 nm measured with Lacern program was only 1.66 nm. These results showed that our developed dry PR has satisfactory performances to realize ultra-fine nano-patterns for reducing dimension of semiconductor devices.

AA-TuP-3 Development of Air-stable Liquid Niobium Precursor with Organic-inorganic Hybrid Ligand for Conformal Atomic Layer Deposition of Nb_2O_5*, **Sun Young Baik**, Sangbum Han,* EGTM, Republic of Korea

Metal halide precursors are widely used in Atomic Layer Deposition (ALD) and Chemical Vapor Deposition (CVD) due to their high reactivity with common oxygen sources and exceptional thermal stability. These characteristics enable excellent conformality and often produce high-purity films with lower carbon and oxygen contamination compared to many organometallic precursors. However, despite their effectiveness, a notable limitation is that most metal halides exist in the solid phase, which complicates precursor delivery and necessitates the use of specialized canisters. Additionally, corrosive reaction byproducts (e.g., HF, HCl) can damage ALD chamber components. To address these limitations, we developed a novel niobium (Nb) precursor by combining halide and organic ligands. This new Nb precursor synergizes the advantages of both ligand types; it retains the reactivity of halides while exhibiting exceptional air stability and existing in the liquid phase at room temperature. Notably, the precursor demonstrated excellent properties during the deposition process. Its liquid state facilitates stable delivery, and its superior thermal stability allows for deposition at higher temperatures. Consequently, the precursor was confirmed to achieve perfect step coverage (~100%) on patterned wafers, comparable to that of conventional metal halide precursors. We expect this new Nb precursor to be a suitable candidate for the ALD of Nb2O5 interfacial oxide layers.

AA-TuP-4 ZnO Thin Film Transistor-Based Hydrogen Sensor Fabricated by Atomic Layer Deposition*, Kaito Otsuka, Kyosuke Nakazawa, Ryo Miyazawa, Masanori Miura, Bashir Ahmmad, **Fumihiko Hirose**,* Graduate School of Science and Engineering, Yamagata University, Japan

Hydrogen sensors are crucial devices for securing hydrogen based power generation systems. As the conventional technologies, palladium nanoparticle films were used as measuring its resistance as the H_2 signal. Moreover, the transparent oxide semiconductors such as ZnO were used as the sensing resistor for hydrogen. On the other hand, thin–film–transistor (TFT)–based sensors are attracting increasing attention because a TFT matrix can be used as a two–dimensional sensing platform. In the present study, ZnO–based TFT sensors were fabricated by atomic layer deposition to explore their potential for hydrogen detection.

In Fig. 1, the schematic of the TFT is illustrated. A nanometer–thick (12 nm) ZnO film was used as the channel layer, and the thickness was minimized to enhance the sensitivity. The ZnO film was deposited by room–temperature atomic layer deposition. The deposition system is shown in Fig. 2. The precursors were dimethylzinc and plasma–excited humidified argon. The deposition temperature was room temperature. The film was then annealed in dry air at 450°C for 30min to promote crystallization. In this TFT, the channel length and width were 60μm and 1mm, respectively.

For the hydrogen sensing test, we measured the time variation of the drain current with gate and drain voltages of 0 and 20V, respectively. The hydrogen partial pressure was increased stepwise from 200 to 6400Pa. The drain current clearly increased with increasing partial pressure, although no saturation was observed. It was also confirmed that the slope of the drain–current response correlated with the partial pressure, suggesting the applicability of the present device as a hydrogen sensor. We assume that hydrogen molecules were adsorbed on the palladium oxide, dissociated into atomic hydrogen, and diffused into the ZnO channel, where the enhanced carrier conduction led to the steep increase in drain current.

At the conference, we will discuss the operation mechanism together with more detailed experimental results.

AA-TuP-5 Titanium Nitride Protective Coatings for High-Performance Proton Exchange Membrane Water Electrolysis*, **Bhavesh Chavan**, Ruud Kortlever, Ruud van Ommen,* Delft University of Technology, Netherlands

Proton-exchange membrane (PEM) water electrolysis is a leading technology for green hydrogen production, offering high efficiency and compact design. However, its widespread adoption is hindered by the reliance on costly platinum group metals and titanium-based components required to endure the acidic, oxidizing environment during operation [1].

Titanium-based components, such as the porous transport layer (PTL) and bipolar plates, play critical roles in facilitating mass transport, ensuring uniform current and heat distribution, and providing mechanical stability to the system. Yet, under operational conditions, these components form semiconducting oxide layers, which reduce electrical conductivity and compromise system efficiency. Additionally, they require high hydrophilicity to improve gas-liquid contact and mass transfer. To address these challenges, these components are often coated with thick layers (~200nm) of precious metals such as platinum or gold, increasing costs significantly [2].

In this work, titanium nitride (TiN) coatings are investigated as a cost-effective alternative to conventional Pt or Au coatings on PTLs, aiming to provide high corrosion resistance, conductivity, and hydrophilicity [3,4]. Three gas-phase coating techniques to make TiN are explored in this work: atomic layer deposition (ALD), reactive sputtering (physical vapor deposition), and direct plasma nitridation. ALD offers excellent coating conformality and high penetration depth but involves a more complex and time-intensive process. In contrast, reactive sputtering is a simpler and more cost-effective method, though it can compromise coating conformality. The conformality achievable with direct plasma nitridation remains uncertain and requires further evaluation.

Initial studies involved TiN film deposition on silicon wafers to evaluate coating quality, followed by application on 3D PTL structures. Electrochemical testing was first conducted in a three-electrode setup, after which the coated PTLs were evaluated under PEM water electrolysis conditions. The results of our work demonstrate the potential of titanium nitride coatings as a scalable protective layer for PEM water electrolysis components, offering a pathway toward cost-effective and efficient green hydrogen production.

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This project receives a Dutch National Growth Fund contribution from the NXTGEN programme HIGH-TECH.

AA-TuP-6 Controlled Interface Oxidation of Ru/RuO$_2$ Thin Films Through High Concentration H$_2$O$_2$ Exposure, ***Austen Adams,*** *Dan Le,* RASIRC

The modern trend of semiconductor device design approaching increasingly smaller scales, alongside the desire for devices to be integrated into complex three-dimensional architectures, has caused an industry-wide need for precise control over film quality and interface properties. The interface between bottom electrode materials and dielectric layers is of particular interest as the thickness of a modern dielectric decreases to the single nanometer range. Ru is a well-studied bottom electrode material for dynamic random-access memory applications, in part due to its low bulk resistivity (7.1 μΩ cm) and high work function (4.7eV). Unfortunately, during oxidation cycles of dielectric ALD the industry standard O_3 exposure often causes the formation of volatile RuO_4. The result of this oxidation effect being lower quality Ru-based interfaces with etched RuO_2. In previous semiconductor generations this surface roughness for a bottom electrode interface would be a minor concern, but as modern semiconductor designs demand thinner films, the need for a higher quality and uniform interfaces has become pertinent.

Here we showcase evidence of higher quality uniform RuO_2 thin film formation via BRUTE Peroxide (high concentration H_2O_2)exposure, mitigating the formation of RuO_4. We compare these films to comparable O_3 exposed Ru/RuO$_2$ films and as-deposited Ru films. Resulting structures are characterized through scanning electron microscopy surface imaging, x-ray reflectivity and x-ray photoelectron spectroscopy analysis, among other techniques.

AA-TuP-7 Plasma-Enhanced Atomic Layer Deposition of Niobium Nitride Using a New Nb Precursor and Its Application to Diffusion Barriers for Cu and Ru Interconnects, ***Kyungmin Kim,*** Department of Energy and Chemical Engineering, Ulsan National Institute of Science and Technology (UNIST), Republic of Korea*; Chaehyun Park, Minjeong Kweon,* Graduate School of Semiconductor Materials and Devices Engineering, Ulsan National Institute of Science and Technology (UNIST), Republic of Korea*; Yongjoo Park, Donghyun Kim,* Advanced Reasearch Development Team, SK Trichem Co. Ltd., Sejong, 30068, Korea*; Soo-Hyun Kim,* Graduate School of Semiconductor Materials and Devices Engineering, Ulsan National Institute of Science and Technology (UNIST), Department of Materials Science and Engineering, Ulsan National Institute of Science and Technology (UNIST), Republic of Korea

Continued scaling of semiconductor interconnects has led to increased RC delay, reduced Cu volume, size-effect-induced resistivity increase, and degraded electromigration reliability. Conventional Cu interconnects rely on complex TaN/Ta diffusion barrier and liner stacks. However, this multilayer scheme faces severe scaling limitations, thereby motivating the search for alternative diffusion barrier and liner materials. Transition-metal nitrides (TMNs) especially niobium nitride (NbN) offer high melting point (≈2400 °C), strong chemical stability, and metallic conductivity (58–78 μΩ·cm), making them suitable diffusion barrier candidates for advanced interconnect integration [1] [2]. As interconnect dimensions continue to shrink, atomic layer deposition (ALD) becomes essential due to its self-limiting surface reactions, excellent conformality, and precise thickness control in high-aspect-ratio device structures. In this study, we investigate the ALD feasibility of NbN_x thin films using a novel liquid Nb precursor, which offers higher volatility and stable vapor delivery compared with conventional solid precursors such as $NbCl_5$ or NbF_5. Multiple reactants including NH_3 molecule, NH_3 plasma, N_2 plasma, and N_2:H_2 mixture plasma were examined to identify effective nitridation pathways. Among them, NH_3 plasma was the only reactant capable of forming crystalline NbN_x and further experiments were done mainly using NH_3 plasma. The ALD-NbN_x process was conducted in a showerhead-type PEALD reactor (IOV dX1 PEALD, ISAC RESEARCH, Korea). Self-limiting growth behavior was confirmed through both precursor and reactant pulsing time, with a saturated growth rate of approximately 0.18 Å/cycle. A stable ALD temperature window was identified between 250–350 °C, with the best film quality achieved at 300 °C. The properties of ALD-grown NbN_x films were characterized using XRD, XRR, SEM, XPS and TEM. Finally, the ALD-grown NbN_x films were evaluated as diffusion barrier for Cu and Ru interconnects, demonstrating their potential for advanced interconnect applications. Detailed barrier performance results will be presented at the conference.

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Acknowledgements

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AA-TuP-8 Ultrathin Sn-Doped In$_2$O$_3$ Films for Scalable Semiconductor Transistors, ***Seung Ho Ryu,*** *Seong Keun Kim,* Korea University, Republic of Korea*; Taikyu Kim,* Stanford University, Republic of Korea*; Taeseok Kim,* Korea University, Republic of Korea

As transistor scaling progresses, ultrathin channel structures are increasingly required to suppress short-channel effects and enhance gate control in advanced device architectures such as FinFETs and gate-all-around (GAA) transistors. However, reducing channel thickness typically leads to severe degradation in conductivity, limiting the electrical performance of thin-film transistors (TFTs). In this study, we investigate an ultrathin Sn-doped In_2O_3 (ITO) channel to overcome this challenge. The uniform Sn doping enhances carrier density and mitigates the conductivity degradation associated with ultrathin channels, ensuring stable electrical performance. As a result, we successfully fabricate enhancement-mode TFTs with a 1.5 nm-thick ITO channel, achieving a high field-effect mobility of 33.4 ± 1.5 $cm^2/V{\cdot}s$, a subthreshold swing of 129 ± 30 mV/dec, and a threshold voltage of 0.3 V. These findings provide a crucial strategy for realizing high-performance oxide TFTs with ultrathin conducting channels, addressing a key challenge in the development of next-generation semiconductor devices.

AA-TuP-9 A Film-Quality-Aware ALD Integration Framework for Top-Gated MoS$_2$ FETs, ***Minjong Lee****, Thi Thu Huong Chu, Inhong Hwang, Doo San Kim, Dushyant Narayan, Dan Le, Soham Shirodkar, Jiyoung Kim,* University of Texas at Dallas

Top-gated MoS_2 FETs require conformal, ultrathin high-k dielectrics with low interface trap density [1]. However, the surface-limited reactions in atomic layer deposition (ALD) can also perturb MoS_2 channel chemistry, degrading electrostatic control and limiting reproducibility [2]. It is thus critical to establish a process-channel framework that decouples nucleation-driven interface formation from channel-damaging reactions. In this work, we examine how MoS_2 film quality governs top-gate insulator integration and defines the boundary between chemistry-enabled interface improvement and defect-activated channel damage.

We first established a single-crystal benchmark using mechanically exfoliated few-layer MoS_2. Comparative oxidant studies show that H_2O_2-based ALD of HfO_2 yields improved gate controllability relative to conventional oxidants (H_2O, O_3), consistent with a chemically stabilized interface associated with S-O bond formation. These results indicate that oxidant engineering can overcome the conventional nucleation-interface-quality tradeoff without relying on seed or interfacial-layer strategies, providing a practical route for scaled top-gated 2D devices.

We then extend the same gate-stack process to wafer-scale MoS_2 films from multiple sources (e.g., chemical vapor deposition (CVD)- and chemical vapor transfer (CVT)-grown). In contrast to exfoliated single-crystal flakes, large-area MoS_2 exhibits overall degradation after high-k deposition, indicating that film non-idealities and spatial variability dominate the integration outcome. We attribute this divergence to defect-mediated interfacial chemistry, where abundant reactive sites in wafer-scale MoS_2 promote localized oxidation and non-ideal bonding even under H_2O_2-

enabled deposition, thereby degrading transport and gate controllability. This trend further suggests that defective MoS_2 films require milder ALD windows (e.g., lower temperature and reduced oxidant reactivity) to suppress defect-activated parasitic reactions while preserving nucleation.

Overall, this study establishes process-structure-property relationships linking MoS2 quality to top-gate dielectric integration and provides actionable design rules for reliable 2D FET gate stacks toward future 3D-integrated electronics.

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AA-TuP-10 Atomic Layer Deposition of Pt on Plasma-Activated Tungsten Oxide Support for Durable PEMFC Anodes*, **Hyung Jong Choi,*** Stanford University*; Hae Wook Park, Beum Geun Seo, Jung Woo Shim, Nam Il Kim, Yun Sung Choi,* Korea University, Republic of Korea*; Fritz B. Prinz,* Stanford University*; Joon Hyung Shim,* Korea University, Republic of Korea

Atomic layer deposition (ALD) can provide a unique pathway to maximize the utilization of noble metal catalysts by controlling the distribution and loading at the nanoscale. This study fabricated Pt nanoparticles on WO3 support using plasma-enhanced ALD (PEALD) to develop a high-performance anode catalyst for polymer electrolyte membrane fuel cells (PEMFCs) operated under fuel starvation conditions. Prior to Pt deposition, the surface of the WO3 support was treated by Ar plasma to generate oxygen vacancies and enhance the electrical conductivity of the support. The surface treatment could accelerate Pt island formation on the WO3 surface, which is driven by activation of the WO3 surface. The resulting Pt–WO3 interface could enhance hydrogen spillover and form HxWO3 species, which can act as a temporary proton–electron buffer via reversible decomposition, which is helpful in fuel starvation situations. The species also helps consume intruding oxygen during start-up/shutdown, thereby stabilizing the anode potential. As a result, the resulting catalyst platform fabricated by Ar plasma treatment and the subsequent PEALD Pt process showed enhanced stability compared to commercial Pt/C across multiple harsh protocols, including fuel-starvation transients.

AA-TuP-11 Impact of Mid-Interlayer Insertion on the Ferroelectric Performance Enhancement of $Hf_{0.5}Zr_{0.5}O_2$ Thin Films through Remote Plasma ALD*, **MinGyun Kang**, HyeonWu Nam, YongWoon Jang, ByungWook Kim, ChangYun Hong, JiWon Kim, ChangBun Yoon,* Department of Advanced Material Engineering. Tech University of Korea., Republic of Korea

Ferroelectric HZO is a promising candidate for next-generation memory. However, stabilizing the ferroelectric orthorhombic phase (o-phase) while suppressing the monoclinic phase remains a challenge in ultra-thin films. Furthermore, leakage current and reliability issues, such as wake-up effects and retention loss in Metal-Ferroelectric-Metal (MFM) structures, require advanced interface engineering strategies. This study investigates the impact of mid-interlayer (Mid-IL) insertion (SiO2,TiO2, and Al2O3) on the performance of HZO films fabricated by remote plasma ALD (RP-ALD). Metal-Ferroelectric-Metal (MFM) capacitors were fabricated on highly doped n++ Si wafers. A 50-nm-thick TiN bottom electrode was deposited via thermal ALD. Subsequently, HZO films were deposited using a plasma-enhanced ALD system in a 1:1 super-cycle scheme of Hf and Zr precursors. RP-ALD was performed with a high plasma power of 2600W to ensure high-quality film densification while minimizing plasma-induced damage. An asymmetric HZO(2nm)/Interlayer(1nm)/HZO(7nm) stack was specifically designed to optimize phase evolution. In this structure, the 2-nm bottom HZO acts as a seed layer influenced by the TiN electrode, while the interlayer effectively promotes o-phase crystallization in the upper 7-nm HZO. A 50-nm-thick TiN top electrode was sputtered, followed by post-metallization annealing (PMA) at 400-700℃. The electrical characterization reveals that the insertion of a mid-interlayer significantly influences the crystallization kinetics and phase evolution of the HZO films. Moreover, the bandgap engineering provided by the 1nm insulating interlayer contributed to a substantial reduction in leakage current density by blocking the charge carrier transport paths. Consequently, the engineered HZO/IL/HZO capacitors demonstrated remanent polarization (2Pr) of 20-25 μC/cm^2 and a significantly suppressed leakage current density of ~ 10^{-8} A/cm^2, along with enhanced breakdown voltage, superior reliability characteristics, including stable retention compared to the single layer HZO counterparts. This study suggests that mid-interlayer engineering, combined with the low-damage RP-ALD process, is a viable solution for optimizing the performance of HZO-based ferroelectric memory devices. This work was supported by K-CHIPS(Korea Collaborative & High-tech Initiative for Prospective Semiconductor Research) (2410011219, RS-2023-00237030, 23027-15FC) and by the Technology Innovation Program (Materials & Components Technology Development (R&D)– Package-type) (RS-2025-02220734, Development of Manufacturing Technology for High-Purity iron chloride (>99.5%) and Sodium Silicate (>97.0%) via Utilization of Bayer Process Byproducts) funded By the Ministry of Trade Industry & Energy(MOTIE, Korea).

AA-TuP-12 High-quality CeO_2 thin films by low temperature atomic layer deposition using a new heteroleptic Ce precursor*, **Juri Kim**, Yewon Seo, Soo-Hyun Kim,* Ulsan National Institute of Science and Technology (UNIST), Republic of Korea

Cerium oxide (CeO_2) is a rare-earth oxide with a high dielectric constant, moderate bandgap, excellent chemical stability, and multiple valence states (Ce^{3+}/Ce^{4+}). Owing to these properties, CeO_2 has been widely investigated for applications such as CMOS gate dielectrics, SOFCs, gas sensors, and resistive switching memories. The formation of CeO_2 requires complete oxidation of Ce^{3+} to Ce^{4+}, which demands a relatively high oxidation potential. However, under low-temperature ALD conditions,the limited oxidation capability of conventional O_2- and H_2O-based oxidants often results in degraded film quality due to incomplete oxidation and residual organic species.To overcome these limitations, O_3 was selected as the oxidant in this study. Ozone (O_3) generates highly reactive oxygen species upon decomposition, providing strong oxidation capability and enabling effective low-temperature oxidation without plasma assistance. In this work, CeO_2 films were deposited by ALD (IOV dX1 PEALD reactor, ISAC Research, Korea) using aheterolepticcyclopentadienyl-amidinate Ce precursor and O_3 as the reactant. As shown in Figure 1, CeO_2 films deposited using O_3 exhibit stronger diffraction peaks than those grown with conventional oxidants (H_2O, O_2, and O_2 plasma), indicating improved crystallinity. The deposition temperature was conducted at temperatures ranging from 150 to 350 °C, with 200 °C determined as the optimal growth temperature. The self-limiting growth behavior was shown with both precursor pulsing and reactant pulsing and the saturated growth-per-cycle (GPC) was approximately 1.15 Å/cycle. Film properties varied with deposition conditions and were characterized by SEM (thickness), TEM (step coverage, thickness), XRR (density and thickness), XRD (crystallinity), XPS (composition) and RBS (impurity). Electrical properties were evaluated via Metal–Oxide–Semiconductor capacitors, focusing on dielectric constant and leakage current. The detailed results will be presented at the conference.

Acknowledgements

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AA-TuP-13 Drain-Current-Enhanced TiO_2-Thin-Film Transistors Fabricated by Atomic Layer Deposition*, **Ryo Miyazawa**, Tsubasa Takami, Masanori Miura, Bashir Ahmmad, Fumihiko Hirose,* Graduate School of Science and Engineering, Yamagata University, Japan

Nanometer-thick TiO_2-channel thin-film transistors (TFTs) are promising not only as high surface-sensitive sensors but also as active-matrix switching devices. InGaZnO (IGZO) has been used as a high-mobility TFT channels, offering around 10 cm^2/Vs. However, IGZO includes rare metals such as indium and gallium, leading to issues related to high cost geopolitical risks. On the other hand, TiO_2 is abundant on earth, non-toxic, although the field effect mobility of TiO_2-TFT was reported to be low due to defects in the film. In this study, the drain current enhanced TiO_2 TFTs were developed using atomic layer deposition.

We fabricated TiO_2-TFTs with a channel thickness of 16 nm as shown in Fig. 1, in which the channel surface was covered with an aluminum-silicate and SiO_2 periodical stacks. The stack layer serves as both the alkali metal absorber in the chloride solution and the meal diffusion source. The TiO_2 channel was deposited by atomic-layer deposition, followed by being annealed in dry air to induce crystallization. TFT samples were immersed in the alkali metal chloride solution, and it was assumed that the adsorbed metals were automatically diffused to the channel layer, which might contribute to deactivating the defects in the channel layer.

We confirmed the enhanced drain currents with CsCl and NaCl solutions as shown in Fig. 2. This suggests their potential as a high-mobility TFT. The effective mobility was calculated to be 83 and 46 cm^2/Vs for Cs and Na, respectively. XPS measurements suggested a reduction of TiO_2, which might contribute to the deactivation of the Oxygen-deficiency-related defects in the TiO_2 channel layer. In the conference, we shall discuss the current enhancement mechanism and applicability as an active-matrix switching devices.

AA-TuP-14 Exploring Dopant Candidates to Improve the Electrical Properties of TiO_2 Dielectric Thin Film*, Seungwoo Lee,* *Gaeul Kim,* Kyung Hee University, Republic of Korea*; Hansol Oh, Hanbyul Kim, Donghun Shin, Yongjoo Park,* SK trichem, Republic of Korea*; Woojin Jeon,* Kyung Hee University, Republic of Korea

Dynamic random-access memory (DRAM) has been continuously scaled down to reduce production costs and increase integration density, thereby reducing the area occupied by cell capacitors and decreasing cell capacitance. This decrease in cell capacitance reduces sensing margin in read operations. Therefore, a material with a higher dielectric constant (*k*) is required as an insulator in DRAM capacitors to recover cell capacitance. TiO_2 in the rutile phase is an attractive candidate due to its high *k* value (>100) and compatibility with atomic layer deposition. However, it has leakage current issues due to its small bandgap (~3 eV). Therefore, suppressing leakage current via conduction band offset control between TiO_2 and the electrode film, such as Al doping, was effective. However, Al doping significantly decreases the capacitance density of TiO_2.

In this work, we evaluated the effectiveness of Mg, Sc, Gd, and In as alternative dopants for replacing Al. Crystallinity of each doped TiO_2, as a function of dopant and concentration, was analyzed by grazing-incidence X-ray diffraction, and the trend was consistent with dopant formation energy results obtained from density functional theory (DFT)-based simulations. Additionally, we evaluated the electrical properties of each doped TiO_2 and elucidated the dopant-dependent mechanism of electrical properties changes using X-ray photoelectron spectroscopy analysis and DFT simulations. Consequently, the Sc dopant did not significantly degrade the dielectric constant of TiO_2 among dopant candidates, thereby further improving the electrical properties by controlling the Sc doping concentration gradient.

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AA-TuP-15 Leakage suppression and memory window optimization via Gd-doped HfO_2 charge-trap layers in 3D NAND*, **Lee Jonghyeok**, Jeon Woojin,* Kyung Hee University, Republic of Korea*; Nam Jihun,* Kyung Hee university, Republic of Korea*; Oh Hansol, Kim Hanbyul, Park Yongjoo,* SK trichem, Republic of Korea

Three-dimensional NAND (3D NAND) memories demand charge-trap stacks that provide wide memory windows at low programming voltages for reliable multi-level cell operation and reduced cell-to-cell interference. Hafnium oxide (HfO_2) has emerged as a promising charge-trap layer material because of its high dielectric constant and strong trapping capability.[1]However, uncontrolled intrinsic defects and non-uniform trap distributions in pristine HfO_2 often lead to leakage current and unstable charge storage.

To address these issues, previous studies have reported that Gd doping was employed to engineer the trap characteristics of HfO_2.[2]The substitution of Hf^{4+} by Gd^{3+} induces local lattice distortion and defect complexes, which suppress shallow oxygen-vacancy-related traps and generate energetically deeper trap states. These deep traps enhance charge confinement and suppress leakage pathways, resulting in an enlarged memory window and improved retention characteristics.

In this work, $Al_2O_3/HfO_2/Al_2O_3$ capacitors with Gd-doped HfO_2 layers (1–10%) were fabricated and evaluated using incremental step pulse programming. The 5% Gd-doped HfO_2 stack exhibited the widest memory window and the most efficient programming behavior, indicating an optimal deep trap density for charge storage. Electrical measurements further revealed that Gd doping improves the blocking characteristics by reducing leakage current, thereby enhancing charge retention performance.

Post-metallization annealing at 400 °C significantly modified the trap distribution, promoting the formation of deeper trap states and improving programming efficiency. In contrast, excessive Gd doping (≥10%) led to degraded hysteresis behavior, suggesting leakage-dominated transport due to excessive defect generation.

These results demonstrate that Gd-induced deep trap engineering, combined with thermal processing, provides an effective strategy for optimizing HfO_2-based charge-trap stacks, enabling low-voltage, wide-window, and high-reliability operation for future 3D NAND flash memory applications.

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AA-TuP-16 Leakage Current Suppression at Grain Boundary in Rutile TiO_2 via La Doping*, **Gaeul Kim**, Seungwoo Lee,* Kyung Hee University, Korea (Democratic People's Republic of)*; Hansol Oh, Hanbyul Kim, Donghun Shin, Yongjoo Park,* SK Trichem Co., Ltd., Korea (Democratic People's Republic of)*; Woojin Jeon,* Kyung Hee University, Korea (Democratic People's Republic of)

As dynamic random-access memory (DRAM) devices continue to scale down, the reduction of equivalent oxide thickness in cell capacitors has become increasingly critical, necessitating the use of high-k dielectric materials. Rutile-phase TiO_2 is a representative high-k material with dielectric constant of approximately 100 or higher; however, its relatively narrow bandgap and donor levels associated with oxygen vacancies lead to high leakage current. Therefore, acceptor doping using trivalent cations, particularly Al, has been investigated as an approach to reducing leakage current.

In this study, we propose a new approach to effectively suppress leakage current through grain boundary in TiO_2. Grain boundary is defect-rich regions where electron accumulation can readily occur, thereby acting as leakage current conduction paths. To suppress leakage current through grain boundary, La was doped to induce segregation toward grain boundary. Because La^{3+} has a larger ionic radius than Ti^{4+}, its substitution into the TiO_2 lattice is limited, and this significant ionic radius mismatch can promote preferential segregation of La at grain boundary. After La doping, post-deposition annealing (PDA) was performed to induce La segregation. Grazing-incidence X-ray diffraction analysis revealed that the rutile TiO_2 peak shifted toward higher angles after PDA at 600 °C compared to the as-deposited state. This shift indicates a reduction in the d-spacing of TiO_2 as La initially present within the lattice migrated to grain boundaries during annealing, supporting the occurrence of La grain boundary segregation. Furthermore, electrical characterization showed a significant reduction in leakage current in La-doped TiO_2 dielectrics, which is attributed to the effective suppression of grain-boundary-related conduction paths. These results suggest a novel mechanism for reducing leakage current in rutile TiO_2-based high-k dielectrics and provide a promising approach for next-generation DRAM capacitor applications.

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AA-TuP-17 Development of Si-C-Si Bond-Containing Precursors for SiOC Thin Films*, **Kazutaka Takahashi**, Akihiko Ohtsu, Tomonori Takahashi, Aina Ushiyama, Motomasa Takahashi, Shuhei Yamaguchi, Masaki Morita, Takeshi Yoshioka, Nobuhiko Takano, Hiroshi Komatsu,* FUJIFILM Corporation, Japan

This study reports on the development of novel organosilicon precursors specifically tailored for the atomic layer deposition (ALD) process of silicon oxicarbide (SiOC) thin films. First, to design precursor structures effective for ALD, we established a computational framework for systematically evaluating the adsorption energy, activation energy, and reaction energy of precursors. This enabled the selection of an optimal precursor structure with a stable Si-C-Si backbone. Subsequently, we successfully synthesized the precursor based on a unique chemical path. The resulting ALD of the precursor demonstrated obviously higher growth per cycle (GPC) compared to conventional precursors, and the ALD film included Si-C-Si bonds well. Furthermore, by analyzing dependency of process temperature, precursor dose time, and ozone dose time, ALD based film growth mechanism was clarified. A notable challenge in high–temperature ALD processes is that the carbon concentration in the film generally decreases as process temperature increases. Moreover, process modifications aimed at increasing the carbon ratio typically led to a deterioration in both GPC and in–plane uniformity. In this work, however, by carefully optimizing the process conditions, we successfully achieved high carbon concentration, high GPC, and good in–plane uniformity simultaneously, even under high–temperature deposition conditions.

AA-TuP-18 Modeling of Negative Capacitance FETs for Sub-60 mV/dec Switching through PEALD-HZO Ferroelectric Thin Films, ***Bo Hyeon Kim**, So Won Kim, Jae Hyuk Choi, Hee Chul Lee,* Department of Advanced Materials Engineering, Tech University of Korea

Since the discovery of negative capacitance (NC) in ferroelectrics, extensive research has been conducted in the field, with the Negative Capacitance Field-Effect Transistor (NC-FET) emerging as a breakthrough technology. NC-FETs have attracted significant attention for their ability to lower the subthreshold swing (SS) below the fundamental limit of 60 mV/dec at room temperature, making them highly advantageous for suppressing leakage current and realizing ultra-low-power devices.

In our previous study [1], we successfully deposited (HZO) ferroelectric thin films with relatively good polarization and reliability characteristics using a Co-Plasma ALD (CP-ALD) process, which simultaneously utilizes both direct and remote plasmas, as shown in Fig. 1. However, the inherent polarization hysteresis of ferroelectrics remains a significant challenge for switching device applications. To precisely control the NC characteristics, optimized capacitance matching through a ferroelectric-dielectric (FE/DE) stacked structure is essential [2].

Based on the characteristics of the HZO thin films deposited via our group's CP-ALD process, we modeled the electrical performance of MFIS-structured NC-FETs by stacking ferroelectric and dielectric layers, as illustrated in Fig. 2(a). For a 15-nm-thick ferroelectric HZO layer, the subthreshold swing (SS) was modeled as a function of the dielectric layer thickness, using Al_2O_3(k9) and HfO_2(k25) as the dielectric materials.

The results indicate that sub-60 mV/dec SS values are achieved when the dielectric thickness is below 1.4 nm for Al_2O_3 and 5.4 nm HfO_2. In particular, the most stable and lowest SS values were observed at thicknesses of 1.4 nm for Al_2O_3 and 3.8 nm for HfO_2. Especially, HfO_2 exhibited a much broader thickness window for maintaining an SS below 60 mV/dec compared to Al_2O_3. The optimized SS of the NC-FET improved by up to 12 mV/dec compared to that of a conventional MOSFET without a ferroelectric layer.

Additionally, to analyze the NC phenomenon in a practical polarization-switching environment, we will present modeling results based on the Nucleation-Limited Switching (NLS) theory, which accounts for the time-dependent transient polarization characteristics of ferroelectrics.

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AA-TuP-19 Enhancing Tetragonal Phase Stability of HfO_2 Dielectrics via Oxidation-State Engineering of VOx Interlayer, ***Yejin Han**, Woojin Jeon, Iksun Kwon,* Kyung Hee University, Republic of Korea*; Jaemin Kim, Duckhyeon Seo, Juhwan Jeong, Sunyoung Baik, Woongjin Choi, Kyuho Cho,* EGTM Co., Ltd., Republic of Korea

As Dynamic random-access memory (DRAM) capacitors continue to scale down, capacitance loss and increased leakage current become critical challenges, necessitating high-k dielectrics with improved phase stability. HfO_2 is widely used due to its high dielectric constant and adequate bandgap;[1] however, its stable monoclinic phase limits further equivalent oxide thickness (EOT) scaling, and stabilization of the tetragonal HfO_2 phase is therefore required.[2]

In this work, vanadium oxide (VO_x) was employed as an interfacial layer to modulate the interfacial oxygen environment and promote tetragonal HfO_2 formation. VO_x films were deposited by atomic layer deposition, and their oxidation states were analyzed by X-ray photoelectron spectroscopy as a function of process temperature. At 150 °C, the VO_x film exhibited a V^{5+}-dominant composition (84.22%, O:V = 2.88), whereas increasing the temperature to 300 °C increased the V^{4+} fraction to 58.07% (O:V = 2.16), indicating controllable oxidation-state tuning from V_2O_5-like to VO_2-like.

When an ultrathin VO_x interlayer (1–2 nm) was inserted between TiN and HfO_2, the tetragonal HfO_2 phase emerged after annealing, while no tetragonal phase was observed without VO_x. Post-annealing of VO_x at 500 °C revealed that VO_2(M) crystallization occurred only under an oxygen partial pressure of 25 mTorr, whereas higher oxygen partial pressures led to excessive oxidation and V_2O_5 formation.

In TiN/HfO_2/VO_x/TiN structures, the tetragonal HfO_2 fraction exhibited a dome-shaped dependence on oxygen partial pressure, reaching a maximum when the VO_x interlayer was VO_2-like (V^{4+}-dominant). These results demonstrate that oxidation-state-engineered VO_x effectively regulates interfacial oxygen vacancy conditions, enabling stable tetragonal HfO_2 formation and providing a viable pathway for advanced DRAM capacitor scaling. Such stabilization of the tetragonal HfO_2 phase is expected to enhance the effective dielectric constant, enable further EOT scaling, and improve leakage current characteristics through optimized oxygen vacancy control.

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AA-TuP-20 Minimisation of Platinum Loading on the Porous Transport Layer in Pem Water Electrolysers, ***Athina Tzavara-Roussi**, Volkert van Steijn, Ruud van Ommen,* Delft University of Technology, Netherlands

Proton exchange membrane water electrolysis (PEMWE) is considered a highly promising technology for converting intermittent renewable electricity into green hydrogen, yet it relies on scarce platinum-group metal for their catalytic activity and chemical stability, which could significantly limit scalability. The porous transport layer (PTL) is a critical component, typically made of titanium, on the anode of PEM electrolysers, since it facilitates the electron and mass transfer between the catalyst sites and the bipolar plates. A major challenge stems from the oxidation of the PTL in the highly oxidative anodic environment, which significantly reduces electrical conductivity and limits catalyst utilization. To protect the contact points between the anodic layers, the commercial solution involves the platinization of the PTL. However, this approach not only increases further the manufacturing costs, but also results in poor coating conformity thus risking its long-term durability.

This study investigates the use of ALD to achieve a conformal and uniform Pt coating on the PTL surface, in combination with evaporation to increase the coating thickness. We examine how the Pt loading, morphology, and thickness affect the performance and durability of the layer in a 4 cm^2 single PEM cell, identifying which coating configuration provides optimal protection for the PTL. Finally, we evaluate the deposition of iridium oxide to transform the PTL into a porous transport electrode and assess its electrochemical performance.

This project receives a Dutch National Growth Fund contribution from the programme NXTGEN HIGHTECH.

AA-TuP-21 Characterization of ALD-like SiCO Layers for MOL and BEOL Applications: Influence of Etching Plasma and Wet Clean, ***Alexandre Ponchon**, Emmanuel Petitprez, Pierre Brianceau, Benoit Martin, Melanie Dartois, Antoine Raison, Nicolas Gauthier,* CEA/LETI-University Grenoble Alpes, France

Atomic Layer Deposition (ALD) enables precise control of layer thickness at the atomic level, making it more suitable than Chemical Vapor Deposition (CVD) for etch stop layers (ESLs) in advanced transistor manufacturing. ESLs are crucial for precise pattern transfer and underlying structures protection during etching. As device dimensions continue to scale, there is an increasing demand for ultrathin and uniform ESLs with well-controlled thickness and etch selectivity.

In this work, we investigate the use of SiCO layers deposited by Single Precursor Activated Radicals Chemistry [1] (SPARC) process (a new technique in-between CVD and ALD), as SiN dry etch stop layer for MOL (middle of line) and BEOL (back-end of line) applications. We focus on the impact of the carbon elemental composition on the SiCO layer's resistance to standard wet clean chemistries and its ability to maintain ESL properties under etching plasma exposure.

We use 30nm thick SiCO layers, deposited at 400°C, with carbon content varying from 3% to 13%. We characterize the material resistance to standard wet clean chemistries and to two plasma etching chemistries (CH3F/O2/Ar and CH3F/H2), by monitoring the layer thickness before and after the process steps using a spectrometric ellipsometer. We assess the impact of the etching plasma on the remaining SiCO material through Secondary Ion Mass Spectrometry (SIMS) elemental depth profiles.

Results show that SiCO layers exhibit high resistance to wet clean chemistries, with minimal thickness loss observed only in low carbon content films exposed to diluted HF, and its resistance increases as the carbon composition increases. After exposure to the plasma chemistries used for SiN dry etch, all SiCO layers show thickness reduction, with oxygen-based plasma causing greater removal than hydrogen-based plasma. Plasma etching modifies a few nanometers of the remaining SiCO film, which becomes an O-rich layer that can be removed with a dHF dip. The altered layer thickness is more substantial with hydrogen-based plasma, and higher carbon content results in shallower modifications.

These findings show that this SiCO layer deposited by SPARC is a promising material for MOL and BEOL ESL applications as it has a high resistance to both dry and wet etching processes while being easily removable after undergoing a plasma etch.

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AA-TuP-22 In Situ, Simultaneous Spectroscopic Ellipsometry and Quadrupole Mass Spectrometry Studies of Aluminum Doped ZnO Etching Using β-Diketones*, **Maahir Rahi**, Terrick Mcnealy-James, Justin Moore, Titel Jurca, Parag Banerjee,* University of Central Florida

Atomic layer etching (ALE) offers sub-nm level control over film removal and presents promising solutions to address patterning challenges in device manufacturing. These mechanisms become particularly important when the extended atomic structure of films such as crystal facets, grain boundaries, and dopants are taken into consideration.

In this work, we investigate the thermal ALE of aluminum doped zinc oxide (Al:ZnO) using β-diketonate-etchants such as, acetylacetonate (Hacac) and hexafluoro acetylacetonate (HFacac), by depositing monolayers of Aluminum into Zinc oxide. We utilize *in situ* spectroscopic ellipsometry (SE) and quadrupole mass spectrometry (QMS), enabling real time correlation between thickness evolution and reaction by-products. By coupling these techniques, this work provides insight into kinetics, reaction pathways, and the role of dopants.

AA-TuP-23 Terpineol Doped ALD Al_2O_3 Films for Low-K Materials: Effect of Terpineol Ratio and Metal Precursor Size on Structural and Dielectric Properties*, **Sovendo Talapatra**, Noah Zahn, Nicholas Strandwitz,* Lehigh University

Research on low-κ dielectric materials is becoming critically important to deal with capacitance delays of due to decreasing dimensions of integrated circuits. Herein, we will report the structural and dielectric properties of terpineol-doped Al_2O_3 films where terpineol acts as a sacrificial agent or porogen, leaving porosity in the films after post-deposition annealing treatment. Terpineol-doped films were deposited by atomic layer deposition (ALD) and the modification of the porosity by changing the ratio of terpineol pulse in between the metal precursor and H_2O co-reactant was explored. The choice of metal precursor also influences the porosity generation in the film because of the steric hindrance and reactivity of the precursor. Three metal precursors, trimethylaluminum (TMA), aluminum tri-sec-butoxide, and tri-i-butylaluminum will be used to study the density, dielectric constant of the films. X-ray reflectivity will be used to measure the density of the films. For TMA to terpineol ratio 1:1, initial result showed 17% decrease of density for as deposited terpineol doped films than ALD Al_2O_3 at 120°C. Dielectric constant of the films will be measured using capacitance-voltage measurement. For as-grown terpineol-doped films the initial measurement also showed dielectric constants as low as 4 compared to a value of ~7 for ALD grown Al_2O_3. Our work shows that small molecule inclusions in ALD is a useful strategy for the growth of porous and low-κ thin films, while still retaining the benefits of precise thickness control and conformality afforded by ALD.

AA-TuP-24 High Rate, Tuneable Dielectric Nitrides by Plasma Atomic Layer Deposition Enabling Volume Manufacturing for Gan Device Integration*, **Arpita Saha**, Elliot Gay, Dmytro Besprozvannyy, Aileen O'Mahony, Michael Powell, Andrew Newton,* Oxford Instruments Plasma Technology, UK

Gallium Nitride (GaN) has recently expanded into power electronics, RF,microLEDs and VCSELsmarkets.The adoption of GaN transistors in high volume consumer-based power electronicsis driven by the need for smaller, faster, efficient mobile device chargers.It has been predicted the GaN power device market will reach $3B by 2030[1]supported by a broader range of applications including renewable energy, data centres, electric vehicles, and infrastructure for 5G and 6G networks.

These emerging GaNmarkets require uniform,conformal,low damage plasma processing solutions optimised for 200 mm wafers to improve device performance,throughput, andyieldat reduced cost.Plasma enhanced atomic layer deposition (PEALD) has been used in GaN transistors for low damage,[2]uniform passivation layers (Al_2O_3,[3] SiN), as a method of optimizing the interface using native oxide removal nitridation[4,5]followed by deposition of high-quality nitrides like AlN.

High throughput plasma ALD of SiN is beneficial for GaN device processing at low temperature (≤500 °C) compared to LPCVD (≥700 °C)and thermal ALD (>450 °C) without compromising on conformality (compared to PECVD)[10]or uniformity up to 200 mm wafer size. PEALD SiN has also been shown to reduce trap defect density in GaN transistors compared to other deposition techniques and materials.[11]Optimisation of the plasma processing parameter scan achieve SiN films with tuneable growth rate,composition,and refractive index.[12, 13].

PEALD processes forAlN and SiN have been developed achieving excellent thickness and refractive index uniformity across 200 mmSi wafers using Oxford Instruments Atomfab ALD system which uses apatented capacitively coupled (CCP)[3] remote plasma source. Using Oxford Instruments' novel CCP remote plasma source, and a low chamber volume, increase in deposition rate has been achieved when comparing to an inductively coupled plasma source (ICP) process. For example, we have been able to achieve 8 times faster deposition rate for AlN films using our CCP remote plasma source compared to ICP plasma.The composition of the AlN and SiN films were measured by XPS resulting in low C% and O% content. The ToF-ERDA showed low H% content in SiNx films while the wet-etch rate was better for the films produced using the CCP plasma source compared to the films produced by ICP plasma source. The breakdown voltage and the dielectric constant for the as deposited SiNx film obtained was >10.5 MV/cm and >6 for 30 nm film respectively.

To support the production ramp of the GaN transistors, high throughput tuneable AlN and SiN processes using plasma ALD along with optimized surface pre-treatment has been developed by Oxford Instruments negating the need for extended plasma exposure,high temperature depositionor temperature ramping within the process.The estimative wafers produced per hour for AlN (3 nm films) is 11 WPH and for SiNx (5 nm films) is 10 WPH.

AA-TuP-25 Enhanced Electrical Characteristics in CAAC-IGZO Memory Devices Using 2600W Remote-Plasma-Processed HfO_2 and H_2 Passivation at the CAAC-IGZO/Al_2O_3 Tunneling Interface*, **Hyeon Wu Nam**, Chang Bun Yoon, Byung Wook Kim, Yong Woon Jang, Min Kyun Kang, Chang Yun Hong,* Department of Advanced Material Engineering, Tech University of Korea

Charge trap memory devices employing a sputtered CAAC IGZO channel were fabricated using an Al_2O_3/HfO_2/Al_2O_3 dielectric stack as the blocking, charge trapping, and tunneling layers. All dielectric layers were deposited by remote plasma atomic layer deposition, while the CAAC IGZO channel was formed by sputtering to preserve its crystalline–amorphous composite structure. The electrical characteristics of the devices were systematically compared with those incorporating dielectric layers deposited by direct plasma ALD. Devices with remote plasma–processed dielectrics exhibited an enlarged memory window and reduced leakage current. Material analysis revealed a decreased concentration of oxygen vacancies in the HfO_2 charge trap layer for the remote plasma ALD process compared to direct plasma ALD. In addition, remote hydrogen plasma treatment was employed at the channel–tunneling layer interface, effectively passivating interfacial defects between the CAAC IGZO channel and the Al_2O_3 tunneling layer. This interfacial defect reduction enhanced charge injection and trapping efficiency. The combined effects of reduced bulk defects in HfO_2 and improved interfacial quality in the dielectric stack contribute to enhanced charge storage characteristics in CAAC IGZO–based memory devices.

Quantitatively, the incorporation of remote plasma–processed dielectrics led to a substantial enhancement in device performance, with the memory window expanded by up to ~6 V, a ~0.1 V dec^{-1} improvement in subthreshold swing, and an on/off current ratio increased to the order of ~10^7.In addition, the field-effect mobility reached values as high as ~20 cm^2 V^{-1} s^{-1}, demonstrating that the RP approach effectively improves both charge storage capability and channel transport characteristics.

This work was supported by K-CHIPS(Korea Collaborative & High-tech Initiative for Prospective Semiconductor Research) (2410011219, RS-2023-00237030, 23027-15FC) and by the Technology Innovation Program (Materials & Components Technology Development (R&D)– Package-type) (RS-2025-02220734, Development of Manufacturing Technology for High-Purity iron chloride (>99.5%) and Sodium Silicate (>97.0%) via Utilization of Bayer Process Byproducts) funded By the Ministry of Trade Industry & Energy(MOTIE, Korea).

AA-TuP-26 Impact of Oxidant on Conformal HZO ALD in High Aspect Ratio Structures

***Soham Shirodkar**, Dushyant Narayan,* The University of Texas at Dallas*; Dan N. Le,* RASIRC, University of Texas at Dallas*; Thi Thu Huong Chu, Soubhik De, Minjong Lee,* The University of Texas at Dallas*; Adrian Alvarez, Lorenzo Diaz,* RASIRC*; Jiyoung Kim,* The University of Texas at Dallas

The scaling of advanced DRAM technologies requires complex structures with high aspect ratio (HAR) trenches and cavities and is currently transitioning to 3D integration to sustain performance improvements.[1] Hafnium based oxides are key materials for the cell capacitor in DRAM cells due to their high dielectric constant and wide bandgap. To achieve conformal growth in HAR structures, ALD processes often use large precursor and oxidant doses to ensure reactant transport into deep features [2]. However, excessive oxidant dosing can promote undesirable interfacial oxidation, particularly on metal electrodes. To address this, we identify differences in oxidant efficiency during HAR filling and evaluate the role of various counter-reactants on conformal growth.

To understand the effect of counter reactant choice, we first investigated growth characteristics on planar substrates. We found that the oxidant dose required to reach saturation was different for each oxidant. Namely, we found that H_2O_2 required a smaller dose than O_3 to saturate each ALD cycle. Saturation at a reduced oxidant dose implies a potential for improved filling in HAR structures at lower doses while mitigating excessive interfacial oxidation due to high dosing.

Based on the observations for planar substrates, vertical HAR substrates with AR ranging from ~20:1 up to ~60:1 were used to evaluate the conformality of each process. Furthermore, to enable quantification of penetration depth, specially designed horizontal Ultra-HAR structures with AR up to 10,000:1 were used, and analysis of growth areas were performed using SEM and EDX (Fig. 1). The extent of growth into the cavity was used to assess the deepest achievable filling as a function of both oxidant and precursor dosing. Alongside the horizontal structures, conformality was also evaluated in vertical trenches with smaller critical dimensions, providing access to more extreme confinement where precursor transport is further limited (Fig. 2). We found that increasing precursor dose improves transport into confined geometries, with signatures of oxidant-dependent effects on HAR filling. Overall, these results show that oxidant choice plays an important role in ALD growth in HAR structures for the stringent demands of next-gen semiconductor devices.

We acknowledge RASIRC for providing BRUTE® Peroxide and TMEIC for providing the ozone generator (OP-250H). This work was supported by Samsung Electronics Co., Ltd. (No. IO221018-03002-01). We would also express our gratitude to Chipmetrics for providing the UHAR substrates.

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AA-TuP-27 Stable High-k Morphotropic Phase of $HfZrO_4$ Using Uniformly Distributed Dopants

***Nguyen Vu**, Charlene Chen, Sunil Ghimire, Ray Meck, Jared McWilliams,* EMD Electronics, USA

Since the 1950s, the morphotropic phase boundary (MPB) has attracted considerable attention due to the anomalous increase in the dielectric constant in this region. It is now gaining rapid growth in research on hafnia-based dielectrics as a novel approach to achieve low equivalent oxide thickness (EOT) without sacrificing leakage. Unlike the traditional nanolaminate approach, this work investigates the formation of the MPB phase in HZO dielectrics with uniformly distributed dopants through atomic layer deposition and annealing within the back-end-of-line thermal budget. It is found that the more homogeneous the dopant distribution, the better the dielectric performance. The resulting doped HZO with a physical thickness of 50 Å exhibits a low leakage current of $2x10^{-5}$ A/cm^2 and an EOT of 5.4 Å. Different strategies for achieving the desired dopant distributions are discussed, highlighting the potential of precursor development to reach the optimal performance.

AA-TuP-28 ALD Oxide Coatings for Anti-Stiction MEMS Applications Compatible with 500 and 1000 °C Wafer Bonding

***Eric Reed**, Matthew Weimer, Arrelaine Dameron,* Forge Nano*; Robert MacDonald, David Lin,* GE Aviation, USA*; Mohammad Megdadi,* University of Nebraska - Lincoln*; Mary Ann Maher,* Soft MEMS

As MEMS devices continue to shrink and the operational range demands increase, they increasingly suffer from irreversible stiction, in which surface forces, such as van der Wall forces and electrostatic forces, exceed the forces required to separate moving components, the restoring force. Some attempts to reduce surface adhesion include the reduction of surface energy by application of self-assembled monolayers (SAM) or diamond-like carbon coatings (DLC) and low surface area contact points, such as bump stops. However, these methods become less effective as MEMS devices continue to approach nanoscales. For example, SAM coatings become more susceptible to defects and non-conformal films as the aspect ratio increases. Additionally, DLC and SAM coatings are incompatible with high-fidelity packaging methods, like direct wafer bonding, which occurs under >1000 °C annealing conditions. DLCs suffer from adhesion instability while SAM coatings completely degrade at this temperature. Atomic Layer Deposition (ALD) overcomes these deficiencies by providing conformal, temperature-stable films. Engineering surface roughness and film stability is, therefore, one path to improving device reliability. This study investigates which ALD thin films provide the greatest surface roughness with sufficient adhesion to silicon substrates. Silica (SiO2), hafnia (HfO2), and titania (TiO2) films were deposited on Si 〈100〉 coupons using thermal ALD and subsequently annealed in an inert environment, at 500 °C and 1000 °C, to simulate various MEMS wafer bonding processes. The films were evaluated for changes in crystallinity, surface roughness, and composition. SiO2, used as a control, exhibited minimal changes in structure and roughness. HfO2, initially polycrystalline, showed increased crystallinity and surface roughness with annealing while maintaining film stability. When applied to a MEMS test structure, the 1000 °C annealed HfO2 film showed a significant reduction in stiction, compared to the coated features. In contrast, TiO2 underwent a significant crystallographic phase transition at >700 °C and delaminated, likely due to film stress. These results indicate that polycrystalline HfO2 offers a stable, roughened surface capable of reducing attractive forces responsible for MEMS stiction failures. Future work will evaluate thermally deposited ALD HfO2 directly on MEMS accelerometers and gyroscopes to quantify its impact on device performance and reliability.

AA-TuP-29 Enhancing ZrO_2–based DRAM capacitor performance by employing atomic layer deposited In_2O_3 electrode via Mo doping

***Hunseok Son**, Woojin Jeon,* Kyung Hee University, Republic of Korea

As dynamic random-access memory (DRAM) scales down to achieve higher integration, electrode engineering to mitigate insufficient capacitance and excessive leakage current remains a critical challenge. TiN electrodes and ZrO_2 dielectrics are widely used in metal-insulator-metal (MIM) capacitors because of their excellent process compatibility. However, TiN electrodes deplete oxygen from ZrO_2 at the ZrO_2/TiN interface via an oxygen-scavenging effect, forming undesirable TiO_xN_y. This accelerates leakage and degrades performance.[1] The formation of these oxygen defects degrades not only the electrical characteristics but also the overall performance of the MIM capacitor. The initial spacing is not correctly formatted. Furthermore, nitrogen diffusion into ZrO_2 reduces the bandgap, resulting in degradation of leakage current characteristics.[2] Therefore, oxide-based electrodes are more suitable for use with ZrO_2 than nitrogen-based electrodes. To overcome these limitations, we propose an approach that uses Mo-doped In_2O_3 bottom electrode grown by atomic layer deposition (ALD). During thermal treatment, Mo-doped In_2O_3 exhibits a change in oxidation state to Mo^{4+}, which substitutes for In^{3+}, resulting in high electrical conductivity due to increased free electrons and low resistivity.[3] Furthermore, its low roughness provides excellent electrode characteristics for MIM capacitors. [4] In terms of crystallinity, here to, the initial spacing is incorrect. The cubic phase In_2O_3 (400), formed by Mo doping in In_2O_3, exhibits good crystallographic compatibility with the tetragonal phase ZrO_2 (002). The formation of t-ZrO_2 (002) enables higher capacitance in ZrO_2-based MIM capacitors fabricated on Mo-doped In_2O_3. The high work function (~5 eV[5]) of Mo-doped In_2O_3 provides a distinct advantage over TiN (~4.2 eV[6]). This high work function contributes to leakage suppression, thereby enhancing the device's overall performance. Additionally, In_2O_3 has a significantly lower oxygen vacancy formation energy (~2.4 eV) than ZrO_2(~6.2 eV), enabling oxygen transfer to ZrO_2.[5] This mechanism not only suppresses the formation of sub-interface oxides, unlike TiN electrodes, but also reduces defect density within the ZrO_2 layer, minimizing unwanted conduction and improving interface stability. Consequently, replacing TiN with the ALD-grown Mo-doped In_2O_3 bottom electrode offers a practical, scalable solution. Mo-doped In_2O_3 provides sufficient capacitance while suppressing leakage current and enhancing stability, thereby strengthening the integrity of the MIM capacitor structure. This paves the way for continued dielectric scaling and improved reliability in advanced DRAM technology.

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AA-TuP-30 Advanced Seamless Lateral Gap-fill Process for 3D Structures via a New Approach*, **Yudeuk Kim,** Seunghee Cho, Kwangseon Jin,* Wonik IPS, Republic of Korea*; Hoon Kim,* Wonik IPS*; Wontae Noh, Taewan Lee, KYUNGPIL NA, Jaehun Lee, Jiwon Moon, Hyung mook Lim,* Wonik IPS, Republic of Korea

Like 3D NAND scaling progresses, the integration of 3D DRAM and advanced logic architectures requires highly conformal dielectric gap–fill capability within increasingly complex high–aspect–ratio structures. Conventional deposition schemes optimized for vertical profiles exhibit insufficient step coverage in lateral cavities, resulting in seam and void formation due to precursor transport limitations and restricted surface reaction accessibility. Moreover, the enlarged effective surface area significantly reduces throughput, forcing reliance on iterative deposition–etchback cycles that remain inefficient and inherently unsuitable for uniform lateral gap–fill.

To overcome these limitations, a novel ALD based gapfill strategy has been developed, enabling fully seamless void free filling across both vertical and lateral geometries. TEM analysis confirms that while conventional processes show pronounced internal seams shown in Fig. 1 (a), the newly engineered process demonstrates complete elimination of interfacial defects, ensuring structurally dense and continuous films throughout the entire 3D topology in Fig. 1 (b). This approach delivers improved structural robustness, enhanced conformality, and high productivity, positioning it as a key enabling technology for next generation high density 3D device fabrication.

AA-TuP-31 *Modeling the Dynamics of Surface Coverage in Atomic Layer Deposition for Multilayer Lateral Trench Structures, Jin Hak Kim,* *Yoon Jae Won, Jun Soo Shin,* WONIK IPS, Republic of Korea

As AI technology advances and the need for high-performance memory semiconductors increases, 3D DRAM manufacturing technology is one of the promising technology to increase memory capacity. To reduce high experimental costs and increase process development speed, it is important to estimate processing time in the atomic layer deposition process. As the number of lateral trenches increases, the adsorption area increases compared to when there are only vertical trenches. Our simulation shows that the minimum saturation time for conformal atomic layer deposition is proportional to the aspect ratio in the lateral and vertical directions. Due to the effect of gas particles being re-emitted from the bottom of the trench, the minimum surface coverage area is located away from the bottom of the lateral and vertical trench surfaces. The result is similar to those in a paper simulating adsorption inside lateral channels.1

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AA-TuP-32 Nucleation Dependence of ALD on Diamond for Surface Processing in Quantum Applications*, **Jessica Jones,** Jeffrey Elam,* Argonne National Laboratory, USA

The surface termination and interfacial interactions of materials for quantum technologies are critical.Use of atomic layer deposition (ALD) has been explored to provide insight on the chemical environment of the surface while passivating the surface.We explore the nucleation and growth of ALD Al_2O_3 and TiO_2 on diamond surfaces used for quantum sensing.We demonstrate the suppression of dark spins on diamond surface after coalescence of the TiO_2 ALD film on the surface.Additionally, we demonstrate that the nucleation of ALD Al_2O_3 using dimethylaluminum isopropoxide (DMAI) and water is sensitive enough to distinguish between the common surface termination types (H- terminated and O-terminated).We also evaluated methods to pretreat the diamond surface prior to passivating the surface with ALD Al_2O_3. We used in situ spectroscopic ellipsometry measurements to monitor the surface reactions and evaluate the ALD Al_2O_3 nucleation process as a function of different ex situ and in situ surface pretreatments. We found that in situ water dosing and high vacuum annealing provided the most favorable environments for nucleation of ALD Al_2O_3 using DMAI and water ALD. Hydrogen termination passivated both smooth and rough surfaces while triacid cleaning passivated the smooth surface only, with striking effectiveness.

AA-TuP-33 Atomic Layer Deposition on Reduced Activation Ferritic Martensitic Steel for Nuclear Fusion Applications*, **Soren Bentley,*** UK Atomic Energy Authority, UK*; Zachary Robinson, Mark Wittman,* University of Rochester*; Matthew Sharpe,* University of Rochester, UK*; Rashad Ahmadov, Josh Ruby,* University of Rochester*; Jeffrey Woodward,* Naval Research Laboratory*; Alexander Kozen,* University of Vermont

Nuclear fusion holds immense potential to reshape the global energy landscape. To develop mature technologies that can be deployed at power-plant scale, numerous materials-science challenges must be solved. One critical example is the safe, efficient, and loss-free handling of tritium (hydrogen-3), an essential fuel for fusion energy. Tritium permeates many of the materials used in reactor components, leading to structural embrittlement and other hazards associated with the fuel's radioactive properties. Atomic layer deposition (ALD) is emerging as a promising technique for the development of Al_2O_3 permeation barrier coatings that reduce loss of tritium. ALD's ability to produce high-quality, uniform films across complex geometries and components makes it advantageous compared to techniques limited to planar substrates. Though ALD Al_2O_3 coatings are well studied on semiconductor-relevant substrates, the work presented here reports the use of a custom-built ALD system to carry out the first syntheses on fusion-grade reduced-activation-ferritic-martensitic (RAFM) steel.

Prior to deposition, 1 cm × 1 cm RAFM steel substrates were prepared by polishing them to ~15 nm root mean square surface roughness. Al_2O_3 films were then deposited using a thermal ALD process with trimethylaluminum (TMA) and water precursors. Deposition was performed at temperatures between 100–200 °C to determine optimal growth conditions. Once this was achieved, growth rate curves were measured.

The films were characterized using X-ray photoelectron spectroscopy (XPS), X-ray diffraction (XRD), X-ray reflectivity (XRR), and spectroscopic ellipsometry. Our XPS results indicate that the RAFM surface is predominantly iron, in addition to small quantities of chromium oxide. ALD films were primarily stoichiometric Al_2O_3, with some growth conditions resulting in a small aluminum hydroxide component. The XRR and ellipsometry data were used to determine film characteristics such as morphology and ALD film thickness. This required the development of a model in which the film was represented as three layers: a low-density surface oxide, a denser bulk oxide, and an interface oxide in contact with the substrate surface. Growth rate curves and other process development will be presented.

AA-TuP-34 Mitigating Bow CD in Sub–20 nm HARC: SEM3D Modeling of Mask Taper and Cyclical Deposition–Etch Dynamics*, **Prabhat Kumar,** Lin Yu, Lin Zhao, Harsh Meena, Min Huang, Nandita Ghodki, Sankar Sarma, Sasan Shadpour, Jeff Lucas, Mingmei Wang, Taner Ozel,* Lam Research Corporation

As HARC feature sizes push below 20nm, maintaining stringent critical dimension (CD) control is essential for device performance, reliability, and yield. In advanced etch stacks, post–etch profiles are highly sensitive to incoming mask geometry, with across–wafer bow CD emerging as a dominant systematic variation. Tapered or necked mask profiles exacerbate ion angular scattering and polymer transport imbalance, producing non–uniform sidewall evolution and CD drift. To quantify and mitigate these effects, we employed a physics–based SEMulator3D (SEM3D)† workflow calibrated via Bayesian optimization to experimental profiles and plasma fundamentals. The calibrated model captured ion–limited etching, neutral–assisted deposition, and polymer redeposition, with the incident ion angular distribution represented by a Voigt profile consistent with pulsed–bias operation.

Tapered, straight, and reverse taper masks revealed a near linear dependence of both bow CD and mask selectivity on mask taper: larger taper increases bow while improving selectivity due to a larger effective opening. A design of experiments (DOE) varying top and bottom CDs confirmed the trade space—bow CD decreases with smaller bottom CD, whereas selectivity improves with larger top CD—exposing a fundamental limitation when taper is left unaddressed. To break this constraint, we introduced a targeted deposition step engineered to reduce taper and drive the mask toward a straighter geometry prior to etch. By tuning the sticking coefficient of depositing neutrals, we modulated within via deposition depth—lower sticking promoted deeper, more conformal coverage—thereby straightening the sidewall and suppressing taper induced aberrations. Simulations showed substantial bow reduction for straightened profiles.

In addition, we investigated **cyclical deposition–etch** sequencing to manage the *dynamic* evolution of bow and the risk of top–CD clogging. A dedicated cyclical–process DOE varying sticking coefficient, per–cycle deposition thickness, and cycle count demonstrated that bow growth rate can be actively controlled by tuning deposition parameters and cadence. Low–sticking, moderate–thickness cycles provided the best balance—minimizing bow growth (30–60% retardation observed in simulation) while avoiding opening pinch–off—whereas high–sticking films favored top–side accumulation and premature constriction.

Overall, this study quantifies its impact with a calibrated SEM3D model and demonstrates two complementary mitigation paths: (1) pre–etch deposition to straighten the incoming profile and (2) optimized cyclical deposition–etch to dynamically stabilize sidewalls and suppress bow growth without inducing clogging. Together, these strategies improve across–wafer CD uniformity and expand process window for next–generation HARC nodes.

†SEMulator3D® is a semiconductor process modeling platform that offers wide ranging technology development capabilities. This product is offered through Lam Research.

AA-TuP-35 Low-Temperature ALD Rutile TiO_2 Buffer Layers for VO_2-Based Smart Windows: Towards Flexible Substrates*, **Jan Leithäuser**, Waafa Al Nachwati, Philip Klement, Jörg Schörmann, Sangam Chatterjee, Martin Becker,* Justus Liebig University Giessen, Germany

Vanadium dioxide (VO_2) is a premier candidate for thermochromic smart windows due to its ability to dynamically modulate solar heat gain. However, achieving high solar modulation (ΔT_{sol}) typically requires a rutile-phase TiO_2 buffer layer to lower the growth temperature of VO_2 [1]. Such buffers are often produced via high-temperature sputtering (>400 °C), limiting the use of temperature-sensitive flexible substrates.

In this work, we demonstrate a low-T ALD route to rutile TiO_2 at process temperatures as low as 220 °C. Utilizing a thermal TDMAT/H_2O process at 200 °C [2,3], we generate "black TiO_2" films. Based on literature [2,3], the characteristic Ti^{3+} defects and oxygen vacancies in these films are believed to bypass the common high-temperature anatase-rutile conversion.

Integrated into $VO_2|TiO_2|$glass architectures, we achieve $\Delta T_{so} > 9\%$ comparable to benchmarks using high-temperature sputtered references (650 °C) [1]. Crucially, this approach removes a major barrier for VO_2 coatings on polymer-based substrates. Preliminary results indicate that this low-T process can be transferred to polyimide (PI), paving the way for flexible VO_2 smart windows.

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AA-TuP-36 ALD and Surface Chemistry of p-type Tin Oxides*, Asare Dua, Michael Foody,* Illinois Institute of Technology*; Bo Liu, **Adam Hock**,* illinois Institute of Technology

Low temperature ALD of p-type conducting oxides remains a challenge, particularly as surface chemistry can dominate contact quality and therefore device performance as a function of overall scaling.Furthermore, the surface of p-type oxides is often susceptible to reaction with atmospheric oxygen and water, altering dopant concentrations and affecting process conditions.We have developed a new tin ALD precursor and utilized it for low-temperature, thermal ALD of p-type tin oxides.We have characterized the chemical and physical properties of the precursor, its ALD growth window, and resulting p-type film mobilities.We also have studied the effects of surface treatments on mobility and stability of the resulting films.

In this talk we discuss the results of these studies on p-type tin oxide thin films grown using a novel precursor.This includes QCM measurements under ALD conditions, solution model reactions, and synchrotron studies conducted at the Advanced Photon Source (APS) located at Argonne National Laboratory.The surface reactions of Sn precursors and half-reactions provide insight into the surface of the film and overall manufacturability of p-type oxides in the future.The results of these studies were applied to improved p-type oxide ALD, including doping strategies.Device characterization will also be discussed as time allows.

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.

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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 μC/cm^2.

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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 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.

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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.

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Financial support from EIC Pathfinder METASPIN project (Grant n. 101098651).

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.

ALD Applications
Room Ybor Salons I-IV - Session AA2-WeM
ALD for Memory II

Moderators: Ji Hwan Ahn, POSTECH, **Andrea Illiberi**, ASM

10:45am **AA2-WeM-12 Upper-Layer-Induced Crystallization of Metastable Rutile TiO_2*, Jihoon Jeon,* *Seung keun Kim,*** Korea Institute of Science and Technology (KIST), Republic of Korea

The relentless scaling of dynamic random-access memory (DRAM) technology shrinks capacitor dimensions, thereby degrading charge retention time and triggering read instabilities. This drives the demand for high-permittivity dielectrics that surpass conventional HfO_2 or ZrO_2. Rutile TiO_2, with orientation-dependent permittivity ranging from 80 to 170, emerges as a compelling candidate. However, rutile TiO_2 is metastable under atomic layer deposition (ALD) conditions and requires elevated crystallization temperatures, which pose barriers to integration. Established ALD strategies stabilize rutile TiO_2 by employing lattice-matched bottom electrodes such as RuO_2, IrO_2, SnO_2, or MoO_2. Yet these approaches necessitate either replacing the bottom electrode or introducing additional rutile phase–inducing layers, thereby complicating compatibility with DRAM process flows. Moreover, the industry-standard TiN electrode, lacking lattice matching with rutile TiO_2, remains incompatible with such stabilization routes.

Here, we report for the first time the formation of crystal structure induced by an upper-layer during post-deposition crystallization. This upper-layer-driven templating effect provides a new pathway to control phase selectionin ALD-grown TiO_2thin films. After inducing rutile crystallization, the upper layer can be selectively removed without affecting the underlying structure, leaving a fully crystallized rutile TiO_2. This strategy enables the integration of high-k rutile TiO_2 while preserving the TiN bottom electrode, thereby ensuring full compatibility with DRAM fabrication processes

11:00am **AA2-WeM-13 Surface-Reaction-Energetics-Driven Stabilization of Rutile TiO_2 at Low Temperatures in Atomic Layer Deposition*, Seungwan Ye,*** *Jihoon Jeon, Jongseo Kim, Seong Keun Kim,* Korea Institute of Science and Technology (KIST), Republic of Korea

As the physical dimensions of dynamic random-access memory (DRAM) continue to scale down, maintaining sufficient charge capacitance has emerged as a key challenge for next-generation memory technology. Therefore, to overcome the limitations of current Zr-based dielectrics, high-k materials with a higher dielectric constant are essential. Among them, rutile TiO_2 is the most promising dielectric due to its high dielectric constant ($k > 80$).

However, the rutile phase of TiO_2 is thermodynamically metastable, typically requiring high temperature process above 600℃, which exceeds the thermal budget for the DRAM fabrication process. Although using lattice-matched rutile bottom electrodes such as RuO_2, IrO_2 and MoO_2 has been proposed to form rutile TiO_2 at low temperatures, their poor process compatibility with the industry-standard TiN bottom electrode remains a critical obstacle.

In this study, we propose a novel method using surface reaction during ALD that enables the growth of metastable rutile TiO_2 thin films at a low temperature of approximately 330°C, irrespective of the bottom electrode. This breakthrough allows for the successful deposition of high-quality rutile TiO_2 on various substrates, including the industry-standard TiN, thereby dramatically enhancing its commercialization potential for next-generation memory devices.

11:15am **AA2-WeM-14 Magnetism of Ultrathin TiO_2 Films Prepared by Atomic Layer Deposition*, Jhonatan Rodriguez Pereira,*** *Jan Macak,* University of Pardubice, Czechia

Semiconducting oxides are gaining attention for spintronic applications due to their tunable electronic and magnetic properties.[1,2] Among them, TiO_2 is a widely studied semiconducting oxide for a wide range of applications owing to its chemical stability, wide band gap and versatile functionality.[3-5] The observation of room-temperature ferromagnetism in undoped TiO_2 films has raised fundamental questions regarding its origin, which has been frequently linked to intrinsic defects, reduced dimensionality, and interface effects rather than conventional magnetic doping.[6-8] Several studies addressing this phenomenon have focused on films prepared by pulsed laser deposition.[9-11] Given the strong sensitivity of defect-induced magnetism to film thickness and interface quality, a deposition method enabling atomic-scale control is particularly desirable.

Atomic Layer Deposition (ALD) provides an ideal platform to address this necessity, owing to its precise control over thickness and composition, as well as its ability to produce smooth and conformal ultrathin films.

In our recent paper, [12] we showed for the first time the ALD growth of ultrathin TiO_2 films (below 10 nm) on $LaAlO_3$ substrates. Structural characterization confirmed the formation of anatase TiO_2 films. Magnetic measurements revealed a pronounced thickness-dependent behavior, with ferromagnetic responses observed for films of intermediate thickness, while thinner films remained diamagnetic. The magnetic signal was strongly anisotropic and confined to the film plane, suggesting a two-dimensional origin associated with surface and interface effects. Complementary chemical and computational analysis indicate the presence of oxygen-related defects, whose concentration varies with film thickness.[12]

The presentation will introduce and describe the ALD growth of ultrathin TiO_2 films, together with their structural, chemical, magnetic, and theoretical characterization, and will discuss the role of defects and interfaces in the emergence of ferromagnetism.

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11:30am **AA2-WeM-15 Low-Temperature Peald of Silicon Nitride Using Diiodosilane for High-Conformality Spacers of Three-Dimensional Memory Devices*, Jiabao Sun,*** *Tielu Liu, Xin Zhang, Gang Song, Hongbo Sun, Baodong Han, Chao Tian, Chao Zhao,* Beijing Superstring Academy of Memory Technology, China

Silicon nitride (SiN_x) thin films are critical insulating spacers for next-generation high-density memory devices[1]. Transitioning to extreme 3D stacking with deep lateral pockets imposes rigorous demands on plasma-enhanced atomic layer deposition (PEALD)[2]. Specifically, maintaining high-quality films at low thermal budgets is vital for integration with temperature-sensitive amorphous oxide channels. In this work, we investigate a low-temperature PEALD SiNx process using Diiodosilane (DIS, SiH_2I_2). The selection of DIS is motivated by the low dissociation energy of the Si-I bond (~284 kJ/mol)[3], which facilitates efficient precursor activation and surface reactions at reduced temperatures compared to chlorinated or aminated silanes.

We report a comprehensive optimization to address two critical research questions: the achievement of high lateral conformality and the spatial uniformity of the wet etch rate (WER) across complex 3D geometries. A significant reduction in the WER (30:1 HF) of the SiN_x films is achieved, dropping from ~120 nm/min to ~3 nm/min via precise plasma chemistry modulation (Fig. 1). A strong positive correlation between WER and growth per cycle (GPC) indicates that high-growth regimes are associated with plasma-induced damage and reduced film density. X-ray Photoelectron Spectroscopy (XPS) analysis revealed that high WER correlates with a shift in nitrogen bonding environments, specifically the presence of sub-stoichiometric NSi_2O and $NSiO_2$ species over the preferred NSi_3 configuration (Fig. 2). Furthermore, a distinct I peak is identified in high-WER samples, indicating that unreacted precursor fragments at high radiofrequency (RF) power and H_2 flow rates degrade the structural integrity of the film.

To address 3D integration challenges, we achieved ~94% lateral conformality within high-aspect-ratio structures (Fig. 3). Reducing the process pressure from 22.5 Torr to 4 Torr increases the molecular mean free path, enhancing precursor diffusion into deep features. Additionally, minimizing RF power reduces ion directivity, promoting the conformal profile essential for lateral coverage. Notably, the WER within the confined side-pockets was reduced by approximately one order of magnitude, achieving exceptional spatial uniformity across the 3D architecture (Fig. 4). These optimizations provide a robust process window for subsequent Wet etch or Certas gas etching, ensuring structural integrity in 3D integration. This study provides a viable pathway for high-quality SiN_x spacers in temperature-sensitive 3D memory architectures.

Reference

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11:45am **AA2-WeM-16 A Nanolaminate Cushion Approach for Stabilizing Ultrathin Al_2O_3 and SiO_2 Dielectrics in Future Logic and Memory Technologies***, Mahesh Nepal, Tanka Bhushal,* ***Tara Dhakal****,* Binghamton University

Continued scaling of DRAM capacitor dielectrics and emerging memory devices requires ultrathin insulating layers that maintain low leakage and high reliability. Comparable challenges are also present in embedded and BEOL decoupling capacitors, where capacitance density and electrical stability are critical. However, once oxide dielectrics reach the few-nanometer regime, leakage increases dramatically and breakdown margins collapse, making dielectric reliability a primary limiter to further scaling. Here, we present a novel dielectric stabilization strategy using an atomic layer deposited (ALD) Al_2O_3/TiO_2 nanolaminate engineered to function as a controlled conductive “cushion” interlayer that enables reliable scaling of ultrathin dielectric films.

Spectroscopic analysis using hard X-ray photoelectron spectroscopy indicates oxygen-deficient TiO_2 and compositionally modified Al_2O_3 networks, producing a quasi-conductive nanolaminate that suppresses catastrophic dielectric failure. Electrical impedance measurements confirm that while the nanolaminate exhibits non-ideal dielectric characteristics independently, integration with ultrathin capping dielectrics restores stable capacitive behavior.

Using planar metal–insulator–metal capacitor test structures, we demonstrate that an optimized nanolaminate period enables scaling of Al_2O_3 dielectrics to ~3 nm while achieving leakage current densities near 10^{-7} A/cm^2 at 1 V and capacitance densities approaching 20 fF/um^2 across large-area devices. The stabilization approach is further shown to be transferable to SiO_2-based dielectric stacks, indicating broader material compatibility.

From a memory-scaling perspective, modeling suggests that integration with three-dimensional capacitor geometries could significantly amplify capacitance density, positioning this cushion-enabled architecture as a promising pathway for next-generation DRAM applications. More broadly, this work demonstrates how intentionally engineered leaky nanolaminates can serve as functional interfacial layers to overcome reliability bottlenecks in aggressively scaled dielectric stacks.

ALD Applications
Room Ybor Salons I-IV - Session AA-WeA

Novel ALD Applications

Moderators: Jessica Jones, Argonne National Laboratory, **Austin Minnich**, Caltech

1:30pm **AA-WeA-1 Nanolaminate Bragg Reflectors for Acoustic Phonons in the > 100 Ghz Range***, **John Murphy**, Jeremy Robinson, Maxim Zalalutdinov, Kyle Munson, Jeffrey Woodward,* U.S. Naval Research Laboratory

Nanolaminates grown by atomic layer deposition (ALD) offer a well–controlled platform capable of confining longitudinal acoustic (LA) phonons in > 100 GHz regime through engineered Bragg reflection. LA phonons in this frequency range strongly influence thermal and electronic behavior and require individual layers of Bragg reflectors to be < 10 nm thick with sub-nm roughness, while providing high contrast in acoustic impedance. ALD is unique in its ability to produce nanolaminate Bragg reflectors through sequential growth of ultra-thin, uniform, and low–roughness amorphous multilayers; with tailorable acoustic impedances through material selection. An ALD-based approach also allows conformal coating on planar and three–dimensional geometries where current state-of-the-art GaAs/AlAs, or other epitaxially grown superlattices cannot be realized. Additionally, the semi-surface-agnostic nature of the amorphous oxide ALD growth provides a route for integrating phononic mirrors, cavities, and filters into a variety of a fabrication flows in addition to well-established devices platforms, opening opportunities for next–generation acousto–optic and acousto–electronic systems compatible with current and emerging MEMS architectures.

In this work, we report results for Al_2O_3/HfO_2 nanolaminates grown via ALD using layer design guided by transfer–matrix simulations and targeting LA phonons in the frequency range 100-500 GHz. Effective sound speeds and mass densities of both single–layer films and stacked nanolaminates are extracted via ultrafast pump-probe measurements and x–ray reflectivity, respectively, allowing elastic properties to be correlated with ALD growth conditions. We compare the simulated spectral response for phonon lifetime with pump–probe measurements using ultrathin optoacoustic transducer layers that act both as acoustic cavities and a source of optically generated strain pulses. Exploiting this architecture, we are able to validate simulated reflection response with thin optoacoustic transducer layers deposited directly onto nanolaminate films. These results establish ALD nanolaminates as a tunable, integrable platform for GHz–sub–THz phonon control and phononic component design beyond conventional epitaxial III–V and nitride superlattice systems.

1:45pm **AA-WeA-2 Next Generation ALD Functionalization of Lead-free MCPs for the Photomultiplier Tube: HRPPD***, **Stefan Cwik**, Melvin, J. Aviles, Stephen M. Clarke, Matthew Grden, Cole J. Hamel, Alexey V. Lyashenko, Mark A. Popecki,* Incom Inc.*; Jeffrey W. Elam,* Argonne National Laboratory, USA*; Michael J. Minot,* Incom Inc.

Microchannel plates (MCPs) find application in image intensifier tubes for night vision goggles, in spectrometers, and in photo multiplier tubes (PMTs) for time-of-flight (TOF) measurements based on their high resolution, ultra-fast timing (10-50 ps) and high gain ($>10^4$). Conventionallead glass MCPs have been the industry standard since the 1960s. The manufacture includes a hydrogen firing step in which lead oxide gets reduced to bring the plate to target resistance and to simultaneously generate the electron emission layer limiting the adjustability of the MCP properties to target applications.

Incom Inc. has commercialized the ALD-GCA-MCP technology, applying ALD technology from Argonne (ANL) on Incom's glass capillary array (GCA) substrates. The physically and chemically robust silicate glass allows the fabrication of large area GCAs up to 20x20 cm^2 and the high substrate resistance enables functionalization by ALD. ALD functionalization of the GCA comprises resistive and emissive layers. The resistive layer is a tunable nanocomposite of conductive and insulating materials and defines most electrical characteristics of the MCP since it serves as a strip layer to recharge the emissive layer during operation. The emissive layer is composed of a high secondary electron yield material like MgO or Al_2O_3 to maximize gain for intensifier applications.

Incom's 1st generation MCPs rely on the combination of Incom proprietary Chem1 resistive coating and MgO emissive coating, which provide high gain stability and durability for open MCP applications in space-flight applications. However, for application in sealed MCP-PMTs, high gain in dry UHV and minimum out-gassing are critical to limit the effects of after-pulsing. This maximizes the device lifetime, crucial for long-term applications such as TOF experimentation in Electron Ion Collider programs. Herein, we report the performance of Incom's new proprietary halide-free Chem5-MgO MCP technology in sealed MCP-PMTs such as Incom's 10x10 cm HRPPD, which was developed to optimize the application specific MCP characteristics. The Chem5-MgO performance under dry UHV conditions is compared with MCPs based on Chem1-MgO chemistry used in HRPPDs. Notably, the higher gain provided by Chem5 allows lower voltage operation (ΔV=200V) thereby reducing electric fields in the PMT and minimizing after-pulsing. Large area MCPs with the advanced Chem5-MgO coatings are also being incorporated into Incom's LAPPD, the world's largest planar MCP-PMT.

This work was supported by the US Department of Energy (NNSA), DE-SC0018778

2:00pm **AA-WeA-3 Growing Grass for the Stars: Conformal Nanostructured Ar Coatings for Astronomical Micro-Optics***, **Ishan Rana**, Suvrath Mahadevan,* Pennsylvania State University

Many Astronomical Instruments require high precision micro-optics with complex free form geometries. A new and attractive choice to fabricate such microoptics is the IPX clear photoresin, this resin offers very high internal transmission (>99.9%) in the visible and near infra-red wavelength range and has excellent shape fidelity. However, fresnel reflections at the air-polymer interface introduce significant photon loss (~4%). This is detrimental for photon starved fields like astronomy. To reduce photon loss we need to apply antireflective coatings on the microlenses. However, due to the complex shape of the microlenses we need highly conformal coatings. We use Atomic Layer Deposition to create these AR coatings.

In our project, we study the application of grass-like anti reflective coatings on IPX clear micro-optics. These coatings are created by first depositing alumina using thermal ALD on the microlenses and then generating nanostructures on the surface of the alumina by treating the samples in de-ionized water. The treated samples with nanostructured surfaces can then again be coated with various other materials like SiO_2, TiO_2, and HfO_2 to create a multilayer grass like coating. These coatings mimic a gradient change in refractive index, suppressing surface reflections. Such coatings can improve average transmission from 91.9% up to 99%

While in previous work ALD has been used to coat micro-optics, we demonstrate here for the first time application of ALD on micro-optics with nanostructured surfaces and the antireflective performance of such coatings, as well as discuss the challenges and process steps of such applications.

2:15pm **AA-WeA-4 Electrochemical Oxidation of Perfluorobutanoic Acid using ALD Thin Film Electrocatalysts Deposited on Reactive Electrochemical Membranes***, **Saurabh N Misal**,* Argonne National Laboratory, USA*; Atefeh Nadeali, Brian P Chaplin,* University of Illinois at Chicago*; Jeffrey W Elam,* Argonne National Laboratory, USA

Electrochemical oxidation of per- and polyfluoroalkyl substances (PFAS) using Magnéli-phase titanium suboxide (Ti_nO_{2n-1}) reactive electrochemical membranes (REMs) is a promising and effective approach for mineralizing concentrated PFAS wastes. Still, it can lead to the accumulation of short-chain PFAS as byproducts. Perfluorobutanoic acid (PFBA) is one such short-chain product observed during PFAS oxidation and is also commonly detected in groundwater and industrial wastewater. Due to its low hydrophobicity, low polarizability, and high mobility, PFBA adsorbs poorly at the anode surface, leading to sluggish kinetics. In this work, we focused on the synthesis of an electrocatalyst using atomic layer deposition (ALD) on REMs to further enhance the removal and defluorination of PFBA during oxidation. In the first part of the study, thin films of SnO_2, Sb_2O_5, and Pd were deposited on REMs. For the ALD process, the reactor temperature, precursor dose time, and number of cycles were optimized for high-aspect-ratio (~5000) REMs. The synthesized electrocatalytic REMs were characterized using X-ray photoelectron spectroscopy to confirm oxidation states of the electrocatalyst. Moreover, top surface and cross-sections of the REMs were mapped using scanning electron microscopy with energy-dispersive X-ray spectroscopy. In the second part of the study, the synthesized REMs were tested for the electrochemical oxidation of ~21 mg L^{-1} PFBA in a flow-through reactor at a constant potential and flux. The permeate samples collected from oxidation experiments were analyzed using ion chromatography. At 150 L m^{-2} h^{-1} permeate flux and a constant potential of 3.6 V/SHE, ~80% PFBA was removed with ~100% fluorine recovery using thin-film-deposited REM. The analysis showed the presence of trifluoroacetic acid and perfluoropropanoic acid in µg L^{-1} levels (10—20% product yield), along with the formation of fluoride ions in mg L^{-1} levels (80—90% fluoride yield). In the final part of the study, insulating TiO_2 films were deposited on the synthesized electrocatalytic REM by ALD to suppress oxygen evolution side reaction, and electrochemical oxidation of PFBA was tested using the synthesized thin-film-deposited REM.

2:30pm **AA-WeA-5 Development of an Atomic Layer Deposition System for Tritium Permeation Barriers on Arbitrary Geometries*, Zachary Robinson,*** University of Rochester*; Jeffrey Woodward,* NRL*; Alexander Kozen,* University of Vermont*; Tyler Liao,* University of Rochester*; Soren Bentley,* UKAEA, UK*; Luke Herter, Rashad Ahmadov, Josh Ruby, Mark Wittman, Matthew Sharpe,* University of Rochester

Atomic layer deposition (ALD) is an ideal technique for deposition of films on arbitrarily shaped containers such as those used to contain tritium for fusion applications. In this work we present the design, construction, and initial experimental results from a custom ALD system built to deposit hydrogen isotope permeation barriers. This challenge is motivated by the extreme difficulty of producing and containing tritium while mitigating losses. The ALD films developed in this project could be used to filter, purify, store, and transport tritium, increasing the efficiency of Fusion fuel management.

The primary benefit of our ALD system is the ability to deposit films on arbitrarily shaped surfaces, such as the interior walls of tubing and canisters used to contain tritium. In our initial experiments, we deposited thermal ALD alumina films on both silicon wafers and planar copper foil substrates. Characterization with ellipsometry yielded ALD growth rates of~1.1 Å/cycle for temperatures between 100 °C and 210 °C on the Si witness samples. X-ray photoelectron spectroscopy (XPS) on both the Cu foils and Si substrates indicates stoichiometric Al_2O_3. To quantify the permeation reduction factor (PRF) of the of the ALD films, the permeability of deuterium through 25 µm Cu-foils coated with 10 nm of alumina was measured. It was found that thin ALD films have a PRF of around 25 at permeation temperatures between 275 °C and 350 °C.

Following our initial characterization of the system, a 1 L type 316 stainless steel (SS316) canister was installed in our ALD reactor, with 10 silicon witness samples mounted throughout the interior volume of the canister. ALD process conditions were systematically varied, and the uniformity of the alumina films throughout the volume of the canister was optimized such that the inlet side of the reactor was about 10% thicker than the outlet. All of the witness samples had sub-nm roughness. Experiments were also performed on highly polished SS316 to compare film properties between the Si and the stainless substrates. XPS indicates that an aluminum hydroxide forms on SS316 for growth temperatures below 200 °C. Experiments are currently underway to fill a canister with tritium and study the residual gases that exist in the canister as a function of time.

2:45pm **AA-WeA-6 Argon Ion Implantation in ALD PbTe Thin Films for Phonon Engineering*, Haifeng Cong,*** *Helmut Baumgart,* Old Dominion University

Lead telluride (PbTe) is a promising thermoelectric material due to its high Seebeck coefficient and large figure of merit (ZT) at elevated temperatures. While atomic layer deposition (ALD) enables high-quality PbTe thin films, strategies to enhance thermoelectric performance via phonon engineering remain limited.In this study, PbTe thin films were grown on silicon substrates with native oxide using thermal ALD, employing $Pb(C_{11}H_{19}O_2)_2$ and $(Me_3Si)_2Te$ as precursors. Films were deposited at 130–170 °C under 500 mTorr, following surface functionalization to ensure reproducible chemisorption. To engineer phonon transport, argon ions were implanted at 180 keV with a fluence of 1×10^{15} cm^{-2} and subsequently annealed to generate controlled lattice defect clusters.The effects of implantation were characterized using X-ray diffraction (XRD) for crystal structure, FE-SEM and AFM for morphology and roughness, TEM to directly observe defect profiles, and EDS for composition and stoichiometry. Seebeck coefficient, Hall effect, and thermal conductivity measurements were conducted to assess the impact of defects on thermoelectric performance.Results demonstrate that argon implantation introduces well-distributed lattice defects, effectively scattering phonons and reducing thermal conductivity without significant degradation of electrical properties, leading to enhanced ZT. These findings highlight defect engineering via inert ion implantation as an effective route to improve the thermoelectric performance of ALD PbTe thin films.

3:00pm **AA-WeA-7 Multifunctional Hierarchically Restructured Antibacterial Neural Interfacing Electrodes via Plasma-Enhanced Atomic Layer Deposition*, Shahram Amini,*** Drexel University*; Feng Gang, Henna Khosla,* Villanova University*; Wesley Seche, Kriti Panchal, Steve May, Ekaterina Pomerantseva,* Drexel University*; Jacob Elmer,* Villanova University*; Gregory Caputo, Jeffrey Hettinger,* Rowan University

Next-generation neural and cardiac implantable electrodes are increasingly constrained by the coupled requirements of miniaturization, electrochemical performance, and resistance to bacterial colonization. Hierarchical Surface Restructuring (HSR™) enables substantial amplification of electrochemically active surface area on metallic electrodes, thereby addressing charge-transfer limitations associated with geometric scaling. However, translating these surface architectures into long-term implantable devices requires additional surface-level functionality to mitigate infection risk without degrading electrochemical efficiency. In this work, plasma-enhanced atomic layer deposition (PEALD) is employed as a conformal, thickness-controlled surface-engineering strategy to functionalize HSR™ Pt–10Ir electrodes with ultrathin ZnO-based films. The self-limiting reaction chemistry of PEALD enables uniform coating of complex micro- and nanoscale features while preserving the underlying hierarchical morphology. By modulating plasma chemistry during deposition, ZnO films with distinct phase compositions are integrated onto HSR™ electrodes, enabling independent tuning of antibacterial and electrochemical responses. Antibacterial activity is demonstrated under dark, aerobic conditions, decoupling the observed bactericidal behavior from photocatalytic mechanisms and establishing controlled Zn^{2+} ion release as the dominant mode of action. Simultaneously, select ZnO–Zn nanocomposite coatings enhance electrochemical performance, exhibiting reduced impedance and increased charge storage capacity relative to uncoated HSR™ electrodes. Collectively, these results establish PEALD as a scalable and manufacturing-compatible approach for introducing multifunctionality onto hierarchically restructured neural interfacing electrodes, providing a practical pathway toward infection-resistant bioelectronic interfaces that maintain high electrochemical performance under clinically relevant conditions.

3:15pm **AA-WeA-8 ALD Al_2O_3 on Nanocellulose Substrates – Tailoring Barrier and Wetting Properties for Food Packaging*, Hugo Patureau,*** SIMAP, Grenoble-INP, CNRS, France*; Chloé Parisi, Julien Bras,* LGP2, France*; Erwan Gicquel,* CILKOA, France*; Frédéric Mercier,* SIMAP, Grenoble-INP, CNRS, France*; Elisabeth Blanquet,* SIMAP, grenoble-INP, CNRS, France*; Arnaud Mantoux,* SIMAP, Grenoble-INP, CNRS, France

Cellulosic products are a promising alternative to plastics for food packaging due to being biodegradable and recyclable. Nanocellulose is especially promising in the food packaging industry due to high oxygen barrier performances. However, high moisture sensitivity leads to poor water vapor barriers while also compromising oxygen barrier performance under humid conditions. Recent studies have shown that Al_2O_3 deposited by atomic layer deposition (ALD) on cellulosic substrates increases water vapor and oxygen barrier performance and grants hydrophobic properties [1–4]. However, the influence of ALD process parameters on the performances obtained remain insufficiently explored.

In this work, we demonstrate how deposition temperature, number of ALD cycles and different co-reactants (H_2O, O_2 plasma and ethanol) govern the water vapor barrier and wettability performance of Al_2O_3 films on different nanocellulose substrates. Findings demonstrate a significant increase in wettability using few ALD cycles of TMA and ethanol as co-reactant (figure 1), with correlations observed between wettability and surface energy, surface chemistry, and film morphology. Water vapor transmission rates (WVTR) were measured and also displayed a high dependence on deposition temperature, ALD cycles and co-reactants (figure 2). Experiments revealed a critical thickness of Al_2O_3 on nanocellulose, where no reduction of WVTR was observed beyond that point. The results highlight the critical role of ALD processing conditions in developing high performance nanocellulose food packaging.

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(3) Mirvakili, M. N.; et al. ACS Appl. Mater. Interfaces 2016, 8, 13590–13600.

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