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 μΩ·cm and 10 nm of Ir measured 16 μΩ·cm. Successful copper ECD was demonstrated with 10 nm of Ir (resistivity 16 μΩ·cm) and 20 nm of Ru (resistivity 22 μΩ·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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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.

References

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