ALD Applications
Room Hall 3D - Session AA1-WeA
More than Moore Applications

Moderators: Benjamin Greenberg, Naval Research Laboratory, **Sami Sneck**, Beneq

1:30pm **AA1-WeA-1 ALD Solutions for Compound Semiconductor Devices***, **Mikko Söderlund**, A. Voznyi, T. Ivanova, A. Perros, P. Rabinzohn,* Beneq Oy, Finland **INVITED**

Among the wide bang gap (WBG) WBG semiconductors, SiC and GaN offer attractive performance over Silicon-based devices for the realization of high-voltage switches to be used in power converters and have been widely adopted for many applications.Tesla's adoption of SiC in 2017 for the onboard, or traction, inverters for its Model 3 was an early and major win. EV traction inverters typically range from about 35 kW to 100 kW for a small EV to about 400 kW for a large vehicle.On the other hand, AlGaN/GaN High-Electron-Mobility-Transistors (HEMTs) have allowed realization of low on-resistance and high-switching frequency transistors, enabling GaN-based power FETs rating 650 V with preferred normally-off device performance achieved using a p-GaN gate stack.

However, both SiC and GaN-based power transistors face challenges with defectivity of the semiconductor-dielectric interface, reducing the device electrical performance and especially on-resistance to less than ideal. In particular, low electron mobility at the SiO2/SiC interface due to carbon-related interface defects resulting from thermal oxidation remains the number one challenge for SiC devices and is associated with hysteresis of threshold voltage. Thus, a clear industry trend is to eliminate oxidation from the SiO2 formation process. The formation/deposition of highest-quality gate dielectric stacks (including SiO_2 and high-k) by atomic layer deposition (ALD) with the capability to control the dielectric/SiC interface by in-situ surface treatment and plasma enhanced atomic layer deposition (PEALD) Interfacial Layers (IL) are expected to play a significant role in the manufacturing of high performance SiC MOSFETs.

This paper presents an industrially proven three-step PEALD/thermal ALD cluster tool approach to engineer and perfect the semiconductor/dielectric interface quality and deposition of dielectric stack applicable to both GaN and SiC power devices. Characteristics of capacitance voltage (CV) and current density voltage (JV) for 4H-SiC MOS capacitors that utilize either ALD SiO_2 only, or ALD SiO_2 after plasma preclean (PP) or ALD SiO_2 with IL, are measured and presented. Overall, all devices demonstrate high-breakdown, low leakage current and negligible CV hysteresis indicating high-quality of ALD SiO_2 film and low-density of traps at the SiC/SiO_2 interface. In the best condition with PP/SiO2, nearly ideal SiC-SiO2 interface with hysteresis of less than 20 mV is achieved while demonstrating very low trapped charges. Improvement of p-GaN gate HEMT dynamic Rds on-resistance by ALD passivation layer will also be presented.

2:00pm **AA1-WeA-3 Plasma Effects on the Epitaxial Growth of Aluminum Nitride Thin Films on (0001)4H-SiC by PE-ALD***, **Bruno Galizia**, P. Fiorenza, C. Bongiorno,* Consiglio Nazionale delle Ricerche, Istituto per la Microelettronica e Microsistemi (CNR-IMM), Italy*; B. Pécz, Z. Fogarassy,* Centre for Energy Research, Institute of Technical Physics and Materials Science, Hungary*; G. Greco, F. Giannazzo,* Consiglio Nazionale delle Ricerche - Istituto per la Microelettronica e Microsistemi (CNR-IMM), Italy*; F. Roccaforte,* Consiglio Nazionale delle Ricerche - Istituto per la Microelettronica (CNR-IMM), Italy*; R. Lo Nigro,* Consiglio Nazionale delle Ricerche - Istituto per la Microelettronica e Microsistemi (CNR-IMM), Italy

Aluminum Nitride (AlN) is considered a suitable candidate for the replacement of SiO_2 as gate dielectric in 4H-SiC based power MOSFETs because of its high permittivity constant (~9.1), large bandgap and good band-offset with 4H-SiC. Moreover, epitaxial growth and good interface quality could be favored by its low in-plane lattice mismatch with 4H-SiC (~0.9%) and because of their similar thermal expansion coefficients. Several deposition techniques such as molecular beam epitaxy, metal-organic chemical vapour deposition or physical vapour deposition have been used as AlN thin film synthesis technique, but they all suffer from high temperature processing.In this work, we investigated lower temperature PE-ALD processes, depositing AlN thin films on (0001)4H-SiC substrate at 300°C and we studied the effects of NH_3 plasma pulse time on crystalline quality, structural and electrical properties. Precursor nucleation and plasma effects have been monitored via *in-situ* ellipsometric spectroscopy half-cyle and end-cycle measurements and it has been observed that different AlN cristallyne phases have been formed as a function of plasma time pulsing. In particular, the wurtzite AlN structure is always present at the interface with the 4H-SiC substrate, while upon increasing thickness a poly-crystalline wurtzite phase was obtained by short-pulse NH_3-plasma, whereas longer plasma exposure resulted in a mixture of wurtzite and zincblende defective phases. The different phase formation has been also related to electrical properties by nanoscopic characterization using conductive atomic force microscopy (C-AFM). The C-AFM characterization, in fact, demonstrated that zincblende defective AlN layer resulting in poorer insulating properties while the totally wurzite AlN (0001) oriented films can be considered good insulator materials. This work has been supported by the European Union (NextGeneration EU), through the MUR-PNRR projects SAMOTHRACE (ECS00000022).

2:15pm **AA1-WeA-4 Novel Low Temperature Thermal ALD of Aluminum Nitride Utilizing a Non-Metal Catalyst***, **Sara Harris**, M. Weimer, D. Lindblad, A. Dameron,* Forge Nano

Quality aluminum nitride (AlN) with conformal step coverage is crucial for the performance of current and next-generation microelectromechanical (MEMS) and microelectronic devices, including energy harvesters, ultrasonic transducers, high-frequency wide band communications, and power semiconductors.[1] AlN is widely utilized due to a unique combination of high piezoelectric quality factor (Q=5000 at 10 MHz),[2] high thermal conductivity (up to 320 W/m·K)[3] and a high dielectric constant (k= 9.0).[3] State of the art technology relies on AlN deposited via physical vapor deposition (PVD) or metal organic chemical vapor deposition (MOCVD); techniques unable to deliver the step coverage over high aspect ratio features necessary for device miniaturization. AlN deposited via ALD typically requires plasma or elevated temperatures (>350 °C) affecting process scalability and thermal budget, ultimately disincentivizing industry adoption.[4] In this work, AlN was grown at 285 °C via thermal ALD through the addition of a novel nonmetal catalyst during the nitride conversion step, referred to as a CRISP process. We demonstrate the power of CRISP on two different AlN processes: trimethylaluminum (TMA)/hydrazine (HZ) and TMA/monomethylhydrazine (MMH) and report a 15 % increase in refractive index (RI) for the TMA/HZ-CRISP process and binary off/on growth for the TMA/MMH-CRISP process. Normal ALD AlN films grown using TMA/HZ in the absence of a catalyst have an RI of 1.65 and GPC of 1.17 Å/cy. In comparison, AlN films grown via the novel TMA/HZ-CRISP process, using the nonmetal catalyst, have an RI of 1.95 and GPC of 1.50 Å/cy, as measured via spectroscopic ellipsometry. The partial pressure ratio between HZ and the nonmetal catalyst must be finely tuned to maximize AlN RI. To enhance understanding of the catalytic reaction pathways accessed by the CRISP process, ALD of TMA and MMH was conducted at 285 °C where the process is not kinetically favorable [4]. The absence of TMA/MMH film growth in traditional ALD fashion at 285 °C was confirmed, then a CRISP-based catalysis was introduced to facilitate proton transfer [4] and AlN was grown with RI of 1.62 and a GPC of 0.92 Å/cy. While under these conditions the TMA/MMH-CRISP film is of lower quality than those deposited with HZ/CRISP, this result highlights the ability of the nonmetal catalyst to enhance surface reactivity. GPC and RI improvement between a standard ALD process and the CRISP process is shown in Figure 1 for TMA/HZ and TMA/MMH. Additional characterization of the density and crystallinity of AlN films grown via the CRISP process will be discussed.

2:30pm **AA1-WeA-5 Thermal and Plasma Enhanced ALD growth of functional Al_2O_3/AlN dielectric stacks for silicon carbide MOSFETs***, **Raffaella Lo Nigro**, B. Galizia, P. Fiorenza, E. Schilirò, F. Roccaforte,* Consiglio Nazionale delle Ricerche – Istituto per Microelettronica e Microsistemi (CNR-IMM), Italy

Over the last years, silicon carbide (4H-SiC) semiconductor has become suitable for high-power applications due to its superior properties compared with silicon, such as lower intrinsic carrier concentration, higher breakdown field, saturation velocity, and thermal conductivity. Nevertheless, there are still some open topics related to the exploitation of the full potentiality of this material and among them, the nature of the gate dielectric in metal-oxide-semiconductor-field effect-transistors (MOSFETs) is a crucial issue to be faced. In fact, the traditionally used SiO_2 dielectric suffers from low dielectric constant (≈3.9) compared to the one of 4H-SiC (≈9.7), so that, according to Gauss' law, the high breakdown field of 4H-SiC (3 MV/cm) cannot be fully exploited because of the earlier breakdown of SiO_2 layer. Consequently, high dielectric constant, large band-offset and good thermal stability as well as low density of defects are the ideal properties for gate dielectric in 4H-SiC power devices.

Aluminum oxide (Al_2O_3) possesses most of the ideal dielectric properties, nevertheless, did not demonstrate a better interface quality than SiO_2 layers. In this context, another high-κ insulator of interest is the aluminium nitride (AlN) having not only high dielectric constant, but also a low lattice mismatch to 4H-SiC (~0.9%).These properties make it promising for a very good interface quality if epitaxially grown on (0001)4H-SiC.

In this work, a new solution is proposed: Al_2O_3/AlN bilayers were fabricated on 4H-SiC via ALD methods. In particular, thermal-ALD and PE-ALD processes of Al_2O_3 layers on AlN thin interfacial layer have been compared. Structural and electrical characterization of the two Al_2O_3/AlN bilayers obtained by T-ALD or PE-ALD depositions of the Al_2O_3 layers, are reported. Poor electrical behavior of the PE-ALD Al_2O_3/AlN bilayer has been correlated to its structural characteristics. In particular, the presence of degradation at the interface between plasma-deposited Al_2O_3 and AlN has been detected probably due to an oxidation interaction caused by oxygen plasma even at deposition temperature as low as 250°C.

By contrast, the structural and electrical properties of the T-ALD Al_2O_3/AlN bilayers showed promising characteristics such as a reduction of the oxide trapped charges (almost one order of magnitude down to 10^{11}-10^{12}), as well as of the interface traps density and an increase of dielectric constant (from 7.5 to 8.5) compared with a single Al_2O_3 reference layer. These preliminary results encourage the investigation of Al_2O_3/AlN bilayers as a candidate for future 4H-SiC power applications.

2:45pm **AA1-WeA-6 Reduction of Defects at or Near ALD-Al_2O_3/GaN Interfaces for Improved Electrical Performance of GaN Power Devices***,* ***Caleb Glaser****, B. Rummel, J. Klesko, M. Meyerson, P. Dickens, A. Binder, R. Kaplar,* Sandia National Laboratories*; D. Feezell,* University of New Mexico

Wide bandgap (WBG) semiconductors, such as gallium nitride (GaN) and silicon carbide (SiC), are ideal candidates for high-power switching applications due to their high electron saturation velocity, lower conduction losses, and higher operating temperature capabilities compared to traditional silicon-based devices. GaN power devices often demonstrate clear technological improvements over their silicon counterparts and are competitive with SiC products in many high-power application spaces. However, there exist significant manufacturing challenges and reliability concerns associated with the complex architectures utilized by GaN-based designs, including the lack of a dependable thermally grown oxide. Atomic layer deposition (ALD) provides the opportunity to form reliable films for gate dielectrics or passivation layers in GaN structures. Electronic traps at or near the semiconductor/dielectric interface in MOS structures severely impact gate and channel performance by introducing leakage current pathways and threshold voltage instabilities as well as reduced channel mobilities. In addition, the formation of Ga_xO_y interlayers during the ALD formation of oxides like Al_2O_3 or HfO_2 may create additional defect sites leading to further deterioration of device performance.

This study explores the defect distributions at or near the ALD-Al_2O_3 interface in MOS gates and their impact on the electrical performance of GaN MOSCAPs and MOSFETs. Relative improvements to dielectric leakage, D_{IT} distributions, and capacitance-voltage hysteresis in MOSCAP structures have been analyzed to understand how the elimination of native oxides and reduction of potential defect sites improve electrical characteristics. Characterization of observable chemical bonds and surface morphology via XPS and AFM imaging and mapping shows the reduction of native oxide interlayers when exposed to precursor TMA cycling prior to Al_2O_3 film growth by ALD. The optimized deposition techniques and early detection methods for defect sites show an observable reduction of interface trap states, mid-gap trap states, and hysteresis measured by quasi-static C-V. Initial findings for improved semiconductor/dielectric interfaces on GaN MOSCAP devices were implemented into vertical GaN power MOSFETs and show significant improvements to device leakage currents and breakdown voltage. This marked increase in device performance follows the optimized ALD procedure that includes TMA cycling and reduces the calculated defect densities at or near the Al_2O_3/GaN interface through quasi-static C-V analysis.

3:00pm **AA1-WeA-7 Fabrication of RuS2 Photodetector Via Post Sulfurization of Atomic Layer Deposition Ru Thin Film***,* ***Jaehyoek Kim,*** Yonsei University, Korea*; N. Tatsuya,* TANAKA Kikinzoku Kogyo K.K, Japan*; D. Kim,* Samsung Advanced Institute of Technology, Republic of Korea*; K. Yohei,* TANAKA Kikinzoku Kogyo K.K, Japan*; S. Chung,* Yonsei University, Korea*; S. Kim,* Ulsan National Institute of Science and Technology, Republic of Korea*; H. Kim,* Yonsei University, Korea

Near Infrared (IR) photodetectors are essential for many emerging applications in machine vision, health imaging, consumer electronics, and optical communications. Especially spectral responses of the photodetector at 940 nm are required for daylight applications due to the low interference intensity of the sunlight near that wavelength. Compound semiconductor materials have been mainly used in NIR photodetectors, but the exploration of novel semiconductor materials for excellent performance and effective fabrication processes continues to date.

Among the various emerging materials, the pyrite group semiconductors are promising candidates for optoelectronics. It belongs to the transition metal dichalcogenides (TMDs) family, and due to high absorption coefficient, extensive research on photovoltaic applications is being carried out to explore. In the case of Ru chalcogenides, RuS_2 is n-type semiconductor with suitable bandgap (0.8~1.4 eV) for NIR wavelength ranges and was identified as an optical and photoelectrode material with excellent environmental resistance and long lifespan. However, NIR photodetector studies based on RuS_2 to fabricate devices and measure photocurrent has not been conducted due to the difficulty of the RuS_2 thin film synthesis method.

In this report, RuS_2 film was synthesized based on Ru thin film deposition using atomic layer deposition (ALD) and post sulfurization process. Compared to sputtered Ru film, ALD of Ru film can be expected to improve the electrical and optical properties because ALD process provides uniform surface control and accurate thickness due to layer-by-layer deposition. Ru thin films with a thickness of 2, 4, and 6 nm were produced through ALD cycle control and post sulfurization were performed,and it was confirmed that 4 nm was optimized for RuS_2. After that, the RuS_2 characteristics of ALD Ru and Sputtered Ru were compared through several analyses such as XRD and XPS. The results suggest that the surface morphology of Ru thin film was important during sulfurization process, indicating that ALD Ru was excellent. We also fabricated RuS_2 photodetector with interdigitated comb-structured electrodes and measured at 940 nm NIR light. In this work, RuS_2 is proposed as a candidate material for the NIR photodetector and was the first to fabricate RuS_2 photodetector.

3:15pm **AA1-WeA-8 Spatial Atomic Layer Deposition: A New Revolution in Ultra-Fast Production of Conformal and High-Quality Optical Coatings***,* ***John Rönn****, P. Maydannik, S. Virtanen, K. Niiranen, S. Sneck,* Beneq, Finland

Since its invention 50 years ago, atomic layer deposition (ALD) has shown tremendous performance in depositing thin film structures for various applications in physical, chemical, biological, and medical sciences. Due to the unique layer-by-layer growth mechanism of ALD, thin films with exceptional uniformity, conformality and quality can be deposited not only on planar substrates, but also on the most complicated surfaces. Despite its superior advantages, traditional ALD, or temporal ALD, suffers from relatively low deposition rates (20-50 nm/h), which has greatly limited ALD's application in many systems where thin films with thicknesses of several hundreds or even microns are required. Such examples are often found in optical coatings that are widely used in our everyday lives in the form of self-driving cars, augmented reality goggles or mobile phones, to name a few.

In this work, we present our latest achievements with the novel C2R spatial plasma-enhanced rotary ALD system. The results include ultra-fast production of SiO_2, Ta_2O_5 TiO_2, HfO_2 and Al_2O_3 with deposition rates reaching up to 2 µm/h. In addition, we show that the deposition of these films can be controlled in such a way that no coating induced stress is obtained on the substrate, ultimately allowing extremely thick layer configurations to be deposited for optical applications. Finally, we show that these films exhibit low optical losses which make them very advantageous for novel optical applications where conformal, thick, and low-loss coatings are highly desirable.

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