Electronic Materials and Photonics Division
Room: 14 - Session EM-MoA

Novel Materials and Devices for Electronics
Moderators: Shalini Gupta, Northrop Grumman ES, Rehan Kapadia, University of Southern California

1:40pm **EM-MoA1 2D Materials for Advanced Devices: Integration Challenges and Opportunities**, ***Robert M. Wallace***, University of Texas at Dallas **INVITED**

The size reduction and economics of integrated circuits, captured since the 1960's in the form of Moore's Law, continues to be challenged. Challenges include addressing aspects associated with truly atomic dimensions, while the cost of manufacturing is increasing such that only 3 or 4 companies can afford leading edge capabilities. To address some of the materials physical limitations, "2D materials" such as graphene, phosphorene, h-BN, and transition metal dichalcogenides have captured the imagination of the electronics research community for advanced applications in nanoelectronics and optoelectronics. Among 2D materials "beyond graphene," some exhibit semiconducting behavior, such as transition-metal dichalcogenides (TMDs), and present useful bandgap properties for applications even at the single atomic layer level. Examples include "MX_2", where M = Mo, W, Sn, Hf, Zr and X = S, Se and Te

Integration of these materials with semiconductor industrial fabrication processes presents a number of challenges. For example, several synthesis methods have been employed to study 2D material thin film properties including mechanical/liquid exfoliation, chemical bath deposition, vapor phase deposition, and molecular beam epitaxy (MBE). From a manufacturability and cost perspective, vapor phase (including chemical and atomic layer) deposition are the subject of intense research activity in the electronics industry, while MBE methods facilitate the research of large thin films in advance of precursor development for CVD and ALD.

This presentation will examine the state-of-the-art of these materials in view of our research on 2D semiconductors, and the challenges and opportunities they present for electronic and optoelectronic applications. [1]

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1. S. J. McDonnell and R.M.Wallace, "Critical Review: Atomically-Thin Layered Films for Device Applications based upon 2D TMDC Materials", Thin Solid Films, 616, 482-501 (2016).

3:00pm **EM-MoA5 Enhancement-mode AlGaN/GaN HEMTs Enabled by ALD ZrO2 Gate Dielectrics**, ***Charles Eddy, Jr.***, *V.D. Wheeler,* U.S. Naval Research Laboratory, *D.I. Shahin,* University of Maryland, *T.J. Anderson, M.J. Tadjer, A.D. Koehler, K.D. Hobart,* U.S. Naval Research Laboratory, *A. Christou,* University of Maryland, *F.J. Kub*, U.S. Naval Research Laboratory

If power switches based on gallium nitride (GaN) transistors are to achieve widespread adoption, then reliable enhancement-mode (normally-off) operation must be demonstrated. The most advanced GaN transistor, the high electron mobility transistor (HEMT), is naturally a depletion-mode (normally-on) device and is finding rapid adoption in RF applications requiring high power and efficiency. To extend these performance benefits to power switches requires fully depleting the two-dimensional electron gas below the gate in absence of a gate bias. This is often achieved by recess etching the AlGaN barrier under the gate. However, to ensure low gate leakage in such a device further requires a reliable gate dielectric on this recessed surface. Here we report on the development and application of ALD deposited ZrO_2 gate dielectrics on recessed etched GaN surfaces. First, a thorough investigation of recessed surface pretreatments is conducted. Then, ALD is used to deposit ZrO_2 dielectrics on these surfaces using two precursors – zirconium (IV) tertbutoxide and tetrakis(dimethylamino)zirconium. Through careful variations in ALD growth conditions and precursor selection, we demonstrate the ability to achieve a record positive shift in the threshold voltage for a HEMT of up to +3.99V [1] and low gate leakage currents (5 orders of magnitude lower than reference HEMTs) under on-state conditions (Vgs= +10V and Vds= +20V).

These promising early results have been followed by studies of traps in these device structures using a previously established method [2]. Details of recessed surface preparation and trap behavior will be presented.

[1] T.J. Anderson et al., Appl. Phys. Express 9, 071003 (2016).

[2] J. Joh and J. A. del Alamo, IEEE Trans. Electron. Dev. 58, 132 (2011).

3:20pm **EM-MoA6 Interface Engineering with Al_2O_3-HfO_2 Nanolaminate Gate oxides on Silicon Germanium**, ***Mahmut Kavrik***, University of California at San Diego, *K. Tang,* Stanford University, *E. Thomson, J. Cheng, A.C. Kummel,* University of California at San Diego

Silicon Germanium (SiGe) alloys are promising alternative for silicon in semiconductor industry due to their tunable bandgap and carrier mobility through variation in composition. However, replacement of Si with SiGe requires a new class of high-k dielectric gate oxides with low leakage current for CMOS processing. Germanium content in semiconductor induces new interface defects due to its bonding with oxygen; GeOx is soluble in water and also can out diffuse into the gate oxide. Al_2O_3 and HfO_2 oxides were incorporated into nanolaminate stacks on the SiGe by Atomic Layer Deposition (ALD). Al_2O_3 was deposited with organic precursor trimethylaluminum (TMA) and H_2O on SiGe at 250C after HF and sulfur surface treatments. Sulfur treatment forms Ge-S and Ge-S-Ge bonds and prevents GeOx formation. Subsequently, HfO2 oxide layers were grown with organic precursor Tetrakis(dimethylamido) hafnium(TDMAH) and H_2O at 250C. Al_2O_3-HfO_2 nanolaminates were terminated with one layer of Al_2O_3 to protect oxide from gate metal damage. MOSCAP studies showed low Dit with hig Cox with Nanolaminate structure.

4:00pm **EM-MoA8 Encapsulation of AlGaN/GaN High Electron Mobility Transistor based Hydrogen Sensor for Humid Ambient Sensing Application**, *S. Jung, H. Kim,* Dankook University, *K.H. Baik,* Hongik University, *F. Ren, S.J. Pearton,* University of Florida, ***Soohwan Jang***, Dankook University

Hydrogen is environmentally friendly alternative energy source and carrier for automotive and fuel cell applications as well as in many industrial processes. Hydrogen gas is colorless, odorless, extremely reactive with oxygen, and has very low ignition energy. Especially, leaking gas from pressurized container may elevate its temperature, and induce spontaneous flammable ignition due to its negative Joule-Thomson coefficient. Therefore, hydrogen gas sensing systems are essential in various hydrogen related applications. GaN based material system is well-suited to hydrogen sensing because of its wide bandgap for high temperature operation, and mechanical and chemical robustness for device reliability. Many types of devices based on the GaN, including Schottky diodes, metal oxide semiconductor diodes, GaN nanowires and AlGaN/GaN high electron mobility transistors have been developed for fast and sensitive detection of hydrogen. Among them, AlGaN/GaN HEMTs with a 2 dimensional electron gas (2DEG) channel induced by piezoelectric and spontaneous polarization between the AlGaN and GaN layers showed high sensitivity to change in surface charge created by catalytic reaction of Pt or Pd with hydrogen. With 30 % Al concentration in AlGaN layer, 5~10 times higher electron densities in 2DEG are obtained compared to typical GaAs or InP HEMTs, which induces higher current and better sensitivity of the device. However, one of issues with semiconductor based hydrogen sensors is the fact that their sensitivity is significantly degraded in the presence of humidity or water. Water molecules block the catalytically active sites of sensing material, and results in the significant reduction in hydrogen detection signal. By employing encapsulation layer which prevents water molecules from adsorbing on the active sites of the sensor while selectively allowing penetration of hydrogen molecules, this issue can be solved. In this paper, we demonstrate that the device encapsulated with a moisture barrier does not suffer from any significant change in hydrogen detection sensitivity in the presence of moisture and that the devices can be repeatedly cycled to temperatures up to 300°C without any change in characteristics. Also, the device did not respond to the other gases including CH_4, CO, NO_2, CO_2, and O_2.

4:20pm **EM-MoA9 Work Function Measurements of Metal Gate - TiAlC by Ultraviolet Photoelectron Spectroscopy**, ***Yibin Zhang***, *H. Wang, D. Shao, Y. Liang,* GlobalFoundries Inc

In order to obtain high performance and low power in integrated circuits (IC), feature sizes continue to shrink and new materials are being developed. One major challenge is finding a metal gate electrode with the appropriate work function when paired with a gate oxide. Titanium-Aluminum-Carbide (TiAlC) films deposited by Atomic Layer Deposition (ALD) were introduced in the semiconductor industry in the 22nm and beyond FINFET technology node. TiAlC can provide the necessary work function and ALD offers better thickness control, uniformity and conformity compared to Plasma Vapor

Deposition (PVD). Electrical measurements are typically used to measure a film's work function. However, in an IC manufacturing environment this type of measurements can be performed only after several processing steps following the TiAlC deposition. It is often difficult and not cost effective to "rework" the affected wafers resulting in the loss of both product and time. Thus, it is important to monitor the work function during manufacturing. X-ray Photoelectron Spectroscopy (XPS) is used for in-line monitoring of the film composition and thickness, but it cannot directly measure the work function of TiAlC. In this work we demonstrate that Ultraviolet Photoelectron Spectroscopy (UPS) can provide work function measurements directly after the film deposition, to more effectively control the TiAlC ALD process parameters and resulting film properties. In addition, X-ray reflectivity (XRR) and X-ray diffraction (XRD) were used to investigate TiAlC film's density and crystallinity.

4:40pm **EM-MoA10 Nitride Based Avalanche Photodiode Detector Structures for Nuclear Detection Applications**, ***Vincent Woods***, *L. Hubbard*, *L. Campbell*, Pacific Northwest National Laboratory, *N. Dietz*, Georgia State University, *Z. Sitar*, North Carolina State University **INVITED**

Group III-N avalanche photodiodes (APD) offer tailorable UV sensitivity and selectivity not currently available for scintillated light detectors. Materials growth challenges continue to hamper the development and implementation of UV III-N detectors. This presentation details the efforts at Pacific Northwest National Laboratory in collaboration with North Carolina State University and Georgia State University to develop device structures and fabrication processes Group III-N APDs. The focus of these efforts is to produce nitride photomultiplier (NPM) devices similar to a silicon photomultiplier (SiPM). Compared to traditional photomultiplier tubes (PMTs), the NPMs can be smaller, more rugged, consume less power than PMTs, and have lower dark currents than SiPMs for UV light detection.

The large bandgap of III-N systems allows for UV photo-detection that is solar blind resistant to ambient stray light. Unlike silicon, the bandgap and associated dark current in the III-N system can be tuned by changing the composition of the $Al_xGa_{1-x}N$ materials system. A direct advantage of the III-N APDs over SiPMs and PMTs is the matching of the device (by matching the band gap) to a scintillator.

Conventional radiation detection relies on the use of dyes to wavelength shift the scintillated light to match the PMT or SiPM. Tailoring the APD to the scintillator allows for increased resolution of scintillated light without broadening/attenuation from dye interactions. A tailorable APD also allows for exploration of scintillating materials which cannot be dye matched to a SiPM or PMT. The tailorable III-N system opens up new avenues in radiation detection. Research into the selection of appropriate scintillator materials and compositional requirements of the Nitride-based APD structures will be presented. In addition to the materials characterization, optoelectronic modeling aimed towards efficient APD operation will be shown.

The progress in the growth of nitride heterostructures in both Al-rich and Ga-rich AlGaN materials systems will be presented along with detailed materials characterization. This project is developing the materials capability to tailor III-N APDs to match scintillated light. The development of materials knowledge and capability will enable tailorable III-N APDs for direct matching to UV scintillated light, a significant improvement over current technology.

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