Electronic Materials and Photonics
Room 102A - Session EM-MoA

Surface and Interface Challenges in Wide Bandgap Materials

Moderators: Charles Eddy Jr., U.S. Naval Research Laboratory, Rachael Myers-Ward, Naval Research Laboratory

1:40pm **EM-MoA1 ALD Gate Dielectrics for GaN HEMTs*, Andrea Corrion,*** HRL Laboratories, LLC **INVITED**

While most reported GaN high-electron mobility transistors (HEMTs) to-date have utilized a Schottky barrier gate, there is a significant need for high-performance insulated-gate devices. Gate dielectrics play a critical role in reducing gate leakage as well as increasing the forward-bias gate voltage swing in normally-off devices. Atomic layer deposition (ALD) gate dielectrics have recently generated significant interest for GaN HEMTs due to the wide variety of high-k materials available, highly controlled deposition rates and film quality, and low-temperature process compatibility. ALD Al_2O_3 in particular has been widely investigated and initial promising performance has been reported for both high-frequency RF and high-voltage power switch devices. However, significant challenges remain for the interface trap density, device reliability, and stability of the gate dielectric. This talk will review the status of ALD gate dielectrics for GaN HEMTs and on-going materials challenges, and will describe processes and device results for HRL's insulating-gate RF and power switching device technologies.

2:20pm **EM-MoA3 Advances in High-k Dielectric Integration with Ga-polar and N-polar GaN*, Charles Eddy, Jr.,*** U.S. Naval Research Laboratory*; C.R. English,* University of Wisconsin*; V.D. Wheeler,* U.S. Naval Research Laboratory*; D.I. Shahin,* University of Maryland College Park*; N.Y. Garces,* U.S. Patent & Trade Office*; A. Nath, J.K. Hite, M.A. Mastro, T.J. Anderson,* U.S. Naval Research Laboratory

Gallium- and nitrogen-polar GaN surfaces are subjected to a variety of pretreatments, including oxidation, before the application of high-k dielectrics by atomic layer deposition (ALD) in order to assess their ability to produce smooth, clean and electrically high-performing dielectric semiconductor interfaces. In terms of topographical and chemical cleanliness, a pretreatment with a wet chemical piranha etch (H_2SO_4:H_2O_2) was found to be optimum for both surfaces and, additionally, $(NH_4)_2S$ is effective for N-polar surfaces. Both thermal and plasma oxidations were employed for controlled growth of native oxides. For Ga-polar surfaces, all native oxides were as smooth as pretreated surfaces, while for N-polar surfaces all native oxides are much rougher except for very short, high temperature oxidations. Thermal ALD high-k dielectrics, including Al_2O_3, HfO_2 and ZrO_2, were deposited on "optimally" treated surfaces. ALD Al_2O_3 films on Ga-polar surfaces are smoother for pre-treated surfaces than for as-received surfaces, whereas for N-polar surfaces the opposite is true. In general, ALD HfO_2 films on Ga-polar surfaces are rougher (0.8 nm rms) than Al_2O_3 films (0.1 nm rms), whereas for piranha treated N-polar surfaces HfO_2 films are smoother than Al_2O_3 films. ZrO_2 films are smoother than HfO_2 but rougher than Al_2O_3 films. For Ga-polar surface, capacitance-voltage measurements of simple Al_2O_3 (measured k = 9) capacitors show the smallest hysteresis for unintentionally oxidized surfaces (0.37 V), whereas simple HfO_2 (measured k = 14) capacitors show the smallest hysteresis for a thermal GaO_x at the interface (0.1 V). In both cases, the thicker the GaO_x at the interface the larger the negative threshold voltage shift – suggesting an electron trap. Calculated total trapped charges associated with the dielectrics range from $3.2x10^{11}$ cm^{-2} (for HfO_2 on thermally oxidized GaN) to $1x10^{12}$ cm^{-2} for Al_2O_3 on thermally oxidized GaN and HfO_2 on plasma oxidized GaN. Finally, the leakage current density for nearly all capacitors is $<10^{-5}$ A-cm^{-2} for up to a +8V bias. Interestingly, without additional GaN oxidation, ZrO_2 films present a significant positive threshold shift which could be beneficial for enhancement-mode transistor operation. Further details of ZrO_2 performance on "optimally" treated Ga-polar surfaces will also be presented.

2:40pm **EM-MoA4 Effects of Surface Cleaning and Different Metals as Schottky Contacts to Bulk and Epitaxial β-Ga_2O_3*, Yao Yao,*** *R. Gangireddy, J. Kim,* Carnegie Mellon University*; T. Salagaj, N. Sbrockey, G.S. Tompa,* Structured Materials Industries, Inc.*; K.K. Das,* JBP Materials*; R.F. Davis, L.M. Porter,* Carnegie Mellon University

Beta-gallium oxide (*β*-Ga_2O_3) has emerged over the past few years as a promising next-generation wide bandgap semiconductor. It has a bandgap of ~4.8 eV and a breakdown electric field of ~8 MV/cm, giving it a superior figure-of-merit compared to traditional wide bandgap semiconductors like SiC and GaN. Moreover, it can be produced from the melt, and single-crystal (2-in diameter) substrates have recently become commercially available. Devices based on *β*-Ga_2O_3 that have so far been demonstrated include Schottky diodes, metal-semiconductor field effect transistors (MESFETs), metal-oxide-semiconductor field-effect transistors (MOSFETs), and ultra-violet (UV) photodiodes. However, since research on *β*-Ga_2O_3 as a wide bandgap semiconductor is in its very early stages, there is little understanding on how to control device-relevant interfaces to this material. In this work, we have investigated Schottky diodes fabricated on Sn-doped ($5x10^{18}$ cm^{-3}) single-crystal Ga_2O_3 (-201) substrates and lightly doped (~10^{17} cm^{-3}) Ga_2O_3(010) homoepilayers. A surface study was first performed to evaluate the effect of different surface cleaning techniques on contact performance. The surface cleaning methods consisted of (1) an organic solvent clean only (acetone and isopropanol), and an organic clean followed with a (2) HCl, (3) BOE, (4) HCl and H_2O_2 or (5) BOE and H_2O_2. The corresponding Schottky barrier heights (SBHs) were calculated from the *I-V* and *C-V* behaviour of Ni Schottky diodes fabricated on bulk Ga_2O_3 (-201). SBHs were lowest for the organically cleaned sample, and highest for the sample treated in HCl and H_2O_2. The latter also had the lowest leakage current in reverse bias and showed the most stable performance even after a period of several weeks after deposition. We have therefore established that organic clean followed by HCl and H_2O_2 treatment is the most effective of the cleaning methods tested. We have also investigated Schottky diodes fabricated using different Schottky metals. On the bulk Ga_2O_3 (-201) substrates, we calculated SBHs from the *I-V* behavior of Ir, Ni, Au and Sn to vary from ~1.0–0.7 eV in approximate correspondence with the metal workfunctions. On the lightly doped *β*-Ga_2O_3 (010) epilayer, preliminary measurements indicate a SBH > 1.0 eV for Ni. Electrical behavior of other metals on the (010) epilayer will also be investigated and reported in the presentation.

3:00pm **EM-MoA5 Deep Traps in Wide Bandgap Semiconductors: From GaN to beta-Ga_2O_3*, Steven Ringel,*** *A. Arehart, E. Farzana, Z. Zhang,* The Ohio State University*; E. Ahmadi, Y. Oshima, J. Speck,* University of California at Santa Barbara **INVITED**

Deep level defects are pervasive in wide bandgap (WBG) semiconductors such as GaN. Over the years deep levels in GaN have been extensively studied. Several states have been directly linked with device degradation mechanisms in high electron mobility transistors and there is continued exploration of defect mitigation strategies to improve reliability. At the same time, there has been intense interest on the so-called ultra-wide bandgap (UWBG) semiconductors, whose bandgaps are > 3.4 eV, driven by the desire to develop devices that can sustain even higher fields, operate at higher temperatures, while maintaining good high frequency performance. Of these UWBG materials, beta-phase gallium oxide (β-Ga_2O_3) is attracting particular interest due to its large, direct bandgap of ~ 4.8 eV, the availability of n doping, the ability to create heterostructures, and the availability of native substrates to support homoepitaxial growth. This latter point is unique amongst WBG and UWGB materials.

However, compared with incumbent technologies, β-Ga2O3 is in its infancy, with transistors recently announced that have created excitement regarding the future of this material.[1] This presentation will build from our work on GaN and focus on basic aspects of β-Ga_2O_3: (a) the application of deep level optical and transient spectroscopy (DLOS/DLTS) to reveal traps throughout the entire material bandgap, (b) comparative DLOS/DLTS studies made on substrates and epitaxial layers grown by molecular beam epitaxy, and (c) the influence of wafer orientation on the properties of β-Ga_2O_3 Schottky diodes using various metals. DLTS and DLOS measurements revealed a spectrum of distinct bandgap states at Ec – 0.62 eV, 0.82 eV, 1 eV, 2.4 eV and 4.42 eV, with a total trap concentration of ~ mid 10^{16} cm^{-3} range, dominated by the traps at Ec –0.82 eV and Ec – 4.42 eV.[2] Several traps show strong lattice-coupling effects. Regarding Schottky contacts, Ni Schottky contacts were fabricated on (010) and (-201) surfaces, revealing a change in barrier height of almost 0.5 V, as measured by both internal photoemission and C-V methods, suggesting a surface orientation dependence of Schottky barrier formation. Comparing Ni, Au, Pt and Pd contacts on (010) β-Ga_2O_3, barrier heights appear partially unpinned with barriers ranging from ~ 1.2 eV for Pd, to ~ 1.55 eV for both Ni and Pt and as high as ~ 1.8 eV for Au. In all cases, nearly ideal Schottky barrier transport characteristics were observed. This presentation will focus on the extension of trap studies from GaN to β-Ga_2O_3.

[1] M. Higashiwaki, et al., Appl. Phys. Lett. **100**, 013504 (2012)

[2] Z. Zhang, et al., Appl. Phys. Lett. 108, 052105 (2016)

4:00pm **EM-MoA8 Study of Oxygen and Moisture Effect on Device Instability of Bottom-Gate ZnO Transistors with Sol-Gel Derived Channel Layers**, ***Kosala Yapabandara***, *M. Park, M.C. Hamilton, D.-J. Kim, V. Mirkhani, S. Wang, M. Sultan, B. Ozden, M.P. Khanal, S. Uprety, Y. Chung,* Auburn University; *M.H. Sk,* Qatar University, Qatar

ZnO has been widely studied due to its promising material properties such as wide energy bandgap, optical transparency, and high carrier mobility for thin film transistor (TFT) technology. Solution-based ZnO can easily be deposited on large areas of substrates at low temperatures, which makes this material a good candidate for commercial device manufacturing. In the case of device reliability and performance, device stability under electrical stress is of imminent importance.

In this work, we report on the device instability of solution-based ZnO TFTs by studying the electrical characteristics during electrical stressing and subsequent relaxation. In order to elucidate the major source for device instability under electrical stress, the electrical characteristics of the transistors under the vacuum and ambient conditions were measured and compared. The positive shift of threshold voltage (V_T) of the device under gate stressing and negative shift under relaxation for both the vacuum and ambient conditions were observed, which suggest that the charge trapping near or at the semiconductor/dielectric interface and charge injection to dielectric layer may be main mechanisms for device instability. However, the continuous degradation of the field effect mobility with electrical bias-stressing in both environmental conditions and a full recovery of the device with a longer relaxation time provided evidence to disregard the assumption of charge injection to the dielectric layer.

Variation in sub-threshold swing (S) with biasing process indicates a new defect level creation. A negligible change in S during gate stressing and relaxation under the vacuum condition, compared to a significant change in S under ambient conditions confirmed that there is no new defect level creation in the absence of oxygen and moisture. Under ambient conditions, oxygen and moisture were adsorbed on the channel surface with the presence of a positive electric field. Upon adsorption, oxygen molecules can capture electrons from the conduction band and a depletion layer can be formed in the ZnO channel layer. Previously, it has been reported that oxygen molecules cannot diffuse into the channel layer at room temperature. However, we have suggested a plausible mechanism that oxygen can be located closer to semiconductor/dielectric interface in thin films upon acceptor-like reaction of H_2O that diffused into the channel *via* voids in grain boundaries. Further confirmation of charge trapping and new defect level creation was carried out by fitting the V_T shift *vs*. time curve with the power law and stretched exponential functions for the vacuum and ambient conditions, respectively.

4:20pm **EM-MoA9 Depth Dependent Modification of Optical Constants Arising from H^+ Implantation in n-type 4H-SiC Measured using Coherent Acoustic Phonons**, ***Andrey Baydin***, *H. Krzyzanowska,* Vanderbilt University; *M. Dhanunjaya, S.V.S. Nageswara Rao,* University of Hyderabad, India; *J.L. Davidson,* Vanderbilt University; *L.C. Feldman,* Vanderbilt University, Rutgers University; *N.H. Tolk,* Vanderbilt University

Silicon carbide is a promising material for new generation electronics including high power/high temperature devices and advanced optical applications such as room temperature spintronics and quantum computing. Both types of applications require the control of defects particularly those created by ion bombardment. In this work, modification of optical constants of 4H-SiC due to hydrogen implantation at 180 keV and at fluences ranging from 10^{14} to 10^{16} cm^{-2} is reported. The depth dependence of the modified optical constants was extracted from coherent acoustic phonon spectra. Implanted spectra shows a strong dependence of the 4H-SiC complex refractive index depth profile on H^+ fluence. These studies provide basic insight into the dependence of optical properties of 4H silicon carbide on defect densities created by ion implantation, which is of relevance to the fabrication of SiC-based photonic and optoelectronic devices.

4:40pm **EM-MoA10 Electrical and Thermal Stability of ALD-TiN Schottky Gates for AlGaN/GaN HEMTs**, *D.I. Shahin,* University of Maryland College Park; ***Travis Anderson***, *V.D. Wheeler, M.J. Tadjer, A.D. Koehler, K. Hobart, C.R. Eddy, Jr., F. Kub,* U.S. Naval Research Laboratory; *A. Christou,* University of Maryland College Park

AlGaN/GaN high electron mobility transistors (HEMTs) are useful devices for next-generation RF and power electronics systems[1,2]. Traditional Ni-based Schottky gates in these devices have been shown to degrade when subjected to electrical stress, thermal stress, and radiation due to Ni migration into adjacent metal or semiconductor layers[3,4]. The instability of these Ni-based gates limits device reliability, rendering the search for replacement gate materials that are electrically- and thermally-stable a topic of tremendous importance. Of the transition metal nitrides, TiN is a particularly promising material, due to its near-metallic conductivity, suitable Schottky barrier heights and ideality factors on GaN and AlGaN, and high temperature stability. This work investigates the performance of atomic layer deposited (ALD) TiN gates and directly compares them to traditional Ni/Au gates.

ALD TiN gates (75nm thick) were deposited on AlGaN/GaN HEMTs in an Oxford FlexAL system at 350°C using Tetrakis(dimethyamido)titanium (TDMA-Ti)and an N_2/H_2 plasma as precursors. Devices with TiN gates exhibited improved static and dynamic on-state characteristics compared to the identical Ni/Au-gated HEMTs. Reverse bias gate stressing indicated a higher critical voltage (V_{gsTiN} = -210V, $V_{gsNi/Au}$ = -120V) and a higher breakdown voltage (V_{gsTiN} = -270 ± 10 V, $V_{gsNi/Au}$ = 240 ± 30V)for the TiN gates. Furthermore, the TiN gates exhibited a decrease in reverse leakage current after stressing indicating enhanced stability. Gate thermal stability was assessed through sequential device annealing from 400-800C in 100C increments. The TiN gated devices exhibited stable DC operation up to 800°C, while the Ni/Au gates showed significant degradation after annealing above 500°C and failed above 700°C. This suggests that ALD TiN gates are a strong candidate for reliable HEMT gate metallization and other applications where increased stability is required at higher temperatures.

[1] R.S. Pengelly, et al., *IEEE Trans. Microwave Theory Tech.***60** [6], 1764 (2012).

[2] S.J. Pearton, et al., *J. Vac. Sci. Technol. A* **31** [5], 050801 (2013).

[3] Y.H. Choi, et al., *Materi. Res. Soc. Symp. Proc.***1167**, 1167-O05-06 (2009).

[4] A.D. Koehler, et al., *IEEE Elect. Dev. Lett.***35** [12], 1194 (2014).

5:00pm **EM-MoA11 Spectroscopic Photo Current Voltage Measurements to Investigate Non-uniform Defect Distributions in AlGaN/GaN HEMT Heterstructures**, ***Burcu Ozden***, *M.P. Khanal, C. Yang, L. Shen, V. Mirkhani, K. Yapabandara, M. Park,* Auburn University

The nature and distributions of the electrically-active sub-bandgap point defects in the heterostructures of the AlGaN/GaN high electron mobility transistors (HEMTs) layers have been analyzed by using spectroscopic photo current voltage (SPIV) measurement. Despite the great potential, device performance for the next generation of high power electronics is often limited by the presence of electronic traps in the AlGaN/GaN HEMTs device structures. Therefore, the knowledge of defect distribution is critical in understanding the origin of the surface traps for mitigation in future device applications.

In this work, the AlGaN/GaN HEMT epi-layers were grown on a 6" Si wafer by metal-organic chemical vapor deposition (MOCVD). Ni contacts with 600μm diameter and 20nm thickness were fabricated on the samples which are chosen from the three different locations of 6" wafer. The SPIV measurement was performed using a variable-wavelength light illumination from a Xe lamp. Vertical bias was applied between circular semi-transparent Ni Schottky contacts and the bottom ohmic contact.

Presence of sub-bandgap defects at different energy levels among the wafer were revealed by SPIV measurements indicating nonhomogeneous defect distribution among the wafer. It was concluded that observed defects are most probably due to either Ga vacancies in GaN or Al vacancies in AlGaN by comparing the energy level of the defects with the formation energies of these vacancies. In conclusion, we have demonstrated the wafer quality in terms of the distribution of electrically active defects can be successfully assess by using SPIV measurements which will be useful for AlGaN/GaN HEMT wafer vendors as a diagnostic tool.

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