Electronic Materials and Photonics Division
Room 101A - Session EM+2D+SS-WeA

Wide and Ultra-Wide Bandgap Materials for Electronic Devices: Growth, Modeling and Properties

Moderators: Erica Douglas, Sandia National Laboratories, Rachael Myers-Ward, U.S. Naval Research Laboratory

2:40pm **EM+2D+SS-WeA2 2300 V Reverse Breakdown Voltage Ga_2O_3 Schottky Rectifiers**, ***Jiancheng Yang***[1], *F.R. Ren,* University of Florida*; M.J. Tadjer,* U.S. Naval Research Laboratory*; S.J. Pearton,* University of Florida*; A. Kuramata,* Tamura Corporation and Novel Crystal Technology, Inc., Japan

A reverse breakdown voltage of 2300 V with corresponding breakdown field of 1.15 MV/cm was demonstrated for 20 µm epi-β-Ga_2O_3 edge-terminated vertical Schottky rectifiers. This breakdown voltage is the highest ever reported for Ga_2O_3 rectifiers. Ga_2O_3 has an energy band gap of range 4.5 – 4.9 eV, which correlates to the theoretical breakdown electric field of ~8 MV/cm. The theoretical Baliga figure of merit (defined as V_B^2/R_{ON}, where V_B is the reverse breakdown voltage and R_{ON} is the on-state resistance) of Ga_2O_3 estimated to be 400% higher than GaN.[1] Previously reported, an unterminated Ga_2O_3 rectifier shown a breakdown voltage of 1600 V, and a field-plated Schottky diode has a breakdown voltage of 1076 V with the epi thickness 7 µm [2,3] This work has shown the improvement of the Ga_2O_3 vertical rectifiers breakdown voltage using a field-plate terminated approach with a lightly doped 20 µm Ga_2O_3 epitaxial layer . The edge-terminated Schottky rectifiers of various dimensions (circular geometry with diameter of 50-200 µm and square diodes with areas 4×10^{-3}- 10^{-2} cm^2) fabricated on 20µm lightly doped ($n=2.10 \times 10^{15}$ cm $^{-3}$) β-Ga_2O_3 epitaxial layers grown by hydride vapor phase epitaxy on conducting ($n=3.6 \times 10^{18}$ cm^{-3}) Ga_2O_3 substrates grown by edge-defined, film-fed growth. The R_{ON} for these devices was 0.25 Ω-cm^2, leading to a figure of merit (V_B^2/R_{ON}) of 21.2 MW/cm^2. The Schottky barrier height with the Ni/Au based metallization was 1.03 eV, with an ideality factor of 1.1 at room temperature. The Richardson's constant of 43.35 A/cm-K^2 was extracted from the temperature dependent forward IV. The breakdown voltages for the different size devices ranged from 1400-2300V, with a general, but not a linear trend of decreasing breakdown voltage for larger area rectifiers. The diode reverse recovery time of ~22 ns was measured by switching the diode from +2V to -2V.

1. J. Green, K. D. Chabak, E. R. Heller, R. C. Fitch, M. Baldini, A. Fiedler, K. Irmscher, G. Wagner, Z. Galazka, S. E. Tetlak, A. Crespo, K. Leedy, and G. H. Jessen, IEEE Electron Device Lett., vol. 37, no. 7, pp. 902–905, Jul. (2016)

2. J. Yang, S. Ahn, F. Ren, S. J. Pearton, S. Jang, and A. Kuramata, IEEE Electron Device Lett,. 38(7), 906 (2017).

3. K. Konishi, K. Goto, H. Murakami, Y. Kumagai, A. Kuramata, S. Yamakoshi, and M. Higashiwaki, Appl. Phys. Lett. 110, 103506 (2017).

3:00pm **EM+2D+SS-WeA3 Characterization of β-$(Al,Ga,In)_2O_3$ Epitaxial Films for UV Photodetector Applications**, ***Luke Lyle***, *L.M. Porter, R. Davis,* Carnegie Mellon University*; S. Okur, G.S. Tompa,* Structured Materials Industries, Inc.*; M. Chandrashekhar, V. Chava, J. Letton,* University of South Carolina

β-Ga_2O_3 has garnered increased attention over the last few years due to its ultra-wide bandgap of ~5.0 eV and the ability to grow Ga_2O_3 single crystals from the melt. In addition to its desirability for high power electronics, Ga_2O_3 is well suited for solar-blind UV photodetectors. These detectors are coveted by numerous industries and the military for applications ranging from flame- and missile-plume detection to ozone hole monitoring. In this study we have grown $(Al,Ga,In)_2O_3$-based alloy epitaxial films on sapphire via metalorganic chemical vapor deposition (MOCVD) to investigate their potential application for wavelength-tunable UV photodetectors. The films were characterized structurally, optically, and chemically using x-ray diffraction (XRD), optical transmittance, and energy dispersive x-ray spectroscopy (EDX). Based on XRD and EDX results, β-$(Al_xGa_{1-x})_2O_3$, β-$(In_xGa_{1-x})_2O_3$, and β-Ga_2O_3 epitaxial films with compositions through x = 0.29 (for Al) and x = 0.13 (for In) were grown. The optical bandgap was found to correspondingly vary between 5.5±0.1 and 4.3±0.3 eV, as a function of composition. MSM- and Schottky-based solar-blind UV photodetectors were also fabricated on selected films. The devices showed responsivities up to 1E5 A/W and quantum efficiencies up to 6E5 at 220 nm from a deuterium lamp. The wavelength tunability of the photodetectors is currently being investigated and will be discussed in this presentation.

3:20pm **EM+2D+SS-WeA4 High Three-terminal Breakdown Voltage Quasi-two-dimensional β -Ga_2O_3 Field-effect Transistors with a Dual Field Plate Structure**, ***Jinho Bae***, Korea University, Republic of Korea*; H.W. Kim, I.H. Kang,* Korea Electrotechnology Research Institute (KERI), Republic of Korea*; G.S. Yang, S.Y. Oh, J.H. Kim,* Korea University, Republic of Korea

β-Ga_2O_3 is an intriguing material because of its large direct bandgap (4.85 eV), high breakdown field (~8 MV/cm) and excellent thermal and chemical stability. Baliga's figure of merit of β-Ga_2O_3 is 3214.1, superior to those of other materials such as GaN (846.0) or SiC (317.1). Although β-Ga_2O_3 is not a van der Waals material, β-Ga_2O_3 can be mechanically exfoliated from single crystal substrate into thin layer due to the large anisotropy of the unit cell. Quasi-2D β-Ga_2O_3 devices shows superior electrical properties and robustness in harsh environment, which shows potential of β-Ga_2O_3 as nanoscale power devices. However, quasi-2D β-Ga_2O_3 power devices show premature breakdown due to the electric field concentration. Adopting multiple field plates to relieve the electric field concentration and prevent premature breakdown greatly enhance the performance of power devices, which can be applied to β-Ga_2O_3 nanoelectronic power devices.

H-BN has been used as a dielectric material of 2D devices due to its excellent thermal conductivity and high dielectric constant, as well as atomically flat surface, which can be obtained through mechanical exfoliation. In our work, we used h-BN as a gate field plate dielectric layer by selective transfer on β-Ga_2O_3 channel using PDMS film. SiO_2 dielectric layer was deposited on devices followed by metal deposition for source field plate structure. By applying dual field plate structure, β-Ga_2O_3 devices can show excellent performance in high voltage condition.

β-Ga_2O_3 MESFETs with h-BN gate field plate were fabricated by using the β-Ga_2O_3 and h-BN flakes obtained from respective crystals. Ohmic metal was deposited on mechanically exfoliated β-Ga_2O_3 flakes, followed by precise positioning of exfoliated h-BN flakes on the channel. Gate field plate was fabricated with a part of the electrode overlapped with h-BN. Dual field plate structure was fabricated after deposition of SiO_2 and source field plate metal. Fabricated devices showed excellent output and transfer characteristics even after one month storage, which shows excellent air-stability. Three-terminal off-state breakdown voltage of fabricated device was measured, which shows improvement in breakdown voltage. The electric field distribution was calculated by Silvaco Atlas framework to study the effect of dual field plate on electric field, which explains the improvement of breakdown voltage in those structure. In this study, we present that the performance of β-Ga_2O_3 MESFET as a power device can be improved by adopting dual field plate structure, paving a way to the high-power nanoelectronic β-Ga_2O_3 devices. The details of our work will be discussed in the conference.

4:20pm **EM+2D+SS-WeA7 GaN Vertical Device Technology and its Future**, *S.C. Chowdhury,* ***Dong Ji***, UC Davis **INVITED**

Vertical GaN devices are ideal for high power applications owing to their wide bandgap-originated material properties, similar to SiC. What makes GaN vertical devices more attractive than SiC, is the capability to offer bulk regions with electron mobility over 1200cm^2/V·sec. Due to higher carrier mobility made possible by superior growth techniques, the figure of merit offered by GaN diodes or FETs is higher compared to SiC counterparts. From TCAD drift diffusion simulation we have shown the advantage of GaN devices become rapidly significant over SiC diodes at higher voltages. In our experimental studies we have successfully demonstrated transistors blocking over 1.4kV.

In this presentation, we will go over various types of vertical devices for power conversion that we are pursuing in our group and go over the achievements and challenges in each.

CAVETs were the first vertical devices[1] that demonstrated the potential of GaN in these technology. CAVETs are realized with Mg-ion implanted [2] current blocking layers (CBLs) with regrown channel. Alternatively they can have Mg-doped CBLs with a regrown channel layer on a trench. In our trench CAVETs we have successfully blocked up to 880V with an R_{on} less than 2.7milli-ohm cm^2.

To date, most successful results in GaN vertical devices have come out of MOSFETs, which traditionally rely on inversion channels. MOSFETs with an un-doped GaN interlayer as a channel and in-situ MOCVD oxide, called OG-FET have demonstrated superior performance with low specific on-state resistance (R_{on}) Over 1.4kV blocking with an R_{on} less than 2.2milli-ohm cm^2

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[1] **National Student Award Finalist**

was recently demonstrated by our group where the role of channel mobility got highlighted[3].

One of common issue in all these devices is the realization of a robust buried p-n junction, which we will also go over along with other challenges faced by each of these device types and discuss paths to overcome those.

1. S. Chowdhury, M. H. Wong, B. L. Swenson, and U. K. Mishra, IEEE Electron Device Letters **33**, 41 (2012).

2. S. Mandal, A. Agarwal, E. Ahmadi, K. M. Bhat, D. Ji, M. A. Laurent, S. Keller, and S. Chowdhury, IEEE Electron Device Letters, **38**, 7 (2017)

3.D. Ji, C. Gupta, S. H. Chan, A. Agarwal, W. Li, S. Keller, U. K. Mishra, and S. Chowdhury, *International Electron Devices Meeting, IEDM*, 2017

5:00pm **EM+2D+SS-WeA9 Effects of Proton Irradiation Energy on SiN_x/AlGaN/GaN Metal-insulator-semiconductor High Electron Mobility Transistors**, ***Chaker Fares**, F.R. Ren,* University of Florida*; J.H. Kim,* Korea University, Republic of Korea*; S.J. Pearton,* University of Florida*; C.F. Lo, J.W. Johnson,* IQE*; G.S. Yang,* Korea University, Republic of Korea

The effects of proton irradiation energy ranging from 5 to 15 MeV on the electrical properties of SiNx/AlGaN/GaN metal-insulator-semiconductor high electron mobility transistors (MISHEMTs) using in-situ grown silicon nitride as the gate dielectric were studied. In applications such as satellite-based communication, remote sensing, radar technology, and nuclear energy production, microelectronics that are resistant to radiation must be utilized. Of the many materials and device architectures previously investigated, AlGaN/GaN high electron mobility transistors (HEMTs) show significant potential for environments where radiation hardness, elevated temperature, and high-power operation are required. Although several studies have been performed to analyze how HEMTs respond to irradiation damage, data on the effects of proton irradiation energy on MISHEMTs are scarce. In this study, AlGaN/GaN MISHEMT samples were irradiated at various proton irradiation energies at a fixed dose of 2.5×10^{14} cm^{-2} to determine the effects on device performance. After proton irradiation, all devices were functional and showed minimal degradation compared to previous reports of HEMTs irradiated at similar conditions.The dc saturation current was reduced by 10.4, 3.2 and 0.5% for MISHEMTs irradiated with proton energies of 5, 10, and 15 MeV, respectively. Device performance degradations were more pronounced in the irradiated samples under high-frequency operation. At a frequency of 100 KHz, the saturation drain current reduction at a gate voltage of 3 V was 40%, 19% and 17% after proton irradiation at 5, 10, and 15 MeV, respectively. At higher duty cycles, the drain current reduction is less severe. The results of this study demonstrated the device reliability of AlGaN/GaN MISHEMTs in environments where a resilience to radiation is required.

5:20pm **EM+2D+SS-WeA10 Cesium-Free III-Nitride Photocathodes Based on Control of Polarization Charge**, ***Douglas Bell**,* Jet Propulsion Laboratory, California Institute of Technology*; E. Rocco, F. Shahedipour-Sandvik,* SUNY Polytechnic Institute*; S. Nikzad,* Jet Propulsion Laboratory, California Institute of Technology

III-nitride photocathodes are well-suited for ultraviolet (UV) detection, with commercial, defense, and astronomical applications. Photocathodes detect light by absorbing photons which create electron-hole pairs, and emitting those electrons into vacuum, where they are detected and amplified by a gain-producing device such as a microchannel plate. This type of device is capable of ultra-low dark current and enables photon counting. The wide bandgaps available in the AlGaN family provide intrinsic solar blindness, and the long-wavelength cutoff may be tuned by control of composition.

Among other properties, negative electron affinity (NEA) is desirable for these structures in order to maximize quantum efficiency (QE), or the number of electrons emitted per incident photon. Normally surface cesiation is used to create low or negative electron affinity of the GaN photocathode surface; however, the resulting highly reactive surface must be protected from air during fabrication and use, necessitating a sealed-tube configuration. Even so, the reactive surfaces of these devices cause degraded performance over time. Cesium-free photocathodes would offer lower cost, smaller size and mass, improved robustness, and greater chemical stability, in addition to the major advantages of higher QE and longer lifetimes.

We will report on the use of polarization engineering in order to achieve high QE without the use of Cs. We will discuss progress in design, fabrication, and characterization of polarization-engineered III-nitride photocathodes. An important component of these designs is the use of N-polar GaN and AlGaN. The nitride polarity affects the interface and surface polarization charge, and the ability to achieve low electron affinity depends critically on control of this charge. Designs using polarization charge engineering also enable optimization of the near-surface potential to further increase QE. We will describe the growth challenges of N-polar GaN and AlGaN and its implementation in photocathode devices. We will present results demonstrating high (>15%) QE for non-cesiated N-polar GaN photocathodes, with a clear path toward higher efficiency devices.

5:40pm **EM+2D+SS-WeA11 Current Enhancement for Ultra-Wide Bandgap AlGaN High Electron Mobility Transistors by Regrowth Contact Design**, ***Erica Douglas**, B. Klein, S. Reza, A.A. Allerman, R.J. Kaplar, A.M. Armstrong, A.G. Baca,* Sandia National Laboratories

Recently, ultra-wide bandgap (UWBG) materials, such as Al-rich AlGaN with bandgaps approaching 6 eV, are being investigated to drive high-power electronic applications to even higher voltages, due to increased critical electric field compared to wide bandgap materials, such as GaN.[1] However, challenges have been encountered with Al-rich AlGaN, and in particular an increase in contact resistance as the bandgap for heterostructures increases.[2] High contact resistance ultimately limits the performance that can be achieved for these novel heterostructure-based devices, as source and drain resistances can be dominated by Ohmic contacts. While planar metal stacks with a rapid thermal anneal have shown some level of success, a complimentary approach using doped regrowth for the Ohmic contact regions with materials of lower bandgap has also shown a potential path for lowering contact resistance.[2] Our work explores regrown Ohmic contacts composed of lower bandgap Si-doped GaN to $Al_{0.85}Ga_{0.15}N/Al_{0.7}Ga_{0.3}N$ heterostructures , achieving a maximum saturated drain current of ~ 45mA/mm. Additionally, we demonstrate the ability to increase the saturated drain current almost 3X (from ~45 mA/mm to ~130 mA/mm) for UWBG HEMTs through a circular perforation design as well as a comb-type structure by means of regrowth contact design engineering.

[1] R. J. Kaplar, *et. al*, “Review—Ultra-Wide-Bandgap AlGaN Power Electronic Devices,” ECS J. Solid State Sci. Technol., vol. 6, no. 2, pp. Q3061-Q3066, Jan. 2017.

[2] B. A. Klein, *et. al*, “Planar Ohmic Contacts to $Al_{0.45}Ga_{0.55}N/Al_{0.3}Ga_{0.7}N$ High Electron Mobility Transistors,” ECS J. Solid State Sci. Technol., vol. 6, no. 11, pp. S3067-S3071, Aug. 2017.

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6:00pm **EM+2D+SS-WeA12 Understanding Homoepitaxial GaN Growth**, ***Jennifer Hite**, T.J. Anderson, M.A. Mastro, L.E. Luna, J.C. Gallagher, J.A. Freitas,* U.S. Naval Research Laboratory*; C.R. Eddy, Jr.,* U. S. Naval Research Laboratory

The availability of high quality, free-standing GaN substrates opens windows for new device applications in III-nitrides, especially in vertical structures. With the introduction of these native substrates, the properties of nitrides are no longer dominated by defects introduced by heteroepitaxial growth. However, additional materials challenges are coming to the forefront that need to be understood and surmounted in order to allow homoepitaxial devices to achieve their full potential.

In order to enable device-quality epitaxial layers, a deeper understanding of substrate preparation and the effects of the substrate and growth initiation on the characteristics of the epitaxial layers is required for metal organic chemical vapor deposition (MOCVD) growth of homoepitaxial films. We investigate these effects on epi morphology, uniformity, and impurity incorporation at the interface and in the films. Although the initial substrate factors influencing the epi can be subtle, they can have far reaching impact on device performance. Additionally, the interface between substrate and epitaxy is examined to enable reduction of unintentional impurity incorporation, especially Si, at this surface. By studying these effects using wafers from several different vendors, with substrates from both hydride vapor phase epitaxy (HVPE) and ammonothermal techniques, an understanding of the requirements for device quality MOCVD homoepitaxy can be determined.

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