Electronic and Photonic Devices, Circuits and Applications Room Davis Hall 101 - Session EP+ET+MD-WeM

Process/Devices III

Moderator: Marko Tadjer, Naval Research Laboratory

10:45am **EP+ET+MD-WeM-10 Recent Progress of Ga_2O_3 Power Technology: Large-Area Devices, Packaging, and Applications***, **Yuhao Zhang**,* Virginia Tech **INVITED**

The Ga_2O_3 power device technology has witnessed fast advances towards power electronics applications. Recently, reports on large-area (ampere-class) Ga_2O_3 power devices have emerged globally, and their scope has gone well beyond the bare-die device demonstration into the device packaging, circuit testing, and ruggedness evaluation. These results have placed Ga_2O_3 in a unique position as the only ultra-wide bandgap semiconductor reaching these indispensable milestones for power device development. This talk will review the state of the art of the ampere-class Ga_2O_3 power devices (current up to >100 A and voltage up to >2000 V), covering the following topics:

1. Static electrical performance of Ga_2O_3 diodes and MOSFETs with ampere-class demonstrations (Fig. 1), with a summary of their key parameters including breakdown voltage, on-state current, and specific on-resistance (Fig. 2).
2. Dynamic performance of large-area Ga_2O_3 diodes and MOSFETs, including the reverse recovery, switching charge, as well as turn-ON and turn-OFF characteristics. A large-area Ga_2O_3 diode with NiO junction termination extension will be analyzed as a case study (Fig. 3).
3. Packaging and thermal management of Ga_2O_3 devices, highlighting the global efforts on junction-side packaging and cooling to overcome the low thermal conductivity of Ga_2O_3 (Fig. 4).
4. Circuit-level applications of Ga_2O_3 power devices, such as PFC circuits and double-pulse tests, as well as their circuit-level overcurrent/overvoltage ruggedness.

These results of large-area Ga_2O_3 devices allow for a direct comparison with commercial Si, SiC, and GaN devices. Accordingly, research opportunities and critical gaps for Ga_2O_3 power devices will also be discussed.

Reference:

[1] Y. Qin *et al.* , "Recent progress of Ga2O3 power technology: large-area devices, packaging and applications," *Jpn. J. Appl. Phys.*, vol. 62, no. SF, p. SF0801, Feb. 2023.

[2] Y. Qin *et al.*, "Thermal management and packaging of wide and ultra-wide bandgap power devices: a review and perspective," *J. Phys. Appl. Phys.*, vol. 56, no. 9, p. 093001, Feb. 2023.

[3] B. Wang *et al.*, "2.5 kV Vertical Ga2O3 Schottky Rectifier With Graded Junction Termination Extension," *IEEE Electron Device Lett.*, vol. 44, no. 2, pp. 221–224, Feb. 2023.

[4] B. Wang *et al.*, "Low Thermal Resistance (0.5 K/W) Ga_2O_3 Schottky Rectifiers With Double-Side Packaging," *IEEE Electron Device Lett.*, vol. 42, no. 8, pp. 1132–1135, Aug. 2021.

[5] M. Xiao *et al.*, "Packaged Ga2O3 Schottky Rectifiers With Over 60-A Surge Current Capability," *IEEE Trans. Power Electron.*, vol. 36, no. 8, pp. 8565–8569, Aug. 2021.

11:15am **EP+ET+MD-WeM-12 Forward and Reverse Current Transport of (001) β-Ga_2O_3 Schottky Barrier Diodes and TiO_2/β-Ga_2O_3 Heterojunction Diodes with Various Schottky Metals***, **Nolan Hendricks**,* AFRL, UCSB*; E. Farzana,* UCSB*; A. Islam, D. Dryden, J. Williams,* Air Force Research Lab*; J. Speck,* UCSB*; A. Green,* Air Force Research Lab

β-Ga_2O_3 (BGO) has great potential for power devices due to its predicted breakdown field of 8 MV/cm, ease of n-type doping, and availability of melt-grown native substrates. The TiO_2/BGO heterojunction diode (HJD) has been shown to reduce reverse current compared to Schottky barrier diodes (SBDs) due to the high permittivity of TiO_2 without significantly affecting forward conduction losses due to the band alignment. [1] We demonstrate SBDs and HJDs with Ni, Pt, Cr, and Ti contacts, analyzing the current transport mechanism and showing similar or lower conduction losses in the HJD for all metals and reduced leakage current at higher electric fields in reverse bias.

SBDs and HJDs were fabricated on 8.5 µm of Si-doped BGO grown by HVPE on a Sn-doped (001) BGO substrate. Fabrication began with a backside Ti/Au cathode. 6.5 nm of TiO_2 was deposited on the HJD sample by plasma-enhanced ALD. Circular anode contacts (D=150 µm) of Pt/Au, Ni/Au, Cr/Au, and Ti/Au (20/180 nm) were patterned by separate lithography steps.

Capacitance-voltage (C-V) behavior was measured at 1 MHz. N_D-N_A and Φ_B were extracted from $1/C^2$. Current-voltage-temperature (J-V-T) characteristics of each device were measured, and Richardson plots were created from fitting the exponential region of each curve. Φ_B and the Richardson constant (A*) were extracted from each plot. Φ_B extracted for HJD is lower than in the SBD for Ni and Pt, while it is slightly higher for Cr. Unlike the Ti SBD, the Ti HJD showed rectifying behavior and exponential J-V in forward bias. Φ_B from C-V was similar but lower than J-V-T. In the linear-scale forward J-V characteristics at 25 °C, the lower Φ_B leads to lower V_{on}. No meaningful change in differential $R_{on,sp}$ is seen.

The reverse J-V behavior of each device at 25 °C was measured up to breakdown. To compare devices with different doping, J_R is plotted against the average electric field (E) at the BGO surface. In all cases, the HJDs saw higher E_{bk} than the corresponding SBDs. At lower field, the leakage current is higher in devices with lower Φ_B as expected from thermionic emission. However, at higher field, the leakage current is lower in all HJDs than the corresponding SBDs, indicating suppression of thermionic field emission current due to the wider energy barrier in the HJD. More detailed analysis indicating TFE as the primary leakage mechanism will be shown. Sharp increases in reverse current associated with defect-mediated soft breakdown are not observed for the HJDs. The reduced forward and reverse losses with higher V_{bk} of the TiO_2/BGO HJD demonstrate its potential to unlock the benefits of BGO in power diodes.

11:30am **EP+ET+MD-WeM-13 Vertical β-Ga_2O_3 Diodes with PtO_x/Interlayer Pt Schottky Contact and High Permittivity Dielectric Field Plate for Low Loss and High Breakdown Voltage***, **Esmat Farzana**, S. Roy, S. Krishnamoorthy, J. Speck,* University of California Santa Barbara

β-Ga_2O_3 is promising for high-power devices due to a bandgap of 4.8 eV, high breakdown field of 8 MV/cm, melt-grown substrates and shallow donors. However, the breakdown of β-Ga_2O_3 Schottky barrier diode (SBD) is often dictated by tunneling leakage through metal Schottky contacts with a limited Schottky barrier height (SBH) of 1.5 eV. Although oxidized noble metals (e.g, PtO_x) with SBH>2 eV can reduce tunneling leakage and improve breakdown voltage, the trade-off comes with increased on-state loss. Here, we report an alternative scheme of composite Schottky contact, PtO_x/Interlayer Pt, as a solution of reducing leakage but minimizing turn-on loss compared to PtO_x. As shown with vertical GaN SBDs,[1] the sputtered PtO_x with an interlayer e-beam deposited Pt, can reduce leakage, increase breakdown voltage, while enabling low turn-on voltage. Moreover, for edge leakage management, we integrated high permittivity ZrO_2 field-plate in these SBDs.

The SBDs were fabricated on halide vapor phase epitaxy (HVPE) (001) β-Ga_2O_3 of 10 µm epitaxy (doping ~1×10^{16} cm^{-3}). Three different Schottky contacts were fabricated, Pt, PtO_x (24 nm)/Interlayer Pt (1.5 nm), and PtO_x (24 nm). The PtO_x/Interlayer Pt SBDs were also investigated with a field-plate dielectric of 100 nm ZrO_2 (dielectric constant~26) on top of a 11 nm Al_2O_3 formed by atomic layer deposition (ALD) to protect the surface from sputtering-induced damage.

In bare SBDs, the forward current density-voltage (J-V) provided near unity ideality factor and SBHs of Pt (1.1 eV), PtO_x/Interlayer Pt (1.49 eV) and PtO_x (1.90 eV). The $1/C^2$-V provided similar trend of SBH with Pt (1.48 eV), PtO_x/Interlayer Pt (1.92 eV) and PtO_x (2.28 eV). Thus, the interlayer Pt allows tuning of SBH to lower values than PtO_x, leading to lower turn-on loss. All SBDs showed punchthrough breakdown where the fully depleted condition is reached at -910 V (estimated). The bare PtO_x/Interlayer Pt SBDs showed lower leakage and higher breakdown voltage (V_{br}) of 1.76 kV compared to Pt with 1.32 kV. The ZrO_2 field-plate further increased V_{br} to 2.34 kV. With a minimum on-resistance of 8 mΩ-cm^2, the Baliga's figure-of-merit (BFOM) of the field-plate SBD was obtained as 0.684 GW/cm^2. SILVACO simulation showed a parallel plane peak field of 3.25 MV/cm at anode center, peak field of 8 MV/cm at edge in β-Ga_2O_3, and 8.86 MV/cm in Al_2O_3. The barrier height engineering and field management involving processing techniques with reduced or minimal material damage presented here is promising for realizing robust high performance β-Ga_2O_3 vertical power devices.

[1] Z. Shi et al., Semi. Sci. Tech. 37, 065010 (2022).

11:45am **EP+ET+MD-WeM-14 Ni/TiO_2/β-Ga_2O_3 Heterojunction Diodes with NiO Guard Ring Simultaneously Increasing Breakdown Voltage and Reducing Turn-on Voltage***, J. Williams, N. Hendricks,* Air Force Research Lab*; **Weisong Wang**,* Wright State University*; A. Adams,* Apex Micro Devices*; J. Piel, D. Dryden, K. Liddy,* Air Force Research Lab*; N. Sepelak,* KBR Inc.*; B. Morell,* Cornell University*; A. Miesle,* University of Dayton*; A. Islam, A. Green,* Air Force Research Lab

β-Ga_2O_3 is an ultra-wide bandgap semiconductor (~4.8 eV) with numerous merits that potentially surpass the material limits other semiconductors for power electronic applications, namely a high predicted critical field strength of 8 MV/cm. Vertical Schottky barrier diodes (SBD) are a fundamental application for β-Ga_2O_3 to demonstrate power handling capabilities. However, breakdown behavior is limited by electric field crowding at the contact edge and high tunneling current under large reverse bias. We are reporting a novel integration of vertical heterojunction diode based on Ni/TiO_2/β-Ga_2O_3 with p-type NiO as the guard ring (GR). The heterojunction improves off-state losses and breakdown voltage (V_{bk}) without adding significant on-state losses. Leakage current is reduced by the additional barrier width, but the negative conduction-band offset between TiO_2 and β-Ga_2O_3 maintains low V_{on}. P-type NiO guard ring is to surround heterojunction to screen the high electric field generated at this region.

The devices were fabricated on an 8.5 µm Si-doped β-Ga_2O_3 drift region grown by HVPE on a heavily Sn doped (001) substrate. A back-side Ohmic contact was formed by evaporated Ti/Au. The NiO GR was created by sputtering and lift-off. A thin TiO_2 layer (42 Å) by ALD was shaped to overlap the anode. The Ni/Au anode was deposited before mesa was etched to provide edge termination to the SBD and HJD. The devices have circular contacts (D=100 µm) with an additional 5 µm GR. SBDs were co-fabricated on the same substrate as references. HJD showed a lower V_{on} (0.8 V) than the SBD (1.1 V) from linear extrapolation of the J-V curve. Temperature dependent I-V behavior was measured from 25 ºC to 200 ºC. Both device types show excellent fits to the thermionic emission model, and barrier heights of 0.6 eV and 1.2 eV were fit for the HJD and SBD respectively. The HJD had higher V_{bk} of 1190 V compared to the SBD (685 V), and the GR HJD saw even further improvement with V_{bk} of 1777 V (826 V for GR SBD). The BFOM ($V_{bk}^2/R_{on,sp}$) of 518 MW/cm^{2}for the GR HJD is competitive with other literature results.

This work demonstrates an average breakdown field beyond the material limits of SiC and GaN in a device that has even lower conduction losses than the co-fabricated SBD. Lowering V_{on} while raising V_{bk} simultaneously improves both on- and off-state parameters that are typically in competition with each other. With further optimized field management, the Ni/TiO_2/β-Ga_2O_3-HJD presents a path to realistically utilizing the high critical field of Ga_2O_3 without large forward conduction losses from a high-barrier junction.

12:00pm **EP+ET+MD-WeM-15 Fabrication of Self Aligned β-Ga_2O_3 Junction Barrier Schottky Diodes with NiO Field Termination***, **Joseph Spencer**,* Naval Research Laboratory*; B. Wang, M. Xiao,* Virginia Tech*; A. Jacobs, T. Anderson, K. Hobart,* Naval Research Laboratory*; Y. Zhang,* Virginia Tech*; M. Tadjer,* Naval Research Laboratory

While the ultra-wide bandgap (4.8 eV) and the high critical field (6-8 MV/cm) of Ga_2O_3 is promising, the lack of shallow acceptors and the self-trapping of holes prevents this material from being doped p-type. The lack of complementary conductivity limits the practical device and termination structures for Ga_2O_3. Without the availability of p-type Ga_2O_3, Ga_2O_3 power devices must rely on a heterojunction for forming critically-important pn junctions. The naturally p-type nickel oxide (NiO, 3.6-4.5 eV [1]) forms a heterojunction with Ga_2O_3 and has been used to demonstrate Ga_2O_3 JBS diodes [2, 3].

In this work we have developed a self-aligned JBS diode fabrication process at 1 µm resolution that is capable of withstanding high-temperature thermal and chemical treatments such as annealing and relevant plasma/acid etches for Ga_2O_3 (e.g., BCl_3, HCl, H_3PO_4). This novel dry lift-off process incorporates a XeF_2 etch for undercut and lift-off steps producing a self-aligned process enabling fine device features without misalignment. A tri-layer mask consisting of, in order of deposition, amorphous Silicon (a-Si), SiO_2, and Ni, allow for the dry etching of the Ga_2O_3 epilayer prior to NiO self-aligned deposition. The Ni, SiO_2, and a-Si layers were patterned using Transene Ni-etchant, CF_4-plasma, and a SF_6-plasma dry etching, respectively. Subsequently, a ~250 nm deep trench in the Ga_2O_3 epilayer was etched via BCl_3 plasma, and a post-dry etch clean in warm (80 °C) H_3PO_4 was performed for 10 minutes, wherein the Ni hard mask was also removed. The a-Si mask layer was undercut using a 1" burst of dilute XeF_2 in a Xactix XeF_2 etcher. P-type NiO with 10% O_2 was sputtered (200 W, 12.5 mTorr) in the trench regions, followed by a dry lift-off of the remaining mask (a-Si/SiO_2) in XeF_2 gas by selective undercutting of the a-Si layer. At the conclusion of this self-aligned process, a tri-layer NiO junction termination extension (JTE) region was deposited around the anode perimeter in order to facilitate electric field spreading and improve V_{BR} [4]. Ni/Au anode was deposited atop the JBS region and the inner portions of the NiO JTE to conclude device fabrication (Figs. 1-4). Current-voltage characteristics in forward and reverse bias are shown in Figs. 5-6, respectively. This novel self-aligned process as shown by the fabrication of Ga_2O_3 NiOJBS diode serves to advance Ga_2O_3 heterojunction device technology and fabrication capabilities.

12:15pm **EP+ET+MD-WeM-16 Ni/$BaTiO_3$/β-Ga2O3 Solar-Blind UV Photodetectors with Deep Etch Edge Termination***, **Nathan Wriedt**, S. Rajan,* Ohio State University

We report on the design and demonstration Ni/$BaTiO_3$/β-Ga_2O_3 photodetectors, where high-permittivity $BaTiO_3$ is introduced to enable high fields approaching the material (avalanche breakdown) limit. β-Ga_2O_3 has a bandgap of 4.8eV and a corresponding photon absorption edge at 270-280nm, making it a prime candidate for utilization in solar blind UV photodetectors applications. Furthermore, the excellent material quality and low doping densities achievable through epitaxy on bulk-grown substrates can enable extremely low dark currents. Schottky diodes suffer breakdown well before the 8 MV/cm material limit. However, inserting the extreme-k $BaTiO_3$ dielectric between the metal and β-Ga_2O_3 prevents tunneling breakdown of the metal-semiconductor interface, and has been shown to support extremely high breakdown fields in β-Ga_2O_3 [1].When high electric fields occur in the β-Ga_2O_3 the electric field in the $BaTiO_3$ is low due to the relative permittivity, thus maintaining a tunneling barrier. Additionally, the valence band offset between the $BaTiO_3$ and Ga_2O_3 presents no barrier to transport of holes. Device were fabricated using (001)-oriented HVPE-grown Ga_2O_3 films (10-µm, N_d=1x10^{16} cm^{-3}) on Sn-doped Ga_2O_3 bulk substrates. The device structure investigated consisted of 1000 µm diameter circular mesas where the epitaxial layer was etched using a BCl_3/Cl_2-based ICP-RIE process to produce 0, 3, and 6-um pillars that have been shown to be effective in achieving high junction termination efficiency [2]. 10 nm $BaTiO_3$ was then deposited conformally by RF sputtering onto the etched surface. Device fabrication was completed by e-beam evaporation of Ti/Au backside ohmic contact and Ni top contacts. Extremely low dark currents (~0.25nA/cm^2) were measured under reverse bias up to 200 V. The devices showed an excellent UV/visible rejection ratio [R(244)/R(400)=3.65 *10^7]. We estimated the peak responsivity to be 970 mA/W at 244 nm at a reverse bias of -20 V. In conclusion, the work here shows the promise of Ni/$BaTiO_3$/β-Ga_2O_3 for realizing photodetectors with excellent operating characteristics. This work lays the foundation for future studies where the high breakdown strength enabled by $BaTiO_3$ could enable the design of solar-blind photodetectors with avalanche gain. We acknowledge funding from Department of Energy / National Nuclear Security Administration under Award Number(s) DE-NA0003921, and AFOSR GAME MURI (Award No. FA9550-18-1-0479, project manager Dr. Ali Sayir).[1] Xia et al, Appl. Phys. Lett. 115, 252104 (2019)[2]Dhara et al, Appl. Phys. Lett. 121, 203501 (2022)

12:30pm **EP+ET+MD-WeM-17 Best Paper Awards, e-Surveys, and Closing Remarks***,*

Author Index

Bold page numbers indicate presenter