

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 Ga₂O₃ Power Technology: Large-Area Devices, Packaging, and Applications, Yuhao Zhang, Virginia Tech INVITED

The Ga₂O₃ power device technology has witnessed fast advances towards power electronics applications. Recently, reports on large-area (ampere-class) Ga₂O₃ 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 Ga₂O₃ 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 Ga₂O₃ power devices (current up to >100 A and voltage up to >2000 V), covering the following topics:

1. Static electrical performance of Ga₂O₃ 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 Ga₂O₃ diodes and MOSFETs, including the reverse recovery, switching charge, as well as turn-ON and turn-OFF characteristics. A large-area Ga₂O₃ diode with NiO junction termination extension will be analyzed as a case study (Fig. 3).
3. Packaging and thermal management of Ga₂O₃ devices, highlighting the global efforts on junction-side packaging and cooling to overcome the low thermal conductivity of Ga₂O₃ (Fig. 4).
4. Circuit-level applications of Ga₂O₃ power devices, such as PFC circuits and double-pulse tests, as well as their circuit-level overcurrent/overvoltage ruggedness.

These results of large-area Ga₂O₃ devices allow for a direct comparison with commercial Si, SiC, and GaN devices. Accordingly, research opportunities and critical gaps for Ga₂O₃ 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. 5F, 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) Ga₂O₃ 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-Ga₂O₃ Schottky Barrier Diodes and TiO₂/β-Ga₂O₃ 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-Ga₂O₃ (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 TiO₂/BGO heterojunction diode (HJD) has been shown to reduce reverse current compared to Schottky barrier diodes (SBDs) due to the high permittivity of TiO₂ 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 TiO₂ 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/C². 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 TiO₂/BGO HJD demonstrate its potential to unlock the benefits of BGO in power diodes.

11:30am EP+ET+MD-WeM-13 Vertical β-Ga₂O₃ 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-Ga₂O₃ 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-Ga₂O₃ 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 ZrO₂ field-plate in these SBDs.

The SBDs were fabricated on halide vapor phase epitaxy (HVPE) (001) β-Ga₂O₃ of 10 μm epitaxy (doping ~1×10¹⁶ 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 ZrO₂ (dielectric constant~26) on top of a 11 nm Al₂O₃ 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/C²-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 ZrO₂ field-plate further increased V_{br} to 2.34 kV. With a minimum on-resistance of 8 mΩ-cm², the Baliga's figure-of-merit (BFOM) of the field-plate SBD was obtained as 0.684 GW/cm². 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-Ga₂O₃, and 8.86 MV/cm in Al₂O₃. The barrier height engineering and field management involving processing techniques with reduced or minimal material damage presented

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here is promising for realizing robust high performance β -Ga₂O₃ vertical power devices.

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

11:45am **EP+ET+MD-WeM-14 Ni/TiO₂/β-Ga₂O₃ 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 -Ga₂O₃ 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 -Ga₂O₃ 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/TiO₂/β-Ga₂O₃ 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 TiO₂ and β-Ga₂O₃ 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-Ga₂O₃ 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 TiO₂ 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 °C to 200 °C. 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/cm² 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/TiO₂/β-Ga₂O₃ HJD presents a path to realistically utilizing the high critical field of Ga₂O₃ without large forward conduction losses from a high-barrier junction.

12:00pm **EP+ET+MD-WeM-15 Fabrication of Self Aligned β-Ga₂O₃ 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 Ga₂O₃ 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 Ga₂O₃. Without the availability of p-type Ga₂O₃, Ga₂O₃ 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 Ga₂O₃ and has been used to demonstrate Ga₂O₃ 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 Ga₂O₃ (e.g., BCl₃, HCl, H₃PO₄). This novel dry lift-off process incorporates a XeF₂ 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), SiO₂, and Ni, allow for the dry etching of the Ga₂O₃ epilayer prior to NiO self-aligned deposition. The Ni, SiO₂, and a-Si layers were patterned using Transene Ni-etchant, CF₄-plasma, and a SF₆-plasma dry etching, respectively. Subsequently, a ~250 nm deep trench in the Ga₂O₃ epilayer

was etched via BCl₃ plasma, and a post-dry etch clean in warm (80 °C) H₃PO₄ 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 XeF₂ in a Xactix XeF₂ etcher. P-type NiO with 10% O₂ was sputtered (200 W, 12.5 mTorr) in the trench regions, followed by a dry lift-off of the remaining mask (a-Si/SiO₂) in XeF₂ 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 Ga₂O₃ NiOJBS diode serves to advance Ga₂O₃ heterojunction device technology and fabrication capabilities.

12:15pm **EP+ET+MD-WeM-16 Ni/BaTiO₃/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/BaTiO₃/β-Ga₂O₃ photodetectors, where high-permittivity BaTiO₃ is introduced to enable high fields approaching the material (avalanche breakdown) limit. β-Ga₂O₃ 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 BaTiO₃ dielectric between the metal and β-Ga₂O₃ prevents tunneling breakdown of the metal-semiconductor interface, and has been shown to support extremely high breakdown fields in β-Ga₂O₃ [1]. When high electric fields occur in the β-Ga₂O₃ the electric field in the BaTiO₃ is low due to the relative permittivity, thus maintaining a tunneling barrier. Additionally, the valence band offset between the BaTiO₃ and Ga₂O₃ presents no barrier to transport of holes. Device were fabricated using (001)-oriented HVPE-grown Ga₂O₃ films (10-μm, $N_d=1 \times 10^{16}$ cm⁻³) on Sn-doped Ga₂O₃ bulk substrates. The device structure investigated consisted of 1000 μm diameter circular mesas where the epitaxial layer was etched using a BCl₃/Cl₂-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 BaTiO₃ 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/cm²) were measured under reverse bias up to 200 V. The devices showed an excellent UV/visible rejection ratio $[R(244)/R(400)]=3.65 \times 10^7$. 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/BaTiO₃/β-Ga₂O₃ for realizing photodetectors with excellent operating characteristics. This work lays the foundation for future studies where the high breakdown strength enabled by BaTiO₃ 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**,

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