International Workshop on Gallium Oxide and Related Materials (IWGO-6)
Room ESJ 0202 - Session IWGO-WeA
Advanced Device Scaling and Fabrication Techniques I

Moderators: Siddarth Rajan, The Ohio State University, **Yuhao Zhang**, University of Hong Kong

2:00pm **IWGO-WeA-1 Recent Advances in β–Ga_2O_3 Power and RF Device Technologies*, Uttam Singisetti,*** University at Buffalo **INVITED**

The ultrawide-bandgap semiconductor β-gallium oxide (Ga_2O_3) has emerged as a promising material for power electronics, RF, and high–speed switching applications. This talk presents recent advances in Ga_2O_3 device technologies developed by our group. We demonstrate lateral Ga_2O_3 MOSFETs incorporating optimized field–plate designs that achieve beyond–kilovolt breakdown voltages, along with their switching characteristics under electrical stress conditions. The role of in situ Mg–doped MOCVD-grown Ga_2O_3 films as efficient current–blocking layers (CBLs) is discussed. In addition, trench MOSFET architectures incorporating CBLs are presented for high–voltage, high–speed operation targeting grid–level power applications. Strategies for mitigating thermal management challenges in Ga_2O_3 devices are also addressed.

Owing to its high Johnson's figure of merit, Ga_2O_3 is also a strong candidate for high power density RF amplifiers. We report significant improvements in RF power performance using Ga_2O_3 technology. By aggressively scaling gate lengths and gate–source spacing, $(Al_xGa_{1-x})_2O_3/Ga_2O_3$ heterostructure FETs were fabricated, demonstrating record RF performance. We will also report the radiation tolerance of the RF devices.

2:25pm **IWGO-WeA-6 1.5 kV/0.6 A Double Pulse Test Switching Of Cr_2O_3/β-Ga_2O_3 Heterojunction Diodes With > 3 kV Breakdown Voltages And Record Low Reverse Recovery Charge*, Chinmoy Nath Saha,*** University of California Santa Barbara*; Yuzhou Yao, Juchen Yang,* The Ohio State University*; Yizheng Liu,* University of California at Santa Barbara*; Pengyu Fu, Shuwei He,* The Ohio State University*; James S. Speck,* University of California at Santa Barbara*; Jin Wang,* The Ohio State University*; Sriram Krishnamoorthy,* University of California at Santa Barbara

β-Ga_2O_3 heterojunction diodes (HJD) incorporating different p-type oxides (NiO_x, Cu_2O, Cr_2O_3) have been demonstrated with multi-kV-class breakdown voltages. In this work, we report the first experimental demonstration of kV-class static and switching performance of Cr_2O_3/β-Ga_2O_3 heterojunction diodes (HJD) with > 3 kV breakdown voltages. The devices were fabricated on (001)-oriented 9.5 µm thick β-Ga_2O_3 drift layer grown by halide vapor phase epitaxy (HVPE) on a conductive β-Ga_2O_3 substrate. Bi-layer Cr_2O_3 and anode metal (Ni/Au/Ni) were lifted off simultaneously to fabricate the HJD. A 1.5 µm mesa etch was employed to realize an effective edge termination. The fabricated HJDs exhibited a forward current density of 125 A/cm² at 4.5 V and a differential specific on-resistance of ~19 mΩ·cm². Breakdown voltage of ~3.2 kV was achieved for a wide range of device dimensions (diameter = 60-300 µm) with noise floor reverse leakage up to 2.5-3 kV. This is a significant achievement since breakdown voltage showed no substantial degradation with increasing device dimensions [1]. Based on a punch-through model, the estimated parallel-plane breakdown field approached ~ 4 MV/cm. In addition, the switching performance of β-Ga_2O_3 power diodes is critical for high-frequency power conversion applications. A double pulse test (DPT) was employed, where Ga_2O_3 HJD served as the upper device and a commercially available SiC MOSFET served as the lower switching device. At a reverse voltage of 1.5 kV and a peak forward current of about 0.6 A, the HJD showed a peak reverse recovery current (I_{rr}) of −0.128 A, a reverse recovery time (t_{rr}) of 12.8 ns, and an ultralow reverse recovery charge (Q_{rr}) of 0.74 nC. This is the highest test voltage and lowest reverse recovery charge reported for the β-Ga_2O_3 diode switching test. Additional measurements at 1 kV with peak forward currents ranging from 0.3 to 0.7 A showed relatively stable I_{rr}, t_{rr}, Q_{rr} at 0.1 A, 15 ns, and 0.6 nC, respectively. In comparison with a commercial SiC MPS diode exhibiting Q_{rr} of 41 nC and t_{rr} of 20 ns at 1.2 kV, the Cr_2O_3/β-Ga_2O_3 HJDs reported here show improved reverse recovery characteristics. In summary, we have achieved > 3 kV breakdown voltages with 4 MV/cm parallel plane electric field for a wide range of device dimensions by fabricating Cr_2O_3/β-Ga_2O_3 heterojunction diodes (HJD) with an optimized edge termination. The combination of multi-kV static breakdown voltages with sub-nC reverse recovery charge at 1.5 kV test voltage highlights the strong potential of Cr_2O_3/β-Ga_2O_3 HJDs for future medium-voltage and high-frequency power conversion applications.

[1]. Liu, AIP Advances, **15**, 015114 (2025).

2:40pm **IWGO-WeA-9 Sub-Micron β-Ga2O3 FinFETs with >700 mA/mm Current Density and >10^8 ON/OFF Ratio Using Si δ-Doped Channels*, Nabasindhu Das,*** Arizona State University

β-Ga_2O_3 is a promising ultra-wide bandgap semiconductor for RF/mm-wave transistors due to its large critical breakdown field (~8 MV/cm), high saturation velocity (~2x10^7 cm/s), and availability of bulk substrates. However, achieving high current density and strong electrostatic control in scaled devices remains challenging with uniformly doped channels due to short-channel effects. In this work, we demonstrate sub-micron gated depletion-mode β-Ga_2O_3 FinFETs employing Si δ-doped channels with sheet charge density exceeding 3×10^{13} cm^{-2}, enabling enhanced carrier confinement and improved device performance. The δ-doped epitaxial structure was grown by MOCVD as shown in Fig.1 (b). Fin structures with 100 nm width and 200 nm spacing were defined using e-beam lithography and ICP-RIE etching (Fig.1 a, c). Ohmic contact regrowth was used to achieve low contact resistance, followed by ALD deposition of a 7 nm Al_2O_3 gate dielectric and fabrication of sub-micron gates (L_G ≈ 150 nm). Hall measurements indicate a sheet carrier density of ~3.3×10^{13} cm^{-2} with mobility of ~89 cm^2/V·s. Devices exhibit low contact resistance and a sharp doping profile with ~4.8 nm FWHM. Transfer characteristics show clear pinch-off with threshold voltage ~ −17 V, subthreshold slope ~239 mV/dec, and ON/OFF ratio exceeding 10^8 with low gate leakage. Output characteristics demonstrate current saturation with peak drain current >700 mA/mm. Pulsed I–V measurements reveal ~20% current collapse, indicating the need for improved surface passivation. Small-signal RF measurements yield f_T ≈ 6.3 GHz and f_{MAX} ≈ 2 GHz. These results highlight the potential of δ-doped β-Ga_2O_3 FinFETs as promising platform for high power RF applications. This work is supported by the Army Research Office UWBG RF center under award No. W911NF2520005

2:55pm **IWGO-WeA-12 Over 3 kV Ultra-low Leakage Vertical (011) β-Ga_2O_3 Diodes with Schottky Contact Engineering and High-κ Field Plate*, Emerson Hollar*,** *Esmat Farzana,* Iowa State University

The β-Ga_2O_3 has achieved great interest for high-power devices due to its large critical breakdown field, shallow dopants, and melt-grown native substrates. To achieve the desired multi-kV β-Ga_2O_3 power switches, vertical devices with low-doped, thick drift layer and minimal defects are essential requirements. However, to date, scaling up the voltage rating of vertical β-Ga_2O_3 devices has remained severely limited due to the presence of killer dislocation defects and unintentional [Cl] impurities that creates difficulties in achieving high-quality thick drift layer (>10 µm) and lower doping (<8×10^{15} cm^{-3}) with the existing (001) β-Ga_2O_3 epiwafers grown by halide vapor phase epitaxy (HVPE). To overcome these constraints, the recently emerged HVPE (011) β-Ga_2O_3 epiwafers has brought tremendous potential by offering reduced dislocation effects due to the dislocation being parallel to the (011) plane as well as low unintentional [Cl] impurities [1]. However, due to their early stage, high-power vertical Schottky barrier diodes (SBD) on (011) β-Ga_2O_3 epiwafers are yet to be reported.

In this work, we report high-voltage vertical (011) β-Ga_2O_3 SBDs on HVPE-grown 20 µm thick drift layer with 1 MHz C-V extracted doping ~5×$10^{15}$$cm^{-3}$. Two different Schottky contact diodes were co-fabricated with 100 µm diameters, including Pt/β-Ga_2O_3 and PtO_x/thin Pt (1.5 nm)/β-Ga_2O_3. The PtO_x/thin Pt contact merges the benefits of both low turn-on voltage from interfacing Pt while allowing improved reverse blocking by PtO_x [1]. To reduce edge field crowding, we integrated high-permittivity (κ) ZrO_2 field-plate (FP) for both contacts using a stack of sputtered ZrO_2 (226 nm) on interfacing thin ZrO_2 (9 nm) formed by atomic layer deposition to protect the surface from sputter damage. The forward J-V showed excellent transport properties with near unity ideality factor and similar turn-on voltage for both cases. At reverse bias, the SBDs without FP revealed similar breakdown voltage of ~1.5 kV for both cases. However, with FP, the PtO_x/thin Pt SBDs showed significantly enhanced breakdown voltage ~3.7 kV compared to the Pt ones (2.75 kV) and punch-through field with a peak of 5 MV/cm at FP edge, reaching ZrO_2 breakdown limit. Moreover, the FP PtO_x/thin Pt SBDs demonstrated ultra-low leakage which is order of magnitude lower compared to existing reports of (001) β-Ga_2O_3 SBDs of same 100 um diameter at 3 kV operation. **To the best of our knowledge, this is the first report of high-power vertical (011) β-Ga_2O_3 SBDs** that shows its great potential to expand the performance limit of low-loss multi-kV β-Ga_2O_3devices**.**

[1] E. J. Hollar and E. Farzana, *Appl. Phys. Lett.* **128**, 053503 (2026).

3:10pm **IWGO-WeA-15 Vertical Ga_2O_3(010) FinFETs Processed with Nitrogen Radical Irradiation***, **Zhenwei Wang,*** National Institute of Information and Communications Technology, Japan*; Jin Inajima, Kohki Tsujimoto, Yusuke Teramura,* Osaka Metropolitan University, Japan*; Yoshiki Iba, Yuma Terauchi,* Tokyo University of Agriculture and Technology, Japan*; Junya Yoshinaga,* Tokyo University of Agriculture and Technology/TAIYO NIPPON SANSO CORPORATION, Japan*; Takafumi Kamimura,* National Institute of Information and Communications Technology, Japan*; Yoshinao Kumagai,* Tokyo University of Agriculture and Technology, Japan*; Masataka Higashiwaki,* Osaka Metropolitan University/NICT, Japan

We studied the effects of nitrogen (N) radical irradiation on device characteristics of vertical Ga_2O_3(010) fin field-effect transistors (FinFETs). A positive threshold voltage (V_{th}) shift for the nitridated FinFET from the V_{th} value for the non-nitridated one was observed. The in-plane uniformity of V_{th} was also improved for the nitridated FinFETs. Finally, a multi-FinFET with fin width of 300 nm showed superior device characteristics such as a V_{th} of +1.0 V, a specific on-resistance (R_{on}) of 9.5 mΩcm^2, a breakdown voltage (V_{br}) of 1,213 V, and a power figure of merit (V_{br}^2/R_{on}) of 0.15 GWcm^{-2}. These results indicate that N radical irradiation can be a useful technique to fabricate normally-off Ga_2O_3 FinFETs with an excellent in-plane uniformity of device performance.

3:25pm **IWGO-WeA-18 Enhancement-Mode Ga_2O_3 CAVETs with Improved Breakdown Voltage by Hot Implantation***, **Jun Morihara,*** Osaka Metropolitan University, Japan*; Daisuke Matsuo, Shun Konno, Kosuke Usui, Shinya Takemura,* Nissin Ion Equipment Co., Ltd., Japan*; Zhenwei Wang,* National Institute of Information and Communications Technology, Japan*; Romualdo Ferreyra,* Osaka Metropolitan University, Japan*; Kohei Tanaka,* Nissin Ion Equipment Co., Ltd., Japan*; Masataka Higashiwaki,* Osaka Metropolitan University, Japan

Normally-off operation is highly demanded for FETs to ensure fail-safe capability in high-voltage and high-power applications. Enhancement-mode (E-mode) Ga_2O_3 current aperture vertical FETs (CAVETs) fabricated using room-temperature Si- and nitrogen (N)-ion implantations have been demonstrated [1]. Overall on-state device characteristics of the CAVETs were decent; however, the off-state breakdown voltage (V_{br}) was as low as 263 V [1], which could be attributed to the insufficient recovery of crystal damage caused by the implantations. In this work, we employed hot ion implantation to minimize the crystal damage and enhance V_{br}.

We used n-Ga_2O_3 (001) epitaxial substrates having an n^--Ga_2O_3 drift layer grown by halide vapor phase epitaxy. The CAVET fabrication process started with N hot implantation. N ions with a dose of 1×10^{14} cm^{-2} were implanted into the n^--Ga_2O_3 drift layer at 450ºC, followed by activation annealing at 1000ºC for 20 min in N_2 atmosphere. Subsequently, multiple Si implantations were performed at 300ºC to form an n-channel layer, n^+-access regions, and n^{++}-drain and source ohmic regions. The activation annealing of the Si implants was carried out at 800ºC for 30 min. A 50-nm-thick Al_2O_3 gate dielectric was formed by atomic layer deposition on the channel layer. Source and drain ohmic electrodes, and gate electrodes were fabricated with Ti/Au and Ti/Pt/Au metal stacks, respectively. The aperture size and the Si-implanted channel area were 20 µm and 210 × 25 µm^2, respectively.

Drain current–drain voltage (I_d–V_d) characteristics showed that at a gate voltage (V_g) of + 6 V, the CAVET exhibited near-linear I_d turn-on behavior in the low V_d range and quasi-saturation at V_d ~ 20 V, and reached the maximum I_d of 0.123 kA/cm^2 at V_d = 40 V. The I_d–V_g characteristics at V_d = 20 V provided a high I_d on/off ratio of 1×10^{11}, which can be attributed to superior current-blocking capability of the N-implanted region formed by hot implantation. The threshold V_g extracted from linear extrapolation of the I_d–V_g curve was + 3.8 V, ensuring the E-mode normally-off operation. The off-state I_d leakage at V_g = 0 V monotonically increased with increasing V_d and saturated at 10^{-3} – 10^{-2} A/cm² for V_d > 100 V. Then, destructive breakdown occurred near the gate electrode edge at V_d = 756 V. All on- and off-state device characteristics of the CAVET in this work were superior to those of the previous one [1]. Among the improvements, the most significant was the threefold increase in V_{br}. These results indicate that the hot implantation process is effective in improving endurance of Ga_2O_3 CAVETs.

[1] M. H. Wong *et al.*, IEEE Electron Device Lett. **41**, 296 (2020).

3:40pm **IWGO-WeA-21 Enhancement-Mode Vertical β-Ga_2O_3 U-Trench MOSFET with N-doped CBL and MOCVD regrown n⁺ Contact Layers***, **Walid Amir**, Jiawei Liu, Surajit Chakraborty,* University at Buffalo-SUNY*; Dongsu Yu, Md. Mosarof Hossain Sarkar, Hingping Zhao,* Ohio State University*; Uttam Singisetti,* University at Buffalo-SUNY

Due to its large bandgap (~4.8 eV) and strong critical electric field (~8 MV/cm), β-Ga_2O_3 has drawn a lot of attention as an ultra-wide-bandgap (UWBG) semiconductor for high-power applications. However, because traditional n^+ contact methods rely on ion implantation followed by high-temperature activation annealing, which increases process complexity and may degrade material quality, the realization of cost effective and low-resistance ohmic connections is still difficult. In this work, we reduce thermal budget while preserving electrical performance by using a regrown n^+ contact layer to create highly doped contact areas without post-implantation annealing.

The fabrication process started on commercially available Sn-doped (001) β-Ga_2O_3 substrates with a ~10 µm HVPE-grown epitaxial drift layer. The CBL was formed by N-ion implantation at multiple energy levels followed by annealing in N_2 atmosphere to activate the nitrogen dopants. In contrast to the conventional approach of using Si-ion implantation for ohmic contact formation, which requires additional high-dose implantation steps, dedicated masking, and high-temperature activation annealing, this work introduces a regrown Si-doped n^+ contact layer (~75 nm) with a high carrier concentration of ~10^{18} cm^{-3} deposited directly by MOCVD epitaxial regrowth.

The ohmic contact quality was validated by transmission line model (TLM) measurements, yielding a transfer length L_T = 0.13 µm, contact resistance R_C = 0.38 Ω·mm, sheet resistance R_{SH} = 1389 Ω/sq, and specific contact resistivity ρ_C = 2.65 × 10^{-7} Ω·cm². Transfer characteristics demonstrated normally-off operation with a clear threshold voltage of V_{TH} = 5V and an I_{ON}/I_{OFF} ratio of 8.5 × 10^5. From the output (I_D–V_{DS}) characteristics swept with V_{GS} = 0 to 20 V in 5 V steps, a peak current density exceeding 100 A/cm² was achieved, with an on-resistance R_{ON} = 94.6 mΩ·cm².

Three-terminal off-state breakdown measurements were performed in Fluorinert (FC-40) liquid to suppress air arcing. At V_{GS} = 0 V, breakdown voltages of 920 V-980 V were recorded across three representative devices, demonstrating excellent device-to-device uniformity and robust blocking capability. The resulting Baliga figure of merit (BFOM = V_{BR}^2/R_{ON}) makes this work well competitive with state-of-the-art vertical β-Ga_2O_3 devices.

This work demonstrates a high-performance enhancement-mode vertical β-Ga_2O_3 trench-gate MOSFET with N-ion implanted CBL and a simplified ohmic contact scheme based on epitaxial n^+ regrowth. The regrown n^+ contact approach offers a practical, cost-effective, and thermally efficient alternative to ion-implanted contacts, without sacrificing electrical performance.

Author Index

Bold page numbers indicate presenter