

Large-Area β -Ga₂O₃ Schottky Barrier Diodes with Sputtered NiO Edge Termination

CNF Project Number: 3238-25

Principal Investigator(s): Jonathan McCandless

User(s): Kazuki Nomoto

Affiliation(s): Gallox Semiconductors, Inc.

Primary Source(s) of Research Funding: Gallox Semiconductors, Inc.

Contact: jon@galloxsemi.com, kazuki@galloxsemi.com

Reserach Group Website: <https://www.galloxsemi.com/>

Primary CNF Tools: Heidelberg MLA 150 Maskless Aligner, Heidelberg Mask Writer DWL2000, Autostep i-line Stepper (GCA AS200), AJA sputter deposition tools, Oxford atomic layer deposition system, high-density-plasma chemical vapor deposition system, SC4500 electron-beam evaporators, P7 profilometer, Zeiss scanning electron microscope

Abstract:

Large-area vertical β -Ga₂O₃ Schottky barrier diodes (SBDs) incorporating sputtered nickel oxide (NiO) edge terminations were fabricated and evaluated. Four 1 mm-diameter anode layouts were compared: no edge termination, a continuous NiO termination, NiO with guard rings, and NiO with 20 guard rings plus an extended field plate. The devices were fabricated on (001) β -Ga₂O₃ samples thinned to <200 μ m. Capacitance-voltage measurements indicated a net donor concentration of approximately $1 \times 10^{16} \text{ cm}^{-3}$. All layouts showed similar forward conduction, while the NiO-based terminations substantially improved reverse blocking. The highest measured breakdown voltage approached 900 V, compared with less than approximately 300 V for unterminated diodes.

Summary of Research:

The objective of this work was to investigate an edge-termination process for large-area vertical β -Ga₂O₃ SBDs. Electric field crowding at the perimeter of a Schottky anode can cause premature breakdown and prevent the drift layer from supporting its expected voltage. Sputtered p-type NiO provides a deposited heterojunction termination that can redistribute the surface electric field without ion implantation into β -Ga₂O₃ [1-3].

Two 10 x 10 mm² samples were co-processed. The starting (001) β -Ga₂O₃ substrate was mechanically thinned to <200 μ m. The test mask contained sixteen 2 x 2 mm² dies and four device groups: SBDs without edge termination; SBDs with a continuous NiO edge

termination; SBDs with a continuous NiO region and NiO guard rings; and SBDs combining NiO, guard rings, and an extended metal field plate, as shown in figure 1. A metal oxide semiconductor capacitor was included as a dielectric control.

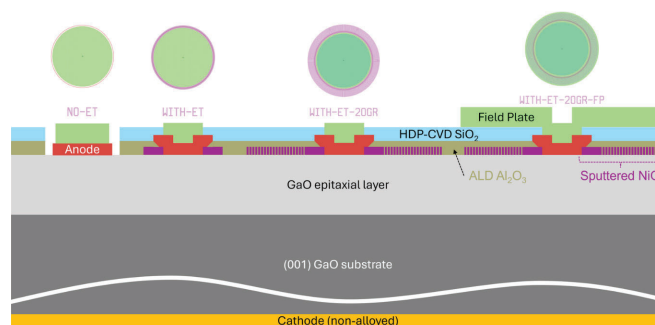


Figure 1: Cross-sectional schematics of the four vertical β -Ga₂O₃ SBD layouts: no edge termination, continuous NiO termination, NiO with 20 guard rings, and NiO with 20 guard rings plus an extended field plate.

The process began with liftoff patterning of sputtered NiO around the anode perimeter. An Al₂O₃ layer was then deposited by atomic layer deposition at 200°C and patterned to open the anode contact region. After anode metallization, SiO₂ was deposited by high density plasma chemical vapor deposition. The SiO₂ was opened above the anode, followed by field plate metallization and anode pad thickening. A non-alloyed cathode metal was deposited on the thinned backside. The completed sample showed good alignment of the large circular anodes, NiO rings, and field plate structures.

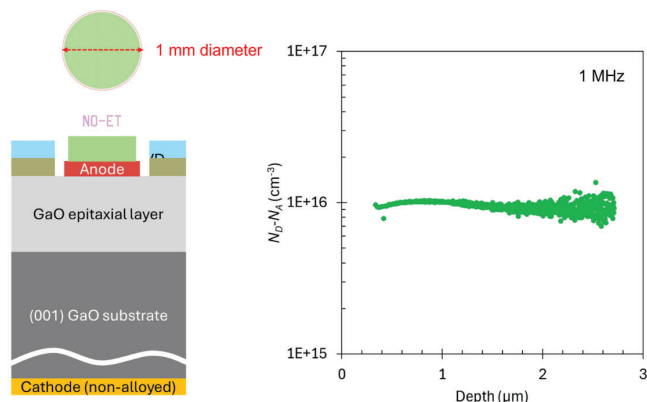


Figure 2: (a) CAD layout and photograph of the processed 10 x 10 mm² sample. (b) Net donor concentration extracted from 1 MHz capacitance-voltage measurements on a 1 mm-diameter diode.

In figure 2, capacitance-voltage measurements at 1 MHz on a 1 mm-diameter diode yielded a nearly uniform net donor concentration near 1×10^{16} cm⁻³ over the measured depletion depth. In figure 3, forward current-voltage characteristics were comparable among the four layouts, showing turn-on near 0.8 V and current density above 100 A/cm² at high forward bias. The minimum differential specific on-resistance was approximately 10–15 mΩ·cm², indicating that the added termination structures did not introduce a substantial forward conduction penalty.

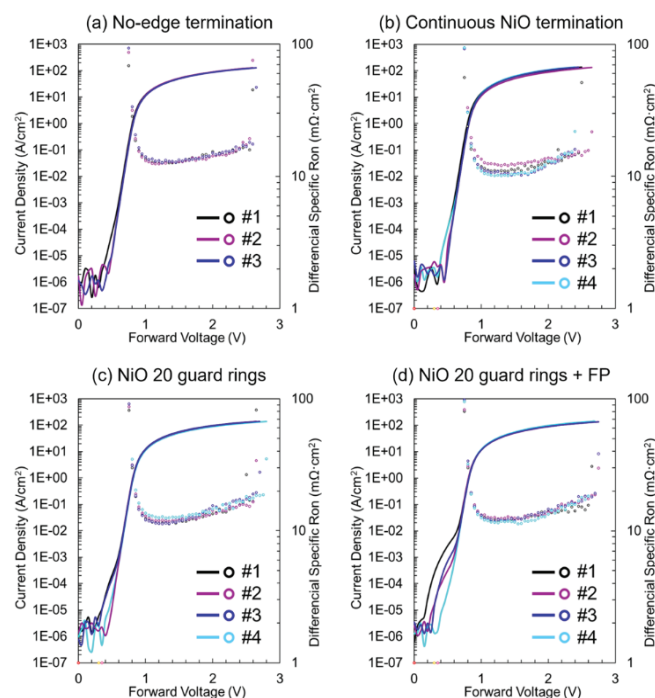


Figure 3: Forward current-voltage characteristics of the four termination designs. All designs exhibit comparable turn-on and high-current behavior, indicating a negligible forward-conduction penalty from the NiO termination structures.

Reverse characteristics were measured in insulating oil using a Keithley 2657A source measure unit, as shown in figure 4. Unterminated devices exhibited premature breakdown below approximately 300 V. Devices with a continuous NiO termination extended the blocking voltage into the 700 V range. Including guard-rings increased the breakdown to roughly 900 V.

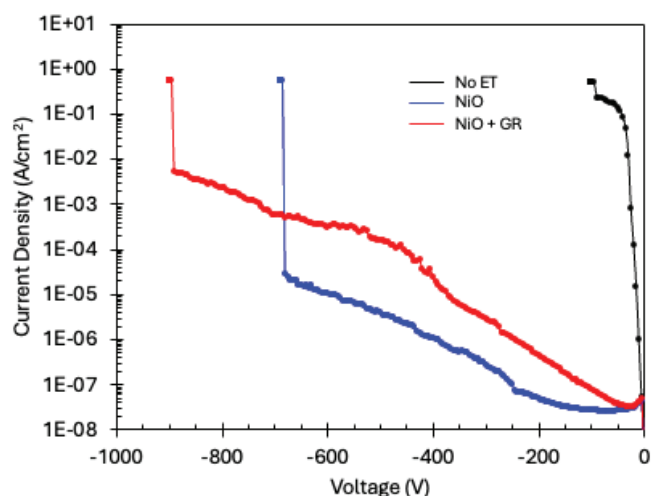


Figure 4: Reverse current-voltage characteristics and device locations. Measurements were performed in insulating oil using a Keithley 2657A. The best device approached breakdown of 900 V, whereas the unterminated control devices broke down below approximately 300 V.

Conclusions and Future Steps:

Sputtered NiO edge termination was successfully integrated with large-area vertical β -Ga₂O₃ SBDs and improved reverse blocking without degrading the forward characteristics. The results confirm that deposited NiO can reduce anode edge field crowding. Future work will optimize NiO conductivity and thickness, guard-ring spacing, dielectric quality, and field-plate overlap. A larger statistical data set, spatial correlation with pre-shipment wafer inspection maps, and post breakdown optical and electron-microscopy analysis will be used to distinguish design limitations from crystal- or process related failure sites.

References:

- [1] M. Xiao et al., "NiO junction termination extension for high-voltage (>3 kV) Ga₂O₃ devices", *Applied Physics Letters*, 122, 183501 (2023).
- [2] W. Hao et al., "Improved vertical β -Ga₂O₃ Schottky barrier diodes with conductivity-modulated p-NiO junction termination extension", *IEEE Transactions on Electron Devices*, 70, 2129-2134 (2023).
- [3] C. Liao et al., "Optimization of NiO/ β -Ga₂O₃ heterojunction diodes for high-power application", *IEEE Transactions on Electron Devices*, 69, 5722-5727 (2022).