Experimentally Validated Innovative Edge Termination for Vertical GaN Diodes

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Abstract

Planar vertical gallium nitride devices are capable of utilizing the beneficial material properties inherent to bulk GaN without interference of surface leakage pathways or premature breakdown, however, high voltage field termination is paramount to utilizing these properties. Here we validate a novel hybrid termination scheme shown computationally to have broad process windows and robust performance by approximating a bevel termination with a hybrid approach while maintaining a planar morphology. Computationally, vertical p-i-n diodes achieve near ideal breakdown voltages. Experimentally, these calculation trends are borne out by varying the hybrid termination design and compared to expected breakdown voltages from published impact ionization coefficients. For a 8µm thick drift layers, breakdown voltages were achieved up to ~1.4kV, in line with simulations with the hybrid termination, while simultaneously exhibiting avalanche behavior.

INTRODUCTION

Gallium nitride (GaN) has been pursued for power electronics owing to its wide bandgap and accompanying large critical electric field, which leads to almost 1000× improvement in Baliga's figure of merit (BFOM) over Si. [1] As the availability and quality of bulk GaN substrates has improved, the advantages of vertical GaN devices are being exploited. For example, the higher critical fields allow thinning of the drift layer in vertical GaN diodes, reducing ON-resistance and improving system size, weight, and power (SWaP) metrics. However, to fully leverage the high blocking voltage potential of vertical GaN diodes, field management needs to be optimized and viable manufacturing schemes must be developed. [2-4] In this work, we demonstrate a fully implanted hybrid edge termination (HET) approach where guard rings (GRs) are superimposed upon a single-zone junction termination extension (JTE) to create regions of alternating nitrogen implantation depth. [5-6] This is realized by depositing a SiO_2 hard mask in the termination region before nitrogen implantation. From a manufacturability standpoint, this approach presents a simple solution that allows large processing forgiveness while achieving significant improvements in breakdown strength.

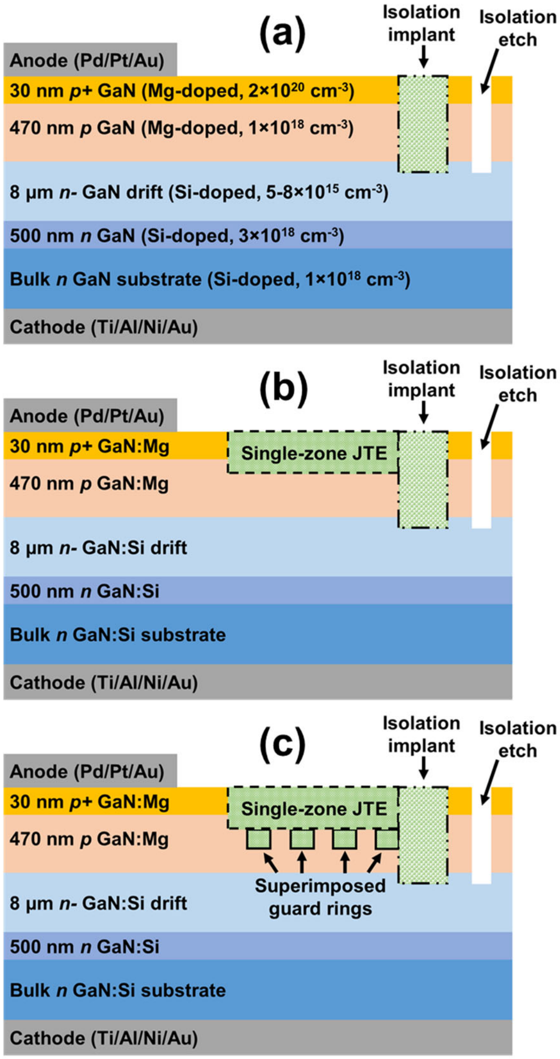

Fig 1. Cross-sectional schematics of the vertical GaN p-i-n diode structures with (a) isolation implant only, (b) isolation implant and a single-zone JTE, and (c) hybrid edge termination with four superimposed rings.

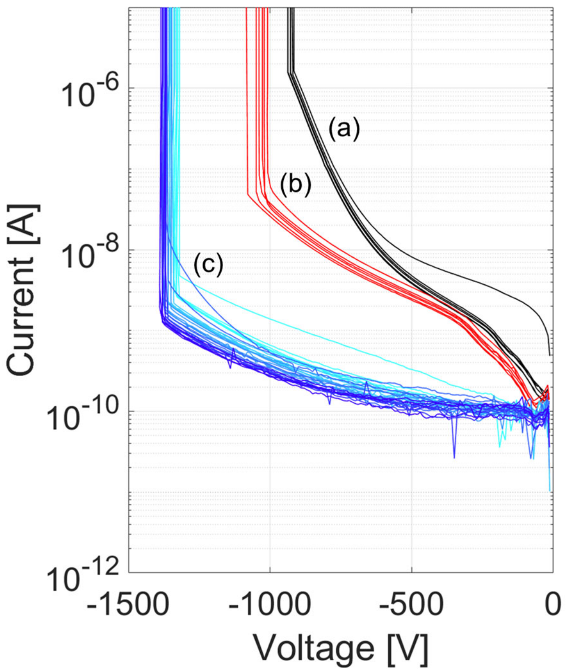

Fig. 2. Reverse breakdown measurements of the (a) isolation implant only structure, (b) isolation implant and single-zone JTE structure, and (c) hybrid edge termination with 2, 4, 6, 8, 10, and 12 superimposed rings. Darker blue lines corresponds to an increasing number of superimposed rings of the hybrid edge termination structure tested.

EXPERIMENTAL

Vertical GaN p-i-n diodes were grown on a bulk *n* GaN substrate by metal organic chemical vapor deposition (MOCVD) as previously described. [7-9] Fig.1(a) contains the doping concentration and thickness of the GaN epitaxial layers. The electron-beam evaporated anode and cathode metal stacks were Pd/Pt/Au (50/25/400 nm) and Ti/Al/Ni/Au (20/120/40/400 nm), respectively. An implant cap of 10 nm of SiN_x was deposited via plasma-enhanced CVD for surface protection. Nitrogen implantation (up to 350 keV) was used for the isolation while 100 nm of patterned SiO_2 and implantation (up to 135 keV) was used for the edge termination. Devices were fabricated with isolation implantation only (Fig. 1(a)), isolation implantation and a single-zone JTE (Fig. 1(b)), and the HET approach (Fig. 1(c)) wherein a single-zone JTE was superimposed by 2-12 rings to approximate a beveled edge termination chare profile. [5] Electrical characterization was performed using a Stanford Research Systems PS375 and a Keithley 2657A on wafer and under vacuum (≈10^{-3} Torr). Sentaurus technology computer aided design (TCAD) was used to develop a device model to and validated with these experimental results and furthermore to investigate the electric field distribution.

RESULTS AND DISCUSSION

Fig. 2 shows reverse breakdown measurements of the vertical GaN p-i-n diodes with the isolation implant only (black lines, structure in Fig. 1(a)), the single-zone JTE (red lines, structure in Fig. 1(b)), and the HET design (blue lines, structure in Fig 1(c)). The simplest HET structure with 2 rings had a breakdown voltage of 1333V, which is 44% and 28% higher than the isolation implant only and the single-zone JTE, respectively. Furthermore, as the number of rings in the HET structure increases, the breakdown voltage increases (2 rings: 1333V; 12 rings: 1383V). This improvement in simulations stems from a better approximation to the ideal bevel charge profile with reduced intensity of field concentrations at each superimposed guard ring region. Finally, as shown in Fig. 2, the reverse leakage current was significantly reduced for the HET structures.

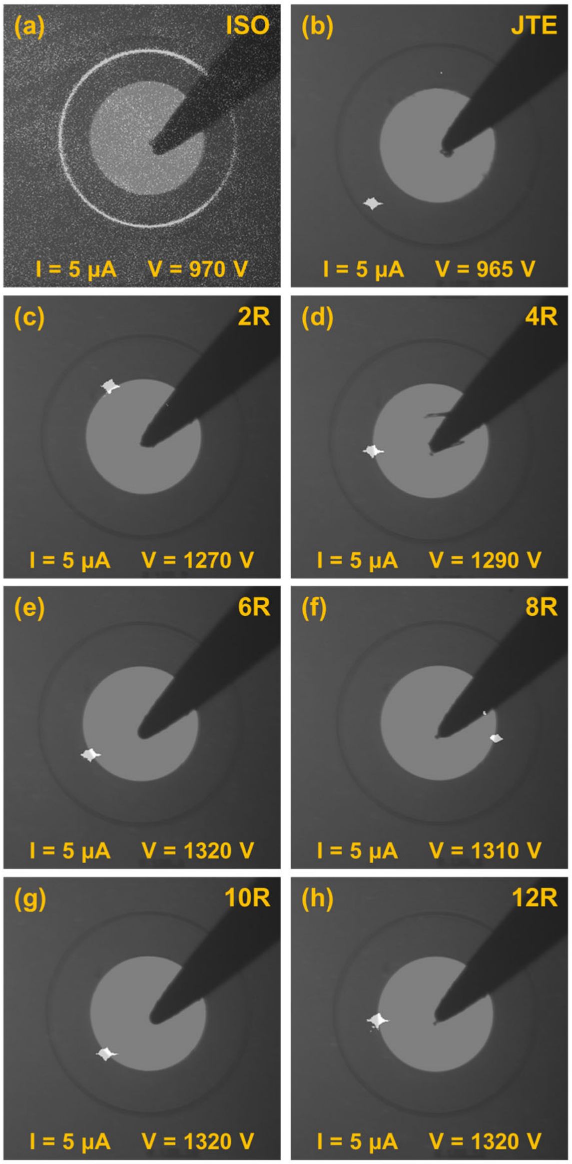

Fig. 3. Electroluminescence imaging of (a) Isolation only termination, (b) JTE only, (c)-(h) HET structures of increasing rings from 2-12.

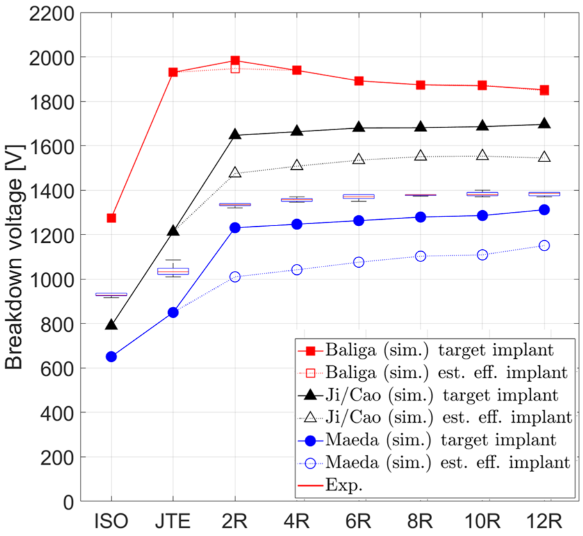

Fig. 4. Measured and simulated breakdown voltage of HET terminated diodes. Measured data (box and whisker) and simulated with optimum (closed symbols) and estimated effective (open symbols) HET implant depth.

Electrolumescence (EL) of diodes, shown in Fig. 3, highlights the breakdown points within the diode termination. For diodes terminated with a nitrogen implant fully through the magnesium doped anode, EL emission is localized at the outer periphery of the diode at this implant location. Termination with a JTE structure produced a localized emission within the isolation implant, yet still near the periphery. With 2 rings, shown in Fig. 3(c), the EL signature is shifted much closer to the anode metal edge and continues to shift closer to the anode with increasing number of rings indicating the high field point is at the innermost ring as indicated by simulations.

Trends in the breakdown voltage for the various termination structures is shown in Fig. 4 and compared to the published impact ionization coefficients [10-17] used for simulation of the HET. As the approximation of an ideal bevel termination becomes more precise with an increasing number of rings, the simulated breakdown voltage is expected to increase toward ideal. Simulated curves for both the best-fit termination as well as the effective implant depth are included where the effective depth was determined from additional experiments with deeper implants indicating an offset between the nominal implant depth and effective depth.

The vertical GaN diodes also exhibited avalanche breakdown capability. Temperature dependent reverse breakdown measurements for a HET structure with 2 rings are shown in Fig. 5. The breakdown voltage increased with temperature as a result of the delayed onset of impact ionization for avalanching.

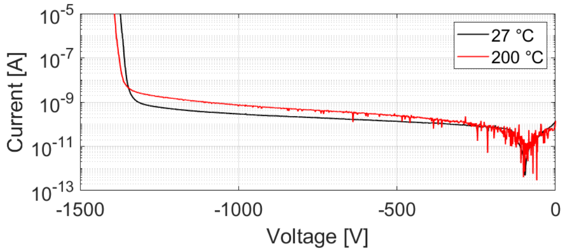

Fig. 5. Reverse current-voltage data at room temperature and 200°C exhibiting avalanche behavior.

CONCLUSIONS

Here we validate a novel and robust hybrid termination scheme for GaN p-i-n diodes consisting of planar ion-implanted guard rings superimposed on a junction termination extension exhibiting avalanche capability and a ~1.4kV breakdown voltage. By use of this hybrid edge termination, the breakdown current was both reduced and moved from localizing at the isolation edge to near or under the anode metal as shown by electroluminescence imaging. A positive temperature coefficient of breakdown voltage was observed, indicative of avalanche behavior, and breakdown voltage was shown to systematically vary with the number of rings in the hybrid termination consistent with simulations.

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ACRONYMS

GaN: Gallium Nitride
BFOM: Baliga's Figure of Merit
SWaP: System Weight and Power
HET: Hybrid Edge Termination
GR: Guard Ring
JTE: Junction Termination Extension
MOCVD: Metalorganic Chemical Vapor Deposition
CVD: Chemical Vapor Deposition
EL: Electroluminescence
TCAD: Technology Computer Aided Design