Three-Zone Junction Termination Extensions for Improved Performance of Vertical GaN PN Diodes

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***Abstract*—The design of three-zone junction termination extensions (JTE) to improve the breakdown voltage of vertical GaN diodes is explored. Simulation results show that the three-zone JTE distributes the electric field more effectively and reduce the peak electric fields compared with one-zone structure, without requiring complex fabrication processing. The edge terminations of the diodes are formed by nitrogen ion implantations. Temperature dependent reverse I-V characteristics of fabricated p-n diodes show three-zone structures have lower leakage current and higher breakdown compared to single-zone structures. This approach is promising for cost-effective fabrication of GaN power electronics.**

I. INTRODUCTION

GaN power devices are excellent candidates for high efficiency power switching applications due to wide band gap, large critical electric field, high electron mobility of GaN. For power devices in SiC and Si, junction termination extensions can be formed by ion implantation or diffusion. However, applying this approach for GaN-based devices is difficult because implant activations in GaN are challenging, and the p-type dopant normally used (Mg) is a deep acceptor. An alternative to doping by implant is to use nitrogen implantation to selectively compensate dopants incorporated during growth to form a JTE. By choosing suitable implantation energy and dose, a bilayer JTE consisting of upper fully compensated (intrinsic) and lower partially compensated (p^-) regions can be formed [1]. This structure has been demonstrated experimentally to enhance breakdown voltage. However, in this design the breakdown voltage is very sensitive to the JTE thickness [2]. In this work, we demonstrate a 3-zone JTE structure that more effectively distributes the field, using only simple, cost-effective processing. Simulations and measurements show that the 3-zone JTE structure reduces the peak electric field, reduces the leakage current, and improves the breakdown voltage of vertical GaN diodes.

II. DEVICE STRUCTURE AND SIMULATION

The cross-sectional view of diodes with the 1-zone and 3-zone JTE structures can be seen in Fig. 1. The p- layer thickness (t_p) is constant for the 1-zone JTE structure, but decreases with distance from the junction for the 3-zone JTE case. An important issue in any JTE design is the electric field profile. TCAD was used to simulate and compare the 1-zone and 3-zone JTE structures. The electric field distributions inside the diodes are shown in Fig. 2(a) and (b); the electric field along the p-n junction (dashed lines in Fig. 2(a) and (b)) is extracted and compared in Fig. 2(c). For the 1-zone case, the electric field is sharply peaked at both the main junction edge (point A) and the outer JTE edge (point B). In contrast, for the 3-zone JTE design, the electric field gradually decreases along the edge termination and the peak electric field is much smaller.

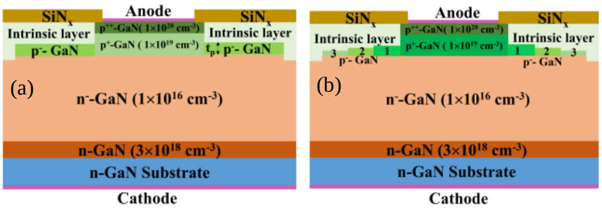

Fig. 1 Cross-sectional schematic of the (a) 1-zone and (b) 3-zone JTE GaN vertical p-n diodes.

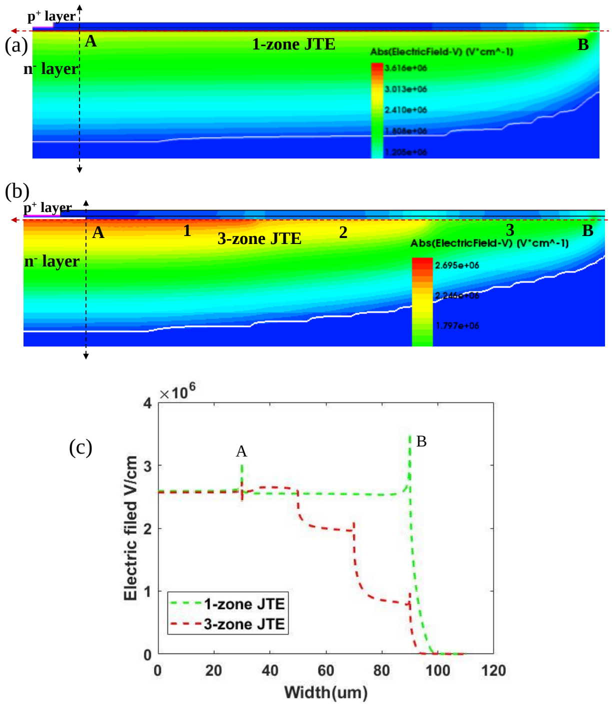

Fig. 2 Electric field distribution inside diodes of (a) 1-zone and (b) 3-zone JTE structures, and (c) electric field distribution along the interface of p-n junction as indicated by dashed line for 1-zone and 3-zone JTE structures.

III. EXPERIMENTS AND RESULTS

To verify the efficacy of the 3-zone JTE structure, we fabricated vertical GaN p-n diodes with both 1-zone and 3-zone JTE structures. A top view of a fabricated p-n diode is shown in Fig. 3(a). For the 1-zone JTE structure and the 1st zone of the 3-zone JTE structure, nitrogen triple implants with energies of 30, 100, and 145-180 KeV at doses of 3.3×10^{12}, 6.7×10^{12}, and 1.2×10^{13} cm^{-2}, respectively, were used. The defect density vs depth as calculated using SRIM for each of the implant energies is shown in Fig. 3(b). The thickness of the partially compensated layer p^- layer, t_p, was tuned by

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adjusting the highest ion-implantation energy, with higher energy resulting in thinner t_p. The second and third zone of the 3-zone JTE structures were formed by increasing the highest ion-implantation energy, at the same dose.

The measured forward-bias I-V characteristics of diodes with each type are shown in Fig. 3(c) and 3(d). Devices with diameters from 70 µm to 550 µm were fabricated and tested. The current density is higher for the smaller-area devices, indicative of edge leakage. Low-bias ideality factors of 1.97 and 1.96 were measured for 1-zone and 3-zone JTE structures, respectively, indicating Shockley-Read-Hall (SRH) recombination. The ideality factor drops to 1.5 and 1.6 at a bias of 2.8 V for 1-zone and 3-zone JTE structures respectively, indicating the onset of diffusion-dominated current. Above this, the ideality factor increases due to series resistance. Capacitance-voltage (C-V) measurements were performed on 160 µm diameter diodes as shown in Fig. 4(a). The $1/C^2$ vs. V plot and a linear fit shown in Fig. 4(b) shows the net doping density in n-GaN is 9.6×10^{15} cm^{-3}. Fig. 4(c) compares the temperature dependent reverse-bias I-V characteristics of 70 µm diameter diodes with both edge termination designs. The slope of the reverse leakage plots, suggests an electron variable-range-hopping (VRH) mechanism for the both designs, but the better field control of the 3-zone structure results in much lower leakage than for the 1-zone design. Breakdown measurement for the two structures are shown in Fig. 5. The maximum breakdown voltage is 908 V and 1270 V respectively for 1-zone and 3-zone JTE structures, illustrating the breakdown improvement for the 3-zone design.

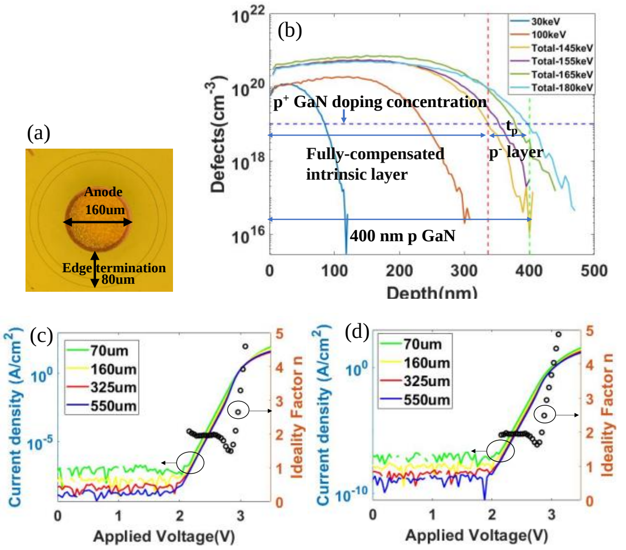

Fig. 3(a) A top view of a fabricated p-n diode. (b) SRIM simulation results of defects versus depth, the dashed line represents the Mg concentration of the p^+ GaN layer. Measured forward-bias I-V characteristics of the diodes with (c) 1-zone and (d) 3-zone JTE.

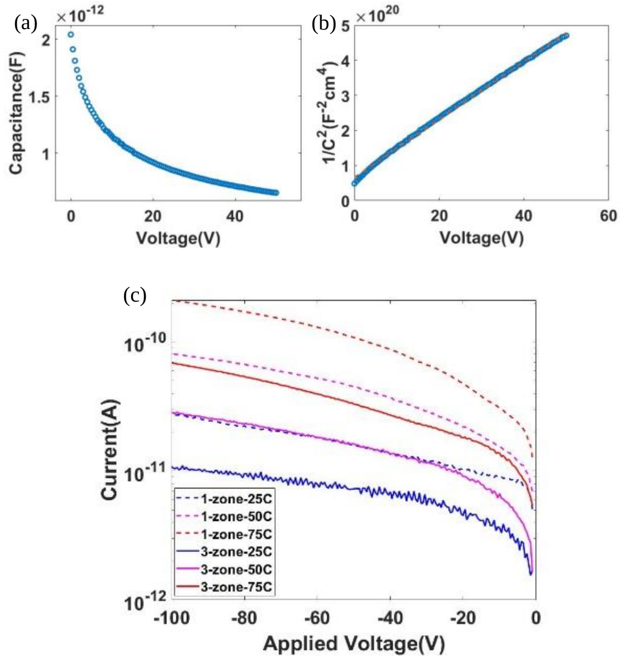

Fig. 4 (a) C-V characteristics of GaN p-n junction diodes, (b) $1/C^2$ as a function of reverse voltage, and (c) temperature dependent reverse I-V characteristics of diodes as indicated by dashed line for 1-zone and solid line for 3-zone JTE structures.

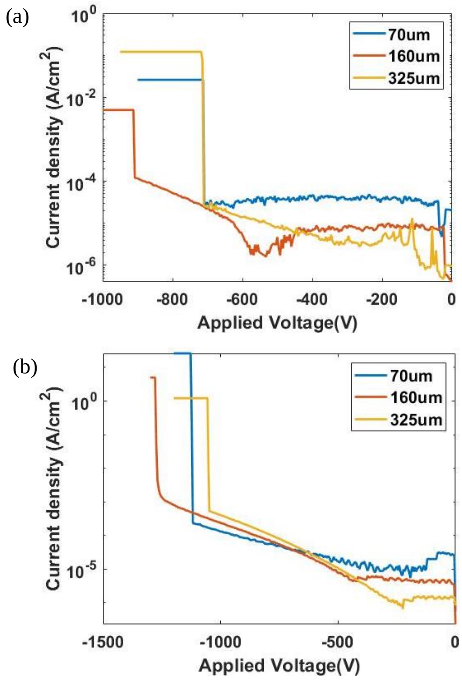

Fig. 5 breakdown measurements of the diodes with (a) 1-zone and (b) 3-zone JTE structures.

IV. CONCLUSION

In conclusion, a 3-zone JTE structure that reduces the peak electric field and improves the breakdown voltage of vertical GaN diodes has been demonstrated experimentally and modeled in simulation. Using simple, cost-effective processing, this approach is promising for enhancing the performance of vertical GaN devices.

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