Impact of Anode Thickness on Breakdown Mechanisms in Vertical GaN PiN Diodes with Planar Edge Termination


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Abstract: GaN vertical PiN diodes with different anode thicknesses were fabricated on three native GaN wafers with the same p-layer doping concentrations, and planar hybrid edge termination. The breakdown behavior in terms of the breakdown voltage and the electroluminescence were studied as functions of the anode thickness. A repeatable avalanche breakdown and highest breakdown voltage were measured with the thinnest anode of 300 nm and with the thinnest edge termination region. This indicates the efficacy of the nitrogen-implanted hybrid edge termination design that comprises of junction termination and guard rings hybrid design. As the anode thickness increases, the edge termination thickness increases, and the devices exhibit lower breakdown voltages and less robust breakdown characteristics, often destructive. From this study, we also conclude that a very high p-layer doping of $2 \times 10^{19}$ cm$^{-3}$ is not a practical doping level, because it is too sensitive to the edge termination thickness.

Keywords: GaN; edge termination; breakdown; electroluminescence

1. Introduction

Vertical GaN structures are the most promising design for efficient and compact power converters as they take full advantage of GaN’s wide bandgap, enabling a thinner blocking layer, reduced ON resistance and switching with less losses [1]. The quality of the thick drift layer in vertical devices is an important factor in determining the device’s breakdown voltage [2–4]. The maximum electric field that a device can sustain is restricted by the location and the magnitude of the electric field peak in the region near the anode edge. Therefore, managing the field at the periphery of the device is a crucial step in power device design. Every power device requires edge termination that is optimized to prevent field crowding [5–7]. Large area GaN power devices are seldom reported to avalanche, and the theoretical studies of their edge termination still struggle to match experimental results especially for planar structures [5,8,9]. We report for the first time a method to monitor and optimize the edge termination design to fit the device structure. Our method has paired TCAD simulation of avalanche breakdown in GaN devices to reverse electroluminescence (EL) broadband images of power GaN device to better understand the relationship between the remaining charge in the anode extension region and the thickness of extension region.

2. Experimental Procedure

Vertical PiN diodes with three different anode thicknesses were fabricated on three inhomogenous GaN substrates. Using Metal Organic Chemical Vapor Deposition (MOCVD),
Mg-doped GaN layers with thicknesses ranging from 300 to 500 nm and with a targeted doping of \(2 \times 10^{19} \text{ cm}^{-3}\) were grown on a lightly doped n-type layer of 8 µm with a doping concentration of the order of 1-2 \(10^{16} \text{ cm}^{-3}\). Next to the trench is the isolation nitrogen implant using a box profile with three different energies and total depth of \(~650\) nm. Finally, the junction termination extension and guard rings (JTE/GR) hybrid is implemented by nitrogen implant to achieve a full planar device structure with final depth of 300 nm. Additional fabrication details were discussed elsewhere [10,11]. The same JTE/GR hybrid implant depth into three different anode thickness which results in different extension region thickness (\(t_{\text{ET}}\)) that is expected to impact the field management. Figure 1a shows a cross section cartoon of a representative device structure.

\[
BV(T) = BV(T)_{300K}(1 + \alpha(T - 300))
\]  

(1)

Figure 1. (a) Cross section schematic of the PiN Diode (b) I-V DC forward DC I-V sweep for the three samples in this work and (c) I-V DC forward DC I-V sweep for the three samples.

As the devices had identical nitrogen implant conditions (on the three different anode thicknesses) and were fabricated in a single lot, the impact of edge termination region’s thickness on the device performance can be directly evaluated.

3. Results and Discussion

The DC characteristics of devices from the three wafers were tested with a Keithley 4200 semiconductor parameter analyzer. The DC-IV forward characteristics of devices from wafers of each anode thickness are relatively similar with an ideality factor \(\sim 2.2\) as shown in Figure 1b. The DC-IV reverse test was measured under vacuum to prevent surface flashover while maintaining optical access to the active region. Figure 1c compares the results from representative devices on the three wafers. The 300 nm anode has the highest breakdown voltage and the lowest leakage, in contrast and despite having the same termination design and anode doping, the 500 nm anode has a soft breakdown at \(~500\) V less than 300 nm and \(~300\) V less than the 400 nm. The clear trend between the anode thickness and breakdown behavior is indicative of the importance of the edge termination region thickness. The 300 nm has the thinnest \(t_{\text{ET}}\) which advantageously impacts its reverse performance. To further understand the mechanism of breakdown, a reverse sweep was applied at 25, 100, 150, and 200 °C on all three devices. Figure 2a–c displays their behavior. For devices with an anode thickness of 300 nm, the breakdown voltage was found to increase by 10V for every 50 °C, as shown in Figure 2c inset, which is an indicator of the dominance of impact ionization in the breakdown current [9]. The temperature coefficient of the breakdown voltage for the 300 nm anode device was determined using:
was assumed in the simulated device region with a geometry consistent with the corner which explains the higher breakdown voltage over 500 nm device. Finally, the leakage current path is at the anode edge of the 300 nm anode device, an indicative of full activation of the termination extension region which explains the high breakdown voltage and the typical avalanche behavior.

The devices were tested in a custom-made vacuum probe station coupled with a Photon, Etc. IMA-EL hyperspectral imager, operated in broadband mode. The use of a vacuum environment presents an advantage over Fluorinert testing as it preserves optical access to the device for imaging under high-voltage stress conditions [10]. Broadband electroluminescence images were collected from all three wafers at reverse bias condition. Figure 3a–c shows broadband images of the three PiN devices under reverse bias condition. In order to investigate the reverse performance disparity, we used our electroluminescence tool to obtain broadband images of the three PiN devices under reverse bias condition. The devices were tested in a custom-made vacuum probe station coupled with a Photon, Etc. IMA-EL hyperspectral imager, operated in broadband mode. The use of a vacuum environment presents an advantage over Fluorinert testing as it preserves optical access to the device for imaging under high-voltage stress conditions [10]. Broadband electroluminescence images were collected from all three wafers at reverse bias condition. Figure 3a–c shows broadband images of the three devices under the reverse current hold. The EL emission of 500 nm anode device at the edge of the isolation implant region appears to indicate the inefficacy of the termination design, a result that is not surprising considering the high leakage current and the low breakdown voltage. The leakage current path is only 15µm from the anode edge in the 400 nm anode device, suggesting some depletion of the charge in the extension region. Therefor the hybrid edge termination is partially activated in the case of 400 nm anode which explains the higher breakdown voltage over 500 nm device. Finally, the leakage current path is at the anode edge of the 300 nm anode device, an indicative of full activation of the termination extension region which explains the high breakdown voltage and the typical avalanche behavior.

4. Simulation Results

To explain the results observed in experimental EL imaging at breakdown, TCAD simulations of avalanche breakdown in devices with varying edge termination region thickness were carried out using the Silvaco ATLAS device simulator. Cylindrical symmetry was assumed in the simulated device region with a geometry consistent with the corner regions of experimental devices. Simulation runs were carried out with a fixed drift layer thickness and doping of 8 µm and 1 × 10¹⁶ cm⁻³, respectively. The device structure is shown in the upper right of Figure 4. Electron and hole mobility were modeled using Caughey–Thomas models with parameters from [14] for electrons and from [15] for holes. Avalanche multiplication coefficients for electrons and holes were assumed to be isotropic and modeled using a fit to Chynoweth’s law determined from experimental work carried out in [13,16]. Figure 4a shows the extension region thickness verses breakdown for 2 × 10¹⁹ cm⁻³ anode doping [10].
Figure 3. Electroluminescence broadband. (a) 500 nm anode; (b) 400 nm anode; (c) 300 nm anode; (d) DC-IV of the -20μA reverse hold.

Figure 4. TCAD simulations of avalanche breakdown in devices with varying edge termination region thickness. (a) Breakdown voltage vs. edge termination thickness, for anode doping of $2 \times 10^{19}$ cm$^{-3}$; (b) the simulated structure schematics; (c) 2D electric field distribution at $t_{ET} = 6$ nm; (d) 2D electric field distribution at $t_{ET} = 112$ nm.

It is clear that the optimum window for breakdown is very narrow in this case, which indicates that a slight change in the extension region thickness can lead to dramatic drop in the breakdown voltage. Furthermore, Figure 4c–d depicts the 2D electric field distribution around the termination anode interface. In the case of 5 nm extension region thickness, the breakdown occurs at the edge of the anode, and this scenario is analogous to the 300 nm anode device. On the other hand, the 112 nm extension region shows no distribution of the...
electric field in the termination region and electric field crowding at isolation edge which is analogous to the 500 nm anode. Though the breakdown values do not match exactly our experimental results the trend in the simulation results matches our experimental findings. The results of EL imaging, temperature-dependent reverse IV measurements, and the results of simulations indicate that the thinner the edge termination region (t\(_{ET}\)) the better the control over the charge in the extension region and the better the management of the electric field.

5. Conclusions

Planar GaN vertical PiN diodes with different anode thicknesses were fabricated with same edge termination process. The breakdown voltage and the electroluminescence were studied as functions of edge termination thickness. Simulation and experimental data suggest that at a very high p-layer doping of \(2 \times 10^{19} \text{cm}^{-3}\), the window for the any edge termination technique to deplete the charge in the termination region is very narrow and hence this doping level is very difficult for any effective edge termination design. The repeatable avalanche breakdown and highest breakdown voltage were measured with the thinnest p-GaN anode layer thickness of 300 nm, with the thinnest t\(_{ET}\), indicating the efficacy of the hybrid edge termination. The thicker anodes exhibit lower breakdown voltages and less robust breakdown characteristic (higher leakage) due to the lack of full activation of the termination region.

Author Contributions: M.A.E. was responsible for collecting the electrical measurements, Electroluminescence measurements, Temperature dependent measurements and data analysis on all data sets, and leading the writing of the manuscript. M.A.P. was responsible for the simulation work. R.J.K. and B.P.G. were responsible for the growth of the GaN epilayers. J.C.G. was responsible for material characterization analysis. A.G.J., M.A.E. and T.J.A. were responsible for the diode fabrication. K.D.H., R.J.K. and T.J.A. were responsible for the project management. All authors have read and agreed to the published version of the manuscript.

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