High Voltage Vertical GaN p-n Diodes With Avalanche Capability

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***Abstract*— In this paper, vertical p-n diodes fabricated on pseudobulk gallium nitride (GaN) substrates are discussed. The measured devices demonstrate breakdown voltages of 2600 V with a differential specific on-resistance of 2 mΩ cm^2. This performance places these structures beyond the SiC theoretical limit on the power device figure of merit chart. Contrary to common belief, GaN devices do possess avalanche capability. The temperature coefficient of the breakdown voltage is positive, showing that the breakdown is indeed because of impact ionization and avalanche. This is an important property of the device for operation in inductive switching environments. Critical electric field and mobility parameters for epitaxial GaN layers grown on bulk GaN are extracted from electrical measurements. The reverse recovery time of the vertical GaN p-n diode is not discernible because it is limited by capacitance rather than minority carrier storage, and because of this its switching performance exceeds the highest speed silicon diode.**

***Index Terms*— Avalanche breakdown, gallium nitride (GaN), power diodes, power-semiconductor devices.**

I. Introduction

POWER electronic systems enjoyed tremendous improvements in efficiency, size, and weight as the performance of silicon-based power semiconductor devices improved over the past several decades. These devices are, however, rapidly approaching the fundamental material limits of silicon, resulting in a rapid expansion of efforts to develop wide-bandgap power semiconductors. The material properties of gallium nitride (GaN) are known for some particular period to be highly suitable for high-power and high-frequency devices [1]–[6]. Limitations to standard processing techniques such as selective area doping and the lack of a high-quality native oxide that were used in silicon for many years, has hindered the development of GaN-based products. The necessity of growing GaN on mismatched substrates such as sapphire, silicon, and silicon carbide has also created difficulties for vertical device structures and resulted in high-defect densities and poor material quality. In this paper, high-performance vertical GaN power devices are achieved through homoepitaxial growth on GaN substrates and the development of processing techniques applicable to the vertical p-n device and its edge termination. Transport material parameters such as electron mobility and critical electric field are extracted for figure-of-merit benchmarking.

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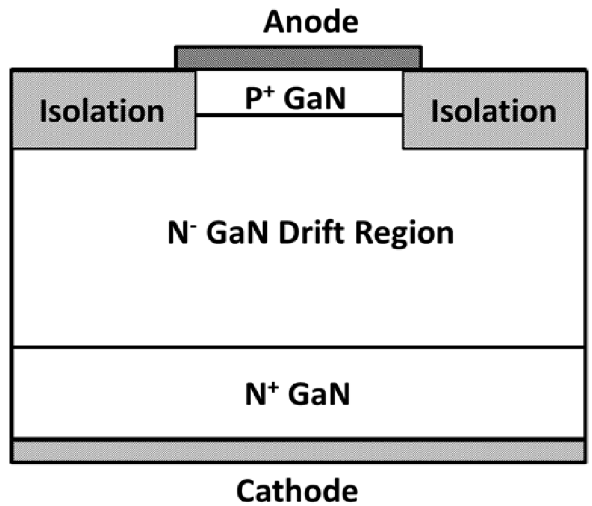

Fig. 1. Schematic cross-sectional view of the vertical GaN p-n diode on bulk GaN.

II. Growth and Fabrication

A schematic cross-sectional diagram of a vertical GaN p-n diode is shown in Fig. 1. The GaN layers comprising the vertical diodes are epitaxially grown by metal-organic chemical vapor deposition on 2-in bulk-GaN substrates. Plain-view cathode-luminescence imaging reveals that the threading dislocation density in the films grown over bulk-GaN substrates is 10^4–10^7 cm^{-2}, or at least two orders of magnitude lower than for GaN films grown in the conventional manner on sapphire, silicon, or SiC substrates. The desired breakdown voltage is determined by the *n*-type drift-layer doping and the thickness. Typical doping densities are $N_D \approx 1$–3×10^{16} cm^{-3}, whereas drift-layer thicknesses of 6–20 μm are targeted. The p-region is realized by *in situ* growth of Mg-doped P$^+$ GaN epitaxial layer on top of the *n*-type GaN epitaxial drift region. This is followed by deposition and patterning of Pd to contact the *p*-type GaN. The *p*-type GaN has a hole concentration of 5×10^{17} cm^{-3} and a hole mobility of 11 cm^2/V s at 25 °C as determined by Hall effect measurements. A proprietary edge-termination design similar to [7] was employed to terminate these experimental devices in an attempt to approach parallel-plane junction breakdown. Backside contacts are formed by evaporating aluminum onto the bottom of an N$^+$-type GaN substrate.

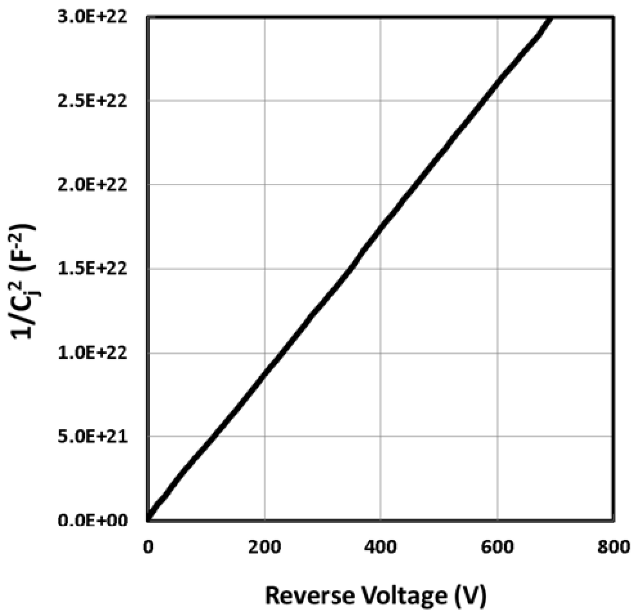

Fig. 2. Measured $1/{C_j}^2$ versus reverse voltage for vertical GaN p-n diode.

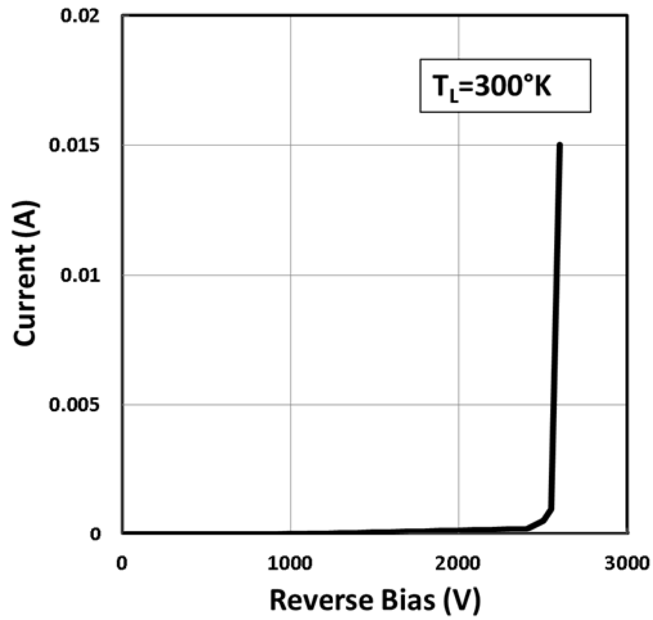

Fig. 3. Reverse characteristics of GaN p-n diode and avalanche breakdown.

III. Measurement and Characterization

The measured capacitance–voltage measurement of the diode is shown in Fig. 2. In this case, we plot $1/Cj^2$ as a function of reverse voltage to confirm the net doping concentration in the n-drift region. From Fig. 2, we observe that the doping concentration (N_D) is $\sim 10^{16}$ cm^{-3}.

To take full advantage of the high critical electric field for the onset of avalanche breakdown in GaN, it is essential to manage the electric field at the edge of the device. An edge-termination structure is used to spread the potential applied to the anode over a distance that is greater than the drift-region thickness. This technique of smoothing the equipotential contours at the edges of the devices results in a manageable electric field (gradient of the electrostatic potential). The edge-termination scheme used in the p-n diodes in this paper is proven to enable the devices to survive and operate in the avalanche region. The reverse characteristics of the p-n diode are shown in Fig. 3. The measurement is performed on-wafer using a temperature stage and needle probes. The blocking voltage of the p-n diode reaches 2600 V at $T = 300$ K. The GaN diodes are driven into avalanche breakdown using 30-mS and 15-mA current pulses demonstrating avalanche energy capability of 1000 mJ.

For power figure-of-merit benchmarking purposes, it is necessary to have independent measurements for majority carrier (electron) mobility and critical electric field. With the extracted N_D and breakdown voltage measured, a lower limit of the critical electric field for GaN can be estimated from (1). In this analysis, it is assumed that the breakdown occurs when the maximum electric field in the depletion region of an abrupt junction reaches E_C

$$BV_\infty = \frac{\varepsilon E_C^2}{2qN_D} \tag{1}$$

where BV_∞ is the breakdown voltage of a planar junction and is the dielectric constant of GaN. Perfect geometric planes are, however, impossible to achieve and an ideal edge-termination structure for GaN vertical devices requires further development. Assuming that we have achieved 75% of the entitled breakdown voltage in our devices, the lower bound for critical electric field in GaN is $E_C > 3.5$ MV/cm. This is consistent with the value of $E_C \approx 3.75$ MV/cm in [8].

Avalanche breakdown initiated by impact ionization processes should have a temperature coefficient that is positive. This is because, at higher temperatures phonon scattering should delay the onset of impact ionization. Hence, the breakdown voltage should increase with the temperature. In Fig. 4, the temperature dependence of leakage current and breakdown voltage is shown for reverse biased p-n diodes that are designed to avalanche at 700 V. It is observed that the diode current at lower reverse voltages increases with the temperature, but the breakdown voltage also increases, indicative of impact ionization. The temperature dependence of the breakdown voltage is $BV(T) \approx BV_{25^\circ C}(1 + \alpha \Delta T)$ where $\alpha \approx 6 \times 10^{-4}$ °K^{-1}, approximately valid for all diodes that we fabricated with breakdown voltages between 600 and 2500 V. The physics behind this phenomenon will be explored in another paper and should provide insight into the electron transport at high electric fields in low-defect density GaN [9], [10].

The p-n diode has a turn-on voltage of $\sim$3.0 V, as expected from the bandgap of GaN as shown in Fig. 5. These devices have active areas much <1 mm^2, but are capable of handling pulsed currents (300-μs pulse width) in excess of 10 A even with nonoptimized packaging and without substrate thinning. Thermal conductivity is known to depend on defect density in other materials. With the low-defect density in GaN grown on bulk-GaN substrates and the lack of thermal boundaries at interfaces between dissimilar materials, the thermal conductivity of GaN is expected to approach 230 W/m K at 300 K [11]. Thermal modeling using finite element

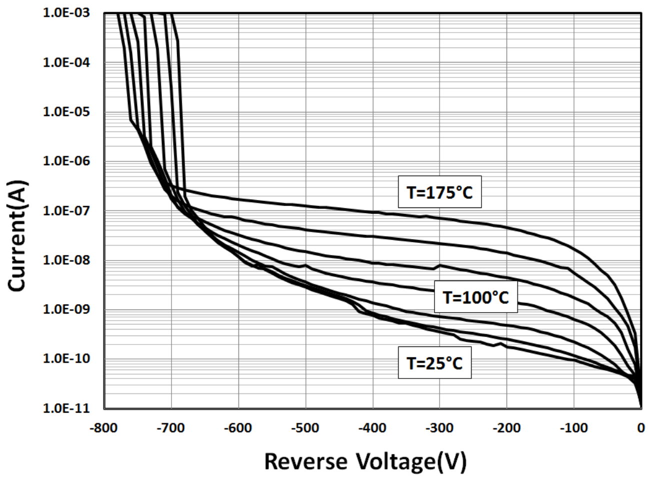

Fig. 4. Temperature dependence of the reverse I–V curves of the GaN diode.

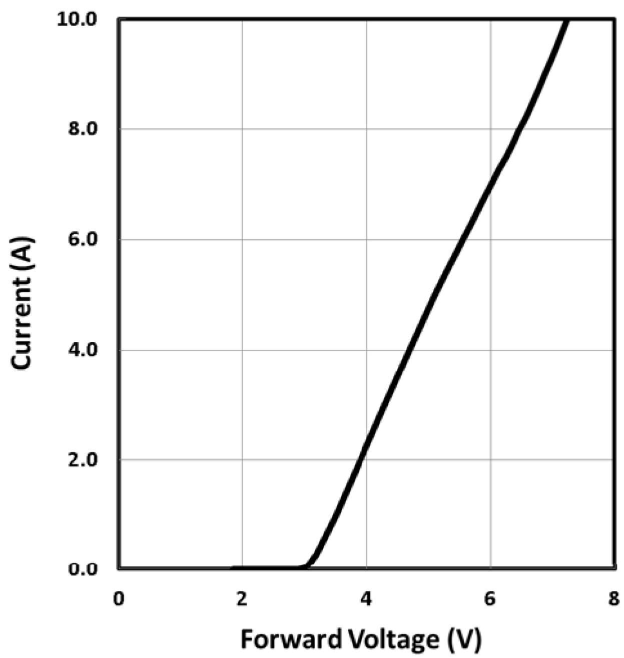

Fig. 5. Forward current–voltage characteristics of the GaN p-n diode.

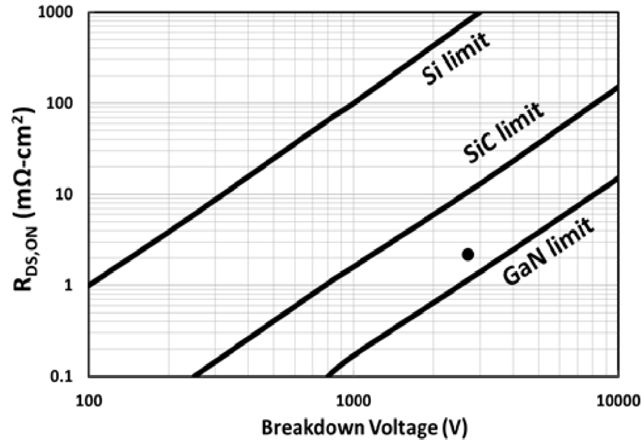

Fig. 6. Power device figure-of-merit comparison of this paper to Si, SiC, and GaN theoretical values.

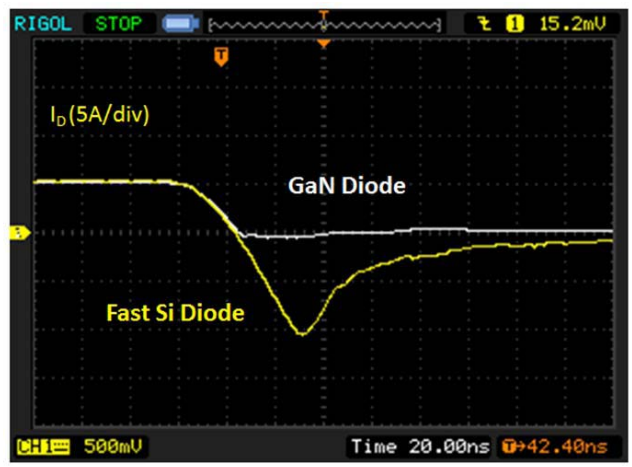

Fig. 7. Double pulse testing of vertical GaN p-n diode and a high speed 1200-V rated Si diode.

analysis, incorporating a temperature-dependent polynomial model based on this higher value, has yielded predictive results that show the validity of this assumption. A differential specific on-resistance of 2 mΩ cm^2 is extracted from the current–voltage measurements, shown in Fig. 5. This data point with respect to the theoretical limits for Si, SiC, and GaN on a power device figure-of-merit chart is shown in Fig. 6.

Although there are abundant data on the electron mobility in the channel of GaN/AlGaN heterostructures, there are very limited data for low doped ($\leq 10^{16}$ cm^{-3}) bulk-GaN material. The device structure with a drift-region doping of $N_D \approx 10^{16}$ cm^{-3} and a drift-region thickness >15 μm is suitable to extract the electron mobility. This is because, the device resistance is dominated by the resistance of the n-drift region and less convoluted by the extrinsic features. We extract an electron mobility of about $\mu_n \approx 1150$ cm^2/V s for our low-defect density bulk-GaN material, in line with the theoretical mobility calculations from [12] and [13].

In Fig. 7, we present double-pulse test measurements for the GaN diodes and compare these with commercially available high-speed Si diodes. The test performed to generate the plot uses $V_{RR} = 600$ V and $I_F = 5$ A. The oscilloscope plot shows diode current versus time. The silicon diode exhibits a reverse recovery region with negative current flow because of the minority carrier storage. As the reverse recovery time of the vertical GaN p-n diode is limited by capacitance rather than minority carrier storage, its performance is far superior to that of the high-speed silicon diode.

IV. Conclusion

Device drift regions epitaxially grown on low-defect density bulk-GaN substrates enabled the diodes that approached the theoretical limits for GaN material in terms of breakdown and on-state resistance. Vertical GaN p-n diodes fabricated on bulk GaN with a breakdown voltage of 2600 V and on-resistance of 2.0 mΩ cm^2 was demonstrated. A positive temperature coefficient of the breakdown voltage proved that the breakdown mechanism in reverse biased diodes was due to impact ionization initiated avalanche. The critical electric field for GaN was demonstrated to be at least 3.5 MV/cm and an electron mobility of 1150 cm^2/V s was extracted. Although the electron transport properties in Wurtzite GaN are highly anisotropic, the material parameters provided can be used for benchmarking and rudimentary modeling. These low-defect density diodes performed well in reliability and extended stress testing, which was verified in various circuit applications [14].

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