Breakdown Voltage and Reverse Recovery Characteristics of Free-Standing GaN Schottky Rectifiers

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***Abstract*—Schottky rectifiers with implanted p^+ guard ring edge termination fabricated on free-standing GaN substrates show reverse breakdown voltages up to 160 V in vertical geometry devices. The specific on-state resistance was in the range 1.7–3.0 $\Omega\cdot cm^2$, while the turn-on voltage was ~1.8 V. The switching performance was analyzed using the reverse recovery current transient waveform, producing an approximate high-injection, level hole lifetime of ~15 ns. The bulk GaN rectifiers show significant improvement in forward current density and on-state resistance over previous heteroepitaxial devices.**

***Index Terms*—Edge termination, GaN, power electronics, rectifiers, reverse recovery.**

I. INTRODUCTION

RAPID progress has been made in recent years in developing GaN-based electronics for use in high-power, high-frequency applications [1]–[8]. The availability of the AlGaN/GaN heterostructure allows modulation doping to form a high-mobility two-dimensional (2-D) electron gas and the formation of piezoelectrically-induced sheet carriers for high-current density [2]–[7]. The GaN materials system has a high breakdown field, good saturation electron velocity, and reasonable thermal conductivity if bulk wafers are available. One of the immediate applications for GaN power rectifiers could be for use in the electric power utility industry. A major problem in the existing grid is momentary voltage sags, which affect motor drives, computers, and digital controls. A system for eliminating power sags and switching transients would dramatically improve power quality [10]. An outage of less than one cycle, or a voltage sag of 25% for two cycles can cause a microprocessor to malfunction. The high cost of motor repairs each year could be dramatically reduced by high-power electronic devices that permit smoother switching and control. In addition, control electronics could dramatically improve motor efficiency. Other end uses include lighting, heating, and air-conditioning [9], [10]. A key component of the inverter modules for these applications is the simple rectifier. There have been a number of reports of mesa and lateral geometry GaN and AlGaN Schottky and p-i-n rectifiers fabricated on heteroepitaxial layers on Al_2O_3 substrates [11]–[19]. A major disadvantage of this approach is the poor thermal characteristics of the sapphire and the limited epilayer thicknesses employed. Factors limiting these thicknesses include cracking of the GaN, rough surface morphologies and auto-doping effects from the sapphire substrate.

A variety of approaches have been used recently to produce free-standing GaN substrates with thicknesses up to ~200 μm. We reported initial results on unterminated rectifiers on these types of substrates as a function of contact diameter (44–148 μm) [19]. The results were promising enough that we fabricated edge terminated devices with a much larger range of diameters (54–7000 μm). The reverse breakdown and reverse recovery characteristics of these rectifiers are reported in this paper.

II. EXPERIMENTAL

The free-standing substrates were ~200 μm thick and were grown by high-rate vapor phase epitaxy on c-plane Al_2O_3 substrates and removed by differential heating from a laser beam [20], [21]. Capacitance-voltage *(C–V)* measurements showed an unintentional n-type doping level of $\sim 8 \times 10^{16}$ cm^{-3}. P-type guard rings (30 μm diameter) were formed by selective area Mg^+ implantation (50 keV, 5×10^{14} cm^{-2}), followed by annealing at 1100 °C for 30 s. Full-area back Ohmic contacts of Ti/Al/Pt/Au were deposited by e-beam evaporation and annealed at 700 °C for 30 s. On some of the samples we also placed Ti/Al/Pt/Au Ohmic contacts on the front surface so we could compare vertical versus lateral device geometries. Schottky contacts of e-beam evaporated, unannealed Pt/Ti/Au with diameters of either 54–75 μm for small devices or 7 mm for large devices were placed on the front (Ga-face) surface. For the large area devices the Schottky contact was extended over an SiO_2 passivation layer (2000 Å thick) deposited by plasma enhanced chemical vapor deposition. Charge-coupled device (CCD) images captured on a microscope and schematic cross-sections of both the small and large area GaN rectifiers are shown in Figs. 1 and 2, respectively. The current–voltage *(I–V)* and reverse recovery characteristics were measured at 25 °C.

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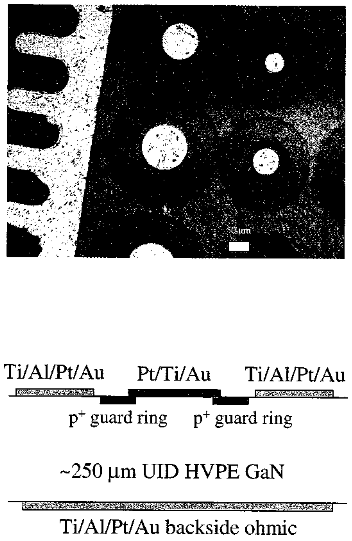

Fig. 1. (Top) CCD image of small-diameter Schottky rectifiers and schematic of device cross section (bottom).

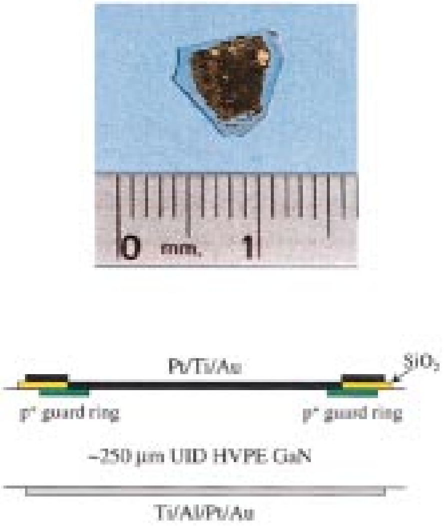

Fig. 2. (Top) Photograph of large diameter Schottky rectifiers and schematic of device cross section (bottom).

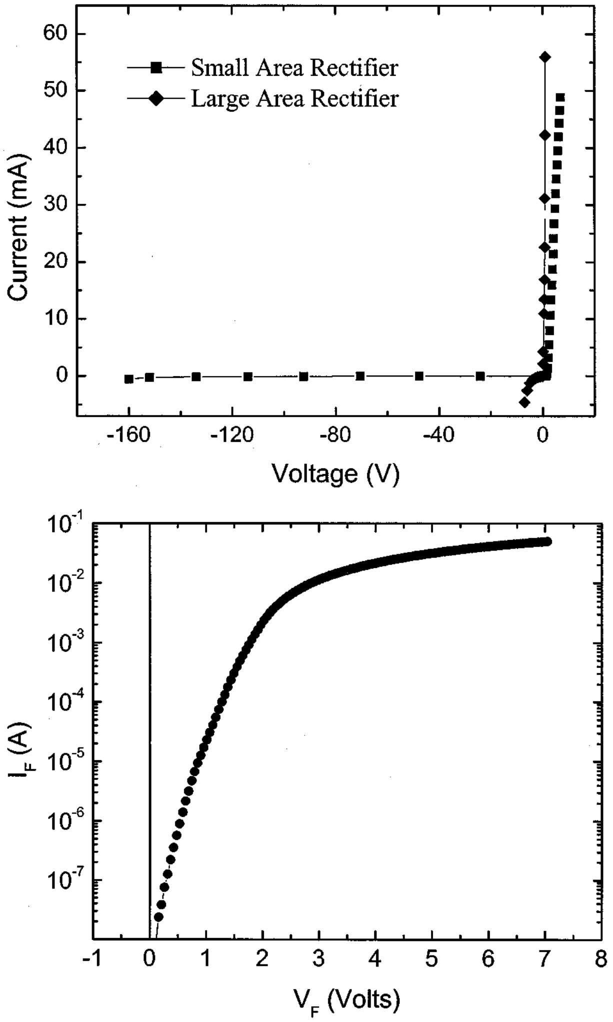

Fig. 3. (Top) *I–V* characteristics from vertical geometry large and small-area rectifiers at 25 °C and expanded view of forward characteristic from small-area device (bottom).

III. RESULTS AND DISCUSSION

The large-area diode had a reverse breakdown voltage, V_B, of only 6 V. By sharp contrast, the small-area diodes show V_B values of ~120 V in the lateral mode and ~160 V in the vertical mode. The *I–V* characteristics from the large and small-area vertical diodes are shown in Fig. 3 (top), along with an expanded view of the forward characteristic of the small-area devices (bottom). These results have several implications. First, they suggest that the presence of defects in the depletion region or around the contact periphery have a major effect on the electrical characteristics. The defect density of the Ga-face is $\sim 10^5$ cm^{-2} in the GaN as measured by etch pit counting by atomic force microscopy. There will obviously be a higher concentration of total defects (by roughly a factor of 10^4) in the region under the contact of the large area devices. In defect-free material, V_B is related to the maximum electric field strength at breakdown, E_M, by the equation

$$V_B = \frac{E_M W_M}{2}$$

where W_M is the depletion depth at breakdown. However it has been amply demonstrated in other materials systems such as SiC that the presence of defects (dislocations, nanopipes) leads to premature breakdown in diodes [22]–[24]. In addition, surface defects around the periphery of the devices will also degrade the breakdown and increase reverse leakage. From plots of reverse leakage versus contact periphery length or area of the type we have published previously [15], it is clear in our diodes that surface leakage is the dominant contributor to the current. The second key implication from Fig. 3 is that the small area diodes show a larger V_B in the vertical geometry. This indicates that the surface plays a major role in determining V_B, because even though the vertical GaN thickness is ~200 μm and the Ohmic-gate spacing is ~30 μm for the lateral diodes, we are in the punch-through region for both types of devices.

Fig. 4 shows the temperature dependence of reverse current in a typical 75 μm diameter vertical geometry rectifier (top),

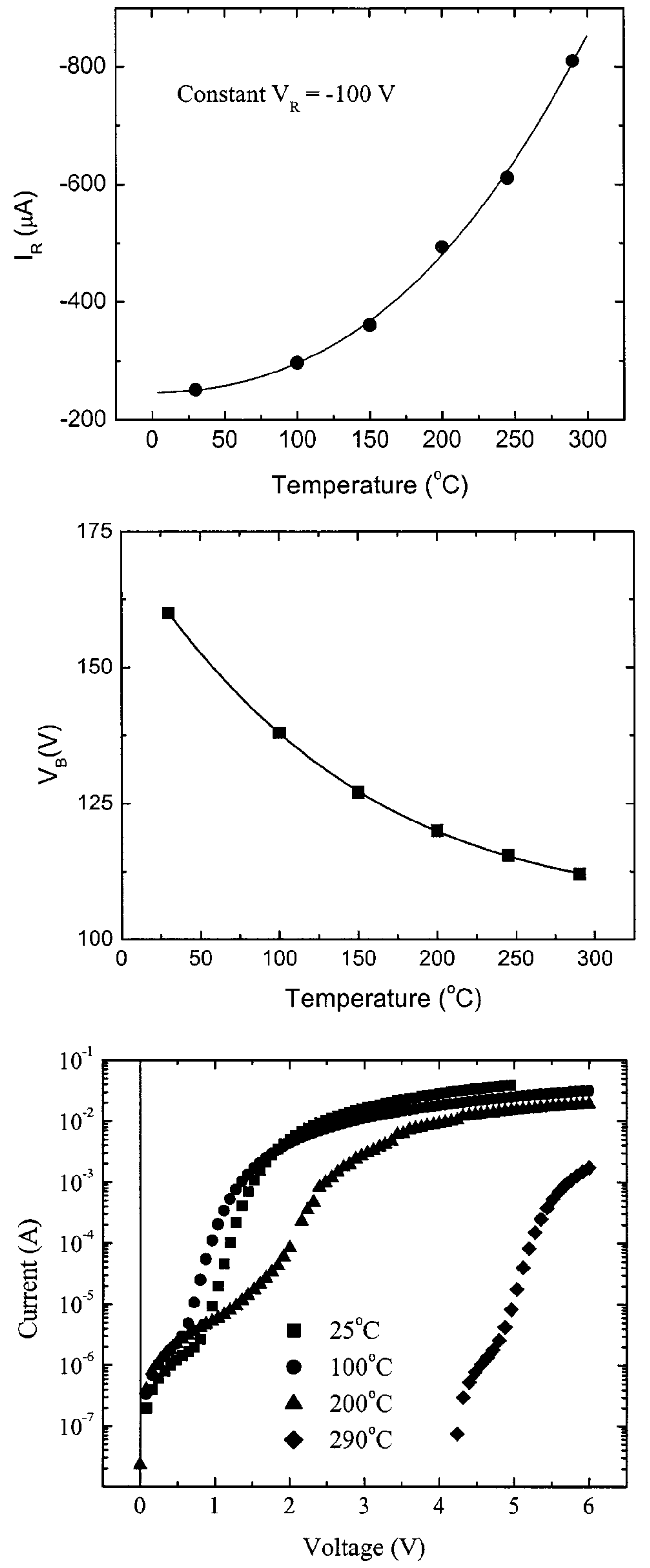

Fig. 4. (Top) Temperature dependence of reverse leakage in 75 μm diameter vertical geometry rectifiers, (middle) reverse breakdown voltage, and (bottom) forward *I–V* characteristics of same diodes.

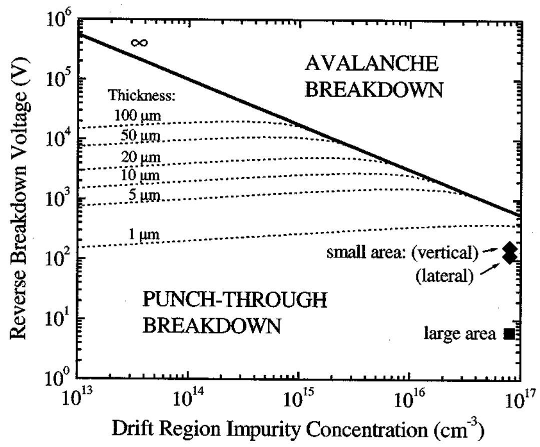

Fig. 5. Calculated breakdown voltage as a function of doping concentration and active layer thickness in GaN rectifiers.

along with the temperature dependence of the reverse breakdown voltage (middle) and forward current (bottom). These bulk rectifiers still show poor thermal characteristics, with both forward and reverse leakage increasing rapidly with operating temperature. The reverse breakdown still showed a negative temperature coefficient, similar to previous work, suggesting that more work needs to be done to reduce the surface and bulk defect density. The reverse current was thermally activated with an activation energy of 0.11 ± 0.04 eV and this may represent the most prominent surface state giving rise to the current since surface leakage was the dominant contributor. As mentioned earlier, over the small range of diameters, reverse current was proportional to contact diameter. This indicates that the reverse current originates from surface periphery leakage.

Fig. 5 shows a plot of avalanche and punch-through breakdown of GaN Schottky rectifiers calculated as a function of doping concentration and active layer thickness. It can be seen that, for example, a 20 kV device could be achieved with ~100 μm thick GaN layer with a doping concentration $<10^{15}$ cm^{-3}. The data points on the plot represent the V_B values from the present work. The biggest issue facing GaN rectifiers achieving very high breakdown voltages is now to reduce the background doping in the free-standing substrates. Our previous work on lateral diodes fabricated on fairly resistive GaN and AlGaN showed V_B values up to 9.7 kV, even though the defect density was very high ($>10^8$ cm^{-2}) [12].

The reverse recovery waveforms from a small-area vertical geometry GaN rectifier and from a standard “fast recovery” 1 A, 600 V, 200 nsec Si diode are shown in Fig. 6 (top). The devices were switched from forward current densities of 400 A·cm^{-2} to a reverse bias of 25 V. The GaN data shows that nanosecond switching times are possible. Note also the significantly lower reverse current in the GaN device due to the smaller amount of stored charge. Following the analysis of Khemka *et al.* [1], we estimate a value of ~15 ns for the high-injection, level hole lifetime in our rectifiers. This is within the range of 1–20 ns for previously reported minority carrier lifetimes in n-GaN [25].

The specific on-state resistances (R_{ON}) for the three types of rectifiers measured were 3 mΩ·cm^2 for the small-area vertical diodes, 1.7 mΩ·cm^2 for the small-area lateral diodes, and 3.4 Ω·cm^2 for the large-area devices. To place these results in context, Fig. 7 shows a plot of R_{ON} versus V_B for GaN rectifiers reported in the literature. The lines show theoretical results for

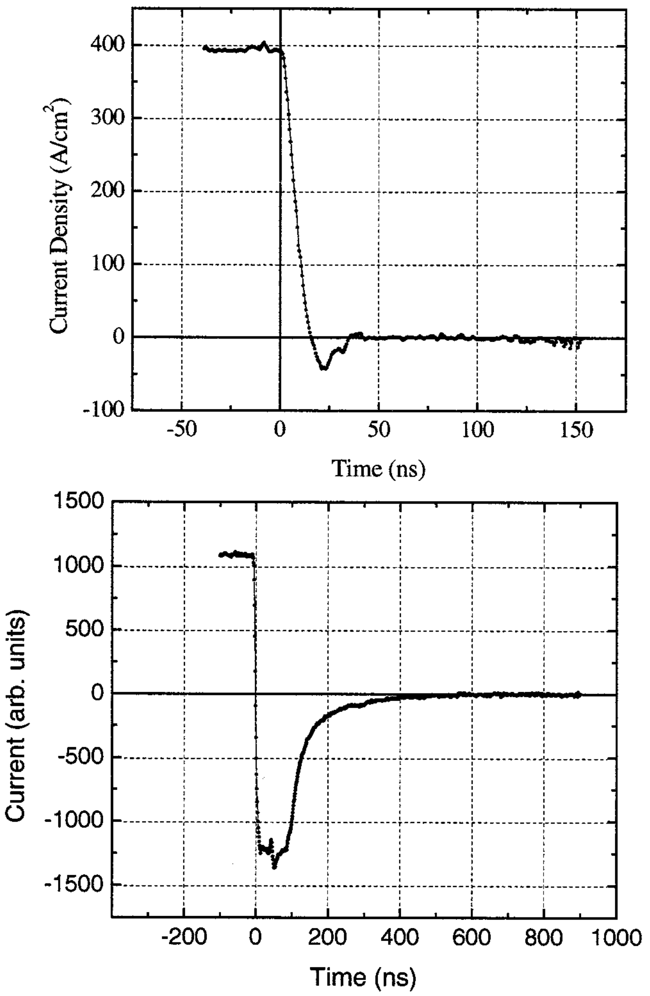

Fig. 6. (Top) GaN rectifier reverse recovery characteristics from 75 μm diameter device, compared to (bottom) standard 1 A, 600 V Si diode.

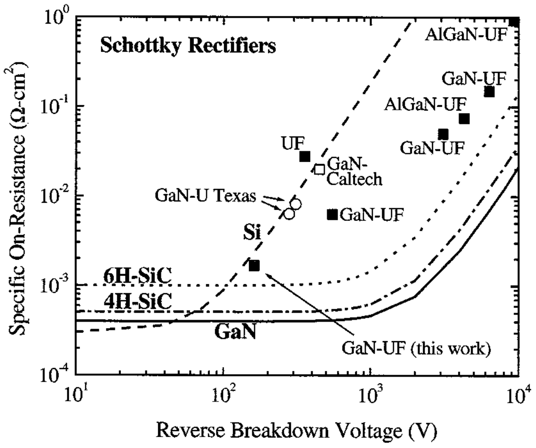

Fig. 7. Specific on-state resistance versus breakdown voltage for GaN rectifiers reported in the literature. The lines show theoretical results for Si, SiC, and GaN.

Si, SiC, and GaN rectifiers from [1]. There has been a steady improvement in the on-state resistances over the past few years as material and processing quality have improved.

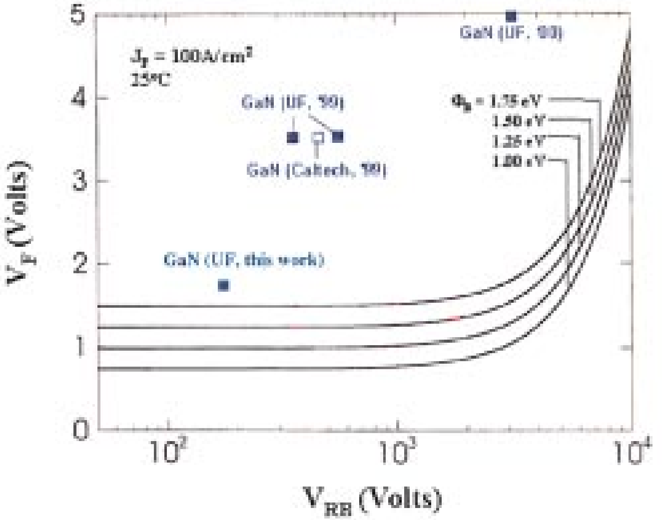

Fig. 8. Forward turn-on voltage versus reverse breakdown voltage for GaN rectifiers. The curves show theoretical values expected for different barrier heights.

The forward turn-on voltage, V_F, for a Schottky rectifier is given by

$$V_F = \frac{nkT}{q} \ln\left(\frac{J}{A^{**}T^2}\right) + n\phi_B + R_{ON} \cdot J_F$$

where n is the ideality factor, T the absolute temperature, q the electronic charge, A^{**} is Richardson's constant, and ϕ_B the Schottky barrier height. Defining V_F as the voltage at which the forward current density is 100 A·cm^{-2}, we obtained values of ~1.8 V for the small-area rectifiers. These are shown in Fig. 8, along with previously reported results from GaN rectifiers. The solid lines are theoretical values assuming various Schottky barrier heights. The V_F values in the present work are significantly lower than reported previously, indicating that surface cleaning and oxide removal steps have improved over time [26], [27].

IV. SUMMARY AND CONCLUSION

Schottky rectifiers fabricated on free-standing GaN substrates show significant improvements in forward turn-on voltages, on-state resistance, and reverse recovery characteristics relative to previously reported devices fabricated on GaN layers grown on sapphire. Future work should focus on lowering the background doping level in the GaN substrates and in measuring the temperature dependence of V_F, R_{ON}, and V_B in rectifiers on this optimized material. Previously reported heteroepitaxial rectifiers have shown a negative temperature coefficient for V_B, but this is expected to reverse sign in low defect material as was observed for SiC [23]. The viability of GaN rectifiers in most applications depends on making very large area devices with high V_B, while retaining low V_F and R_{ON}.

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