Comparison of GaN P-I-N and Schottky Rectifier Performance

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***Abstract*—The performance of GaN p-i-n and Schottky rectifiers fabricated on the same wafer was investigated as a function of device size and operating temperature. There was a significant difference in reverse breakdown voltage (490 V for p-i-n diodes; 347 V for the Schottky diodes) and forward turn-on voltage (∼5 V for the p-i-n diodes; ∼3.5 V for the Schottky diodes). Both types of device showed a negative temperature coefficient for reverse breakdown, with value $-0.34 \pm 0.05\ \mathrm{V} \cdot \mathrm{K}^{-1}$.**

***Index Terms*—GaN, power electronics, rectifiers.**

I. INTRODUCTION

THERE are numerous applications for switching devices and control circuits that can operate at very high power levels (100 kW to 1 MW) and temperatures in excess of 250 °C without liquid cooling. For example, there is a need to improve the transmission and distribution of electric power in the utilities industry, as well as CW and pulsed electrical subsystems in hybrid-electric vehicles, more-electric aircraft and naval ships [1]. While innovative designs are being pursued in light-triggered Si devices, there are advantages to the use of wide bandgap materials such as SiC and GaN [2]–[11]. The current state of development of SiC technology is much more mature than for GaN, with 4H pn diodes demonstrated with blocking voltages up to ∼12 kV [7]–[10] and Schottky rectifiers with blocking voltages up to 3 kV [5]. Several excellent reviews have recently appeared on developments in SiC device research [3], [4].

Much less work has been performed on GaN high power rectifiers [12]–[14]. Vertical geometry Schottky diodes with 450 V reverse breakdown voltage (V_{RB}) [12] and lateral diodes with V_{RB} of 3.1 kV have been reported [14]. Even higher values can be achieved by employing AlGaN, which has a wider bandgap than GaN [14]. In this paper, we report on a careful analysis of the performance of p-i-n diodes and Schottky diodes fabricated on the same GaN structure, including both the size and temperature dependence of forward and reverse currents. We find higher V_{RB} values for the p-i-n diodes and a negative temperature coefficient for this parameter in both types of rectifiers. Perimeter leakage was found to dominate the reverse current at modest biases in these unpassivated and unterminated devices.

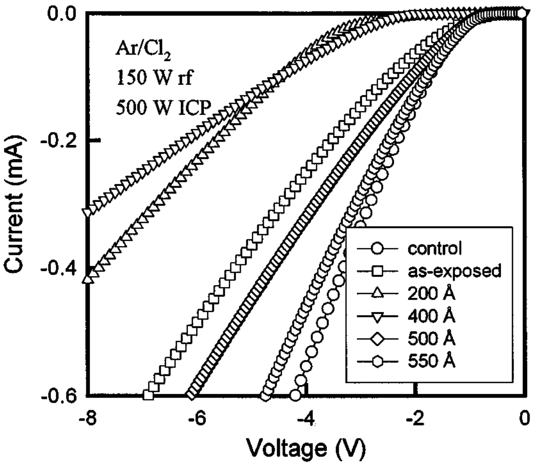

Fig. 1. Reverse *I*–*V* characteristics from n-GaN ($n = 5 \times 10^{17}\ \mathrm{cm}^{-3}$) before and after dry etching in a 10Cl$_2$/5Ar, 150 W rf, 500 W chuck power discharge. The Schottky contacts were deposited after wet etch removal of 200–550 Å of the dry etched surface.

II. EXPERIMENTAL

The structures were grown by atmospheric pressure metal organic chemical vapor deposition at 1050 °C on c-plane Al$_2$O$_3$ substrates at 1 μm·hr^{-1} with V/III ratio of 300 using TMGa and NH$_3$. Growth commenced with a low temperature (530 °C) AlN template ∼300 Å thick, followed by a 1.2 μm thick, Si-doped ($n = 3 \times 10^{18}\ \mathrm{cm}^{-3}$) GaN layer, 4 μm of undoped (normally n-type, $n \sim 10^{16}\ \mathrm{cm}^{-3}$) GaN and 0.5 μm of Mg-doped ($N_A \sim 10^{18}\ \mathrm{cm}^{-3}$) GaN. Both p-i-n and Schottky diodes were fabricated on the same wafer. The double crystal x-ray diffraction full width at half maximum (fwhm) was ∼450 arc·s, with an atomic force microscope fwhm of 2.7 nm. The typical mobility in the undoped layer was 390 cm^2/V·s. This was achieved by dry etch removal of the p$^+$GaN layer in some regions, followed by a wet etch (NaOH, 0.1 M, 80 °C) clean-up of 600 Å of material to remove residual lattice damage prior to deposition of the rectifying contact [15]. As an example of how this process is effective in restoring the electrical properties of dry etched GaN, Fig. 1 shows the reverse current–voltage characteristics from n-type ($5 \times 10^{17}\ \mathrm{cm}^{-3}$) GaN samples on which the

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rectifying contact was deposited either before or after exposure to a Cl_2/Ar plasma. In some cases, various amounts of material were removed by wet etching after plasma exposure and deposition of the rectifying contact.

For both p-i-n and Schottky diode structures, mesas were fabricated by dry etching down to the n^+ layer using Cl_2/Ar inductively coupled plasma etching, followed by annealing at 750 °C under N_2 to remove sidewall damage. Ohmic contacts to the n^+ layer were prepared by lift-off of Ti(500 Å)/Al(200 Å)/Pt(500 Å)/Au(2000 Å) alloyed at 700 °C, while rectifying contacts to the undoped GaN were formed by lift-off of Pt(500 Å)/Ni(1000 Å)/Au(2000 Å). To form an ohmic contact to the p^+ layer, we used Ni(1000 Å)/Pt(500 Å)/Au(2000 Å) metallization. Schematics of the p-i-n and Schottky rectifier structures are shown in Fig. 2. A scanning electron micrograph of a typical diode is shown in Fig. 3. Current–voltage (*I*–*V*) measurements were recorded on a HP 4145B parameter analyzer.

III. Results and Discussion

Fig. 4 shows the *I*–*V* characteristics at 25 °C for p-i-n and Schottky rectifiers fabricated side-by-side on the same wafer. There is a clear difference in the V_{RB} (defined as a reverse current density of 0.1 A·cm^{-2}) of the two devices (~490 V for the p-i-n versus ~347 V for the Schottky). For very high blocking voltages (typically in excess of ~3 kV) or forward current densities (>100 A · cm^{-2}) the p-i-n is expected to have the advantage because of the prohibitive leakage and resistance of the drift region in a Schottky diode [3]. However for high frequency operation the Schottky has an advantage in switching speed due to the absence of minority carriers. The on-state characteristics of the Schottky and V_{RB} characteristics of the p–n junction can be achieved in junction barrier controlled Schottky rectifiers [5].

The forward voltage drop)V_F) of the two types of rectifiers can be written as [4]

$$V_F = \frac{nkT}{e} \ln\left(\frac{J_F}{A^{**}T^2}\right) + n\phi_B + R_{\mathrm{ON}} \cdot J_F \qquad \text{(Schottky)}$$

and

$$V_F = \frac{kT}{e} \ln\left(\frac{n_- n_+}{n_i^2}\right) + V_m \qquad \text{(p-i-n)}$$

where

n ideality factor;
k Boltzmann's constant;
T absolute temperature;
e electronic charge;
J_F forward current density at V_F;
A^{**} Richardson constant;
ϕ_B barrier height;
R_{ON} on-state resistance;
n_- and n_+ electron concentrations in the two end regions of the p-i-n (the p^+/n and n^+/n regions);
V_m voltage drop across the i-region.

The typical values of V_F were ~5 V for the p-i-n rectifiers and ~3.5 V for the Schottky rectifiers, both measured at 25°C and defining V_F as the forward voltage at which the current density was 100 A·cm^{-2}. Both of these values are still well

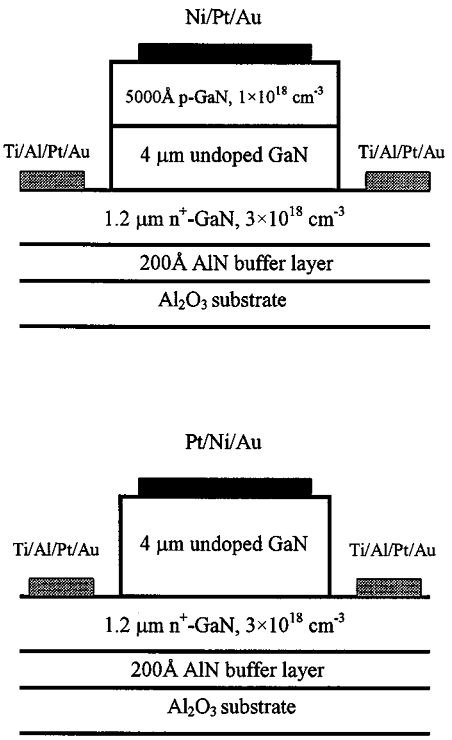

Fig. 2. Schematic of p-i-n (top) and Schottky (bottom) rectifiers.

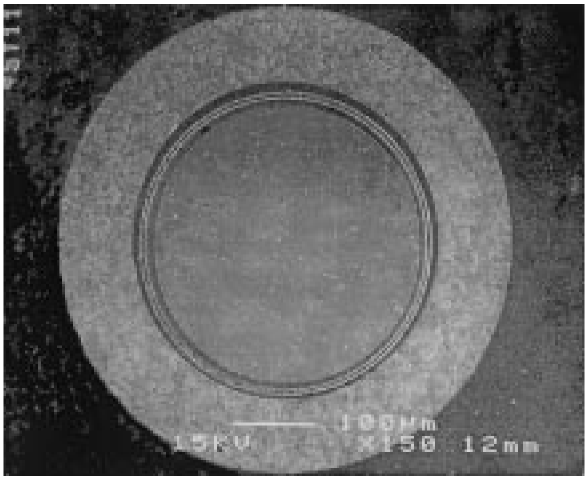

Fig. 3. SEM micrograph of p-i-n rectifier.

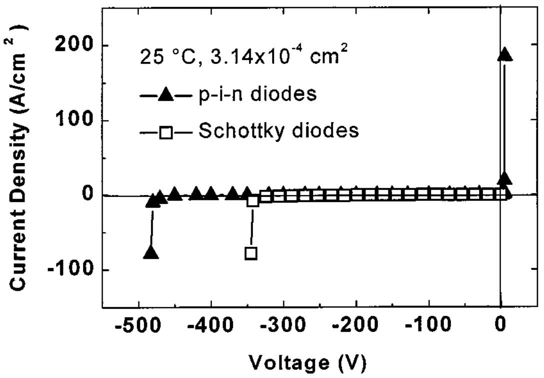

Fig. 4. *I*—*V* characteristics at 25 °C from p-i-n and Schottky rectifiers.

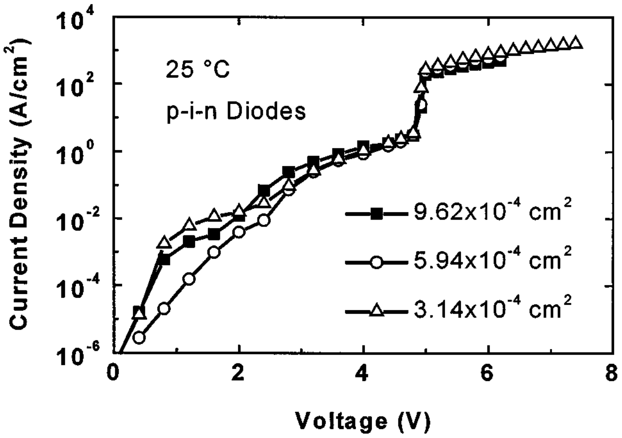

Fig. 5. Forward *I–V* characteristics at 25 °C from p-i-n rectifiers of different contact areas.

above the theoretical minima, which should be of the order of the barrier height for the Schottky metal (between 1 and 1.5 eV in our case) or the bandgap for the p-i-n diode (3.4 eV for GaN). A similar situation occurs in SiC rectifiers, possibly due to interfacial oxides, although there have been reports of V_F values relatively close to the theoretical values [4]. In general it is expected that V_F will remain fairly constant for GaN p-i-n's and Schottky rectifiers to breakdown voltages in the 3–5 kV range, at which point there is a sharp increase due to the increase in on-state resistance [3], [4].

Forward *I–V* characteristics for p-i-n rectifiers of different contact areas are shown in Fig. 5. It is sometimes found for SiC p-i-n rectifiers that the Sah–Noyce–Shockley model for forward current conduction cannot be applied due to the presence of a multiple number of deep and shallow impurity levels in the bandgap which can act as recombination sites [4]. The *I–V* characteristic of Fig. 5 corresponds well to the four different exponential regimes predicted by this model, with ideality factors close to 1 at low bias (<0.6 V), ~2 at higher bias (0.6–5 V), dependent on the number of deep and shallow levels (around 5 V) and then ~2 at higher bias. In the latter case our characteristic becomes dominated by series resistance effects which gives the appearance of a sharp increase in I around 5 V. In the multi- recombination center model, the forward current density J_F can be written as [4], [16]

$$J_F = J_{01}\exp\left(\frac{eV}{2kT}\right) + J_{02}\exp\left(\frac{eV}{nkT}\right) + J_{S2}\exp\left(\frac{eV}{kT}\right)$$

where the first two terms represent the recombination current components and the third represents the diffusion current component originating from the recombination of electrons and holes in neutral regions outside the space-charge region. When we measure the forward *I–V* characteristics at elevated temperatures (150 to 250 °C) for the p-i-n diodes, the shape of the curves became more simplified and appeared to revert to the more common Sah–Noyce–Shockley form. This is probably a result of the fact that recombination through multiple deep and shallow levels becomes far less effective at elevated temperature. The Schottky diodes typically showed ideality factors in

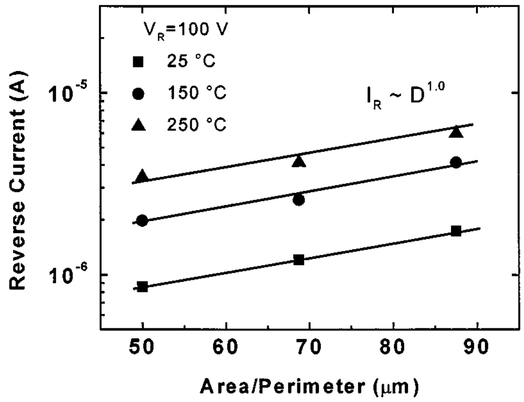

Fig. 6. Reverse current as a function of contact diameter for p-i-n rectifiers at different temperatures.

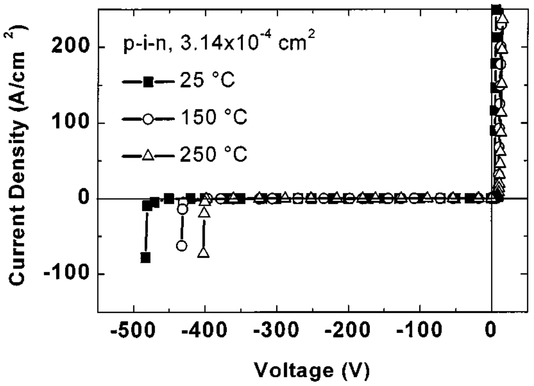

Fig. 7. *I–V* characteristics from p-i-n rectifier as a function of temerpature.

the range 1.3 to 1.6 at $V_F = 2.5$–4 V and $n = 2$ at $V_F > 4$ V, consistent with recombination at low bias and diffusion current at higher bias.

Fig. 6 shows the reverse current measured at 100 V bias for p-i-n diodes with different contact diameters. Under all the temperatures employed for these measurements the reverse current was directly proportional to the diameter of the contact, indicating the dominance of surface perimeter leakage. If bulk leakage were dominant then we would obtain a slope of 2 for the plot of reverse current versus contact diameter. Note again that all of our devices are unpassivated and unterminated so that no effort was taken to minimize surface contributions to the leakage current. However one of the expected attributes of GaN for electronic devices was a relative insensitivity to surface effects. We have consistently observed to the contrary that the GaN surface is easily disrupted during plasma processing or thermal annealing, usually through the preferential loss of nitrogen [15].

Fig. 7 shows the *I–V* characteristics from a p-i-n diode at three different measurement temperature. It is clear that there is a negative temperature coefficient for the reverse breakdown voltage. We observed similar behavior for Schottky diodes and a compilation of such data is shown in Fig. 8 for a constant mesa area of 9.62×10^{-4} cm^2. Once again a reverse current density of 0.1 A $\cdot$ cm^2 is used as the definition of breakdown. Here we have also included results from several other GaN Schottky rectifiers

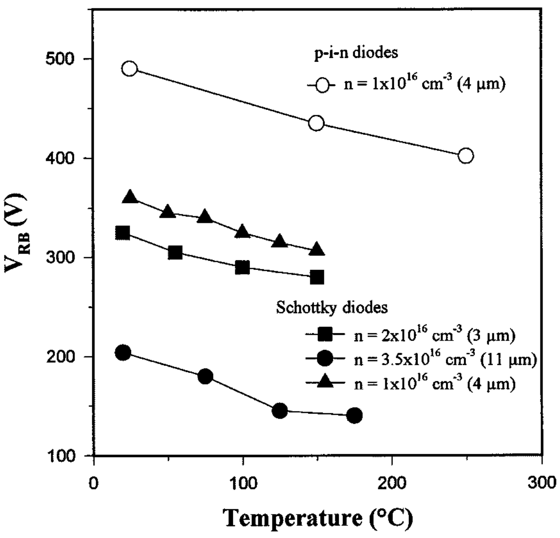

Fig. 8. Temperature dependence of Vrb in p-i-n and Schottky rectifiers.

we have fabricated on n-type material. Note that in all cases the measured breakdown voltage decreases with temperature as

$$V_{RB} = V_{RBO}(1 + \beta(T - To))$$

where $\beta = -0.34 \pm 0.05\ \mathrm{V \cdot K^{-1}}$. Other reports have found positive temperature coefficients for AlGaN–GaN high electron mobility transistors ($+0.33\ \mathrm{V \cdot K^{-1}}$) [17] and GaN p^+-p-n^+ linearly-graded junctions ($+0.02\ \mathrm{V \cdot K^{-1}}$) [11]. In separate experiments, we found that use of edge termination techniques (floating field rings, junction barrier control or metal overlap onto a dielectric on the surface) also produced negative temperature coefficients of V_{RB} in GaN Schottky rectifiers.

IV. SUMMARY AND CONCLUSIONS

A direct comparison of GaN p-i-n and Schottky rectifiers fabricated on the same GaN wafer showed higher reverse breakdown voltage for the former (490 V vs 347 V for the Schottky diodes), but lower forward turn-on voltages for the latter (~3.5 V versus ~5 V for the p-i-n diodes). The forward *I–V* characteristics of the p-i-n rectifiers show behavior consistent with a multiple recombination center model. For the Schottky rectifiers, the forward *I–V* characteristics were consistent with Shockley–Read–Hall recombination at low bias and diffusion currents at higher bias. The reverse current in both types of rectifiers was dominated by surface perimeter leakage at moderate bias. Finally, all of the devices we fabricated showed negative temperature coefficients for reverse breakdown voltage, which is a clear disadvantage for elevated temperature operation.

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