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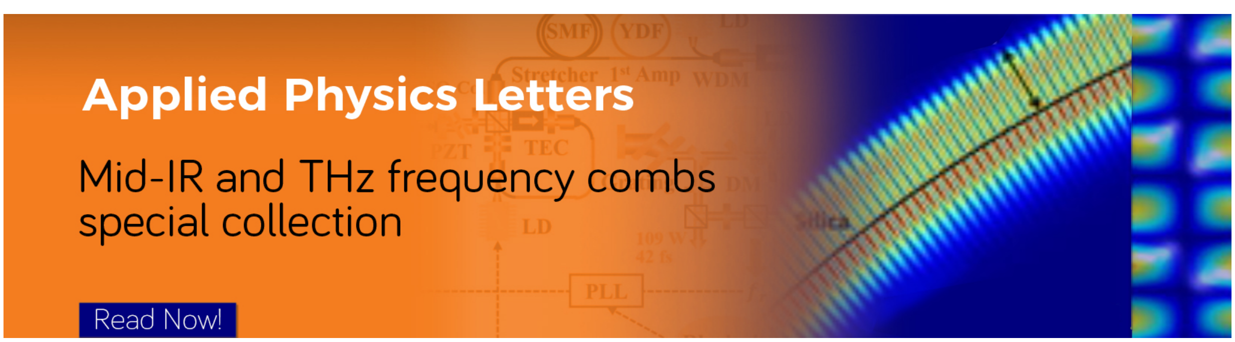
Cite as: Appl. Phys. Lett. **78**, 823 (2001); https://doi.org/10.1063/1.1346622
Submitted: 16 October 2000 . Accepted: 06 December 2000 . Published Online: 02 February 2001

A. P. Zhang, J. W. Johnson, F. Ren, J. Han, A. Y. Polyakov, N. B. Smirnov, A. V. Govorkov, J. M. Redwing, K. P. Lee, and S. J. Pearton



Lateral $Al_xGa_{1-x}N$ power rectifiers with 9.7 kV reverse breakdown voltage

A. P. Zhang, J. W. Johnson, and F. Ren
Department of Chemical Engineering, University of Florida, Gainesville, Florida 32611

J. Han
Sandia National Laboratories, Albuquerque, New Mexico 87185

A. Y. Polyakov, N. B. Smirnov, and A. V. Govorkov
Institute of Rare Metals, Moscow 109107, Russia

J. M. Redwing
Department of Materials Science and Engineering, Pennsylvania State University, State College, Pennsylvania 16802

K. P. Lee and S. J. Pearton[a)]
Department of Materials Science and Engineering, University of Florida, Gainesville, Florida 32611

(Received 16 October 2000; accepted for publication 6 December 2000)

$Al_xGa_{1-x}N$ ($x=0-0.25$) Schottky rectifiers were fabricated in a lateral geometry employing p^+-implanted guard rings and rectifying contact overlap onto an SiO_2 passivation layer. The reverse breakdown voltage (V_B) increased with the spacing between Schottky and ohmic metal contacts, reaching 9700 V for $Al_{0.25}Ga_{0.75}N$ and 6350 V for GaN, respectively, for 100 μm gap spacing. Assuming lateral depletion, these values correspond to breakdown field strengths of $\leqslant 9.67\times 10^5\ \mathrm{V\,cm^{-1}}$, which is roughly a factor of 20 lower than the theoretical maximum in bulk GaN. The figure of merit $(V_B)^2/R_{ON}$, where R_{ON} is the on-state resistance, was in the range 94–268 $\mathrm{MW\,cm^{-2}}$ for all the devices. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1346622]

There has been rapid improvement over the past few years in the performance of GaN-based power electronic devices for applications in commercial broad band communication as well as military radar and communications in the 5–35 GHz range. Most of the attention has focussed on heterostructure field-effect transistors fabricated on AlGaN/GaN structures[1–11] with either Schottky metal or gate oxide control of current flow. There have also been advances in developing GaN and AlGaN power rectifiers[12–18] which are key components of inverter modules for power flow control circuits. Vertical geometry GaN Schottky rectifiers fabricated on conducting materials typically show reverse breakdown voltages (V_B)$\leqslant$750 V[13–18] whereas lateral devices on insulating GaN and AlGaN have V_B values up to 4.3 kV.[14–17]

Since the predicted breakdown field strength in GaN is of order $2-3\times 10^7\ \mathrm{V\,cm^{-1}}$ (Refs. 1 and 6) there appears to be much room for improvement in rectifier performance and a need to understand the origin of reverse leakage currents, breakdown mechanisms, and the effect of contact spacing on V_B. In this letter we report on the variation of V_B with Schottky-to-ohmic contact gap spacing in $Al_xGa_{1-x}N$ diodes ($x=0-0.25$) employing p-guard rings and extension of the Schottky contact edge over an oxide layer for edge termination. V_B values up to 9700 kV were achieved for $Al_{0.25}Ga_{0.75}N$ rectifiers, with breakdown still occurring at the edges of the Schottky contact. The reverse leakage current just before breakdown is dominated by bulk contributions, scaling with the area of the rectifying contact.

The rectifiers were fabricated on resistive ($\sim 10^7\ \Omega$ cm) layers of 2.5–3 μm thick GaN or AlGaN grown on c-plane Al_2O_3 substrates at 1040–1100 °C by metalorganic chemical vapor deposition.[19,20] To create n^+ regions for ohmic contacts, Si^+ ions were implanted at $5\times 10^{14}\ \mathrm{cm^{-2}}$, 50 keV, and activated by annealing at 1150 °C for 10 s under N_2. It is important to control both the heating and cooling rates to avoid cracking of the AlGaN layer. Mg^+ implantation at $5\times 10^{14}\ \mathrm{cm^{-2}}$, 50 keV was used to create 30 μm diameter p-guard rings at the edge of the Schottky barrier metal. The rectifying contact diameter was 124 μm in most cases, while the distance of this contact from the edge of the ohmic contact was varied from 30–100 μm. The Schottky metal was extended over a SiO_2 layer deposited by plasma-enhanced chemical vapor deposition in order to minimize field crowding. Ohmic contacts were created by lift off of e-beam evaporated Ti/Al/Pt/Au annealed at 750 °C for 30 s under N_2. The Schottky contacts were formed by lift off of e-beam evaporated Pt/Ti/Au. A schematic of the completed rectifiers is shown in Fig. 1. Current–voltage ($I-V$) characteristics were recorded on a HP4145 parameter analyzer, with all testing performed at room temperature under a Fluorinert® ambient.

Figure 2 shows the measured V_B values for GaN and $Al_{0.25}Ga_{0.75}N$ rectifiers as a function of the gap spacing between the rectifying and ohmic contacts. For gaps between 40 and 100 μm, V_B is essentially linearly dependent on the spacing, with slopes of $6.35\times 10^5\ \mathrm{V\,cm^{-1}}$ for $Al_{0.25}Ga_{0.75}N$ and $4.0\times 10^5\ \mathrm{V\,cm^{-1}}$ for GaN. We assume the deviation from these values at shorter spacing is due to the fact that the p-guard ring almost covers this region. In vertical geometry diodes V_B is related to the maximum electric field strength at breakdown E_M, through the relation[12]

$$V_B=E_M W_B/2,$$

[a)]Electronic mail: spear@mse.ufl.edu

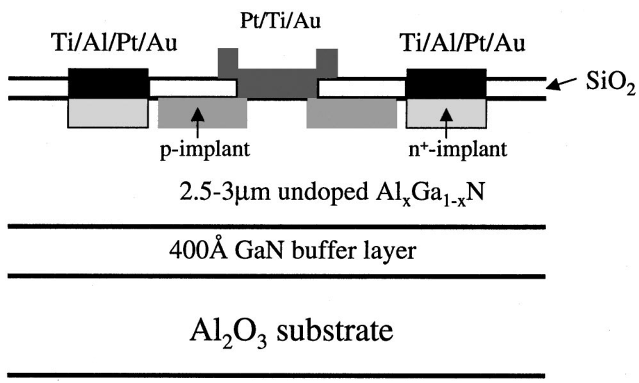


FIG. 1. Schematic of lateral geometry AlGaN rectifiers employing edge termination.

where W_B is the depletion width at breakdown. In our laterally depleting devices the surface quality will dominate the onset of breakdown, which is reflected in the lower breakdown field observed. However, given the current state of defect densities in epitaxial GaN, the lateral geometry seems the most promising, for the time being, for achieving very high V_B values. Quasisubstrates of GaN, produced by thick epigrowth on mismatched substrates and subsequent removal of this template, are soon to be commercially available. In some cases the background doping in these is as low as $7.9 \times 10^{15}\,\mathrm{cm}^{-3}$ (Ref. 21) which makes feasible the use of these thick (200 μm) freestanding GaN films for vertically depleting rectifiers.

Figure 3 shows some $I-V$ characteristics from the 100 μm gap spacing GaN and $Al_{0.25}Ga_{0.75}N$ rectifiers. The best forward turn-on voltages, V_F (defined as the forward voltage at a current density of 100 $\mathrm{A\,cm}^{-2}$) was ~15 V for GaN and ~33 V for $Al_{0.25}Ga_{0.75}N$. These are much higher than the values obtained on more conducting GaN films, where V_F is typically 5–8 V. Note, however, that the ratio V_B/V_F is still very high for the resistive diodes, with values ranging from 294 to 423. The specific on-state resistance for a rectifier is given by

$$R_{\mathrm{ON}} = (4V_B^2/\varepsilon \cdot \mu \cdot E_M^3) + \rho_S W_S + R_C,$$

where ε is the GaN permittivity, μ the carrier mobility, ρ_S and W_S are substrate resistivity and thickness, and R_C is the contact resistance. The best on-state resistances we achieved were 0.15 $\Omega\,\mathrm{cm}^2$ for GaN and 1 $\Omega\,\mathrm{cm}^2$ for $Al_{0.25}Ga_{0.75}N$,

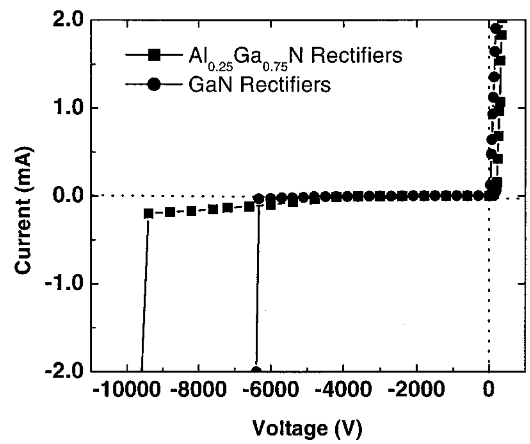


FIG. 3. $I-V$ characteristics of GaN and $Al_{0.25}Ga_{0.75}N$ rectifiers with 100 μm gap spacing between Schottky and ohmic contacts.

leading to figure of merits $(V_B)^2/R_{\mathrm{ON}}$ of 268 $\mathrm{MW\,cm}^{-2}$ and 94 $\mathrm{MW\,cm}^{-2}$, respectively. At low reverse voltages ($\leqslant$ 2000 V), the magnitude of the reverse current was proportional to contact diameter. As the diodes approached breakdown the reverse current was proportional to contact area, suggesting bulk leakage becomes dominant.

The variation of V_B with Al percentage in the AlGaN layer of the rectifiers is shown in Fig. 4, along with the calculated bandgaps.[22] V_B does increase with increasing bandgap Eg, but is not proportional to $(Eg)^{1.5}$ as expected from a simple theory. The presence of bulk and surface defects will have a strong influence on V_B, and these are not well controlled at this stage of AlGaN rectifier technology.

To place our results in context, Fig. 5 shows a compilation of R_{ON} versus V_B data for state-of-the-art SiC and GaN Schottky diode rectifiers, together with theoretical curves for Si, 6H, and 4H–SiC and hexagonal GaN.[12,23] Our results for high breakdown GaN devices show the on resistances are still well above the theoretical values and more work is needed to understand current conduction mechanisms, the role of residual native oxides on contact properties, and impact ionization coefficients in GaN.

In conclusion, lateral geometry Al_xGaN Schottky rectifiers employing edge termination show reverse breakdown voltages up to 9.7 kV. These breakdown voltages scale with contact spacing and the rectifiers appear promising for high power electronics applications.

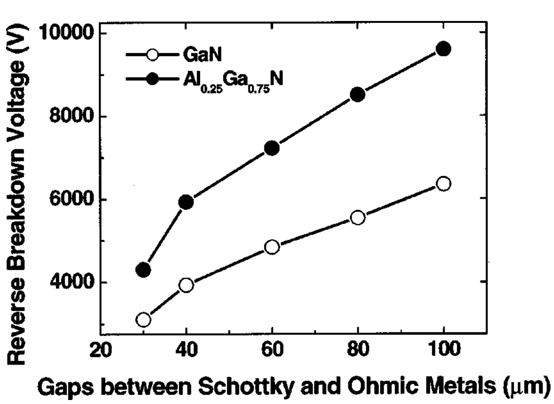


FIG. 2. Effect of Schottky-ohmic contact gap spacing on V_B for GaN and $Al_{0.25}Ga_{0.75}N$ rectifiers.

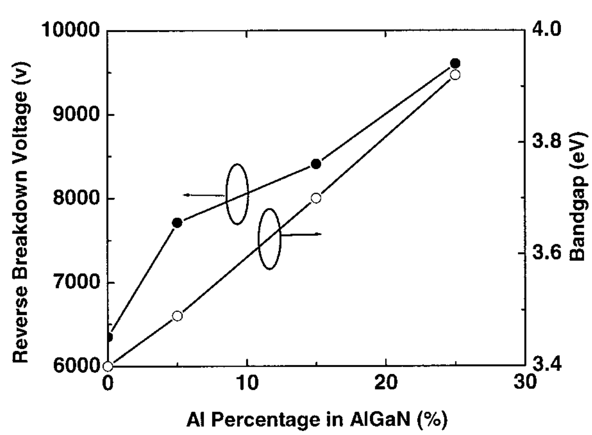


FIG. 4. V_B as a function of Al percentage in AlGaN rectifiers.

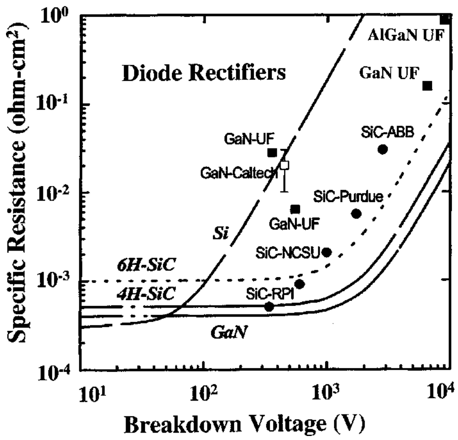


FIG. 5. On-state resistance vs V_B for wide band gap Schottky rectifiers. The theoretical performance limits of Si, SiC, and GaN devices are shown by the solid lines.

The work at UF is partially supported by DARPA/EPRI (D. Radack/B. Damsky), Contract No. MDA 972-98-1-0006 monitored by ONR (J. C. Zolper), and by NSF (Grant No. DMR 97-32865, L. Hess). Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed-Martin company for the US Department of Energy under Grant No. DEAC 04-94-AL 85000.

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