Temperature dependence and current transport mechanisms in $Al_xGa_{1-x}N$ Schottky rectifiers

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GaN and $Al_{0.25}Ga_{0.75}N$ lateral Schottky rectifiers were fabricated either with (GaN) or without (AlGaN) edge termination. The reverse breakdown voltage V_B (3.1 kV for GaN; 4.3 kV for AlGaN) displayed a negative temperature coefficient of $-6.0\pm0.4\,\mathrm{V\,K^{-1}}$ for both types of rectifiers. The reverse current originated from contact periphery leakage at moderate bias, while the forward turn-on voltage at a current density of 100 A $\mathrm{cm^{-2}}$ was ~5 V for GaN and ~7.5 V for AlGaN. The on-state resistances, R_{ON}, were 50 m$\Omega\,\mathrm{cm^2}$ for GaN and 75 m$\Omega\,\mathrm{cm^2}$ for AlGaN, producing figures-of-merit $(V_{RB})^2/R_{ON}$ of 192 and 246 MW $\mathrm{cm^{-2}}$, respectively. The activation energy of the reverse leakage was 0.13 eV at moderate bias. © *2000 American Institute of Physics.* [S0003-6951(00)04725-2]

GaN-based electronic devices are attracting interest for high power switching and microwave amplifiers capable of operation at elevated temperatures.[1–11] For improved control of power flow and quality in the transmission and distribution sections of utility grids and in the electrical subsystems of avionic and naval assets, a key building block is the power rectifier.[8,9] The combination of a switching device such as a thyristor with a power rectifier and appropriate packaging are the key components of inverter modules, which are employed in power flow control circuits.[8] *P-i-n* rectifiers are expected to have larger reverse blocking voltages than Schottky rectifiers, but inferior switching speeds and higher forward turn-on voltages.[12] We have previously demonstrated GaN Schottky rectifiers with reverse breakdown voltage (V_{RB}) to 3.1 kV when p^+ guard rings and metal overlap onto a dielectric are employed as edge termination techniques.[13] Use of $Al_{0.25}Ga_{0.75}N$ instead of GaN produced V_{RB} values up to 4.3 kV.[13]

Since this type of device is intended for elevated temperature operation, there is a need to understand the current transport mechanisms, the origin of the reverse leakage current and the magnitude and sign of the temperature coefficient for V_{RB}. In this letter we report on all of these properties. Over a broad range of voltages, the reverse leakage current is proportional to the diameter of the rectifying contact indicating that surface periphery leakage is the dominant contributor. The temperature coefficient for V_{RB} was found to be negative for both GaN and AlGaN, even in edge-terminated devices.

The GaN and $Al_{0.25}Ga_{0.75}N$ layers were found to be resistive ($\sim10^7\,\Omega$ cm). Each was grown on *c*-plane Al_2O_3 substrates by metal organic chemical vapor deposition using conventional precursors and growth temperatures of 1040 (GaN) or 1100 °C ($Al_{0.25}Ga_{0.75}N$). The layer thicknesses were 2.5–3 μm. Schematics of the completed rectifiers are shown in Fig. 1. The GaN devices employed p^+ guard rings formed (7 μm wide) by Mg^+/P^+ implantation, n^+ source/drain region formed by Si^+ implantation (annealing was performed at 1150 °C for 10 s under N_2) and overlap of the rectifying contact onto an SiO_2 passivation layer. The AlGaN devices did not use any edge termination techniques. The contacts on all rectifiers were formed by lift-off, with the ohmic metallization annealed at 700 °C for 30 s under N_2. The rectifying contact diameters were 45–125 μm with a separation of 124 μm between these contacts and the ohmic contacts.

Current–voltage ($I-V$) characteristics from both types of rectifiers are shown in Fig. 2 as a function of measurement temperature. The most obvious feature of the data is that there is a negative temperature coefficient for V_{RB}. The only previous information for GaN-based devices comes from GaN/AlGaN heterostructure field effect transistors in which a value of $+0.33\,\mathrm{V\,K^{-1}}$ was found,[5] and from linearly graded GaN p^+pn^+ junctions, in which a value of $+0.02\,\mathrm{V\,K^{-1}}$ was determined.[3] In both cases the V_{RB} values were more than an order of magnitude lower than in the present diodes.

Figure 3 shows the variation of V_{RB} with temperature.

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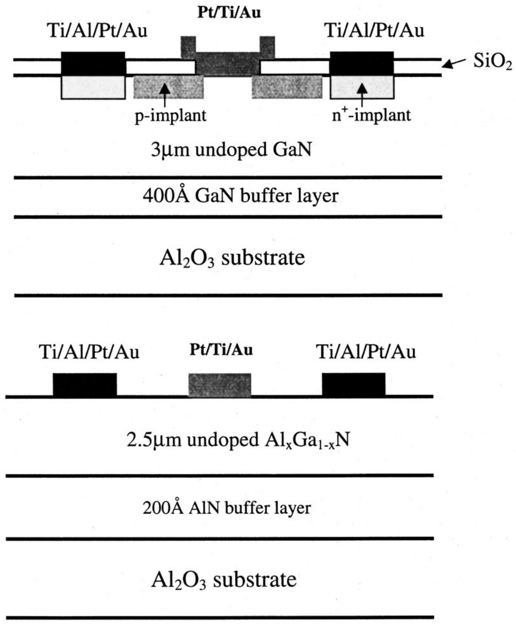

FIG. 1. Schematic of GaN (top) and AlGaN (bottom) rectifiers. The GaN devices employ several edge termination techniques.

The data can be represented by a relation of the form

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

where $\beta = -6.0 \pm 0.4\,\mathrm{V\,K^{-1}}$ for both types of rectifiers. However, in Schottky and *p-i-n* rectifiers we have fabricated on more conducting GaN, with V_{RB} values in the 400–500 V range, the β values were consistently around $-0.34\,\mathrm{V\,K^{-1}}$. Therefore, in present state-of-the-art GaN rectifiers, the temperature coefficient of V_{RB} appears to be a function of the magnitude of V_{RB}. Regardless of the origin of this effect, it is clearly a disadvantage for GaN. While SiC is reported to have a positive temperature coefficient for V_{RB} there are reports of rectifiers that display negative β values.[14] One may speculate that particular defects present may dominate the sign and magnitude of β,[15] and it will be interesting to fabricate GaN rectifiers on bulk or quasibulk substrates with defect densities far lower than in heteroepitaxial material.

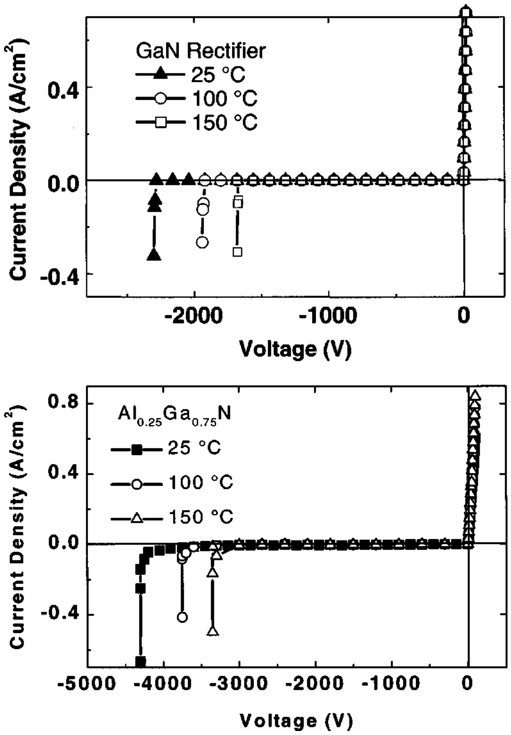

FIG. 2. $I-V$ characteristics as a function of temperature for GaN (top) and AlGaN (bottom) rectifiers.

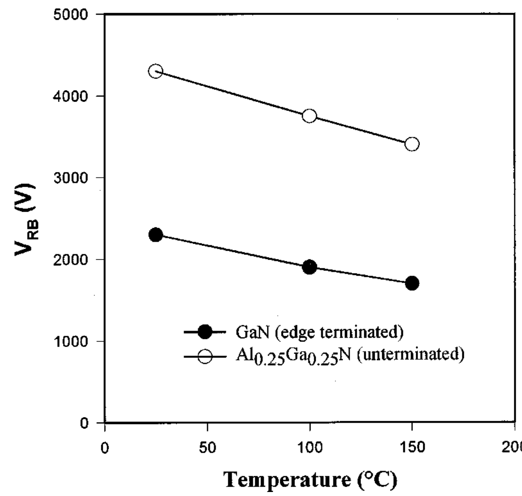

FIG. 3. Temperature dependence of V_{RB} for GaN and AlGaN rectifiers.

The forward turn-on voltage V_F of a Schottky rectifier can be written as[16]

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

where n is the ideality factor, k is Boltzmann's constant, T is the absolute sample temperature, e the electronic charge, J_F the forward current density (usually taken to be $100\,\mathrm{A\,cm^{-2}}$) at V_F, A^{**} the Richardson constant, ϕ_B the barrier height ($\sim$1.1 eV in this case), and R_{ON} the on-state resistance. The typical best V_F values were $\sim$5 V for GaN and $\sim$7.5 V for $Al_{0.25}Ga_{0.75}N$, with best R_{ON} values of 50 and 75 $\mathrm{m\Omega\,cm^2}$, respectively. The ideality factors derived from the forward $I-V$ characteristic were typically $\sim$2 for both GaN and $Al_{0.25}Ga_{0.75}N$ for biases up to $\sim$2/3 of V_F.[17] This is consistent with recombination being the dominant current transport in this bias range. At high voltages, n was typically $\sim$1.5 for both types of rectifiers, indicating that diffusion currents were dominant. Beyond $\sim 2 \times V_F$, series resistance effects controlled the current. This behavior is often reported for SiC junction rectifiers, while Schottky rectifiers in that materials system show ideality factors of 1.1–1.4. In our GaN devices, the higher ideality factors may reflect the high compensation levels in the material.

Figure 4 shows the reverse current (I_R) at -100 V reverse bias for AlGaN rectifiers of different contact diameter, for three different measurement temperatures. Since $I_R \propto$ contact diameter, this indicates that under these conditions the reverse current originates from surface periphery leakage. Similar results were obtained for the GaN rectifiers. The activation energy for this periphery leakage was $\sim$0.13 eV, which may represent the most prominent surface state giving rise to the current. At voltages approximately 90% of the breakdown values, the reverse current was proportional to contact area, indicating that bulk leakage is dominant under these conditions.

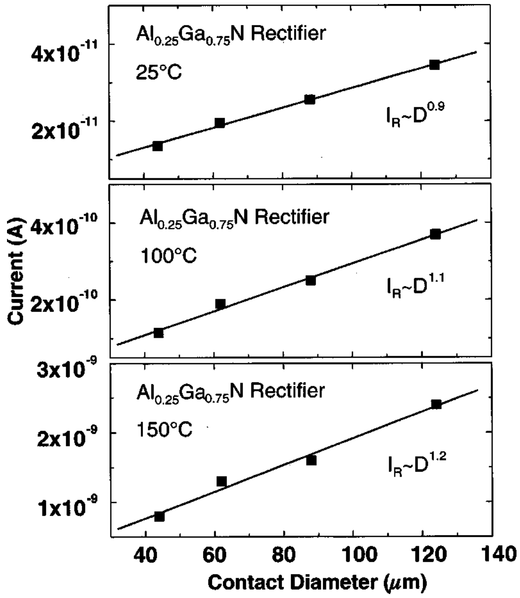

FIG. 4. Reverse current at −100 V bias for AlGaN rectifiers measured at three different temperatures.

In conclusion, the temperature dependence of V_{RB} has been measured in high breakdown GaN and AlGaN Schottky rectifiers. The temperature coefficient is negative, which is a significant disadvantage for devices intended for high temperature operation, and there are indications that it is a function of V_{RB}. The forward current conduction makes a transition from recombination to diffusion currents. The reverse leakage current originates from surface components around the rectifying contact at modest voltages. This current is thermally activated with an energy of 0.13 eV. The yield of acceptable devices (i.e., with V_{RB} at least 90% of the maximum found on a wafer and R_{ON} within 50% of the best values obtained) was rather small (∼15%), so there is still much development needed on both materials and processing.

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[1] J. C. Zolper, Solid-State Electron. **42**, 2153 (1998).
[2] M. S. Shur and M. A. Khan, in *High Temperature Electronics*, edited by M. Willander and H. L. Hartnagel (Chapman and Hall, London, 1999).
[3] V. A. Dmitriev, K. G. Irvine, C. H. Carter, Jr., N. E. Kuznetsov, and E. V. Kalinina, Appl. Phys. Lett. **68**, 229 (1996).
[4] J. Kolnick, I. H. Ogusman, K. F. Brennan, R. Wang, and P. P. Ruden, J. Appl. Phys. **82**, 726 (1997).
[5] N. Dyakonova, A. Dickens, M. S. Shur, R. Gaska, and J. W. Yang, Appl. Phys. Lett. **72**, 2562 (1998).
[6] S. J. Pearton, J. C. Zolper, R. J. Shul, and F. Ren, J. Appl. Phys. **86**, 1 (1999).
[7] M. Trivedi and K. Shenai, J. Appl. Phys. **85**, 6889 (1999).
[8] E. R. Brown, Solid-State Electron. **42**, 2117 (1998).
[9] Z. Z. Bandic, P. M. Bridger, E. C. Piquette, T. C. McGill, R. P. Vaudo, V. M. Phanse, and J. M. Redwing, Appl. Phys. Lett. **74**, 1266 (1999).
[10] F. Ren, A. P. Zhang, G. Dang, X. A. Cao, H. Cho, S. J. Pearton, J.-I. Chyi, C.-M. Lee, and C.-C. Chuo, Solid-State Electron. **44**, 619 (2000).
[11] C. E. Weitzel, J. W. Palmour, C. H. Carter, Jr., K. Moore, K. J. Nordquist, S. Allen, C. Thero, and M. Bhahnagar, IEEE Trans. Electron Devices **43**, 1732 (1996).
[12] C. I. Harris and A. O. Konstantinov, Phys. Scr., T **79**, 27 (1999).
[13] A. P. Zhang, G. Dang, F. Ren, J. Han, A. Y. Polyakov, N. B. Smirnov, A. V. Govorkov, J. M. Redwing, X. A. Cao, and S. J. Pearton, Appl. Phys. Lett. **76**, 1767 (2000).
[14] V. Khemkar, R. Patel, T. P. Chow, and R. J. Gutman, Solid-State Electron. **43**, 1945 (1999) and references therein.
[15] R. Singh (private communication).
[16] B. J. Baliga, *Modern Power Devices* (Wiley, New York, 1994).
[17] G. Dang, Z. P. Zhang, F. Ren, X. A. Cao, S. J. Pearton, H. Cho, J.-I. Chyi, C.-M. Lee, C.-C. Chuo, S. N. G. Chu, and R. G. Wilson, IEEE Trans. Electron Devices **47**, 692 (2000).