2300V Reverse Breakdown Voltage Ga2O3 Schottky Rectifiers
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We report field-plated Schottky rectifiers of various dimensions (circular geometry with diameter 50–200 μm and square diodes with areas $4 \times 10^{-3} - 10^{-2} \text{cm}^2$) fabricated on thick (20μm), lightly doped ($n = 2.10 \times 10^{15} \text{cm}^{-3}$) β-Ga2O3 epitaxial layers grown by Hydride Vapor Phase Epitaxy on conducting (n-Ga2O3) substrates grown by Edge-Defined, Film-Feed growth. The maximum reverse breakdown voltage ($V_{BD}$) was 2300 V for a 150 μm diameter device (area $= 1.77 \times 10^{-1} \text{cm}^2$), corresponding to a breakdown field of 1.15 MV cm$^{-1}$. The reverse current was only 15.6 μA at this voltage. This breakdown voltage is the highest reported for Ga2O3 rectifiers. The on-state resistance ($R_{on}$) for these devices was 0.25 Ω cm$^{-2}$, leading to a figure of merit ($V_{BD}/R_{on}$) of 21.2 MW cm$^{-2}$. The Schottky barrier height of the Ni was 1.03 eV, with an ideality factor of 1.1 and a Richardson’s constant of 43.35 $\text{A cm}^{-2} \text{K}^{-2}$. All of these characteristics are compared to the literature.

Results and Discussion

Currently, β-Ga2O3 is attracting interest for its potential use in high voltage power switching electronics for applications such as hybrid electric vehicles, defense electronics and power conditioning in large industrial motors. Schottky rectifiers are attractive because of their fast switching speed, which is important for improving the efficiency of inductive motor controllers and power supplies. For these rectifiers, the achievable operating voltage will be determined by the maximum field strength in the lightly-doped drift region. This is turn is inversely dependent on the doping level in this layer. While the exact relationship is not yet established for Ga2O3, for GaN, a low background doping in the drift region is needed. Currently, all Ga2O3 rectifiers show performance limited by the presence of defects and breakdown initiated in the depletion region near the electrode corners.

Field plate Schottky rectifiers were fabricated to show the effectiveness of edge termination. Current-voltage (I-V) characteristics were recorded in air at room temperature. The front side Schottky contacts were overlapped with 10 μm of SiNx contacts. The SiNx contact windows were patterned using lithography. The back side of the substrate also polished to remove sub-surface damage and enhance ohmic contact formation.

Rectifier fabrication began with a full area back ohmic contacts of Ti/Au (20 nm/80 nm) deposited by E-beam evaporation, followed by rapid thermal annealing at 550 °C for 30 seconds under a flowing N2 ambient. The contact resistance of 0.49 Ω-mm and specific contact resistance $3.4 \times 10^{-8} \text{Ω cm}^2$ was obtained from calibration pieces using the Transmission Line Method. The front side (epi) surface was treated with O3 in an ozone generator for 10 minutes to remove carbon contamination. A 100 nm thick SiNx layer was deposited by plasma enhanced chemical vapor deposition at 300 °C using silane and ammonia precursors. The SiNx contact windows were patterned using lithography, and opened with 1:10 buffered oxide etch (BOE) solution at room temperature. The front side Schottky contacts were over- lapped 10 μm on the SiNx window openings to form flat plate by lift-off of E-beam deposited Ni/Au (40 nm/160 nm). Figure 1(top) shows a schematic of the rectifier structure. We used a range of different device sizes and geometries, ranging from circular diodes with diameters 50–200 μm to square geometries (with rounded corners to avoid field crowding) with sizes $0.02 \times 0.02$–$0.1 \times 0.1 \text{ cm}^2$. An optical microscopy plan view of these rectifying contact geometries is shown in Figure 1(bottom). We also fabricated some test diodes without field plates as a comparison to show the effectiveness of edge termination. Current-voltage (I-V) and capacitance-voltage (C-V) characteristics were recorded in air at 25–125 °C on a temperature-controlled probe station with an Agilent 4145B parameter analyzer and 4284A Precision LCR Meter.

Results and Discussion

Since the doping in the drift region is such a critical factor in determining breakdown voltage, C-V measurements were performed. Figure 2 shows the C$^{-2}$ characteristics used to obtain n-type donor.
concentrations \(N_D\) from the slope \((6.61 \times 10^{19} \text{ cm}^{-3})\) of this data. The slope is equal to \(2/(e\varepsilon N_D)\), where \(e\) is the electronic charge and \(\varepsilon\) the permittivity of \(\text{Ga}_2\text{O}_3\). The value of \(2.01 \times 10^{15} \text{ cm}^{-3}\) is the one of the lowest reported in the literature for rectifier structures.\(^{12-17}\) Figure 3 shows the size dependence of both forward (top) and reverse (bottom) current density characteristics. The forward characteristics were taken under single sweep conditions, which mitigates self-heating effects. In real applications requiring significant time in forward current, active heat dissipation techniques would be needed because of the moderate thermal conductivity of \(\text{Ga}_2\text{O}_3\). These approaches developed for GaN transistors have included back-side heat sinks as well as deposition of high thermal conductivity nanocrystalline diamond around the gate.\(^{28}\) Note that the forward current density is \(>1 \text{ A cm}^{-2}\) at \(<1.5 \text{ V}\) for many of the rectifiers. Similarly, the reverse breakdown voltages were in the range 1400–2300V, with the latter number being the largest reported for \(\text{Ga}_2\text{O}_3\). The size dependence of breakdown voltage would normally be a fairly straight-

Figure 2. \(C^2-V\) characteristic from 200 \(\mu\text{m}\) diameter diode, revealing a drift layer carrier concentration of \(2.10 \times 10^{15} \text{ cm}^{-3}\).

forward, with larger diodes expected to have a higher probability of incorporating defects and thus have lower breakdown. However, at this still early stage of the technology, there can still be an issue of non-uniformity in the two growth steps needed to make these vertical structures. We observed a decrease in breakdown voltage with increasing device area up to \(\sim 2 \times 10^{-3} \text{ cm}^2\) and then a further decrease for areas above \(\sim 6 \times 10^{-3} \text{ cm}^2\), but in between these values the trend was not linear. This trend is typical of newer materials technologies still being optimized in terms of defect density.\(^{29-33}\) Kasu et al.\(^{30,33}\) found that dislocations are closely related to the reverse leakage current in the rectifier. Dislocation defects along the [010] direction acted as paths for leakage current. By contrast, in the [102] orientation, the defects present had little effect on breakdown.\(^{30,33}\) We also note that devices without field plates fabricated immediately next to the 2300V rectifiers showed breakdown voltage of 1950–1980V, demonstrating the effectiveness of edge termination in suppressing premature breakdown.

Figure 4 shows the expanded data for the rectifiers with the largest reverse breakdown. These had circular top contacts, with diameter 150 \(\mu\text{m}\) (area \(1.77 \times 10^{-4} \text{ cm}^2\)). The reverse current was 15.58 \(\mu\text{A}\) at a reverse bias of 2300V. The on-state resistance \((R_{\text{ON}})\) was 0.25 \(\Omega\text{cm}^2\), leading to a power figure of merit \((V_B^2/R_{\text{ON}})\) of 21.2 MW cm\(^{-2}\). This is well below the values of 102–154 MW cm\(^{-2}\) reported for rectifiers with much smaller contacts (\(\sim 100 \mu\text{m}\) diameter),\(^{14,15}\) but in those devices, the total forward current was more than 3 orders of magnitude lower than achieved here. For these lightly doped layers, the dominant current transport process in Schottky contacts will be thermionic emission.\(^{5,16,18}\) The ideality factor, \(n\), was 1.1 at 25°C with a barrier height of 1.04 eV for the Ni contact, consistent with literature values.\(^{34-40}\) Note that this breakdown voltage corresponds to a
breakdown field of 1.15 MV·cm⁻¹ if the drift layer is fully depleted. We are still limited by drift layer doping and thickness, and further advances in both will lead to higher breakdown. The theoretical breakdown field for Ga₂O₃ is reported to be between 5–9 MV/cm, with extracted peak experimental values reaching 5.3 MV·cm⁻¹ in the channel of lateral geometry, depletion mode Ga₂O₃ metal-oxide semiconductor field effect transistors and simulated values of similar magnitude in the vicinity of the anode and field plate electrode of 1 kV breakdown voltage vertical rectifiers at the verge of catastrophic breakdown. This indicates that further optimization of both material quality (doping and defect density) and field-plate design might lead to even higher reverse breakdown voltages. In addition, the reverse breakdown showed a negative temperature coefficient of −0.45 V·K⁻¹, which is less than reported previously.

The origin of the leakage current can be determined from the size dependence of current density versus voltage characteristics. In materials with relatively high surface recombination velocities, surface processes may dominate over bulk carrier transport. Figure 5 shows that the reverse leakage at a fixed bias of 50V scales more with area than perimeter, indicating that bulk processes still dominate in our rectifiers.

Figure 6 (top) shows the temperature dependence of forward J-V characteristics from 25–125°C for the 150 µm rectifiers. The ideality factor (n) at each temperature was estimated by fitting the linear region of the J-V curve to the thermionic emission (TE) model. The effective barrier height at zero bias was found to be 1.05 eV from this J-V-T data by linear fitting to the Richardson’s plot shown at the bottom of Figure 6. This also produced a Richardson’s constant of 43.35 A·cm⁻²·K⁻², which is generally in line with previous reports.

Figure 7 shows the variation of barrier height and ideality factor on temperature for the range 25–125°C for the 150µm rectifiers. The barrier height decreases with temperature, as reported by a number of groups and is an indication that there may be several transport mechanisms present at elevated temperature. The temperature dependence of I-V provides information regarding both transport mechanism and barrier height, but both are dependent on the particular transport model. To obtain a more direct determination of barrier height, internal photoemission is attractive. Previous reports have shown good correlation between both methods for Ga₂O₃ of the same basic type as used here.

Figure 8 shows the reverse recovery characteristics when switching from +2 V to −2 V, with a recovery time of order 22 ns. In this measurement a 50Ω resistor was used in series with the rectifier. The recovery time is comparable to previous reports with much smaller rectifier dimensions.

Conclusions
In summary, β-Ga₂O₃ Schottky rectifiers with record reverse breakdown voltages were fabricated on 20 µm thick, very lightly doped (∼2 × 10¹⁵ cm⁻³) drift regions. The breakdown voltage generally decreased with rectifier area and the reverse current was dominated by bulk transport. Future efforts should focus on minimizing Ron while continuing to increase breakdown voltage and finding the appropriate niche for high-speed switches made from this material. The results show that β-Ga₂O₃ Schottky rectifiers are promising candidates for high power switching devices at voltages above those accessible to GaN and SiC.
Figure 6. Forward current density as a function of temperature (top) and the Arrhenius plot of $J_0/T^2$ to obtain the Richardson’s constant bottom.

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