Abstract—β-Ga2O3 Schottky barrier diodes were fabricated in a vertical geometry structure consisting of Ni/Au rectifying contacts without edge termination on Si-doped epitaxial layers (10 μm, n−×4×10^{15}cm^{−3}) on Sn-doped bulk Ga2O3 substrates with full-area Ti/Au back Ohmic contacts. The reverse breakdown voltage, \(V_{BR}\), was a function of rectifying contact area, ranging from 1660 V at 3.1 \times 10^{-5}cm^{2} (20-μm diameter) to 250 V at 2.2 \times 10^{-3}cm^{−2} (0.53-mm diameter). The current density near breakdown was not strongly dependent on contact circumference but did scale with contact area, indicating that the bulk current contribution was dominant. The lowest on-state resistance, \(R_{ON}\), was 1.6 mΩ·cm² for the largest diode and 25 mΩ·cm² for the 1600-V rectifier, leading to a Baliga figure-of-merit (\(V_{BR}/R_{ON}\)) of the latter of approximately 102.4 MW·cm^{−2}. The on/off ratio was measured at a forward voltage of 1.3 V and ranged from 3 \times 10^{7} to 2.5 \times 10^{10} for reverse biases from −5 to −40 V and showed only a small dependence on temperature in the range from 25 °C to 100 °C.

Index Terms—Gallium Oxide, Schottky diode, rectifiers, reverse breakdown voltage.

I. INTRODUCTION

Ga2O3 has a theoretical Baliga figure of merit (defined as \(V_{BR}/R_{ON}\), where \(V_{BR}\) is the reverse breakdown voltage and \(R_{ON}\) is the on-state resistance) significantly higher than more familiar wide bandgap semiconductors, due mainly to its larger bandgap (−4.5−4.8 eV) compared to that of 4H or 6H-SiC and GaN (−3.0−3.4 eV) [1]−[4]. It is worth noting that Omura et al. [5] recently measured a direct gap of −4.5 eV, smaller than the often-quoted 4.8 eV common in the literature. The theoretical breakdown electric field is ~8 MV/cm [6]−[17], with experimental demonstrations as high as 3.8 MV/cm [8] and this is already higher than the bulk critical field strengths of both GaN and SiC [18]−[20]. There are five different phases of Ga2O3, the most prominent being the α- and β-phases [3], [4]. The former has the same corundum crystal structure as Al2O3 or sapphire, leading to the possibility of high quality epitaxial layers of Ga2O3 on sapphire substrates [4]. Subsequent lift-off of these Ga2O3 layers and transfer to more thermally conducting substrates is a possible approach to developing cost-effective wide bandgap semiconductor power electronics. Large diameter, twin-free, β-phase bulk, insulating or conducting β-Ga2O3 crystals have been grown by edge-defined film-fed (EFG) and by Czochralski and float zone methods and are commercially available [3]. Ga2O3 is well-placed as a potential option for high power electronics for use in hybrid electric vehicles, power conditioning in large industrial motors and power distribution and switching applications operating at high temperatures or voltages and currents beyond the capabilities of Si [7], [9]. There have been a number of impressive demonstrations to date of the capability of power Ga2O3 Schottky diode rectifiers, metal-semiconductor field-effect transistors (MESFETs) and 750V field-plate terminated metal-oxide-semiconductor field-effect transistors (MOSFETs) [8]−[17].

Schottky rectifiers are attractive because of their fast switching speed, which is important for improving the efficiency of inductive motor controllers and power supplies, as well as their low on-state losses. Their switching speed not suffer from minority-carrier storage effects present in bipolar devices [18]−[20]. Compared with lateral diodes grown on insulating substrates, vertical geometry Schottky diodes on conducting substrates can deliver higher power with full back side Ohmic electrodes and have higher current capability since they take advantage of the entire conducting area. Edge termination can also enhance the performance by preventing premature breakdown due to field crowding around the contact periphery. Initial reports by Sasaki et al. [16] have shown vertical rectifiers with \(V_{BR}\) of ~150 V on n-type homoepitaxial β-Ga2O3 as well as on single-crystal substrates. Oh et al.
showed excellent performance of 210V Ni/β-Ga2O3 vertical Schottky diodes up to 225 °C [20]. Konishi et al. [17] fabricated field-plated Ga2O3 Schottky barrier diodes on a Si-doped n−-Ga2O3 drift layer grown by halide vapor phase epitaxy on a Sn-doped n+Ga2O3 (001) substrate and achieved specific on-resistance of 5.1 mΩ·cm² and a breakdown voltage of 1076V [17]. The diode diameter was 200–400 μm.

In this letter we show that Schottky rectifiers without edge termination on epitaxial layers of β-Ga2O3 on bulk conducting substrates can achieve VBR values up to 1600V and that the reverse currents are dominated by bulk current conduction. The diode on-off ratios are in the range 2.5 × 10⁶–3 × 10⁷ for reverse biases from −5 to −40 V and showed only a small dependence on temperature in the range 25-100 °C.

II. Experimental

The diodes were fabricated on vertical structures consisting of epitaxial layers (10 μm thick) of lightly Si-doped n-type Ga2O3 grown by Metal Organic Chemical Vapor Deposition on n+ bulk, β-phase Sn-doped Ga2O3 single crystal wafers (∼650 μm thick) with (−201) surface orientation grown by the edge-defined film-fed method. These substrates had carrier concentration of 3.6 × 10¹⁸ cm⁻³ from Hall measurements. The dislocation density from etch pit observation was ∼10³ cm⁻².

Diodes were fabricated by depositing full area back Ohmic contacts of Ti/Au (20 nm/80 nm) by E-beam evaporation. We obtained Ohmic behavior without the need for rapid thermal annealing or implantation steps. The front sides were patterned by lift-off of E-beam deposited Schottky contacts Ni/Au (20 nm/80 nm) on the epitaxial layers. The diameter of these contacts ranged from 20 μm to 0.53 mm. Fig. 1 shows a schematic of the rectifier structure (top) and optical images of some of the completed diodes with different diameters (bottom). Current-voltage (I-V) and capacitance-voltage (C-V) characteristics were recorded from 25–100 °C on an Agilent 4145B parameter analyzer using a heated probe station. Fig. 2 shows the C⁻²-V plot to determine the carrier density in the epitaxial layer. The slope corresponds to a donor density of 4.02 × 10¹⁵ cm⁻³. We also measured the Schottky barrier height and ideality factor from the linear portion of the forward J–V characteristics. At 25 °C, the barrier height was 1.22 eV with an ideality factor of 1.07, consistent with previous reports for Ni on Ga2O3. The data was consistent with thermionic emission being the dominant current transport mechanism [20]–[22]. The barrier height decreased with temperature, reaching a value of 1.00 eV at 100 °C with an ideality factor of 1.33.

III. Results and Discussion

Fig. 3 shows the forward and reverse current density-voltage (J-V) characteristic from a 20 μm diameter diode. The VBR at room temperature was ∼1600 V for this diameter smaller diode and 250V for the largest diameter. This trend is typical of newer materials technologies still being optimized in terms of defect density [23]. The on-resistance (Ron) values was approximately 25 mΩ·cm² for the smallest diodes and 1.6 mΩ·cm² for the largest diameter devices. The Baliga figure-of-merit [23] (V²BR/Ron) for the former was approximately 102.4 MW·cm⁻², more than an order of magnitude larger than previous reports [20]. The breakdown field was 1.6 MV·cm⁻¹, which is still well below the theoretical value discussed earlier [8]. We did not use any edge termination methods to reduce electrical field crowding at the contact edges, which is where breakdown is likely occurring. Our results therefore represent a minimum breakdown field
strength of currently available state-of-the-art material and use of field-plate or guard-ring structures as edge termination would enhance this further [17], [20], [23].

Fig. 4 shows the reverse breakdown voltage and current density near breakdown as a function of diode contact area. The current density near breakdown was not strongly dependent on contact circumference but scaled with contact area, indicating that the Ga₂O₃ surface is stable enough during device process- ing that the Ga₂O₃ surface is stable enough during device process- ing steps that it does not dominate the device performance. The $V_{BR}$ values were a function of rectifying contact area, ranging from 1600V at $3 \times 10^{-6}$ cm² (20μm diameter) to ~250V at $2 \times 10^{-3}$ cm² (0.53 mm diameter). The decrease with increasing diode area is expected since the larger diodes have a higher probability of including a defect with potential for initiating breakdown [23].

Fig. 5 shows the on-off current ratio measured at a fixed forward voltage of 1.3V and reverse biases from −5 to −40 V. The on-off ratios ranged from $3 \times 10^7$ to $2.5 \times 10^6$ for this range of biases and showed only a small dependence on temperature in the range 25-100 °C. This is promising for device operating temperatures in this range, since there would be little change in performance characteristics.

**IV. SUMMARY AND CONCLUSIONS**

Vertical geometry β-Ga₂O₃ Schottky rectifiers were fabricated on epilayers on bulk substrates showed $V_{BR}$ values up to 1600 V for 20μm diameter contacts and ~250V for rectifiers with 0.53 mm diameter. The figure-of-merit was 102.4 MWcm⁻² for the smaller sizes. These results show the rapid progress in developing high quality β-Ga₂O₃ epi and bulk growth and that Schottky rectifiers in this materials system exhibit impressive power switching applications.

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**REFERENCES**


