# High Breakdown Voltage (−201) $\beta$-$Ga_2O_3$ Schottky Rectifiers

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***Abstract*—$\beta$-$Ga_2O_3$ 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 $\mu$m, n$\sim 4\times10^{15}$ cm$^{-3}$) on Sn-doped bulk $Ga_2O_3$ substrates with full-area Ti/Au back Ohmic contacts. The reverse breakdown voltage, $V_{BR}$, was a function of rectifying contact area, ranging from 1600 V at $3.1\times10^{-6}$ cm$^2$ (20-$\mu$m diameter) to ∼250 V at $2.2\times10^{-3}$ 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 m$\Omega\cdot$ cm$^2$ for the largest diode and 25 m$\Omega\cdot$cm$^2$ for the 1600-V rectifier, leading to a Baliga figure-of-merit ($V^2_{BR}/R_{on}$) for 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 $3\times10^7$ to $2.5\times10^6$ 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

$Ga_2O_3$ has a theoretical Baliga figure of merit (defined as $V^2_{BR}/R_{ON}$, 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 $Ga_2O_3$, the most prominent being the $\alpha$- and $\beta$-phases [3], [4]. The former has the same corundum crystal structure as $Al_2O_3$ or sapphire, leading to the possibility of high quality epitaxial layers of $Ga_2O_3$ on sapphire substrates [4]. Subsequent lift-off of these $Ga_2O_3$ 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, $\beta$-phase bulk, insulating or conducting $\beta$-$Ga_2O_3$ crystals have been grown by edge-defined film-fed (EFG) and by Czochralski and float zone methods and are commercially available [3]. $Ga_2O_3$ 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 $Ga_2O_3$ 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 $\beta$-$Ga_2O_3$ as well as on single-crystal substrates. Oh et al.

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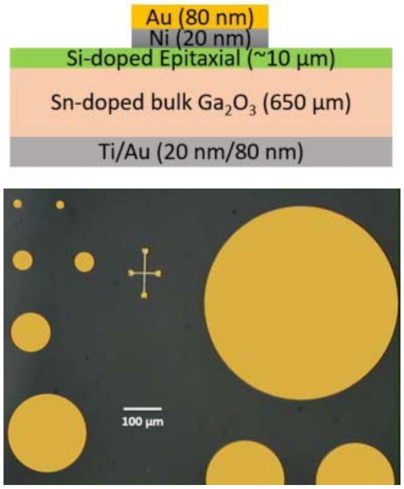

Fig. 1. Schematic of vertical Ni/Au Schottky diode on $Ga_2O_3$ epi layer on a conducting $\beta$-$Ga_2O_3$ substrate (top) and top-view microscope image of the fabricated $\beta$-$Ga_2O_3$ diodes of different diameter (bottom).

showed excellent performance of 210V Ni/$\beta$-$Ga_2O_3$ vertical Schottky diodes up to 225 °C [20]. Konishi *et al.* [17] fabricated field-plated $Ga_2O_3$ Schottky barrier diodes on a Si-doped $n^-$-$Ga_2O_3$ drift layer grown by halide vapor phase epitaxy on a Sn-doped $n^+$-$Ga_2O_3$ (001) substrate and achieved specific on-resistance of 5.1 m$\Omega$·cm$^2$ and a breakdown voltage of 1076V [17]. The diode diameter was 200-400 $\mu$m.

In this letter we show that Schottky rectifiers without edge termination on epitaxial layers of $\beta$-$Ga_2O_3$ on bulk conducting substrates can achieve $V_{BR}$ values up to 1600V and that the reverse currents are dominated by bulk current conduction. The diode on-off ratios are in the range $2.5 \times 10^6 - 3 \times 10^7$ 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 $\mu$m thick) of lightly Si-doped n-type $Ga_2O_3$ grown by Metal Organic Chemical Vapor Deposition on n$^+$ bulk, $\beta$-phase Sn-doped $Ga_2O_3$ single crystal wafers (~650 $\mu$m thick) with (−201) surface orientation grown by the edge-defined film-fed method. These substrates had carrier concentration of 3.6 $\times 10^{18}$ cm$^{-3}$ from Hall measurements. The dislocation density from etch pit observation was ~$10^3$ 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 $\mu$m 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 × $10^{15}$ cm$^{-3}$. We also measured the Schottky barrier height and ideality factor from the linear portion of the forward *I*–*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 $Ga_2O_3$. 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.

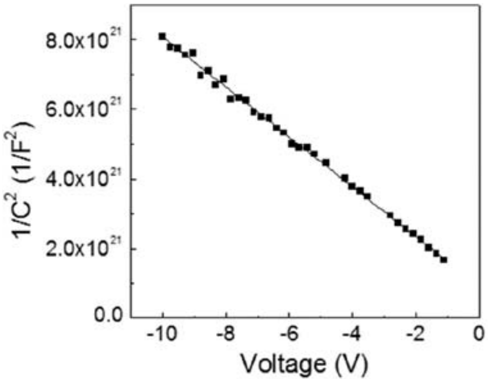

Fig. 2. Inverse depletion layer capacitance squared ($C^{-2}$) measured at 10 MHz versus reverse voltage (V) plot to determine the doping level in the epitaxial $Ga_2O_3$ layer. The extracted value was 4.02 $\times 10^{15}$ cm$^{-3}$.

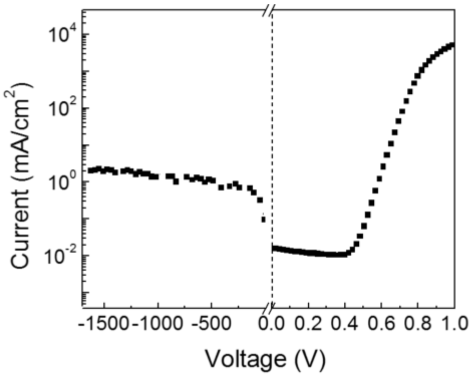

Fig. 3. Forward and reverse current density-voltage characteristics from a 20 $\mu$m diameter diode.

## III. RESULTS AND DISCUSSION

Fig. 3 shows the forward and reverse current density-voltage (J-V) characteristic from a 20 $\mu$m diameter diode. The $V_{BR}$ 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 ($R_{on}$) values was approximately 25 m$\Omega$·cm$^2$ for the smallest diodes and 1.6 m$\Omega$·cm$^2$ for the largest diameter devices. The Baliga figure-of-merit [23] ($V_{BR}^2/R_{on}$) 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

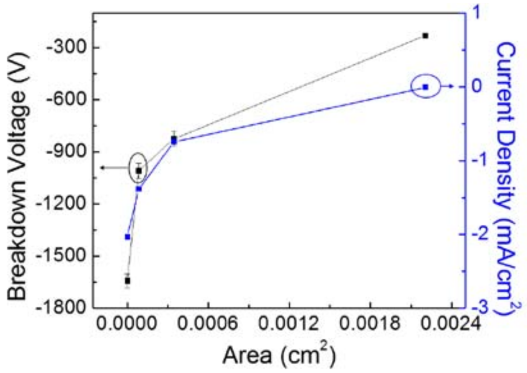

Fig. 4. Breakdown voltage and current density as a function of Schottky contact area.

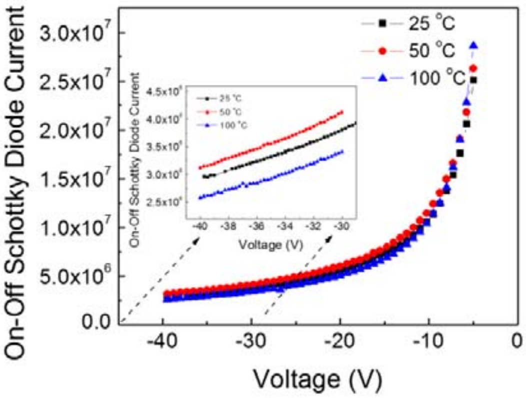

Fig. 5. Diode on/off ratios for temperatures in the range 25-100 °C as a function of reverse bias. The forward bias was held constant at 1.3V.

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 the bulk current contribution was dominant [23]. This indicates that the $Ga_2O_3$ surface is stable enough during device processing steps that it does not dominate the device performance. The $V_{BR}$ values were a function of rectifying contact area, ranging from 1600V at $3.1 \times 10^{-6}$ cm$^2$ (20$\mu$m diameter) to ∼250V at $2 \times 10^{-3}$ cm$^{-2}$ (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-of 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 $\beta$-$Ga_2O_3$ Schottky rectifiers were fabricated on epilayers on bulk substrates showed $V_{BR}$ values up to 1600 V for 20$\mu$m 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 $\beta$-$Ga_2O_3$ epi and bulk growth and that Schottky rectifiers in this materials system exhibit impressive power switching applications.

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