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Vertical geometry Ni/Au-β-Ga_2O_3 Schottky rectifiers were fabricated on Hydride Vapor Phase Epitaxy layers on conducting bulk substrates, and the rectifying forward and reverse current-voltage characteristics were measured at temperatures in the range of 25–100 °C. The reverse breakdown voltage (V_{BR}) of these β-Ga_2O_3 rectifiers without edge termination was a function of the diode diameter, being in the range of 920–1016 V (average value from 25 diodes was 975 ± 40 V, with 10 of the diodes over 1 kV) for diameters of 105 μm and consistently 810 V (810 ± 3 V for 22 diodes) for a diameter of 210 μm. The Schottky barrier height decreased from 1.1 at 25 °C to 0.94 at 100 °C, while the ideality factor increased from 1.08 to 1.28 over the same range. The figure-of-merit ($V_{BR}{}^2/R_{on}$), where R_{on} is the on-state resistance (~6.7 mΩ cm^2), was approximately 154.07 MW·cm^{-2} for the 105 μm diameter diodes. The reverse recovery time was 26 ns for switching from +5 V to −5 V. These results represent another impressive advance in the quality of bulk and epitaxial β-Ga_2O_3. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4983203]

There is strong interest in developing wide bandgap semiconductor rectifiers as an advance on Si rectifiers and switches in power electronic applications operating at high temperatures or voltages and currents beyond the capabilities of Si.[1–5] Alternatives to date have included GaN (3.4 eV), diamond (5.5 eV), and the different polytypes of SiC (4H-SiC 3.3 eV and 6H-SiC 3.0 eV), and impressive performance has been reported for power rectifiers and transistors with low on-resistance (R_{on}), high breakdown voltage (V_{BR}), and fast switching times.[1–5] These materials have high critical electrical fields than Si, as well as reasonable-to-excellent thermal conductivities and low on-state resistances. Advances in use of diamond as a heat sink on GaN and SiC have further pushed the performance limits.[6–9]

There is also interest in developing materials with wider bandgaps than GaN or SiC for extreme environment applications. While diamond has a high Baliga figure of merit (BFOM) for power electronics and excellent thermal conductivity,[2,7] n-type doping remains difficult. Monoclinic β-phase Ga_2O_3 has outstanding potential for power electronics, with a large direct bandgap of ~4.6 eV and the commercial availability of high quality, large diameter bulk crystals and epitaxial layers with a range of controllable n-type doping levels.[2,10–25] It has a high theoretical breakdown electric field (~8 MV/cm), leading to a Baliga figure-of-merit almost four times higher than that for GaN.[2,11,15] Experimentally obtained breakdown field values up to 3.8 MV/cm in Sn-doped Ga_2O_3 metal-oxide-semiconductor field-effect transistors (MOSFETs) grown by Metal Organic Chemical Vapor Deposition (MOCVD) on (100) semi-insulating substrates are already higher than the bulk critical field strengths of both GaN and SiC.[16] Power Ga_2O_3 Schottky diode rectifiers, metal-semiconductor field-effect transistors (MESFETs), and metal-oxide-semiconductor field-effect transistors (MOSFETs) fabricated on either bulk or thin film β-Ga_2O_3 have been reported.[11–28] The MOSFETs exhibited breakdown voltages >750 V with field-plate edge termination.[19]

Schottky rectifiers are ideal devices for establishing material quality and have fast switching speed and low on-state losses, and as unipolar devices, they are good candidates for high power and high frequency applications because they do not suffer from minority-carrier storage effects that limit the switching speed.[1,4,29,30] Compared with lateral diodes grown on insulating substrates, vertical Schottky diodes on conducting substrates can deliver higher power with full back side Ohmic electrodes. Sasaki *et al.*[24] reported rectifiers with a reverse breakdown voltage (V_{BR}) of ~150 V on n-type homoepitaxial β-Ga_2O_3 and on single-crystal substrates, while Oh *et al.* reported the temperature-dependent performance of 210 V Ni/β-Ga_2O_3 vertical Schottky diodes up to 225 °C.[25] Konishi *et al.*[31] reported 1 kV (actually 1076 V) vertical field-plated Schottky diodes with an excellent specific on-resistance of 5.1 mΩ cm^2 for anode diameters of 200- or 400 μm. The breakdown voltage (V_{BR}) is a crucial parameter for power electronic applications. The V_{BR} depends on the doping concentration, doping gradient, junction depth, device design, and the dielectric constant, bandgap, and impact ionization coefficients.[30] The V_{BR} is proportional to the (bandgap)$^{3/2}$ × (doping concentration)$^{-3/4}$.[30]

In this letter, we show that Schottky rectifiers without edge termination on epitaxial layers of β-Ga_2O_3 on bulk conducting substrates can achieve V_{BR} values in the range of

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920–1016 V for 105 μm diameter diodes and that the reverse currents are dependent on the diode diameter.

The starting samples were bulk β-phase Ga_2O_3 single crystal wafers (~650 μm thick) with the (001) surface orientation (Tamura Corporation, Japan) grown by the edge-defined film-fed growth method. Hall effect measurements showed that the Sn-doped samples had a carrier concentration of $3.6 \times 10^{18}\,cm^{-3}$.[32] Epitaxial layers (initially ~20 μm thick) of lightly Si-doped n-type Ga_2O_3 ($\sim 2 \times 10^{16}\,cm^{-3}$) were grown on these substrates by Hydride Vapor Phase Epitaxy (HVPE) at Novel Crystal Technology. After growth, the epi surface is subjected to Chemical Mechanical Polishing (CMP) to remove pits. The final epi layer thickness was ~10 μm. Figure 1 shows Nomarski images before and after the CMP process. The X-ray diffraction full width at half maximum of the (402) peak was ~10 arc sec, and the dislocation density from etch pit observation was of the order of $10^3\,cm^{-2}$. This is the same basic process as in the Konishi samples,[31] but the epi was carried out in different labs, an important distinction since it shows that the basic HVPE/CMP process is transferrable and robust.

Diodes were fabricated by depositing full area back Ohmic contacts of Ti/Au (20 nm/80 nm) by E-beam evaporation. Ohmic behavior was achieved without the need for dry etching. The front sides were patterned by lift-off of E-beam deposited Schottky contacts Ni/Au (20 nm/80 nm) on the epitaxial layers.[31] The diameter of these contacts was 105 or 210 μm. Figure 2 shows schematics (top) and optical images of the completed diodes (bottom). Current-voltage (I-V) characteristics were recorded in air from 25 to 100 °C on an

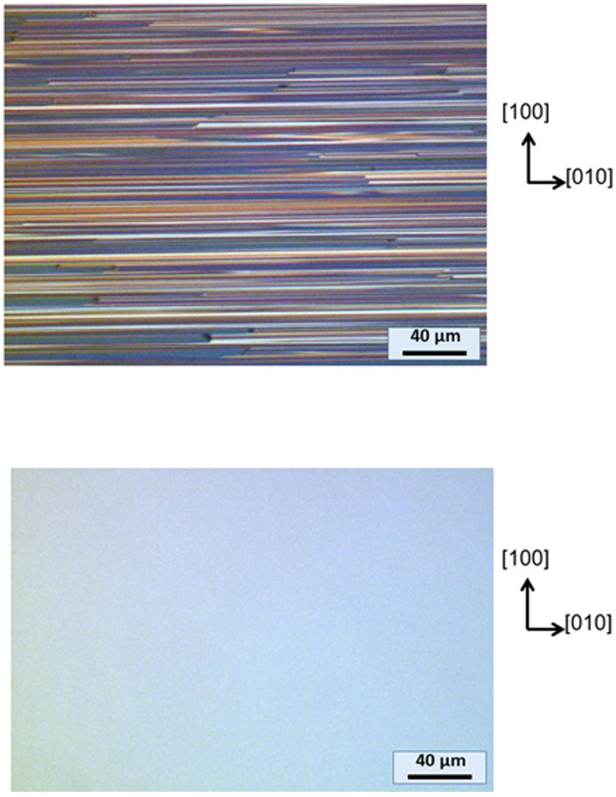

FIG. 1. Nomarski images of the epi surface after HVPE growth (top) and after subsequent CMP (bottom).

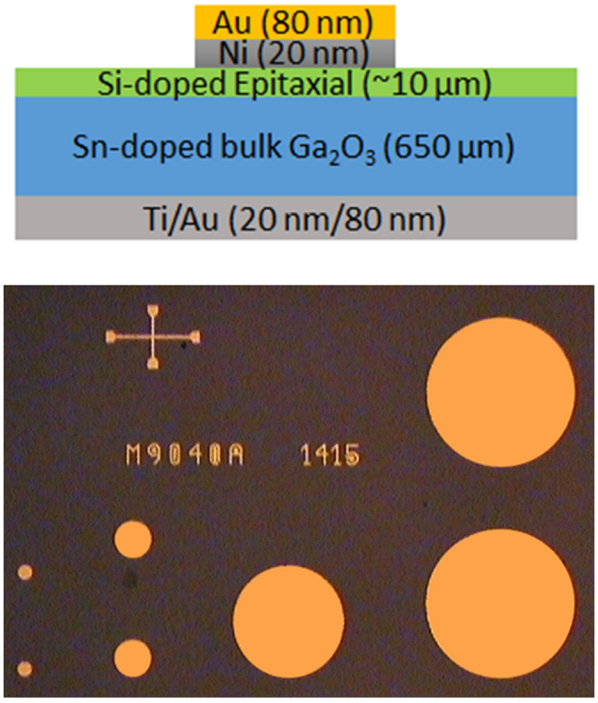

FIG. 2. Schematic of the vertical Ni/Au Schottky diode on the Ga_2O_3 epi layer on a conducting β-Ga_2O_3 substrate (top) and top-view microscopy image of the fabricated β-Ga_2O_3 diodes (bottom).

Agilent 4145B parameter analyzer or a Tektronix 370 A curve tracer using a heated probe station. For these moderately doped layers, the basic current transport processes in Schottky contacts will be thermionic emission that generally dominates for moderately doped semiconductors. The I-V is then given by[30]

$$I = I_S \exp\,(eV/nkT)[1 - \exp\,(-eV/nkT)],$$

where I_S is the saturation current given by

$$I_S = AA^* T^2 \exp\,(-\Phi_B/kT)$$

and A is the contact area, A* is the effective Richardson constant (33.7 A $cm^{-2}K^{-2}$),[30] Φ_B is the effective barrier height, n is the ideality factor, e is the electronic charge, k is Boltzmann's constant, and T is the absolute temperature. If the current flow is dominated by thermionic emission, then the ideality factor n should be close to unity, with a small increase from unity due to the image force effect.[28,30]

Figure 3 shows the forward current density (J-V) characteristics as a function of measurement temperature. We see higher turn-on current, which is explained by the lowering of the barrier height. For extraction of the barrier height from these characteristics, we fitted the linear portions that obeyed the ideal thermionic-emission behavior.[32,33] Figure 4 shows that the barrier height decreased from 1.1 at 25 °C to 0.94 at 100 °C, while the ideality factor increased from 1.08 to 1.28 over the same range. This is expected since pure thermionic emission would lead to a reduced barrier at elevated temperatures.[25,28,30] Higher barrier heights can be achieved with a Pt metal.[31,33] As the operating temperature increases, the turn-on voltage continually decreased, consistent with previous reports.[25,33]

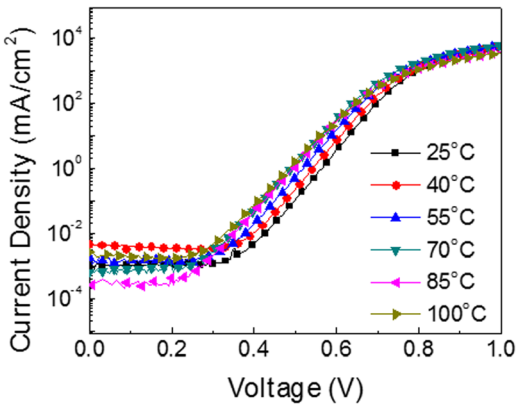

FIG. 3. Forward current density-voltage characteristics as a function of measurement temperature from 25 to 100 °C.

Figure 5 shows some reverse I-V characteristics for two different diameter diodes. The V_{BR} at room temperature was in the range of 920–1016 V for the smaller diode (we show the extreme values here for a total of 25 diodes measured over the wafer area, with the average value from 25 diodes being 975 ± 40 V, with 10 of the diodes over 1 kV) for diameters of 105 μm and consistently 810 V (810 ± 3 V for 22 diodes for a diameter of 210 μm.). This trend is typical of newer material technologies which are still being optimized in terms of defect density.[34] The on-resistance (R_{on}) values obtained from the I–V curves was approximately 6 mΩ·cm^2. The figure-of-merit (V_{BR}^2/R_{on}) was ~154.3 W·cm^{-2} at room temperature. Note that in this simple rectifier design, there will be electrical field crowding at the contact edges, which is where breakdown is likely occurring.[31] The use of field-plate or guard-ring structures as edge termination would increase the V_{BR} of the β-Ga_2O_3 rectifiers.[18,25,31] Konishi *et al.*[31] noted that their 1 kV field-plated diodes in a slightly thinner drift region (7 μm versus 10 μm used here, with similar doping) showed breakdown voltages a factor of 2 larger than non-field-plated devices. The fact that our diodes achieved high breakdown without field plating is indicative of good material quality.

Figure 6 (top) shows the reverse current density as a function of temperature for two different reverse biases. The magnitude of the reverse leakage current determines the

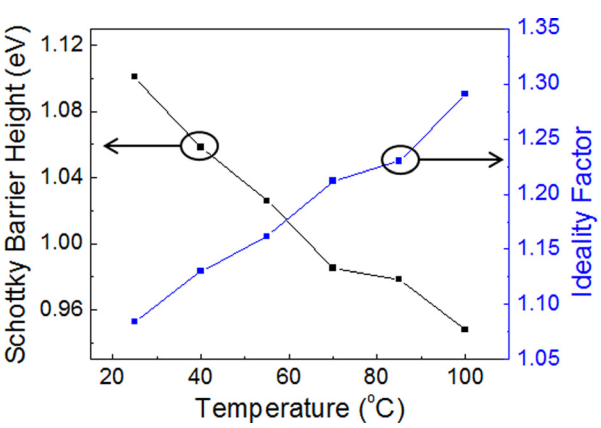

FIG. 4. Schottky barrier height and diode ideality factor as a function of measurement temperatures in the range of 25 to 100 °C.

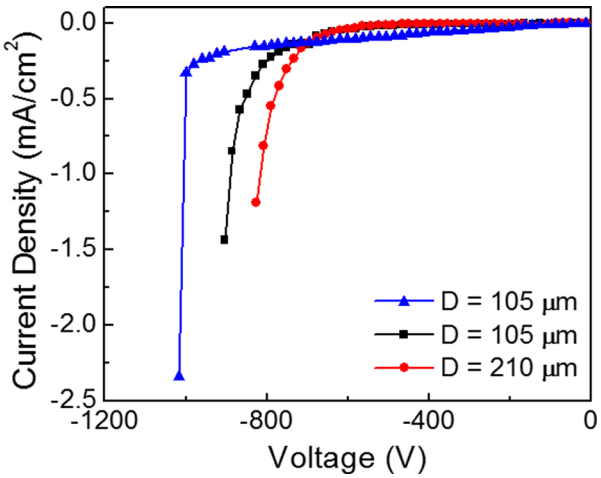

FIG. 5. Reverse current density-voltage characteristics of three diodes of either similar or different contact diameters at 25 °C.

reverse power dissipation. For thermionic emission dominated leakage current, there is an increase in reverse leakage current of around one order of magnitude for every 25 °C increase in the diode junction temperature. In our diodes, the reverse leakage current only increased around 2–4 times. Thus, the reverse leakage current was also affected by the tunneling mechanism, which might be due to ionization of

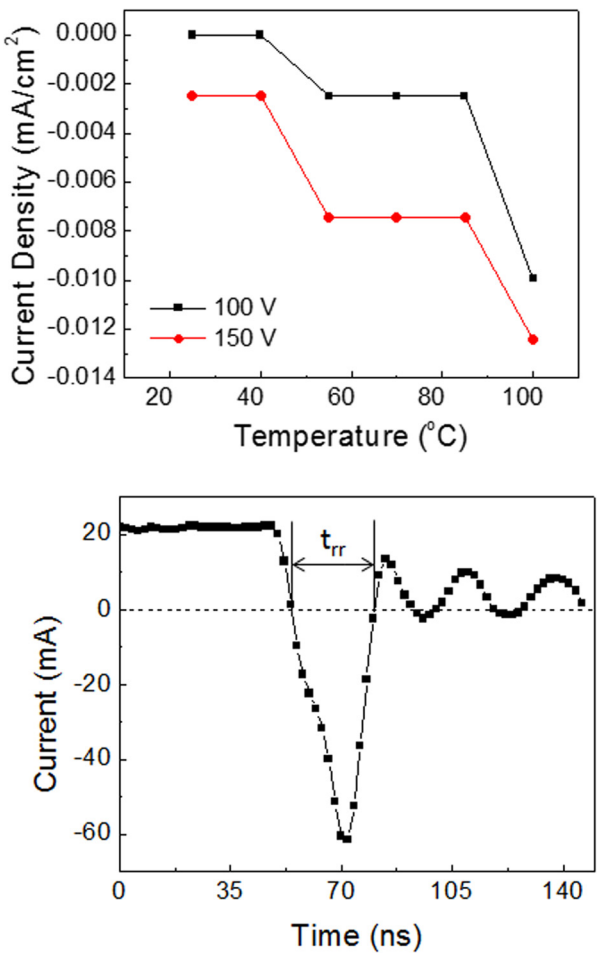

FIG. 6. (Top) Reverse current density at biases of either 100 or 150 V as a function of temperature. (Bottom) Reverse recovery measurement on the 105 μm diameter diode.

different trap states in the epilayer, as found in deep level transient spectroscopy measurements of bulk Ga_2O_3.[35] We also measured the reverse recovery characteristics when switching from +5 V to −5 V and found recovery times of order 26 ns (Fig. 6, bottom). These results show the potential of β-Ga_2O_3 as a promising material for high-performance power devices under elevated temperature conditions.

In summary, vertical β-Ga_2O_3 Schottky rectifiers without field plates fabricated on high quality epilayers on bulk substrates show V_{BR} values in the range of 920–1016 V at room temperature for 105 μm diameters and lower values (810 V) for larger diameter rectifiers. The Schottky barrier height decreased with temperature and was consistent with one dominant conduction mode. The present results show that β-Ga_2O_3 Schottky rectifiers are promising candidates for high power devices.

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