Vertical Ga$_2$O$_3$ Schottky Barrier Diodes on Single-Crystal β–Ga$_2$O$_3$ (-201) Substrates

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Owing to the large bandgap, breakdown electric field ($E_b$) and high carrier mobility, wide-bandgap semiconductor (e.g. SiC and GaN) based power devices have been extensively studied for next-generation power-switching applications [1-2]. Recently, a new wide-bandgap oxide semiconductor, gallium oxide ($\beta$-Ga$_2$O$_3$), has attracted attention for power-switching applications because it has an extremely large bandgap of 4.5–4.9 eV enabling a high breakdown voltage ($V_{br}$) and a high Baliga’s figure of merit [3]. Furthermore, large-area and high-quality bulk substrates of Ga$_2$O$_3$ can be grown by low-cost methods, which remains a significant challenge for both SiC and GaN. Schottky barrier diodes (SBDs), with a low turn-on voltage and a fast switching speed due to majority carrier conduction, are ideal candidates for high-power and high-speed rectifiers. Recently, Higashiwaki et al. have demonstrated excellent device results, which includes SBDs with $V_{br}$ ~115 V on (010) Ga$_3$O$_5$ substrates (with a net doping concentration $N_D$-$N_A$ ~ 5x10$^{16}$ cm$^{-3}$) [4] and SBDs with epitaxial Si-doped n-Ga$_2$O$_3$ drift layers ($N_D$-$N_A$ ~ 1.4x10$^{16}$ cm$^{-3}$) grown by HVPE on (001) Ga$_2$O$_3$ substrates with $V_{br}$ ~ 500 V [5]. Oishi et al reported Ni-based SBDs on (-201) Ga$_2$O$_3$ with a $N_D$-$N_A$ ~ 1x10$^{17}$ cm$^{-3}$ and $V_{br}$ ~ 40 V [6]. However, no high voltage ($V_{br}$ > 100 V) devices have been reported yet on (-201) Ga$_2$O$_3$, the crystal orientation readily available in up to 4 inch diameter wafer. In this work, we report Pt-based SBDs fabricated on unintentionally-doped (UID) (-201) n-type Ga$_2$O$_3$ substrates with $V_{br}$ > 100 V.

Figure 1 shows the schematic cross section and the I/C$^2$-V plot of the fabricated Ga$_2$O$_3$ SBDs. The net doping concentration ($N_D$-$N_A$) in the (-201) Ga$_2$O$_3$ substrates extracted by the $d(I/C^2)/dV$ method is ~1.1x10$^{17}$ cm$^{-3}$. The built-in potential extracted from the $I/C^2$-V plot is $V_{bi}$~1.22 V as shown in Fig.1 (b). The substrate thickness is ~680 μm and the resistivity ~6.3 Ω·sq. The top circular Schottky anode electrodes with diameters of 50 μm and 390 μm were fabricated on Ga$_2$O$_3$ substrates by photolithographic patterning, followed by evaporation of Pt (80 nm) as anode and, and liftoff. The back cathode is formed by evaporation of a Ti (50 nm)/Pt (100 nm) metal stack. A rapid thermal annealing (RTA) process at 470 °C in N$_2$ ambient for 60 s is applied to devices labeled as w/ RTA. No additional surface passivation or field plate is employed for the devices studied in this work. The 50 μm and 390 μm diameter diodes were used for current density-voltage (I-V) and capacitance-voltage (C-V) measurements, respectively. All measurements were performed at room temperature.

Figure 2 shows the $I$-V curves measured between two back-contacts separated by ~160 μm on a test sample using the same substrate and metal stack w/ and w/o RTA. The contacts fabricated with the RTA process showed a reasonable ohmic behavior with high current capability. On the other hand, the as-deposited metal stack contacts show a Schottky behavior thus allowing only very low currents. The detailed mechanism for this improvement is not yet clear and warrants further investigation.

Figures 3(a) and (b) show the forward $J$-$V$ characteristics of the SBDs in logarithmic and linear scales, respectively. The turn-on voltage is about 1 V for both cases. Near unity ideality factors of 1.02 are obtained for both SBDs with and without RTA. The extracted Pt/Ga$_2$O$_3$ barrier height $\phi_B$ is 1.53 eV and 1.35 eV for w/o and w/ RTA process, respectively. The Pt/(-201) Ga$_2$O$_3$ barrier height extracted here is close to the reported values in the range of 1.3-1.5 eV for Pt/(010) Ga$_2$O$_3$ [4]. In Fig.3 (b), the SBD w/ RTA process shows a dramatic improvement in the forward current-carrying capability: from 34 to 400 A/cm$^2$ @ 2V. This is most likely a result of the improved back-contact and a reduction of $\phi_B$. The differential on-resistance $R_{on}$ as determined from the slope of the linear regions in Fig. 3(b) for SBD w/o RTA and w/ RTA is about 29.4 and 2.5 mΩ·cm$^2$, respectively. Since the substrate specific resistivity along the current flowing direction is 26.5 mΩ·cm$^2$, a $R_{on}$ of 2.5 mΩ·cm$^2$ is attributed to current lateral spreading from the top anode to the bottom contact. The reverse $J$-$V$ characteristics are shown in Fig. 4 and $V_{br}$ for both SBDs is about 120 V. The hard breakdown observed in both devices at the edge of the anode electrodes is due to electric-field crowding. This observation indicates that using edge terminations such as a field plate and/or a guard ring will improve $V_{br}$. Nonetheless, the critical surface breakdown field pointing along the [-201] direction can be estimated to be > 2.1 MV/cm.

In summary, we fabricated Pt/Ga$_2$O$_3$ SBDs on single-crystal β–Ga$_2$O$_3$ (-201) substrates for the first time. Ohmic contacts were obtained on the backside with a RTA process. The Pt/Ga$_2$O$_3$ SBDs on (-201) substrates show similar behavior with the devices fabricated on (010) Ga$_2$O$_3$ substrates.
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![Anode (Pt)](image1)

Fig.1 (a) Schematic cross section of SBDs on (-201) Ga$_2$O$_3$ substrate and (b) $1/C^2$-V characteristics of Ga$_2$O$_3$ SBDs w/ RTA showing net doping concentration ~1.1x10$^{17}$ cm$^{-3}$ built-in voltage ~ 1.22 V.

![Cathode (Ti/Pt)](image2)

Fig.2 I–V curves measured between two contacts at the backside of on (-201) Ga$_2$O$_3$ substrate with Ti/Pt and the metal stacks at w/o and w/ RTA process conditions.

![Forward J-V characteristics](image3)

Fig.3 Forward J-V characteristics of Ga$_2$O$_3$ SBD w/o and w/ RTA process plotted in (a) logarithmic and (b) linear scales. With the RTA process, the back contact dramatically improves, which helps to improve the current density from ~34 to 400 A/cm$^2$. Near unit ideality factors of 1.02 were obtained for the both SBDs and extracted barrier for SBDs w/o and w/ RTA process is 1.53 and 1.35 eV, respectively.

![Reverse J-V characteristics](image4)

Fig.4 Reverse J-V characteristics of Ga$_2$O$_3$ SBDs w/o and w/ RTA