Vertical Ga_2O_3 Schottky Barrier Diodes on Single-Crystal β–Ga_2O_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 (β-Ga_2O_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_2O_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_2O_3 substrates (with a net doping concentration N_D-N_A ~ $5\text{x}10^{16}$ cm^{-3}) [4] and SBDs with epitaxial Si-doped n-Ga_2O_3 drift layers (N_D-N_A ~ $1.4\text{x}10^{16}$ cm^{-3}) grown by HVPE on (001) Ga_2O_3 substrates with V_{br} ~ 500 V [5]. Oishi et al reported Ni-based SBDs on (-201) Ga_2O_3 with a N_D-N_A ~ $1\text{x}10^{17}$ cm^{-3} and V_{br} ~ 40 V [6]. However, no high voltage (V_{br} > 100 V) devices have been reported yet on (-201) Ga_2O_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_2O_3 substrates with V_{br} > 100 V.

Figure 1 shows the schematic cross section and the $1/C^2$-V plot of the fabricated Ga_2O_3 SBDs. The net doping concentration (N_D-N_A) in the (-201) Ga_2O_3 substrates extracted by the $d(1/C^2)/dV$ method is ~1.1×10^{17} cm^{-3}. The built-in potential extracted from the $1/C^2$-vs-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_2O_3 substrates by photolithographic patterning, followed by evaporation of Pt (80 nm) as anode metal, 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_2O_3 barrier height $q\phi_B$ is 1.53 eV and 1.35 eV for w/o and w/ RTA process, respectively. The Pt/(-201) Ga_2O_3 barrier height extracted here is close to the reported values in the range of 1.3-1.5 eV for Pt/(010) Ga_2O_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 $q\phi_B$. 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_2O_3 SBDs on single-crystal β–Ga_2O_3 (-201) substrates for the first time. Ohmic contacts were obtained on the backside with a RTA process. The Pt/Ga_2O_3 SBDs on (-201) substrates show similar behavior with the devices fabricated on (010) Ga_2O_3 substrates.

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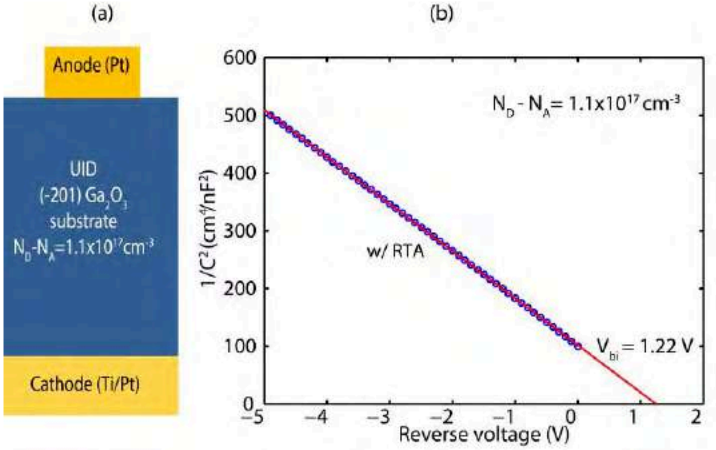

Fig.1 (a) Schematic cross section of SBDs on (-201) Ga_2O_3 substrate and (b) $1/C^2$-V characteristics of Ga_2O_3 SBDs w/ RTA showing net doping concentration ~$1.1x10^{17}$ cm^{-3} built-in voltage ~ 1.22 V.

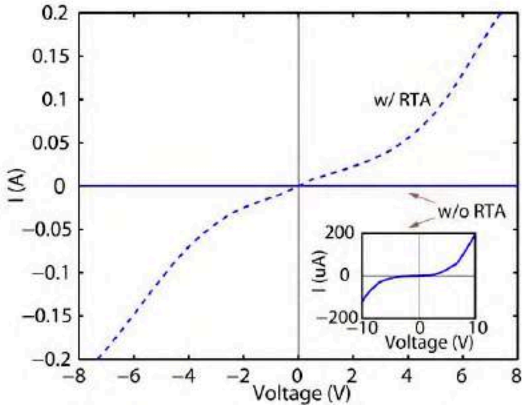

Fig.2 I–V curves measured between two contacts at the backside of on (-201) Ga_2O_3 substrate with Ti/Pt and the metal stacks at w/o and w/ RTA process conditions

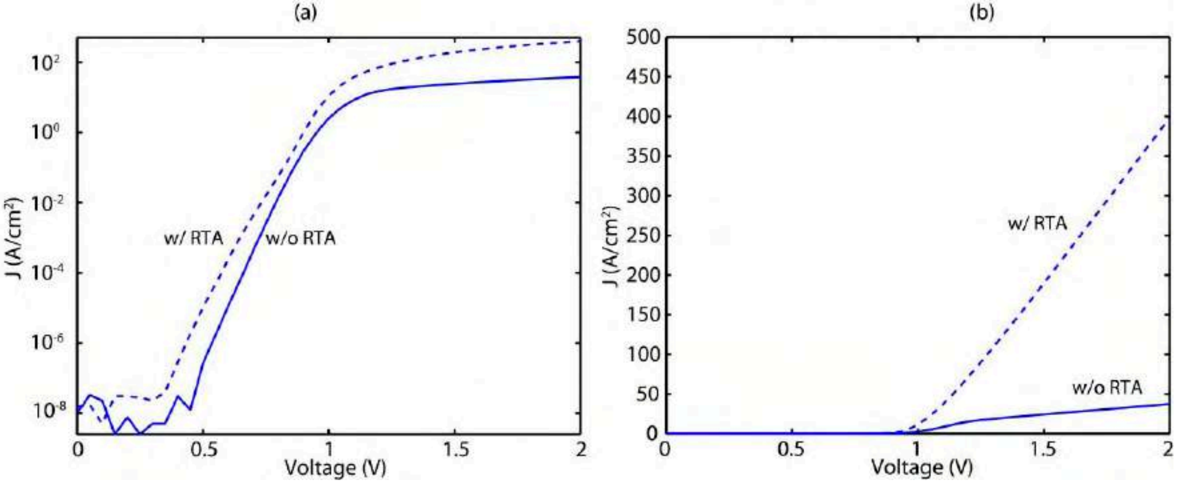

Fig.3 Forward J-V characteristics of Ga_2O_3 SBD w/o and w/ RTA process plotted in (a) logarithmic and (b) linear scales. With the RTA process, the back contact dramatically improves, which helps to improve the current density from ~34 to 400 A/cm^2. Near unit ideality factors of 1.02 were obtained for the both SBDs and extracted barrier for SBDs w/o and w/ RTA process is 1.53 and 1.35 eV, respectively.

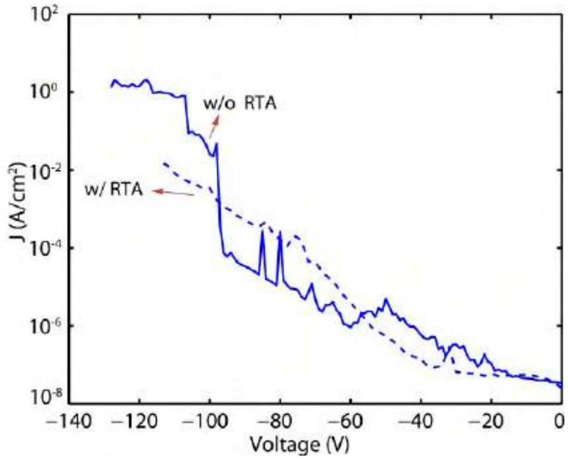

Fig.4 Reverse J-V characteristics of Ga_2O_3 SBDs w/o and w/ RTA