Very High Parallel-Plane Surface Electric Field of 4.3 MV/cm in Ga_2O_3 Schottky Barrier Diodes with PtO_x Contacts

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Introduction β-Ga_2O_3 has emerged as a potentially-disruptive wide-bandgap semiconductor material for high power applications, largely due to its high breakdown electric field of ~8 MV/cm. To access the full benefit of Ga_2O_3, a high electric field close to the breakdown field should be sustained in devices under reverse blocking. This is a challenging task, especially given the fact that functional p-n homojunctions might never be feasible in Ga_2O_3. As a result, alternative reverse blocking junctions, such as Schottky barriers [1], p-n heterojunctions [2] and MIS-structures with high-κ dielectrics [3] are being investigated. Among them, Schottky barriers have highly-desirable advantages, including less stringent requirements on the interface quality compared to p-n heterojunctions, as well as an absence of reliability concerns – an issue in dielectrics.

However, the reverse leakage current under high field in Schottky barriers is often limited by Fowler-Nordheim tunneling or field emission thus the accessible surface electric field is typically below 3 MV/cm. For Ga_2O_3, large Schottky barrier heights over 2 eV are shown possible with oxidized metal contacts [4], where the leakage current can be effective reduced. In this work, we demonstrate that with a barrier height of ~1.8 eV from oxidized platinum (PtO_x) Schottky contacts, field-emission induced leakage current is dramatically reduced, and a parallel-plane surface electric field of 4.3 MV/cm is reached, *the highest among all Ga_2O_3 Schottky barrier diodes (SBDs) to date.*

Experimental Process As shown in Fig. 1, PtO_x SBDs were fabricated on a $(\bar{2}01)$ Sn-doped β-Ga_2O_3 substrate, which has a net doping concentration of 1.55×10^{18} cm^{-3} as determined from *C-V* measurements (Fig. 2). A Ti/Au ohmic contact was first deposited on the backside of the substrate. PtO_x Schottky contacts were deposited by reactive DC sputtering in the presence of an Ar and O_2 mixture, followed by the deposition of a Pt capping layer. Subsequently, a self-aligned dry etching (0.3 μm) process was performed for edge termination. For comparison, regular Pt SBDs were also fabricated with a similar process. All measurements were performed at room temperature (RT, 25°C).

Results and Discussion Fig. 3 shows the $1/C^2$-V plot, where a barrier height ($q\phi_B$) of 2.19 eV is extracted from the PtO_x SBDs. This value is 0.8-eV higher than that of the Pt SBDs (1.42 eV). As expected, PtO_x SBDs exhibit a higher turn-on voltage (Fig. 4). The barrier height extracted from the *I-V* plot is 1.79 eV from the thermionic emission (TE) model considering the correction for image-force lowering (IFL), lower than the $q\phi_B$ extracted from the *C-V* method, likely due to barrier-height inhomogeneity. As shown in Fig. 5, the reverse leakage current is significantly reduced in the PtO_x SBDs compared with the Pt SBDs. As a result, the reverse voltage at 100 mA/cm^2 in the PtO_x SBD reaches 31 V, corresponding to a parallel-plane surface electric field of 4.3 MV/cm. The reverse *J-E* characteristics is analyzed using our numerical reverse-leakage model, which is based on WKB-tunneling probability with IFL considered. An excellent match is observed between the measured and calculated *J-E* characteristics, with the barrier height as the only fitting parameter (Fig. 6). Fowler-Nordheim (F-N) plot (J/E^2 vs. $1/E$) shows linear behaviors for both diodes at RT, indicating that field-emission is the dominant leakage mechanism (Fig. 7). Barrier heights extracted from *C-V*, forward and reverse *I-V* measurements show decent agreements (Fig. 8). We have developed a numerical model to calculate the "practical" maximum electric field (E_{max}) defined at two maximum reverse current densities: 1 and 100 mA/cm^2, as a function of the barrier height. As shown in Fig. 9, the experimentally measured E_{max} for Pt and PtO_x SBDs, together with data reported in the literature, agrees well with the predictions by our numerical model.

Conclusion A dramatic reduction of the reverse leakage current and an increase of the surface electric field up to 4.3 MV/cm are obtained with PtO_x contacts due to the increased Schottky barrier height. These results demonstrate the feasibility of effective reverse blocking with a high Schottky barrier in β-Ga_2O_3. Furthermore, these results validate a model we introduce here (Fig. 9), which predicts a minimum barrier height of 2.2 eV is necessary to reach a "surface" field of 6 MV/cm. Though these high barrier junctions are not suitable as the Schottky barrier themselves for the sake of a low turn-on voltage desired in SBDs, they are highly desirable to be implemented in Ga_2O_3 power devices to manage the electric field, especially field crowding and peak field near buried "surfaces".

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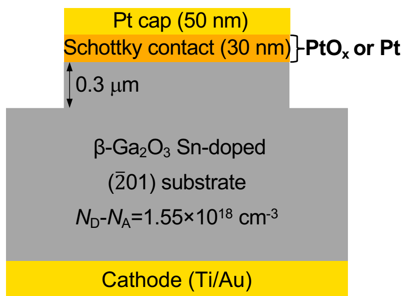

Fig. 1. Schematic cross-section of the β- Ga_2O_3 Schottky barrier diodes with oxidized Pt or regular Pt Schottky contacts.

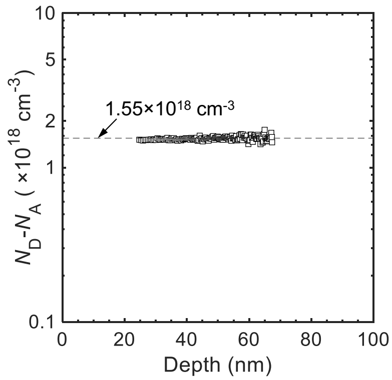

Fig. 2. Net doping concentration (N_D-N_A) profile extracted from *C-V* measurements.

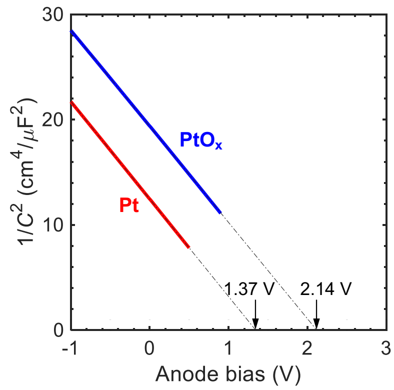

Fig. 3. $1/C^2$-V plot of the Pt and PtO_x SBDs. PtO_x SBDs exhibit a built-in voltage (V_{bi}) of 2.14 V, which is 0.77 V higher than the Pt SBDs.

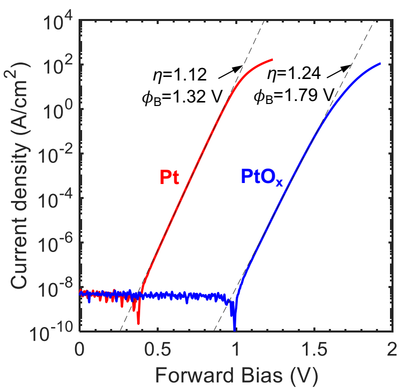

Fig. 4. Forward *I-V* characteristics of the Pt and PtO_x SBDs. The image-force-lowering (IFL) corrected barrier heights (ϕ_B) and ideality factors (η) are extracted using the thermionic emission (TE) model.

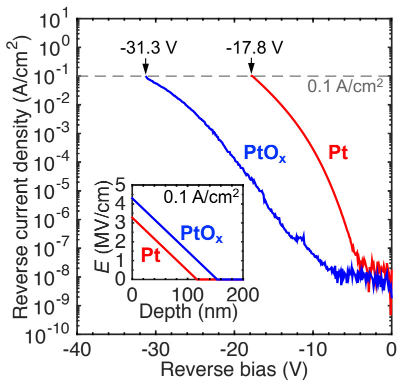

Fig. 5. Reverse *I-V* characteristics. The maximum reverse voltage at 0.1 A/cm^2 is 17.8 V and 31.3 V for Pt and PtO_x SBDs, respectively. Inset shows the corresponding electric-field profile at 0.1 A/cm^2.

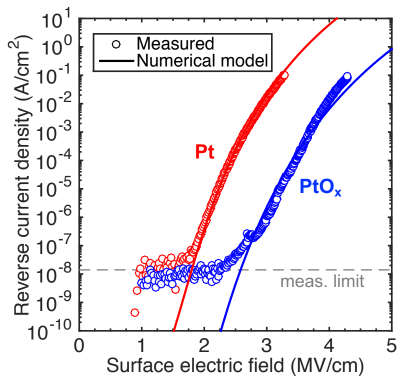

Fig. 6. Measured reverse leakage current, along with calculated leakage current using our numerical model as a function of the surface electric field (*E*).

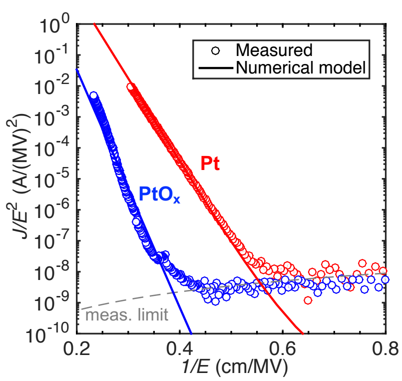

Fig. 7. Fowler-Nordheim (F-N) plot of reverse leakage characteristics. The linear behavior suggests a field-emission dominated leakage mechanism.

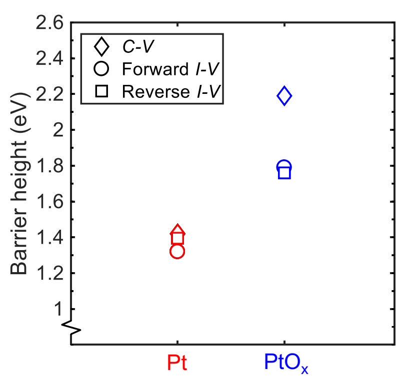

Fig. 8. Barrier heights extracted from *C-V*, forward *I-V* and reverse *I-V* measurements. For PtO_x contacts, the discrepancy between *C-V* and *I-V* methods is likely due to barrier-height inhomogeneity.

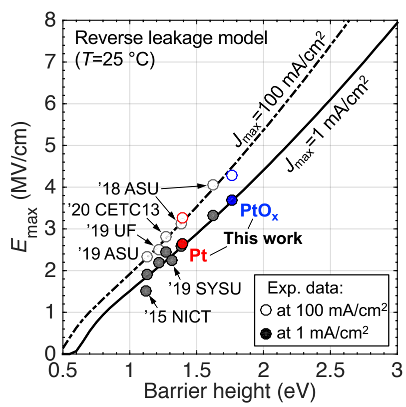

Fig. 9. Calculated and measured practical maximum electric field (E_{max}) in β-Ga_2O_3 SBDs as a function of the barrier height at room-temperature.

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