1.5 kV Vertical Ga_2O_3 Trench-MIS Schottky Barrier Diodes

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Introduction: β-Ga_2O_3 electronic devices for high power applications have seen rapid development over the recent years, due to the excellent material properties including an extremely large band-gap, high critical electric field, decent electron mobility and the availability of low-cost bulk substrates. As unipolar devices, Ga_2O_3 vertical Schottky barrier diodes (SBDs) have fast switching capability, while enjoying all the superior properties of Ga_2O_3. With the development of halide vapor phase epitaxy (HVPE) capable of delivering high quality thick n^- epitaxial layers [1], Ga_2O_3 vertical SBDs have shown promising results with up to 1 kV breakdown voltage (BV) together with decent on-resistance (R_{on}) of 2-6 $m\Omega\cdot cm^2$ [1-3]. However, the results are still far from the projected performance which surpasses GaN and SiC [4]. One important reason is the high reverse leakage current due to the high surface electric field, which causes thermionic-field emission and barrier height lowering, especially at the device edge where field crowding occurs. The leakage current can be much reduced by edge termination techniques such as field-plating [3]. More effectively, a trench-metal-insulator-semiconductor (MIS) structure can be utilized to reduce the leakage current [5], taking advantage of the reduced surface field (RESURF) effect [6]. In this work, we demonstrate Ga_2O_3 trench-MIS SBDs with a record-high 1.5 kV breakdown voltage without edge termination, together with a ~10^4 times reduction in reverse leakage current compared with regular SBDs.

Experimental Process: The schematic cross-section of the device is shown in Fig. 1. Ga_2O_3 (001) n-type bulk substrate with a thickness of 620 μm was used. A 10 μm Si-doped n^--Ga_2O_3 epitaxial drift layer was grown by halide vapor phase epitaxy (HVPE). The key fabrication process is shown in Fig. 2. First, Ni/Pt hard mask was patterned by a lift-off process and served as top Schottky contact as well as hard mask for the subsequent BCl_3-based dry etching, which formed the trenches with a depth of 2 μm. Next, a 60 nm Al_2O_3 dielectric layer was deposited by atomic layer deposition, followed by a dry etching for top opening. A Pt anode electrode was then formed by sputtering. Finally, Ti/Au cathode ohmic contact was formed on the back after a BCl_3-based dry etching process. Optical top-view of a fabricated device with a fin-width (W_{fin}) of 3 μm and a trench-width (W_{tr}) of 5 μm is shown in Fig. 3.

Results: The trench-MIS SBDs were first simulated in TCAD Sentaurus assuming a net doping concentration (N_D-N_A) of 1×10^{16} cm^{-3} in the drift layer. As shown in Fig. 4, the on-current and turn-on voltage of the trench SBDs are similar with those of regular SBDs, whereas the reverse leakage current is much lower, indicating that the RESURF effect can be achieved with little penalty on forward characteristics. The leakage current is smaller with smaller W_{fin}. Experimentally, a net doping concentration of ~1-2×10^{15} cm^{-3} is extracted from C-V measurements, as shown in Fig. 5. Fig. 6 shows the measured forward characteristics of a typical trench SBD compared with a regular SBD fabricated on the same sample. Near ideal ideality-factors (n) of 1.02 and 1.07 are extracted for the regular SBD and trench SBD, respectively. The trench SBD has a similar turn-on voltage, but a slightly lower on-current compared with regular SBDs. The on-current for both types of diodes are lower than expected, possibly due to an even lower net doping concentration deeper into the drift layer and imperfect back ohmic contact. Fig. 7 shows the reverse I-V measurements of the diodes, which have record-high breakdown voltages around 1.5 kV in the absence of edge termination. Compared with regular SBDs, the trench SBDs have around ~10^4 times lower leakage current compared with regular SBDs, demonstrating the desired RESURF effect in the trench-MIS structure. The reverse leakage current of the trench SBDs at -500 V is compared in Fig. 8 with the reported Ga_2O_3 vertical SBDs with a BV higher than 500 V. Our trench SBDs have much lower leakage current than the regular SBDs without edge termination, similar with the field-plated SBD. At higher reverse bias, the advantage of the trench-MIS SBDs in leakage reduction is even more pronounced.

Conclusion: Record-high breakdown voltage of 1.5 kV and reverse leakage current reduction of ~10^4 times is demonstrated in Ga_2O_3 trench-MIS Schottky barrier diodes with similar forward characteristics as regular SBDs, thanks to the RESURF effect. The results showcase the superior electrostatic properties of the trench-MIS structure, which could further improve the performance of Ga_2O_3 vertical SBDs by effective reduction of the leakage current.

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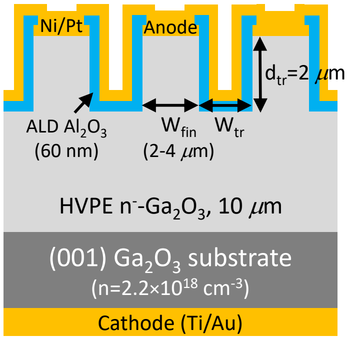

Fig. 1. Schematic cross-section of the Ga_2O_3 trench MIS-SBDs. The fins have widths (W_{fin}) of 2, 3, 4 μm.

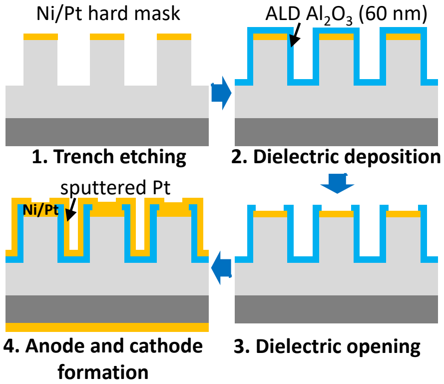

Fig. 2. Fabrication process of the Ga_2O_3 trench MIS-SBDs.

Fig. 3. Optical microscope image of the fabricated Ga_2O_3 trench MIS-SBD with a fin-width of 3 μm.

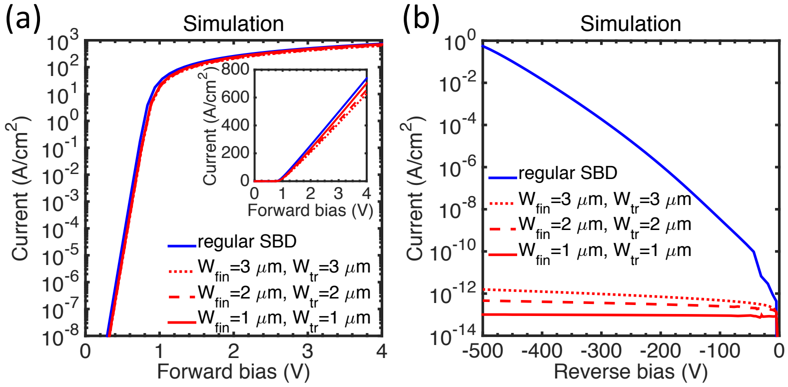

Fig. 4. Simulated (a) forward and (b) reverse I-V characteristics of the Ga_2O_3 trench MIS-SBDs. Current density is calculated from the total anode area. (Parameters used in the simulation: d_{tr}=2 μm; N_D-N_A=1×10^{16} cm^{-3}; anode work-function: 5.15 eV (Ni); electron mobility: 150 cm^2/V·s.)

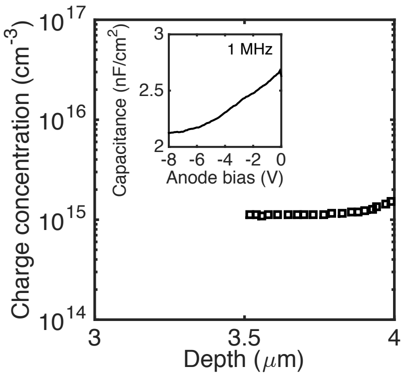

Fig. 5. Extracted charge concentration from C-V measurements on a MOS-capacitor test structure.

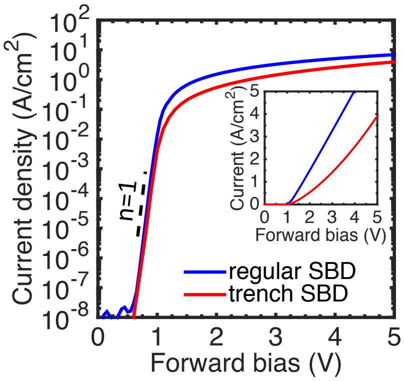

Fig. 6. Forward I-V characteristics of a typical trench SBD (W_{fin}=2 μm) compared with a regular SBD on the same sample. Current density is calculated from the total anode area.

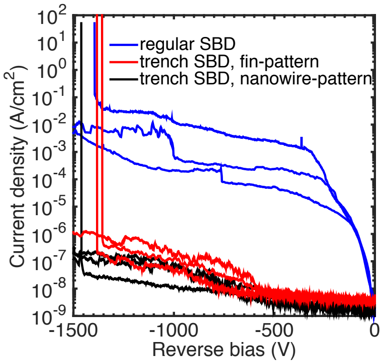

Fig. 7. Reverse I-V characteristics of the trench SBDs (W_{fin}=2-4 μm) compared with regular SBDs on the same sample.

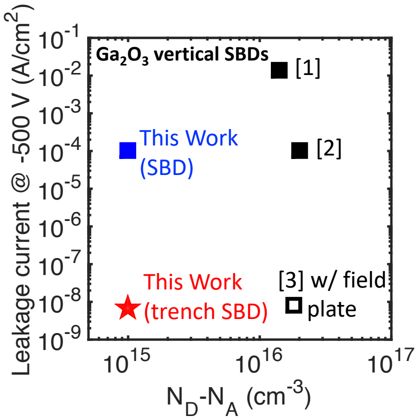

Fig. 8. Reverse leakage current at -500 V *vs.* N_D-N_A for the reported Ga_2O_3 vertical SBDs with >500 V breakdown voltage.

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