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Over 3 GW/cm^2 low leakage vertical β-Ga_2O_3 Schottky rectifier featuring self-aligned multi-zone junction termination extension

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Ultra-wide bandgap (UWBG) semiconductors, including gallium oxide (Ga_2O_3), aluminum nitride (AlN), boron nitride (BN), and diamond, have garnered significant attention due to their substantial critical electric fields (E-field). Among these, β-Ga_2O_3 stands out due to its exceptional properties, such as a broad spectrum of controllable N-doping, a decent electron mobility, and the readily available large-scale melt-grown substrates. These advantages promote high-quality homoepitaxy and potentially cost-effective device fabrication [1]. Edge termination is pivotal for vertical β-Ga_2O_3 power devices. However, the lack of effective native p-type doping poses challenges in managing the electric field in β-Ga_2O_3. To address this issue, various innovative techniques have been developed [2].

Among various methods, the junction termination extension (JTE) utilizing nickel oxide (NiO) has emerged as one of the most promising approaches due to its adjustable acceptor doping and manufacturing flexibility through sputtering. Despite these advantages, existing JTE designs have a key challenge: the breakdown field of the NiO using pure Ar during sputtering is not compatible with the breakdown field of Ga_2O_3. Previous study [3] has pointed out that the p-type NiO has different critical breakdown fields (E_C) with different doping levels. Therefore, achieving a better match of breakdown characteristics in heterogeneous JTE while maintaining the simplicity of JTE fabrication is a critical area that requires further study and development.

This study presents a novel and practical vertical Ga_2O_3 Schottky barrier diode (SBD) featuring a self-aligned multi-zone JTE (SA-MZJTE). Distinct from prior multi-zone JTE SBDs in Ga_2O_3, this multi-zone JTE deploys a self-aligned etching to form multi-zone following the 3-layer single-zone JTE-SBD fabrication. The produced SA-MZJTE SBD exhibits a BV exceeding 3 kV, with a long JTE length of 20 µm. Additionally, the SA-MZJTE SBD is capable of withstanding 2400 V at an elevated temperature of 150°C.

Design and simulation. Figure 1(a) presents a 3-D schematic view of the fabricated β-Ga_2O_3 SA-MZJTE SBD. Figure 1(b) illustrates the C-V and $1/C^2$-V of the SA-MZJTE SBD measured at a frequency of 100 kHz, revealing a net doping concentration of 1.8×10^{16} cm^{-3}. For further device design, we would like to extract the NiO parameter in actual application scenarios (see Appendix A1) through C-V. The average P-type doping of the NiO with Ar:O_2 (20:1) and pure Ar is calculated and determined to be $\sim 1.8 \times 10^{18}$ and $\sim 3 \times 10^{17}$ cm^{-3}, respectively. After that, we can design the JTE through charge compensation (see Appendix A2). For further explanation and understanding, technology computer aided design (TCAD) Sentaurus simulations were performed to investigate the effectiveness of the proposed SA-MZJTE (see Appendix A3) compared with other devices.

Experiment. Figure 1(c) outlines the main fabrication steps of the SA-MZJTE SBD. The detailed descriptions can be found in Appendix B. The lengths of the JTE-1 and JTE-2, which are shown in Figure 1(a), are designed to be equal, referred to as $L_{\rm JTE}$. The diameter of the device is set at 100 µm. Scanning electron microscope (SEM) images of the entire SA-MZJTE are depicted in Figure 1(d), while Figure 1(e) details each JTE region. A 4 µm trench is formed at the edge of JTE-1, and the etching selectivity of NiO to Ga_2O_3 is 1:10.

Results and discussions. Figure 1(f) shows the forward characteristics of the four devices, including UT-SBD, single-zone JTE-SBD, 3-layer single-zone JTE-SBD, and SA-MZJTE SBD. The devices exhibit similar forward characteristics, which means the proposed JTE technology would not degrade the device conducting performance. The $R_{\rm ON,sp}$ of the four devices are about 3.1, 3.25, 3.17, 3.2 mΩ·cm^2, respectively. The differences in these values are due to the slight non-uniformity in the drift region grown by HVPE.

Figure 1(g) presents the corresponding blocking characteristics of the four devices. The UT-SBD demonstrates a maximum BV of 825 V. In contrast, the single-zone JTE-SBD, featuring a 700 nm NiO deposited in pure Ar, breaks down at 1405 V. In addition, when the interface has the medium-doped NiO, the BV can be increased to 1685 V, even if the JTE's dose is very excessive. This is because the breakdown field of medium-doped NiO is higher compared to lowly doped NiO [3]. Furthermore, the SA-MZJTE

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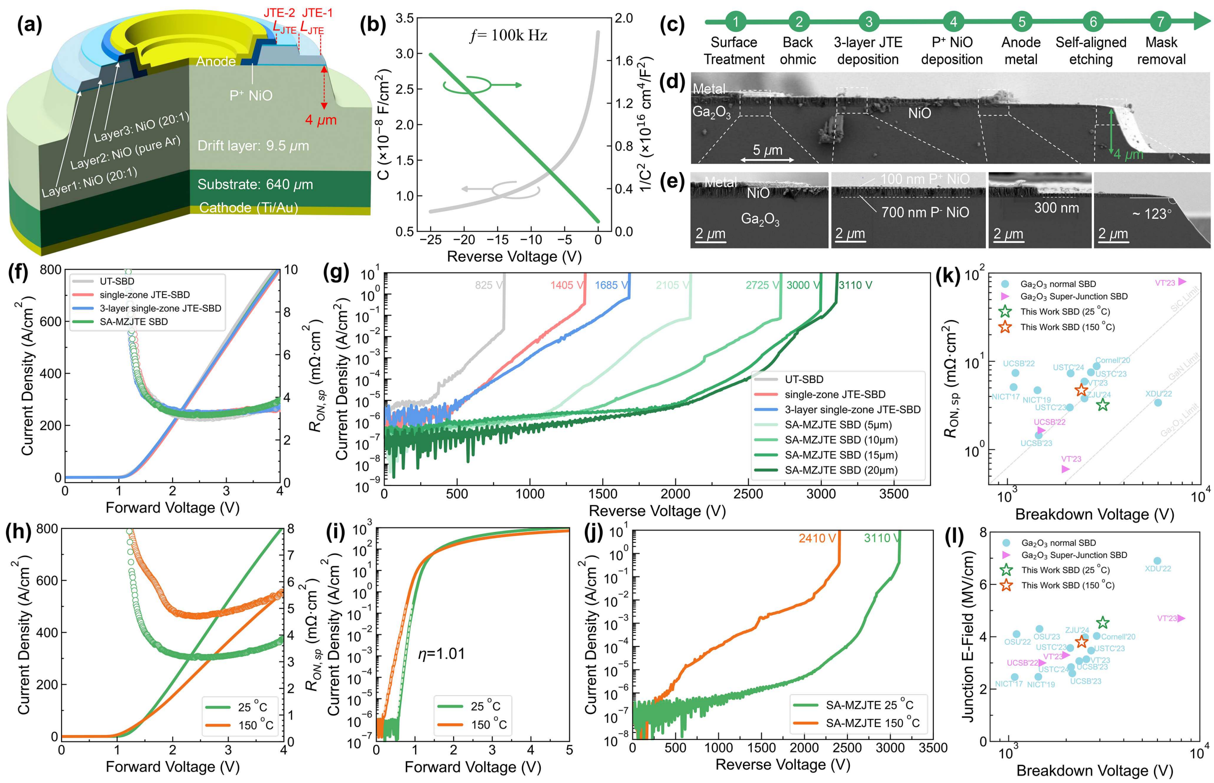

Figure 1 (Color online) (a) 3-D schematic view of the SA-MZJTE SBD; (b) C-V and $1/C^2$-V of the SA-MZJTE SBD, which is measured at a frequency of 100 kHz; (c) main fabrication steps of the vertical Ga_2O_3 SA-MZJTE SBD; (d) SEM image of the entire SA-MZJTE region; (e) magnified SEM image showing each JTE region; (f) forward J-V of the UT-SBD, single-zone JTE-SBD, 3-layer single-zone JTE-SBD, and the SA-MZJTE; (g) reverse J-V of the UT-SBD, single-zone JTE-SBD, 3-layer single-zone JTE-SBD, and the SA-MZJTE with varying JTE lengths of 5, 10, 15, and 20 μm, respectively; typical forward J-V characteristics of the fabricated SA-MZJTE SBD at 25°C and 150°C presented in the (h) linear scale and (i) semi-log scale; (j) reverse J-V characteristics of the SA-MZJTE with a JTE length of 20 μm, measured at 25°C and 150°C; benchmark of the (k) $R_{\mathrm{ON,sp}}$ versus BV and (l) junction electric field versus BV of reported state-of-the-art β-Ga_2O_3 SBDs.

SBD exhibits a breakdown voltage of 2105 V at an L_{JTE} of 5 μm. As the L_{JTE} increases to 10 and 15 μm, the BV gradually rises to 2725, 3000 V, respectively. Notably, when the L_{JTE} is extended to 20 μm, the breakdown voltage only increases to 3110 V, indicating a saturation effect of the L_{JTE}. Additionally, the leakage current of the SA-MZJTE SBD remains relatively low (see Appendix Table C1). At the reverse bias of 1500 V, the leakage is 5 orders of magnitude lower than that of the 3-layer single-zone JTE-SBD.

Figures 1(h) and (i) show the typical forward J-V of the SA-MZJTE SBD at 25°C and 150°C in linear scale and semi-log scale, respectively. The $R_{\mathrm{ON,sp}}$ of the SA-MZJTE SBD is determined to be 3.2 mΩ·cm^2 at 25°C and 4.7 mΩ·cm^2 at 150°C. The ideality factor in the barrier-limited region is about 1.01, indicating that the Schottky interface is well protected during the self-aligned multi-zone JTE etching process. The device also exhibits an excellent on/off ratio of 10^9 at both temperatures. Figure 1(j) illustrates the blocking capability of the SA-MZJTE SBD with a L_{JTE} of 20 μm at 25°C and 150°C.

In Figure 1(k), the power figure of merit (PFOM) of the SA-MZJTE SBD is benchmarked against state-of-the-art Ga_2O_3 SBDs [4]. The SA-MZJTE SBD with a JTE length of 20 μm exhibits a PFOM of 3 GW/cm^2 at 25°C and 1.2 GW/cm^2 at 150°C. Figure 1(l) presents the BV and junction field (see Appendix C for junction E-field extraction) among other Ga_2O_3 SBDs. These results position it among the best in the reported Ga_2O_3-based SBDs.

Conclusion. This study presents a high-performance vertical Ga_2O_3 SBD featuring a self-aligned multi-zone JTE. The fabrication of this NiO JTE utilizes a standard NiO deposition process combined with Ga_2O_3 etching techniques. The fabricated SA-MZJTE achieves a breakdown voltage of 3110 V with an L_{JTE} of 20 μm. The $R_{\mathrm{ON,sp}}$ of the device is determined to be 3.2 mΩ·cm^2, leading to a PFOM of 3 GW/cm^2. Moreover, the SA-MZJTE can withstand a high voltage up to 2410 V at 150°C. This research highlights a straightforward and effective edge protection technology for vertical Ga_2O_3 power devices, underscoring its potential to advance multi-kilovolt Ga_2O_3 devices.

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Supporting information Appendixes A–C. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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