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1.56 kV/30 A vertical β-Ga_2O_3 Schottky barrier diodes with composite edge terminations

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In recent years, large-area wide-bandgap (WBG) semiconductor materials have achieved numerous notable breakthroughs [1, 2]. The ultra-WBG semiconductor β-Ga_2O_3, with its excellent material properties, is ideally suited for the fabrication of power devices. Moreover, it offers easily obtainable large-area substrates, with reported sizes up to 6 inches, produced through melt-grown crystal growth methods. These characteristics make β-Ga_2O_3 highly attractive for future low-cost commercialization. Despite these advances, most research has focused on low-current and small-size diodes, with few studies addressing high-current and large-size diodes. However, industrial applications require power devices that can function as solid-state switches for significant power regulation. Large-area diodes typically have much lower breakdown voltage (BV) than small-area counterparts due to the non-optimized edge terminals (ET) and non-uniform epi-layers. Thus, developing ampere-level high-current with kilovolt-level high-BV large-size diodes is essential for practical application and industrialization of β-Ga_2O_3 power diodes.

In this study, we propose a novel diode structure to enhance the BV of forward current (I_F) $\geqslant 10$ A-level large-size vertical β-Ga_2O_3 Schottky barrier diodes (SBDs). By incorporating self-aligned mesa with N/P ion co-implantation as composite ETs to regulate the electric-field (E-field), we have realized vertical β-Ga_2O_3 SBDs with an area of 9 mm^2 on a 10 µm β-Ga_2O_3 epitaxial layer and achieved a BV of 1.56 kV @ reverse current (I_R) < 100 µA. The same device demonstrated $I_F = 12$ A @ forward voltage (V_F) = 2 V and $I_F = 30$ A @ $V_F = 4.2$ V. These outstanding performance metrics significantly surpass those of other β-Ga_2O_3 SBDs.

Experiments. Figure 1(a) presents a 3D cross-sectional schematic view of the β-Ga_2O_3 SBD with composite-ETs. In order to make the electron concentration of the epi-layer more uniform, an O_2 anneal process at 800°C for 1 h is implemented. Initially, a Ti/Au (60/120 nm) back electrode is evaporated, followed by annealing at 475°C for 1 min under an N_2 ambient to form an Ohmic contact. Subsequently, a 1.5 µm thick Au layer is grown via electroplating to thicken the cathode metal, ensuring the device can withstand high I_F. The anode metal area is then patterned using photolithography, and 50/150/100 nm of Ni/Au/Ni is deposited using electron beam evaporation to form the Schottky contact and etching hard-mask. The top 100 nm Ni layer was used as a hard mask for etching. The mesa isolation termination is created through self-aligned etching. Following this, an N/P co-ion implantation is performed to form the composite-ETs. For N-implantation, energies of 300, 100, and 24 keV were used with corresponding doses of 2.5×10^{14}, 9×10^{13}, and 3×10^{13} atoms/cm^2, respectively. For P-implantation, energies of 95 and 40 keV were used, with doses of 5×10^{11} and 2.5×10^{11} atoms/cm^2. The device was then annealed at 600°C for 5 min in an N_2 atmosphere. After the implantation, the device is soaked in a piranha solution ($H_2SO_4 : H_2O_2 = 7 : 3$) for 1 min to remove some of the damage from etching and ion implantation and to clean any etching residues. Finally, the anode metal is thickened to approximately 1.5 µm to accommodate high current and SiO_2 is deposited as a passivation layer. Figure 1(b) displays a scanning electron microscope (SEM) image at the anode region. Figure 1(c) presents a photograph of the fabricated square-shaped large-size diode, with a side length of 3 mm and an area of 9 mm^2.

Results and discussion. Figure 1(d) shows the well-behaved linear-scale forward characteristics (I_F-V_F) of representative β-Ga_2O_3 SBDs. V_{on} is extracted to be 0.65 V by linear extrapolations and $I_F = 12$ A @ $V_F = 2$ V as well as $I_F = 30$ A @ $V_F = 4.2$ V have all been achieved. The inset of Figure 1(d) illustrates the extracted ideality factor (η) of the diode, which is close to the ideal value of 1 for more than 5 orders of magnitudes, indicating a high-quality interface between anode and the β-Ga_2O_3. Figure 1(e) presents the extracted specific on-resistance ($R_{on,sp}$) versus V_F, yielding $R_{on,sp} = 10$ mΩ·cm^2. A minimal differential $R_{on} = 0.1$ Ω is

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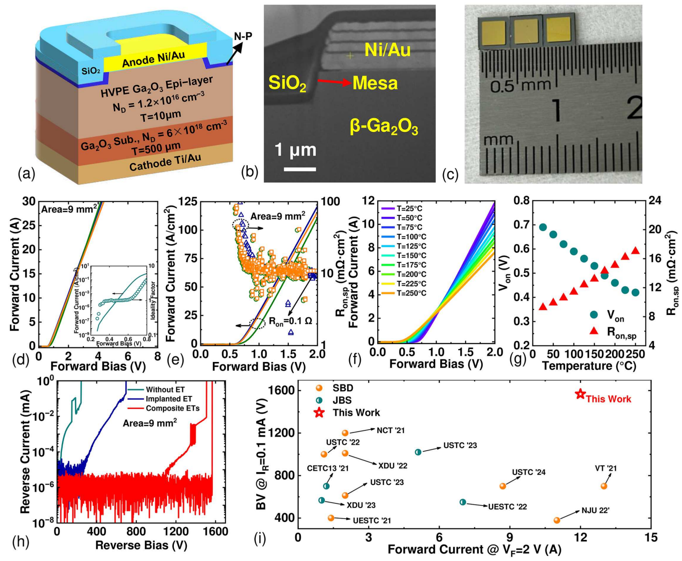

Figure 1 (Color online) (a) 3D cross-sectional schematic view of the β-Ga_2O_3 with composite-ETs SBD, featuring a total area of 9 mm^2; (b) cross sectional SEM image showing the anode edge; (c) photograph of some fabricated SBDs; (d) linear-scale forward I-V characteristics; inset of (d) log-scale forward characteristic and extracted ideality factor; (e) extracted log-scale $R_{on,sp}$; (f) T-dependent forward I-V characteristics; (g) extracted dependence of V_{on} and $R_{on,sp}$ on T; (h) log-scale breakdown characteristics comparison with various β-Ga_2O_3 SBDs; (i) benchmark of BV versus I_F for representative state-of-the-art large area β-Ga_2O_3 SBDs with $I_F \geqslant 1$ A.

also extracted. Temperature (T)-dependent I_F-V_F and extracted V_{on} as well as $R_{on,sp}$ are summarized in Figure 1(f) and (g), when T is increased from 25°C to 250°C. The I_F value @ $V_F = 2$ V is only reduced from 12 to 7.5 A (by 37.5%) even when T is increased by one order of magnitude. This is beneficial to the surge current, especially at elevated Ts. Such a phenomenon is most likely correlated with the T-insensitive electron mobility and improved donor ionization at high Ts. Figure 1(h) presents the reverse characteristics comparison among β-Ga_2O_3 SBDs with composite ETs (as in Figure 1(d)) and other diodes without any ETs or only with implanted ET. During the reverse I-V measurements, the Ohmic contact is biased at 0 V while the Schottky contact is reversely swept until I_R either abruptly increases or reaches 100 μA. Compared with β-Ga_2O_3 SBDs without any ETs or with only implanted ET, the BV is increased by 6× and 2×, respectively. Due to the excellent E-field management technique and annealed epi-layer, our β-Ga_2O_3 SBDs with composite ETs maintain a low I_R before breakdown happens and a maximum BV of 1.56 kV is achieved. These BV values represent the highest reported for all large-area and high-current vertical β-Ga_2O_3 SBDs. The BV is reduced to 1.3 and 0.8 kV at T of 75°C and 150°C, respectively. Combining with an $R_{on,sp}$ of 10 mΩ·cm^2, the P-FOM $= BV^2/R_{on,sp}$ is calculated to be 238 MW/cm^2. Figure 1(i) benchmarks I_F @ $V_F = 2$ V vs. BV @ $I_R = 0.1$ mA of our large size β-Ga_2O_3 SBD with the state-of-the-art β-Ga_2O_3 SBDs with $I_F \geqslant 1$ A @ $V_F = 2$ V, including SBDs and junction barrier Schottky (JBS) diodes. Our device shows the highest BV among all compared SBDs and the BV nearly doubles the prior highest value for all those diodes with $I_F \geqslant 6$ A [3–6].

Conclusion. In conclusion, we have proposed a simple yet effective approach by implementing composite-ETs to regulate the E-field at the anode edge to enhance the BV of large-area vertical β-Ga_2O_3 SBDs. High BV = 1.56 kV @ $I_R < 100$ μA and $I_F = 12$ A @ $V_F = 2$ V as well as $I_F = 30$ A @ $V_F = 4.2$ V are all simultaneously achieved. These results significantly outperform other high-current and high-voltage β-Ga_2O_3 SBDs and advance β-Ga_2O_3 research from the laboratory level to commercial products.

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