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Extended Abstracts of the 2013 International Conference on Solid State Devices and Materials, Fukuoka, 2013, pp950-951

Electrical Characteristics of 21-kV SiC BJTs with Space-Modulated Junction Termination Extension

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1. Introduction

Power bipolar junction transistors (BJTs) based on 4H-SiC are recognized as attractive candidates for high-power switching devices because of such characteristics as high breakdown voltage and low on-resistance [1]. SiC BJTs have been reported in 1-10-kV range with low on-resistance close to the SiC unipolar limit.

Currently, only a few reports on high-voltage (~10 kV) BJTs are available, notably 9.2-kV BJT with β of 7 [2] and 10-kV BJT with β of 28 [3]. It is important to improve the current gain for reduction of loss in the base drive circuits. Furthermore, to expand BJT application to ultra-high-voltage (> 10 kV) range, it is also important to establish the proper edge termination technique to reduce the electric field crowding at the mesa edge. We have reported in p-i-n diodes a novel edge termination technique featuring two-zone junction termination extension (JTE) and space-modulated rings referred to as space-modulated JTE (SM-JTE), which allowed us to achieve a high breakdown capability with an improved JTE dose window [4], [5]. Recently, by applying this termination technique to SiC BJTs, we demonstrated 21-kV 4H-SiC BJTs [6]. In this study, we discuss electrical characteristics of the 20-kV-class BJTs.

2. Device Fabrication

Fig. 1(a) shows the schematic structure of a fabricated 20-kV-class BJT. The BJT structure was grown on n-type 4H-SiC(0001) 8° off-axis substrates with a 186-μm-thick n-SiC collector. The theoretical breakdown voltage for this drift layer is 26.8 kV. A 0.35-μm-thick p-SiC base and a 1.2-μm-thick n^+-SiC emitter were grown continuously in the same reactor by chemical vapor deposition. Multiple Al^+ ion implantations at room temperature were performed to form JTE. We employed SM-JTE (total length of 500 μm) consisting of two-zone JTE plus three rings. The JTE1 dose was 1.2×10^{13} cm^{-2} and JTE2 dose was 0.8×10^{13} cm^{-2}, and the dose of the rings was equal to JTE2 dose. For the passivation, 80-nm-thick deposited oxides nitrided in 10%-diluted NO at 1300°C for 30 min are used in this study. The surface was also passivated by a thick polyimide to insulate the device. The fabricated circular BJT has a total area of 1.33 mm^2 (1300 μm in diameter) and an emitter-mesa diameter of 100 μm.

Fig. 1(b) shows the schematic structure of a fabricated 1-kV-class SiC BJT to compare forward characteristics. The emitter and base epilayers were same as 20-kV-class SiC BJTs. The collector epilayer was designed for 1-kV class of which theoretical breakdown voltage is 1.8 kV, but the BJTs did not employed SM-JTE. The other fabrication processes were similar as 20-kV-class SiC BJTs.

3. Results and Discussion

Fig. 2 shows forward common-emitter current-voltage (*I-V*) characteristics of the fabricated BJTs with an emitter diameter of 100 μm. The on-resistance R_{on} measured at 2 mA is calculated to be 73 mΩ•cm^2 without considering current spreading effect. To estimate the specific on-resistance ($R_{\mathrm{sp\_on}}$) taking account of current spreading effect, the current flow was simulated by using Synopsys TCAD, and the effective active area was 0.035 mm^2, which gives rise to the $R_{\mathrm{sp\_on}}$ of 321 mΩ•cm^2. This $R_{\mathrm{sp\_on}}$ is slightly lower than the drift resistance of 420 mΩ•cm^2, which was estimated by using the carrier concentration of 2.3×10^{14} cm^{-3} and an electron mobility of 1200 cm^2/V•s, indicating that the conductivity modulation may be present.

Figure 3 shows the current gain as a function of the collector current. The BJT showed a current gain of 63 at a base current of 140 μA, which is about twice larger than the previous report of the 10-kV BJT [3]. On the other hand, the fabricated 1-kV-class BJTs shows the maximum current gain of 54, which is good agreement with 20-kV-class SiC BJTs. This result shows that the current gain is just determined by the emitter-base structure.

The open-base blocking characteristics (V_{CEO}) of the fabricated BJT are shown in Fig. 4. A maximum open-base breakdown voltage V_{CEO} of 21 kV (at 0.1 A/cm^2) was obtained, which is 78% of the theoretical breakdown voltage calculated from the epilayer structure. It should be noted that the blocking voltage of 21 kV is, to the authors' knowledge, the highest blocking voltage among any semiconductor switching devices. From these results, SM-JTE can be used as an effective technology for SiC BJTs.

The open-emitter blocking characteristics (V_{CBO}) of the fabricated BJT are also shown by the dashed line in Fig. 4. Unlike conventional Si BJTs, similar blocking characteristics as those of open-base mode (V_{CEO}) were obtained. The mechanism is still under investigation, but we here propose two mechanisms. First, the current gain at $I_{\mathrm{C}} = 0.1$ μA is less than the unity as shown in Fig. 3 because a recombination current is dominant in the low-current range. Therefore, amplification by the current gain of the transistor cannot occur. Second, the electric field crowding may occur at the edge termination. The current gain at the edge termination is approximately zero because the distance from the emitter is large enough (> 100 μm) and transport factor is approximately zero, resulting in no amplification by the gain of the transistor. As a result, the blocking characteristics between open-base and open-emitter mode show similar results.

4. Conclusion

We have reported 20-kV-class 4H-SiC BJTs with SM-JTE. The fabricated BJTs showed a maximum current gain of 63 and a minimum specific on-resistance of 321 mΩ•cm^2 assuming current spreading, which is slightly below the SiC unipolar limit. In OFF-state characteristics, we achieved the open-base blocking voltage of 21 kV at a leakage current of 0.1 mA/cm^2.

Acknowledgment

This work was supported by the Funding Program for World-Leading Innovative R&D on Science and Technology (FIRST Program) and a Grand-in-Aid for Scientific Research (21226008) from the Japan Society for the Promotion of Science.

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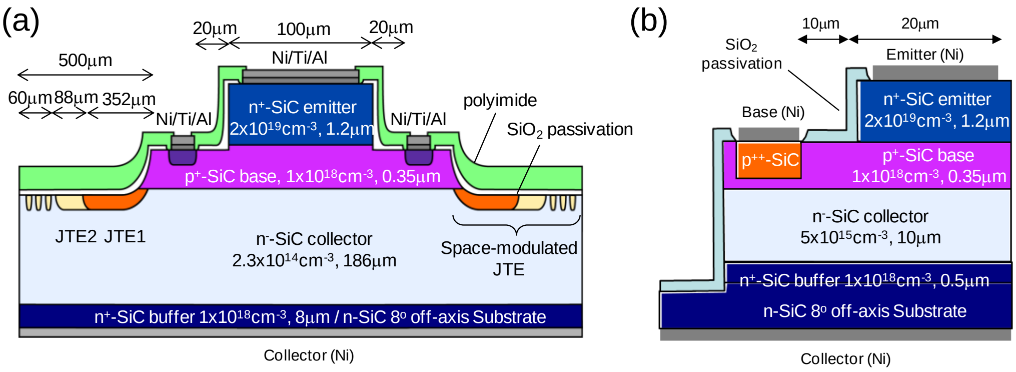

Fig. 1. Schematic cross section of fabricated (a) 20-kV-class SiC BJTs and (b) 1-kV-class SiC BJTs.

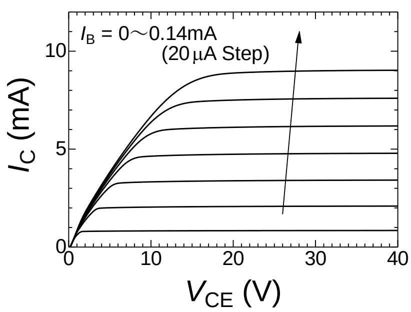

Fig. 2. Common-emitter *I-V* characteristics of a fabricated 20-kV-class SiC BJT.

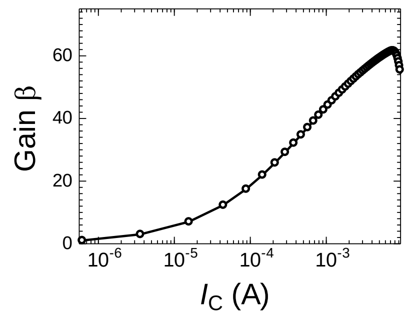

Fig. 3. Measured current gain as a function of collector current for a fabricated 20-kV-class SiC BJT.

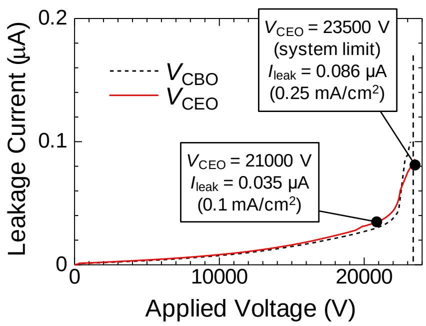

Fig. 4. Blocking characteristics of a fabricated 20-kV-class SiC BJT with open-base or open-emitter mode.