Characteristics of blocking voltage for power 4H-SiC BJTs with mesa edge termination*

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Abstract: According to the avalanche ionization theory, a computer-based analysis is performed to analyze the structural parameters of single- and multiple-zone junction termination extension (JTE) structures for 4H-SiC bipolar junction transistors (BJTs) with mesa structure. The calculation results show that a single-zone JTE can yield high breakdown voltages if the activated JTE dose and the implantation width are controlled precisely and a multiple-zone JTE method can decrease the peak surface field while still maintaining a high blocking capability. The influences of the positive and negative surface or interface states on the blocking capability are also shown. These conclusions have a realistic meaning in optimizing the design of a mesa power device.

Key words: 4H-SiC; BJTs; blocking voltage; junction termination extension; mesa device
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1. Introduction

Silicon carbide (SiC) is currently of great interest because of its properties of wide bandgap, high critical field strength, high saturation electron drift velocity and high thermal conductivity which make it an attractive semiconductor for high voltage power devices. Due to its higher mobility along the *c*-axis compared to the 6H polytype, the 4H-SiC is better suited for vertical power devices[1]. Important for power devices, it is required to have excellent voltage blocking capabilities. Although specialized edge termination structures have been developed for Si devices, directly transferring the Si termination techniques to SiC is difficult because of the inherent differences in material properties and processing methods. In order to enhance the capability to sustain higher external applied voltage, the junction termination extension (JTE) technology[2] is often used to obtain a high blocking voltage due to alleviating the device edge field crowding and lowering field strength of the surface compared to the bulk region. Many authors have used these methods in their designs and some of them have discussed the structure optimization in detail for PiN diodes and Schottky diodes[3−7]. However, there is an obvious contrast in that the PiN and Schottky diodes are planar junction but the mesa structures for most of the power 4H-SiC bipolar junction transistors (BJTs) are adopted. Besides, systematic studies of modeling and optimizing of JTE parameters for BJTs are rare.

In this paper, we investigate the design of single- and multiple-zone JTE for 4H-SiC BJTs typically with mesa structure and perform extensive analysis of the effects of JTE parameters on the breakdown capabilities through quasi-3D ISE-TCAD simulation package[8], while taking into account the unique processing constraints of SiC. Special attention is given to the doping concentration, the implantation depth, the distance from the JTE region to the base mesa, and the influence of the interface states. Breakdown analysis was performed by calculating the electron and hole ionization integral along potential gradient paths through the device structure at each potential update. The calculation results show that the proper design for the edge termination can enhance the breakdown voltage ($V_{\rm br}$) and it provides an effective support when optimizing the device structure.

2. Device structure and calculation setup

Figure 1 shows the cross-section of the single- and multiple-zone JTE structures in 4H-SiC BJTs studied in this paper. The related structure parameters are also shown in Fig. 1.

Typically, the base is grown as a two-layer structure with Al doping: 0.35 μm with 1×10^{17}cm^{-3}, followed by 0.15 μm with 4.6×10^{18} cm^{-3} on top. The two epilayer base structure fabricated by continuous growth can accelerate the transportation of the carriers by the built-in electric field in the base region, hence to avoid the problem of crystal damage caused by the ion implantation and increase the current gain[9]. As shown in Fig. 1, the schematic (a) is formed by a single-zone JTE termination, and the schematic (b) is implemented by two or more P type implantations.

As we know, there are two mechanisms including avalanche and tunneling breakdown which can occur at the PN junction. Since the tunneling breakdown mainly occurred in a very low voltage condition, the avalanche breakdown mechanism is taken into account in this paper.

The impact ionization generation rate can be expressed as:

$$G = \alpha_{\rm n}\frac{J_{\rm n}}{q} + \alpha_{\rm p}\frac{J_{\rm p}}{q}, \tag{1}$$

where $J_{\rm n,\,p}$ is the current density, subscript n and p describe

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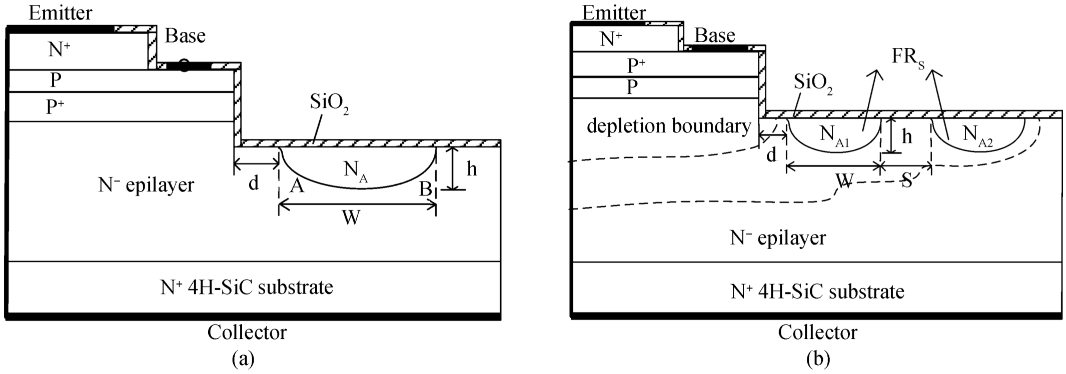

Fig. 1. Schematic cross-section of the NPN 4H-SiC BJTs with edge termination. (a) Single-zone JTE structure. (b) Multiple-zone JTE structure.

electron and hole respectively, and q is the quantity of electricity. α_n and α_p are the impact ionization coefficients for the electron and hole respectively, which is given by:

$$\alpha_{n,p} = R_{n,p}(T)e^{-\left(\frac{c_{n,p}}{E(x)}\right)^{m_{n,p}}}, \tag{2}$$

where $E(x)$ denotes the electric field parallel to the integral direction. c and m are constants to be independent on the electric-field.

When the reverse bias of the B/C junction reaches the blocking voltage, the carriers would generate avalanche multiplication due to the impact ionization. The relationship of the avalanche multiplication factor and the impact ionization coefficient can be expressed as:

$$M = \frac{1}{1-\int \alpha \mathrm{d}x}. \tag{3}$$

It can be seen that the avalanche breakdown condition is that M goes to infinite when

$$\int_0^{W_d} \alpha_p \exp\left[-\int_0^x (\alpha_p - \alpha_n)\mathrm{d}x'\right]\mathrm{d}x = 1. \tag{4}$$

All simulations were performed at 300 K using DESSIS-ISE software, assuming cylindrical geometry and discussing the open base breakdown voltage BV_{ceo}. We define breakdown voltage as the point where the reverse collector current reaches 1×10^{-6} A. This low limit was set to avoid long simulation run times, because no further change in BV_{ceo} was observed after the reverse current reached this value.

3. Results and discussions

3.1. Results of the unterminated reference BJTs

As a reference for the terminated case, a simple two-dimensional structure which has the same geometry parameter as shown in Fig. 1 but with no edge termination structure was first simulated. Figure 2 shows the comparison of experimental and simulation results for BJTs with no edge termination. The solid line denotes the simulation results with the models discussed above and the triangle line is the experimental results with the same structure[10]. From Fig. 2, the breakdown voltage is about 1800 V when the reverse collector current reaches 1×10^{-6} A. The comparison results show that presented model for simulating breakdown voltage is reasonable.

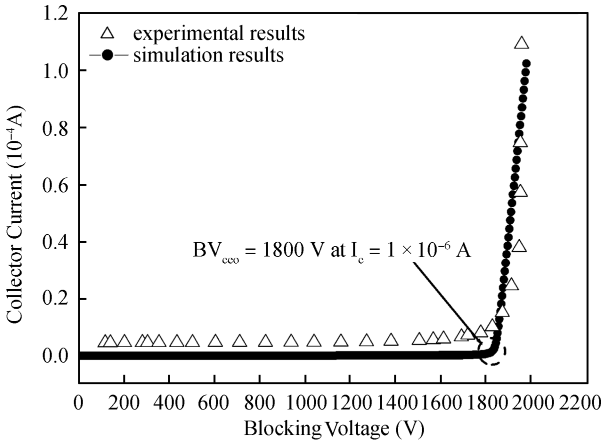

Fig. 2. Comparison of breakdown characteristics of experimental and simulation results for BJTs with no edge termination.

3.2. Single-zone junction termination extension

The JTE technique is used for extending the high doped main junction in order to allow the spreading of the equipotential lines emerging below the junction edge curvature toward the surface. The JTE layer should be designed properly so that it can be fully depleted at the maximum blocking voltage. For a 4H-SiC BJTs, the JTE sheet doping level and the JTE width (W in Fig. 1(a)) are the two major design parameters. Figure 3 displays the variation of the breakdown voltage as a function of doping concentration for different implantation depths. As seen in this graph, the breakdown voltage increases to a maximum value and then decreases as the dose increases for different JTE depths, implying that precise control over the dose is required. Moreover, the peaks occur at somewhat different doses for different depths. It can be explained that at the optimum dose, the electric field distribution is relatively uniform along the termination and there are peaks of equal magnitude in the field at points A and B, as shown in the insert drawing of Fig. 3. When the JTE dose increases beyond the optimum dose, the peak field at point B increases more rapidly with dose than the peak field at A decreases at a fixed bias voltage.

The JTE width is another important parameter that has a significant effect on breakdown voltage. Figure 4 shows the dependence of breakdown voltage on the JTE width. We can see clearly that the value of V_{br} increases as W is increased

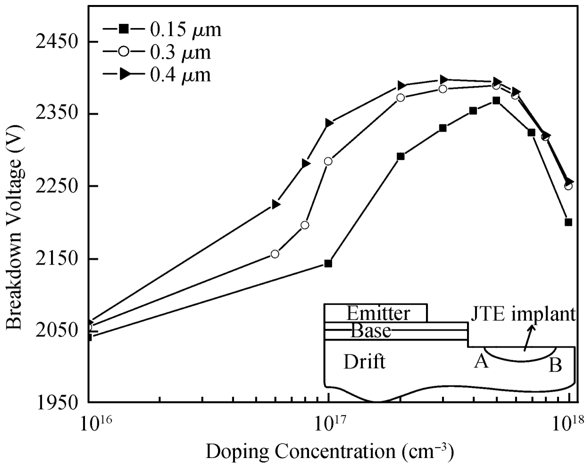

Fig. 3. Variation of V_{br} as a function of doping concentration for different implantation depth.

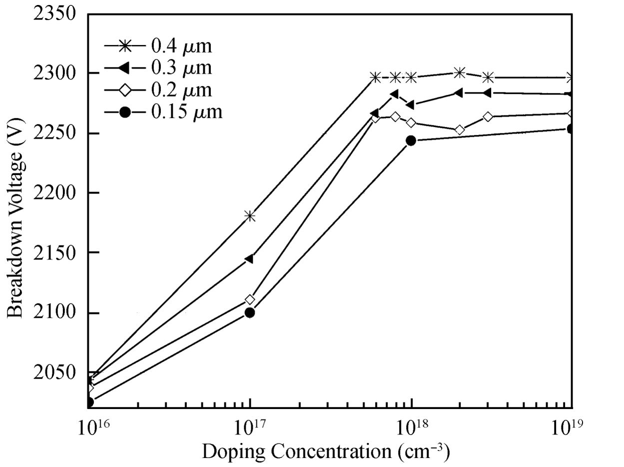

Fig. 6. Variation of V_{br} as a function of doping concentration for the four implantation depth.

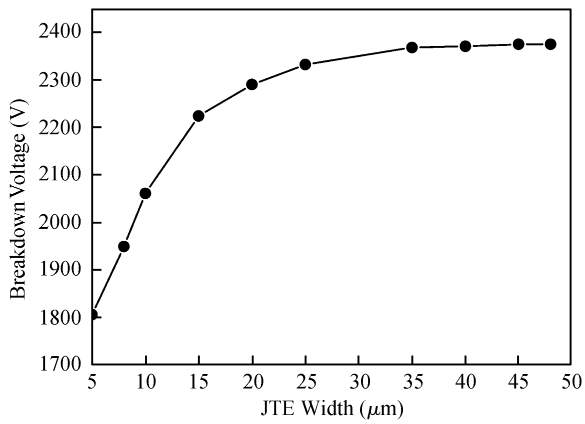

Fig. 4. Dependence of breakdown voltage on the JTE width.

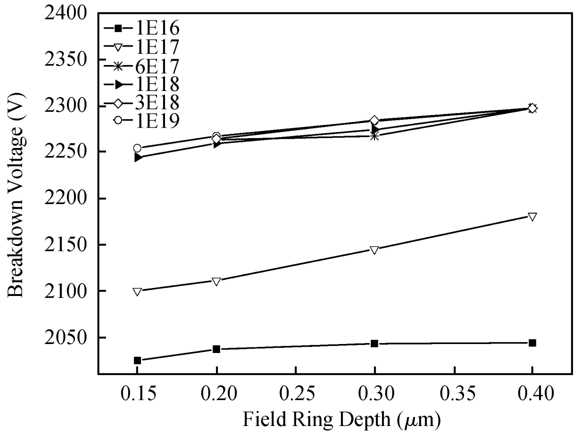

Fig. 7. Variation of V_{br} as a function of implantation depth for different doping concentrations.

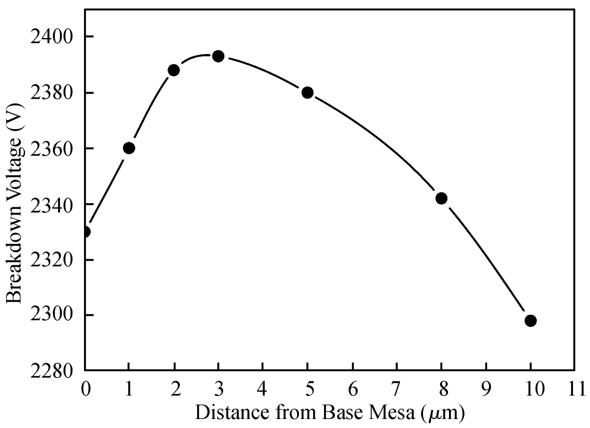

Fig. 5. Dependence of breakdown with variation in the distance of the implant region from the base mesa.

up to a certain value. This saturation occurs because above a sufficient JTE width, there is no additional effect on the field distribution in the JTE region.

Figure 5 displays the dependence of breakdown with variation in the distance of the implant region from the base mesa (d in Figs. 1(a), 1(b)). From the tendency of the curve, we can find that the breakdown voltage is sensitive to the distance from the base mesa and an optimum blocking voltage can be obtained if the space from base mesa is properly controlled.

3.3. Multiple-zone junction termination extension

To increase the tolerance to variations in JTE parameters and decrease the surface field, a multiple zone structure can be employed. With the JTE configuration as shown in Fig. 1(b), the breakdown voltage is calculated for a given implantation width and a constant distance from the base mesa, assuming the same doping concentration of the two rings. The variations of breakdown voltage as a function of doping concentration and the implantation depth are shown in Figs. 6 and 7. Seen from above two graphics, the breakdown voltage increases with the FRs depth from 0.15 to 0.4 μm. However, the breakdown voltage is increasing with the doping concentration at first and basically maintains a relative value when the doping concentration exceeds about 6×10^{17} cm^{-3}. That is mainly because the outermost JTE implantation has fully depleted.

Like the silicon devices, the breakdown voltages of the 4H-SiC devices are found to be very sensitive to the ring position. The relationship between breakdown voltage and the spacing of two rings is illustrated in Fig. 8. The V_{br} reaches a maximum value when the spacing equals to about 5 μm. The outermost

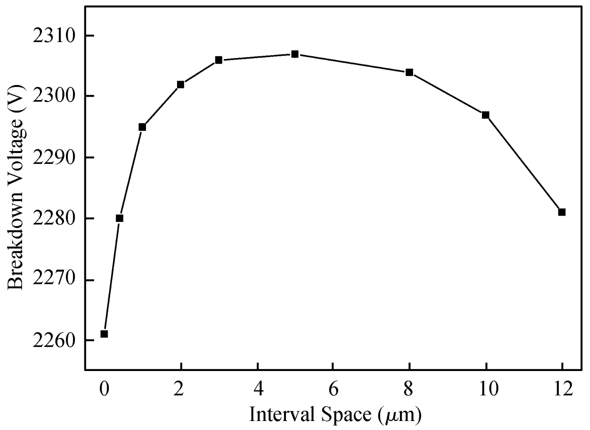

Fig. 8. Relationship between breakdown voltage and the spacing of two JTE rings.

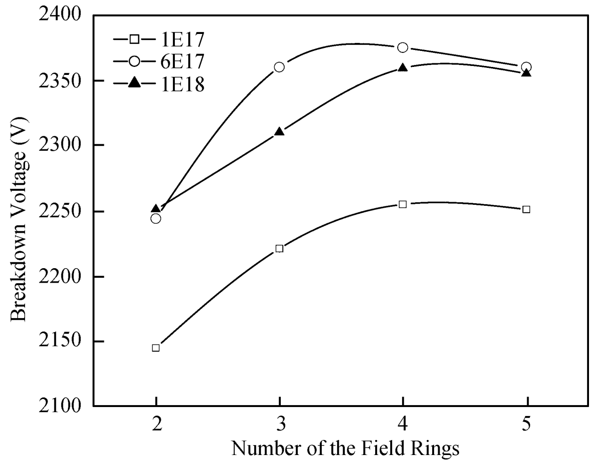

Fig. 10. Variation of V_{br} with the number of the JTE implantation.

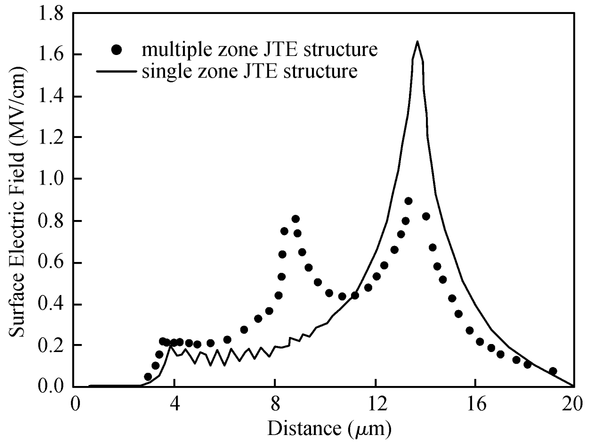

Fig. 9. Surface electric field profile for a single and a multiple-zone JTE structure.

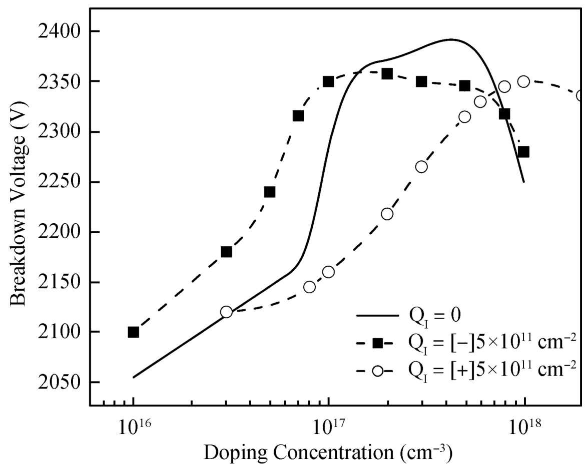

Fig. 11. Comparison of the breakdown voltage with and without considering interface state.

ring is just like a lonely island and is not connected to the adjacent depletion when the spacing is too large. On the contrary, the voltage drop across the two JTE implantation regions will decrease if the spacing interval is too small while the operating voltage increases.

Figure 9 denotes the simulated results of the surface electric field profile for a single and a multiple zone JTE structure. As can be seen, with the addition of the second zone, the peak field is effectively split into two peaks of significantly lower field strength.

Although the multiple-zone JTE structure can decrease the surface field, but there is a limit for the number of the edge termination. Figure 10 is the calculation results of the variation of V_{br} with the number of the JTE implantation when the edge termination is in different doping concentrations. We can see clearly that the blocking voltage increases with the number increment first, and then it is saturated when the number of the JTE implantation exceeds 4.

3.4. Interface state sensitivity

Although progress has been made in recent years, the interface state density in 4H-SiC devices remains much larger than silicon technology. The surface electric field generated by these surface charge acts on the face of the semiconductor, changes the distribution of the electric field near the surface of the devices and modifies the breakdown voltage. Figure 11 shows the comparison results of the breakdown voltage with and without considering interface states. From it we can see that the peak of the curve is shifted toward heavier JTE doping concentration with positive (+) interface states and towards lighter JTE doping concentration with negative (–) interface states. The interpretation of this phenomenon can be shown in Fig. 12. In the case of positive interface charge, electric field lines extend from the surface to many of the acceptors in the depleted regions of the JTE, reducing the net concentration available for electric field spreading, but in the presence of negative interface states, many of the electric field lines extend from the donors in the depleted drift layer to the charge in the oxide, which act like extra JTE acceptors.

4. Conclusion

In order to improve the breakdown characteristics of the 4H-SiC BJTs with mesa structure, the JTE termination for both single and multiple-zone structures have been investigated in this paper. According to the avalanche ionization theory, extensive simulation analysis presented here has provided a detailed

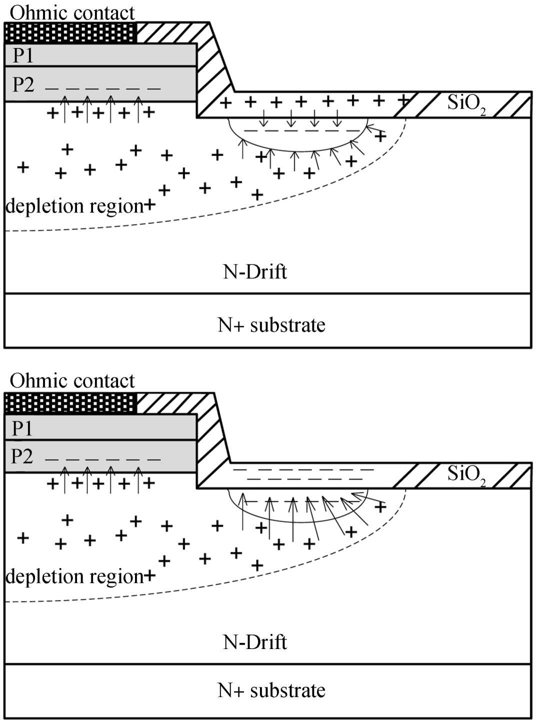

Fig. 12. Electric field distribution of the JTE structure considering both positive and negative interface state.

picture of the behavior of the mesa edge termination based on the analysis of their working principle. The single-zone JTE can yield high breakdown voltages if the activated JTE dose and the implantation width are controlled precisely. Although more complex, using a multiple-zone JTE method can decrease the surface field and still maintain high blocking capability. It maintains a saturation value when the doping concentration exceeds about $6 \times 10^{17} cm^{-3}$. Moreover, it has also shown the influence of the positive and negative interface states on the blocking capability. These conclusions can be useful for device design and optimization.

References

[1] Singh R, Cooper J A Jr, Melloch M R, et al. SiC power Schottky and PiN diodes. IEEE Trans Electron, 2002, 49(4): 665

[2] Temple V A K, Tantraporn W. Junction termination extension for the near-ideal breakdown voltage in p–n junctions. IEEE Trans Electron Devices, 1986, 33: 1601

[3] Tarplee M C, Madangarli V P, Zhang Q, et al. Design rules for field plate edge termination in SiC Schottky diodes. IEEE Trans Electron Devices, 2001, 48(12): 2659

[4] Sheridan D C, Niu G, Merrett J N, et al. Design and fabrication of planar guard ring termination for high-voltage SiC diodes. Solid-State Electron, 2000, 44: 1367

[5] Hiyoshi T, Hori T, Suda J, et al. Simulation and experimental study on the junction termination structure for high-voltage 4H-SiC PiN diodes. IEEE Trans Electron Devices, 2008, 55(8): 1841

[6] Muzykov P G, Bolotnikov A V, Sudarshan T S. Study of leakage current and breakdown issues in 4H-SiC unterminated Schottky diodes.Solid-State Electron, 2009, 53: 14

[7] Wang X, Cooper J A Jr. Optimazation of JTE edge terminations for 10 kV power devices in 4H-SiC. Mater Sci For, 2003, 457–460: 1257

[8] DESSIS-ISE, 2-D semiconductor device simulator. version 8.5. Integrated Systems Engineering, Zurich, 2002

[9] Zhang Qian, Zhang Yuming, Zhang Yimen. Analytical models for the base transit time of a bipolar transistor with double base epilayers. Journal of Semiconductors, 2009, 30(9): 094003

[10] Zhang J, Li X, Alexandrov P, et al. Fabrication and characterization of high-current-gain 4H-SiC bipolar junction transistors. IEEE Trans Electron Devices, 2008, 55(8): 1899

[11] Temple V A K, Tantraporn W. Junction termination extension for near-ideal breakdown voltage in p–n junctions. IEEE Trans Electron Devices, 1986, 33(10): 1601

[12] Bhardwaj A, Ranjan K, Chatterji N S, et al. A new approach to the optimal design of multiple field-limiting ring structures. Semicond Sci Technol, 2001, 16: 849