Fundamental Study on Junction Termination Structures for Ultrahigh-Voltage SiC PiN Diodes

Hiroki Niwa, Jun Suda, and Tsunenobu Kimoto
Department of Electronic Science and Engineering
Kyoto University
Nishikyo, Kyoto 615-8510, Japan
niwa@semicon.kuee.kyoto-u.ac.jp

Abstract—**15 kV-class 4H-SiC PiN diodes with various junction termination extension (JTE) structures have been experimentally investigated. JTE-dose dependence of the breakdown voltage for conventional single and two-zone JTE showed a narrow window of optimum JTE-dose to obtain high breakdown voltage. To widen this window, space-modulated JTE (SM-JTE) was introduced. 4H-SiC PiN diodes with SM-JTE showed a highest breakdown voltage of 15 kV, and a widening of the optimum JTE-dose window to obtain ultrahigh-voltage was realized at the same time.**

Keywords-silicon carbide (SiC); PiN diode; junction termination extension (JTE)

I. INTRODUCTION

For the realization of advanced power distribution and transmission systems, ultrahigh-voltage (>10 kV) SiC devices with low power loss are promising. Although SiC devices with breakdown voltage over 10 kV have been demonstrated in the past [1-3], fundamental studies targeting such a high voltage are still limited.

One of the most important device technologies to realize such ultrahigh-voltage devices is the proper designing of junction termination extension (JTE) structures, which reduces the well-known electric field crowding. While various JTE structures have been investigated to obtain high breakdown voltage in the past, extensive studies on breakdown characteristics in ultrahigh-voltage SiC devices are still needed to understand the basic device physics. In this paper, we have fabricated ultrahigh-voltage 4H-SiC PiN diodes with various implanted JTE structures combined with the mesa structure. The JTE-dose dependence of the breakdown voltage was investigated by experiments and simulation. By introducing a space-modulated JTE (SM-JTE) [4], a breakdown voltage over 15 kV and a wide optimum JTE-dose window to obtain high breakdown voltage was realized.

II. DEVICE FABRICATION

Figure 1 illustrates the schematic structure of a fabricated 4H-SiC PiN diode with two-zone JTE and SM-JTE. A 147 μm-thick n-type epilayer doped to 7×10^{14} cm^{-3} grown on n^{+}-type 8° off-axis 4H-SiC (0001) substrate was used. An improved bevel mesa structure shown in figure 2 was fabricated by reactive ion etching with a CF_4-O_2 chemistry using SiO_2 as an etching mask [2]. The JTE region was formed by Al ion implantation at room temperature with an implantation dose of 0.5-2.45$\times10^{13}$ cm^{-2} to a depth of 0.8 μm.

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III. RESULTS AND DISCUSSION

Figure 3 shows the various JTE structures fabricated in this study. All of the total JTE length was fixed to 500 μm, where the breakdown voltage starts to saturate in numerical device simulation and in experiment (not shown here). In two-zone JTE, the length and the dose ratio of JTE1 and JTE2 were optimized to be 4:1 and 3:2, respectively.

Figure 4 represents the experimentally measured breakdown voltage as a function of JTE1. Reverse characteristics of the fabricated diodes were measured in DC measurement unit by immersing the diodes in Fluorinert^{TM} to avoid air sparking. In the single-zone JTE (Fig. 3 (a)) shown by triangles, a narrow window of the optimum JTE-dose to achieve high breakdown voltage is observed. Due to this narrow window, the tolerance to the deviation of JTE-dose is relatively low, causing difficulties to shoot this peak point and obtain high breakdown voltage. The highest breakdown voltage obtained in this structure was 11.8 kV, only corresponding to about 73 % of parallel-plane breakdown voltage for the epilayer structure (16 kV). In the two-zone JTE (Fig. 3 (b)) shown by circles, the window of the optimum JTE-dose is clearly wider than the single-zone JTE, and realized a breakdown voltage of 15 kV (power supply limit), which corresponds to about 93 % of the parallel-plane breakdown voltage, which is fairly high for over 10 kV-class SiC diodes. Although this conventional structure has realized a breakdown voltage of 15 kV, a wider optimum JTE-dose window to obtain this ultrahigh voltage is required to fabricate the devices in a high yield without increasing the complexity of fabrication processes. Therefore, the authors have introduced SM-JTE, where a part of conventional JTE is fragmented, and the effective JTE-dose is modulated by adjusting the width of the rings and its spaces, to meet the demand. Results on two-zone JTE combined with SM-JTE consisting 3 sets of 10 μm-wide rings and spaces (Fig. 3 (c)) are shown by squares in Fig. 4. While keeping the maximum breakdown voltage of 15 kV, the optimum JTE-dose has extended to the higher JTE-dose region since the field crowding taking place at the outer two-zone JTE is reduced by the SM-JTE.

Figure 5 shows the *I-V* characteristics of the 15 kV-class 4H-SiC PiN diodes with two-zone JTE and SM-JTE (Fig. 2 (c)). The voltage drop at 100 A/cm^{2} is 9.68 V, which is relatively high because the p^{+}-anode layer was

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formed by ion implantation. To improve the forward characteristics, an epitaxial pn junction is essential. For the reverse characteristics, a leakage current below 2×10^{-5} A/cm^2 was obtained even at the reverse voltage of -15 kV.

IV. Summary

Breakdown characteristics of 15 kV-class 4H-SiC PiN diodes with various JTE structures have been investigated. By employing two-zone JTE, or by combining SM-JTE to it, a breakdown voltage of 15 kV has been demonstrated. The SM-JTE has enabled the enlargement of a JTE-dose window to obtain high breakdown voltage, making it a promising termination structure for fabricating ultrahigh-voltage 4H-SiC power devices.

References

[1] Y. Sugawara, D. Takayama, K. Asano, R. Singh, J. Palmour, and T. Hayashi, “12-19 kV 4H-SiC pin diodes with low power loss,” in *Proc. 13th Int. Symp. Power Semicond. Devices ICs*, 2001, pp.27-30.

[2] T. Hiyoshi, T. Hori, J. Suda, and T. Kimoto, “Simulation and experimental study on the junction termination structures for high-voltage 4H-SiC PiN diodes,” *IEEE Trans. Electron Devices*, vol. 55, no. 8, pp.1841-1846, Aug. 2008.

[3] Q. Zhang, C. Jonas, J. Sumakeris, A. Agarwal, and J. Palmour, “12 kV 4H-SiC p-IGBTs with record low specific on-resistance,” *Mater. Sci. Forum*, vol. 600-603, pp. 1187-1190, 2009.

[4] G. Feng, J. Suda, and T. Kimoto, “Space-modulated junction termination extension for ultrahigh-voltage p-i-n diodes in 4H-SiC,” *IEEE Trans. Electron Devices*, vol. 59, no. 2, pp. 414-418, Feb. 2012.

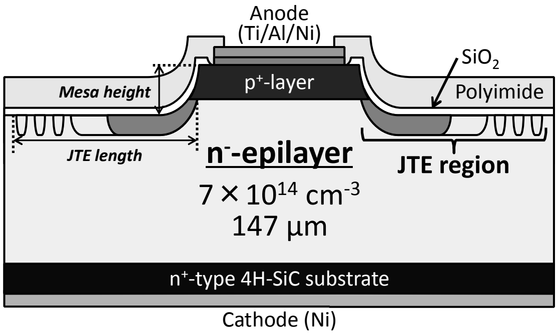

Figure 1. Schematic cross section of a fabricated 4H-SiC PiN diode with two-zone JTE and space-modulated JTE.

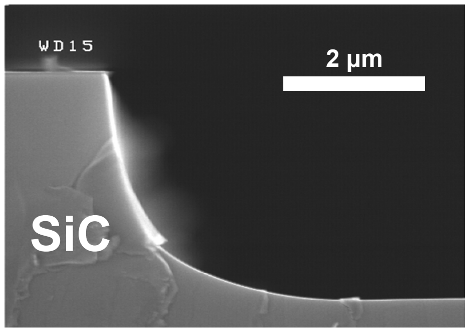

Figure 2. Cross-sectional SEM image of improved bevel mesa structure.

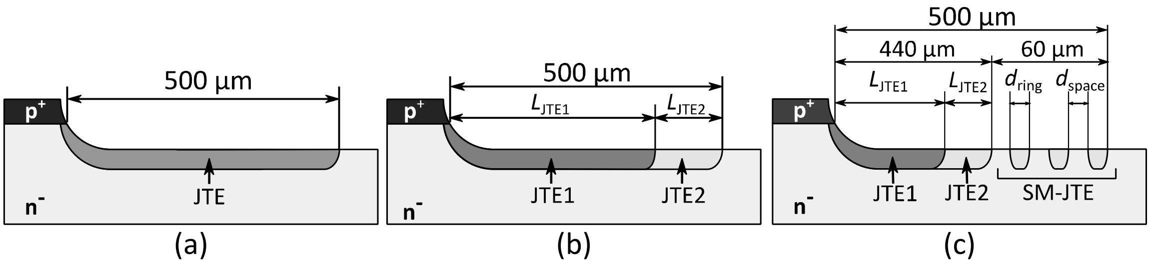

Figure 3. Schematic structure of (a) single-zone JTE, (b) two-zone JTE, (c) two-zone JTE + SM-JTE, fabricated in this study. Ratio of L_{JTE1} and L_{JTE2} are fixed to 4:1, while d_{ring} and d_{space} are 10 µm in SM-JTE.

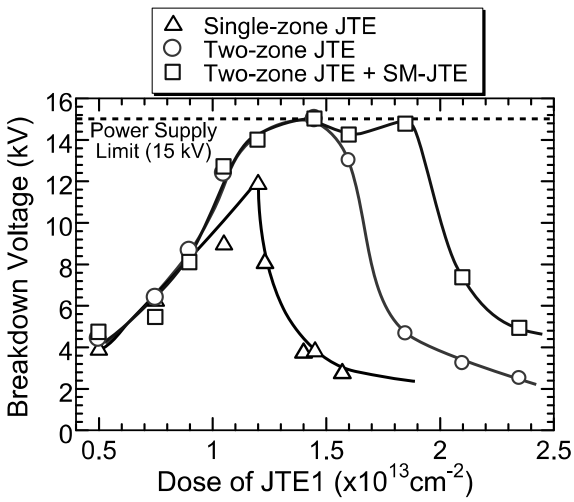

Figure 4. JTE1 dose dependence of the experimental breakdown voltage of SiC PiN diodes with various JTE structures.

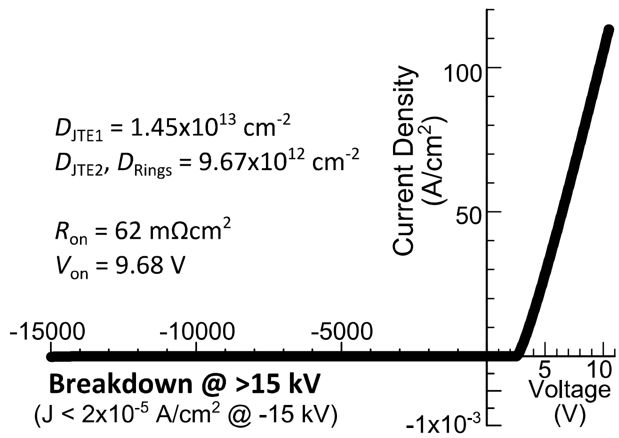

Figure 5. *I-V* characteristics of a fabricated 15 kV-class 4H-SiC PiN diode with two-zone JTE and SM-JTE.