Materials Science Forum
ISSN: 1662-9752, Vol. 1191, pp 75-79
doi:10.4028/p-9L9dhm

Submitted: 2025-09-26
Revised: 2025-12-22
Accepted: 2026-02-26
Online: 2026-05-19

Enhanced Breakdown Voltage and Enlarged Process Window for Junction Termination Extension in SiC Power Devices Using Hybrid Random and Channeling Implantation

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Keywords: SiC, Junction Termination Extension, Channeling Implantation, Breakdown Voltage, Process Window.

Abstract. This work reports enhanced high-voltage blocking capability and an enlarged process window for junction termination extension (JTE) in SiC power devices using a hybrid random and channeling implantation for p-type doping (Al), compared with conventional random-only implantation. A three-step hybrid implantation process has been developed to replace a nine-step random implantation, achieving a similar doping profile and equivalent breakdown voltage in the JTE while significantly increasing fabrication productivity and reducing cost. Moreover, TCAD studies reveal that when using the same number of steps and ion energies as the conventional random implantation method, the JTE realized by the channeling-incorporated hybrid approach enables an increased breakdown voltage and a widened dose window in SiC devices. This is attributed to a deeper Al distribution with a lower average concentration, which effectively alleviates electric field crowding.

Introduction

The JTE structure is widely employed in SiC power devices to enhance off-state performance and reliability, but its effectiveness critically depends on implantation dose and depth [1,2]. To avoid sharp peaks in the electric field at both the main junction and the edge of the JTE, a deep and uniform dopant profile with a relatively low doping concentration is preferred for the JTE design. However, achieving this with conventional random-only implantation requires costly and time-consuming high-energy multi-step processes. While channeling implantation has offered great potential for creating a deep doping profile in SiC [3,4], its specific application to JTE structures has been underexplored.
In this work, combining experimental investigation with TCAD simulation, we propose a hybrid random and channeling implantation technique for JTE formation. Compared with multi-energy random implantation, this hybrid approach achieves a significantly enhanced breakdown voltage and an enlarged process window.

Experimental Details

All samples in this study were fabricated on 4° off-axis 6-inch 4H-SiC substrates. A cross-sectional schematic of the fabricated PiN diode with a single-zone JTE design is illustrated in Fig. 1. The epitaxial layer has a thickness of 12 μm and a doping concentration of 1×10^{16} cm^{-3}. The key fabrication steps are as follows: The P^+ anode and JTE region were formed via ion implantation. Specifically, random implantation was performed at an elevated temperature, while channeling implantation was conducted at room temperature. After implantation, all samples underwent high-temperature annealing for dopant activation. Subsequent steps included inter-layer dielectric (ILD) deposition, ohmic contact formation, pad metallization, silicon nitride (SiN) passivation, and polyimide coating.

Three groups of devices were fabricated: the first group (Reference sample, denoted as Ref.) employed a nine-step random implantation process with different energies for each step for the JTE; the second (denoted as Condition A) and third (denoted as Condition B) groups utilized a hybrid scheme consisting of two random implantation steps and one channeling implantation step for the JTE formation. The implantation energy for all groups ranged from 120 keV to 2300 keV. For both Conditions A and B, the energies of the two random implantations were 120 keV and 2300 keV, respectively, while the channeling implantation employed an intermediate energy. The total implantation doses were designed to satisfy Condition A < Ref. < Condition B. The electrical characterization of all fabricated devices was subsequently performed using a Keysight B1505A power device analyzer.

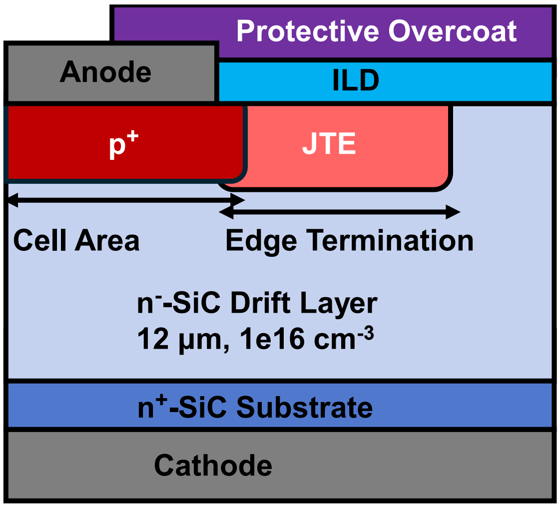


Fig. 1. Cross-sectional schematic of the fabricated SiC diodes with JTE in this work.

Results and Discussion

The aluminum (Al) distribution in the JTE implantation regions of the three samples was characterized using secondary ion mass spectrometry (SIMS). As shown in Fig. 2, the depth profiles of Al under all three implantation conditions exhibit nearly consistent dopant concentration distributions.

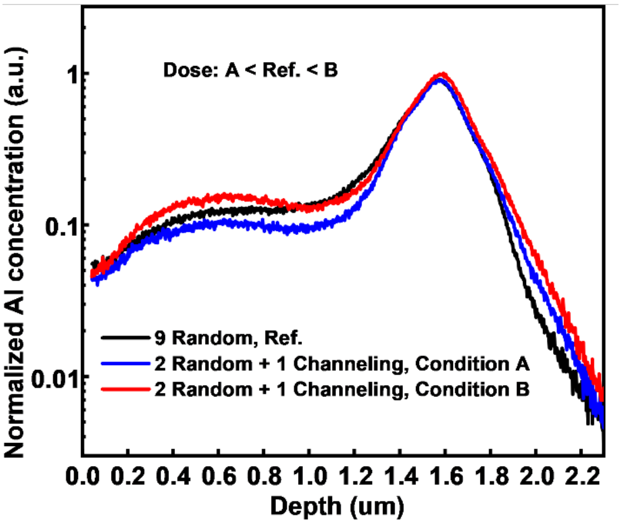


Fig. 2. Comparison of Al depth profiles of SIMS measurement in the JTE structures using random and hybrid implantation.

Notably, electrical characterization results (Fig. 3(a)) demonstrate that diodes with the JTE structure fabricated using the hybrid implantation scheme exhibit competitive breakdown voltages and comparable leakage currents to those of the reference. The average breakdown voltages for Conditions A and B, calculated from 18 devices per group, are 1643 V and 1717 V, respectively, both surpassing the reference value of 1630 V (Fig. 3(b)). These results confirm that the incorporation of channeling implantation significantly simplifies the JTE fabrication process without compromising the electrical performance.

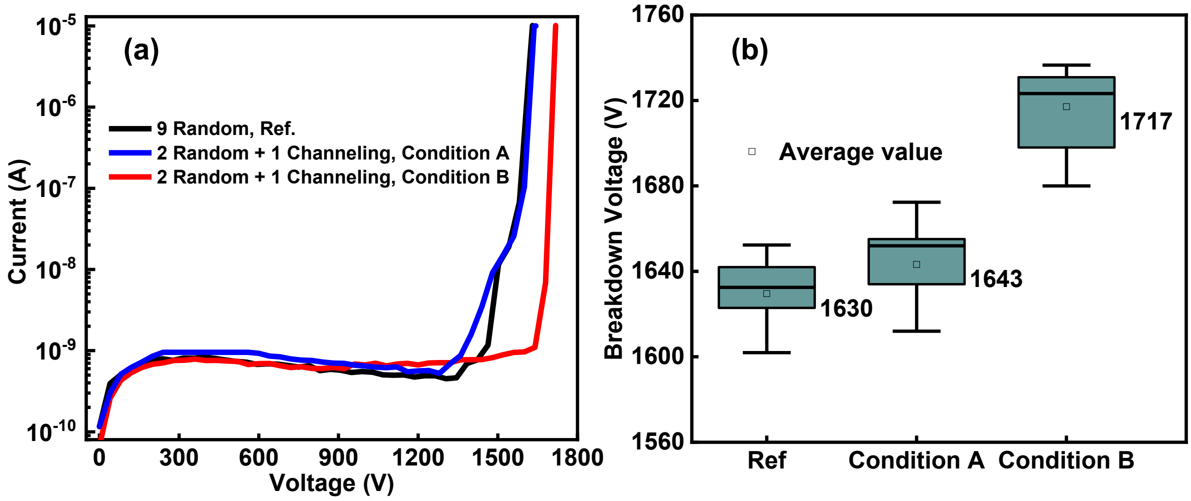
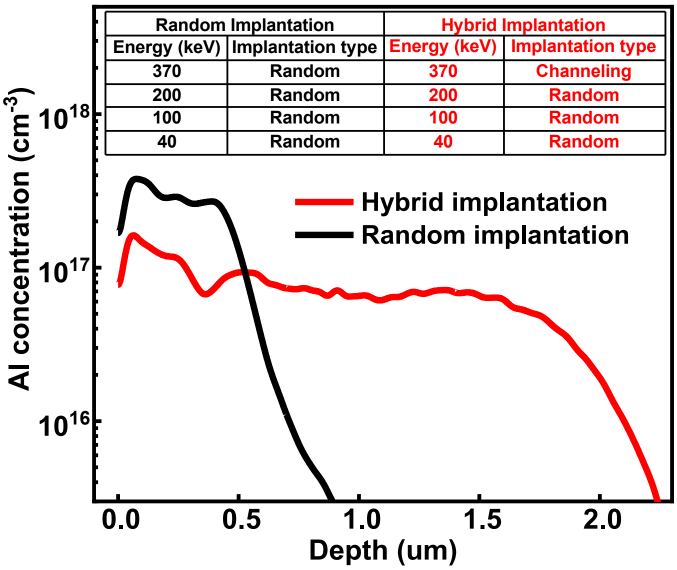


Fig. 3. (a) Measured reverse I-V characteristics for SiC diodes with different JTE implantation conditions; (b) Breakdown voltage distribution of SiC diodes (18 devices per group). Hollow squares denote the mean values, labeled with their respective average voltages of 1630 V, 1643 V, and 1717 V.

Channeling implantation can produce a deep and uniform box-like profile [5], which aligns well with the deep and homogeneous doping distribution required for an effective JTE structure. To further investigate the potential of channeling implantation in optimizing JTE performance, a comparative TCAD simulation study was performed using the device structure shown in Fig. 1. Both implantation schemes maintain the same total dose and implantation energy, with detailed parameters summarized in the table inserted in Fig. 4. In the hybrid scheme, channeling implantation was applied at 370 keV, while random implantation was used at other energies. As illustrated in Fig. 4, despite the same total dose and implantation energy, the hybrid implantation scheme results in a much deeper profile with a lower Al concentration compared to the random implantation approach.



Random Implantation		Hybrid Implantation	
Energy (keV)	Implantation type	Energy (keV)	Implantation type
370	Random	370	Channeling
200	Random	200	Random
100	Random	100	Random
40	Random	40	Random

Fig. 4. Comparison of simulated Al doping profiles under random-only and hybrid implantation conditions with the same number of implantation steps, energy values, and total dose, along with a detailed summary of the implantation schemes.

Fig. 5 presents the simulated reverse breakdown voltage characteristics of the diodes with JTE using the aforementioned two implantation schemes. The hybrid implantation scheme achieves a much higher breakdown voltage in the device along with a wider dose window for the JTE. This improvement can be attributed to its distinctive dopant distribution characteristics: on the one hand, the deeper implantation profile effectively mitigates electric field crowding at the main junction edge (shown in Fig. 6(a)), thereby increasing the breakdown voltage and extending the lower end of the dose window; on the other hand, under the same total dose, the hybrid scheme yields a lower peak Al concentration, which helps suppress the electric field at the JTE periphery—as validated by the two-dimensional electric field distribution shown in Fig. 6(b). As the dose increases, the random implantation scheme suffers from a rapid decrease in breakdown voltage due to a sharp rise in the JTE peripheral electric field. In contrast, the hybrid implantation maintains superior breakdown performance owing to its improved field distribution, thereby extending the upper end of the dose window. In summary, the hybrid implantation scheme facilitates enhanced breakdown voltage and broader process tolerance by producing a deeper and uniform dopant distribution with a low peak concentration.

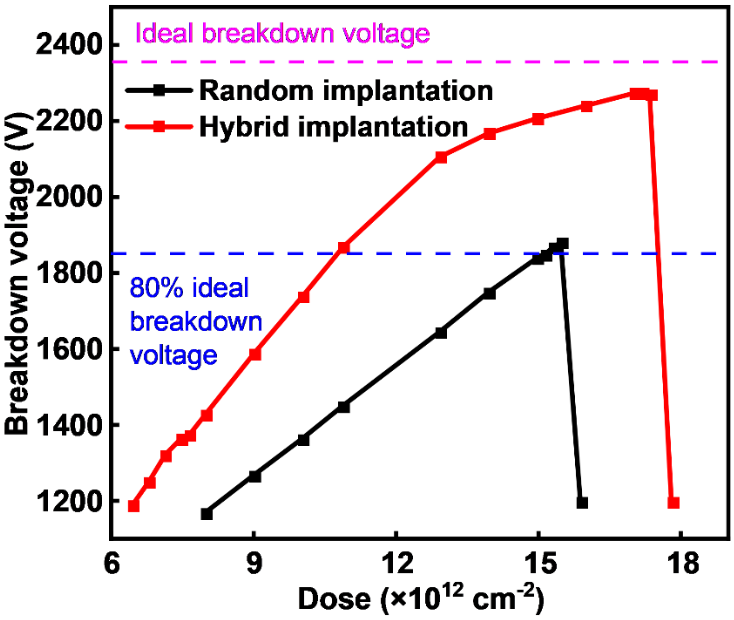


Fig. 5. Simulated results of breakdown voltage as a function of JTE dose in SiC p-n diodes with random and hybrid implantation.

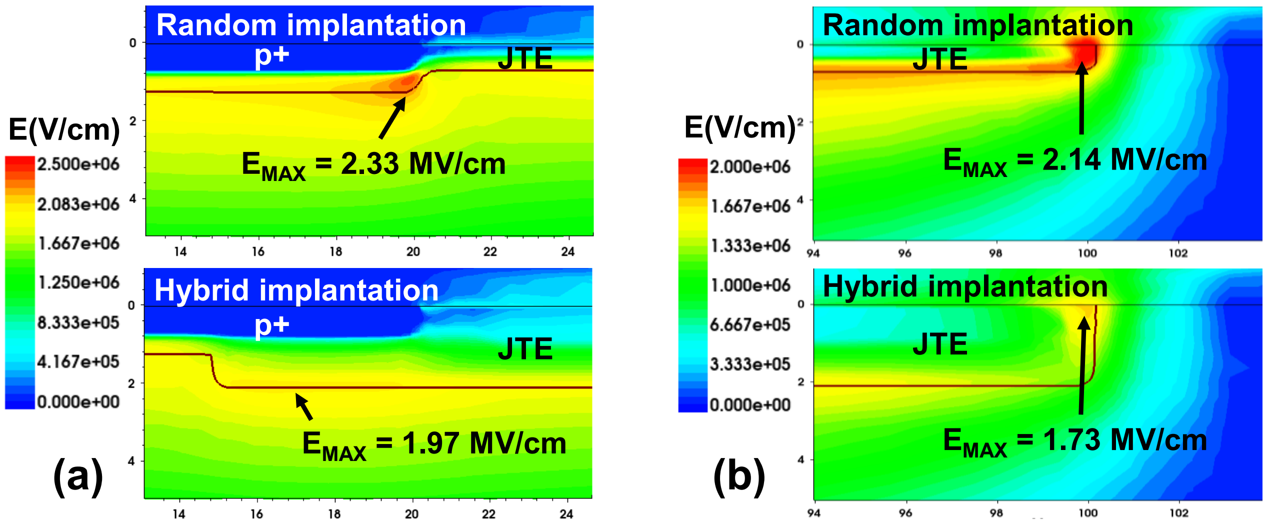


Fig. 6. Simulated electric field distributions at 1.2 kV reverse bias in diodes with JTE formed by random-only and hybrid implantation: (a) near the main junction edge, and (b) near the JTE edge.

Summary

This study systematically investigates the impact of hybrid implantation technology on the reverse blocking capability of the junction termination extension in 4H-SiC power devices. The proposed approach was thoroughly validated through experimental measurements and TCAD simulations. The results demonstrate that, compared to conventional random-only implantation, the hybrid implantation scheme offers two key advantages: first, with the same maximum implantation energy, it achieves a higher breakdown voltage and a wider dose window; second, in deep JTE applications, the hybrid scheme significantly simplifies the implantation process without degrading the breakdown voltage, thereby effectively reducing manufacturing costs. These findings confirm the potential of hybrid implantation technology to enhance both the electrical performance and cost effectiveness of SiC power devices, providing a reliable and efficient approach for the design of high-performance JTE structures.

Acknowledgments

This work was financially supported in part by Guangzhou Municipal Science and Technology Bureau, China under grant 2025A04J5383 and in part by Guangdong Basic and Applied Basic Research Foundation, China under grant 2023A1515011054.

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