Experimental Study of High Performance 4H-SiC Floating Junction JBS Diodes

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This work was supported in part by the National Natural Science Foundation of China under Grant 61804118, Grant 61774117 and Grant 61774119, in part by the Shaanxi Science and Technology Plan under Grant 2018pt02, in part by Wuhu and Xidian University special fund for industry-university-research cooperation under Grant XWYCXY-012019001, and in part by the Fundamental Research Funds for the Central Universities under Grant 20106205935.

ABSTRACT This paper reports the demonstration of a high performance 4H-SiC floating junction junction barrier Schottky (FJ_JBS) rectifier with a 30\(\mu\)m, \(6 \times 10^{15} \text{ cm}^{-3}\)-doped epitaxial layer. Extensive simulations have been performed to design, optimize and analyze the structure of the FJ_JBS rectifier. The fabricated FJ_JBS shows that breakdown voltage (\(BV\)) and differential \(R_{on,sp}\) are 3.4 kV, yielding the highest \(BV\) value reported for 4H-SiC FJ diodes, and 5.67 m\(\Omega\)-cm\(^2\), respectively. Compared with the conventional JBS, the \(BV\) value of FJ_JBS increases by 33.3\% and the \(R_{on,sp}\) only slightly rises by 6.2\%. The corresponding Baliga figure-of-merit (BFOM) (4 \(BV^2/R_{on−sp}\)) of this FJ_JBS diode is 8.16 GW/cm\(^2\).

INDEX TERMS 4H-SiC, FJ structure, JTE termination, FJ_JBS.

I. INTRODUCTION

4H-SiC power devices have received much attention for high-power applications due to the outstanding properties of this material, including its large critical electric field and high thermal conductivity [1]. Junction barrier Schottky (JBS) diodes, which were the first commercialized SiC devices, are ideal device for medium-voltage and fast-switching applications [2], [3]. However, there is a tradeoff between the breakdown voltage (\(BV\)) and specific on-resistance (\(R_{on−sp}\)) for conventional JBS structure, constraining further improvements to device performance. To solve this issue, the floating junction (\(FJ\)) structure has been applied to 4H-SiC power devices [4], [5]. This new structure can modulate the electric field distribution in the drift region, greatly improving \(BV\) at a constant \(R_{on−sp}\). However, although the shape of the FJ structure, design of the FJ structure underneath the termination region have been analyzed and reported, the design of the \(FJ\) device is still complex because the epitaxial layer parameters and the work mechanism of the termination structure should be redesigned and reanalyzed [6]–[9].

In this paper, the design of the epitaxial layer and termination structure for the FJ_JBS structure are first described and analyzed. Then, based on the analysis, we report the fabrication and experimental study of a high-performance 4H-SiC FJ_JBS rectifier adopting the designed epitaxial layer and termination structure. Finally, the conventional device and the \(FJ\) device are compared in terms of performance.

II. DEVICE STRUCTURE ANALYSIS

A. FJ JBS DEVICE STRUCTURE

The structures and electric field distributions at the breakdown condition of the conventional JBS and FJ_JBS are shown in Figure 1. For the conventional structure, it is clear that the depletion layer in the epitaxial layer extends from the surface to the substrate as the reverse voltage increases. There are three cases for the electric field distribution dependent on the doping concentration of the epitaxial layer (\(N_D\)) (assuming that the thickness of the epitaxial layer is constant), as shown in Figure 1(a).
and top epitaxial layer is forward biased. The forward biased through structure and the pn junction between the FJ structure terminated at the FJ structure, showing a p+ FJ structure. The depletion area in the top epitaxial layer is seen as a single pn junction between the top p+ FJ structures. Under this condition, the FJ device can be completely pinched off, and the peak electric field at the surface may remain nearly unchanged, indicating that the breakdown occurs at the FJ structure instead of the surface with the reverse voltage increasing continually. Therefore, it is known that the depletion layer in the epitaxial layer first extends from the surface to the FJ structure with the reverse voltage rising. Combined with our previous work [10], there are also three cases for the electric field distribution with different $N_D$ values (assuming that the thickness of the epitaxial layer is constant and the FJ structure is located in the middle of the epitaxial layer), as shown in Figure 1(b).

1) Case 1 (Premature breakdown state): When $N_D$ is at $N_{D1}$, which is larger than $N_{D1}$ in the Case 1 (top), the peak electric field at the surface reaches the critical value before the depletion layer extends to the substrate, implying premature breakdown occurs at the surface. There is only one triangular electric field distribution in the top epitaxial layer at the breakdown condition.

2) Case 2 (Critical state): With $N_D$ decreasing ($N_{D2} < N_{D1}$), if the peak electric field (which is infinitely close to the critical value) at the surface does not reach the critical value when the depletion layer extends to the FJ structure and the space between the FJ structure is pinched off by the depletion layer, implying premature breakdown occurs at the surface. Therefore, a rectangular electric field distribution in the top epitaxial layer remains nearly unchanged, and the depletion layer extends from the FJ structure to the substrate with the reverse voltage increasing continually. Under this condition, breakdown occurs at the FJ structure, which improves the reverse performance of the FJ device. Because the thicknesses of the top and bottom epitaxial layers are the same and the peak electric field at the surface is infinitely close to the critical value, the peak electric field at the FJ structure reaches the critical value when the depletion layer extends just to the substrate at the breakdown condition, indicating that the electric field distributions at the top and bottom are nearly the same, shown as two triangular shapes.

3) Case 3 (Punch-through state): When $N_D$ is at $N_{D3}$, if the peak electric field (which is infinitely close to the critical value) at the surface reaches the critical value before the depletion layer extends to the FJ structure and the space between the FJ structure is reversely pinched off and then the voltage drop of the bottom epitaxial layer rises. At the same time, the space between the two FJ structures is completely pinched off, and the peak electric field at the surface is lower than the critical value. Under this condition, the breakdown occurs at the FJ structure instead of the surface with the reverse voltage increasing continually. Therefore, it is known that the depletion layer in the epitaxial layer first extends from the surface to the FJ structure with the reverse voltage rising. Combined with our previous work [10], there are also three cases for the electric field distribution with different $N_D$ values (assuming that the thickness of the epitaxial layer is constant and the FJ structure is located in the middle of the epitaxial layer), as shown in Figure 1(b).

1) Case 1 (Non-punch-through state): When $N_D$ is at $N_{D1}$, the electric field at the surface reaches the critical value before the depletion layer extends to the substrate, producing a single triangular electric field distribution in the epitaxial layer.

2) Case 2 (Critical state): With $N_D$ decreasing ($N_{D2} < N_{D1}$), if the electric field at the surface reaches the critical value when the depletion layer extends just to the substrate, then there is also a single triangular electric field distribution in the epitaxial layer.

3) Case 3 (Punch-through state): When $N_D$ is at $N_{D3}$, if the electric field at the surface reaches the critical value after the depletion layer extends to the substrate, implying a trapezoidal electric field distribution or even a rectangular electric field distribution in the epitaxial layer when $N_D$ is too light in the epitaxial layer at the breakdown condition.

For the FJ device, because the FJ structures (p+ region) in the FJ device are discrete and floating, there is no potential difference between the FJ structure and surrounding epitaxial layer at the zero bias, indicating that the space between the two adjacent FJ structures is not pinched off by the depletion area and that there is a current path between the two adjacent FJ structures. Under this condition, the FJ device can be seen as a single pn junction between the top p+ area and the whole epitaxial layer. Therefore, when the lower reverse voltage is applied to the device, the depletion layer occurs only in the top epitaxial layer (extending form the surface to the FJ structure), which is consistent with the conventional device. With the reverse voltage increasing, the boundary of the depletion layer in the top epitaxial layer extends to the FJ structure. The depletion area in the top epitaxial layer is terminated at the FJ structure, showing a p^+n^-p^+ punched-through structure and the pn junction between the FJ structure and top epitaxial layer is forward bias. The forward biased pn junction makes that the electric field at the top boundary of the FJ structure should be nearly zero, inferring that the electric field distribution in the top epitaxial layer is nearly unchanged and triangular and that the voltage drop in the top epitaxial layer remains nearly unchanged too. Therefore, with the reverse voltage increasing continually, the pn junction between the FJ and bottom epi-layer is reversed and then the voltage-drop of the bottom epitaxial layer rises. At the same time, the space between the two FJ structures is completely pinched off, and the peak electric field at the surface may remain nearly unchanged, indicating that the breakdown occurs at the FJ structure instead of the surface with the reverse voltage increasing continually. Therefore, it is known that the depletion layer in the epitaxial layer first extends from the surface to the FJ structure with the reverse voltage rising. Combined with our previous work [10], there are also three cases for the electric field distribution with different $N_D$ values (assuming that the thickness of the epitaxial layer is constant and the FJ structure is located in the middle of the epitaxial layer), as shown in Figure 1(b).
is trapezoidal or even rectangular at the breakdown condition, which is different from the electric field distribution at the top.

Therefore, the electric field distribution can be divided into two parts when the FJ structure works normally, where the slope of each electric field distribution is higher than that of the conventional structure. Compared to the conventional device, the epitaxial layer resistance decreases in the FJ device because a higher \( N_D \) value is adopted to increase the slope of the electric field distribution at the same epitaxial layer thickness. Thus, it can be concluded that there is a new tradeoff between \( BV \) and \( R_{on-sp} \) for the FJ device and that the epitaxial layer should be redesigned to improve the performance of the FJ device over that of the conventional device.

**B. DESIGN OF THE EPITAXIAL LAYER FOR THE FJ JBS**

According to the analysis above, the parameters of the epitaxial layer for the FJ devices should first be designed. Typically, an epitaxial layer thickness of 30 \( \mu m \) is used for a 3 kV-rating SiC device. Therefore, the thickness of the epitaxial layer is selected as 30 \( \mu m \), and \( N_D \) should be redesigned for the FJ device. Based on our previous work [10], Figure 2(a), (b) and (c) show \( R_{on-sp}, BV \) and Baliga figure-of-merit (BFOM) of the FJ_JBS and conventional JBS for comparison versus \( N_D \), where the FJ structure is located in the middle of the epitaxial layer and the thickness, width and spacing of the FJ structure are 0.8 \( \mu m \), 3 \( \mu m \) and 3 \( \mu m \), respectively. Figure 2(a) shows that the \( R_{on-sp} \) of the FJ device decreases with increasing \( N_D \), which is consistent with the behavior of the conventional structure.

However, it is obvious that there is a very large difference in the \( BV \) distribution between the FJ and conventional device structures, as shown in Figure 2(b). \( BV \) exhibits an inflection point when \( N_D \) is approximately \( 7.5 \times 10^{15} \) \( cm^{-3} \). According to the working mechanism of the FJ device described above, it can be concluded that \( 7.5 \times 10^{15} \) \( cm^{-3} \) is a critical value (Case 2: Critical state). If \( N_D \) is lower than the inflection point in our analysis, the electric field distribution corresponds to Case 3: Punch-through state. The depletion layer can extend to the FJ structure successfully before the electric field at the surface reaches the critical value, implying that the electric field distribution appears in both the top and bottom of the epitaxial layers. Otherwise, premature breakdown occurs at the surface, indicating that the FJ structure does not work (Case 1: Premature breakdown state).

Moreover, to improve the tradeoff between \( BV \) and \( R_{on-sp} \), BFOM (\( 4BV^2/R_{on-sp} \)) versus \( N_D \) is displayed in Figure 2(c) to help design \( N_D \) appropriately. The BFOM of the FJ device also has an inflection point induced by the \( BV \) distribution. The BFOM first increases with increasing \( N_D \) and drops sharply when \( N_D \) exceeds the inflection point. Thus, \( N_D \) should be lower and closer to the inflection point to achieve better performance. Our analysis suggests that the doping concentration window of the FJ device is between \( 6 \times 10^{15} \) \( cm^{-3} \) and \( 7.5 \times 10^{15} \) \( cm^{-3} \), which is different from the configuration of the conventional device. Moreover, the BFOM of the FJ device can be increased by approximately 60% compared with the conventional device configuration at suitable \( N_D \) when the thickness of the epitaxial layer is constant, implying that the FJ device performs better. Considering the deviation in the epitaxial layer parameters and termination efficiency, the doping concentration and thickness of the epitaxial layer for the FJ device are selected as \( 6 \times 10^{15} \) \( cm^{-3} \) and 30 \( \mu m \) in our work, respectively, where the FJ structure is located in the middle of the epitaxial layer. The parameters of the epitaxial layer designed for the FJ device are shown in Table I too, and the optimal values of \( R_{on-sp} \) and

![Figure 2. Dependence of \( R_{on-sp} \) (a) BV (b) and BFOM (c) in FJ device and conventional device for varying \( N_D \).](image-url)
TABLE 1. Parameters of the epitaxial layer.

| Parameters            | Value          |
|-----------------------|----------------|
| Doping concentration  | $6 \times 10^{19}$ cm$^{-3}$ |
| Total thickness       | 30 $\mu$m      |
| Thickness of the bottom layer | 15 $\mu$m  |
| Thickness of the top layer | 15 $\mu$m    |
| FJ width              | 3 $\mu$m       |
| FJ spacing            | 3 $\mu$m       |

$BV$ are 5.4 mΩ cm$^{-2}$ and 3.6 kV, respectively, corresponding to a BFOM of 9.6 GW/cm$^2$.

C. MODELS AND PARAMETERS USED IN THE SIMULATIONS

To achieve precise results, the simulations are carried out using the 2-D device simulator ISE-DESSIS at room temperature. The primary function of this simulator is to solve Poisson’s equation along with the continuity and drift diffusion equations to simulate the characteristics of a semiconductor device. The most important simulation models, such as the incomplete ionization model, carrier generation-recombination model and impact ionization model, are used in our analysis without considering dopant activation or defects.

1) INCOMPLETE IONIZATION MODEL

Because of the large ionization energies, the dopants in 4H-SiC are actually in the freeze-out regime at room temperature. Therefore, incomplete ionization should be considered, as shown below [11], [12]:

$$N_A^+ = N_A \left[ \frac{1 + 4g_A \left( \frac{N_A}{N_C} \right) e^{\frac{E}{kT}}} {2g_A \left( \frac{N_A}{N_C} \right) e^{\frac{E}{kT}}} \right]^{0.5} - 1$$  \hspace{1cm} (1)

$$N_D^+ = N_D \left[ \frac{1 + 4g_D \left( \frac{N_D}{N_C} \right) e^{\frac{E}{kT}}} {2g_D \left( \frac{N_D}{N_C} \right) e^{\frac{E}{kT}}} \right]^{0.5} - 1$$  \hspace{1cm} (2)

where $N_D$ and $N_A$ are the total doping concentrations and $EA$ and $ED$ are the acceptor and donor ionization energy levels, respectively ($EA$ (Al)≈200 meV, $ED$(N)≈90 meV) [13]. In addition, $k_B$ is the Boltzmann constant, and $g_A$ and $g_D$ are the appropriate degeneracy factors for the valence and conduction bands, which are assumed to be 4 and 2, respectively. Moreover, $N_V$ and $N_C$ are the densities of states for holes and electrons, respectively, which can be described as [14]

$$N_V = 2.494 \times 10^{19} \cdot \left( \frac{T}{300} \right)^{3/2}$$  \hspace{1cm} (3)

$$N_C = 1.689 \times 10^{19} \cdot \left( \frac{T}{300} \right)^{3/2}$$  \hspace{1cm} (4)

Carrier Generation-Recombination Model: The Shockley-Read-Hall (SRH) and Auger recombination models are used in this work to simulate the carrier generation-recombination effect. The SRH recombination-generation rate and Auger recombination rate are modeled with the equations below [13], [15]–[17]:

$$R_{SRH} = \frac{pn - n_i^2}{\tau_p \left( n + n_i \exp \left( \frac{E_i - E}{kT} \right) \right)} + \tau_n \left( p + n_i \exp \left( \frac{E_i - E}{kT} \right) \right)$$  \hspace{1cm} (5)

$$R_{Auger} = 3 \times 10^{-29} \left( pn^2 - n_i^2 \right) + 3 \times 10^{-29} \left( np^2 - n_i^2 \right)$$  \hspace{1cm} (6)

Here, $n_i$ is the effective intrinsic carrier concentration, $E_i$ is the intrinsic Fermi level, and $E_T$ is the recombination center energy level, which is set to 0 in our simulation. Moreover, $\tau_n \beta$ and $\tau_p \beta$ are the electron and hole lifetimes, which are assumed to be 2.5 $\mu$s and 0.5 $\mu$s, respectively.

2) IMPACT IONIZATION MODEL

The carrier generation rate in the avalanche breakdown condition is described by the equation below:

$$G = \alpha_p n_p + \alpha_n p_n$$  \hspace{1cm} (7)

where $\alpha_n$ and $\alpha_p$ are the impact ionization coefficients for electrons and holes, and $J_n$ and $J_p$ are the electron and hole current densities, respectively. The impact ionization coefficients are modeled as:

$$\alpha_{n,p} = A_{n,p} \exp \left( \frac{B_{n,p}}{E} \right) C_{n,p}$$  \hspace{1cm} (8)

where $E$ is the electric field in the direction of current flow. $A_{n,p}$, $B_{n,p}$ and $C_{n,p}$ are respectively found to be $7.26 \times 10^6$, $2.34 \times 10^8$V/cm and 1 for electrons, and $6.85 \times 10^6$, $1.41 \times 10^8$V/cm and 1 for holes by fitting the reported experimental results [18], [19].

D. DESIGN AND ANALYSIS OF THE TERMINATION STRUCTURE FOR THE FJ JBS

In addition, a junction termination extension (JTE) structure is designed for the FJ device to achieve excellent reverse performance. The schematic cross-section of the FJ_JBS diode with the optimized termination structure is shown in Figure 3(a). According to our previous work [9], the FJ structure underneath the termination region is selected as the discontinuous floating junction structure in this work to protect the FJ structure underneath the termination region from occurring premature breakdown.

Here, a guard-ring-assisted JTE plus outer-rings (GA-JTE-OR) structure is adopted for our designed FJ device [20]. This choice mainly arises from two aspects. 1) Compared with double-zone JTE, step-double-zone-JTE and counter-doped JTE, the fabrication process of GA-JTE-OR is compatible...
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FIGURE 3. (a) Cross-sectional view of the 4H-SiC FJ_JBS diode, (b) SEM image of the FJ structure, and (c) top view of the fabricated FJ device.

FIGURE 4. BV of the FJ device versus the JTE dose for the single-zone JTE and GA-JTE-OR.

TABLE 2. Parameters of the GA-JTE-OR termination structure.

| Parameters                  | Value   |
|-----------------------------|---------|
| Length of the JTE           | 150 µm  |
| Width of the inner rings    | 8 µm    |
| Spacing of the inner rings  | 3 µm    |
| Number of the inner rings   | 5       |
| Width of the outer rings    | 3 µm    |
| Spacing of the outer rings  | 2 µm    |
| Number of the outer rings   | 15      |

With our FJ_JBS fabrication process, where the GA parts can be fabricated with the main junction in the active region and only one additional implantation process is needed to form the JTE and OR parts [21]–[23]. 2) The GA-JTE-OR can shift the highest peak electric field from the edge of the main junction to the last guard ring. Additionally, both GA and OR structures can relieve the high electric field peak at the edge of the main junction and the main JTE structure by increasing the number of the peak electric field, which can enhance the device reliability [24], [25].

The parameters of the GA-JTE-OR termination structure designed for the FJ device are shown in Table 2. The length of the JTE structure is 150 µm. The width and spacing of the inner rings, formed with the main junction, are 8 µm and 3 µm, respectively, which can decrease the sensitivity of BV for the low-dose case of the JTE structure [24], [26]. In addition, the width and spacing of the outer rings, formed with the JTE structure, are 3 µm and 2 µm, respectively, which can reduce the sensitivity of BV for the high-dose case of the JTE structure [20], [25]. Additionally, 5 inner rings and 15 outer rings are used to effectively shift the field crowding away from the main junction and the edge of the main JTE structure [25], [26].

Figure 4 compares the simulated BV values of the single-zone JTE and the optimized GA-JTE-OR, and the breakdown point is set as the current abruptly increases. The GA-JTE-OR shows a better JTE dose tolerance, implying that our selected JTE structure parameters are reasonable. The JTE dose window of the GA-JTE-OR that makes BV exceed 3.3 kV is 1.8 × 10^{13} cm^{-2}. For comparison, the single-zone JTE has a narrow window of only 0.2 × 10^{13} cm^{-2}.

To describe the working mechanism of the JTE structure for the FJ device, the effect of the JTE dose on BV of the FJ device that adopts the GA-JTE-OR structure is analyzed. The electric field distributions at the breakdown point with different JTE doses (6.0 × 10^{12} cm^{-2}, 1.5 × 10^{13} cm^{-2}, and 4.2 × 10^{13} cm^{-2}) are simulated, as shown in Figure 5(a). In addition, the electric field distributions along the surface (AA') and FJ location (BB') are shown in Figure 5(b). When the JTE dose is lower or higher than the optimal value, the maximum electric field (E_{max}) occurs at the inner or outer junction termination region, respectively, implying that premature breakdown occurs at the surface. However, if the JTE dose is suitable, E_{max} is notably located at the FJ region. In this case, the FJ device exhibits bulk breakdown, leading to the surface electric field of the device at the termination region being reduced and uniform and BV increases effectively. Meanwhile, it can be observed that the extension of the electric field at the surface is larger than the extension of the electric field at the FJ structure, indicating that the chip area of the FJ device is determined by the termination structure, which is consistent with the conventional device. The electric field distributions along the Y-coordinate at the position E_{max} (DD', EE' and FF') are shown in Figure 5(c). The top and bottom epitaxial layers can both withstand the high reverse voltage effectively if E_{max} occurs in the bulk. In addition, there is almost no electric field distribution in the bottom epitaxial layer at E_{max} when the electric field at the surface reaches its critical value. Therefore, it can be inferred that the 4H-SiC FJ device will achieve better reverse performance if the breakdown occurs at the bulk region based on a reasonable termination design.

III. DEVICE FABRICATION AND CHARACTERISTICS

The devices were fabricated according to the analysis above. First, the epitaxial layer was grown based on our design.
After RCA cleaning, surface passivation was accomplished by thermal oxidation in wet oxygen and a 200nm SiO2 layer was formed by PECVD process. Then the surface p+ region for the JBS and GA-JTE-OR termination structures were formed using a standard multiple-energy Al⁺ implantation fabrication process, where the total dose of the p+ region and JTE are set as $2.5 \times 10^{14} \text{ cm}^{-2}$ and $1.5 \times 10^{13} \text{ cm}^{-2}$, respectively. Activation annealing was carried out in Ar at 1650 °C for 40 min. Additionally, the back ohmic metal and top Schottky metal used in our devices were both Ni, where the annealing conditions were 1000 °C for 3 min and 650 °C for 3 min, respectively, in Ar. Finally, a thick polyimide was formed as the last passivation layer. The top view of the fabricated FJ_JBS is shown in Figure 3(c). In addition, the FJ Schottky barrier diode(FJ_SBD) structure and conventional devices were fabricated simultaneously for comparison. The typical reverse characteristics of the fabricated FJ_JBS and other structures are shown in Figure 6(a). Compared with the BV value of 2.55 kv achieved by the conventional JBS, the BV value of the fabricated FJ_JBS is as high as 3.4 kv at 100 µA, increasing by approximately 850 V (33.3%) and yielding the highest BV value reported for 4H-SiC FJ devices. The experimental results demonstrate the advantage of the FJ structure for enhancing the device breakdown performance. On the other hand, BV of the fabricated FJ_SBD and SBD are 3.53 kv and 2.6 kv, respectively, at 1 mA, confirming that the FJ structure plays an important role in improving the device reverse characteristic too. Meanwhile, both the fabricated conventional and FJ devices are measured before and after the wafer is diced. The results indicate that there is no change in the reverse characteristic for the conventional and FJ devices, demonstrating that the reverse performance of the FJ device dose not degrade after scribing.

Figure 6(b) shows the forward characteristics of the fabricated 4H-SiC FJ_JBS and other three structures. The current densities of the FJ devices are slightly lower than that of the conventional devices due to the FJ structure embedding the epitaxial layer. The differential values of $R_{on,sp}$ are measured to be 5.67 mΩ·cm², 5.34 mΩ·cm², 5.20 mΩ·cm² and 5.13 mΩ·cm² for FJ_JBS, FJ_SBD, conventional JBS and SBD, respectively. The simulated I-V relation of the FJ_JBS is also shown in Figure 6(b). Good agreement between the simulated and experimental results is indicated, proving that the selected parameters in the simulations are reasonable.

The mean curves and error bars of BV and $R_{on-sp}$ for the fabricated devices are shown in Figure 6(c), and more than 30 diodes are measured for each type. The four types of fabricated devices maintain stable forward and reverse performance. Furthermore, the experimental results verify our design and confirm the reasonableness of the selected parameters.

Figure 7(a) shows the tradeoff between BV and $R_{on-sp}$ for our fabricated devices and some other reported results. Our FJ_JBS successfully breaks the theoretical 1-D limit of a unipolar-SiC device (considering a substrate resistance of 0.6 mΩ·cm²), which is uniquely determined by the material.

After the bottom epitaxial layer grown, the FJ structure was formed by selective multiple-energy Al⁺ implantation with a box profile on the bottom epitaxial layer, where the total dose was $8 \times 10^{13} \text{ cm}^{-2}$. Figure 3(b) shows the SEM image of the fabricated FJ structure in the epitaxial layer, verifying that a box implantation region with a depth of approximately 0.7 µm was achieved, where the width and spacing of the FJ structure were both approximately 3 µm. Finally, the top epitaxial layer was grown. The thickness and doping concentration of the bottom and top epitaxial layers were 15 µm and $6 \times 10^{15} \text{ cm}^{-3}$, respectively.
properties \( R_{\text{on-sp}} = \frac{4BV^2}{\varepsilon_s \mu_n E_c^3} \), showing that the 1-D limit of a unipolar-SiC devices can be experimentally broken by the new \( FJ \) device structure [35].

Figure 7(b) presents the calculated BFOM values \( \text{BFOM} = 4BV^2/R_{\text{on-sp}} \) of the fabricated JBS. The \( FJ \)-JBS achieves a BFOM value of 8.16 GW/cm\(^2\) in this paper, which is lower than that in Ref. [6,7]. Moreover, the fabricated \( FJ \) devices exhibit performance superior to conventional devices, in agreement with our analysis, proving that the \( FJ \) structure can effectively improve the device electrical performance.

Finally, as shown in Figure 2(c), thanks to a \( FJ \) device which adopts a relatively high doping concentration (exceeding \( 6 \times 10^{15} \text{cm}^{-3} \) and closing to \( 7.5 \times 10^{15} \text{cm}^{-3} \)) for the epitaxial layer can achieve a \( BV \) value nearly equal to that available with \( 6 \times 10^{15} \text{cm}^{-3} \) at a lower \( R_{\text{on-sp}} \), it can be inferred that the \( FJ \) device might exhibit better tradeoff in the future if a slightly higher doping concentration of the epitaxial layer is selected and precisely controlled. Moreover, the switch characteristic of the \( FJ \) device is also important, the switch characteristic and corresponding device performance will be evaluated in the future.

**IV. CONCLUSION**

In this paper, we introduce a newly fabricated high-performance 4H-SiC \( FJ \)-JBS diode based on a designed epitaxial layer with a thickness of 30 \( \mu \text{m} \), a doping concentration of \( 6 \times 10^{15} \text{cm}^{-3} \), and the \( FJ \) structure is located in the middle of the epi-layer. The \( BV \) value of the fabricated \( FJ \)-JBS is 3.4 kV, yielding the highest \( BV \) value reported for 4H-SiC \( FJ \) diodes. In contrast, the conventional JBS, whose epitaxial layer is grown twice (15 \( \mu \text{m} \) plus another 15 \( \mu \text{m} \)), fabricated on the same wafer achieves a \( BV \) value of only 2.55 kV, implying that the \( FJ \) structure plays an important role in increasing the device reverse performance and that our design is reasonable. The corresponding BFOM of this \( FJ \)-JBS diode is 8.16 GW/cm\(^2\).

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