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Study of leakage current degradation based on stacking faults expansion in irradiated SiC junction barrier Schottky diodes

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A comprehensive investigation was conducted to explore the degradation mechanism of leakage current in SiC junction barrier Schottky (JBS) diodes under heavy ion irradiation. We propose and verify that the generation of stacking faults (SFs) induced by the recombination of massive electron–hole pairs during irradiation is the cause of reverse leakage current degradation based on experiments results. The irradiation experiment was carried out based on Ta ions with high linear energy transfer (LET) of 90.5 MeV/(mg/cm^2). It is observed that the leakage current of the diode undergoes the permanent increase during irradiation when biased at 20% of the rated reverse voltage. Micro-PL spectroscopy and PL micro-imaging were utilized to detect the presence of SFs in the irradiated SiC JBS diodes. We combined the degraded performance of irradiated samples with SFs introduced by heavy ion irradiation. Finally, three-dimensional (3D) TCAD simulation was employed to evaluate the excessive electron–hole pairs (EHPs) concentration excited by heavy ion irradiation. It was observed that the excessive hole concentration under irradiation exceeded significantly the threshold hole concentration necessary for the expansion of SFs in the substrate. The proposed mechanism suggests that the process and material characteristics of the silicon carbide should be considered in order to reinforcing against the single event effect of SiC power devices.

Keywords: 4H-SiC JBS diode, heavy ion irradiation, single event effect, single event leakage current degradation

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1. Introduction

SiC JBS diode is the first commercialized product in silicon carbide market and has taken a significant place in the power device application.[1] The use of 1200-V 4H-SiC JBS diodes improved the power efficiency by 6% compared to Si diodes in DC–DC conversion circuits.[2] Meanwhile, the critical displacement energy of SiC is 21.8 eV, which suggests the possibility of displacement defects in 4H-SiC under irradiation is generally small.[3] Therefore, SiC JBS diodes have the potential to be used in the power supply system in space environment.

However, a large number of results of heavy ion experiments demonstrated that the leakage current of SiC JBS diodes would increase at low reverse-bias voltage under heavy ion irradiation.[4–6] Researchers have reported that a high temperature in the ion deposition region (1000 K) caused intermixture of the metal and semiconductor at the Schottky interface, which increased the leakage current.[7] And study reported that there were very localized extreme energy pulses induced by heavy ions that exceeded the capabilities of the metal semiconductor interface, leading to the Schottky barrier height (SBH) degradation.[8] Nevertheless, recent studies have indicated that the barrier height remained unchanged after irradiation, suggesting that the increasing of leakage current was not attributed to variations in the inhomogeneity of the SBH.[9]

The extended defects and traps in SiC power devices introduced by heavy ion irradiation were studied. Corinna Martinella *et al.* reported that irradiation might introduce various types of extended defects in SiC devices.[10] Für *et al.* used DLTS and minority carrier transient spectroscopy to investigate electrically active defects in SiC Schottky diodes after heavy ion irradiation. It reported that the DLTS peak with similar parameters to "C" peak might attributed to stacking faults.[11] Instead, we considered the defects induced by heavy ion irradiation as the primary cause of the degradation in leakage current. The former studies indicated that heavy ion irradiation might induce extend defects in SiC power devices. However, there was no evidence to confirm the type of extend defects induced by irradiation.

Researchers found that when the SiC bipolar device was conducted, the energy generated by the recombination of electron–hole pairs would transform BPDs (basal plane dislocations) near substrate into SFs, which would result in the degradation of the reverse current of device.[12] There are also some papers that report SFs in SiC diodes. Brosselard *et al.* reported that SFs were detected by electroluminescence in 3.5-kV SiC JBS diode because PN junction conducted under relative low voltage.[13] Meanwhile, Galeckas *et al.* employed PL imaging on SiC epilayer and found SFs after 75-keV Sb+ ions implant and 2.5-MeV proton irradiation.[14] It should be noted

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that heavy ion irradiation could excite a significant number of electron–hole pairs along the incident path, which might induce the formation of SFs.

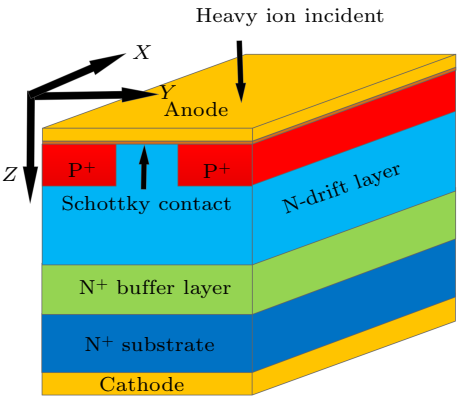
This paper focused on the mechanism of the degradation of leakage current at low reverse voltage in SiC JBS diodes under heavy ion irradiation. To observe the degradation of leakage current, SiC JBS diodes were subjected to heavy ion irradiation at various reverse bias voltages. PL spectroscopy and imaging of irradiated devices were employed to detect SFs in the irradiated devices. An insightful mechanism of leakage current degradation in irradiated diodes was proposed, demonstrating that the stacking faults, which were triggered by the energy released from the recombination of electron–hole pairs, were likely responsible for the degradation. TCAD 3D simulations were employed to investigate the concentration of excessive electron–hole pairs under heavy ion irradiation. The expansion velocity and size of SFs under irradiation were calculated according to the excessive hole concentration in simulation.

2. Experiment results

2.1. Irradiation experiments results

The 1200-V SiC JBS diodes were designed and manufactured. The detailed structural parameters of 1200-V SiC JBS diodes are shown in Fig. 1. These diodes were fabricated in a wafer foundry based on our own designs. Before ion irradiation, the package material of the sample devices was removed to expose the chip surface, as the heavy ions had a limited range in the package material.

The heavy ion irradiations were conducted at Heavy Ion Research Facility in Lanzhou (HIRFL) of Institute of Modern Physics of the Chines Academy of Sciences. The chosen heavy ion species was ^{181}Ta, with linear energy transfer values of 90.5 MeV/(mg/cm^2), simulating the worst-case scenario in a space environment. The energy of used ions was 943.3 MeV and the fluence level was set near 1.2×10^5 ions/cm^2 (the average flux level was 500 ions/cm^2/s$\pm$5%) at the chip surface. The range of ions in SiC was about 40.1 μm, which covered the sensitive area of diodes (epitaxial layer and part of substrate). All the irradiations were performed at normal incidence and room temperature. The cathode of the device was biased and leakage current was monitored by Keithley 2657A in real-time during irradiation. And it sampled 100 times per second, capturing leakage current every 0.01 s.



Parameter	Value
N$^-$ drift layer doping/depth	1×10^{16} cm^{-3}, 10 μm
N$^+$ substrate doping/depth	1×10^{20} cm^{-3}, 180 μm
N$^+$ buffer layer doping/depth	5×10^{17} cm^{-3}, 1 μm
P$^+$ regions doping/depth/width	1×10^{19} cm^{-3}, 0.6 μm, 2 μm
Schottky contact Width/thickness/material	3 μm, 0.1 μm, titanium

Fig. 1. The 3D structure of 120-V SiC JBS diode used in irradiation and the structure parameters is shown in Table 1.

Table 1 presents the forward voltage under rated current and leakage current under low voltage for the selected devices before irradiation (DUT#1∼DUT#5). It demonstrates that the electrical performance of selected devices has a high degree of consistency and there. And there are no critical defects (carrot defects, triangular defects, drop-out defects, stacking fault, and so on) in samples due to normal and stable electrical characteristics. Meanwhile, it is concluded that conducting irradiation experiments on these five devices would not result in experimental bias due to characteristic differences among the devices.

Table 1. The electrical parameters of selected devices before irradiation.

Devices	Forward voltage (V) $-V_F = 15$ V	Blocking voltage (V) $-I_R = 1$ mA	Leakage current (μA) $-V_R = 1200$ V
DUT#1	1.49	1785	0.95
DUT#2	1.47	1775	1.25
DUT#3	1.49	1786	0.96
DUT#4	1.46	1780	1.67
DUT#5	1.48	1784	1.01

Figure 2(a) illustrates the change in reverse leakage current of the 1200-V SiC JBS diodes at biases of different reverse voltages under irradiation conditions. It is observed that under Ta ion irradiation, the reverse current of the device does not degrade when subjected to a reverse voltage of 200 V. At a reverse voltage of 250 V, the leakage current of DUT#2 begins to increase at a fluence of 2×10^4 ions/cm^2. Furthermore, the degradation of leakage current in the devices occurs at lower fluence levels with increasing reverse voltage. Figure 2(b) illustrates the variation in leakage current of the irradiated diode

within the fluence of 10^4 ions/cm^2. It is observed that at a reverse voltage of 350 V, the leakage current of DUT#3 starts to increase at a fluence of 2300 ions/cm^2. For DUT#4, the leakage current begins to degrade at the fluence of 1009 ions/cm^2 at biased voltage of 350 V. When the reverse voltage increases to 400 V, DUT#5 experiences single event burnout at a fluence of 350 ions/cm^2. It is evident that as the reverse voltage increases, both the rate and magnitude of leakage current degradation in the diodes increase.

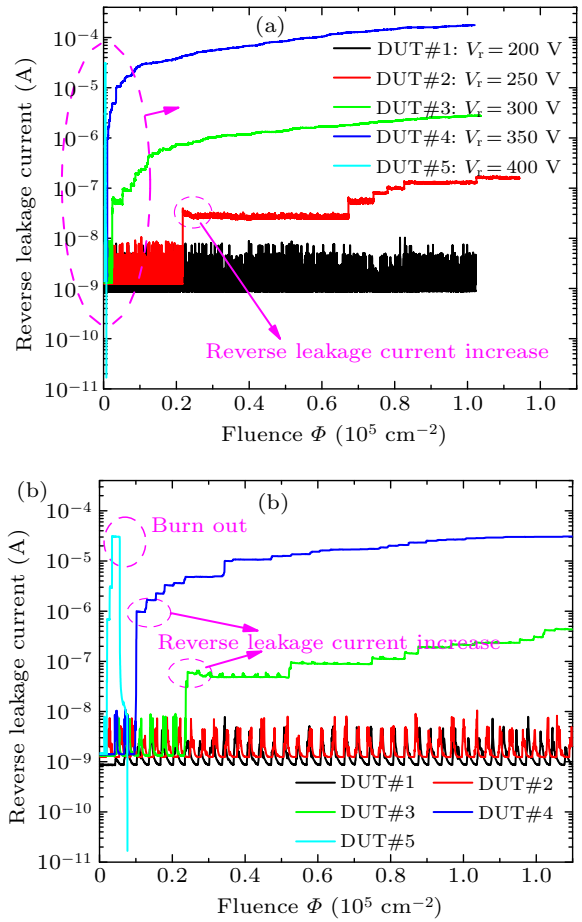


Fig. 2. (a) The change in reverse leakage current of 1200-V SiC JBS diodes at biases of different reverse voltages under irradiation (LET = 90.5 MeV/(mg/cm^2)). (b) The variation in leakage current of the irradiated diodes within the fluence of 10^4 ions/cm^2.

2.2. Defects observation results and analysis

The results of irradiation experiments suggest that some defects or damages are induced in SiC JBS diodes under irradiation with biased at low reverse voltage. To investigate these induced defects, micro-PL spectroscopy and PL micro imaging techniques were employed. PL micro-imaging is a fast and non-destructive technique for the detection of extended defects in SiC. The band-edge luminescence weak near extended defects in SiC but those extended defects exhibit unique luminescence at specific wavelengths, which are dependent on the defect type under PL imaging. The micro-PL spectrums of the irradiated devices were obtained at room temperature to determine the band energy associated with the defects. Subsequently, micro-PL imaging was performed at this specific band energy to spatially profile the distribution and shape of the defects.

The irradiated SiC JBS diodes (DUT#1, DUT#2, DUT#3, DUT#4) were chosen to detect the induced defects. After removing the surface metal layer of the irradiated diodes, PL observations were conducted to detect the induced defects. The PL excitation was accomplished using a 390-nm line from an He–Cd laser, which was then dispersed with a grating monochromator and detected by a photomultiplier.

Figure 3(a) depicts the micro-PL spectra obtained from the irradiated SiC JBS diodes at room temperature. Since the excitation wavelength exceeds 380 nm, the peaks associated with the band edge of 4H-SiC are not evident. It is observed that the irradiated chips except DUT#1 displayed the intensity peak near 424 nm, consistent with the findings of PL spectra acquired from areas with single Shockley SFs in the 4H-SiC.[15] Additionally, DUT#1 does not exhibit any significant peaks within the wavelength range of 400 nm to 550 nm. This absence can be attributed to the lack of degradation in leakage current during irradiation at a reverse voltage of 200 V, suggesting that the irradiation does not introduce relevant defects in DUT#1. This observation suggests that heavy ion irradiation induce the formation of stacking faults in diodes.

Meanwhile, the observed PL spectra peaks of irradiated diodes are quite broad. And the PL spectra of DUT#4 is much different from others. Stacking faults could be classified into various types, based on factors like the specific direction of Si-core slip. PL spectra peaks for single Shockley SF (1SSF) is around 424 nm, double Shockley SF (2SSF) at 503 nm, quadruple SSF and multilayer frank SF at approximately 460 nm.[16] As shown in Fig. 3(a), the peaks in PL spectra of DUT#4 are also observed around 460 nm and 503 nm, corresponding to various SF types. The observed broad peaks suggests that the defects introduced by heavy ion irradiation are not be limited to single stacking fault type, and the irradiation process involves complex transformations among different SF types when biased voltage is high. The precise identification of the specific SF would be conducted in our subsequent work.

Figure 3(b) shows the micro-PL imaging of irradiated diode (DUT#3) at the wavelength corresponding to the intensity peak (424 nm). The emission areas of irradiated diode exhibit several distinct right-angled triangular shapes, confirming their identification as stacking faults, as previously reported in other studies.[12,17] Based on the aforementioned results, a significant increase in the number of stacking faults is observed in the diode after irradiation with heavy ions, thereby indicating that the incidence of heavy ions introduced stacking faults into the device. This occurrence is attributed to the

degradation of reverse leakage current following heavy ion irradiation.

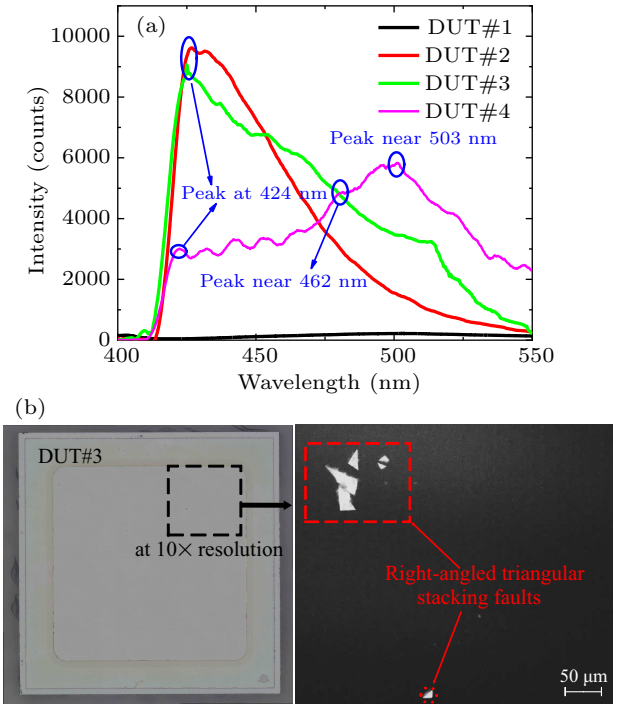


Fig. 3. (a) The micro-PL spectra from irradiated SiC JBS diodes at room temperature. (b) The micro-PL imaging of irradiated SiC JBS diode (DUT#3) near 420 nm.

2.3. Irradiated sample electrical characteristics

In Figs. 4(a) and 4(b), the forward and reverse *I*–*V* characteristics of DUT#3 before irradiation and after irradiation are depicted. It is observed that the reverse leakage current of the diode increases significantly after irradiation. Meanwhile, the forward current of the diode shows negligible variation at low current levels before and after irradiation, thereby establishing that current degradation is unrelated to Schottky contact damage. This observation aligns with recent research findings.[9]

However, the resistance of the irradiated diode increases slightly at high current level. This phenomenon is likely due to the introduction of SF within the diode by irradiation, resulting in the reduction of the bipolar current from PN junction conduction under high current conditions. It was demonstrated that the carrier lifetime was remarkably shortened inside the expanded SFs. For SiC bipolar devices, the reduced conductivity modulation effect in the voltage blocking region due to the shortened lifetime was a major reason for the resistance increase.[18] When a high external voltage is applied in SiC JBS diode, leading to PN junction conduction and the occurrence of the conductivity modulation, SFs introduced by irradiation contributes to the increase in irradiated diode resistance.

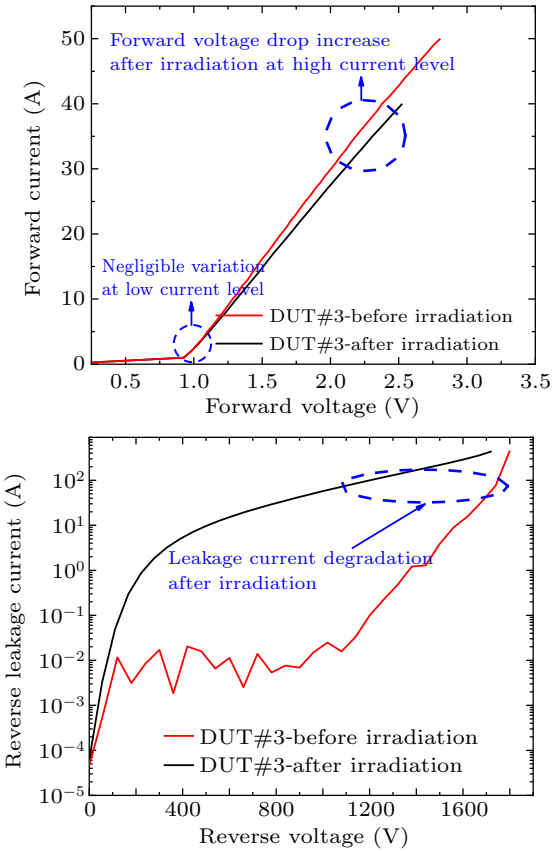


Fig. 4. (a) The forward *I*–*V* characteristics of DUT#3 before irradiation and after irradiation. (b) The reverse *I*–*V* characteristics of DUT#3 before irradiation and after irradiation.

3. Mechanism discussion and 3D TCAD simulation results

3.1. Mechanism discussion

An insightful mechanism for the degradation of leakage current under heavy ion irradiation is proposed based on experimental results. Building upon our prior experimental findings, we postulate that the degradation of leakage current in SiC JBS diodes exposed to heavy ion irradiation can be attributed to the presence of SFs induced by the incident heavy ions.

When heavy particles incident, inducing the excitation of electron–hole pairs, these pairs initiate the recombination process along the incident path. When the diode is negatively biased, an electric field is established within the diode, leading to the motion of holes and electrons. Once the electric field peak relocates into the epitaxial layer due to kirk effect and carriers move under electric field, the recombination of electron–hole pairs takes place near the electric field peak. This recombination process releases a significant amount of energy due to the combination of electron–hole pairs. Subsequently, BPDs near substrate undergo transformation into stacking faults as a consequence of the energy generated during electron–hole pair recombination. The forming of SFs provides a pathway for reverse leakage current.

Figure 5(a) illustrates the process of BPDs being converted into SFs under heavy ion irradiation. The activation energy for glide of dislocations in SiC is about 2.5 eV and thus, without the recombination energy, it would be a near impossibility for dislocations to nucleate and glide at room temperature.[19] The recombination of electron–hole pairs, initially excited by heavy ions, furnishes sufficient energy. This reduces the activation energy required for the propagation of plane dislocations near the substrate the process of BPDs being converted into SFs under heavy ion irradiation in turn. In 4H-SiC the activation energy for the dislocation glide decreases to about 0.27 eV under the excess carrier injection.[20] This phenomenon is referred to as the recombination-enhanced dislocation glide (REDG) mechanism, which is characterized by a pronounced reduction in the activation energy for glide velocity.[21,22] Consequently, the expansion of stacking faults takes place during irradiation. We have included a distribution map of BPD defects in the substrate used for 1200-V SiC JBS diode fabrication as shown in Fig. 5(b). The density of BPDs in the wafer substrate used for preparing our diode samples is approximately 300 cm^{-2} and there are enough BPDs in substrate to transform to SFs during irradiation.

It has been well established that stacking faults can be introduced in SiC power devices under electron beam irradiation, leading to a degradation in reverse current.[23–25] It found that BPDs undergone dissociation into two partial dislocations following 20 minutes of electron-beam irradiation, resulting in the formation of an SF between them.[24] Under electron beam irradiation, the injection of electron–hole pairs provided sufficient localized energy through recombination at the dislocation, thereby reducing the activation energy for facilitating the expansion of SFs.[26] It is concluded that the mechanism of SFs expansion under heavy ion irradiation is similar with that under electron irradiation, which is related to the REDG mechanism.

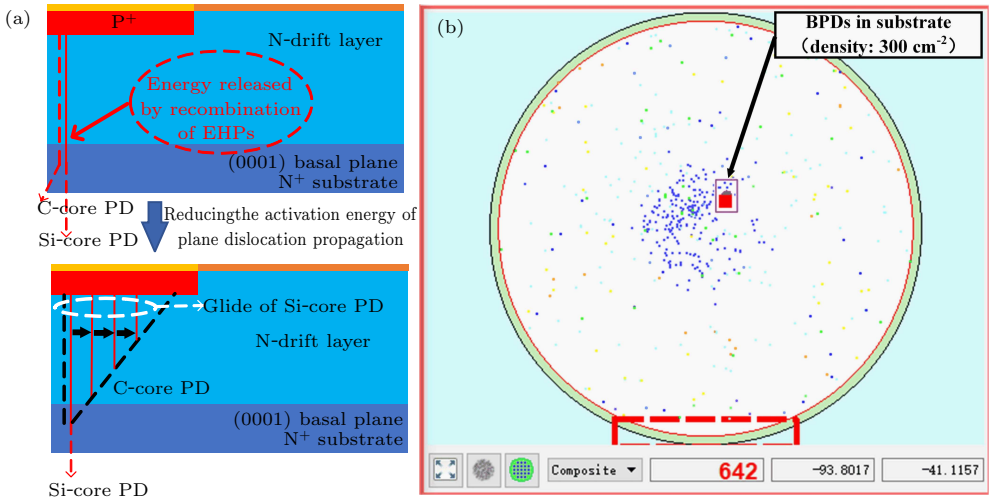


Fig. 5. (a) The process for transforming BPDs into SFs in N-drift layer under heavy ion irradiation. (b) The distribution map of BPDs in the substrate used for 1200-V diode fabrication.

3.2. The 3D simulation results and SFs extension velocity calculation

Three-dimensional TCAD simulations of SiC JBS diodes under heavy ion irradiation were established and formulated using Silvaco Atlas. These simulations were devised to explore the excitation, motion, and recombination of electron–hole pairs during and after heavy ion irradiation. The structural details and model parameters of the device utilized in the simulations were outlined in Table 2.

In the simulation, heavy ions were incident on the middle of the surface, as illustrated in Fig. 1. The parameters pertaining to these ions were also detailed in Table 2. The structural parameters and process conditions for the simulated diode were also identical to those of the actual irradiated devices. In the simulation, the reverse voltage applied to the diode during irradiation was set at 300 V.

Table 2. The structure and model parameters of devices in 3D simulations.

Parameter	Value
N-drift layer doping/depth	1×10^{16} cm^{-3}, 10 μm
N+ substate doping/depth	1×10^{20} cm^{-3}, 169 μm
N+ buffer layer doping/depth	5×10^{17} cm^{-3}, 1 μm
P+ regions doping/depth/width	5×10^{19} cm^{-3}, 0.7 μm, 2 μm
Schottky contact width/barrier height	3 μm, 1.1 eV
Ion track radius/length/gauss time profile/LET value	50 nm, 80 μm, 4 ps, 90.5 MeV/(mg/cm^2)
Impact ionization model	Aniso
Recombination model	SRH, Auger recombination
Reverse bias voltage	300 V

Figures 6(a) and 6(b) portray the carrier density along the path of incidence from 4 ps to 1 μs. Figure 6(a) reveals that the electron concentration near the anode of the diode is significantly lower than the hole concentration from 4 ps to 200 ps. At 200 ps, the electron concentration peaks at the

junction between the epitaxial layer and the substrate, subsequently maintaining a constant value within the substrate. Figure 6(b) shows that the distribution of carriers within the diode at 500 ps mirrors the trends observed at 200 ps. However, from 3 ns to 10 ns, a notable shift occurs which the electron concentration significantly surpasses that of holes within the substrate. Within a duration of 10 ns, the hole concentration within the epilayer and near substrate remains above 1×10^{17} cm^{-3}. At 1 μs, the internal hole concentration within the diode approaches zero, which is why it is not depicted in the figure.

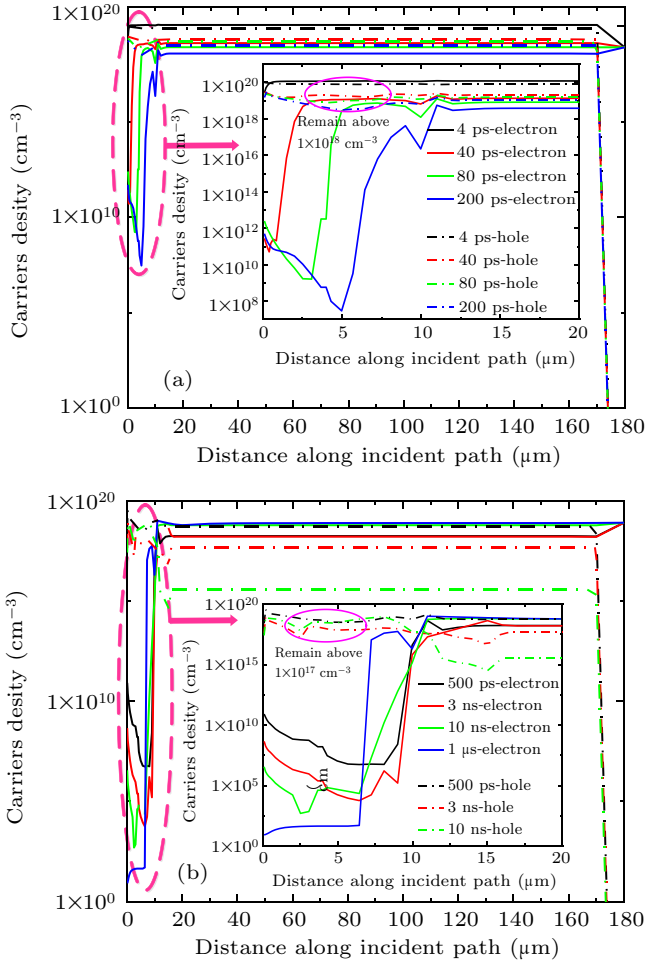


Fig. 6. (a) The carrier density along incident path at different time points (4 ps, 40 ps, 80 ps, and 200 ps) in simulation. (b) The carrier density along incident path at different time points (500 ps, 3 ns, 10 ns, and 1 μs) in simulation.

Tawara *et al*. experimentally estimated the threshold injected hole density (a certain level of injected hole density when an SF starts to expand) in SiC epilayer with concentration of 1×10^{16} cm^{-3} and width of 10 μm.[27] During the expansion of SFs, the glide velocity of the Si-core PDs was regarded as the expand velocity of SFs. They have established two empirical equations delineating the relationship between the expansion velocity of SFs and the injected holes concentration. According to their results, the average threshold hole concentration required for the expansion of SFs in the substrate is determined to be 1.6×10^{16} cm^{-3}–2.5×10^{16} cm^{-3} for diodes, which is much lower than the hole concentration in SiC JBS diode under heavy ion irradiation from our simulation results. And it reveals that SFs expansion could happen during heavy ion irradiation.

Due to the similarity of the SiC epilayer parameters they used with ours, we employed their model and hole concentration from our simulations to calculate the SFs expansion velocity in SiC JBS diode under heavy ion irradiation. Equation (1) is used to calculate the SFs expansion velocity in epilayer and equation (2) is for calculating the velocity in substrate[27]

$$v = 1.2\times10^{-18}\times p^{1.151}, \tag{1}$$

$$v = 1.2\times10^{-16}\times p^{1.064}. \tag{2}$$

In the equations, v is SFs expansion velocity and p is the hole concentration. For both situations in the model, the hole concentration used to calculate SFs expansion velocity was taken from the center of the epitaxial layer.[27] Figures 6(a) and 6(b) reveal that the hole concentration distribution in the epitaxial layer is uniform and high after irradiation. Thus, the hole concentration from the center of the epitaxial layer was also employed in calculating the SF expansion velocity in these regions under irradiation. Figure 7 presents the changes of the hole concentration from the center of epilayer and SF expansion velocity in the epilayer and substrate as a function of time post-irradiation according to simulation and calculation results. It reveals that after heavy on incidence, SFs expansion velocity decreases over time. And it decreased nearly to zero after 0.1 μs.

Consequently, the expansion width of SF defects introduced in the irradiation experiment can be estimated using the following equation:

$$W = A\times\text{Fluence}\times\int_{t_0}^{t_1} v(t)\,\mathrm{d}t. \tag{3}$$

where A is the die area of 1200-V SiC JBS diode and W is the width of SFs expansion under irradiation. And v is the SFs expansion velocity. The start time of irradiation is referred as t_0 and t_1 is the time when hole concentration nearly equals to zero.

Finally, the width of SFs expansion in SiC epi-layer was 1.6 μm and the width of SFs expansion in substrate was 26.1 μm from the calculation results. Simultaneously, studies have shown that heavy ion irradiation can induce extremely high lattice temperatures within SiC shortly after irradiation.[6,28] When the reverse bias voltage arrives at 20 V, the peak lattice temperature within the SiC exceeds 1000 K.[29] Such high lattice temperatures reduce the threshold energy required for stacking faults formation and expansion, while simultaneously accelerating the velocity of SF formation and propagation.[30] However, the detailed process of SFs expansion in both epitaxial layer and substrate during

heavy ion irradiation and high lattice temperature remains an area for future research to explore more thoroughly.

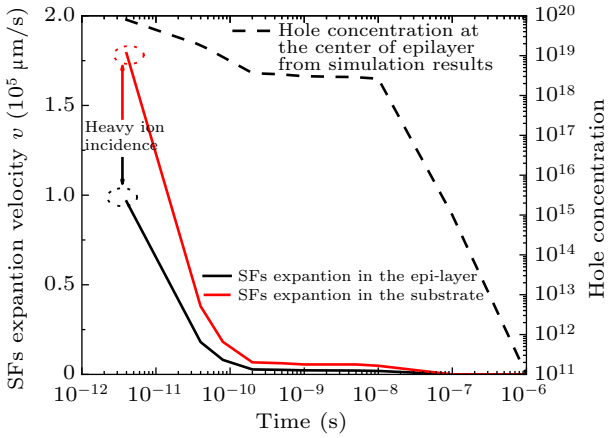


Fig. 7. The changes of hole concentration from the center of epilayer and SF expansion velocity in the epilayer and substrate as a function of time post-irradiation according to simulation and calculation results.

4. Conclusion

In summary, the study combines the phenomenon of leakage current degradation of SiC JBS diodes under heavy ion irradiation with the defects introduced by irradiation, innovatively verifying that irradiation introduces SFs in the SiC and proposing the physical mechanism of SF expansion under irradiation. Experimental findings reveal that the reverse leakage current in SiC JBS diodes increases under various bias voltages when exposed to heavy ions with LET values of 90.5 MeV/(mg/cm^2). The presence of stacking faults is detected in irradiated diodes, confirmed through micro-PL spectroscopy and PL imaging. Based on the experimental results, an insightful mechanism for the degradation of reverse current is proposed. In the brief timeframe immediately after the impact of heavy ions, a significant number of electron–hole pairs recombine along the path of particle incidence, leading to the release of a substantial amount of energy. This released energy from the recombination of electron–hole pairs within the diodes transforms BPDs within the drift layer and substrate into stacking faults, which subsequently account for the degradation of reverse leakage current. We simulated the hole concentration induced by heavy ion irradiation, which was much higher than the threshold injected hole density needed for the expansion of SFs. And the size of extended SFs under heavy ion irradiation was calculated, which was consistent with the size of SFs observed from PL micro-imaging. This perspective offers valuable insights for the design of radiation-hardened SiC power devices, calling for further research.

References

[1] Zhu L, Chow T P, Jones K A and Agarwal A 2006 *IEEE Trans. Electron Dev.* **53** 363
[2] Piszczor M, McNatt J, Mercer C, Kerslake T and Pappa R 2012 38*th IEEE Photovoltaic Specialists Conference*, 2012, Austin, TX, USA, p. 3287
[3] Barry A L, Lehmann B, Fritsch D and Braunig D 1991 *IEEE Trans. Nucl. Sci.* **38** 1111
[4] Javanainen A, Galloway K F, Nicklaw C, *et al*. 2017 *IEEE Trans. Nucl. Sci.* **64** 415
[5] Javanainen A, Galloway K F, Nicklaw C, *et al*. 2017 *IEEE Trans. Nucl. Sci.* **64** 2031
[6] Abbate C, *et al*. 2015 *IEEE Trans. Nucl. Sci.* **62** 202
[7] Witulski A F, *et al*. 2018 *IEEE Trans. Nucl. Sci.* **65** 256
[8] Ball D R, *et al*. 2020 *IEEE Trans. Nucl. Sci.* **67** 22
[9] Wu Z K, Bai Y, *et al*. 2022 *IEEE Trans. Nucl. Sci.* **69** 932
[10] Martinella C, Bathen M E, Javanainen A and Grossner U 2023 *Mater. Sci. Forum* **1090** 179
[11] Für N, Belanche M, Martinella C, Kumar P, Bathen M E and Grossner U 2023 *IEEE Trans. Nucl. Sci.* **70** 1892
[12] Konishi K, Fujita R and Shima A 2019 *J. Electron. Mater.* **48** 1704
[13] Brosselard P, *et al*. 2008 *Mater. Sci. Forum* **600–603** 935
[14] Galeckas A, *et al*. 2006 *Mater. Sci. Forum* **527–529** 395
[15] Gan F, Suda J and Kimoto T 2009 *Physica B* **404** 4745
[16] Na M, Bahng W, Jung H, Oh C, Jang D and Hong S 2024 *Mater. Sci. Semicond. Process.* **175** 108247
[17] Tsunenobu K and Heiji W 2020 *Appl. Phys. Express* **13** 120101
[18] Mashi K, Shinya K, Yoshihito I, Shunta H and Tsunenobu K 2018 *J. Appl. Phys* **124** 095702
[19] Godet J, *et al*. 2009 *Phys. Rev. B* **73** 092105
[20] Galeckas A, Hallén A, *et al*. 2006 *Phys. Rev. B* **74** 233203
[21] Galeckas A, Linnros, *et al*. 2006 *Phys. Rev. Lett.* **96** 025502
[22] Skowronski M, *et al*. 2002 *J. Appl. Phys.* **92** 4699
[23] Ishikawa Y, *et al*. 2018 *J. Appl. Phys.* **123** 225101
[24] Yakimov E E and Yakimov E B 2020 *J. Alloys Compd.* **837** 155470
[25] Yao Y Z, Yoshihiro S, *et al*. 2011 *J. Appl. Phys* **109** 123524
[26] Chen B, *et al*. 2008 *Appl. Phys. Lett.* **93** 033514
[27] Tawara T, *et al*. 2018 *J. Appl. Phys* **123** 025707
[28] Tomoyuki Shoji, *et al*. 2014 *Jpn. J. Appl. Phys.* **53** 04EP03
[29] Zhang H, *et al*. 2023 *Chin. Phys. B* **32** 028504
[30] Joshua D, Caldwell, *et al*. 2010 *J. Appl. Phys.* **108** 044503