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Investigation of 4H-SiC Schottky barrier diodes irradiated with 6 MeV Au ions at low temperature

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ABSTRACT

The change in the electrical properties of 4H-SiC Schottky barrier diodes (SBDs) irradiated by 6 MeV Au ions at low temperature (LT) is investigated. The SBDs are characterized by current–voltage (I-V) and capacitance–voltage (C-V). The SRIM software is used to calculate the Au ion transportation process. The experimental results indicate that the ideality factor (n) and the reverse leakage current (I_R) increase, and Schottky barrier height (*SBH*) decreases with the increase in fluence. It is found that series resistance (R_S) and effective impurity concentration (N_D) are recovered at 5×10^{15} ions/cm^2. Calculation results show that the mental layer can prevent most of the Au ions, while the secondary particles will enter the SiC layer. Therefore, these results demonstrate that the secondary particles induce many defects at the metal-SiC interface and the SiC epitaxial layer after LT heavy ion (HI) irradiation.

1. Introduction

4H-SiC materials have attracted recent attention due to their important application in radiation space domain and advanced nuclear reactors because of their excellent properties (i.e., high thermal conductivity and good radiation hardness). Compared to silicon, there are less ionization damages for 4H-SiC materials with a wide bandgap under the same irradiation conditions [1]. Currently, these 4H-SiC Schottky barrier diode (SBD) devices are applied in aerospace, and their performance can be significantly affected due to the impact of the radiation space environment, which always has different types of radiation sources and ambient temperature variability. Therefore, there are many studies on the irradiation effect of 4H-SiC SBDs by protons, neutrons, electrons [2], swift heavy ion irradiation (SHI) [3,4], etc. To date, most of these studies have focused on room temperature (RT) irradiation effects.

The power semiconductor devices (PSDs) may be applied or operated under radiation and low temperature (LT) conditions. The performance of PSDs will change dramatically at the LT environment. For example, Turn-on voltage (V_{ON}) and the ideality factor (n) will increase with the decrease in 4H-SiC SBD temperature [5]. However, there are few studies on LT irradiation effects. To the best of our knowledge, only the LT irradiation effects of GaN and GaAs SBDs have been reported [6–8]. R. Singh et al. reported that the GaAs SBDs were irradiated by 180 MeV $^{107}Ag^{14+}$ ion at LT [6] and indicated that they are obviously different from the current transport mechanisms between LT and RT irradiation. Kumar et al [7] investigated the effects of Ni/GaN SBDs irradiated by 200 MeV Ag ions at RT and demonstrated that their parameters were almost unchanged with the increase in the irradiation fluence. However, it is significantly observed that the n factor increases and leakage current (I_R) decreases with the increase in irradiation fluence for Ni/GaN SBDs irradiated by 200 MeV Ag^{14+} at LT irradiation (80 K) [8]. The difference is attributable to the formation of different defects under different temperature irradiations. Some new defects may disappear again or involve significant recovery due to the healing effect of the accumulation of intense electronic energy deposition with increasing irradiation fluence, particularly at the RT irradiation. For 4H-SiC devices, the data for LT irradiation are still absent. To promote the application of 4H-SiC power devices in special circumstances, it is necessary to study the LT irradiation effects of 4H-SiC power devices.

According to our previous work, the phenomenon of recrystallization and atom migration between metal and SiC for the 4H-SiC SBDs

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irradiated by SHI (1.9 GeV) irradiation was revealed by cross section transmission electron microscopy [3,4] and Micro-Raman Spectroscopy [9]. Previous results suggest that it is important for the defects induced by SHI irradiation to produce a thermal effect. To avoid thermal accumulation effect under the SHI irradiation process, we select not only the relatively low energy (6 MeV) ion irradiation with difference in fluence, but also LT irradiation condition to carry out irradiation experiment in this work.

2. Experiment details and simulation model

In this paper, commercial 4H-SiC SBDs used in this experiment were fabricated by Cree Inc. The net donor concentration of the sample was 4.49×10^{15} cm^{-3} from capacitance-voltage (C-V) measurements [3]. The packages of 4H-SiC SBDs had been removed by boiling concentrated sulfuric acid before HI irradiation experiment. The radiation experiments were performed on a 3 MV tandetron accelerator at the Institute of Nuclear Science and Engineering at Sichuan University, which was characterized as a high-fluence radiation source [10]. The samples were irradiated by 30.A 46 keV/u ^{197}Au ion beam vertically at 77 K with a different fluence of 1×10^{13}, 1×10^{14}, 1×10^{15}, and 5×10^{15} ions/cm^2, respectively, which were named as 1E13, 1E14, 1E15, and 5E15. The Current-Voltage (I-V) and C-V characteristics of all samples were measured at RT (300 K).

To investigate the specific process of 6 MeV Au^{2+} ions transport in 4H-SiC SBDs, Monte Carlo software (SRIM) was used to simulate the transport process of Au ions. The cross-sectional view of 4H-SiC SBD device structure is shown in Fig. 1. There are three metal layers (1 μm Al, 0.22 μm WTi, and 0.1 μm Ti) and 1 μm SiC epitaxial layer. The 4H-SiC SBD is vertically irradiated by 6 MeV energy with 1×10^5 ions, and then, the average result for a single particle is calculated.

3. Results and discussion

The SRIM can calculate the energy deposition of transport and defect distribution such as vacancies for the process of HI irradiation 4H-SiC SBD. When HI penetrates the Al, WTi, and Ti layers (as shown in Fig. 2 (a)), there are many progenies to be produced by ion collision and scattering. The green, purple, blue, and black particles represent Al atoms, W atoms, Ti atoms, and Au atoms, respectively. It can be seen that the average Au ion penetration depth is approximately 1.2 μm (as shown in Fig. 2 (b)). Fig. 2 (c), (d), and (e) indicate the different distributions of vacancies, recoil atoms distribution, and displacement damage (displacements produced/atom, DPA) in each layer caused by HI irradiation, respectively. First, it is apparent that only a few of the Au ions can penetrate three metal layers into the SiC layer, and the ranges of numerous Au ions and vacancies are from ~1 μm to ~1.2 μm. This means that most of the Au ions remain in the metal layer, but a few Au ions and other secondary particles in the SiC layer will generate many recoil Si and C atoms. At the fluence with 1×10^{13} ions/cm^2, the concentration of recoil Si and C atoms will reach orders of magnitude of 10^{19}, which could greatly affect the samples' electrical properties.

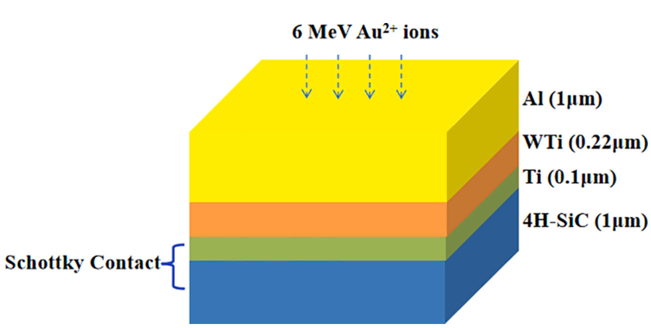

Fig. 1. The across sectional view of 4H-SiC SBD device structure for simulation.

Secondly, the DPA of SiC layer is much less than the metal layers. The inset of Fig. 2 (e) clearly depicts that the DPA of the SiC layer is $\sim 10^{-17}$ order of magnitudes, which unexpectedly agrees well with the values reported in our previous research with 1.9 GeV Bi ion irradiation on 4H-SiC SBD [11]. This may be explained from the electronic (dE/dx_E) and nuclear energy loss (dE/dx_N). From Fig. 2 (f), we can clearly see that there is a maximum value of dE/dx in the WTi layer; most of the energy is deposited in three metal layers, which would be transferred to generate a huge amount of heat. In addition, the dE/dx_E is larger than dE/dx_N in all layers of the device structure.

Theoretically, when HI beams pass through metal material, the ionization effect and displacement effect are observed due to the interaction between ions and valence electrons/atomic nucleus. As we are well aware, the dE/dx_N generates the recoil atoms and the dE/dx_E produces abundant secondary particles. When secondary particles reach the SiC layer, they would generate some complicated defects at the interface between the metal layers and the SiC layer or in the SiC layer, such as traps and recombination centers. These defects severely affect the electric properties of SBD. The simulation cannot consider the influence of the thermal effects from the HI irradiation; hence, it is necessary to study the effect of thermal accumulation during the HI irradiation process on the electrical performance of 4H-SiC SBD through experiment methods.

To investigate the influence of irradiation on electric properties of samples, the measurements of I-V and C-V characteristics are taken at RT. Fig. 3 (a) shows the forward I-V characteristic for all samples. In this work, all curves exhibit approximate linearity versus voltage from 0.5 to 0.9 V, which has also been observed extensively in previous articles [12,13]. The most interesting phenomenon is that the forward current (I_F) between the low voltages ranging from 0 to 0.5 V obviously increases with the increase in irradiation fluence, but the phenomenon disappears above 0.5 V as the irradiation fluences increases. We will discuss this phenomenon later.

According to the Schottky barrier thermionic emission theory [14,15], a list of parameters, including *n* factor, Schottky barrier height (*SBH*), and series resistance (*Rs*), which can be obtained through linear data fitting in the different regions of I-V curves, are used to describe the properties of 4H-SiC SBDs. The relationship of I - V can be expressed as follows:

$$I = I_s[\exp\left(\frac{q(V - IR_s)}{nkT}\right) - 1] \quad (1)$$

$$I_s = A^* ST^2 \exp(-\frac{q\phi_b}{kT}) \quad (2)$$

where A^* is the effective Richardson constant (146 A cm^{-2} K^{-2}) for 4H-SiC, S (=0.5 mm^2) is the effective cross-sectional area of samples, I_s is the saturation current derived from the straight line interception of the ln (n) axis at zero bias, ϕ_b is the SBH, k is the Boltzmann constant, and T is the absolute temperature. Parameters, including *n*, *SBH*, and *Rs*, can be obtained from equation (1) [4], and they can be expressed as follows:

$$n = \frac{kT}{q} \frac{dV}{d(lnI)} \quad (3)$$

Fig. 3 (b) depicts the relationship between R_S and irradiation fluence. It can be observed that R_S increases from ~ 106 Ω to ~ 108 Ω after irradiation at 1E13, while there is no obvious change of R_S in the range of fluence from 1E13 to 1E15. The rate of change of R_S is only 1.9% in all samples. However, when irradiation fluence reaches 5E15, R_S recovers to the unirradiated R_S value. According to Fig. 4 (b), we can see that N_D decreases with the increase in irradiation fluence, while it increases abnormally at fluence 5E15. In previous SHI irradiation research, the recovery of the crystal structure or defects caused by the thermal effect result in the recovery of both R_S and I_R at the same time [3–5]. However, the recovery of R_S cannot be caused by the thermal effect induced HI in

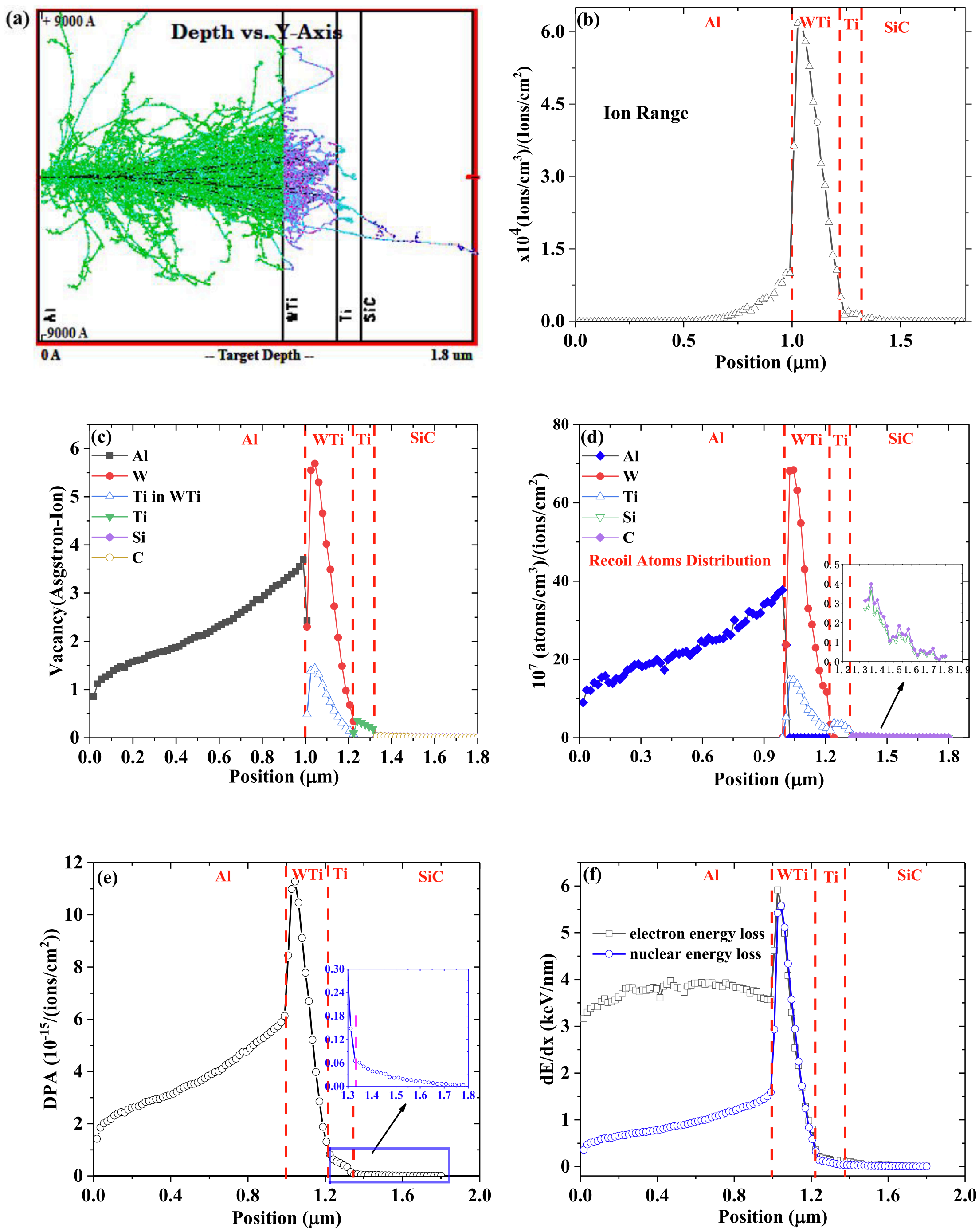

Fig. 2. (a) Schematic diagram of Au ions transport. (b) Trajectories of the Au ions into 4H-SiC SBD. (c) The distribution of vacancies at each layer. (d) Recoil atoms distribution. (e) The depth profiles of DPA and (f) The electronic (dE/dx_E) and nuclear energy (dE/dx_N) loss with depth.

this work because the irradiation experiment is conducted at LT. Therefore, there are new reasons for the recovery of R_S. The phenomena of R_s and N_D changes are similar in this work. This implies that the change of R_s should be from the change of carrier concentration caused by HI irradiation. Based on the semiconductor physics theory, the resistance of semiconductor material is inversely proportional to conductivity, and the conductivity is a function of the effective carrier concentration and mobility. It is assumed that the effect of irradiation on mobility is negligible. Therefore, the recovery of R_S at high fluence can be explained from the recovery of N_D (as shown in Fig. 4 (b)). The N_D of 5E15 rises abnormally even more than that of nonirradiated samples, which also cause the decrease of R_S of 5E15.

As shown in Fig. 3 (c), *n* factor increases steadily with the increase in irradiation fluence, while *SBH* decreases abnormally, which is different from the results of previous research [6,10,15,16]. For example, in 4H-SiC SBDs irradiated by electrons [16,17], the phenomenon of decrease of *SBH* appears. Therefore, the essence of 6 MeV Au irradiation may produce a secondary electron for 4H-SiC SBDs.

It can be found that I_R increases with the increase in irradiation fluence in Fig. 3 (d). The increase of I_R is caused by the defect-assisted tunneling [18], whereas the decrease of *SBH* has introduced interface state-assisted tunneling by HI. On the basis of the common semiconductor physics theory [19], the tunneling induces the decline of *SBH*, which reduces with an increase in voltage. In the derivation of the ideal

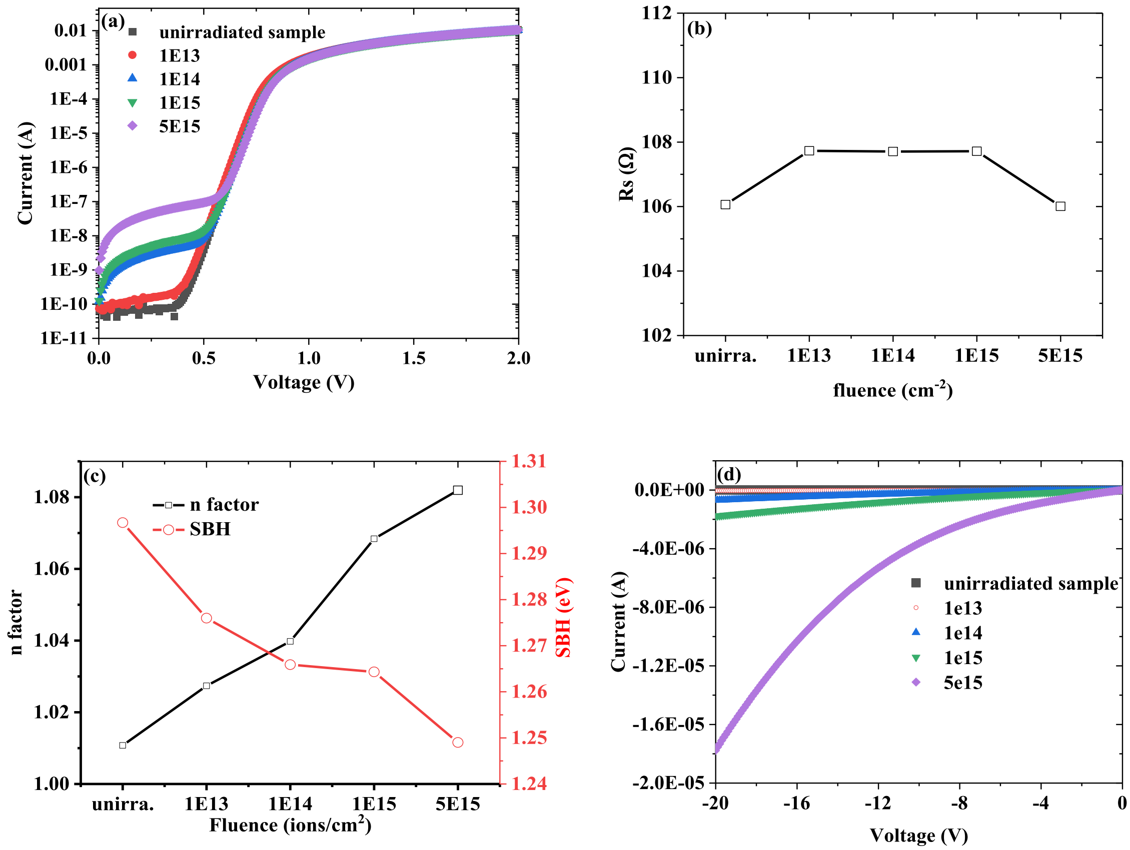

Fig. 3. (a) The forward I-V characteristics of the 4H-SiC SBD between 0 and 2 V; (b) The relationship between *Rs* and irradiation fluence; (c) The plot of *n* factor and *SBH* versus irradiation fluence and (d) The reverse I-V characteristics of the 4H-SiC SBDs from −20 to 0 V.

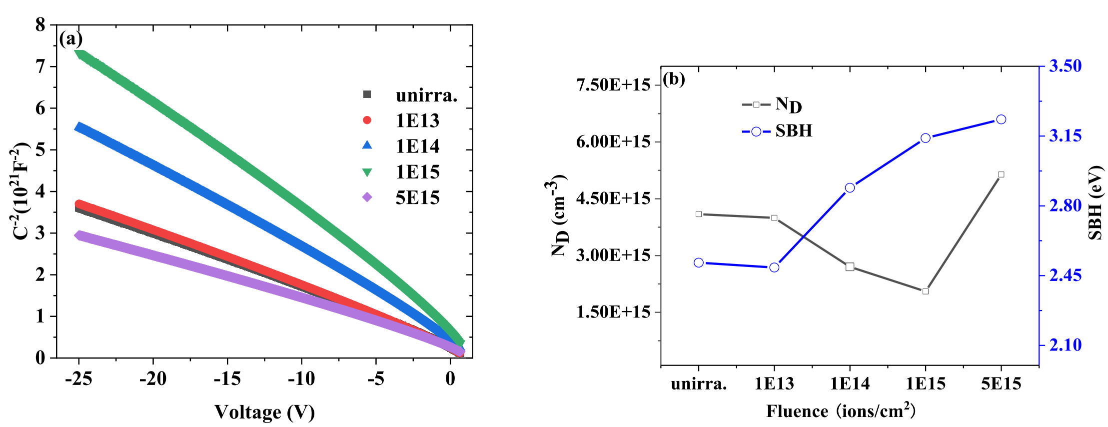

Fig. 4. (a) 1/C^2-V plots for all samples; (b) N$_D$ and *SBH* versus irradiation fluence.

I-V relationship, it assumes low injection and neglects any effects that occur within the space charge region. In fact, the total forward bias current density (J_F) is the sum of the recombination (J_{rec}) and the ideal diffusion current densities (J_D). At low forward voltage, the J_{rec} dominates, and at high forward voltage, the J_D dominates (n≈1). In this experiment, there are some new deep level defects/trap in 4H-SiC SBDs formed by LT HI irradiation; hence, we note that the J_{rec} increases below 0.5 V as irradiation fluence increases. While the diffusion current dominates at high voltage, the J_{rec} mostly change with increasing irradiation fluence. Therefore, the increase in J_{rec} and I_R are attributes to the HI-induced recombination centers. The phenomena of Fig. 3 (a) and Fig. 3 (d) can be well explained.

The C-V characteristics of all samples are measured with the frequency of 1 MHz at room temperature. The C^{-2}-V plot is depicted in Fig. 4 (a). The capacitance increases with the increase in voltage at different irradiation fluences. The capacitance decreases with an increase in irradiation influence between nonirradiation and 1E15, while it slightly increases when influence arrives at 5E15. The barrier capacitance can be expressed as follows:

$$C = \sqrt{\frac{q\varepsilon N_D A^2}{2(V_{bi} - V - V_T)}} \tag{4}$$

$$N_D = -\frac{2}{q\varepsilon A^2}\frac{1}{d(C^{-2})/dV} \tag{5}$$

where $\varepsilon$is the dielectric constant of 4H-SiC semiconductor material, V_{bi} is the build-in voltage potential, $V_T(=kT/q)$ is the thermal voltage, and S (0.5 mm^2) is the area of SBD.

The N_D and *SBH* can be obtained from equations (4) and (5) and C^{-2}-V plot, which are shown in Fig. 4 (b). It can be seen that the value of N_D of 5E15 is even more than that of the unirradiated sample. In this work, the thermal effect may not be the main irradiation effect due to the LT irradiation environment. Thus, there is a need for a new type of irradiation mechanism to expiate the increase of N_D. There are two reasons for N_D decrease at low fluence. One reason is the compensated effect due to the tiny positively charged Au^{2+} ions that arrive at the SiC epitaxial layer, while the other reason may be the formation of traps at the metal-SiC interface by HI irradiation, which can capture electrons.

The change of N_D has been used to explain the abnormal increase of R_S. The aforementioned calculation results suggest that only a small amount of Au ions can directly enter the SiC layer, while the secondary particles will enter into it. The secondary particles introduce abundant defects, which will greatly affect the property of M−S interface theoretically and cause the increase of J_{rec} and I_R. In literature, the common defects of SiC mainly include $V_{Si/C}$ [20] and Z_1/Z_2 defects [21,22] (preformed probably by V_C or V_C-related complex [23]), which have different energy levels.

The previous calculation results of ionization energy deposition indicate that the increase of irradiation fluence will result in the increase in the concentration of the secondary particles (electron and vacancy). Therefore, it can be speculated that LT HI irradiation introduces a kind or kinds of defects, which provide more than one energy level. Moreover, the defects are deep level defects that capture the electron at low irradiation fluence; however, while the concentration of the secondary electron increases with the increase in irradiation fluence, the compensated role of Au^{2+} ions increases and eventually results in the increase of N_D. This will need more work to verify the assumption.

4. Conclusion

In this work, 4H-SiC SBDs are irradiated by 6 MeV Au^{2+} ions with different fluence at 77 K. The results reveal that *n* slightly increases, *SBH* decreases, the phenomenon of abnormal recovery of R_S and N_D is consistent, and I_R and J_{rec} distinctly increase. Although the SRIM software analysis shows that tiny Au particles can reach the SiC substrate and the secondary particles induce abundant defects at the M–S interface and inner SiC. Therefore, the secondary particles may be induced by LT HI irradiation with some deep level defects with relatively low energy, which greatly influence the electrical performance of 4H-SiC SBDs, particularly J_{rec} and I_R. To promote the application of the SiC device in the aerospace field and special harsh environment, the influence of environmental temperature on complex defects formation during LT HI irradiation process needs to be understood; thus, additional studies on LT HI irradiation need to be performed.

CRediT authorship contribution statement

Shaomin Wang: Conceptualization, Methodology, Formal analysis, Investigation, Writing - original draft. **Rongbin Hu:** Investigation, Formal analysis. **Gang Chen:** Investigation, Formal analysis. **Chengtao Luo:** Conceptualization, Methodology. **Min Gong:** Writing - review & editing, Supervision. **Yun Li:** Methodology, Investigation, Data curation, Project administration. **Mingmin Huang:** Software, Writing - review & editing. **Yao Ma:** Conceptualization, Resources, Writing - review & editing. **Zhimei Yang:** Conceptualization, Writing - review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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