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STUDY ON PROTON RADIATION EFFECT AND SELF-REPAIR OF SiC-JBS DIODES

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Abstract

In this study, the influence of proton irradiation experiments at 40 MeV and 2.2×10^{12} p/cm^2 on Silicon Carbide Junction Barrier Schottky (SiC-JBS) diodes with stripe cell and hexagonal cell was investigated, respectively. The experiment was implemented based on 100 MeV high intensity proton cyclotron of China Institute of Atomic Energy. The results show that the current voltage (IV) and capacitive voltage (CV) characteristics of the SiC-JBS diodes are obviously degraded by proton irradiation. After 168 h and 336 h room temperature annealing, the forward IV characteristics of the diodes are basically restored but the reverse leakage current is increased. And the CV characteristics are degraded of the two kinds of diodes permanently, which indicating that room temperature annealing cannot restore the proton radiation displacement damage defects. The analysis of structure of the diodes shows that the diodes with hexagonal cells are more resistant to proton irradiation and have stronger room temperature annealing self-repair ability than the diodes with stripe cells, even though its chip area is smaller. This means that the SiC-JBS diodes with hexagonal cells can be used preferentially in the radiation environment where there is a large amount of proton.

INTRODUCTION

The physical and electronic properties such as band gap width, thermal conductivity, electric field strength of SiC is attractive [1]. Also, the energy required to kick an atom out of the lattice position, i.e., the mean displacement energy, is higher than silicon (Si) [2]. Compared with other semiconductor materials, the performance advantages of SiC are shown in Fig. 1.

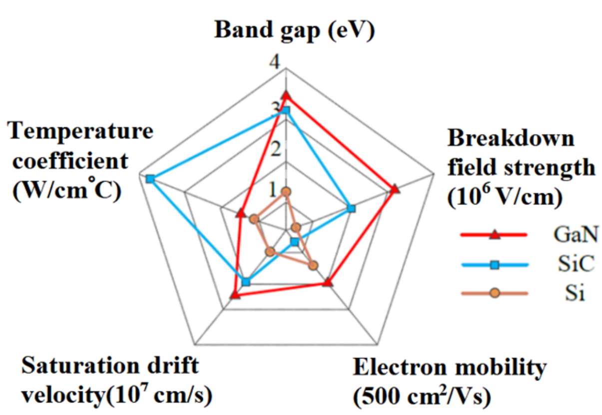

Figure 1: Performance advantages of SiC compared with other semiconductor materials.

As can be seen from Fig. 1, SiC is a promising semiconductor material for power device applications with additional advantages for harsh environments with high temperature and radiation [3]. At present, power systems for examples electric propulsion systems and photovoltaic inverter systems based SiC diodes, have further developed towards miniaturization, lightweight, high efficiency and low loss [4, 5]. And one of the most important points is radiation hardness, which makes SiC power devices the better choice than Si to complete space exploration tasks.

SiC junction barrier Schottky (JBS) diodes is a kind of SiC power device with simple structure and excellent performances. The previous researches show that after proton irradiation with a certain fluence, the breakdown voltage of SiC-JBS diodes will degrade, which is mainly related to the change of ionized charge at the SiO_2/4H-SiC interface in the device and the reduction of carrier concentration in the drift region [6]. And, the decrease of carrier concentration is attributed to the carrier removal phenomenon caused by radiation defects [7]. However, numerous degradation performances after proton or other high energy particles irradiation on SiC-JBS diodes without power supply are attributed to the displacement damage effect of irradiation defects, and there is little analysis on the impact of ionized charges [8, 9]. In order to study the influence of proton irradiation defects on the macro electrical performance of SiC-JBS diodes, and explore whether the diodes are also affected by ionization defects in the process of displacement damage, a proton irradiation experiment of SiC-JBS diodes under unbiased voltage was carried out, and the influence of ionized charges was investigated through room temperature annealing method.

PROTON IRRADIATION EXPERIMENT

Two kinds of 1200 V/40A SiC-JBS diodes with different cell designs were selected and named #a and #b respectively. The top surface and section structure of the diodes obtained by scanning electron microscope (SEM) analysis technology are shown in Fig. 2. Combined with the microstructure of these SiC-JBS diodes, the key performance parameters such as barrier height and carrier concentration can be calculated theoretically. It can be seen from Fig. 2 that the #a is with hexagonal cell designs, and its typical breakdown voltage (BV) is about 1230 V, the average Schottky barrier height (SBH) is about 1.15 eV, the average ideality factor (n) is about 1.02. The #b is with stripe cell design, and its typical BV is about 1450 V, the average SBH is about 1.13 eV, and the average n is about 1.06, respectively. Both diodes have extremely stable switching on voltages of about 0.4 V.

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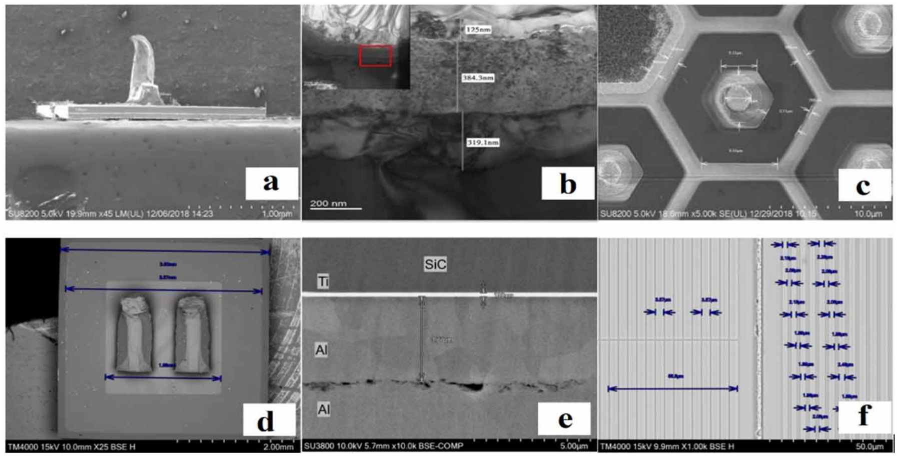

Figure 2: Microstructure images of the whole, section and top of #a (a)-(c) and #b (d)-(f) SiC-JBS diodes.

Realizing the reliable application of SiC power devices in today's typical aerospace orbit is an important step for SiC to help aerospace development. Considering that the proton energy on nowadays typical orbit is concentrated at 10 - 100 MeV [10], and the proton flux of 30 - 50 MeV is at the peak, the irradiation experiment of 40 MeV proton was carried out. The proton fluence accumulates to 2.2×10^{12} cm^{-2}. For SiC power devices, it can show the performance change coming from the accumulated displacement damage dose under the condition of geosynchronous orbit (GEO) operation for 20 years [11]. And the electrical characteristics of the diodes were measured using the Agilent B1505A power device analyzer.

RESULTS AND DISCUSSION

Forward IV

Before and after proton irradiation, the forward electrical properties of the SiC-JBS diodes were tested, and the self-repair of the diodes after room temperature annealing for 168 h and 336 h were analyzed. The forward IV characteristics of #a and #b at every condition are shown in Fig. 3. At lower forward voltages, there is an increase in current consistent with the introduction of recombination centers associated with proton-induced displacement damage [12]. At higher forward voltages, the current is decreased due to the defect energy level and interface state caused by irradiation. Figure 3 top shows the magnitude of the decrease of current measured at a forward voltage of 2 V. Note the percentage decrease in current is ~4% for #a and ~8% for #b separately after a fluence corresponding to more than 20 years in GEO. This decrease in the forward current and increase in the forward voltage drop after irradiation and annealing is attributed to the vacancies created by the impinging particles which in turn increase the resistance of the drift layer. However, after 168 h or 336 h annealing, we didn't observe the obvious self-repair of positive electrical characteristics, which shows that the room temperature annealing treatment has little effect on the self-repair of SiC-JBS diodes damaged by proton displacement damage defects.

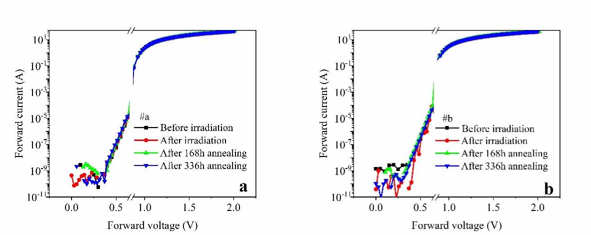

Figure 3: I_F-V_F of #a (a) and #b (b).

The SBH was extracted from the relationship [13]

$$J_F = A^*T^2 \exp\left(-\frac{qSBH}{nkT}\right)\left[\exp\left(\frac{qV}{nkT}\right)-1\right]. \qquad (1)$$

where J_F is the forward current density at voltage V, A^* is effective Richardson's constant, which is about 146 $A\cdot cm^{-2}\cdot K^{-2}$ for 4H-SiC, T is the absolute measurement temperature, q is electronic charge, n is ideality factor, k is Boltzmann's constant, T is the absolute measurement temperature.

The forward voltage drop V_F for a SiC-JBS diodes, is related to the SBH and on-state resistance R_{on} from

$$V_F = \frac{nkT}{q}\ln\left(\frac{J_F}{A^*T^2}\right)+nSBH+R_{on}J_F. \qquad (2)$$

where V_F is usually defined as the voltage at which J_F is 100 A/cm^2. The values of both diodes at every condition calculated according to the above equations is shown in Fig. 4, and both increase after irradiation and decrease after annealing.

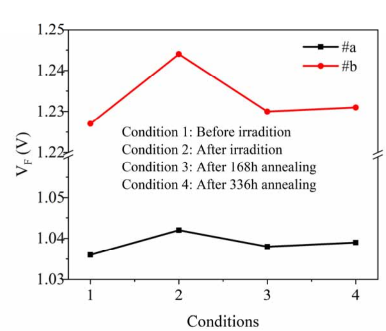

Figure 4: Forward voltage of SiC-JBS diodes.

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Reverse IV

The reverse electrical property of the SiC-JBS diode at each condition is tested, as shown in Fig. 5. The leakage current of # a has changed slightly, which is stable around 12 μA at 1200 V from before irradiation to 336 h annealing. But the leakage current of #b increases violently from 1 μA to 8 μA at 1200 V after 336 h annealing.

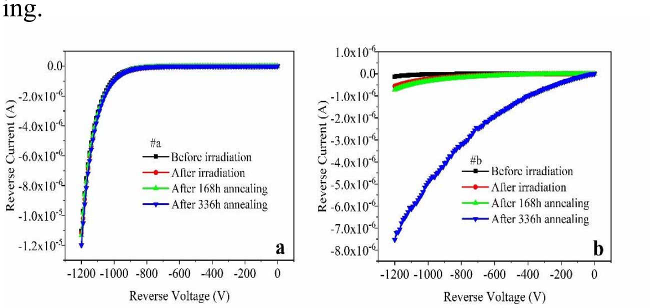

Figure 5: I_F-V_F of #a (a) and #b (b).

At the same time, Fig. 5(b) demonstrates the drain current of the #b after irradiation and annealing when the reverse voltage is applied. This is due to that irradiation defects will lead to the generation of interface state, and the damage of interface materials will lead to the formation of a leakage channel, which will enhance the tunneling current [14]. Therefore, this also means that damage introduced by proton irradiation is permanent and will not disappear completely through self-repair at room temperature.

Reverse CV

The relationships between capacitance C and voltage V after proton irradiation and annealing are shown in Fig. 6. The capacitance of #a is about 1480 pF at -1 V before irradiation, but is about 1380 pF after irradiation or annealing. The capacitance of #b is about 1650 pF at -1 V before irradiation, but the values are about 1300 pF, 1310 pF and 1390 pF respectively after irradiation, 168 h annealing and 336 h annealing. While the capacitance decreases significantly for #b, because the defects introduced by proton irradiation can form an interface state at the #b diode interface much easily than #a.

For SiC-JBS diodes, after numerical transformation, the CV relationship curve can be changed to a $1/C^2$ ~V relationship curve, which can be described by Eq. (3) [15]:

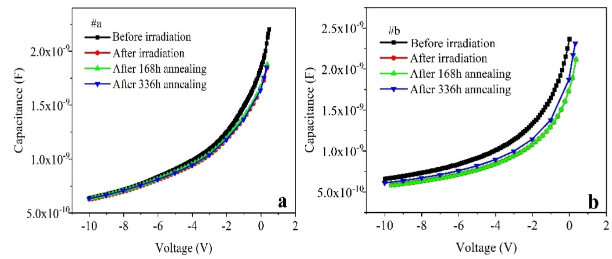

Figure 6: CV of #a (a) and #b (b).

$$\frac{1}{C^2} = \frac{2}{\varepsilon_s q A^2 N_{eff}}(V_{bi} + V) \tag{3}$$

where A is the Schottky junction area, N_{eff} is the effective carrier concentration, V_{bi} is the value of built-in electric field, V is the external bias, ε_s is dielectric constant, which is about 9.7 F/m for SiC. And ε_s of the material is related to the polarization type, ambient temperature, electric field strength and other factors, its value affects the capacitance characteristics. Combining Eqs. (1) to (3) with the data in Figs. 4 and 6, the SBH, N_{eff}, R_{on} and n of the diodes were extracted. The results are shown in Fig. 7.

As we can see that the key electrical properties of the SiC-JBS diodes have changed significantly after proton irradiation and annealing. Proton irradiation leads to the increase of SBH and R_{on}, which leads to the decrease of forward current. In addition, proton irradiation introduces defects into the diode to form defect energy levels and trap levels, causing the increase in carrier removal or temporary trapping. The n represents the ratio of hot electron emission current. Some defects can form composite centres after irradiation by protons, which lead to an increase in the proportion of the composite current of the current. The interface defects also lead to the increase of tunneling current, so the ratio of hot electron emission current decreases and the value of increases after proton irradiation [16]. However, even after proton irradiation, then is still close to 1, indicating that the current of the diodes still dominated by thermionic emission current.

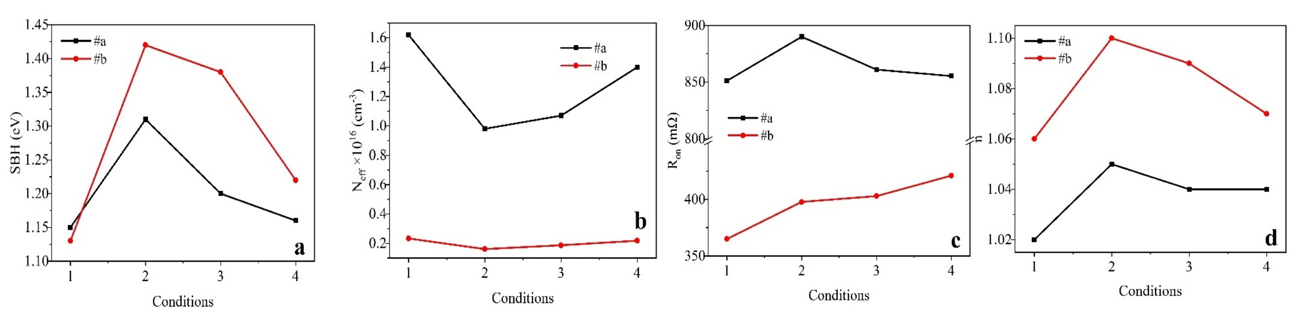

Figure 1: SBH (a), N_{eff} (b), R_{on} (c) and n (d) of SiC-JBS diodes.

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CONCLUSION

The proton irradiation experiments at 40 MeV and 2.2×10^{12} p/cm^2 were carried out using the 100 MeV high current proton cyclotron of the China institute of atomic energy. The displacement damage effect and room temperature self-repair phenomenon of SiC-JBS diodes were studied. The experimental results show that proton irradiation will introduce defects in the diodes, causing the potential barrier to rise and the carrier concentration to drop, resulting in changes in the electrical characteristics, especially the reverse leakage current will increase significantly under the impact of the operating bias voltage, and the capacitance characteristics of the diodes will also be significantly degraded due to the increase of interface states. The research on the self-repair phenomenon at room temperature shows that the defects caused by proton irradiation are difficult to be completely repaired. Even if the diodes show not degradation immediately after irradiation, potential damage has been formed inside the diodes, which seriously affects their service life and reliability. Comparing devices with different structures, it is found that the diodes with hexagonal cell have better radiation resistance and robustness. The principle of this phenomenon will be studied later, and suggestions for radiation resistance reinforcement will be put forward.

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