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Citation: Chin. Phys. B, 2022, 31 (**2**): 028502. DOI: 10.1088/1674-1056/ac1331

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Radiation effects of 50-MeV protons on PNP bipolar junction transistors

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(Received 1 March 2021; revised manuscript received 29 June 2021; accepted manuscript online 12 July 2021)

The effects of radiation on 3CG110 PNP bipolar junction transistors (BJTs) are characterized using 50-MeV protons, 40-MeV Si ions, and 1-MeV electrons. In this paper, electrical characteristics and deep level transient spectroscopy (DLTS) are utilized to analyze radiation defects induced by ionization and displacement damage. The experimental results show a degradation of the current gain and an increase in the types of radiation defect with increasing fluences of 50-MeV protons. Moreover, by comparing the types of damage caused by different radiation sources, the characteristics of the radiation defects induced by irradiation show that 50-MeV proton irradiation can produce both ionization and displacement defects in the 3CG110 PNP BJTs, in contrast to 40-MeV Si ions, which mainly generate displacement defects, and 1-MeV electrons, which mainly produce ionization defects. This work provides direct evidence of a synergistic effect between the ionization and displacement defects caused in PNP BJTs by 50-MeV protons.

Keywords: bipolar junction transistors, electrical properties, radiation defects, synergistic effect

PACS: 85.30.Pq, 51.50.+v, 61.80.–x, 81.40.Wx **DOI:** 10.1088/1674-1056/ac1331

1. Introduction

Bipolar junction transistors (BJTs), an important type of electronic component, are highly sensitive to ionization and displacement radiation effects. In their potential applications in space, BJTs would routinely be exposed to several types of particle and ray (for example, α-particles, γ-rays, x-rays, electrons, neutrons, and protons). As one of the significant irradiation particles, protons can cause serious radiation damage to space devices.[1–3] The energy of protons in the space environment ranges from tens of keV to GeV. Within this range of energies, low- and medium-energy (keV to MeV) particles are important in radiation damage production, because high-energy particles are "slowed down" to lower energies by shielding.[4,5] Therefore, studying the radiation effects of particles in the MeV range is particularly crucial for simulating actual effects in space.

Research into the synergistic effects of ionization and displacement in BJTs caused by proton irradiation is a frontier subject that needs to be further developed. Witczak *et al.*[6] analyzed the radiation tolerance of 2N5339 NPN BJTs using 250-MeV protons and 10-keV x-rays under a zero-radiation bias; the results showed that proton radiation caused ionization and displacement damage, while 10-keV x-rays only caused ionization damage. Li *et al.*[7] used 3DG112 NPN BJTs to study the synergistic effects of irradiation by 70-keV, 170-keV, and 5-MeV protons. It was found that 70-keV protons could only cause ionization damage, 170-keV protons showed maximum displacement damage in the base region, and 5-MeV protons could cause ionization and displacement damage. Liu *et al.*[8] used the individual radiation effects of irradiation by 110-keV electrons, 170-keV protons, and sequential radiation effects in 3DG130 NPN BJTs for comparison. They pointed out that sequential exposure simultaneously produced ionization damage in the oxide layer (caused by the 110-keV electrons) and displacement damage in the Si bulk (caused by the 170-keV protons), which resulted in a synergistic radiation effect in the BJTs. However, there is still a lack of research into the synergistic effects of proton irradiation in the MeV range on P-type BJTs.

The purpose of this paper is to study the characteristics of radiation defects in PNP BJTs irradiated by 50-MeV protons, 40-MeV Si ions, and 1-MeV electrons, providing unequivocal proof of the synergistic effects of 50-MeV protons on PNP BJTs.

2. Experimental details

In this experiment, 3CG110 BJTs, which are typical high-frequency, low-noise transistors, are selected as the research object. In 3CG110 BJTs, the emitter, base, and epitaxial-layer doping levels are at approximately 10^{20} cm^{-3}, 10^{18} cm^{-3}, and 10^{15} cm^{-3}, and their thicknesses are about 1.8 μm, 2.5 μm, and 12 μm, respectively. High-energy proton, Si ion, and electron irradiation sources are used for irradiation, respectively. The proton and Si ion irradiation processes are performed in an EN Tandem Accelerator in the State Key Laboratory of Nuclear Physics and Nuclear Technology, Peking

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University. The high-energy electron irradiation tests are completed at the Institute of Technical Physics, Heilongjiang Academy of Sciences. The proton flux is 1×10^{9} p/(cm^2·s) and the irradiation fluences are 5×10^{10} p/cm^2, 2×10^{11} p/cm^2, 5×10^{11} p/cm^2, and 2×10^{12} p/cm^2. The Si ion and electron fluxes are 1×10^{7} ions/(cm^2·s) and 1×10^{10} e/(cm^2·s), respectively. The irradiation fluences chosen are 3.5×10^{8} ions/cm^2–2.5×10^{9} ions/cm^2 and 4×10^{12} e/cm^2–3×10^{14} e/cm^2, respectively.

In order to accurately analyze the damage caused to the BJTs after particle irradiation, all samples are decapped before the experiment and all the pins of the PNP BJTs are grounded during the irradiation, in addition, set 4 is repeated for each fluence to ensure the reproducibility and consistency of the data. The electrical properties of the BJTs are measured using an in-situ test method; the Gummel curve measurement conditions are as follows: the emitter voltage is swept from 0.2 V to 0.9 V, the voltage interval is 0.01 V, the base and collector are grounded.

A DLTS test analysis of the BJTs is carried out after the various particle radiations to study the evolution characteristics of deep-level defects. The collector region of the BJTs, with a lower doping concentration, is selected for testing. During the test, the base of the BJTs is connected to a high potential, and the collector is connected to a low potential. The main test parameters used are as follows: the reverse bias $V_{\rm R}=10$ V, the pulse voltage $V_{\rm P}=0.1$ V, the transient capacitance test period $T_{\rm W}=0.2048$ s, the pulse width $T_{\rm P}=0.01$ s, and the scan temperature ranges from 0 K to 350 K.

3. Experimental results and discussion

3.1. Electrical characteristics

The current gain β is very sensitive to irradiation fluences, so it is one of the most important parameters used to characterize the degradation degree of BJTs subjected to radiation. Compared with the current gain, the reciprocal of the current gain $\Delta(1/\beta)$ can more intuitively reflect the change of the current gain and better reflect the influence of radiation on the electrical performance of the BJTs. For PNP BJTs, β is defined as the ratio of the collector current $I_{\rm C}$ and the base current $I_{\rm B}$, and the change in the inverse of the current gain is $\Delta(1/\beta)=1/\beta-1/\beta_0$, where β_0 and β are the current gains of the PNP BJTs before and after irradiation.[9,10]

It can clearly be seen from Fig. 1 that $\Delta(1/\beta)$ changes as a function of the 50 MeV proton fluence in 3CG110 BJTs (when the emitter–base voltage $V_{\rm EB}=0.65$ V). In Fig. 1, the value of $\Delta(1/\beta)$ after proton irradiation shows an obvious upward trend with increasing irradiation fluence, indicating that proton irradiation produces a large number of defects and greatly reduces the current gain of the BJTs, so that the performance of the BJTs drops sharply, and they even suffer permanent damage.[11]

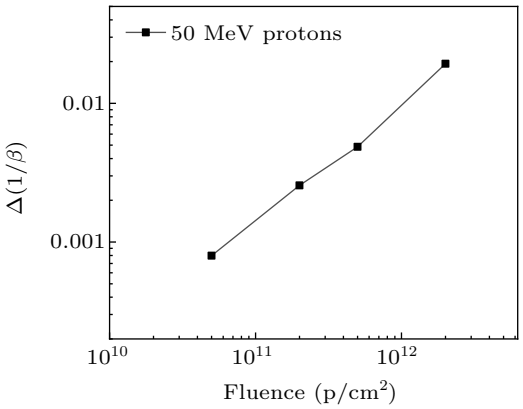


Fig. 1. Reciprocal of the current gain $\Delta(1/\beta)$ as a function of proton irradiation fluence in 3CG110 BJTs.

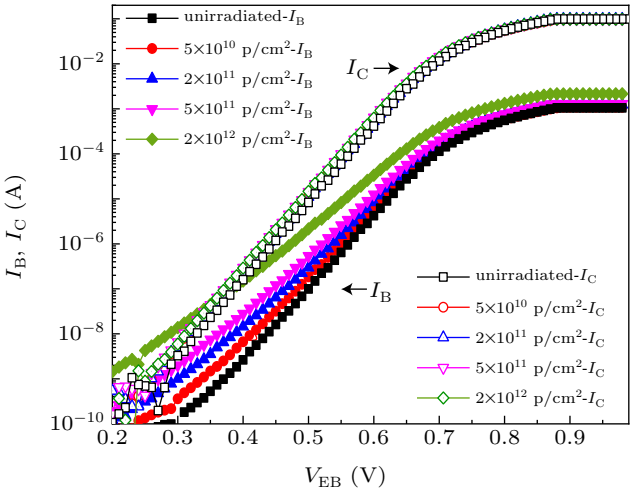


Fig. 2. Variations of $I_{\rm B}$, $I_{\rm C}$ with $V_{\rm EB}$ in 3CG110 BJTs after different fluences of proton irradiation.

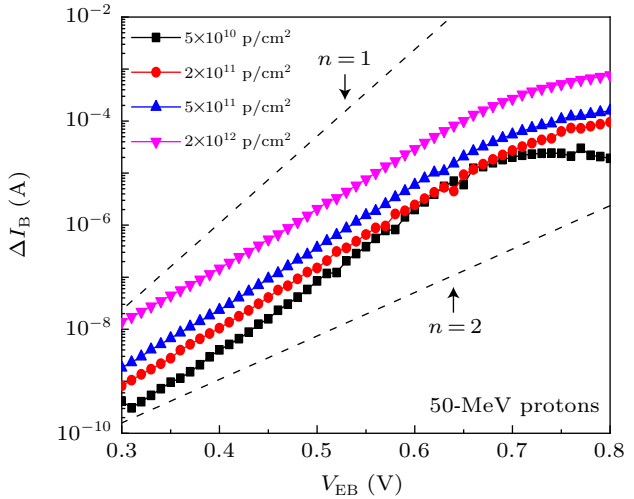


Fig. 3. Variations of $\Delta I_{\rm B}$ with $V_{\rm EB}$ in 3CG110 BJTs after different fluences of proton irradiation.

Figure 2 shows the variation in the relationship between $I_{\rm B}$ and $I_{\rm C}$ of 3CG110 BJTs as a function of $V_{\rm EB}$ after proton irradiation. It can be seen that with an increase in the irradiation fluence, the $I_{\rm B}$ of the BJTs gradually increases, and the

I_C hardly changes, indicating that the influence of radiation on the electrical performance of BJTs is mainly concentrated in I_B, while I_C is insensitive to radiation.[12]

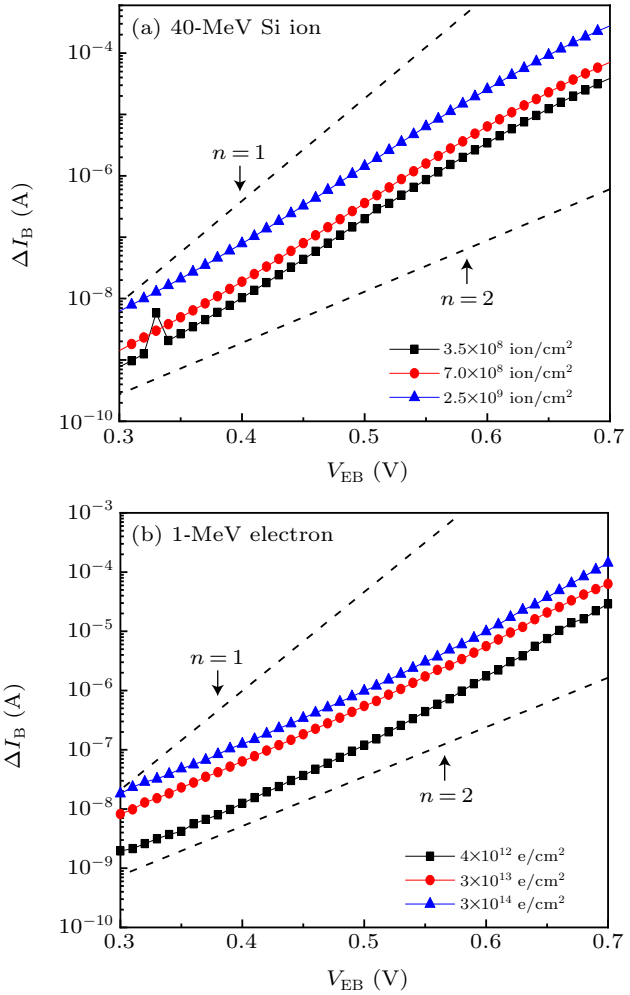


Fig. 4. Variations in ΔI_B with V_{EB} in 3CG110 after Si ions and electrons irradiation: (a) 40-MeV Si ions, (b) 1-MeV electrons.

The excess base current ΔI_B is an important parameter that characterizes the change in the base current of BJTs, and it is also an important basis for an in-depth study of the particle radiation damage mechanism. It is defined as $\Delta I_B = I_B - I_{B\,pre}$, where $I_{B\,pre}$ and I_B are the base currents of the PNP BJTs before and after irradiation.[13,14] In order to better explain the effect of proton irradiation on the radiation damage mechanism of BJTs, a model based on an ideality factor n is utilized to analyze the change in ΔI_B. The expression for ΔI_B is

$$\Delta I_B = K \cdot \exp\left(\frac{q \cdot V_{EB}}{n \cdot k_B \cdot T}\right), \tag{1}$$

where K is the coefficient, q is the electron charge, k_B is the Boltzmann constant, and T is the absolute temperature.[15] Ideally, if the current change during irradiation is dominated by the composite current in the emitter–base space charge region, the ideality factor $n = 2$; if the current change is dominated by the diffusion current in the neutral base region, the ideality factor $n = 1$. Therefore, when ΔI_B is induced by a combination of currents in the space charge region and the neutral base region, the ideality factor is between one and two. Ionization damage mainly affects the insulating layer and the Si/SiO_2 interface of BJTs, due to the oxide charges and interface states generated in the space charge region. When BJTs suffer from displacement damage, the displacement defects act as effective recombination and trapping centers, resulting in a shortened lifetime of minority carriers in the neutral base region, and then the excessive base current increases.

The relationship between the ΔI_B and V_{EB} of 3CG110 BJTs after proton irradiation is presented in Fig. 3. It can be pointed out that after 50-MeV proton irradiation, as the irradiation fluence increases, the ideality factor n of the excess base current is always between one and two, indicating that excess base current is generated in both the neutral base region and the space charge region.[16,17] There is a synergistic effect between ionization and displacement.

Figure 4 shows the relationship between the ΔI_B of the 3CG110 BJTs and V_{EB} under Si ion and electron irradiation. It can be seen that the ideality factor n after Si ion irradiation is close to one, although it is not obvious; the ideality factor n after electron irradiation is obviously close to two.[17] The results show that after electron irradiation, the combination current in the emitter–base space charge region becomes larger than that in the neutral base region, which mainly produces ionization effects.

3.2. Radiation-induced defects measured by DLTS

According to the analysis in Subsection 3.1, it is clear that the electrical performance of PNP BJTs decreases with increasing irradiation fluence, and that proton radiation produces a synergistic effect. In order to better study the mechanism of the synergistic effect of ionization and displacement in BJTs, it is necessary to deeply analyze the evolution process of irradiation defects. DLTS is an effective method for studying the behavior of irradiation defects.[18,19] Figure 5 shows the DLTS test results for the 3CG110 BJTs before and after 50-MeV proton irradiation.

As revealed in Fig. 5, the abscissa of the signal peak corresponds to the energy-level position of the deep-level defects, and the ordinate height corresponds to the concentration of defects. The DLTS signal in the deep-level transient spectrum is positive, indicating that the defect centers generated in the collector region after proton irradiation are multiple sub-trapping centers.[19–21] It can be seen from Fig. 5 that the DLTS spectra show two typical peaks of displacement radiation defects at about 135 K and 165 K after irradiation, which are the $V_2(+/0)$ and $C_iO_i(+/0)$ signal peaks, respectively; the peak H(245) that appears at about 245 K is an interface state trap peak, which is a typical ionization defect; the peak H(42) at 42 K is a body defect. This is similar to the results of Yang *et*

al.,[20] who also found the displacement peaks of $V_2(+/0)$ and $C_iO_i(+/0)$ after irradiation, as well as the interface trap peaks at 260 K and 270 K. This shows that with an increase in the proton irradiation fluence, not only do new defects appear, but interactions also occur between ionization and displacement defects.

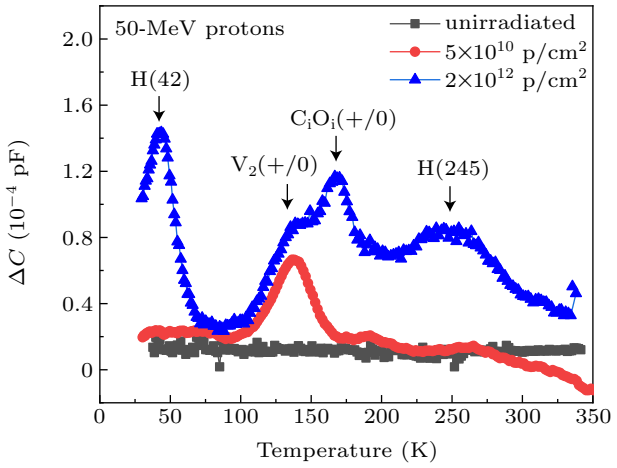


Fig. 5. DLTS test results for 3CG110 BJTs before and after different proton irradiation fluences.

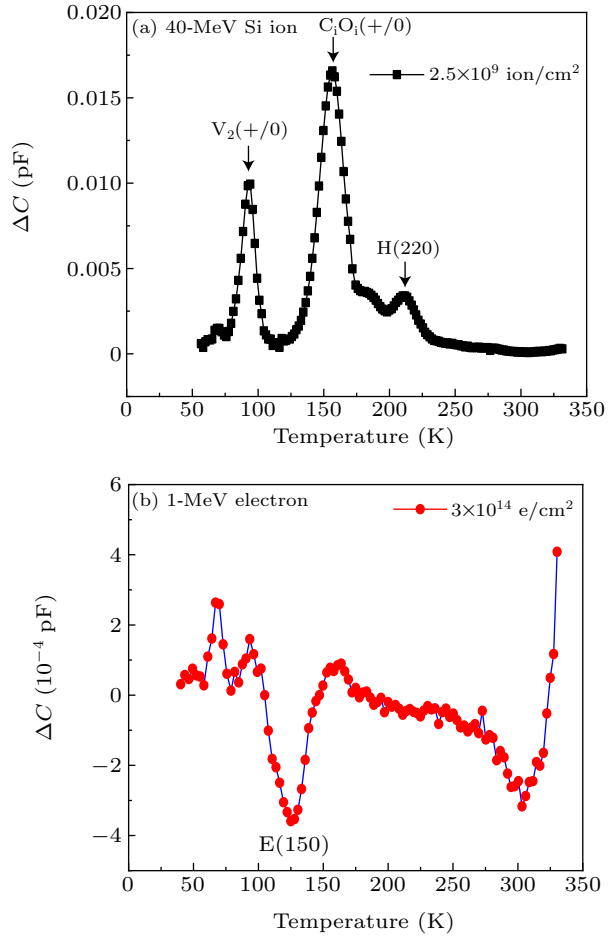


Fig. 6. DLTS test results for 3CG110 BJTs after 40-MeV Si ion and 1-MeV electron irradiation; (a) 40-MeV Si ions, (b) 1-MeV electrons.

The DLTS test results of 3CG110 BJTs after 40-MeV Si ion and 1-MeV electron irradiation are displayed in Fig. 6. As shown in Fig. 6, after 40-MeV Si ion irradiation, a double-vacancy defect $V_2(+/0)$ appears near 100 K, another double-vacancy defect $C_iO_i(+/0)$ appears near 175 K, and the signal peak H(220) has unstable defects. It can be seen that the defects produced by 40-MeV Si ion irradiation are mostly double-vacancy defects, which mainly cause displacement damage. In addition, an obvious negative signal peak called E(150) appears after 1-MeV electron irradiation, which is an ionization defect.[20]

Obviously, 50-MeV proton irradiation can simultaneously generate ionization and displacement signals in 3CG110 BJTs, as opposed to Si ions, which only produce displacement signals, and electrons, which only produce ionization signals. As mentioned above, this proves the synergistic effect of ionization and displacement defects produced by proton irradiation.

4. Conclusion

In this paper, we have described our study of the radiation effects in 3CG110 PNP BJTs irradiated by 50-MeV protons, 40-MeV Si ions, and 1-MeV electrons. The experimental results show that as the 50-MeV proton irradiation fluence increases, the ideality factor of ΔI_B, is between one and two, indicating that ΔI_B is induced by a combination of the currents in both the emitter–base junction and the neutral base region. With an increasing 1-MeV electron irradiation fluence, the ideality factor n becomes close to two, suggesting that ΔI_B is induced by an emitter–base junction recombination current at the silicon's surface. A DLTS analysis showed that 50-MeV proton irradiation can produce both the ionization defect H(245) and two displacement defects associated with $V_2(+/0)$ and $C_iO_i(+/0)$. With an increase in the irradiation fluence, there is an obvious interaction between the ionization defects and the displacement defects. While 40-MeV Si ions can produce a very high concentration of divacancies $V_2(+/0)$ and carbon vacancies $C_iO_i(+/0)$, resulting in a displacement effect in PNP BJTs, 1-MeV electrons can produce minority carrier defects E(150), resulting in ionization effects. By comparing the characteristics of the damage caused by different radiation sources, we have demonstrated by direct means that a synergistic effect takes place in 3CG110 PNP BJTs after exposure to 50-MeV protons.

Acknowledgment

Project supported by No. TZ2018004.

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