Effect of bias condition on heavy ion radiation in bipolar junction transistors*

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The characteristic degradations in a silicon NPN bipolar junction transistor (BJT) of 3DG142 type are examined under irradiation with 40-MeV chlorine (Cl) ions under forward, grounded, and reverse bias conditions, respectively. Different electrical parameters are *in-situ* measured during the exposure under each bias condition. From the experimental data, a larger variation of base current ($I_{\rm B}$) is observed after irradiation at a given value of base-emitter voltage ($V_{\rm BE}$), while the collector current is slightly affected by irradiation at a given $V_{\rm BE}$. The gain degradation is affected mostly by the behaviour of the base current. From the experimental data, the variation of current gain in the case of forward bias is much smaller than that in the other conditions. Moreover, for 3DG142 BJT, the current gain degradation in the case of reverse bias is more severe than that in the grounded case at low fluence, while at high fluence, the gain degradation in the reverse bias case becomes smaller than that in the grounded case.

Keywords: radiation effects, ionization damage, displacement damage, transistors

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1. Introduction

Bipolar junction transistors (BJTs) have important applications in radioactive environments, such as space systems, defense systems, and high-energy particle accelerators. Bipolar transistors have advantages in speed, linearity, transconductance, and current driving. Numerous studies demonstrate that the sensitivity of a bipolar circuit to radiation damage is determined primarily by gain degradation in the critical bipolar junction transistor in the circuit.[1−7] Therefore, it is valuable to research the radiation response of a bipolar junction transistor to find better design strategies for its specific applications.

In space systems, electronic components are susceptible to a radioactive environment composed of cosmic rays, protons, electrons, and other particles.[8−16] These charged particles could induce both ionization and displacement damage to BJTs too, and there are some interactions between them. The ionization effect could affect the displacement damage to some extent in the BJT.[17,18] The study of interactions between ionization and displacement effects on semiconductor devices, in general, is important from the point of view of both basic and space applications.

The bias condition during irradiation or operation is an important factor for bipolar devices. Some studies focused on the bias dependence of the ionization effects induced by electrons and γ-rays.[19−21] Previous investigations show that the bias condition can also affect the displacement effect.[22] However, the effect of bias on the combined ionization and displacement damages induced by incident particles has not been known clearly. Therefore, it is valuable to study the effect of bias on the combined ionization and displacement damage.

2. Experimental details

3DG142 bipolar junction transistors are used as samples in this study. They are generally used for radio frequency and low power applications. The samples were mounted inside a package with removable upper lid for irradiation. The irradiation and measurements were performed at room temperature.

The irradiation tests were performed using the EN Tandem Accelerator in the State Key Laboratory

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of Nuclear Physics and Technology, Peking University, China. 40-MeV Cl ions are chosen as the incident particles in the irradiation tests. The irradiations were carried out in an evacuated chamber with a specially designed Faraday cup, which was used to measure the heavy ions beam current. From these measurements, the flux and fluences were determined for the irradiation experiments. The degradations of transistors irradiated by 40-MeV Cl ions were investigated under the following various bias conditions:

(i) $V_{\rm BE} = V_{\rm BC} = 0$ V, with all terminals grounded;

(ii) $V_{\rm BE} = 0.7$ V, $V_{\rm BC} = 0$ V;

(iii) $V_{\rm BE} = -4$ V, $V_{\rm BC} = 0$ V.

Different electrical parameters of the NPN BJTs were measured *in-situ* using a semiconductor characterization system that consists of a KEITHLEY 4200-SCS. The turn-around time between irradiation and device measurements is approximately less than 10 s.

3. Experimental results

3.1. Gummel characteristics

Gummel characteristics were measured for the NPN transistors before and after irradiation in a common-emitter configuration by applying a sweep in $V_{\rm E}$ from 0 to 1.2 V and keeping $V_{\rm B} = V_{\rm C} = V_{\rm CB} = 0$ V. Figures 1–3 show the variations of collector current ($I_{\rm C}$) and base current ($I_{\rm B}$) with base-emitter voltage ($V_{\rm BE}$) for the 3DG142 transistors irradiated by 40-MeV Cl ions with different fluences, respectively, under three bias conditions: $V_{\rm BE} = V_{\rm BC} = 0$ V, with all terminals grounded; $V_{\rm BE} = 0.7$ V, $V_{\rm BC} = 0$ V; $V_{\rm BE} = -4$ V, $V_{\rm BC} = 0$ V, during exposures. As shown in Fig. 1, the collector current ($I_{\rm C}$) keeps invariable with the increase of fluence, while the base current ($I_{\rm B}$) increases. These phenomena indicate that the base current ($I_{\rm B}$) is more sensitive to the radiation damage caused by 40-MeV Cl ions, while the collector current is only slightly affected by irradiation at any given base-emitter voltage value ($V_{\rm BE}$). As a consequence, for these fluences, the gain degradation is affected mostly by the behaviour of the base current. The results in Figs. 2 and 3 have similar trends to those in Fig. 1. Based on the results in Figs. 1–3, it is also apparent that a significant change in base current can be detected under all the considered bias conditions.

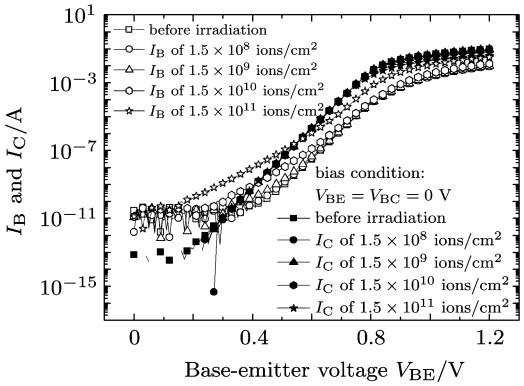


Fig. 1. Variations of collector current ($I_{\rm C}$) and base current ($I_{\rm B}$) with base-emitter voltage ($V_{\rm BE}$) for the 3DG142 transistor irradiated by 40-MeV Cl ions with different fluences (bias condition $V_{\rm BE} = V_{\rm BC} = 0$ V).

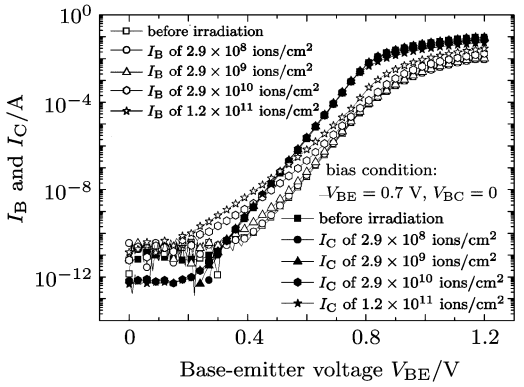


Fig. 2. Variations of collector current ($I_{\rm C}$) and base current ($I_{\rm B}$) with base-emitter voltage ($V_{\rm BE}$) for the 3DG142 transistor irradiated by 40-MeV Cl ions with different fluencies (bias condition $V_{\rm BE} = 0.7$ V and $V_{\rm BC} = 0$ V).

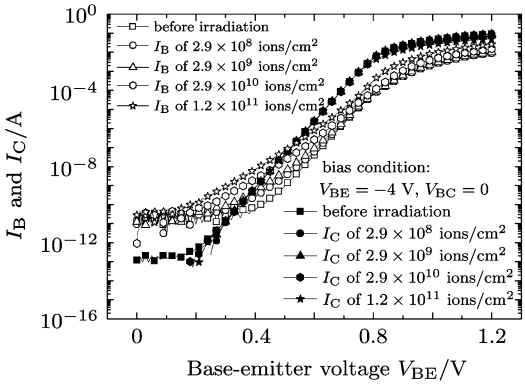


Fig. 3. Variations of collector current ($I_{\rm C}$) and base current ($I_{\rm B}$) with base-emitter voltage ($V_{\rm BE}$) for the 3DG142 transistor irradiated by 40-MeV Cl ions with different fluencies (bias condition $V_{\rm BE} = -4$ V and $V_{\rm BC} = 0$ V).

3.2. Degradation of current gain

In space, radiation-induced gain degradation is a concern for characterizations of BJTs, and is the pri-

mary cause of parametric shifts and functional failures. The gain degradation is affected mostly by the behaviour of the base current, since the collector current is affected only slightly by irradiation. Based on the unchanged collector current (I_C) with increasing irradiation fluence, the current gain ($\beta = I_C/I_B$) of the NPN BJT as a function of the collector current (I_C) could be extracted from Fig. 1 (bias case 1, $V_{BE} = V_{BC} = 0$ V) as shown in Fig. 4. The current gain degrades substantially with the increase of fluence, especially in the lower collector currents (I_C) range. The decrease in current gain is due primarily to an increase in base current (I_B) (see Fig. 1). Similar results are observed in the other two bias conditions.

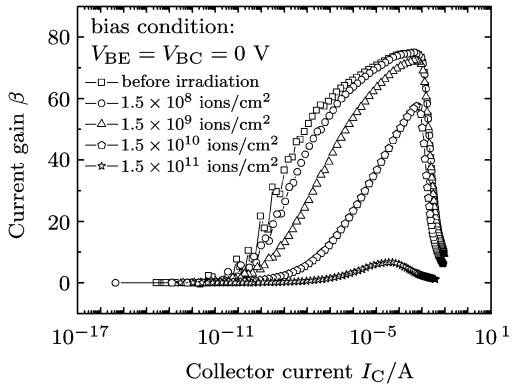


Fig. 4. Current gain versus collector current for the 3DG142 transistor irradiated by 40-MeV Cl ions.

The change in current gain ($\Delta\beta$) is defined as the transistor current gain after irradiation (β) minus the value before irradiation ($\beta_{pre-rad}$), that is, $\Delta\beta = \beta - \beta_{pre-rad)}$. Similarly, the change in the reciprocal of the gain variation ($\Delta(1/\beta)$) is defined as the value after irradiation minus the initial one, that is, $\Delta(1/\beta) = 1/\beta - 1/\beta_{pre-rad}$. Figure 5 shows the changes of current gain ($\Delta\beta$) for the 3DG142 transistor under various bias conditions, irradiated by 40-MeV Cl ions, which could be extracted from Figs. 1–3 with $V_{BE} = 0.65$ V. The trends of the current gain degradation under various bias conditions are similar, showing the current gain decreases with the increase of Cl ions fluence. The slope of the current gain degradation is smaller at low fluence, and it is then followed by a steeper region. From the results in Fig. 5, it is obvious that the variation of current gain in the case of forward bias is much smaller than that in the other conditions. On the other hand, the current gain degradation in the case of reverse bias is larger than that in the zero bias case at low fluence, and smaller at high fluence. Figure 6 shows the changes in the reciprocal of current gain ($\Delta(1/\beta)$) at a base-emitter voltage of 0.65 V each as a function of fluence under the three bias conditions. The dash plot in Fig. 6 is the linear reference line for comparing the curves conveniently. It is shown that $\Delta(1/\beta)$ in zero bias case shows an approximate linear behaviour with irradiation fluence (nonlinear at low fluence, and linear at high fluence). The $\Delta(1/\beta)$ in the forward and reverse bias case varies nonlinearly with the increase of Cl ion fluence.

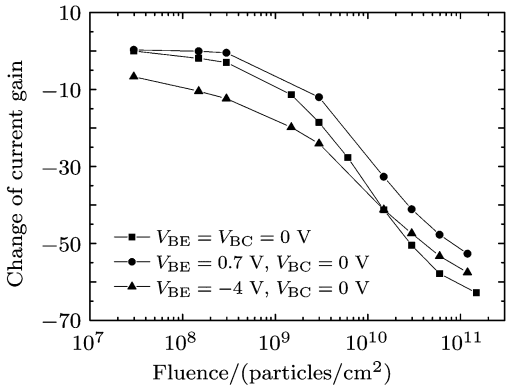


Fig. 5. Changes of current gain each as a function of fluence for a 3DG142 NPN bipolar transistor irradiated by 40-MeV Cl ions under different bias conditions with $V_{BE} = 0.65$ V.

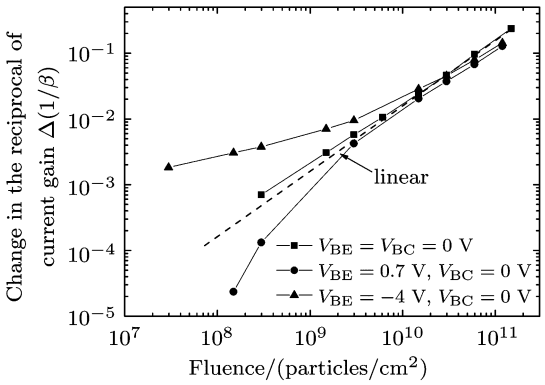


Fig. 6. Changes in the current gain reciprocal each as a function of fluence for the 3DG142 NPN bipolar transistor irradiated by 40-MeV Cl ions under different bias conditions ($V_{BE} = 0.65$ V).

4. Discussion

Heavy ions can induce ionization damage to the oxide layer and displacement damage in the Si bulk. Bipolar junction transistors are sensitive to both ionization and displacement damage, leading to current gain degradation. The displacement damage can produce vacancy defect complexes that are effective re-

combination and trapping centers, leading to a decrease in minority carrier lifetime. The degradation of minority carrier lifetime results in the current gain degradation for the BJT. The ionization damage could cause interface traps and net positive charges in the oxide overlying the base-emitter junction, leading to an increase in base current and current gain degradation.

Based on the results in Fig. 6, $\Delta(1/\beta)$ in the zero bias case shows a little nonlinear behaviour at low fluence, and becomes linear at high fluence. As mentioned above, the nonlinear behaviour for the heavy ions irradiations is attributed to trapped charge in the passivation and field oxide layers of the transistor. This implies that the change in the reciprocal of current gain is dominated by the ionization effects, leading to a nonlinear behaviour at low fluence. At high fluence, the displacement damage provides the main contribution to current gain and results in the linear response that obeys the Messenger–Spratt equation.[23]

As mentioned above, the degradation of current gain is dominated by the ionization effects at low fluence. The ionization damage could cause interface traps and net positive charges in the oxide overlying the base-emitter junction. Base-emitter bias conditions could induce the field of the base-emitter junction, and govern the internal electric field in an oxide. The internal electric field in an oxide can influence the buildup of oxide fixed charges and interface traps during irradiation. Under zero base-emitter junction bias, the internal electric field facilitates the accumulation of positive charge in the oxide and interface traps during irradiation. The internal electric field increases in the reverse bias case, while decreases in the forward bias case. The increase of internal electric field causes the buildup of oxide fixed charges and interface traps, leading to an increase in excess base current. Therefore, at low fluence, the current gain degradation in the reverse bias case is larger than that at zero bias, while the degradation in the forward bias case is lower than that in the zero bias case for NPN transistors, as shown in Fig. 6.

On the other hand, at high fluence, displacement damage makes the main contribution to current gain. Base-emitter bias conditions can affect the displacement effects to some extent in the BJT. The injection annealing can lead to an enhancement of displacement defect reordering by the presence of free charge carriers.[24] The free charge carriers may be introduced in several ways, including electrical injection into devices. When the base-emitter junction is forward biased, extra minority-carriers can diffuse into the base region. When the base-emitter junction is reverse biased or has all terminals grounded, no extra minority-carriers diffuse into the base. Therefore, the electrical injection results in less degradation of current gain in the forward bias case than in other bias cases.

The ionization effects can also affect the displacement damage in a BJT. There may be two different physical mechanisms for the interaction between the ionization and displacement damage. The first may be positive oxide charge. For an NPN device, the positive oxide charges enhance the bulk recombination current by lowering the majority carrier density near the base surface, making the surface become depleted and reducing the difference in carrier density between the subsurface and bulk.[17] These effects can exert an influence on the NPN BJT, and recover a part of the displacement damage caused by 40-MeV Cl ions. The second is interface states. For an NPN device, the interface state is positive, and the difference in carrier density between the subsurface and bulk can be reduced.[18] Therefore, the interface state enhances the displacement damage in an NPN BJT. For the results in Fig. 6, the effect of the positive oxide charge may be the main mechanism. At low fluence, the incident particles induce the larger ionization damage and positive oxide charges in 3DG142 BJT in the reverse bias case. Therefore, the BJT in the reverse bias case shows a more obvious annealing effect than in zero and forward bias conditions at high fluence.

5. Conclusion

In this paper, the characteristic degradations in Si NPN BJT of 3DG142 type is examined under irradiation with 40-MeV Cl ions in various bias conditions. The experimental data show that the collector current (I_C) remains unchanged with the increase of fluence, while the base current (I_B) increases. The gain degradation is affected mostly by the behaviour of the base current. The SRIM calculated data and the experimental results show that the bias condition affects the radiation damage of NPN BJT irradiated by 40-MeV Cl ions. The variation of current gain in the case of forward bias is far smaller than that in the other conditions. At the same time, for the forward, grounded, and reverse bias three cases, the current

gain degradation in reverse bias conditions is largest at low fluence, while the degradation in the gounded case becomes largest at high fluence.

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