Incident particle range dependence of radiation damage in a power bipolar junction transistor*

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The characteristic degradations in silicon NPN bipolar junction transistors (BJTs) of type 3DD155 are examined under the irradiations of 25-MeV carbon (C), 40-MeV silicon (Si), and 40-MeV chlorine (Cl) ions respectively. Different electrical parameters are measured *in-situ* during the exposure of heavy ions. The experimental data shows that the changes in the reciprocal of the gain variation ($\Delta(1/\beta)$) of 3DD155 transistors irradiated respectively by 25-MeV C, 40-MeV Si, and 40-MeV Cl ions each present a nonlinear behaviour at a low fluence and a linear response at a high fluence. The $\Delta(1/\beta)$ of 3DD155 BJT irradiated by 25-MeV C ions is greatest at a given fluence, a little smaller when the device is irradiated by 40-MeV Si ions, and smallest in the case of the 40-MeV Cl ions irradiation. The measured and calculated results clearly show that the range of heavy ions in the base region of BJT affects the level of radiation damage.

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

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1. Introduction

Bipolar junction transistors (BJTs) in space systems are sensitive to a radiation environment composed of cosmic rays, protons, electrons, and other particles.[1−7] These energetic particles degrade the electrical performance of the device. Therefore, understanding the radiation response of the device is extremely important for the accurate prediction of the expected mission lifetime.

In order to make a prediction of how a particular electrical parameter, e.g., the current gain of a BJT, degrades in a space radiation environment, the damage coefficient is needed. Non-ionizing energy loss (NIEL) and linear energy transfer (LET) are very useful damage coefficients for correlating displacement and ionizing damage produced in semiconductors by a series of particle types and energies, respectively.[8] If the incident particle range is much greater than the characteristic dimension of the chip of a semiconductor, the NIEL or LET value of the incident particle can be assumed to be constant. When that is not the case, the NIEL or LET value will not give a good measure of the energy deposition induced by various particles and the particle correlation will not hold any more.[9]

The incident particle range in BJT is an important factor to evaluate the correlation of radiation damage induced by various particles. If the incident particle range is lower than depth between the surface and base region of a BJT chip, the NIEL or LET value of the incident particle will vary a lot, especially in the end of the range. In this case, the radiation damage of BJT could not be the same as those with a constant NIEL or LET value at a given dose or fluence. Therefore, it is useful to investigate the influence of the incident particle range on the radiation effects of BJT. Generally, the range of incident particles chosen is much deeper than the dimension of the BJT chip, as mentioned in Refs. [10]–[16]. Few published papers dealing with the influence of the incident particle range on the radiation effects of BJT are available,[17] which could give much valuable information. In the present paper, 25-MeV carbon (C), 40-MeV silicon (Si), and 40-MeV chlorine (Cl) ions were chosen to investigate the radiation effect of a high power silicon (Si) NPN transistor, of which the maximum range is in the base region of the BJT.

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2. Experimental details

3DD155 bipolar junction transistors were used as samples in this study, which are a type of low radio frequency and high power silicon (Si) NPN transistor. Their thicknesses are about 1, 25, and 40 μm for the insulating silicon dioxide, the emitter, and the base region of the NPN BJTs, respectively. Uncertainties in measured parameters were less than 10 percent. The doping concentrations of the emitter, base, and collector are 1×10^{20}, 1×10^{18}, and 1×10^{15}, respectively. In addition, the samples were mounted inside a package with a removable upper lid for irradiation. The 25-MeV carbon (C), 40-MeV silicon (Si), and 40-MeV chlorine (Cl) ions were chosen to test the 3DD155 BJTs separately.

The heavy ion irradiations were performed using the EN Tandem Accelerator in the State Key Laboratory of Nuclear Physics and Technology, Peking University, China. The irradiations were carried out in a vacuum chamber with a specially designed Faraday cup, which is used to measure the heavy ion beam current. From these measurements, the flux and fluences were determined for the irradiation experiments. Uncertainties in measured radiation fluence were less than 10 percent.

The samples were mounted inside a package with a removable upper lid for irradiation. All terminals of the samples were grounded during all particle irradiations. Electrical parameters of the NPN BJTs were measured *in-situ* using a semiconductor characterization system that consists of KEITHLEY 4200-SCS. The turn-around time between irradiation and device measurements is approximately less than 5 s. The irradiations and measurements were performed at room temperature.

3. Experimental results

3.1. Gummel characteristics

Gummel characteristics were measured for the NPN transistors before and after irradiations, which were obtained in a common-emitter configuration of sweeping from 0 to 1.2 V (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 variation of the collector current ($I_{\rm C}$) and base current ($I_{\rm B}$) with base–emitter voltage ($V_{\rm BE}$) for the 3DD155 transistors irradiated by 25-MeV C, 40-MeV Si, and 40-MeV Cl ions with different fluences, respectively. Based on the results in Fig. 1, it is shown that the collector current ($I_{\rm C}$) remains unchanged with fluence increasing, while the base current ($I_{\rm B}$) increases. These phenomena indicate that

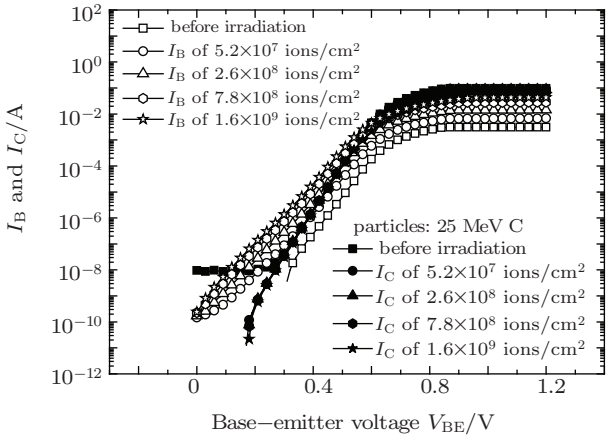


Fig. 1. Variations of collector current ($I_{\rm C}$) and base current ($I_{\rm B}$) with base–emitter voltage ($V_{\rm BE}$) for the 3DD155 irradiated by 25-MeV C ions with different fluences.

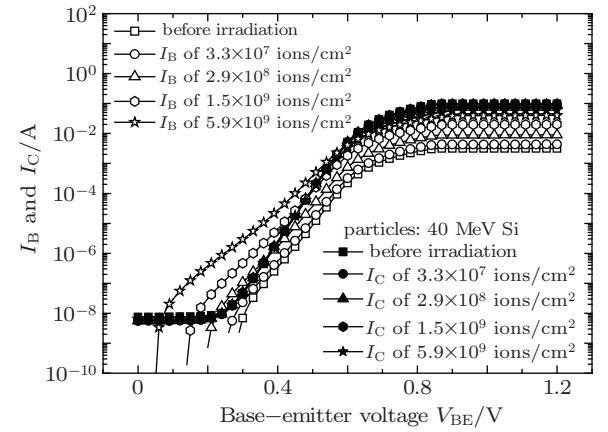


Fig. 2. Variations of collector current ($I_{\rm C}$) and base current ($I_{\rm B}$) with base–emitter voltage ($V_{\rm BE}$) for the 3DD155 irradiated by 40-MeV Si ions with different fluences.

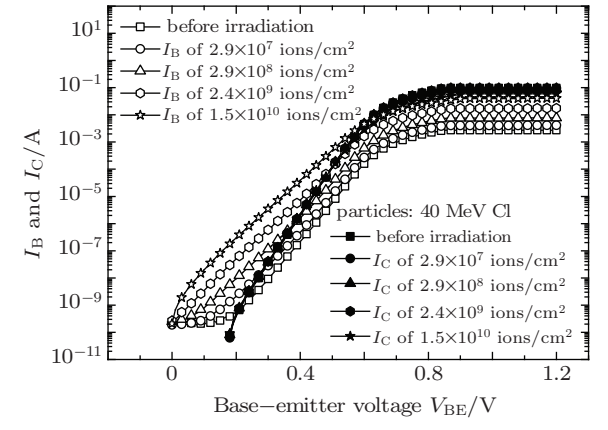


Fig. 3. Variations of collector current ($I_{\rm C}$) and base current ($I_{\rm B}$) with base–emitter voltage ($V_{\rm BE}$) for the 3DD155 irradiated by 40-MeV Cl ions with different fluences.

the base current (I_B) is more sensitive to the radiation damage caused by the 25-MeV C ions, while the collector current is only slightly affected by irradiation at any given base–emitter voltage value (V_{BE}). Consequently, for these fluences, the gain degradation is mostly affected by the behaviour of the base current. The results in Figs. 2 and 3 each have a similar trend to those in Fig. 1. Based on the results in Figs. 1–3, a significant change in the base current can be detected in all heavy ion irradiations.

3.2. Degradation of current gain

The susceptibility of NPN BJT to radiation damage can be examined by current gain degradation. As mentioned above, the gain degradation is mostly affected by the behaviour of the base current, and the collector current is only slightly affected by irradiation. The change in the reciprocal of the gain variation ($\Delta(1/\beta)$) is defined as the difference between the irradiation and its initial one, that is, $\Delta(1/\beta) = 1/\beta - 1/\beta_{\mathrm{pre-rad}}$. Figure 4 shows the change in the reciprocal of current gain ($\Delta(1/\beta)$) at a base–emitter voltage of 0.65 V as a function of the fluence of heavy ions. It is shown that $\Delta(1/\beta)$ increases with the increase of heavy ion fluence. From the results in Fig. 4, the change in the reciprocal of the gain variation ($\Delta(1/\beta)$) of 3DD155 BJT irradiated by 25-MeV C ions is greatest at a given fluence. Compared with the device irradiated by 25-MeV C ions, $\Delta(1/\beta)$ is smaller when the device is irradiated by Si ions and Cl ions, and $\Delta(1/\beta)$ in 40-MeV Cl ion irradiation is a little smaller than that in 40-MeV Si ion irradiation. For 25-MeV C and 40-MeV Si ions, the reciprocal of current gain varies nonlinearly at a lower fluence, but linearly at a higher fluence. The variation of $\Delta(1/\beta)$ in 25-MeV C ion irradiation becomes linear at 2×10^8 ions/cm^2, while $\Delta(1/\beta)$ in 40-MeV Si ion irradiation varies linearly at 2×10^9 ions/cm^2. For 40-MeV Cl ions, the change in the reciprocal of current gain $\Delta(1/\beta)$ varies nonlinearly. The relationship between the reciprocal of current gain and the heavy ions fluence is discussed in the next section.

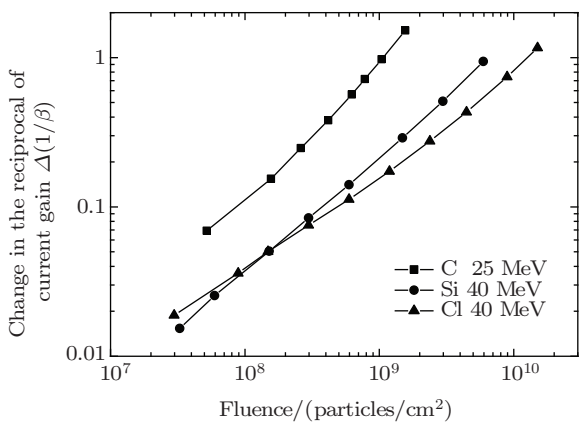


Fig. 4. Variations in the reciprocal of current gain with fluence for the 3DD155 irradiated by 25-MeV C, 40-MeV Si, and 40-MeV Cl ions ($V_{BE} = 0.65$ V).

4. Discussion

Charged particles can induce radiation damage in BJT, which are sensitive to both ionization and displacement damage. The displacement damage would produce vacancy defect complexes that are effective recombination 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 emitter–base junction, leading to an increase in base current and current gain degradation.

The total ionizing absorbed dose D_i and displacement absorbed dose D_d produced by monoenergetic irradiation are calculated using the following equations

$$D_i(t) = 1.6 \times 10^{-8} \times LET(t) \times \Phi, \quad (1)$$

$$D_d(t) = 1.6 \times 10^{-8} \times NIEL(t) \times \Phi, \quad (2)$$

where $D_i(t)$ and $D_d(t)$ are respectively the ionizing dose and the displacement dose, each as a function of depth in chip material of the NPN BJT, and in units of rad; t is the depth in the device chips, in units of μm; 1.6×10^{-8} is the unit conversion parameter and in units of rad·g/MeV; Φ is the fluence of the incident particles, in units of particles/cm^2; $LET(t)$ and $NIEL(t)$ are respectively the ionizing and displacement energy loss each as a function of depth in the chip of device, which are calculated by an SRIM code, and in units of MeV·cm^2/g. The ionizing doses per unit fluence of the 25-MeV C, 40-MeV Si, and 40-MeV Cl ions are plotted in Fig. 5, each as a function of the chip depth of the 3DD155 BJT. The displacement doses per unit fluence versus the chip depth for the 25-MeV C, 40-MeV Si, and 40-MeV Cl ions are plotted in Fig. 6. Figure 7 is a schematic showing the ranges of 25-MeV C, 40 MeV Si, and 40-MeV Cl ions in the 3DD155 power transistor. As shown in Figs. 5–7, the maximum ranges of these incident particles are all in the base region of the 3DD155. Meanwhile, the

range of 25-MeV C ions is biggest. Moreover, the displacement dose per unit fluence varies greatly with chip depth.

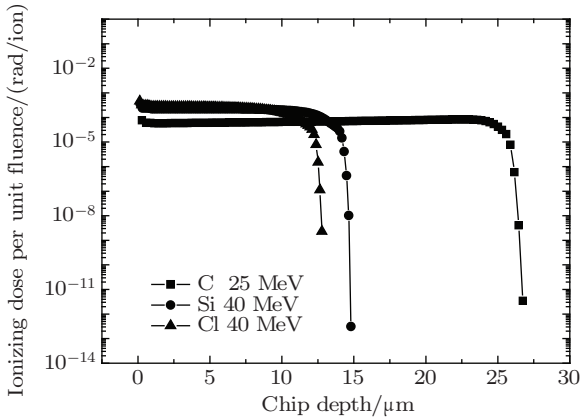


Fig. 5. Ionizing doses per unit fluence versus chip depth for the 25-MeV C, 40-MeV Si, and 40-MeV Cl ions.

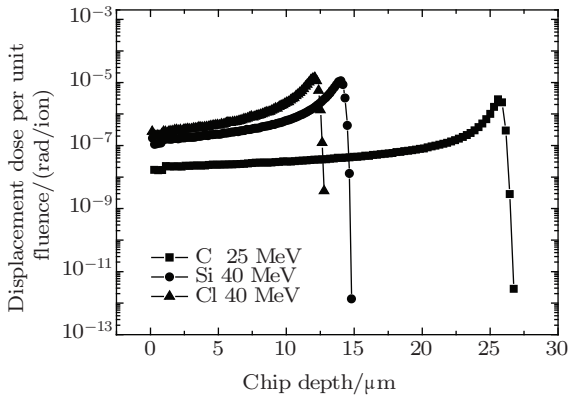


Fig. 6. Displacement doses per unit fluence versus chip depth for the 25-MeV C, 40-MeV Si, and 40-MeV Cl ions.

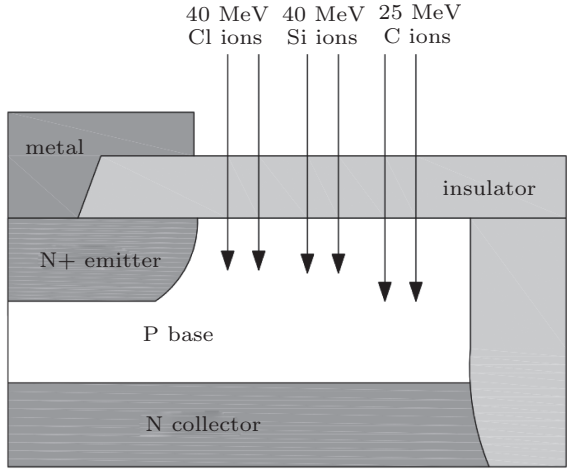


Fig. 7. A schematic diagram showing the range of 25-MeV C, 40-MeV Si, and 40-MeV Cl ions in 3DD155 power transistor.

Previous experimental results indicate that the higher the value of $D_{\rm d}$ of the incident particle, the greater the displacement damage in BJT.[12−16] As shown in Fig. 6, the displacement doses of 40-MeV Si and 40-MeV Cl ions are higher than that of 25-MeV C ions at the same depth of the chip, which is less than 10 μm. At the same time, by numerically integrating the displacement dose per unit fluence in Fig. 6 over the particle track, the total displacement dose of C is much less than those of the other two, which implies that 40-MeV Si and 40-MeV Cl ions should induce larger displacement damages to BJTs and so lead to severe current gain degradation. However, this conclusion is not consistent with the results in Fig. 4. Based on the results in Fig. 4, 25-MeV C ions induce a greater current gain degradation than 40-MeV Si and 40-MeV Cl ions.

From the SRIM calculated results, the numbers of defects induced by 25-MeV C, 40-MeV Si, and 40-MeV Cl ions in BJTs are 1127.6, 4620.6, and 6334.2 vacancies/ion, respectively. The number of defects induced by C ions is much lower than those by the others at the same fluence. That is to say, besides the influence of the number of defects, the range of the incident particles will make another contribution. The 25-MeV C ions have a long enough range to reach the space charge region of the emitter–base (E–B) junction, while 40-MeV Si and 40-MeV Cl ions cannot arrive there. Therefore, the 25-MeV C ions will induce a greater radiation damage to the E–B junction, resulting in severer current gain degradation.

Besides the phenomenon discussed above, a nonlinear behaviour at a low fluence is shown in Fig. 4. This nonlinear behaviour induced by heavy ions is attributed mainly to ionization damage at the lower fluence, which causes a trapped charge in the oxide layer of the BJT. It is shown that the 25-MeV C ions cause a larger degradation in current gain than the 40-MeV Si and Cl ions at a given fluence. The reason for this might be related to the recombination rate of electron–hole pairs in the oxide layer. The electrons produced by ionization are much more mobile than the holes. Although the electrons could be swept out of the oxide layer, some of them might be repaired with the holes. The recombination rate depends greatly on the energy and type of incident particles, as well as the nature of the device. The incident particles that can produce a lower ionizing dose per fluence give a smaller recombination rate for the electron–hole pairs. As shown

in Fig. 5, the 25-MeV C ions can give a much lower ionizing dose per fluence than the 40-MeV Si and Cl ions in the oxide layer. Therefore, under the exposure to 25-MeV C ions, the number of holes trapped in the oxide, which escape from the initial recombination, are more and give bigger damage to the BJT at a given fluence, which is in accordance with the results in Fig. 4. This implies that the change in the reciprocal of current gain is dominated by the ionization damage at a low fluence, leading to nonlinear behaviour. For a high fluence, where the displacement damage dominates, the linear response follows the Messenger–Spratt equation.[18]

5. Conclusions

In this paper, the characteristic degradations in Si NPN BJT of 3DD155 type are examined under the irradiations of 25-MeV C, 40-MeV Si, and 40-MeV Cl ions respectively. The experimental data shows that the collector current ($I_{\rm C}$) remains almost unvaried with the fluence increasing, while the base current ($I_{\rm B}$) increases. The gain degradation is mostly affected by the behaviour of the base current. The change in the reciprocal of the gain variation ($\Delta(1/\beta)$) is largest for 25-MeV C ion irradiation, smaller for 40-MeV Si ions, and even smaller for 40-MeV Cl ions. The value of $\Delta(1/\beta)$ induced by the heavy ion irradiations shows a nonlinear behaviour at a low fluence and linear response at a high fluence for 3DD155 BJT. The calculated results and experimental data show clearly that when the maximum range of the incident particle is in the base region of the BJT, the incident particle range is an important factor in correlating the radiation damage.

References

[1] Kulkarni S R, Ravindra M, Joshi G R and Damle R 2006 *Nucl. Instr. Method* B **251** 157

[2] Kamh S A and Solman F A S 2006 *Nucl. Instr. Method* A **564** 463

[3] Raymond J P and Petersen E L 1987 *IEEE Trans. Nucl. Sci.* **NS-34** 1622

[4] Johnston A H, Swift G M and Rax B G 1994 *IEEE Trans. Nucl. Sci.* **41** 2427

[5] Manghisoni M, Ratti L, Re V, Speziali V, Traversi G and Fallica G 2004 *Nucl. Instr. Method* A **518** 477

[6] Al-Mohamad A and Chahoud M 2005 *Nucl. Instr. Method* A **538** 703

[7] Li X J, Xiao J D, Liu C M, Zhao Z M, Geng H B, Lan M J, Yang D Z and He S Y 2010 *Nucl. Instr. Method* A **621** 707

[8] Summers G P, Burke E A and Xapsos M A 1995 *Radiat. Meas.* **24** 1

[9] Messenger S R, Burke E A, Summers G P and Walters R J 2002 *IEEE Trans. Nucl. Sci.* **49** 2690

[10] Bielejec E, Vizkelethy G, Kolb N R, King D B and Doyle B L 2006 *IEEE Trans. Nucl. Sci.* **53** 3681

[11] Ratti L, Manghisoni M, Oberti E, Re V, Speziali V, Traversi G, Fallica G and Modica R 2005 *IEEE Trans. Nucl. Sci.* **52** 1040

[12] Li X J, Geng H B, Lan M J, Yang D Z, He S Y and Liu C M 2010 *Chin. Phys.* B **19** 056103

[13] Li X J, Geng H B, Liu C M, Zhao Z M, Lan M J, Yang D Z and He S Y 2009 *Nucl. Instr. Method* A **612** 171

[14] Li X J, Geng H B, Lan M J, Liu C M, Yang D Z and He S Y 2010 *Physica* B **405** 1489

[15] Li X J, Geng H B, Liu C M, Zhao Z M, Lan M J, Yang D Z and He S Y 2010 *IEEE Trans. Nucl. Sci.* **57** 831

[16] Li X J, Geng H B, Lan M J, Yang D Z, He S Y and Liu C M 2010 *Chin. Phys.* B **19** 066103

[17] Messenger S R, Burke E A, Summers G P and Walters R J 2002 *IEEE Trans. Nucl. Sci.* **49** 2690

[18] Messenger G C and Ash M S 1992 *The Effects of Radiation on Electronic Systems* 2nd edn. (New York: Van Nostrand Reinhold) pp. 192–265