Degradation mechanisms of current gain in NPN transistors*

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An investigation of ionization and displacement damage in silicon NPN bipolar junction transistors (BJTs) is presented. The transistors were irradiated separately with 90-keV electrons, 3-MeV protons and 40-MeV Br ions. Key parameters were measured *in-situ* and the change in current gain of the NPN BJTS was obtained at a fixed collector current ($I_c = 1$ mA). To characterise the radiation damage of NPN BJTs, the ionizing dose D_i and displacement dose D_d as functions of chip depth in the NPN BJTs were calculated using the SRIM and Geant4 code for protons, electrons and Br ions, respectively. Based on the discussion of the radiation damage equation for current gain, it is clear that the current gain degradation of the NPN BJTs is sensitive to both ionization and displacement damage. The degradation mechanism of the current gain is related to the ratio of $D_d/(D_d + D_i)$ in the sensitive region given by charged particles. The irradiation particles leading to lower $D_d/(D_d + D_i)$ within the same chip depth at a given total dose would mainly produce ionization damage to the NPN BJTs. On the other hand, the charged particles causing larger $D_d/(D_d + D_i)$ at a given total dose would tend to generate displacement damage to the NPN BJTs. The Messenger–Spratt equation could be used to describe the experimental data for the latter case.

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

PACC: 6180, 9350G, 8750G, 7340L

1. Introduction

Bipolar junction transistors (BJTs) have important applications in analog or mixed-signal integrated circuits (ICs) and BiCMOS (Bipolar Complementary Metal-Oxide-Semiconductor) circuits because of their current drive capability, linearity and excellent matching characteristics, some of which are being extensively used in spacecraft.[1−3] Charged particles being abundant in space, like protons, electrons and heavy ions, could be incident upon the semiconductor devices, and their energy is deposited in the semiconductor via two mechanisms, atomic collisions and electronic ionization, producing displacement and ionization damage, respectively.[4,5]

The displacement damage can cause the atoms shifting from the lattice, thereby creating both vacancies and interstitials in the crystal lattice, and produces a significant reduction in minority-carrier lifetime. The radiation-induced defects lead to an increase in the number of minority carriers recombined within the base region of the BJTs, resulting in a detrimental effect on the transistor current gain.[6] The ionization damage could cause interface traps and net positive charges in the oxide overlying the emitter-base junction, resulting in an increased recombination in the emitter-base depletion region of the BJTs, based on two interacting effects: (i) increasing surface recombination rate and (ii) spreading the emitter-base depletion region.[7,8] The ionization damage mechanism to the BJTs can be related to, although not precisely the same as, that being commonly discussed in the MOS technologies.[9−12]

The relative importance of the ionization and displacement damage in BJTs depends on the type of radiation source. In general, the Co-60 gamma rays mainly produce the ionization damage. For neutron irradiation, on the other hand, a large fraction of the deposited energy results in atomic displacement damage. A number of researchers have extensively investigated and reported the radiation effects on the bipolar devices, which are produced by protons, neutrons, electrons and Co-60 gamma rays.[13−20] However, only a few reference papers are available on the radiation effects of heavy ions on the NPN BJTs, which are

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important for understanding the interaction mechanism of heavy ions with the devices. Especially, when the incident particles produce both the ionization and displacement damage to the NPN BJTs, like protons, little investigation distinguishes the damage for their contribution to the current gain degradation.

The objective of this investigation is to reveal the degradation mechanisms for the current gain of the NPN BJTs. An attempt is made to characterize the radiation-induced damage of the NPN BJTs, based on discussion of the radiation damage equation for current gain. The reciprocal of the gain variation as a function of the displacement dose given by protons, electrons and Br ions is compared in order to show the relative importance of the ionization and displacement damage to the current gain degradation of NPN BJTs.

2. Experimental

The high radio frequency and low power silicon 3DG112D NPN transistors are used as samples in this study. The thickness of the passivation layer (SiO_2) of the sample is about 600 nm. The thickness of the emitter (n^+), the base (p^+) and the epitaxial layer (n^-) is approximately 1 μm, 1.3 μm and 12 μm, respectively. Uncertainties in measured parameters are less than 10 percent.

The EN Tandem Accelerator in the State Key Laboratory of Nuclear Physics and Technology, Peking University, China, was used for proton and Br ion irradiation. The electron irradiation was performed in an accelerator at Harbin Institute of Technology, China. The irradiation tests were conducted in vacuum. A Faraday cup (with a current integrator), located near to the samples during irradiation, was used to measure the beam current for protons, electrons and Br ions. Beam areas were 40 mm×50 mm for electrons and 20 mm×150 mm for protons and Br ions. To ensure accuracy, the beam current on the samples was monitored by the Faraday cup during irradiation. Based on the measurements, the fluences of electrons, protons and Br ions were determined from the current integrator, and the total absorbed dose in the NPN BJTs was calculated through SRIM[21] and Geant4 codes.[22]

The NPN BJTs were unbiased during irradiation. The electrical characteristics were measured *in-situ* using a semiconductor parameter measurement system, including KEITHLEY 4200-SCS and AGILENT E4980A. Each measurement was performed within one minute. The turn-around time between the irradiation and device measurements was maintained within approximately 5 seconds or less. The irradiation and measurements were carried out at room temperature, and all the samples were decapped. For the *in-situ* measurement, a matrix board switching system located outside the irradiation chamber is used as a control panel, which is designed with very high insulation resistance to avoid an interference with generating current.

3. Results and discussion

3.1. Current gain versus irradiation fluence

The I_C–V_{CE} characteristic curve of the NPN BJTs is a plot of collector current (I_C) versus collector–emitter voltage (V_{CE}) at a constant emitter-base current (I_B). The I_C of the NPN BJTs was measured by varying V_{CE} from 0.0 to 10 V with a step size of 0.01 V at a given I_B (I_B = 40 μA). The current gain (h_{FE}) of the NPN BJTs was obtained for all samples using the same setup before and after irradiation at a fixed collector current (I_C = 1 mA). The change in the current gain (Δh_{FE}) is defined as the transistor current gain after irradiation subtracting the value before irradiation, and the reciprocal of the gain variation ($\Delta(1/h_{FE})$) as the value after irradiation subtracting its pristine one. The I_C–V_{CE} characteristic curves are shown in Figs. 1, 2, and 3 for the 3-MeV protons, 90-keV electrons and 40-MeV Br ions, respectively. It is clear that the collector current of the NPN BJTs reduces with increasing fluence, and the Br ions give the biggest radiation damage to the current gain if compared at a given fluence.

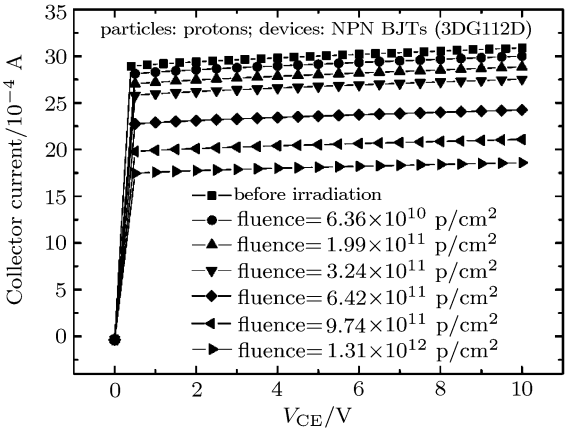


Fig. 1. The I_C–V_{CE} characteristic curve versus fluence at I_B = 40 μA for 3-MeV proton irradiation.

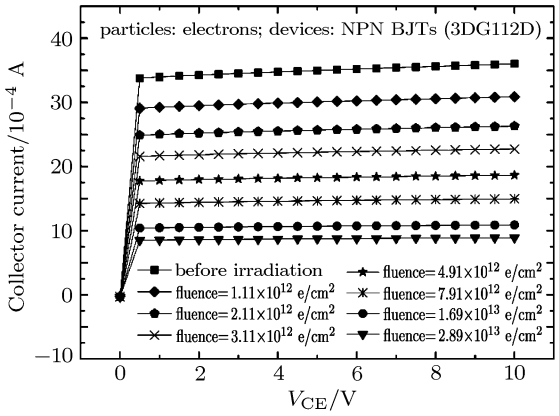


Fig. 2. The I_C–V_{CE} characteristic curve versus fluence at $I_B = 40$ μA for 90-keV electron irradiation.

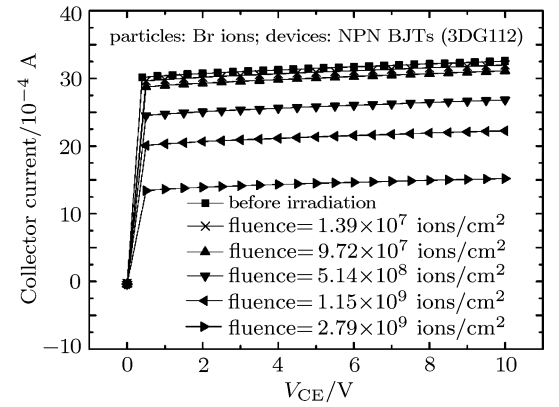


Fig. 3. The I_C–V_{CE} characteristic curve versus fluence at $I_B = 40$ μA for 40-MeV Br ion irradiation.

Figure 4 shows the change in reciprocal of the current gain as a function of fluence for the NPN BJTs irradiated by Br ions, protons and electrons. The change in the reciprocal of the current gain varies linearly with the Br ion fluence, while the curve for the 3-MeV protons can be divided into two portions. In the latter case, before and after the fluence of approximately 2.0×10^{11} p/cm^2, the curve varies nonlinearly and linearly, respectively. The change in the reciprocal of the current gain caused by 90-keV electrons is nonlinear for all of the fluences. If compared at a given change in the reciprocal of the current gain, the fluence for the 90-keV electrons is the highest, the middle for the 3-MeV protons and the lowest for the 40-MeV Br ions.

3.2. Current gain versus radiation absorbed dose

3.2.1. Calculation of the ionizing and displacement dose

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, as functions of depth-in-chip material of the NPN BJTs, and the units are rad; t is the depth in the device chips, μm; 1.6×10^{-8} is the unit conversion parameter and the unit is rad·g/MeV; Φ is the fluence of the incident particles, particles/cm^2; $LET(t)$ and $NIEL(t)$ are respectively the ionizing and displacement energy losses as functions of depth in the chip of devices, which are calculated by SRIM for protons and Br ions and by Geant4 code for electrons, MeV·cm^2/g. The ionizing dose per unit fluence of the Br ions, protons and electrons is plotted in Fig. 5, as a function of the chip depth of NPN BJTs. The displacement dose per unit fluence versus the chip depth for the Br ions, protons and electrons is plotted in Fig. 6.

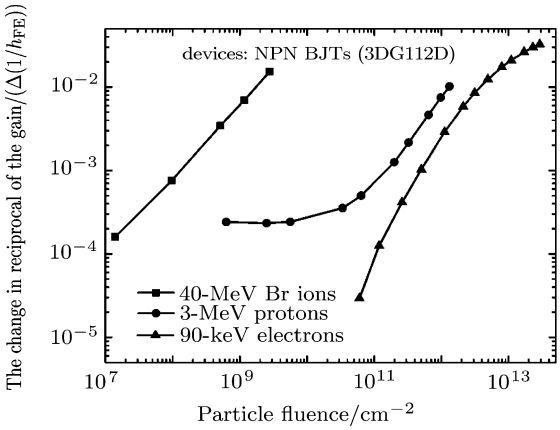


Fig. 4. The change in the reciprocal of the current gain as a function of fluence for NPN BJTs irradiated by 40-MeV Br ions, 3-MeV protons and 90-keV electrons.

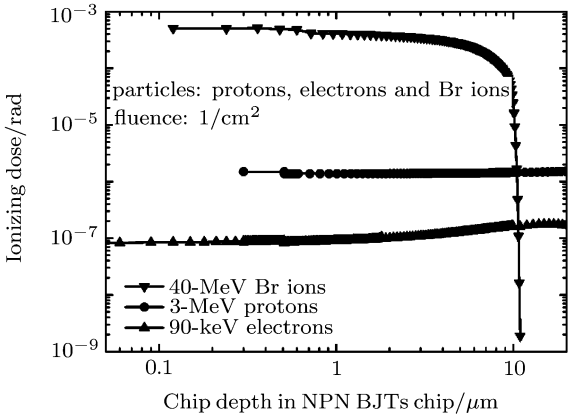


Fig. 5. The ionizing dose per unit fluence of Br ions, protons and electrons as a function of chip depth in NPN BJTs.

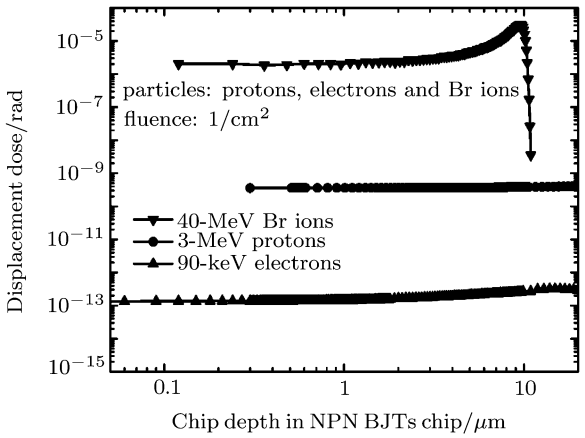


Fig. 6. The displacement dose per unit fluence of Br ions, protons and electrons as a function of chip depth in NPN BJTs.

It is obvious from Figs. 5 and 6 that the 40-MeV Br ions, compared to 90-keV electrons and 3-MeV protons, produce both the highest ionization and displacement doses at a given depth in the NPN BJTs before 10 μm, while the 90-keV electrons give the lowest ionization and displacement doses. Based on Figs. 5 and 6, the ratio of $D_{\rm d}/(D_{\rm d}+D_{\rm i})$ can be calculated as approximately 5.18×10^{-3}, 2.63×10^{-4} and 1.03×10^{-6} for the 40-MeV Br ions, 3-MeV protons and 90-keV electrons, respectively, when the depth t equals 1.3 μm that is beyond the base region in the NPN BJTs Si bulk.

Through the above results, it is shown that the ratio of $D_{\rm d}/(D_{\rm d}+D_{\rm i})$ at the same depth caused by the 40-MeV Br ions is much higher than those by 3-MeV protons and 90-keV electrons. The ratio of $D_{\rm d}/(D_{\rm d}+D_{\rm i})$ could be used to show the displacement damage capability for the incident particles. If the ratio is smaller, the displacement damage per unit fluence to the NPN BJTs will be less. The ratio of $D_{\rm d}/(D_{\rm d}+D_{\rm i})$ is much lower for the 90-keV electrons, implying that they will cause very little displacement damage to the NPN BJTs. In general, the energy threshold of electrons for displacement damage is believed to be about 200 keV in p-type and 150 keV in n-type silicon. Therefore, the displacement damage due to the 90-keV electrons is negligible.

3.2.2. Current gain versus displacement dose

The change in the reciprocal of current gain at a fixed collector current ($I_{\rm C}$ = 1 mA) as a function of the displacement dose is given in Fig. 7. It is observed that when the displacement dose is higher than about 0.2 Gy, the change in the reciprocal of the gain caused by the 3-MeV protons is linear with the displacement dose, and the trend is parallel to that caused by 40-MeV Br ions. When the displacement dose is lower than about 0.2 Gy, on the other hand, the change in the reciprocal of the gain varies non-linearly with the displacement dose, similar to that caused by the 90-keV electrons. The above results imply that a critical displacement dose exists in the NPN BJTs to distinguish the linear and nonlinear variation in the reciprocal of current gain with increasing displacement dose.

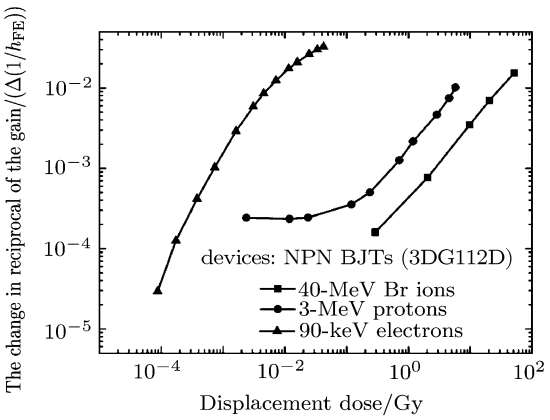


Fig. 7. The change in the reciprocal of current gain as a function of displacement dose for 3-MeV protons, 90-keV electrons and 40-MeV Br ions.

3.2.3. Current gain versus ionizing dose

Figure 8 shows the change in current gain as a function of the total dose for the NPN BJTs. The total dose is the sum of doses for both the ionizing and displacement ones. The flux of the protons, electron and Br ions were chosen as 6.55×10^{8}, 1.01×10^{10} and 1.12×10^{7} p/cm^2·s, respectively. It is observed that the

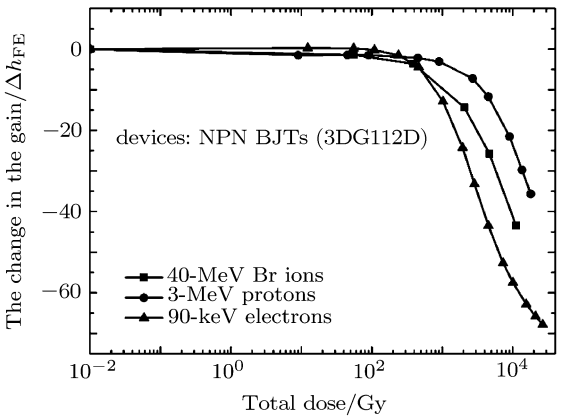


Fig. 8. The change in current gain as a function of total dose for NPN BJTs irradiated by the protons, electrons and Br ions.

current gain is sharply degraded after the total dose is more than 200 Gy, and decreases with increasing dose. The degradation of the current gain is different for the protons, electrons and Br ions, when the total dose tops 200 Gy. Compared to 40-MeV Br ions

and 3-MeV protons, the 90-keV electrons produce the highest radiation damage to the current gain at the same total dose.

3.3. Discussion

3.3.1. The radiation damage equation for current gain

The susceptibility of bipolar devices to radiation damage can be examined by current gain degradation. Charged particles induce ionization damage in the oxide layer and displacement damage in Si bulk, both of which will cause the current gain degradation. The ionisation damage and displacement damage can be related to characteristics of the incident particles and the nature of the devices. In terms of the transistor physical parameters, a basic current gain equation is expressed as follows:[23]

$$1/h_{\rm FE} = s \cdot A_{\rm s} \cdot W/(D_{\rm b} \cdot A_{\rm e}) + \sigma_{\rm b} \cdot W/(\sigma_{\rm e} \cdot L_{\rm e}) + W^2/[2D_{\rm b} \cdot \tau_{\rm b}], \quad (3)$$

where $1/h_{\rm FE}$ is the reciprocal of the current gain; s is the surface recombination rate; $A_{\rm s}$ is the area for surface recombination; W is the base width; $D_{\rm b}$ is the minority carrier diffusion coefficient in the base; $A_{\rm e}$ is the cross-sectional area of the conduction path, which is roughly the same as the emitter junction area; $\sigma_{\rm b}$ and $\sigma_{\rm e}$ are the base and the emitter conductivities, respectively; $L_{\rm e}$ is the minority carrier diffusion length in the emitter; $\tau_{\rm b}$ is minority carrier lifetime in the base.

The first term on the right-hand side of Eq. (3) is regarded as the surface recombination term, the second the emitter efficiency term and the third the volume recombination term. For most well-designed modern transistors, the second term dominates the pristine gain before irradiation. In an ionizing radiation environment, the first term becomes dominant with increasing irradiation fluence. In the displacement radiation environment (like neutron environment), the third term dominates for increasing irradiation fluence. In this study, the second term will not be discussed since it hardly changes due to irradiation.

3.3.2. Displacement damage

The incident charged particles, which could produce large displacement damage to bipolar devices, can produce various defects in the Si bulk and the resulting stable defects in the lattice at room temperature. These defects introduce deep levels to serve as actual physical recombination sites within the lattice, and reduce the minority carrier lifetime. The degradation of the minority carrier lifetime can be represented by a rate-balance equation written in terms of inverse lifetime;[24]

$$1/\tau = 1/\tau_0 + K \cdot \Phi, \quad (4)$$

where τ_0 and τ are the minority carrier lifetime before and after irradiation, respectively; Φ is the incident charged particle fluence. Since the third term on the right-hand side of Eq. (3) characterizes the base recombination, it defines the current gain degradation due to displacement damage. Based on Eqs. (3) and (4), the Messenger–Spratt equation can be given by

$$\frac{1}{h_{\rm FE}(\Phi)} - \frac{1}{h_{\rm FE0}} = K \cdot \Phi/\omega_{\rm T}, \quad (5)$$

where the $1/h_{\rm FE0}$ is the initial reciprocal gain; the $1/h_{\rm FE}(\Phi)$ is the reciprocal gain after irradiation; $\omega_{\rm T} = 2D_{\rm b}/W^2$ is the unity gain corner frequency, being tantamount to the gain-bandwidth product angular frequency of the transistor and usually dependent on the collector current; K is the damage factor; Φ is the incident particle fluence. Therefore, the Messenger–Spratt equation is often used to characterize the current gain degradation of bipolar devices caused by displacement damage.

As shown in Fig. 4, the change in the reciprocal of the current gain varies linearly with the Br ions fluence, according with the Messenger–Spratt equation. This phenomenon implies that the Br ions mainly cause displacement damage to the NPN BJTs and reduce the minority carrier lifetime. It is also observed that before and after the fluence of approximately 2.0×10^{11} p/cm^2, the curve caused by 3-MeV protons varies nonlinearly and linearly, revealing that the proton irradiation mainly causes the bulk displacement damage at larger fluences. At lower fluences, the proton irradiation exhibits non-bulk damage that is associated with the ionizing dose as discussed in the next section. The Messenger–Spratt equation could not be used to characterize the experimental data given by the 90-keV electrons throughout all the fluences. This illustrates that the 90-keV electrons mainly produce ionization damage to the NPN BJTs.

A critical displacement dose in the NPN BJTs sensitive region is required to characterize the displacement damage caused current gain variation, because there must be sufficient displacement damage defects to obviously reduce the minority carrier lifetime. When the displacement dose tops this critical value, the current gain degradation of the BJTs could follow the displacement damage. Therefore, the critical or a minimum displacement dose is required to characterize the relation between the change in the reciprocal of current gain and the Messenger–Spratt

equation. As shown in Fig. 7, such a minimum displacement dose for the 3-MeV protons is approximately 0.2 Gy, so that the Messenger–Spratt equation could be used to characterize the experimental data.

As mentioned above, the ratio of $D_{\rm d}/(D_{\rm d}+D_{\rm i})$ at the same depth sensitive region in the BJTs can be calculated to be approximately 5.18×10^{-3}, 2.63×10^{-4} and 1.03×10^{-6} for 40-MeV Br ions, 3-MeV protons and 90-keV electrons, respectively. The ratios of $D_{\rm d}/(D_{\rm d}+D_{\rm i})$ for the protons and electrons are less than one or three orders of magnitude to that given by Br ions. This indicates that the ratio of $D_{\rm d}/(D_{\rm d}+D_{\rm i})$ is another important indication to characterize the reciprocal of current gain variation. The higher the ratio of $D_{\rm d}/(D_{\rm d}+D_{\rm i})$, the easier the characterisation for the reciprocal of gain variation using the Messenger–Spratt equation. As shown in Fig. 7, the lines given by Br ions and protons are parallel in the logarithm coordinate system, when the displacement dose is higher than 0.2 Gy. In the linear coordinate system, the two lines should accord with the Messenger–Spratt equation but have different slopes, showing that the damage factors are different. The reason for this phenomenon is that Br ions and protons could produce different defects in the Si bulk. Br ions lead to large clusters of displacement defects, while protons are generally assumed to generate a mixture of point defects and clusters. Therefore, the Br ions could give larger displacement damage than the protons at a given total dose.

3.3.3. Ionization damage

The ionization damage would cause interface traps and net positive charges in the oxide overlying the emitter-base junction, leading to an increase in the base surface current. The increase can be attributed to two factors: (i) increased surface recombination rate and (ii) spreading of the emitter-base depletion region. The increase in the surface recombination velocity is proportional to the formation of recombination centres at the silicon/silicon-dioxide interface that covers the emitter-base junction. For the NPN transistors in this study, the depleted region over the emitter-base junction will spread on the P-side of the junction, as shown in Fig. 9. This phenomenon is similar to that shown in Ref. [25]. Consequently the ionization damage causes an increase in the surface recombination rate, leading to an increase in the total base current that eventually reduces the current gain, as characterized by the first term on the right-hand side of Eq. (3).

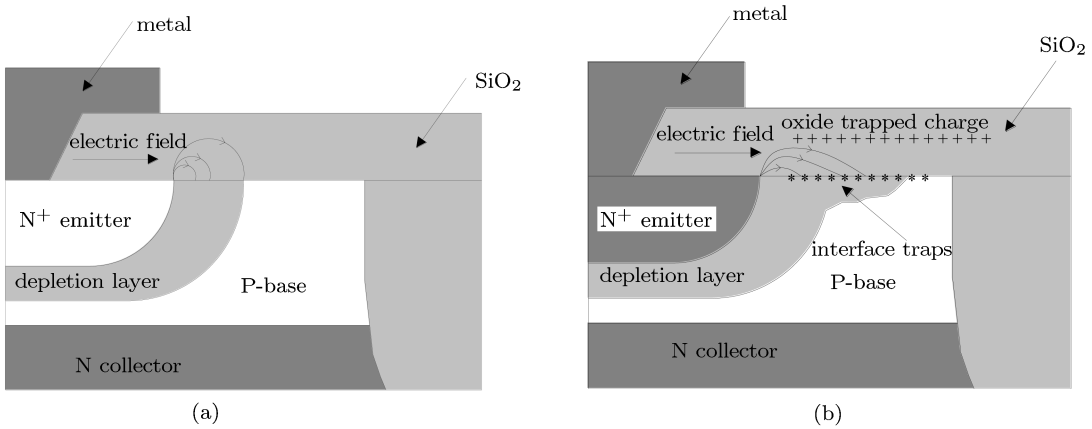


Fig. 9. Schematic illustration of the base–emitter junction of an NPN transistor before (a) and after (b) irradiation, showing the ionization damage effects.

Based on the discussion above, it is clear that the ionization damage mainly results in an increase in the surface recombination rate s. The ionization damage produces the electron–hole pairs in the oxide layer and Si bulk. The electrons produced by ionizing are much more mobile than holes, and they are swept out of the oxide layer within a picosecond or less. Meanwhile, some of the electrons and holes will be recombined. The recombination fraction will depend greatly on the energy and type of incident particles, as well as the nature of the devices. The number of holes trapped in the oxide layer, which escape from the initial recombination, influences the ionization damage to the BJTs. A larger number of trapped positive charges

in the oxide of BJTs could cause more severe ionization damage, which is similar to the situation for MOS devices.[9] The number of trapped positive charges $N_{\rm h}$ in the oxide could be expressed as follows:

$$N_{\rm h} = f(E_{\rm ox}, P_{{\rm p},E}) \cdot g_0 \cdot D_{\rm i} \cdot t_{\rm ox}, \tag{6}$$

where $f(E_{\rm ox},\ P_{{\rm p},E})$ is the probability of un-recombined holes, being related to the oxide electric field ($E_{\rm ox}$) and the energy and type of incident particles ($P_{{\rm p},E}$); $D_{\rm i}$ is the ionizing dose, the value of which almost equals total dose, rad or Gy (100 rad); $t_{\rm ox}$ is the oxide thickness, cm; g_0 is the initial electron–hole pair (ehp) density per rad of dose, ehp/(cm^3·rad). The g_0 is obtained using the following conversion formula:

$$g_0 = \frac{1}{A} \cdot \frac{\rho}{w_0}. \tag{7}$$

where $A = 1.6 \times 10^{-14}$ is the unit conversion parameter, eV/(g·rad); ρ is the density of materials, g/cm^3; w_0 is the ionization energy, depending on the bandgap of the material, eV/ehp. The density, the ionization energy and the ehp density per rad are given in Table 1 for Si and SiO_2.

Table 1. The density, ionization energy and the ehp density per rad for materials.

material	density, ρ (g/cm^3)	mean ionization energy,[26] w_0 (eV/ehp)	electron–hole pair generated per rad, g_0 (ehp/cm^3·rad)
Si	2.33	3.6	4.05×10^{13}
SiO_2	2.27	17	8.35×10^{12}

The probability of un-recombined holes $f(E_{\rm ox}, P_{{\rm p},E})$ in the oxide layer is a pivotal parameter influencing the ionization damage, and depends on the ionizing dose per particle or LET. The charged particles that can produce a higher ionizing dose per particle give lower $f(E_{\rm ox},\ P_{{\rm p},E})$ values. This is because the higher the ionizing dose per particle, the larger the recombination rates of the electron–hole pairs produced by the charged particles.[27] As can be seen in Fig. 1, the 40-MeV Br ions give a higher ionizing dose per particle, and the 90-keV electrons show a much lower ionizing dose per particle in the NPN BJTs sensitive region. Therefore, the 90-keV electrons cause much more severe ionization damage to the NPN BJTs at the same total dose, which is accordant with the results in Fig. 7.

Comparing the results in Figs. 7 and 8, it is obvious that the ionization damage caused by 90-keV electrons produces the highest degradation in current gain, the displacement damage caused by 40-MeV Br ions leads to higher damage, and the 3-MeV protons result in the lowest damage at the same total dose. This demonstrates that the ionization damage can give a larger radiation effect than displacement damage to the current gain of the NPN BJTs. The 3-MeV protons produce both ionization and displacement damage to the NPN BJTs, but both of them are not strong enough. Compared to 90-keV electrons and 40-MeV Br ions, the 3-MeV protons produce both the lower ionization damage and the lower displacement one, as shown in Figs. 1 and 2. Therefore, the 3-MeV protons result in lower damage to the NPN BJTs at a given total dose.

4. Conclusions

The NPN bipolar junction transistors (NPN BJTs) are a basic type of electric devices, which are commonly used in spacecraft. It is of significance to examine their response to the radiation of protons, electrons and heavy ions. It is shown that the current gain of the NPN BJTs is markedly degraded under the exposure of 3-MeV protons, 90-keV electrons and 40-MeV Br ions. There are two primary mechanisms responsible for the gain degradation, including the ionization and displacement damage. The SRIM and Geant4 code are used to the ionizing dose $D_{\rm i}$ and displacement dose $D_{\rm d}$. Based on the calculated and experimental results, as well as the discussion of the radiation damage equation for current gain, it could be believed that the susceptibility of current gain degradation of the NPN BJTs to ionization damage and displacement damage can be characterized in terms of a critical displacement dose and the ratio of $D_{\rm d}/(D_{\rm d} + D_{\rm i})$. The reciprocal of the gain variation is compared as a function of the displacement dose, showing that when the displacement dose tops the critical value, the displacement damage dominates the current gain degradation. In this case, the higher

the ratio of $D_{\rm d}/(D_{\rm d}+D_{\rm i})$, the easier the characterization for the reciprocal of the gain variation using the Messenger–Spratt equation. When the displacement dose is lower than the critical value, the lower the ratio of $D_{\rm d}/(D_{\rm d}+D_{\rm i})$, the larger the ionization damage to the BJTs.

References

[1] Summers G P, Burke E A, Dale C J, Wolicki E A, Marshall P W and Gehlhausen M A 1987 *IEEE Trans. Nucl. Sci.* **34** 1134

[2] Dinesh C M, Ramani, Radhakrishna M C, Dutt R N, Khan S A and Kanjilal D 2008 *Nucl. Instrum. Meth.* B **266** 1713

[3] Zhang Y R, Zhang B, Li Z H, Lai C J and Li Z J 2009 *Chin. Phys.* B **18** 763

[4] Minson E, Sanchez I, Barnaby H J, Pease R L, Platteter D G and Dunham G 2004 *IEEE Trans. Nucl. Sci.* **51** 3723

[5] Gao X, Yang S S, Xue Y X, Li K, Li D M, Wang Y, Wang Y F and Feng Z Z 2009 *Chin. Phys.* B **18** 5015

[6] Pease R L 2003 *IEEE Trans. Nucl. Sci.* **50** 539

[7] Kosiert S L, Schrimpft R D, Nowlintt R N, Fleetwood D M, DeLaus M, Pease R L, Combsw W E, Weit A and Chait F 1993 *IEEE Trans. Nucl. Sci.* **40** 1276

[8] Yan B P and Luo J S 1996 *Chin. Phys.* **5** 923

[9] Schwank J R, Shaneyfelt M R, Fleetwood D M, Felix J A, Dodd P E, Paillet P and Ferlet-Cavrois V 2008 *IEEE Trans. Nucl. Sci.* **55** 1833

[10] Oldham T R and McLean F B 2003 *IEEE Trans. Nucl. Sci.* **50** 486

[11] He B P, Chen W and Wang G Zh 2006 *Acta Phys. Sin.* **55** 3546 (in Chinese)

[12] Li D M, Wang Z H, Huang L Y and Gou Q J 2007 *Chin. Phys.* **16** 3760

[13] Mandić I, Cindro V, Kramberger G, Krištof E S, Mikuž M, Vrtačnik D, Ullan M and Anghinolfi F 2004 *IEEE Trans. Nucl. Sci.* **51** 1752

[14] Vuppala S, Li C, Zwicknagl P and Subramanian S 2003 *IEEE Trans. Nucl. Sci.* **50** 1846

[15] Chen X J, Barnaby H J, Vermeire B, Holbert K, Wright D, Pease R L, Dunham G, Platteter D G, Seiler J, McClure S and Adell P 2007 *IEEE Trans. Nucl. Sci.* **54** 1913

[16] Kamh S A and Solman F A S 2006 *Nucl. Instrum. Meth.* A **564** 463

[17] Kulkarni S R, Ravindra M, Joshi G R and Damle R 2006 *Nucl. Instrum. Meth.* B **251** 157

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

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

[20] Zheng Y Z, Lu W, Ren D Y, Wang Y Y, Guo Q, Yu X F and He C F 2009 *Acta Phys. Sin.* **58** 5572 (in Chinese)

[21] Ziegler J F 2004 *Nucl. Instrum. Meth.* B **219-220** 1027
SRIM web site: http://www.SRIM.org

[22] Agostinelli S et al. (GEANT4 Collaboration) 2003 *Nucl. Instrum. Meth.* A **506** 250
Geant4 web site: http://cern.ch/geant4

[23] Messenger G C 1992 *IEEE Trans. Nucl. Sci.* **39** 470

[24] Messenger G C and Ash M S 1992 *The Effects of Radiation on Electronic Systems* 2nd ed. (New York: Van Nostrand Reinhold) p. 225

[25] Nowlin R N, Enlow E W, Schrimpf R D and Combs W E 1992 *IEEE Trans. Nucl. Sci.* **39** 2026

[26] Barnaby H J 2006 *IEEE Trans. Nucl. Sci.* **53** 3107

[27] Paillet P, Schwank J R, Shaneyfelt M R, Ferlet-Cavrois V, Jones R L, Flament O and Blackmore E W 2002 *IEEE Trans. Nucl. Sci.* **49** 2656