Comparison of total dose effects on SiGe heterojunction bipolar transistors induced by different swift heavy ion irradiation*

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The degradations in NPN silicon-germanium (SiGe) heterojunction bipolar transistors (HBTs) were fully studied in this work, by means of 25-MeV Si, 10-MeV Cl, 20-MeV Br, and 10-MeV Br ion irradiation, respectively. Electrical parameters such as the base current (I_B), current gain (β), neutral base recombination (NBR), and Early voltage (V_A) were investigated and used to evaluate the tolerance to heavy ion irradiation. Experimental results demonstrate that device degradations are indeed radiation-source-dependent, and the larger the ion nuclear energy loss is, the more the displacement damages are, and thereby the more serious the performance degradation is. The maximum degradation was observed in the transistors irradiated by 10-MeV Br. For 20-MeV and 10-MeV Br ion irradiation, an unexpected degradation in I_C was observed and Early voltage decreased with increasing ion fluence, and NBR appeared to slow down at high ion fluence. The degradations in SiGe HBTs were mainly attributed to the displacement damages created by heavy ion irradiation in the transistors. The underlying physical mechanisms are analyzed and investigated in detail.

Keywords: heavy ion irradiation, displacement damage, SiGe heterojunction bipolar transistor

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1. Introduction

Recently, many applications, such as space exploration platforms and high-energy particle detectors, require electronic devices to operate in extreme environments that fall outside the domain of conventional devices. Typical extreme environments include cryogenic temperature (e.g., 77 K), high temperature (e.g., 300 °C) and a radiation environment (e.g., space), which are usually unfriendly to devices and may cause some reliability challenges.[1–8] The special device structure and unique band gap engineering in the base enable SiGe HBTs to have a wide temperature range capability and multi-Mrad total ionizing dose (TID) tolerance without hardening.[9–13] As a result, SiGe HBTs gain significant attention as a candidate in extreme environment applications, especially in radiation-rich space explorations. Therefore, it is essential to explore the irradiation characteristics and underlying damage mechanisms in SiGe HBTs and related circuits to find suitable hardening strategies for practical applications.

In real radiation-rich environments, space particles can create both ionization damages and displacement damages to electron components and circuits. For bipolar transistors, ionization damages induce the interface states and positive oxide trapped charges around the emitter-base (EB) spacer oxide, leading to an increase of the base current and decrease of the current gain.[10–12] Typical radiation sources to assess ionization damages are ^{60}Co gamma ray, proton and electron. Displacement damages can create different intermediate trap levels in bulk materials, which reduces the minority carrier lifetime and thereby degrades the base current.[14] The neutron is a typical radiation source to quantify displacement damages in the last few years. However, neutron reactors are less and less available now, and large residual radiation exists in the samples exposed to neutron irradiation. Recently, it is found that high energy heavy ions can create a collision cascade in materials and cause the degradation in several key merits of transistors.[3] Though there have been many reports on single event effects by utilizing the high energy heavy ions, few data are available about the total dose effects of high-energy heavy ions on SiGe HBTs up to now.[15,16] Besides, compared to proton or ^{60}Co facilities, heavy ion irradiation only needs a relatively shorter time to obtain the same dose level, which is suitable for the assessment of device degradation under a high dose level (such as 1 MGy in LHC).[16] Therefore, studies on the total dose effects of swift heavy ions on SiGe HBTs are of interest.

In this work, we explore a comparison of radiation effects on SiGe HBTs irradiated by four kinds of heavy ions. The equivalent absorbed dose ranged from 3 kGy (Si) to 100 kGy (Si) for each kind of heavy ion. Electrical parameters, such as the forward Gummel and neutral base recombination (NBR), were studied before and after irradiation. The basic physical mechanisms for performance degradation are analyzed and explored in detail.

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2. Experiment

The devices under test are vertical NPN SiGe HBTs, and the cross-section view is shown in Fig. 1. The detailed description has been reported in our pervious study.[15] The device adopts an interdigital layout design and consists of 68 emitter fingers, with the dimension of 1.2 μm × 15 μm for each finger. The substrate and emitter are connected together through metal interconnection. The chips are mounted in a metal-ceramic package and the package lid is removed for heavy ion irradiation.

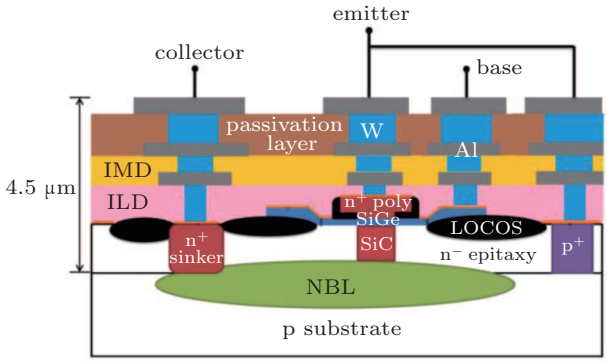


Fig. 1. (color online) The cross-section view of SiGe HBTs under investigation, where the LOCOS, NBL, SIC, ILD, and IMD represent local oxidation of silicon, N^+ type buried layer, selectively implanted collector, inter layer dielectric, and inter metal dielectric, respectively.

The swift heavy ions chosen in the present study were 25-MeV Si, 10-MeV Cl, 20-MeV Br, and 10-MeV Br ion, respectively. To obtain a uniform fluence over the transistors, the ion beams were scanned by a magnetic scanner within an area of 10 cm×2 cm at room temperature. All terminals of devices were floating during the heavy ion irradiation. The ion fluence ranged from 9.1×10^8 to 4.46×10^{10} ions/cm^2 with equivalent absorbed dose varying from 3 kGy (Si) to 100 kGy (Si). The samples were measured with an Agilent B1500 semiconductor parameter analyzer at room temperature before and after irradiation.

3. Results and discussion

Generally, the swift heavy ions deposit energy to material through two processes: electronic energy loss ($\langle dE/dx\rangle e$) and nuclear energy loss ($\langle dE/dx\rangle n$). The former brings about the excitations of extranuclear electrons in the atoms, producing an abundant of electron–hole pairs along their path. Part of the holes will be trapped in the SiO_2 layer and SiO_2/Si interface, which create interface charges and oxide positive charges in the oxide layer.[17] The nuclear energy loss is a direct interaction between the incident particle and the atomic nucleus of the target material, then a series of atomic collisions and point defects (such as the Frenkel pairs) are created. Due to a smaller elastic scattering cross section, the nuclear energy loss is much smaller than the electronic energy loss and it becomes dominant at the end of the ion range. The SRIM-2010 was used to estimate the energy loss and the range of incident ions in the transistor structure, and the results are shown in Table 1.[18] From the results shown in Table 1, it is revealed that the incident heavy ions can reach the active region and stopped in the p-type substrate.

Table 1. The energy loss and range of four swift heavy ions in the transistor structure.

Source	$\langle dE/dx\rangle e$/MeV·cm^2·mg^{-1}		$\langle dE/dx\rangle n$/MeV·cm^2·mg^{-1}		Range/μm	
	Si	SiO_2	Si	SiO_2	Si	SiO_2
25-MeV Si	14.00	15.66	0.0274	0.0282	9.51	8.80
10-MeV Cl	14.42	16.48	0.1014	0.1046	4.49	4.44
20-MeV Br	20.87	23.65	0.4228	0.433	6.49	6.41
10-MeV Br	15.18	15.81	0.7131	0.7331	4.21	4.31

Figure 2 depicts the forward Gummel plots of SiGe HBTs before and after heavy ion irradiations. It is indicated that as ion fluence goes up, the base currents (I_B) increase monotonically throughout the entire range of base-emitter voltage (V_{BE}). As reported in Refs. [14]–[16], the swift heavy ions can produce ionization damages and displacement damages in the transistors, simultaneously. Ionization damages create some positive oxide trapped charges and interface states around the EB spacer oxide layer, which act as generation–recombination (G–R) centers and increase the base surface recombination current in the low V_{BE} region.[12–15] Displacement damages are induced by the collision between incoming particles and atoms in the semiconductor lattice. When the swift heavy ion passes through the semiconductor material, the lattice atoms will deviate from their original position. As a result, a series of vacancies, interstitial atoms and other types of lattice disorder exist in the semiconductor material after irradiation.[19,20] The created defects reduce the minority carrier lifetime and this in turn increases the base current I_B of the transistors.[20,21]

Two distinct trends exist in the collector current (I_C) after four kinds of heavy ion irradiations. For 25-MeV Si and 10-MeV Cl ion irradiation, I_C is held nearly constant over the whole irradiation process. However, for 20-MeV Br and 10-MeV Br ion irradiation, an unexpected degradation in I_C ap-

pears with the fluence increasing, that is an increase at the low V_{BE} region and but a decrease at the high V_{BE} region, as shown in Figs. 2(c) and 2(d). The parasitic collector–substrate (CS) diode contributes to the observed non-ideal I_C at the low V_{BE} region. Br ion creates many irradiation damages around the CS junction. During the forward Gummel test, the CS diode is reverse biased. It is the generation current in the space charge region of the reversed CS junction that leads to I_C increasing at the low V_{BE} region. Two possible factors contribute to I_C degradation at the high V_{BE} region. One is the high injection effect and the other is the increased emitter series resistance R_E. The high injection effect may occur in advance due to the irradiation damage in the transistors, leading to a decrease in the collector current at the high V_{BE} region. Meanwhile, the increasing R_E might decrease the collector current at the high V_{BE} region, which will be verified in the following discussion.

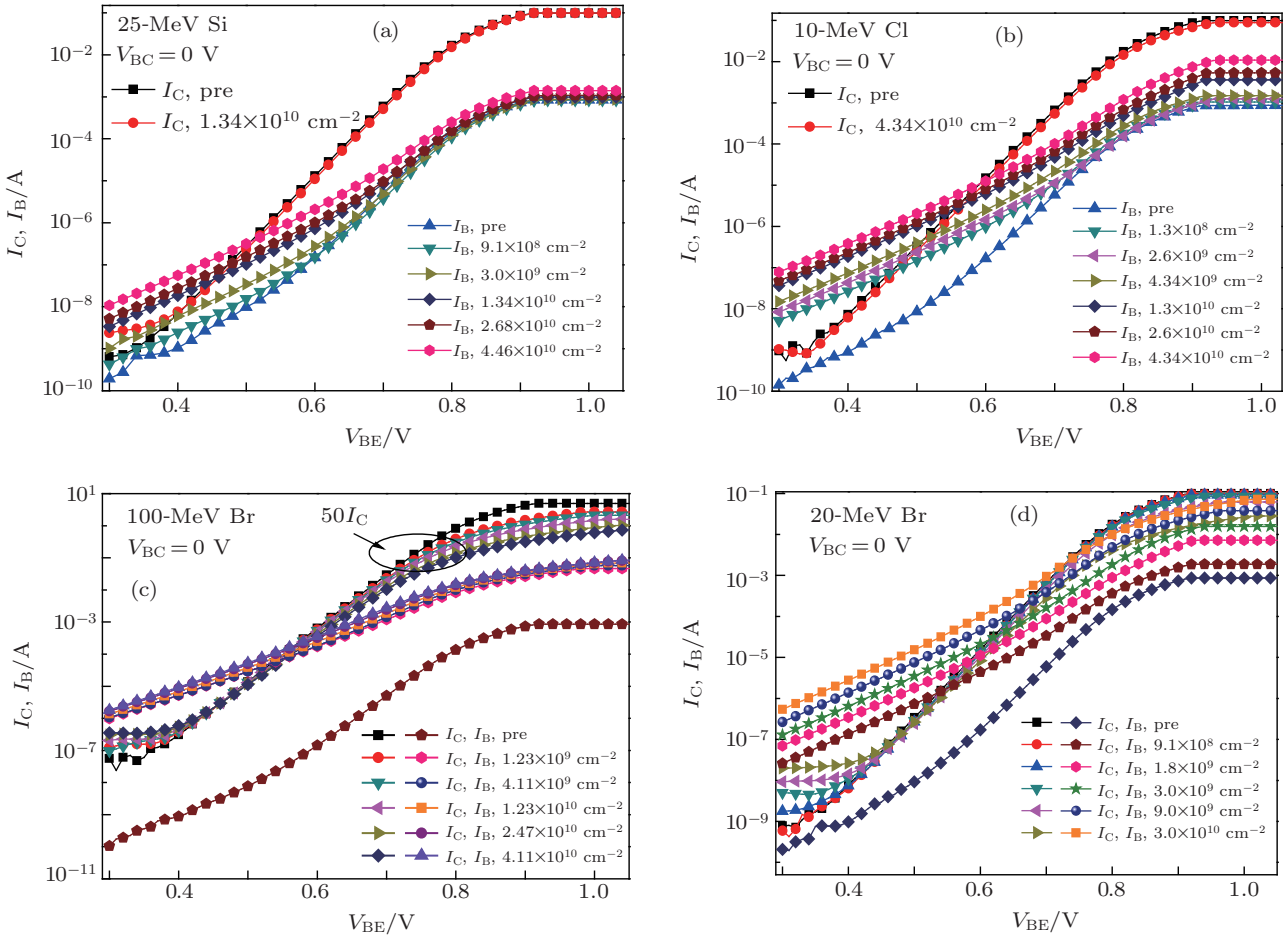


Fig. 2. (color online) Forward Gummel plots for SiGe HBTs irradiated by (a) 25-MeV Si, (b) 10-MeV Cl, (c) 10-MeV Br, and (d) 20-MeV Br ion with different ion fluences.

The self-annealing effects were also studied at room temperature. Figure 3 shows the variation of I_B at fixed V_{BE} of 0.6 V after 4.34×10^{10} cm^{-2} 10-MeV Cl ion and 4.11×10^{10} cm^{-2} 10-MeV Br ion irradiation, respectively. Considering the uncertainty of measurement, I_B keeps nearly unchanged over the period of 362 h annealing at room temperature. It demonstrates a relatively small influence of self-annealing on the degradation of SiGe HBTs after heavy ion irradiation. The same is true for the self-annealing effect in SiGe HBTs irradiated by the 25-MeV Si ion and the 20-MeV Br ion, and the details are not shown here.

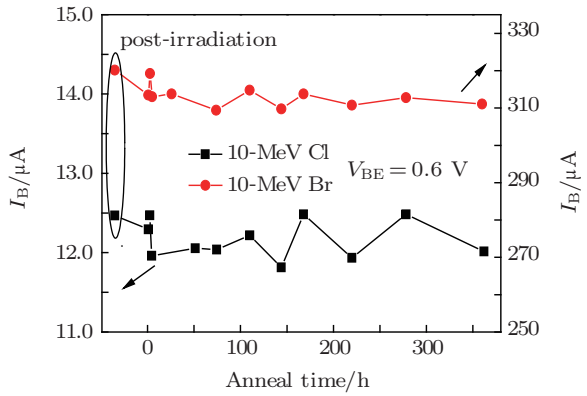


Fig. 3. (color online) The self-annealing effect on I_B after 10-MeV Cl and 10-MeV Br ion irradiation.

In oder to quantitatively compare the performance degradation in SiGe HBTs irradiated by different heavy ions, the common-emitter current gain (β) calculated at fixed V_{BE} of 0.6 V is shown in Fig. 4. A significant decline in current gain is found with ion fluence increasing, and the 25-MeV Si ion induces the smallest degradation, while the 10-MeV Br ion creates the largest degradation at arbitrary ion fluence.

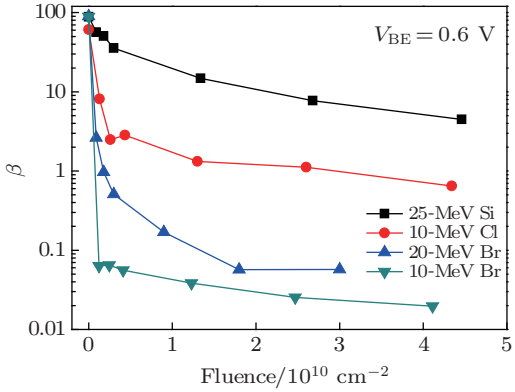


Fig. 4. (color online) Comparison of current gain β at fixed $V_{BE} = 0.6$ V for four kinds of heavy ion irradiations.

The variation of the reciprocal current gain $\Delta(1/\beta)$, defined as $1/\beta_{post} - 1/\beta_{pre}$, is shown in Fig. 5 at fixed V_{BE} of 0.6 V after four kinds of heavy ion irradiation, where β_{pre} and β_{post} are the current gain before and after irradiation, respectively. It is indicated that all four ion curves show a non-linear (linear) behavior at low (large) fluence, following the Messenger–Spratt equation[14,22]

$$\Delta\left(\frac{1}{\beta}\right) = \frac{1}{\beta_{post}} - \frac{1}{\beta_{pre}} = K\Phi, \tag{1}$$

where the factor K is the linear fitting slope of $\Delta(1/\beta)$ versus ion fluence Φ. As mentioned above, both ionization damages and displacement damages contribute to the gain degradation in SiGe HBTs irradiated by swift heavy ions. In order to verify the main contributor to the gain degradation, it is necessary to make a comparison with the case of gamma irradiation, where only ionization damages exist. Figure 6 shows the variation of $\Delta(1/\beta)$ at fixed V_{BE} of 0.6 V after 10-MeV Cl ion and ^{60}Co gamma irradiation. An obvious sub-linear behavior is found after ^{60}Co gamma ray irradiation, and $\Delta(1/\beta)$ tends to saturate at the high dose region. This is a typical result contributed by interface states and oxide trapped charges,[3,7,14] which implies that the degradation in the current gain is dominated by ionization damages. However, for the 10-MeV Cl ion irradiation, $\Delta(1/\beta)$ increases non-linearly when the absorbed dose is lower than 6 kGy (Si), and it increases linearly when the absorbed dose is larger than 10 kGy (Si). It means that ionization damages dominate the gain degradation for an ion dose lower than 6 kGy (Si) (i.e., fluence lower than 2.6×10^9 cm^{-2}), and displacement damages dominate when the absorbed dose is larger than 10 kGy (Si) (i.e., fluence larger than 4.34×10^9 cm^{-2}). Therefore, the linear variation of $\Delta(1/\beta)$ at high ion fluence after heavy ion irradiation, as shown in Fig. 5, demonstrates that displacement damages dominate the gain degradation of SiGe irradiated by swift heavy ions.

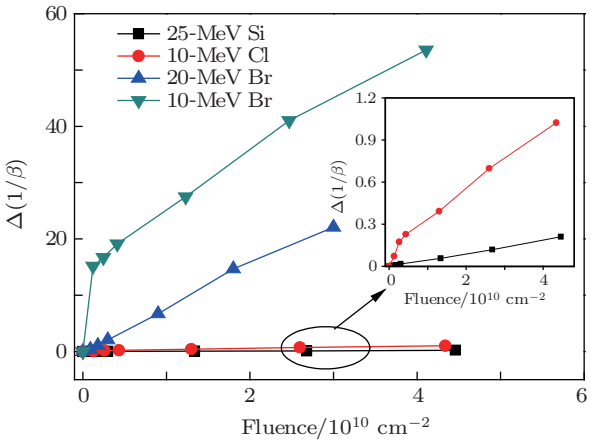


Fig. 5. (color online) Variation of $\Delta(1/\beta)$ with ion fluence after four kinds of heavy ion irradiation at a fixed V_{BE} of 0.6 V. The inserted plot shows the zoom-in variation for 25-MeV Si and 10-MeV Cl ion irradiation.

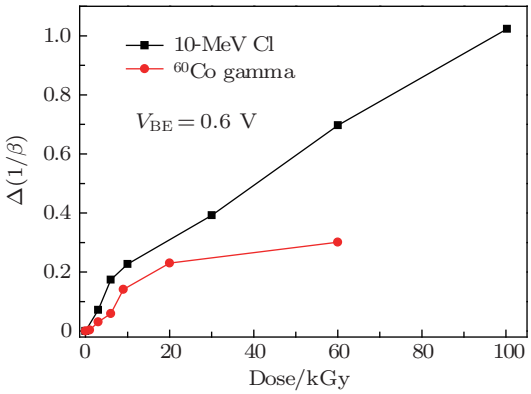


Fig. 6. (color online) Comparison of $\Delta(1/\beta)$ for 10-MeV Cl ion and ^{60}Co gamma ray irradiation as a function of the equivalent absorbed dose.

The damage factors K for different heavy ions, extracted by a linear fitting to $\Delta(1/\beta)$ versus ion fluence Φ, are shown in Fig. 7, from which we can find that the slope K increases monotonically with the ion nuclear energy loss ($\langle dE/dx\rangle n$) increasing. The damage factor for the 25-MeV Si ion is the smallest while that for the 10-MeV Br ion is the largest. The heavy ions with larger $\langle dE/dx\rangle n$ impart more energy to the target material and create much more displacement damages in the semiconductor material. The larger the ion nuclear energy loss is, the more the displacement damages created in the transistors are, and then the more serious the performance degradation in SiGe HBTs is. Compared to the 10-MeV Cl and 25-MeV Si ions, the 20-MeV Br and 10-MeV Br ions have a larger nuclear energy loss that then can create much

more displacement damages in the transistor structure, leading to a serious performance degradation of SiGe HBTs. The larger displacement damages may make the occurrence of high injection effects earlier and then decrease the collector current at the high V_{BE} region, as shown in Figs. 2(c) and 2(d).

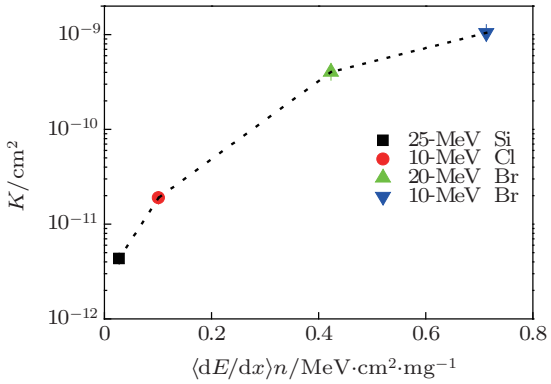


Fig. 7. (color online) The extracted displacement damage factors for different heavy ions.

The neutral base recombination (NBR) is another important physical quantity to characterize displacement damages in bipolar transistors.[15–19] The NBR includes the recombination of injected electrons with holes in the neutral base region via intermediate trap levels (take NPN HBT for example). According to Ref. [23], NBR current can be written as the ratio between the excess minority carrier density (Δn_b) and the minority carrier lifetime (τ_{nb})

$$I_{NBR} = q\int_0^{W_b} \frac{\Delta n_b(x)}{\tau_{nb}(x)}\,\mathrm{d}x, \tag{2}$$

where W_b represents the width of the neutral base region. A conventional way to characterize NBR in bipolar transistors is to investigate the rate of the normalized base current decreasing with variable V_{CB} at fixed V_{BE}. Figure 8 depicts the normalized base current as a function of V_{CB} at fixed $V_{BE} = 0.65$ V after four kinds of heavy ion irradiations. The negative slope at low V_{CB} ($V_{CB} < 3$ V) means the existence of NBR, and a larger slope represents a serious NBR in the transistors. For the transistors irradiated by 25-MeV Si and 10-MeV Cl ions, the NBR increases monotonously with ion fluence increasing, as shown in Figs. 8(a) and 8(b). However, for 20-MeV Br and 10-MeV Br ions irradiated SiGe HBTs, the NBR increases at first and then descends with further ion fluence increasing. For example, for the ion fluence lower than 1.8×10^{10} cm^{-2}, the NBR in SiGe HBTs irradiated by the 20-MeV Br ion increases with ion fluence increasing. When ion fluence increases to 3×10^{10} cm^{-2}, the NBR appears to slow down compared to that at a fluence of 1.8×10^{10} cm^{-2}, as shown in Fig. 8(c).

Displacement damages involve some deep-level defects in the neutral base region, which can act as the effective recombination center. As a result, the minority carrier lifetime τ_{nb} decreases and then NBR will increase, as certified by the monotonously increased slope of $I_B(V_{CB})/I_B$ ($V_{CB} = 0$ V) versus V_{CB} at the low V_{CB} region in Figs. 8(a) and 8(b). Similar to the case of 25-MeV Si and 10-MeV Cl ion irradiation, when the Br ion fluence is low, NBR also increases with the ion fluence increasing due to the decrease of the carrier lifetime τ_{nb}. For the NBR decrease at high fluence in SiGe HBTs irradiated by 20-MeV and 10-MeV Br ions, a plausible hypothesis might be given below. Supposing that more than enough displacement damages are created in the transistors after a higher fluence Br ion irradiation, there may exist some damages near the emitter/base interface, which could decrease the electron injection efficiency from the emitter to the base region. Thus, the magnitude of excess minority carrier density Δn_b drops with further ion fluence increasing at fixed V_{BE}, leading to a decreasing NBR component for higher fluence Br ion irradiation. Therefore, the decline in NBR for high fluence Br ion irradiated SiGe HBTs may be explained in this way. Of course, the potential physical mechanisms need to be further justified and explored.

For the fresh device, the rapid decline in normalized I_B at the large V_{CB} region ($V_{CB} > 3$ V) is a result of the impact ionization in the transistor. After heavy ion irradiation, the slopes at this region decrease compared to those of the fresh devices, as shown in Fig. 8, which means that the impact ionization weakens. The decline in impact ionization might be due to the lattice disorder in the BC depletion region created by heavy ion irradiation. The existence of lattice disorder may prevent the collision between the electron and lattice atom and thereby weaken the impact ionization.[15]

Early voltage (V_A) is a critical design parameter of bipolar transistors in many analog circuits. The influences of heavy ion irradiation on Early voltage were also investigated. The output characteristics at fixed V_{BE} of 0.6 V after 25-MeV Si and 10-MeV Br ion irradiation are shown in Fig. 9, from which we can find that collector currents (I_C) decline monotonously with ion fluence increasing. Two factors contribute to I_C decreasing after heavy ion irradiation: one is the degradation in the current gain β (as shown in Fig. 4) and the other is the increased collector series resistance R_C.[14,15] The deep level transient spectroscopy (DLTS) studies have shown that swift heavy ions can create a variety of point defects such as interstitials, vacancies and divacancies in the collector region,[24] then the effective dopant density and carrier mobility will degrade, and thereby collector series resistance (R_C) increases after heavy ion irradiation, as demonstrated in Fig. 10. It is the increase in the collector series resistance R_C that is responsible for the decrease in the collector current.

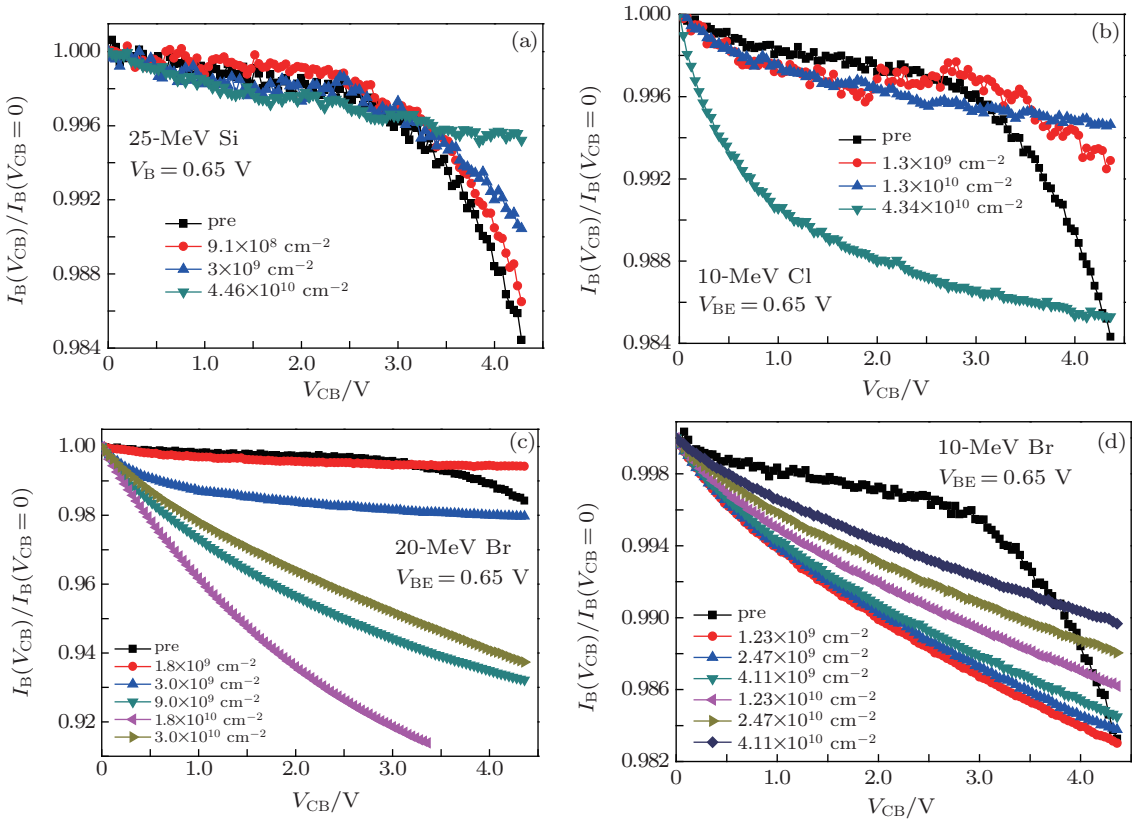


Fig. 8. (color online) Normalized I_B as a function of V_{CB} in SiGe HBT at fixed V_{BE} of 0.65 V after (a) 25-MeV Si, (b) 10-MeV Cl, (c) 20-MeV Br, and (d) 10-MeV Br ion irradiation.

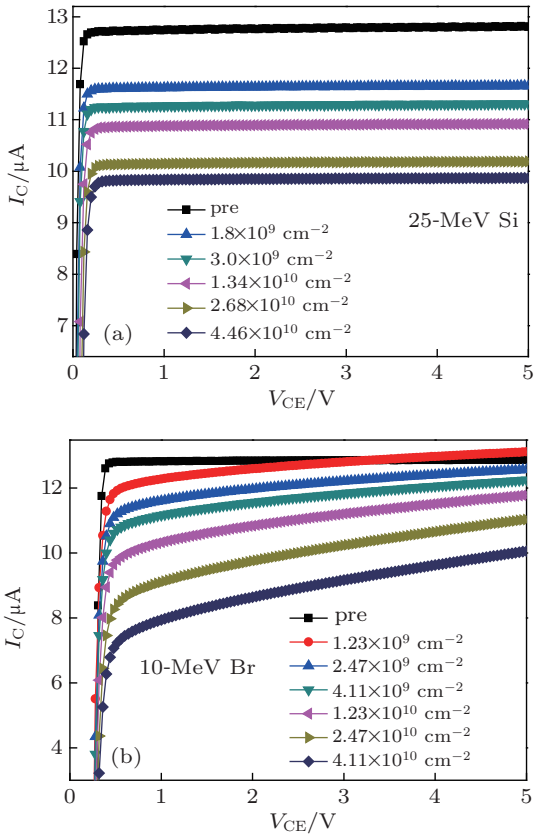


Fig. 9. (color online) The output characteristics for SiGe HBTs irradiated by (a) 25-MeV Si and (b) 10-MeV Br ion irradiation at fixed $V_{BE} = 0.6$ V.

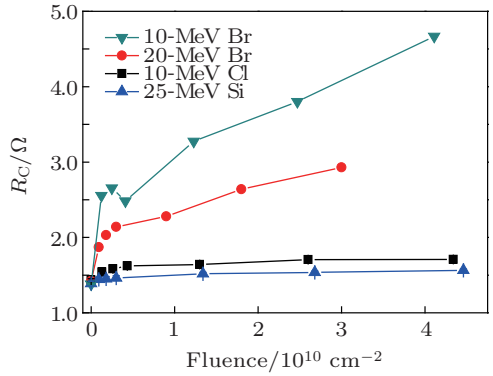


Fig. 10. (color online) The extracted R_C as a function of ion fluence after four kinds of heavy ion irradiations.

Besides, as shown in Fig. 9(b), a significant base width modulation appears in the transistors irradiated by 10-MeV Br ion, compared with the nearly ideal output characteristics of the fresh device, which is almost independent of V_{CE}. A direct consequence of the base width modulation is the decline in Early voltage (V_A). The variations of V_A after four kinds of heavy ion irradiations are depicted in Fig. 11 as a function of ion fluence. Considering the calculation error, V_A remains nearly unchanged after 25-MeV Si and 10-MeV Cl ion irradiation, i.e., there is no significant base width modulation in the transistor. For the case of 20-MeV Br and 10-MeV Br ion irradiation, however, V_A declines dramatically with ion fluence increasing. The V_A degradation may be a result of the

decreased concentration of the ionized impurities in the base region due to the impurities passivation induced by the displacement damage.[22] The Early voltage V_A for a NPN SiGe HBT can be expressed as follows:[23]

$$V_A = \frac{qD_n(W_B)n_i^2(\mathrm{SiGe},W_B)\int_0^{W_B}\frac{N_B(x)}{D_n(x)n_i^2(\mathrm{SiGe},x)}\mathrm{d}x}{C_{jC}}, \quad (3)$$

where C_{jC} represents the small-signal collector capacitance per unit area. The integral in the numerator is the Gummel number in the base. The displacement damage in the base region can result in dopant deactivation and then the effective base dopant density N_B will decrease, thereby causing a reduced V_A.[10] Due to the larger nuclear energy loss, 20 MeV and 10 MeV Br ions are capable of creating more displacement damages in the neutral base region, and the effective base dopant density N_B declines and thereby V_A decreases after irradiation. However, 25-MeV Si and 10-MeV Cl ions create relatively less displacement damages, and no significant degradation in V_A appears, as shown in Fig. 11.

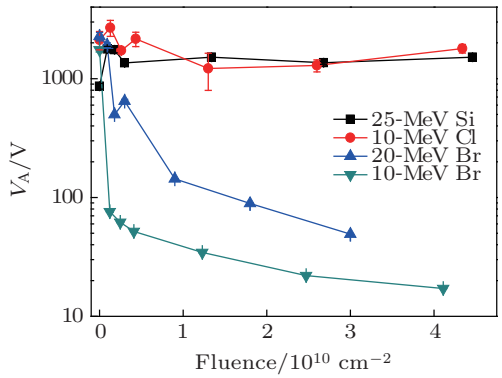


Fig. 11. (color online) The extracted V_A as a function of ion fluence after four kinds of heavy ion irradiation.

4. Conclusions

This work throws light on the comparison of radiation effects on SiGe HBTs induced by different swift heavy ions (25-MeV Si, 10-MeV Cl, 20-MeV Br, and 10-MeV Br ions). Experiment results show that the base current increases with ion fluence increasing, resulting in a remarkable drop in the current gain. Displacement damages are found to dominate the performance degradation in irradiated transistors. The degradation strongly depends on the ion nuclear energy loss, and the larger the ion nuclear energy loss is, the more serious the degradation is. Compared with 25-MeV Si and 10-MeV Cl ions, the heavy ions with a larger nuclear energy loss (10-MeV and 20-MeV Br ions) are capable of creating more displacement damages in the transistors. As a result, an unexpected I_C increasing at the low bias region and a significant degradation in Early voltage appear after 10-MeV and 20-MeV Br ion irradiation. Due to the decreased excess minority carrier injected from the emitter to the base, the neutral base recombination appears to slow down at high ion fluence in the transistors irradiated by 10-MeV and 20-MeV Br ions.

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