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Degradation differences in the forward and reverse current gain of 25 MeV Si ion irradiated SiGe HBT

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ABSTRACT

The silicon–germanium (SiGe) heterojunction bipolar transistors (HBTs) were exposed to 25 MeV Si ions with ion fluence from 9.1×10^8 to 4.46×10^{10} ions/cm^2 at room temperature. The forward current gain (β_F) and reverse current gain (β_R) were studied before and after irradiation and the bias dependences of the displacement damage factor for β_F and β_R were also presented. Measurement results indicated that β_F and β_R all decline with the ion fluence increasing. The reciprocal of β_R was found to vary linearly throughout all ion fluence for arbitrary base-collector voltage. However, a non-linear behavior for the reciprocal of β_F appeared at low fluence for the low and medium base-emitter voltage. Besides, it was found that the bias dependence of displacement damage factor for β_F was significantly different from that for β_R. The underlying physical mechanisms were analyzed and investigated in detail.

1. Introduction

Degradation and failure caused by radiation damages are a major challenge to electronic components and systems operated in space radiation environment [1–3]. Due to the excellent low temperature performance and inherent multi-Mrad total ionizing dose (TID) tolerance [4–9], Silicon–germanium (SiGe) heterojunction bipolar transistors (HBTs) recently have gained significant attention in spacecraft and other irradiation application, such as ATLAS detector of the Large Hadron Collider (LHC) [6]. In order to find better design and hardening strategies for practical applications, it is valuable to investigate the irradiation response of SiGe HBTs under various irradiation environments. Previous researches have shown that two kinds of irradiation damages, ionization damage and displacement damage are responsible for SiGe HBTs performance degradation [10]. The ionization damages create plenty of oxide trapped charges and interface states in oxide layer that lie over the intrinsic base interface, leading to an increase in base current and degradation in current gain [11]. The neutron was traditionally used to characterize the displacement damage effect in bipolar devices [4,12,13]. The displacement damages induce some kinds of trap levels in the bandgap of semiconductor material, which reduce the minority carrier lifetime and hence degrade the current gain.

Recently, with the pulsed neutron reactors less and less available all over the world, the swift heavy ions have been employed to characterize the displacement damage effect in the transistors [6,14–18]. Unlike the neutron irradiation where only the displacement damages exist, additional ionization damages also appear in the transistors during the heavy ion irradiation, and there may be some complicated interactions between ionization damages and displacement damages. Furthermore, compared to gamma ray or proton 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 on a substantially high dose level (such as 100 Mrad in LHC application). Although a few swift heavy ion irradiation on SiGe HBT have been reported [6,19,20], some important unanswered questions still remain about the irradiation effects of swift heavy ion on SiGe HBTs, such as the interactions between ionization damages and displacement damages at different bias regions, the degradation diversity between forward and reverse current gain. Besides, the displacement damage coefficients at different operating bias conditions have not been known clearly. To investigate these questions, we have performed 25 MeV Si ion irradiation experiments on SiGe HBTs, and the results and detailed physical mechanism are presented herein.

2. Experiment

The devices under test (DUTs) in this work are NPN SiGe HBTs, which features f_T of 7 GHZ, BV$_{CBO}$ of 20 V and BV$_{CEO}$ of 12 V, and

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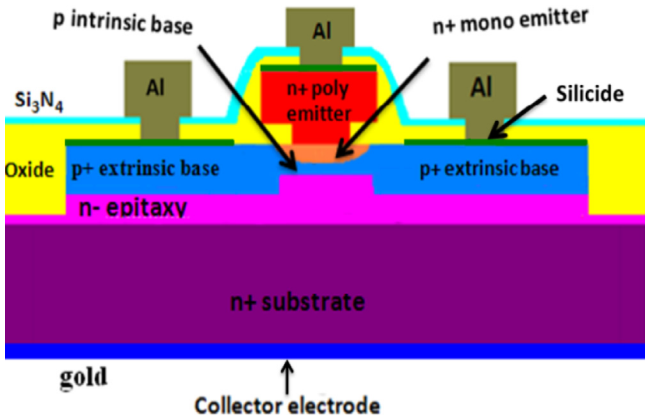

Fig. 1. The cross-section of SiGe HBT under investigation.

Table 1
The energy loss and range of 25 MeV Si ion in the transistor structure.

Source	LET in MeV cm^2/mg		NIEL in MeV cm^2/mg		Range in μm	
	Si	SiO_2	Si	SiO_2	Si	SiO_2
25 MeV Si	14.00	15.66	2.744e−2	2.824e−2	9.51	8.80

the cross section is shown in Fig. 1. The details about this technology can be found elsewhere [5]. The collector electrode is directly elicited from the backside of the substrate through gold evaporation. An interdigital layout is adopted in chip design, and 15 emitter fingers are contained with each finger of $0.6 \times 20\ \mu m^2$. The transistors are mounted in a metal–ceramic package with the package lid removed for the heavy ion irradiation.

The samples were exposed to 25 MeV Si^{4+} ions at room temperature. The irradiations were carried out in an evacuated chamber with a specially designed Faraday cup, which was used to measure the ion beam current. The typical beam current was about 30 nA. The ion beam was scanned over the transistors with an area of $10 \times 2\ cm^2$ by a magnetic scanner to obtain a uniform fluence. The ion fluence was varied from 9.1×10^8 to 4.46×10^{10} ions/cm^2 with equivalent adsorbed dose ranging from 300 Krad(Si) and 10 Mrad(Si). The formula for conversion of ion fluence to equivalent adsorbed dose for heavy ion is given as follows:

$$D_i(\text{rad}) = \text{Fluence}(\text{cm}^{-2}) \times \text{LET}(\text{MeV cm}^2/\text{mg}) \times K \quad (1)$$

$$D_{\text{NIEL}}(\text{rad}) = Fluence(\text{cm}^{-2}) \times \text{NIEL}(\text{MeV cm}^2/\text{mg}) \times K \quad (2)$$

where D_i and D_{NIEL} are ionizing dose and displacement dose, respectively. The conversion factor K is about 1.6018×10^{-5} with a unit of rad mg/MeV. LET and NIEL are separately the ionizing energy loss and nuclear energy loss, which are estimated by SRIM-2010 and the results are shown in Table 1. In order to ensure the statistical nature of the experiment, twelve devices with all terminals floating are irradiated simultaneously and then measured at specified ion fluence with the Keithley 4200 semiconductor parameter analyzer at room temperature. Then all the experiment data were analyzed in detail and the degradation characteristics were summarized in present study.

3. Experiment results

3.1. Degradation in forward current gain

The forward Gummel characteristics before and after irradiation are shown in Fig. 2. It is indicated that the base current (I_B) increases monotonically with ion fluence increasing, while the collector current (I_C) keeps invariable during the whole irradiation process. This indicates that base current is more sensitive to the radiation damages created by 25 MeV Si ion compared to collector current I_C. As a consequence, a remarkable drop in the forward current gain ($\beta_F = I_C/I_B$) can be found with the ion fluence increasing, as shown in Fig. 2(b).

The $\Delta(1/\beta_F)$, defined as the change in the forward current gain reciprocal after irradiation (subtracting its initial value), is shown in Fig. 3 as a function of ion fluence for various base-emitter voltages (V_{BE}). It is observed that there are three significant trends between $\Delta(1/\beta_F)$ and ion fluence under different V_{BE}. For the low bias region (e.g. $V_{BE} = 0.4$ V), $\Delta(1/\beta_F)$ varies sub-linearly with the ion fluence and tends to saturate at high fluence, as shown in Fig. 3(a). For the high bias region (e.g. $V_{BE} = 0.9$ V) depicted in Fig. 3(d), $\Delta(1/\beta_F)$ varies linearly throughout all the ion fluence. However, for the medium bias region (e.g. $V_{BE} = 0.6$–0.8 V), $\Delta(1/\beta_F)$ varies non-linearly at low fluence and then linearly at high ion fluence, as shown in Fig. 3(b) and (c).

The damage factor (K_F) for forward current gain, i.e., the linear regression slope of $\Delta(1/\beta_F)$ versus ion fluence Φ, can be calculated from the linear portion of the curves in Fig. 3, and the results are shown in Fig. 4 as a function of bias voltage V_{BE}. It is indicated that K_F highly depends on V_{BE}. A significant decrease in damage factor K_F is observed with V_{BE} increasing until some critical value. Once V_{BE} is larger than the critical value, 0.8 V in this case, the damage factor K_F begins to rebound with V_{BE} increasing, as shown in Fig. 4. Besides, the reverse extension of the linear region of the curves in Fig. 3 generally does not pass through the ordinate origin unless V_{BE} is large enough ($V_{BE} = 0.9$ V in present study), which is not similar to the case of neutron irradiation where the curve always pass through the ordinate origin for arbitrary V_{BE} [21]. The intercept for heavy ion irradiation, defined as S_L, is shown in Fig. 5 as a function of V_{BE}. It is found that the S_L dramatically decreases with the bias voltage V_{BE} increasing.

3.2. Degradation in reverse current gain

The reverse Gummel plots before and after irradiations are shown in Fig. 6. The emitter current (I_E) keeps unchanged during the whole irradiation process, while the base current (I_B) increases monotonically with the ion fluence increasing. As a result, the reverse current gain ($\beta_R = I_E/I_B$) also declines as the ion fluence goes up, as shown in Fig. 6(b).

Fig. 7 shows the variation in the reciprocal of β_R ($\Delta(1/\beta_R)$) after heavy ion irradiation as a function of ion fluence Φ. In contrast to $\Delta(1/\beta_F)$ shown in Fig. 3, $\Delta(1/\beta_R)$ approximately varies linearly throughout all the ion influence for arbitrary V_{BC} from 0.4 V to 0.9 V. The damage factor (K_R) for reverse current gain, determined by the linear regression slope of $\Delta(1/\beta_R)$ versus ion fluence, is shown in Fig. 8. It is observed that K_R decreases with the base-collector voltage (V_{BC}) increasing until it reaches saturation and there is no similar rebound phenomenon with V_{BC} increasing.

4. Discussion

Compared to ^{60}Co gamma ray and neutron irradiation, the swift heavy ions (such as 25 MeV Si ions in present study) can create ionization damages and displacement damages simultaneously in the transistors. The ionization damage generally induced the positive trapped charges and interface states in the oxide layer near base-emitter (BE) junction and base-collector (BC) junction [4,10], which can act as effective generation–recombination (G–R) centers and increase the base recombination current. The