Total ionizing dose effects of domestic SiGe HBTs under different dose rates

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Abstract: The total ionizing radiation (TID) response of commercial NPN silicon germanium hetero-junction bipolar transistors (SiGe HBTs) produced domestically are investigated under dose rates of 800 mGy(Si)/s and 1.3 mGy(Si)/s with a Co-60 gamma irradiation source. The changes of transistor parameters such as Gummel characteristics, and excess base current before and after irradiation, are examined. The results of the experiments show that for the KT1151, the radiation damage is slightly different under the different dose rates after prolonged annealing, and shows a time dependent effect (TDE). For the KT9041, however, the degradations of low dose rate irradiation is higher than for the high dose rate, demonstrating that there is a potential enhanced low dose rate sensitivity (ELDRS) effect for the KT9041. The possible underlying physical mechanisms of the different dose rates responses induced by the gamma rays are discussed.

Keywords: SiGe HBTs, TID, ELDRS, annealing

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1 Introduction

Over the last twenty years, silicon germanium (SiGe) hetero-junction bipolar transistor (HBT) technology has been considered to be one of the most promising candidates for future space applications due to its high current gain, low noise response and cryogenic temperature performance, especially the built-in tolerance of total ionizing dose (TID) radiation and displacement damage (DD)[1]. A lot of literature has been published about the radiation tolerance of SiGe HBTs with various radiation sources, bias, device structures and dose rate [2–7]. However, most of the experiments were performed with the dose rate above 500 mGy(Si)/s, which is much higher than that of the actual space radiation environment, which is as low as 10^{-3} mGy(Si)/s–0.1 mGy(Si)/s, causing a risk of overestimating the radiation resistance of SiGe HBTs with high dose rate to evaluate the radiation-hard performance of SiGe HBTs. Therefore, it is necessary to carry out the experiments in a low dose rate condition that can approximately simulate the actual space low dose rate environment.

In this work, taking the time and material resources consumption into consideration comprehensively, we performed radiation experiments with two Chinese-produced commercial NPN SiGe HBTs devices with gamma rays under two different dose rates, 800 mGy(Si)/s and 1.3 mGy(Si)/s, according to the reference of MIL-STD-883J Method 1019.9, and give a detailed investigation of the dose rate response of these commercial SiGe HBTs. The measurement results of the direct current (DC) parameters show that the different devices have different performance degradation under different dose rate irradiation. The KT9041 shows more resistance to radiation compared to the KT1151, but the KT9041 experienced more serious degradation under low dose rate irradiation than high dose rate, showing that there may be an enhanced low dose rate sensitive (ELDRS) effect in KT9041. Then, the potential physical mechanisms of the different dose rate responses induced by the gamma rays are discussed in detail

2 Experiments

The devices investigated in this work were two different types of NPN SiGe HBTs designed and fabricated in China with different processes by Huajie-tech. They

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are designed for high frequency low noise amplifier with the advantages of low noise figure, high power gain, high voltage, broad dynamic range and good linearity. The major characteristics of the two different devices are listed in Table 1,

Table 1. Characteristics of the devices.

sample	polarity	Ic/mA	Vceo/V	f_T/GHz	β
KT9041	NPN	30	4.5	25	150
KT1151	NPN	20	12	7	300

where Ic is the typical value of the collector current, Vceo is the breakdown voltage with base opened, f_T is the cut-off frequency of the transistor, and β is the common-emitter current gain of the transistor.

The irradiation experiments described in this paper were performed at room temperature with a 60-Co water-well gamma irradiation source at Xinjiang Technical Institute of Physics & Chemistry of Chinese, Academy of Sciences. The high dose rate (HDR) and low dose rate (LDR) used in the experiments was 800 mGy (Si)/s and 1.3 mGy(Si)/s, respectively. The selected 24 devices were mounted in the irradiation boards with all terminals grounded ($V_B = V_E = V_C$=0.0 V) during the irradiation and annealing process, and irradiated to a maximum total ionizing dose level of 11 kGy(Si). The electrical parameters used to characterize the degradation, including Gummel characteristics and direct current gain, were measured with a KEITHLEY 4200-SCS Semiconductor Parameter Analyzer, removed from the irradiation room within 20 minutes at room temperature before and after each specified value of accumulated dose.

3 Results and discussion

3.1 Degradation of base current and current gain

Figure 1 and Fig. 2 present the Gummel characteristics of the two devices as a function of accumulated total dose under the two different dose rates. For the two devices, the base currents I_B are both monotonically increasing with the increased accumulating total dose under the high and low dose rates, especially at the low base-emitter junction voltage (V_{BE} <0.8 V). Compared with I_B, the collector current I_C remains the same, with only slight changes. Thus, the direct current gains ($\beta = I_C/I_B$) of the two devices decreases after irradiation under the high and low dose rates. These experimental phenomena indicate that the base current I_B is more sensitive to the radiation damage caused by Co-60 gamma irradiation, while the collector current I_C is only slightly affected by irradiation at the given base-emitter voltage value (V_{BE}). It can also be seen clearly from Fig. 1 and Fig. 2 that the changes in I_B of the KT1151 are greater than that of KT9041 under the different dose rates. Comparing the degradation of I_B under the high and low dose rates, the changes of the I_B under the high dose rate are smaller than the changes under the low dose rate.

In order to quantitatively compare the effect of the degradation of the devices induced by the radiation under different dose rates, we define two parameters, the excess base current $\Delta I_B (\Delta I_B = I_{B\text{-post}} - I_{B\text{-pre}})$ and normalized current gain $\beta_{\text{post}}/\beta_{\text{pre}}$, in which the $I_{B\text{-pre}}$, $I_{B\text{-post}}$ and β_{pre}, β_{post} are corresponding to the base current I_B and direct current gain β extracted from Fig. 1 and Fig. 2 at V_{BE}=0.7 V before and after the irradiation.

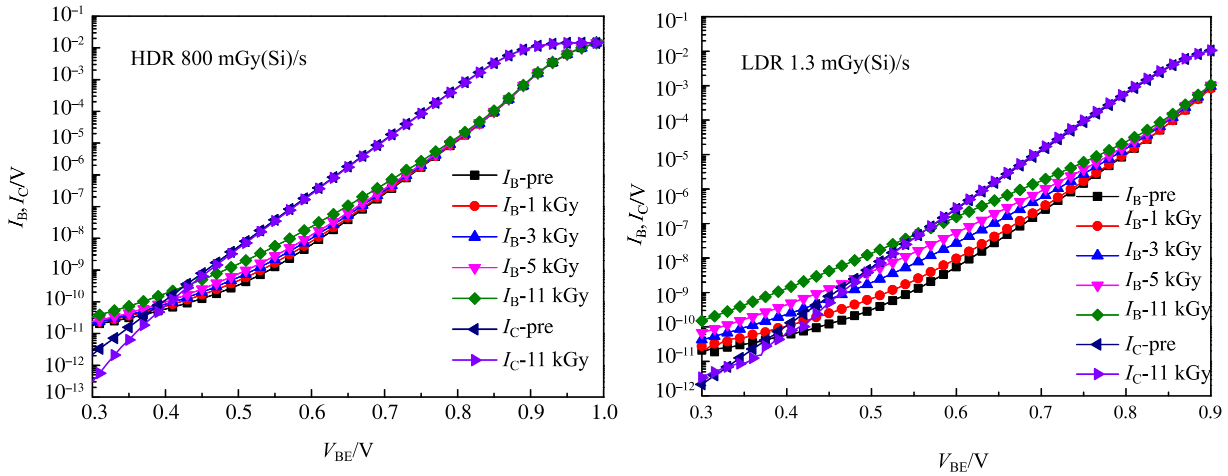

Fig. 1. (color online) Forward-mode Gummel characteristics of KT9041 as a function of total dose.

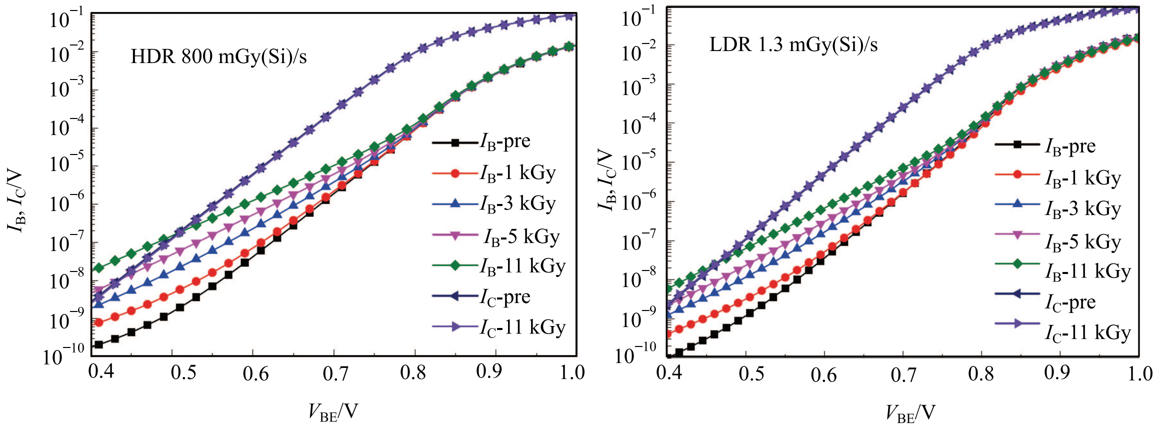

Fig. 2. (color online) Forward-mode Gummel characteristics of KT1151 as a function of total dose.

Figure 3 and Fig. 4 shows the changes of the excess base current ΔI_B of KT9041 and KT1151 as a function of total dose and annealing time under the different dose rates, respectively. With the dose accumulating, ΔI_B increases under both dose rates at the voltage of 0.7 V. However, there is a great deal of difference between the KT9041 and KT1151. For the KT9041, it can be seen clearly from Fig. 3 that the changes of ΔI_B are approximately two orders of magnitude after the dose goes up to 11 kGy(Si) under the low dose rate of 1.3 mGy(Si)/s. The changes of ΔI_B under the high dose rate of 800 mGy(Si)/s are much less than that of low dose rate and there is to some extent an increasing trend with annealing time after the irradiation, which indicates that there may be 'post-radiation damage' in the KT9041. Contrary to the KT9041, the ΔI_B of the KT1151 under the high dose rate is greater than ΔI_B under the low dose rate. The ΔI_B decreased dramatically in the first few tens of hours of annealing, and then decreased slowly down to a value smaller than the value of ΔI_B irradiated to 11 kGy(Si) under the low dose rate with increasing annealing time.

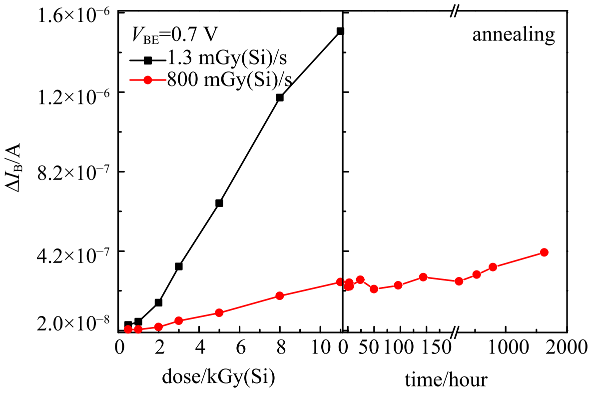

Fig. 3. (color online) Excess base current of KT9041 as a function of total dose and annealing time.

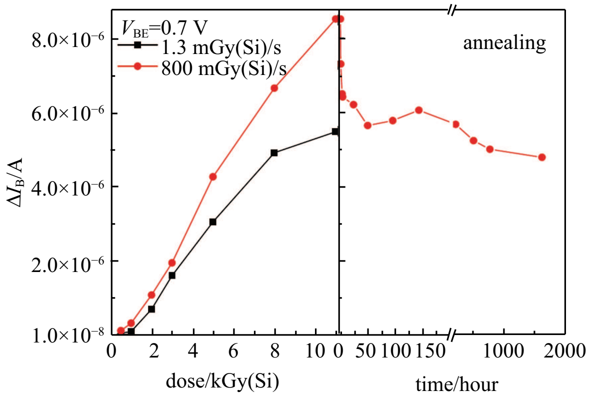

Fig. 4. (color online) Excess base current of KT1151 as a function of total dose and annealing time.

The normalized current gain of KT9041 and KT1151 as a function of total dose and annealing time are shown in Fig. 5 and Fig. 6 under the different dose rates. The normalized current gains of the two devices are monotonically decreasing with the increasing irradiation dose under the different dose rates. The difference is that the degradation of normalized current gain of KT9041 under low dose rate is greater than the degradation under high dose rate, while for the KT1151, the degradation of normalized current gain is almost the same after irradiation to the dose of 11 kGy(Si). The degradation of normalized current gain under the high dose rate is nearly the same as the value of irradiation at 11 kGy(Si) with the annealing time increasing for the KT9041, which shows a clear effect of enhanced low dose rate sensitivity (ELDRS). For the KT1151, it recovers quickly to the value of irradiation at 11 kGy(Si) under the low dose rate, and then remains unchanged, which shows there is a time dependent effect (TDE) in the KT1151.

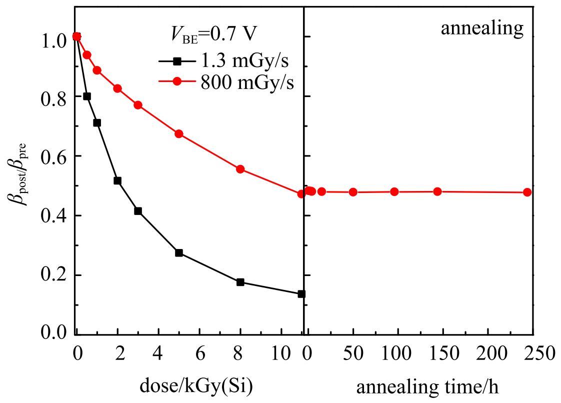

Fig. 5. (color online) Normalized current gain of KT9041 as a function of total dose and annealing time.

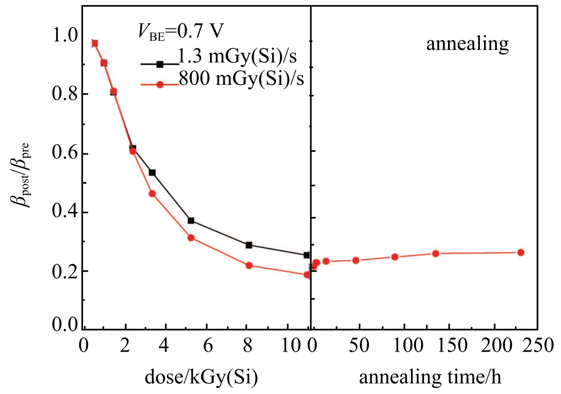

Fig. 6. (color online) Normalized current gain of KT1151 as a function of total dose and annealing time.

3.2 Discussion

3.2.1 Total ionizing effects

The above experimental results show that the base current increases with increasing accumulated dose for the high and low dose rate irradiation, causing a significant drop in current gain for both the KT9041 and KT1151. Generally speaking, the degradation of the base current of the SiGe HBTs is due to increase of the surface recombination current ($I_{\rm bsr}$) in the base region, which is related to the radiation induced oxide trap charge ($N_{\rm ot}$) and interface trap charge ($N_{\rm it}$) in the SiGe HBTs base-emitter spacer oxide and the interface of Si /SiO$_2$ [2]. The surface recombination current can be approximately characterised by the equation below [8],

$$I_{\rm bsr} \sim N_{\rm it}\exp(\alpha N_{\rm ot}^2), \qquad (1)$$

where $\alpha = 1/2q\varepsilon\varepsilon_0 N_{\rm a}$ is connected with the electronic charge q, absolute dielectric constant ε_0, relative dielectric constant ε and the doping of the substrate $N_{\rm a}$. Thus, the larger the radiation induced oxide trap and interface trap, the more the degradation of surface recombination current $I_{\rm bsr}$.

The effect of the radiation induced surface trap charge on the base current can be expressed by the surface recombination velocity (SRV)[9]. In the low injection condition, the relationship between surface recombination velocity SRV and surface trap charge $N_{\rm it}$ can be approximated as

$$\text{SRV} \cong \sigma N_{\rm it} V_{\rm th}, \qquad (2)$$

where σ is the trap capture cross section and $V_{\rm th}$ is the thermal velocity of carriers in silicon. The radiation induced buildup in $N_{\rm it}$ increases base current in the SiGe HBTs by increasing the surface recombination rate. The radiation induced excess base current $\Delta I_{\rm B}$ can be expressed as a function of SRV by the following equation:

$$\Delta I_{\rm B} = q\int_s \Delta U ds = q\Delta\text{SRV}\int_s \frac{(np-n_{\rm i}^2)}{(n+p+2n_{\rm i})}{\rm d}s, \qquad (3)$$

where q is the electronic charge, ΔU is the change of the surface recombination rate induced by radiation, s is the recombination surface area, and n, p, $n_{\rm i}$ are the concentration of the electron, hole and intrinsic carriers, respectively. Therefore, the accumulation of $N_{\rm it}$ can not only cause a linear increase in surface recombination velocity SRV according to Eq. (2), but can also affect the carrier concentration of the device according to Eq. (3), inducing a non-linear increase of $\Delta I_{\rm B}$ as shown in Fig. 3 and Fig. 4. Finally, this causes the drop of the current gains of the two devices under different dose rates.

Both the oxide trap charge and interface trap charge can contribute to the degradation of the devices, but there are still some differences during the post-irradiation annealing. Due to the competition between the oxide trap charge and interface trap charge, according to the literature [10], there is more interface trap charge induced by the prolonged low dose rate irradiation, while more oxide trap charge is induced by the high dose rate. For different devices fabricated by different processes, the amounts of the oxide trap charge and interface trap charge induced by radiation may differ because of the numbers of defects introduced in the oxide. The oxide trap charge can be eliminated by annealing at room temperature, but the interface trap charge cannot be significantly removed by annealing at 100°C, thus causing different annealing performance of the two devices under the different dose rates [11], as shown in Figs. 3–6.

3.2.2 Dose rate effects

The dose rate effects of the two different devices were then investigated. As shown in Fig. 3 and Fig. 5 for the KT9041, the lower the dose rate, the higher the radiation damage, and after the prolonged annealing there is only slight recovery for the ΔI_{B}, which demonstrates a significantly enhanced low dose rate sensitivity (ELDRS) effect. As for the KT1151 in Fig. 4 and Fig. 6, contrary to the KT9041, with the increasing annealing time the difference between the high dose rate irradiation and low dose rate narrows and finally approximately stays the same as the degradation under the low dose rate, which shows a time dependent effect (TDE).

According to the ELDRS theory of traditional Si BJT (Bipolar Junction Transistor), compared with low dose rate irradiation, high dose rate irradiation-induced excess holes can react with the defects and release neutral hydrogen atoms [12–14]. The released hydrogen atoms combine into molecular hydrogen, and then interact with the neutral trap site and in the process, protons are released. The produced protons can combine with the interface defect near the $\mathrm{Si/SiO_2}$ interface into an interfacial state. The hydrogen can diffuse quickly, however, to the interface of the $\mathrm{Si/SiO_2}$ and passivate the dangling bonds due to the lower diffusion barrier of the molecular hydrogen in $\mathrm{SiO_2}$, reducing the concentration of the interfacial state, thus suppressing the further increasing of the base current.

Contrary to high dose rate irradiation, when the irradiation is carried out under low dose rates, the combination between radiation induced hydrogen is difficult because of the lower yield of hydrogen atoms under the low dose rate. Most of them capture holes and release protons, which then couple with the dangling bonds to form a great number of interfacial states. Consequently, the concentration of the interfacial states of the low dose rate irradiation is higher than that of the high dose rate irradiation, thereby causing the ELDRS effects.

However, Refs. [2] and [15] consider that because of the thin emitter-base (EB) spacer oxide and heavily doped base region of the SiGe HBTs, the leakage of the base current results from the interface traps induced by the irradiation is suppressed, which results in an excellent performance of radiation-hardness of TID. Strictly controlled processes and special steps make sure that all the hydrogen contaminants introduced by the epitaxial Si growth are eliminated, bringing about an immunity to ELDRS effects. For the two commercial SiGe HBTs devices investigated in this paper, because the specific manufacturing process is still unclear, for the moment we cannot give an explicit conclusion that the ELDRS effect is caused by different numbers of interfacial states related to the introduced hydrogen. Therefore, based on the discussions above, the different dose rate responses between the different devices and manufacturer may be related to the interfacial traps at the $\mathrm{Si/SiO_2}$ interface induced by the TID exposure.

4 Conclusion

In this paper, we investigated the degradation of electric parameters and annealing behavior of two commercial SiGe HBTs with 800 mGy(Si)/s and 1.3 mGy(Si)/s Co-60 gamma total ionization dose irradiation. The radiation sensitive electric parameters of both SiGe HBTs, like many Si BJTs, are base current and current gain. Based on the obtained experiment results, we discussed the dose rate dependence of radiation tolerance of the SiGe HBTs and concluded that there is an obvious ELDRS effects in the KT9041, while there is only TDE effects for the KT1151. The different radiation responses of the different SiGe HBTs under the high and low dose rate may be due to the different numbers of defects introduced by the manufacturing process. The different radiation responses between the different devices and manufacturers needs further research, taking the different manufacturing processes and device structures into consideration.

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