

Chapter 2

Ionization Damage Effect in SiGe HBT

In space environment, many charged particles, such as protons, electrons, and gamma rays, can cause ionization damages and performance degradation, resulting in serious threats to the reliability of the space electronic system. Due to the special device structure, SiGe HBT has shown an inherent multi-Mrad total dose tolerance and gained significant attention as a candidate for extreme environmental electronic applications. However, due to the complexity of fabrication process and the diversity of device structure, the ionization damage effects are complicated. It is necessary to carry out some radiation experiments to study its ionization damage effect in SiGe HBT with different process and device structure. In this chapter, we will first introduce the interaction mechanism between gamma rays and materials and then discuss the ionization damage effects of SiGe HBTs for two kinds of layout structure under different dose rates and bias conditions.

2.1 Interaction Mechanism Between Gamma Rays and Materials

Gamma ray is a kind of an electromagnetic wave with a wavelength less than 0.2 Å. Due to the shorter wavelength, gamma ray generally has a higher energy and a stronger penetrating power. According to the different incident energy, the interaction between gamma ray and material can be divided into the following three kinds: photocurrent effect, Compton scattering effect, and electron–hole pair effect, as shown in Fig. 2.1 [1]. When the incident energy is low, some electron in material will be excited and the photocurrent is created. When gamma ray with high energy strikes at the material surface, the electrons in valence band absorb enough energy to excite to the conduction band, creating a free electron–hole pair. For the gamma ray with middle energy, the Compton scattering effect dominates, where the photon energy is not completely absorbed and lower energy secondary electrons (known as

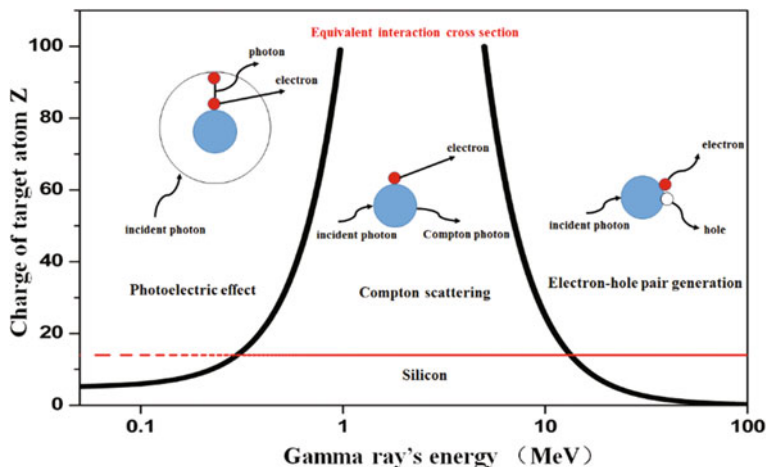


Fig. 2.1 Diagram of interaction between gamma rays with different energies and material, the solid line represents the case of silicon

Compton electrons) are produced. If the second electron energy is still high enough, it can even excite another electron. In general, the generation of electron-hole pairs becomes very important if the photon energy exceeds 1.02 MeV. ^{60}Co radiation source undergoes two decays, producing ^{60}Ni and two kinds of gamma ray flux with energy of 1.17 and 1.33 MeV (average of 1.25 MeV). The gamma ray with this energy can produce a large number of electron-hole pairs with Compton effect.

2.2 Experiment

The devices under test (DUT) are two kinds of SiGe HBT designed and fabricated by the Institute of Microelectronics, Tsinghua University. The first one is a microwave low-noise SiGe HBT, named SiGe HBT1, and the schematic cross-sectional view is shown in Fig. 2.2. The main process is as follows: After the formation of n^+ buried layer (NBL) on the p-type substrate, the lightly phosphorus-doped ($7\text{--}15\text{ cm}^{-3}$) n^- collector epitaxy is completed. An n^+ collector sinker is then formed, followed by local oxidation of silicon (LOCOS) for device isolation, in situ 120 nm boron-doped graded SiGe base epitaxy, selectively implanted collector (SIC), and heavily doped n^+ polysilicon emitter contact. An interdigital layout (4E5B2C) is adopted for chip design with each emitter finger of $0.4 \times 20\text{ }\mu\text{m}^2$. The typical BV_{CEO} is 4.5 V, BV_{CBO} is 9 V, and current gain β_F is 100. Emitter and substrate are connected together via metal interconnection.

A schematic cross-sectional view of second DUT, named SiGe HBT2, is shown in Fig. 2.3. The device architecture features low resistivity n^+ substrate, lightly doped n^- collector epitaxy layer, in situ boron-doped SiGe intrinsic base epitaxy

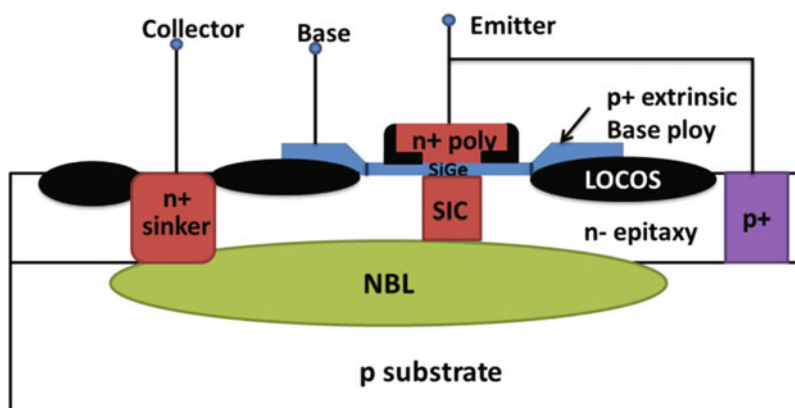


Fig. 2.2 Cross-sectional view of SiGe HBT1 with emitter and substrate connected together

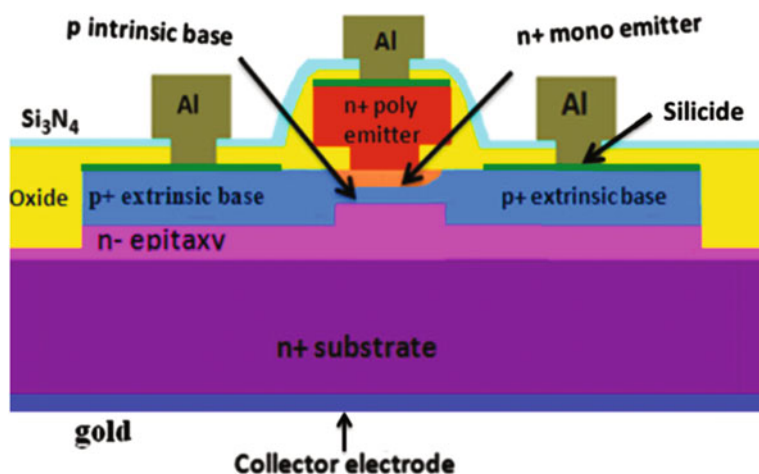


Fig. 2.3 Cross-sectional view of SiGe HBT2 with the collector electrode elicited from the backside of the substrate

region, heavily doped n^+ polysilicon emitter, extrinsic p^+ extrinsic base region formed through heavy dose implant self-aligned to the emitter-poly, and self-aligned titanium silicide formed based on the emitter-base sidewall spacer oxide. There is no SIC in the fabrication process. The collector electrode is elicited from the backside of the substrate through gold evaporation. The layout of the SiGe HBT consists of 15 emitter fingers, with the dimension of $0.6 \times 20 \mu\text{m}^2$ for each finger. The device is encapsulated in a standard SOT-23 plastic package. Owing to the thick n^- collector epitaxy layer, the SiGe HBT is a high-voltage transistor with $f_T = 7 \text{ GHz}$, $\beta_F = 200$, $BV_{CBO} > 20 \text{ V}$, and $BV_{CEO} > 12 \text{ V}$.

The examples were irradiated with ^{60}Co gamma source at room temperature. A Pb/Al box was used to decrease the flux of secondary gamma ray and ensure a monochromatic gamma ray spectrum. Two dose rates of 50 rad (Si)/s and 0.1 rad (Si)/s were adopted to investigate the effects of dose rate on ionization damage. For convenience, the unit of rad(Si)/s here is simplified as rad/s throughout this dissertation. The transistors were removed from the irradiation chamber at specified intervals and then characterized with an Agilent B1500 Semiconductor Parameter Analyzer at room temperature. The irradiation resumed after the characterization until the required accumulated dose was reached.

2.3 Results and Discussion

The DC performance degradation, including forward Gummel, reverse Gummel, leakage current, output characteristic, parasitic resistance, and neutral base recombination, are first discussed under high-dose-rate irradiation (50 rad/s). During the exposure, all the device terminals are floating.

2.3.1 SiGe HBT1 with Emitter and Substrate Connecting Together

The forward Gummel characteristics of SiGe HBT1 under different irradiation dose are shown in Fig. 2.4. The base currents (I_B) all increase monotonically with accumulated total dose, especially in low emitter–base voltage (V_{BE}) region, while collector current (I_C) remains unchanged during the whole irradiation; thereby, a remarkable drop appears in the current gain β ($\beta = I_C/I_B$). The peak value of β is

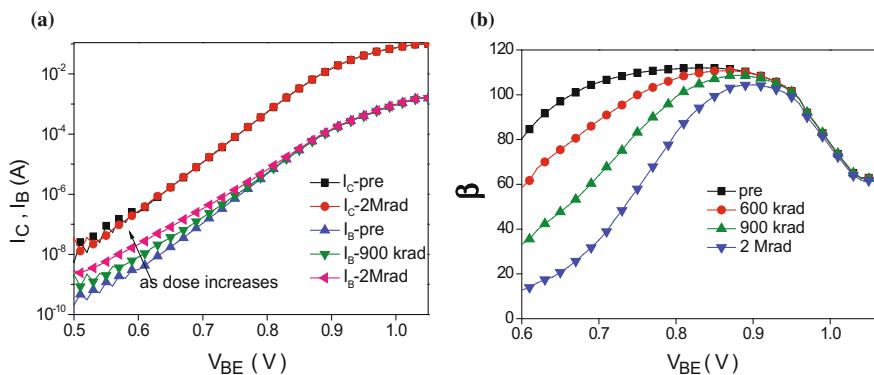


Fig. 2.4 **a** Forward Gummel characteristics and **b** current gain β of SiGe HBT1 before and after gamma irradiation with different dose levels

still higher than 100 and decreases only 7.2% after 2 Mrad dose irradiation, which demonstrates an inherent multi-Mrad total ionizing dose (TID) tolerance.

For a PN junction, we have

$$I = I_S \left(e^{\frac{V}{nV_T}} - 1 \right) \quad (2.1)$$

where I_S is the inverse-saturation current, V_T is thermal voltage and is about 25.6 mV at room temperature, and n is ideality factor. When the PN junction is forward biased, there exists $V \gg n \cdot V_T$, and n is given as

$$n \approx \frac{1}{V_T} \cdot \left(\frac{d \ln(I)}{dV} \right)^{-1} \quad (2.2)$$

Generally, n has a value between 1 and 2. If n is close to 1, the diffusion current dominates I_B , while a value of 2 means the recombination current dominates. At a given temperature, the larger n means a greater ration of non-ideal recombination current to total current. Figure 2.5 shows the ideality factor of base current and collector current for SiGe HBT1 before and after irradiation. Ideality factor n_{IC} remains constant of 1 during the whole irradiation. However, the ideality factor n_{IB} is found to increase from 1.02 to 1.38 as irradiation dose increases at medium V_{BE} region ($V_{BE} = 0.7\text{--}0.75$ V), which suggests that there exists an abundant of recombination current and I_B is mainly dominated by the recombination current.

In order to quantitatively analyze the performance degradation after gamma ray irradiation, electrical parameter $\Delta(1/\beta)$, defined as $1/\beta_{\text{post}} - 1/\beta_{\text{pre}}$, is calculated at $V_{BE} = 0.6$ and 0.7 V, where β_{pre} and β_{post} are separately current gain before and after irradiation. The variation of $\Delta(1/\beta)$ is depicted in Fig. 2.6. A nonlinear trend between $\Delta(1/\beta)$ and irradiation dose is expected, and a saturation value appears at high-dose level.

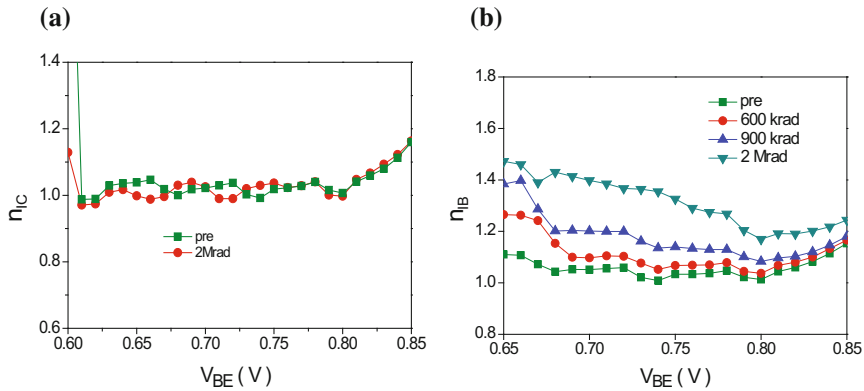
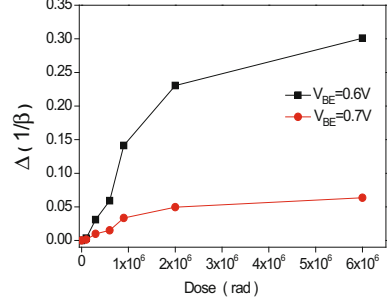


Fig. 2.5 Variation of current ideality factor before and after ^{60}Co irradiation for **a** base current and **b** collector current

Fig. 2.6 Variation of $\Delta(1/\beta)$ for SiGe HBT1 under two base voltages V_{BE}



Similar to the previous studies [2–4], a distinct increase in the low-injection base current of inverse-mode Gummel characteristics appears when the transistors are exposed to gamma irradiation, as shown in Fig. 2.7a. It is the result of radiation-induced generation–recombination (G/R) traps near LOCOS oxide interface regions. However, unlike current reports, for SiGe HBT1 there exists an unexpected increase in I_E under low V_{BC} region, as depicted in Fig. 2.7b. The relevant discussion will be presented in the following section.

The leakage current of BC and BE junctions was also investigated, and it is shown in Fig. 2.8. The reverse leakage currents for both the junctions almost keep unchanged with total dose increasing. Besides, the reverse leakage current of BC junction is nearly invariable with V_{BC} increasing; however, the reverse leakage current of BE junction is not saturated and greatly increases with reverse bias voltage increasing. The reverse leakage current for BC and BE junction is composed of reverse minority diffusion current (I_{DR}) and generation current in the space charge region (I_G). The I_{DR} for the BE junction (N^+P) is given by Meng et al. [5]

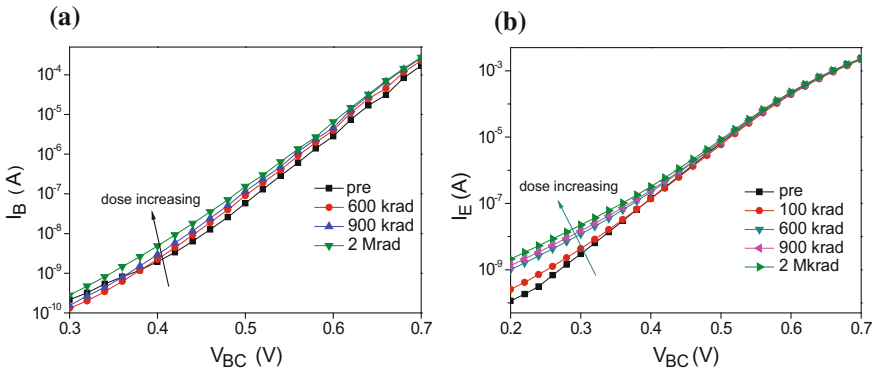
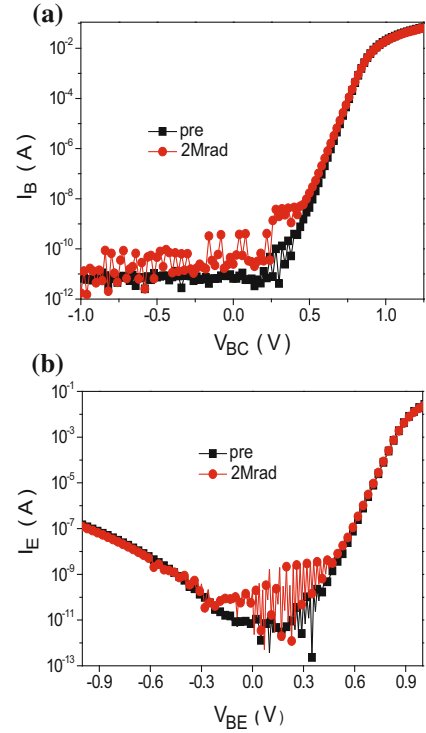


Fig. 2.7 Variation of reverse Gummel plot before and after ^{60}Co irradiation: **a** base current I_B and **b** emitter current I_E

Fig. 2.8 Variation of leakage current for **a** BC junction and **b** BE junction



$$I_{DR} \approx qA \frac{D_n n_i^2}{L_n N_B} \quad (2.3)$$

where A stands for the area of BE junction, and D_n , n_i , L_n , and N_B represent the electron diffusion coefficient, the intrinsic carrier density, the electron diffusion length, and the doping concentration in base region, respectively. The I_{DR} is saturated and independent of the reverse bias voltage of BE junction. The I_G is given by Meng et al. [5]

$$I_G \approx qA \frac{n_i^2 W_{BE}}{2\tau} \quad (2.4)$$

where τ is minority carrier lifetime in the BE junction depletion region. W_{BE} is the width of BE junction depletion region and increases with the reverse bias voltage

increasing, and therefore, I_G is not saturated and increases with the reverse bias voltage V_{BE} increasing.

The ratio of I_{DR} to I_G is given by

$$\frac{I_{DR}}{I_G} \Big|_{BE} = \frac{2L_n}{N_B W_{BE}} \quad (2.5)$$

Similarly, for the case of BC junction (P^+N), the ratio of I_{DR} to I_G is as follows:

$$\frac{I_{DR}}{I_G} \Big|_{BC} = \frac{2L_p}{N_C W_{BC}}. \quad (2.6)$$

where L_p and N_C represent the hole diffusion length and the doping concentration in collector region, respectively. W_{BC} stands for the width of BC junction depletion region. Compared to the BC junction, a greater proportion of generation current (I_G) appears in the total leakage current of BE junction due to the heavy base doping N_B , and I_G might dominate the reverse leakage current. Therefore, the reverse leakage current for BE junction is not saturated and greatly increases with the reverse bias voltage increasing, and the reverse leakage current for BC junction slightly increases with the reverse bias voltage increasing, as shown in Fig. 2.8.

The variation of parasitic emitter resistance R_E , base resistance R_B , and collector resistance R_C before and after irradiation is depicted in Fig. 2.9. Considering the measurement error, those parasitic resistances remain unchanged during the whole irradiation process, which demonstrates that no significant displacement damage appears and the effective doping concentration of each region does not change significantly.

The output characteristic of the SiGe HBT1 at different I_B is shown in Fig. 2.10. It is found that the collector current (I_C) declines with the ion fluence increasing, which is a result of the degradation in current gain, as shown in the Fig. 2.4b. For the low I_B level (such as 100 μA), the curve slope at high V_{CE} region remains nearly unchanged after 2 Mrad dose irradiation, i.e., there is no significant base-width

Fig. 2.9 Variation of series resistance in SiGe HBT1 before and after ^{60}Co irradiation

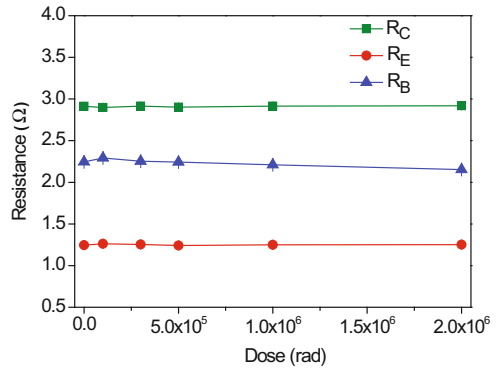
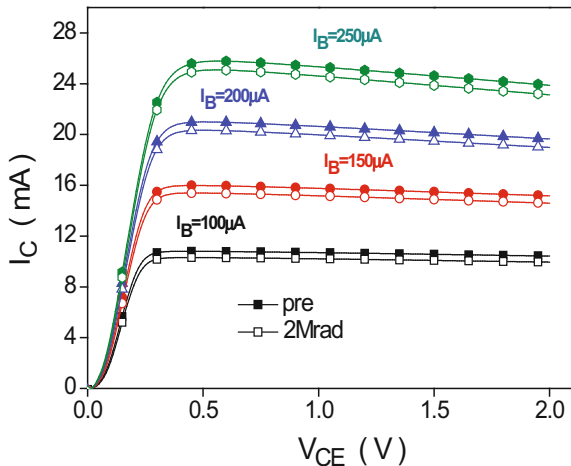


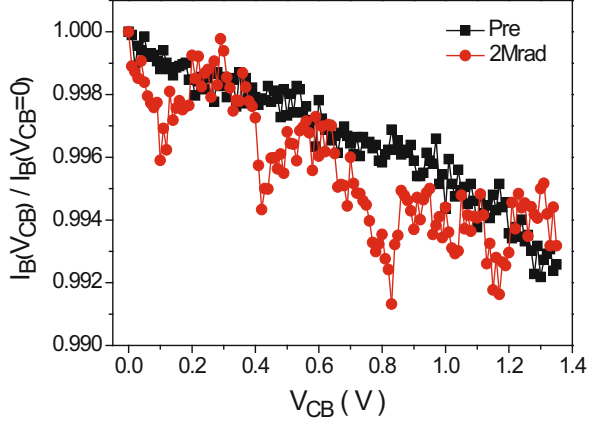
Fig. 2.10 Variation of output characteristics at fixed base current



modulation in the transistor and Early voltage (V_A) remains nearly unchanged, as shown in Fig. 2.10. Besides, negative differential resistance characteristics occur at high I_B level (such as $250 \mu\text{A}$) region before the gamma irradiation, which is due to the self-heating effect. The self-heating effect can induce a decreased current gain β with the internal temperature increasing.

Four significant components generally contribute to I_B of the conventional SiGe HBT under arbitrary forward-active bias: the recombination current in the BE depletion region and the interface between the extrinsic base and the BE spacer oxide, the neutral base recombination (NBR) current, the impact ionization current in the BC depletion region, and the hole current injected into the emitter. The impact ionization only occurs in the high V_{CB} region. NBR includes the recombination of injected electrons with holes via intermediate trap levels in neutral base region. It is proportional to total charge Q_B injected from emitter to base and is inversely proportional to the lifetime of minority carrier τ in neutral base [6]. Therefore, any method that changes Q_B and τ can vary NBR in the transistor. Q_B is proportional to the width of neutral base region W_B , which is changed by the voltage V_{BC} across base-collector junction. Thus, a conventional way to characterize NBR is to observe the rate of normalized base current decreasing with varied V_{CB} at fixed V_{BE} [3, 4]. Figure 2.11 depicts the normalized base current $I_B(V_{CB})/I_B(V_{CB} = 0)$ as a function of V_{CB} at $V_{BE} = 0.65 \text{ V}$. The negative slope at low V_{CB} ($V_{CB} < 3 \text{ V}$) is indicative of NBR in the transistors, which means there is no distinct increased NBR in transistor after 2 Mrad dose radiation.

Fig. 2.11 Variation of I_B (V_{CB}/I_B ($V_{CB} = 0$) as function of V_{CB} under $V_{BE} = 0.65$ V



2.3.2 Ionization Damage in SiGe HBTs with Backside Collector Electrode

As for the SiGe HBT2 with backside collector electrode, forward Gummel characteristics before and after irradiation are depicted in Fig. 2.12. Similar to the case of SiGe HBT1, I_B increases while I_C keeps unchanged with accumulated total dose increasing, resulting in a decline in current gain β . The peak value of β is still higher than 100 after 2 Mrad dose irradiation, which can meet the requirements of most applications, and an inherent multi-Mrad TID tolerance is demonstrated.

The variation of current ideal factor n_{IB} and n_{IC} for SiGe HBT2 is shown in Fig. 2.13. Before irradiation, n_{IB} and n_{IC} are about 1, which means that the diffusion current dominates and there is no significant recombination current. During the whole irradiation, n_{IC} remains nearly unchanged; however, n_{IB} sharply increases to

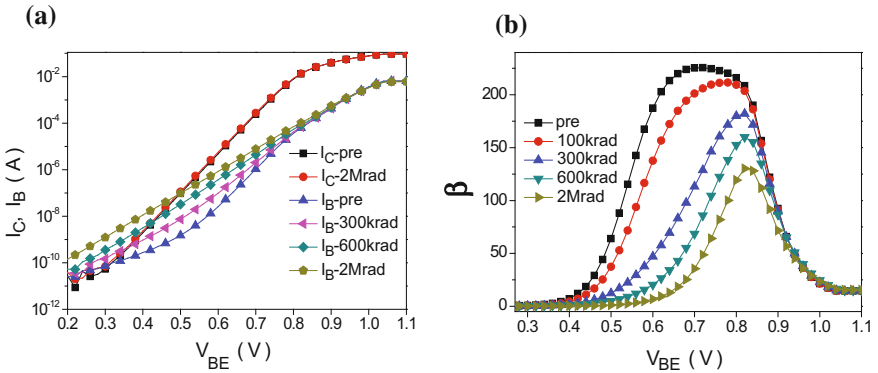


Fig. 2.12 Variation of **a** forward Gummel and **b** current gain before and after ^{60}Co radiation

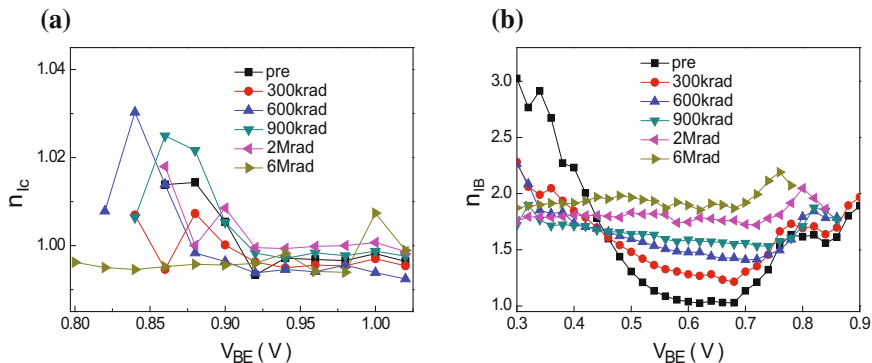


Fig. 2.13 Variation of **a** collector current ideal factor n_{IC} and **b** base current ideal factor n_{IB} before and after ^{60}Co radiation

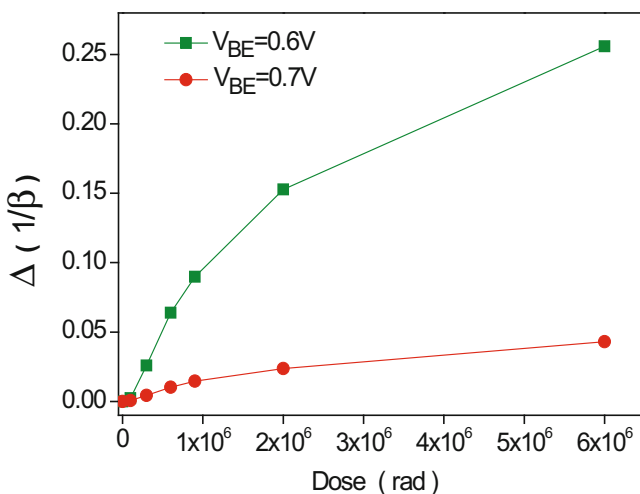


Fig. 2.14 Variation of $\Delta(1/\beta)$ for SiGe HBT2 under two different V_{BE}

2 after 2 Mrad total dose irradiation, implying that much recombination current appears in base current.

Figure 2.14 depicts the variation of $\Delta(1/\beta)$ for SiGe HBT2 before and after gamma irradiation. Similar to the case of SiGe HBT1, $\Delta(1/\beta)$ here increases nonlinearly until saturation is reached.

Figure 2.15 shows the reverse Gummel curve of SiGe HBT2 before and after ^{60}Co irradiation. It can be seen that the irradiation has less influence on the reverse Gummel characteristic of SiGe HBT2, and I_B and I_E hardly change with the total dose of 2 Mrad, which has not been reported previously. This may be due to the special device structure and will be discussed and analyzed in the following section.

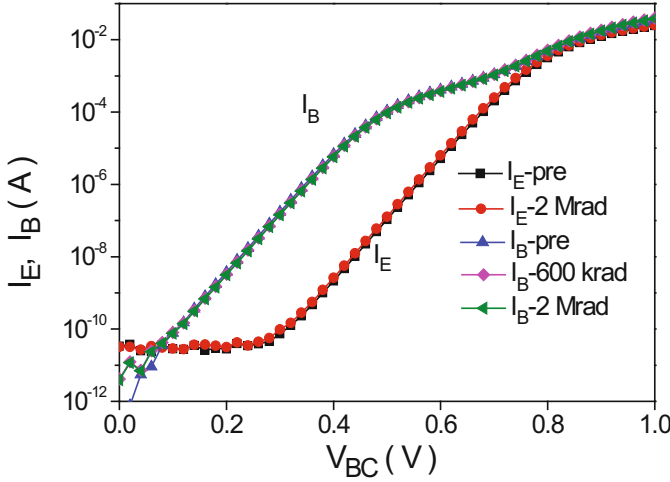


Fig. 2.15 Variation of reverse Gummel characteristics of SiGe HBT2

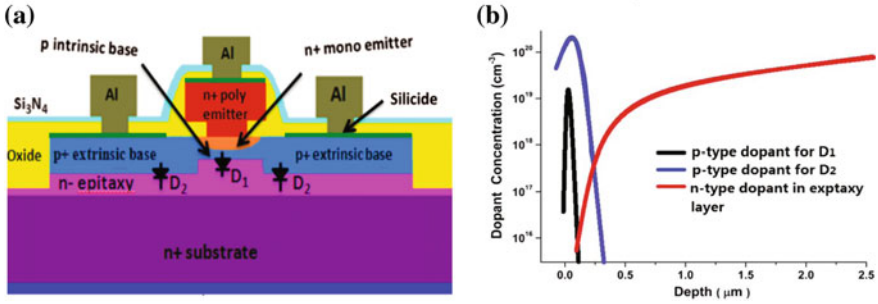


Fig. 2.16 **a** Schematic cross-sectional view of SiGe HBT2. D_1 and D_2 represent intrinsic and extrinsic BC junctions. **b** Schematic doping profile for the extrinsic D_2 and intrinsic D_1

It is found that an interesting “double shoulder” appears in base current, as shown in Fig. 2.15. The special shape of I_B curve can be interpreted in the following way. As for the device architecture shown in Fig. 2.16a, the whole BC junction may be considered as intrinsic base diode D_1 and extrinsic base diode D_2 in parallel. The schematic doping distribution for D_1 and D_2 diodes is shown in Fig. 2.16b. Because of the heavy dose extrinsic base implant, the p-type concentration for the extrinsic D_2 diode is much larger than that for the intrinsic D_1 diode. Because of the inevitable upward diffusion of n-type impurities from the n+ substrate during the device manufacturing process, the p-type doping profile will intersect with the n-type doping profile at a much larger concentration for D_2 than for D_1 . The forward current of D_1 is larger in the low-injection region, but affected by the high-injection effect earlier due to the lighter n-type doping concentration.

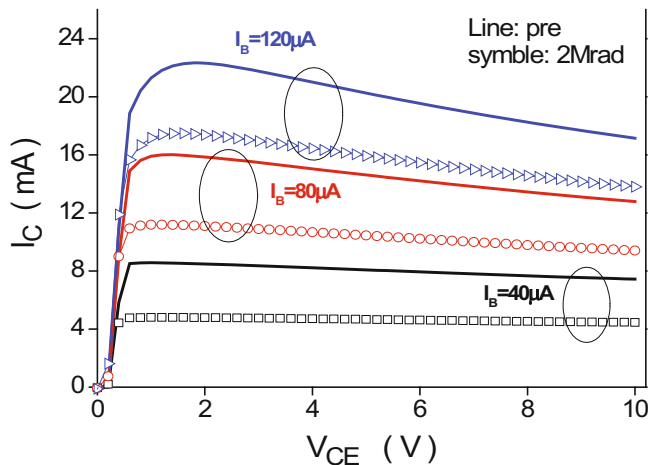


Fig. 2.17 Variation of output characteristics of SiGe HBT2 before and after irradiation

On the contrary, the higher n-type doping level of D_2 gives a smaller forward current under low bias conditions, while the high-injection effect is delayed to a higher critical current value. Therefore, a “double shoulder” I_B appears as a superposition of the two diode current curves in the semi-logarithmic scale reverse Gummel plot [7], as shown in Fig. 2.15.

Figure 2.17 shows the variation of the output characteristic of SiGe HBT2 before and after irradiation at fixed base current. Because of self-heating effect, I_C will decrease as V_{CE} increases when transistors are biased at high base current level (such as 120 μA). Due to the degradation of current gain, the collector current I_C of the irradiated transistor decreases with the total dose increasing. Besides, when base current was relatively low (40 μA), the slope of IV curves keep nearly unchanged, i.e., the gamma irradiation has less influence on V_A .

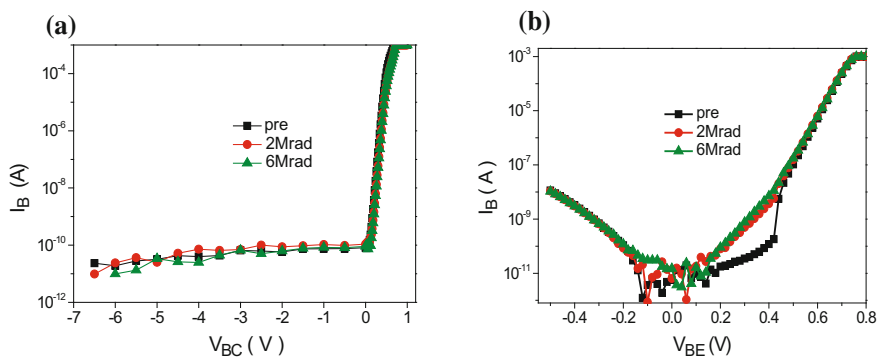


Fig. 2.18 Variation of **a** BC junction leakage current and **b** BE junction leakage current of SiGe HBT2 before and after ^{60}Co radiation

Figure 2.18 shows the variation of leakage current of SiGe HBT2 before and after irradiation. Similar to SiGe HBT1, the leakage current of BC junction is nearly invariable with V_{BC} increasing, while the reverse leakage current of BE junction is not saturated. Besides, when the transistors are exposed to irradiation, the leakage current keeps nearly unchanged.

2.3.3 Degradation Mechanism in Gamma Ray Irradiated SiGe HBTs

Experiment results show that base current and current gain will suffer degradation when the transistors are exposed to ^{60}Co irradiation. Large quantity of EHPs will be generated in the oxide as ionizing radiation passes through the SiO_2 film. Some fraction of the EHPs will recombine within a very short time, and the remains will transport within the oxide. The electrons, being much more mobile than holes, are swept out of the oxide rapidly. While the hole will slowly travel to the SiO_2/Si interface and a fraction will be trapped in deep energy-level sites in SiO_2 region, creating the positive oxide-trapped charges [6]. Besides, the radiation-induced holes will release proton (H^+) as they transport through the oxide, and the released protons transport toward the interface where they react with the passivated Si-H bond to form the interface traps [8, 9]. In bipolar transistor, the above irradiation damages generally appear in the spacer oxide near EB junction and the LOCOS edge near BC junction [10, 11], as shown in Fig. 2.19.

When the transistors are biased under forward-active mode, as depicted in forward Gummel measurement, base current is mainly composed of three parts: hole current I_{B1} injected from base to emitter region, recombination current I_{B2} near the interface and space charge region, and the neutral base recombination current I_{B3} . For modern SiGe HBT, I_{B1} plays a major role in the base current before radiation. It

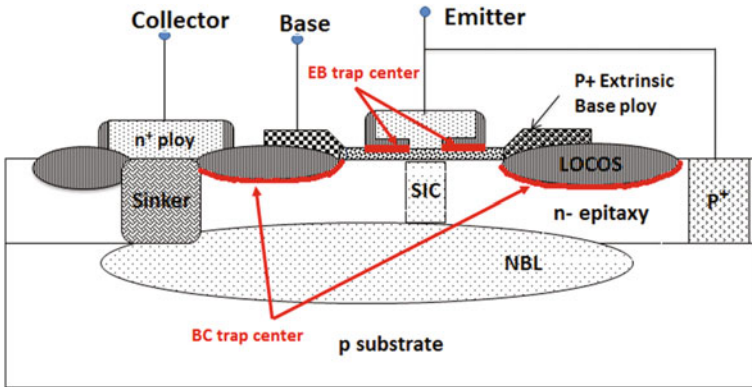


Fig. 2.19 Sensitive region of bipolar transistor for ^{60}Co radiation distribution

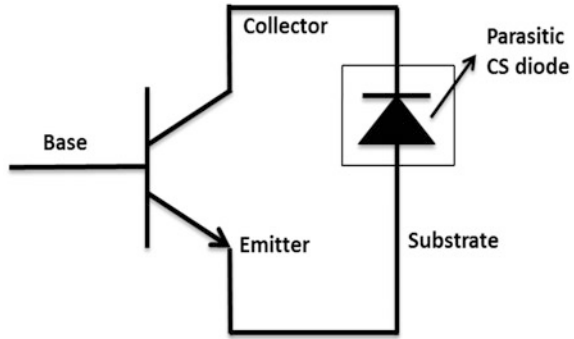
is the increment in I_{B2} that leads to the base degradation after γ -ray irradiation. The irradiation-induced trapped charges and interface states at SiO_2/Si interface near EB junction act as recombination centers, resulting in the significant increase in base current [12–14], as shown in Figs. 2.4 and 2.12. As for NPN bipolar transistor, the positive oxide trap charge in the SiO_2 produces a downward positive electric field; as a result, the depletion layer of EB junction extends toward the low-doped p-type base region and increases the depletion layer area. Besides, the surface electric field reduces hole concentration near p-type base surface and then decreases the concentration difference between the hole and electron near the base surface. Based on the Shockley–Read–Hall (SRH) recombination theory, a lower carrier concentration difference will result in a larger base region recombination current.

For a given radiation damage, base current degradation at a low V_{BE} region is more severe than at high V_{BE} region. It means that the radiation damage at low V_{BE} region is significantly pronounced. Ignoring the neutral base recombination current, the base current includes two parts: the hole reverse-injection current from base to emitter and the surface recombination current. At high V_{BE} region, the base current is dominated by hole reverse-injection current and the ideality factor is 1. At low V_{BE} region, the surface recombination current dominates and the ideality factor is 2. The ionization damages in the spacer oxide near EB junction increase the base surface recombination current and have less influence on the hole reverse-injection current. Therefore, in the semi-logarithmic coordinate system, the surface recombination current is more obvious under the low V_{BE} region and increases with irradiation dose increasing, while it is hidden by the hole reverse-injection current at high V_{BE} region [15]. It should be noted that the carrier concentration injected from emitter to base depends on the bias conditions, base doping concentration, the Ge composition in base, and so on. Under a given V_{BE} voltage, the increase in surface recombination current only increases the base current and emitter current, while the collector current cannot be reduced. However, if the electrons injected into the base region are recombined in the neutral base region and cannot reach the collector region, the collector current will decrease.

The sub-linear variation of $\Delta (1/\beta)$ with radiation dose in Figs. 2.6 and 2.14 is the result of interaction between the oxide trap charge and the interfacial state [15]. The generation of interface states is related to the radiation dose and time, and only after high enough dose, the interfacial states can be created. However, the formation time for the oxide-trapped charge is relatively short, usually earlier than the interface states. The electric field induced by the oxide trap charge will prevent the subsequent formation of interface states. However, once the interface states are formed, the generated electric field will hinder the further increase in the oxide trap charge. It is due to the mutual inhibition between interface states and oxide-trapped charges that the degradation of current gain gradually decreases with the radiation dose increasing, in a form of sub-linear trend.

Similar to the case of spacer oxide near EB junction in forward-active mode, ionization irradiation damages also appear around LOCOS edge near BC junction during the gamma ray irradiation, resulting in a base current degradation in the

Fig. 2.20 Equivalent circuit of the SiGe HBT1 with parasitic CS diode



reverse-active mode [2–4, 16, 17]. However, due to the special device structure, the base current degradation here shows a different degradation result.

As for SiGe HBT1, unlike the previous studies, an unexpected increase in emitter current appears after irradiation. The emitter and substrate are connected together in this case, and the equivalent circuit of the SiGe HBT is shown in Fig. 2.20. The parasitic collector-substrate (CS) diode contributes to the observed non-ideal excess emitter current. During the reverse Gummel test, the collector terminal is connected to the ground and the substrate (emitter) is connected to the high potential. Under this case, the parasitic CS diode becomes forward biased and two current components contributed to the forward current of this CS diode: One is hole injection current from substrate to n-epitaxy and NBL layer (collector), and the other is electron injection current from n-epitaxy and NBL layer to substrate. The forward CS diode current contributes to the excess emitter current [2–4, 16, 17]. The forward current of this CS diode may exceed the intrinsic emitter current and dominate the emitter current in the reverse Gummel plots. The increased emitter current ideality factor at low voltage bias regime ($V_{BC} = 0.4$ V) demonstrates that non-ideal recombination current appears after irradiation, and much ionization damages are created in the spacer charge of CS junction. Therefore, the recombination current in CS junction is increased due to the irradiation-induced G/R centers. However, for the forward Gummel test, the emitter (substrate) terminal is connected to the ground and the collector is connected to the high potential. Hence, the parasitic CS diode is reversed biased. Compared to the collector current of intrinsic SiGe HBT in the forward-active mode, the reverse leakage current of CS diode is negligible. As a result, the effect of parasitic CS diode cannot be observed in the forward-model Gummel plot.

As shown in Fig. 2.15, the reverse Gummel characteristics for SiGe HBT2 are not influenced by gamma irradiation, which is due to the special device structure [18]. Figure 2.21 shows the distribution of forward base current and reverse base current in SiGe HBT2. The forward base current flows in parallel with the BE junction, but the reverse base current flows across the BC junction down to the backside collector contact through the collector region. That is to say, the forward base current flow is confined to the thickness of base region, while the reverse base

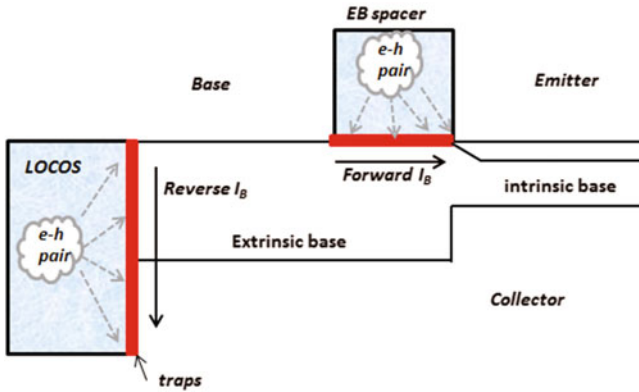


Fig. 2.21 Paths of forward and reverse base current in SiGe HBT2. The forward I_B flows along the base surface and in parallel with BE junction, whereas the reverse I_B flows across BC junction down to the backward collector contact

current flow is distributed over the width of base region. Since the base width is generally much larger than the base thickness, as a result, in contrast to much more chance for carrier recombination happening at the EB spacer oxide/Si interface in the forward mode, a much smaller fraction of the base current flow in the reverse mode will pass through the isolation oxide/Si interface. Therefore, no detectable excess recombination current is found to contribute to the I_B curve in the reverse Gummel plot.

From Fig. 2.22, one can clearly distinguish the degradation of base current measured in forward mode at $V_{BE} = 0.6$ V and reverse mode at $V_{BC} = 0.6$ V. The post-irradiation I_B in two modes exhibits an obvious increase as a function of the equivalent gamma dose. Due to the larger LOCOS area around collector epitaxy

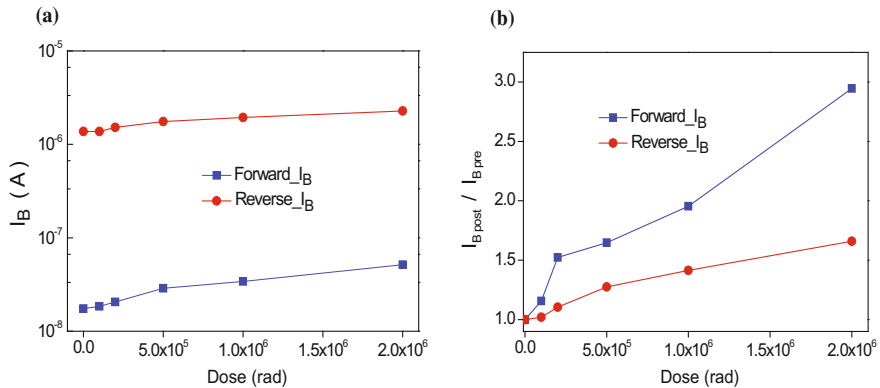


Fig. 2.22 Variation of **a** base current and **b** normalized base current of SiGe HBT1

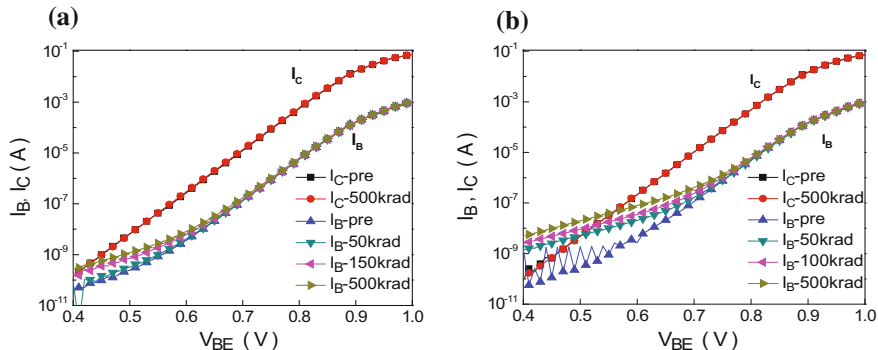


Fig. 2.23 Forward Gummel characteristics of SiGe HBT irradiated by two dose rates: **a** 50 rad/s; **b** 0.1 rad/s

layer, the base current in reverse mode is larger than that in forward mode, as shown in Fig. 2.22a. The normalized base current, defined as $I_{B\text{post}}/I_{B\text{pre}}$, is depicted in Fig. 2.22b. Compared to the base current in reverse mode, the base current in forward mode is found to be more sensitive to gamma irradiation, which might be due to the following two factors. The first one is the different components of EB spacer oxide and LOCOS oxide. Generally, the EB spacer oxide is the oxide/nitride through the deposition process, whereas the LOCOS oxide is silicon dioxide (SiO_2) through the thermal oxidation process. Compared to the former, the quality of LOCOS oxide might be relatively well and is immune to gamma irradiation. The second one is the different current directions. The base current in reverse mode flows across the BC junction and is distributed over the width of base region, while that in forward mode flows in parallel with BE junction and is confined to the thickness of base region. As a consequence, there is much more chance for carrier recombination around EB spacer oxide, and a much smaller fraction of base current will pass through the LOCOS interface in the reverse mode. Therefore, the base current in forward mode is more sensitive to gamma irradiation.

2.4 Ionization Damage in SiGe HBT at Different Dose Rate

In general, the irradiation dose rate in real space environments is very low (about 10^{-4} – 10^{-2} rad/s). Under such low-dose rate, some bipolar devices (e.g., Si BJT) exhibit significant enhanced low-dose-rate sensitivity (ELDRS) [19, 20]. However, less data are available about the ELDRS effect in SiGe HBT, and the unified understanding of the physical mechanism is not achieved [21, 22]. Besides, ELDRS effect in bipolar devices is closely related to the device structure, manufacturing process, etc. Therefore, it is necessary to carry out a series of radiation experiments

on SiGe HBT. In this study, SiGe HBT1 was irradiated at high-dose rate (50 rad/s) and low-dose rate (0.1 rad/s). The accumulated doses are 50, 100, 170, 300, and 500 krad, respectively. During the whole irradiation process, the transistor is biased at forward-active mode with $V_{CE} = 2$ V, $I_C = 5$ mA. For high-dose-rate irradiated samples, room temperature annealing was performed at the same bias conditions when the total dose reached 500 krad. The annealing time equals the low-dose-rate irradiation time.

2.4.1 Results of Ionization Damage at Different Dose Rate

The forward Gummel characteristics for high-dose-rate and low-dose-rate irradiation are shown in Fig. 2.23. The base currents all increase monotonically with accumulated total dose, especially in low V_{BE} region, while collector current remains unchanged during the whole irradiation; thereby, a remarkable drop appears in the current gain.

In order to quantitatively compare the influence of dose rates on performance degradation, two electrical parameters, excess base current ΔI_B ($\Delta I_B = I_{B,post} - I_{B,pre}$) and normalized current gain β_{nor} ($\beta_{nor} = \beta_{post}/\beta_{pre}$), are calculated at $V_{BE} = 0.6$ V, where $I_{B,pre}$, β_{pre} , $I_{B,post}$, and β_{post} are base currents and current gains before and after irradiation, respectively. Figure 2.24 depicts ΔI_B at V_{BE} of 0.6 and 0.7 V after high- and low-dose-rate irradiation, and the room temperature annealing for high-dose-rate irradiation is also performed. It is indicated that a larger ΔI_B appears under low-dose-rate irradiation, demonstrating a more ionizing damage at low-dose-rate irradiation. During the subsequent room temperature annealing, the base current for high-dose-rate irradiation first decreased in the initial 25 h and then increased, and its final stable value is still lower than that for low-dose-rate irradiation.

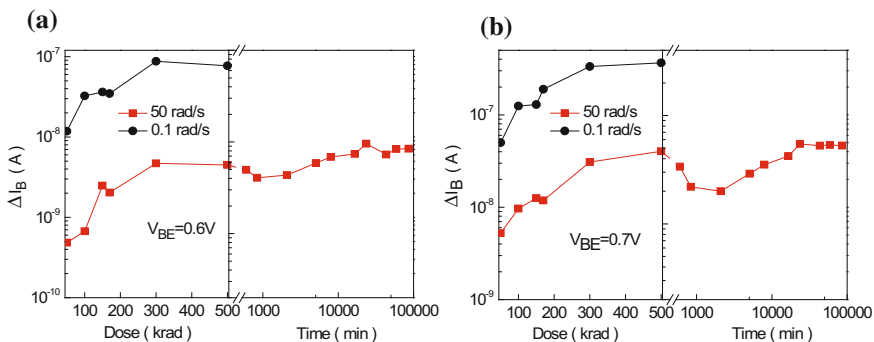


Fig. 2.24 Variation of excess base current ΔI_B after high- and low-dose-rate irradiation at **a** $V_{BE} = 0.6$ V; **b** $V_{BE} = 0.7$ V

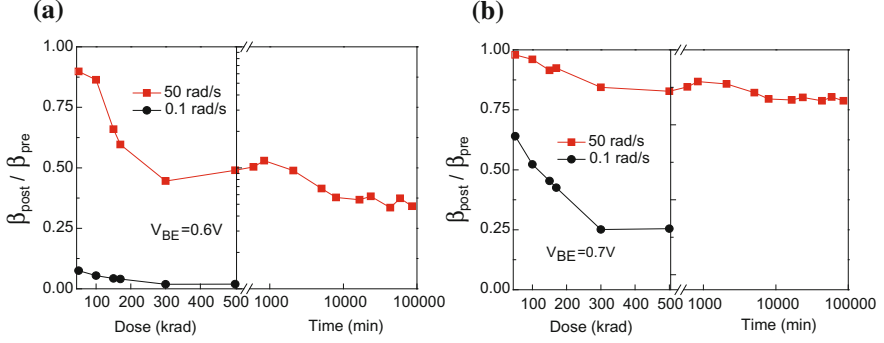


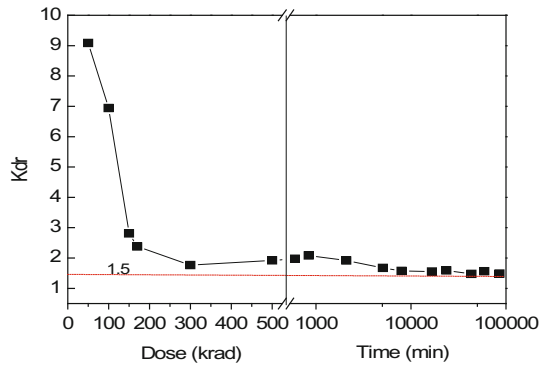
Fig. 2.25 Variation of normalized current gain β_{nor} after high- and low-dose-rate irradiation at **a** $V_{\text{BE}} = 0.6 \text{ V}$; **b** $V_{\text{BE}} = 0.7 \text{ V}$

Consistent with the excess base current, β_{nor} declines with the accumulation dose increasing and the current gains at low-dose-rate irradiation are smaller than those at high-dose-rate irradiation, as shown in Fig. 2.25. The base current for high-dose-rate irradiation first increases in the initial 25 h and then decreases in subsequent room temperature annealing process; however, it cannot rebound to the level of low-dose-rate irradiation even after a long-term annealing, which indicates that the radiation damage at low-dose rate cannot be estimated by high-dose-rate irradiation followed by a room temperature annealing, i.e., a “true” dose rate effect exists in SiGe HBTs.

In order to characterize the effect of dose rate on current gain degradation, an over-enhanced factor (K_{dr}) is introduced and defined as

$$K_{\text{dr}} = (\beta_{\text{pre}} - \beta_{\text{post}})_{\text{low}} / (\beta_{\text{pre}} - \beta_{\text{post}})_{\text{high}} \quad (2.7)$$

Fig. 2.26 Variation of ratio K_{dr} under $V_{\text{BE}} = 0.6 \text{ V}$ as a function of radiation dose and annealing time



where the subscripts “high” and “low” denote the high- and low-dose-rate radiation, respectively. According to MIL-STD-883G [23], if the ratio K_{dr} exceeds 1.5 for any of the most sensitive parameters, then the part is considered to be ELDRS susceptible, and the larger the K_{dr} , the stronger the ELDRS effect. Figure 2.26 shows the over-enhanced factor K_{dr} under $V_{BE} = 0.6$ V as a function of gamma dose and annealing time. It can be seen that K_{dr} is still greater than 1.5 after room temperature annealing, which means that SiGe HBT has a real ELDRS effect rather than a time-cumulative effect of radiation damage.

2.4.2 Mechanism of Enhanced Low-Dose-Rate Sensitivity

In bipolar transistor manufacturing process, some defects containing H atoms, such as the non-bridging oxygen defect S_{OH} , are inevitably introduced in SiO_2 layer [24]. These defects have a great influence on the ionization damages in SiGe HBT under low-dose-rate radiation. Assuming that the radiation dose rate is g , then the generation rate of electron-hole pairs in the per unit volume of SiO_2 is γg , where γ is a constant (for SiO_2 , $\gamma = 8.1 \times 10^{12} \text{ cm}^{-3} \text{ rad}^{-1}$) [25]. The electrons drift out of the oxide layer quickly, but the holes only slowly move toward the SiO_2/Si interface. When a part of hole moves to the vicinity of the non-bridging oxygen defect S_{OH} in SiO_2 layer, they can release the neutral H atom, as shown in the following equation [24]



where p is the generated hole. Assuming that the concentration of S_{OH} in SiO_2 layer is large enough, then the release rate of the neutral H atom is $x\gamma g$, where x is the percentage of holes involved in the reaction (2.8). Due to the lower activation energy, H atom can capture another H atom, forming a H_2 molecule



The reaction rate constant of (2.9) is assumed as k_{HH} . Then, under the steady conditions, H atom concentration C_H satisfies [24]

$$x\gamma g - k_{HH}C_H^2 - r_H C_H = 0 \quad (2.10)$$

where the first term is the release rate of the neutral H atom, the second term is the consumption in (2.9), and the third term is the lost part captured by the other trap. Then, we can obtain

$$C_H = r_H \left(\sqrt{1 + \frac{4x\gamma g k_{HH}}{r_H^2}} - 1 \right) / 2k_{HH} \quad (2.11)$$

Part of neutral H atom can capture hole and releases protons



Assuming that the ratio of H atoms in the reaction (2.12) is α , then the proton concentration C_{H^+} satisfies $C_{\text{H}^+} = \alpha C_{\text{H}}$. Once the protons arrive at SiO_2/Si interface, they will combine the interface dangling bond Si-H and create the interface state [26], as shown in the following equation:



Si-H dangling bond is generally formed in the device passivation process. P_{b}^+ is the interface state. The forward reaction rate constant of (2.13) is assumed as k_{f} , and then, the concentration of P_{b}^+ can be written as [24]

$$\frac{dC_{\text{P}_{\text{b}}^+}}{dt} = k_{\text{f}} C_{\text{Si-H}} C_{\text{H}^+} \quad (2.14)$$

where $C_{\text{P}_{\text{b}}^+}$, $C_{\text{Si-H}}$ and C_{H^+} are separately the concentration of interface state P_{b}^+ , Si-H dangling bond, and proton H^+ . Assuming that the concentration of Si-H dangling bond at SiO_2/Si interface is sufficiently large, then we will arrive at

$$C_{\text{P}_{\text{b}}^+}(t) = \frac{\alpha r_{\text{H}} C_{\text{Si-H}} k_{\text{f}}}{2k_{\text{HH}}} \left(\sqrt{1 + \frac{4x\gamma g k_{\text{HH}}}{r_{\text{H}}^2}} - 1 \right) t \quad (2.15)$$

where $C_{\text{P}_{\text{b}}^+}(t)$ is the concentration of P_{b}^+ at any time t . When the dose rate is high enough ($\frac{4x\gamma g k_{\text{HH}}}{r_{\text{H}}^2} \gg 1$ generally exists), (2.15) can be simplified as

$$C_{\text{P}_{\text{b}}^+}(D) = \alpha k_{\text{f}} C_{\text{Si-H}} D \sqrt{\frac{x\gamma}{g k_{\text{HH}}}} \quad (2.16)$$

where $D = gt$ is the accumulated total dose level, $C_{\text{P}_{\text{b}}^+}(D)$ is the concentration of P_{b}^+ at any dose level D . It can be seen that $C_{\text{P}_{\text{b}}^+}(D)$ increases with the radiation dose rate decreasing, and the lower the dose rate, the higher the $C_{\text{P}_{\text{b}}^+}(D)$ under the same total dose level. When the dose rate decreases to the level that satisfies $\frac{4x\gamma g k_{\text{HH}}}{r_{\text{H}}^2} \ll 1$, then Eq. (2.15) can be reduced to

$$C_{\text{P}_{\text{b}}^+}(D) = \alpha k_{\text{f}} C_{\text{Si-H}} x\gamma D / r_{\text{H}} \quad (2.17)$$

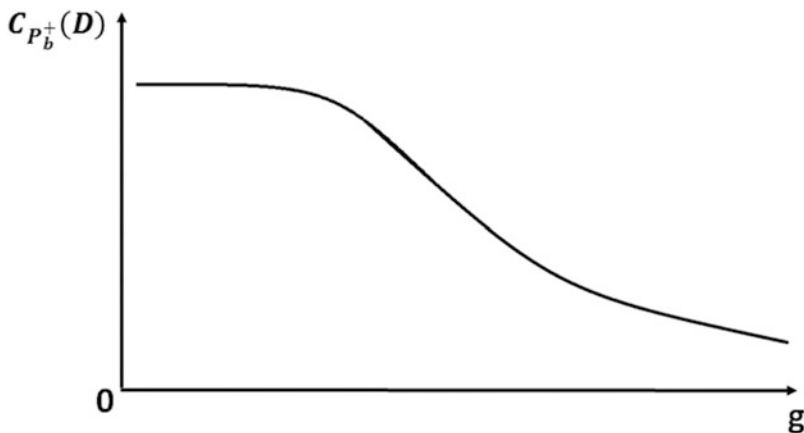


Fig. 2.27 Variation of interface states concentration as a function of dose rate

It can be seen that the concentration of interface state P_b^+ is a constant value and independent of the radiation dose rate. As the dose rate decreases gradually from high level to low level, the interface state concentration increases, and the radiation damages and performance degradation increase. When the dose rate reduces to a certain extent, the concentration of interface states reaches a constant value, as shown in Fig. 2.27 [27]. The above analysis is a good explanation of ELDRS effect in SiGe HBTs.

As for the physical mechanism, during the high-dose-rate irradiation, a large number of H atoms are produced with high generation rate. Most of the H atoms combined with each other to form H_2 molecules in a short time. Only a few H atoms can move to the SiO_2/Si interface creating the interface states. The generated H_2 molecules, with a lower diffusion barrier in SiO_2 film [24], can quickly spread to the SiO_2/Si interface and re-passivate the Si–H dangling bond, decreasing the concentration of interface states. However, in the case of low-dose-rate radiation, it is difficult for H atoms to interact with other H atoms to form H_2 molecules due to the low radiation generation rate. On the contrary, most of the H atoms will capture holes to release H^+ and then create the interface states at the SiO_2/Si interface, leading to serious radiation damage and performance degradation.

As shown in Fig. 2.24, the excess base current ΔI_B under high-dose-rate radiation first decreases and then increases in the subsequent annealing process. It may be due to the different annealing properties of oxide trap charge and interface state. Because of the low activation energy, the oxide trap charge can release the captured hole at room temperature, but the interface state only anneals at above 100 °C due to the high binding energy [15]. Besides, the generation of interface state is related to the total dose and radiation time. Compared to the oxide trap charge, the interface state can only be formed at a certain high total dose level and a relatively long

radiation time. The radiation-induced holes and H^+ transport to the SiO_2/Si interface in the subsequent annealing process and react with the $Si-H$ bond to produce more interface states. This epigenetic effect of interface state and the annealing effect of oxide trap charge together determine the base current annealing characteristics as shown in Fig. 2.23. The decrease in ΔI_B during the initial annealing period may be caused by the annealing of oxide trap charge, and the subsequent formation of more interfacial states results in the increase in ΔI_B .

2.5 Bias Dependence of Ionization Damage in SiGe HBT

In practical applications, SiGe HBTs usually operate at different bias conditions. In current mirror and emitter follower, SiGe HBTs usually work in forward-active mode, and in certain RF circuit, the transistors are biased in saturation mode, while in some BiCMOS logic circuit, SiGe HBTs often operate in the cutoff state. In order to evaluate the total ionizing dose effect of SiGe HBT in practical circuit, it is necessary to study the ionization damage effect in SiGe HBT under different bias conditions. In this section, SiGe HBT1 is irradiated at high-dose rate of 50 rad/s and low-dose rate of 0.1 rad/s, separately. Three different bias conditions are selected: (1) all terminals are floating, (2) saturation mode ($V_{CE} = 0.4$ V, $I_C = 5$ mA), (3) forward-active mode ($V_{CE} = 2$ V, $I_C = 5$ mA), radiation dose rates of 50 and 0.1 rad/s. The effects of bias conditions on the ionization damage of SiGe HBT at high- and low-dose-rate radiation are presented.

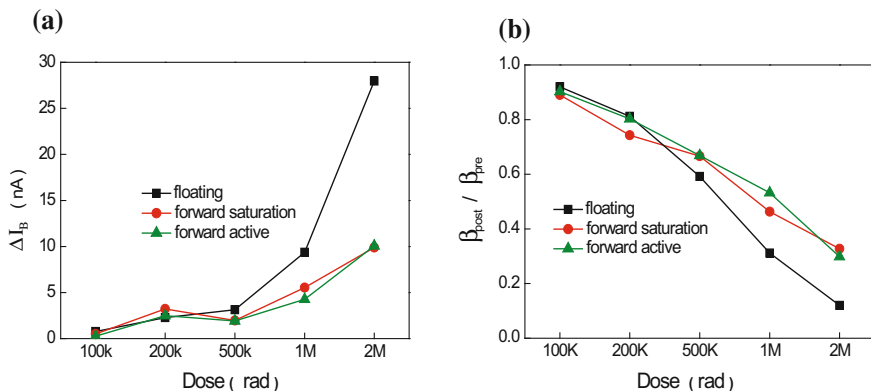


Fig. 2.28 Excess base current **a** and normalized current gain **b** for high-dose-rate irradiation as a function of accumulated doses at V_{BE} of 0.6 V for the three bias conditions

2.5.1 Irradiation Under High-Dose Rate

Figure 2.28 shows the excess base current ΔI_B and normalized current gain β_{nor} as a function of accumulated doses for the three bias conditions at V_{BE} of 0.6 V. The dose rate is 50 rad/s. It can be seen that the degradation is closely related to the bias conditions. For the accumulated doses below 200 krad, ΔI_B and β_{nor} for the three bias conditions are similar. However, with the doses increasing from 500 krad to 2 Mrad, the difference between the three bias conditions begins to appear and increases monotonously as the total doses go up. Compared to the forward-saturation and forward-active configurations, the case with all terminals floating shows a largest degradation in base current and current gain, especially at the dose of 2 Mrad. Therefore, the floating case can be considered as the worse bias condition from the radiation assurance viewpoint during the high-dose-rate irradiation

Normally, the spacer oxide layer around the emitter-base (EB) junction is well known to play an important role in the performance degradation of modern SiGe HBTs under gamma irradiation. In order to better investigate the effect of electrical field on gamma irradiation, a 2D simulation of electrical field was performed using TCAD Sentaurus. The 2D device structure of the SiGe HBT was first constructed using Sentaurus process simulation and then used to the Sentaurus device simulation. The physics models used in the device simulation are doping-dependent SRH recombination, Auger recombination, velocity saturation, phillips unified mobility model, and band gap narrowing, respectively. The fixed charges in the EB spacer oxide layer were set to $1\text{--}15\text{ cm}^{-3}$. The simulated bias conditions are same as these during the irradiation process. Part of simulation structure including the EB spacer oxide layer is shown in Fig. 2.29a, and the electrical field distribution along the cutline A (as shown in Fig. 2.29a) is depicted in Fig. 2.29b. Note that this electrical field directs from the SiO_2 to Si region as shown in Fig. 2.29b. Compared to the forward-active and forward-saturation mode where EB junction is forward

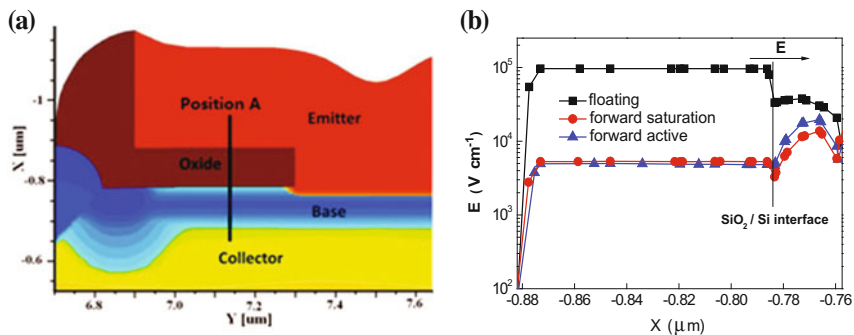


Fig. 2.29 **a** Simulation structure of extrinsic SiGe HBT including EB spacer oxide layer; **b** the electric field distribution near the SiO_2/Si interface for two different bias conditions

biased, for the floating case a larger electrical field exists in the oxide and the silicon underneath the SiO_2/Si interface.

The electrical field distribution can be explained in terms of fringing field approach. The fringing electric field in spacer oxide originates from the built-in potential of EB junction for the floating case, and it decreases under forward-active and forward-saturation mode due to the forward bias of BE junction. The bias voltage of BC junction has little influence on the BE junction, and therefore, the electrical field distribution under forward-active mode is similar to that under forward-saturation mode.

As discussed above, some fraction of the generated electron-hole pairs in SiO_2 film will recombine within a very short time and the remains will transport within the oxide. The concentration of the remaining hole strongly depends on the electric field in the oxide and increases with the electric field increasing. The bias dependence of the ionizing radiation at high-dose rate can be explained by the trapping and transport of the created holes in EB spacer oxide. As the electric field in the oxide increases, hole fractional yield will rise up and more holes and protons become available for acceleration toward the interface in the existing fields, creating more positive oxide-trapped charges and interface states in the EB oxide layer. In other words, the bias condition causing a larger electrical field distribution in the oxide layer might result in enhanced degradation, when more radiation-induced holes and protons are available to transport to SiO_2/Si interface and produce the irradiation damage. Based on the above 2D electric field simulations in Fig. 2.29b, the forward-active and forward-saturation case weakens the electric field in the EB spacer oxide, resulting in a less degradation compared to the floating case.

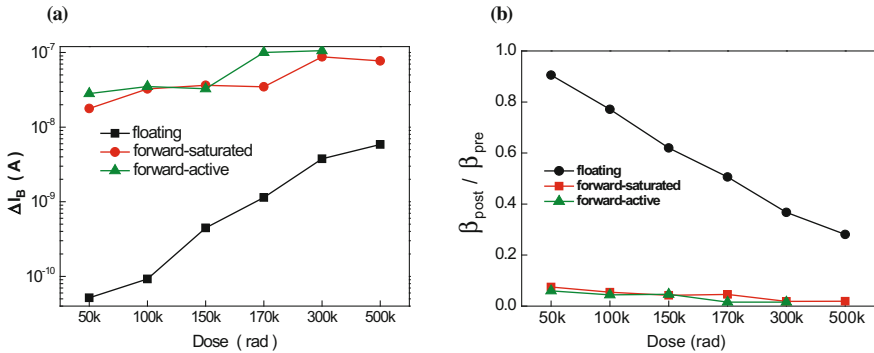


Fig. 2.30 Excess base current **a** and normalized current gain **b** for low-dose-rate irradiation as a function of accumulated dose at V_{BE} of 0.6 V for the three bias conditions

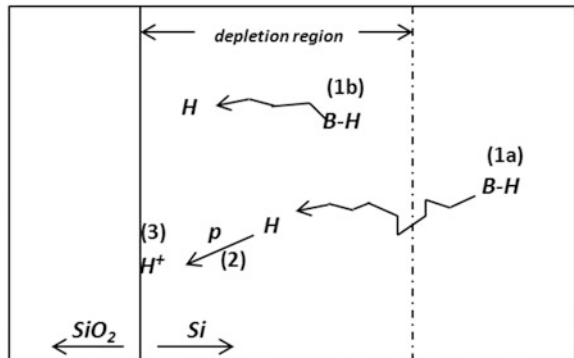
2.5.2 Irradiation Under High-Dose Rate

The bias influences on performance degradation at low-dose-rate irradiation (0.1 rad/s) were also investigated. The excess base currents and normalized current gains at V_{BE} of 0.6 V for low-dose-rate irradiation are shown in Fig. 2.30. There is no significant difference in the performance degradation between the forward-active and forward-saturation mode. Compared to the floating case, however, the forward-active and forward-saturation cases suffer more degradation in base current and current gain at the low-dose-rate irradiation, which contrasts with the degradation at the high-dose-rate irradiation, where larger irradiation damage appears in floating case. Even at the low dose of 50 krad, there exists a large difference in current gain degradation between the both bias conditions, while the difference only begins to appear for the doses larger than 500 krad during the high-dose-rate irradiation. The large degradation gap between the floating and forward-active mode at low-dose-rate irradiation may be due to the enhanced low-dose-rate sensitivity (ELDRS) effect.

Based on the above results, it is indicated that the bias dependence on irradiation damage at low-dose-rate irradiation varies greatly from that at high-dose-rate irradiation. As discussed above, the trapping and transport of the created holes and H^+ in EB spacer oxide layer are responsible for the bias dependence at high-dose-rate irradiation. However, it cannot well explain the bias dependence at low-dose-rate irradiation. These results suggest that other mechanisms in addition to hole and H^+ transport within the SiO_2 can lead to radiation-induced interface-trap formation and the different bias dependence from the high-dose-rate irradiation.

Previous study demonstrated that neutral hydrogen H atoms could be released easily from dopants in bulk Si, especially near SiO_2/Si interfacial area as shown in Fig. 2.31 [20]. The typical hydrogen precursors in Si are identified as hydrogen-dopant complexes. The most stable configuration in the boron-doped silicon corresponds to H resting in the bridge bond between dopant boron (B) atom and a neighboring Si atom [24]. The extrinsic base region is formed through heavy dose implant self-aligned to the emitter-poly for the SiGe HBT under test, and there

Fig. 2.31 Interface states formation origin from the extrinsic base region: (1a)–(1b) release of H from B–H complexes, (2) release of H^+ due to the capture of holes, and (3) formation of interface states [20]



might be many B–H complexes in the extrinsic base region. The binding energy of B–H bond is about 0.61 eV, and the B–H complex can capture a minority carrier (where it is electron) and release H when minority carriers are introduced in the extrinsic base region under the EB spacer oxide



where e denotes an electron. The released H is a highly mobile species in silicon due to very small diffusion barrier of about 0.1–0.2 eV. If H captures another hole, as happening during irradiation, it will release a proton H^+ . The released H^+ moves to the SiO_2/Si interface and react with the interfacial passivated Si–H bond to create the interface states.

For the high-dose-rate irradiation, the duration is relatively short and the electrical field hampers the transport of hole and proton in extrinsic base to the SiO_2/Si interface. Therefore, there is not enough time for the hole and proton in extrinsic base to reach the interface. The bias dependences at high-dose rate are only determined by the transport of hole and H^+ in SiO_2 region. As discussed above, the floating mode with a large electrical field distribution in the SiO_2 region is expected to cause a serious degradation in SiGe HBT. However, the irradiation time is very long during the low-dose-rate irradiation. Most of the hole and proton in extrinsic base can transport to the SiO_2/Si interface and create the interface states. Besides, the concentration of hole and proton in extrinsic base is much larger than that in the SiO_2 region [25]. Therefore, the formation of interface states in low-dose-rate irradiation might be determined by the transport of the hole and H^+ in extrinsic base. As shown in Fig. 2.29b, the electrical field hampers the transport of hole in extrinsic base to the SiO_2/Si interface. The lower the electrical field in extrinsic base, the more the holes and H^+ transporting to SiO_2/Si interface. Compared to the case with all terminals floating, the forward-active configuration may suffer more radiation damage due to the smaller electrical field in extrinsic base, and only the trapping and transport of holes and H^+ in EB spacer oxide are responsible for the bias dependence at high-dose-rate irradiation, which is reasonable due to the short time at high-dose-rate irradiation. However, during the low-dose-rate irradiation, the contribution of holes and proton in extrinsic base should be included, especially when there are abundant B–H complexes in the extrinsic base region, since the hole and proton in the extrinsic base may reach the SiO_2/Si interface during such a long irradiation time, which is not paid attention to in pervious researches. Of course, the underlying detail of physical mechanisms needs to be further justified and explored.

According to MIL-STD-883G, if the ratio K_{dr} exceeds 1.5 for any of the most sensitive parameters, then the part is considered to be ELDRS susceptible, and the larger the K_{dr} , the stronger the ELDRS effect. Figure 2.32 shows the over-enhanced factor K_{dr} for the two bias configurations as a function of gamma dose. As shown in Fig. 2.32, the over-enhanced factor K_{dr} for forward-active mode is significantly larger than that for the floating case, especially at the doses below 170 krad(Si). The transistors under forward-active mode exhibit a significant ELDRS effect; however, no distinct ELDRS effect appears in the transistors with all terminals floating.

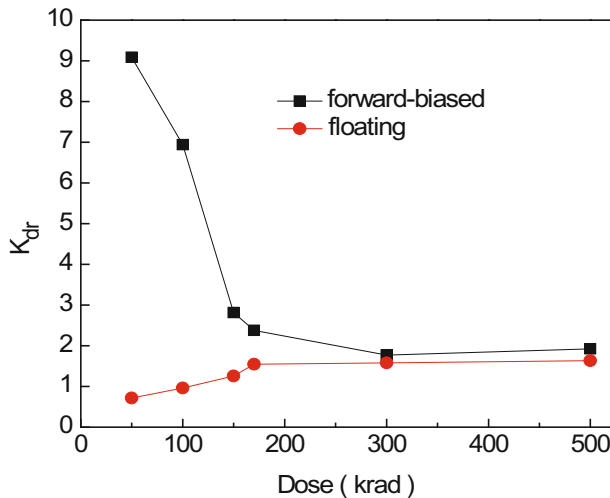


Fig. 2.32 Over-enhanced factor K_{dr} for the two bias conditions

Besides, it is found that the enhanced factor K_{dr} decreases, i.e., the ELDRS effect declines with the accumulated dose increasing for the SiGe HBTs under forward-active mode. For example, the enhanced factor K_{dr} is about 11.23 for an accumulated dose of 50 krad(Si), while it is only about 1.78 when the accumulated dose reaches 500 krad(Si).

As the positive oxide-trapped charges and interface traps build up in the oxide layer, two crucial time parameters exist. One is the characteristic time (τ_g) required to build up the space field in the oxide, and the other is the characteristic time (τ_h) required for holes and H^+ transport across the oxide. Carefully observing the result in Fig. 2.32, we find that the forward-active mode has a more serious ELDRS effect than that of the floating case, which can be explained from the viewpoint of τ_h decreasing in the floating case. Compared to the forward-active mode, SiGe HBTs with terminals floating have a larger fringe field across the BE spacer oxide; furthermore, the larger fringe field could accelerate the holes transport to Si/SiO₂ interface and reduce the characteristic time τ_h . For the high-dose-rate irradiation, a decreased τ_h will reduce the density of holes trapped in oxide bulk and then weaken the space electric field; as a result, the impediment of space electric field to the holes transport declines and more irradiation damages appear at the Si/SiO₂ interface. However, during the low-dose-rate irradiation, due to the small value of τ_h , the further decrease in τ_h has almost no influence on the buildup of space electric field in oxide bulk, and the irradiation damage remains nearly unchanged. Therefore, a larger fringe field will reduce the gap of irradiation damage between high-dose-rate and low-dose-rate irradiation, i.e., alleviating the ELDRS effect. The fringe field in floating SiGe HBTs is relatively larger than that in the forward-active mode; therefore, the transistors with all terminals floating will experience a smaller

ELDRS effect compared to those biased in forward-active mode [28], as shown in Fig. 2.32.

ELDRS effect in the forward-active mode weakens monotonously with the accumulated total dose increasing, and it saturates for total dose larger than 300 krad(Si), which might be attributed to the increased impediment of space field to the transport of hole and H^+ to the interface in the low-dose-rate irradiation. The space field EQ gradually increases with the accumulated total dose increasing during the low-dose-rate irradiation. The increased space field EQ hinders the further transport of holes and H^+ to the interface and slows the accumulation of interface traps. Besides, the increased space field EQ weakens the total electric field within the oxide layer and then decreases the hole fractional yield, which will also slow the accumulation of interface traps near the Si/SiO₂ interface. Therefore, with increasing accumulated dose, the degradation of base current is mitigated in the low-dose-rate irradiation, thereby resulting in a decreased ELDRS effect as shown in Fig. 2.32.

2.6 Conclusion

In this chapter, we mainly study the ionization damage effects in SiGe HBTs and analyze the corresponding physical mechanism. The results show that SiGe HBT naturally has multi-Mrad total ionizing dose (TID) tolerance, due to the special device structure. The performance degradation closely depends on the device structure. For SiGe HBTs with emitter and substrate connected together, an unexpected increase in emitter current appears in the reverse Gummel characteristic. For the transistors with collector elicited from the backside of the substrate through gold evaporation, the reverse Gummel characteristic is almost kept unchanged. Therefore, in order to improve the device's anti-radiation performance, the emitter and substrate should not be shorted.

Then, we study the effects of radiation dose rate on ionization damages from the point of the actual space radiation environment and find ELDRS effect. Besides, the effects of bias conditions are also compared. The floating configuration shows an enhanced degradation in the high-dose-rate irradiation, while the forward-active mode suffered more irradiation damage in the low-dose-rate irradiation. ELDRS effect is also bias dependent, and the transistors under forward-active mode exhibit a more severe ELDRS effect than those with all terminals floating. Therefore, the influence of dose rate and bias condition on ionization damages should be considered when evaluating the transistor anti-radiation capability.

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