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Experimental Investigation of the Effects of Reactor Neutron-Gamma Pulse Irradiation on SiGe HBTs Under Different Bias Conditions

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ABSTRACT The degradation characteristics of silicon-germanium heterojunction bipolar transistors (SiGe HBTs) under different bias modes (forward, cutoff and saturation) during irradiation were reported after multiple pulsed neutron-gamma irradiation at room temperature. The radiation-sensitive parameters of the test samples, including base current I_B, collector current I_C and DC current gain β, were measured and compared before and after every reactor n-γ pulse irradiation. The test results show that I_B increased with increasing fluence, and I_C slightly increased in the low base-emitter voltage V_{BE} region (approximately from 0.4 V to 0.5 V) and decreased in the high-V_{BE} region (approximately $V_{BE} > 0.5$ V). Moreover, the degradation degree of the test samples was different under different bias conditions. The performance of the test samples under cutoff bias mode displayed the most serious degradation, while those under forward bias mode suffered minimum damage. Meanwhile, the time-dependent annealing characteristics of the DC current gain for SiGe HBTs at various bias conditions were compared and analyzed.

INDEX TERMS Silicon germanium, heterojunction bipolar transistors, neutron radiation effects, annealing.

I. INTRODUCTION

Over the past decades, the device performance of silicon germanium heterojunction bipolar transistors (SiGe HBTs) has been significantly improved to satisfy the growing need for microelectronic fields [1], [2]. Compared with Si bipolar junction transistors (BJTs), SiGe HBTs have shown great potential in extreme environments due to their excellent total dose resistance, such as high-energy particle detectors [3], [4], military [5], [6] and space-based applications [7], [8]. Thus, the degradation mechanisms of SiGe HBTs have been studied in various radiation conditions. Total ionizing dose (TID) effects induced by electrons, protons and gamma on Si/SiGe bipolar transistors were investigated in [9]. The studied results indicate that the interface traps in the base-emitter junction and trapped positive charge in the space oxide induced by TID increased the base recombination current and degraded the DC current gain degradation. Meanwhile, the displacement damage defect characteristics in Si BJTs and SiGe HBTs induced by heavy ions [10], [11] and steady neutrons [12]–[15] were reported. These investigations deduced that the minority carrier lifetime of the experimental samples was decreased by the vacancy defects and trapping centers, which were introduced by displacement damage, and the current gain was degraded. However, the pulse neutron irradiation effects on SiGe HBTs were very few. The preliminary degradation characteristics of SiGe HBTs irradiated by reactor pulse neutron and gamma rays are reported in [16], which indicates that the pulse neutron fluence initially creates unstable displacement defects, and additional fluence of neutron generates cluster defects to form more stable configurations. Nevertheless, earlier studies seldom reported the annealing performance of SiGe HBTs after multiple-pulse n-γ irradiation and the bias mode impacts on the SiGe HBT degradation during pulse n-γ irradiation.

In addition, SiGe HBTs in electronic systems can be set in different bias states according to their specific applications. For example, transistors are often forward biased in most high-speed logic circuits. For particular RF applications such as low-noise amplifiers and high-speed switches, the transistors operate in saturation or reverse bias [17]–[19].

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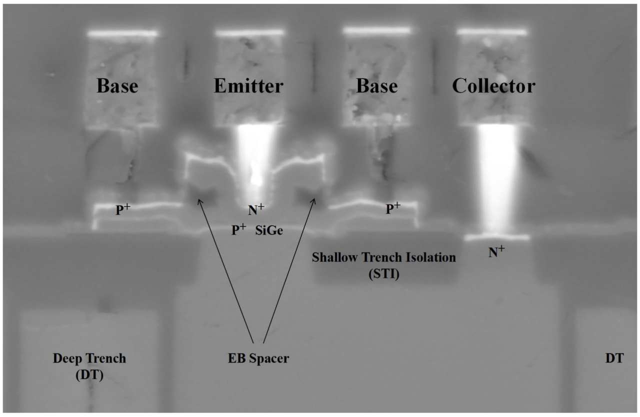


FIGURE 1. Cross section of the SiGe HBT fabricated with 0.2 μ lithographytechnology.

Previous studies [20]–[22] have reported the bias impacts on the performance degradation for SiGe HBTs irradiated by heavy ions, gamma rays and protons. However, the bias effect on the irradiation response of SiGe HBTs induced by pulse n-γ irradiation is unclear.

This work aims to investigate the degradation mechanisms and annealing characteristics of SiGe HBTs under various bias conditions irradiated by reactor pulse n-γ rays. Experimental results of 1 MeV equivalent pulse neutron irradiation on BFU730F SiGe HBTs under three common bias conditions are presented. The reactor pulse n-γ radiation experimental design on SiGe HBTs is introduced in detail in Section II. The test results are presented and discussed in Section III. Section IV provides a summary and the conclusions of this work.

II. EXPERIMENT

A. DEVICES UNDER TEST

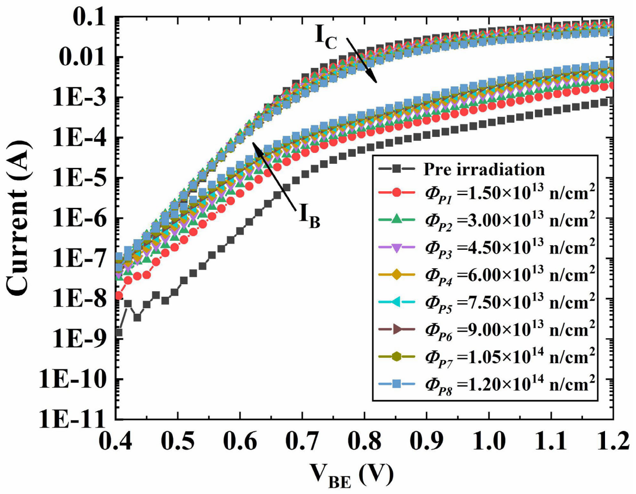
The devices under test (DUTs) are silicon germanium NPN RF transistors (BFU730F) fabricated with 0.25 μm SiGe:C technology from the QUBiC4 process of NXP semiconductors. The cross-sectional view of the test SiGe HBT sample including the key parameters is shown in Fig. 1. The SiGe HBT combines robust nonselective epitaxial growth with a double-poly structure and deep- and shallow-trench isolation for high performance. Due to its high speed and low noise characteristics, BFU730F transistors are widely used in low noise amplifiers, oscillators, Wi-Fi/WLAN, *etc*. Samples were mounted on a circuit evaluation board and placed inside a BC_4/Pb shielding box in the irradiation channel of the Xi'an Pulse Neutron Reactor. Three common operating bias conditions were set during reactor pulse n-γ irradiation (B = base, E = emitter, C = collector): (i) forward bias, $V_{BE} = 1.2$ V, $V_{CE} = 1.5$ V, $V_E = 0$ V; (ii) cutoff bias, $V_{BE} = 0$ V, $V_{CE} = 1$ V, $V_E = 1.2$ V; and (iii) saturation bias, $V_{BE} = 1.2$ V, $V_{CE} = 1$ V, $V_E = 0$ V. To compare samples under different bias conditions, the DC characteristics of all samples were measured before irradiation. The results show good consistency of the test samples. For each bias condition, two samples were measured before and after pulse irradiation. In total, six samples were used for the irradiation experiment. The voltage supply of the DUTs was controlled by a switching matrix and a multi-channel DC voltage source.

B. MEASUREMENT

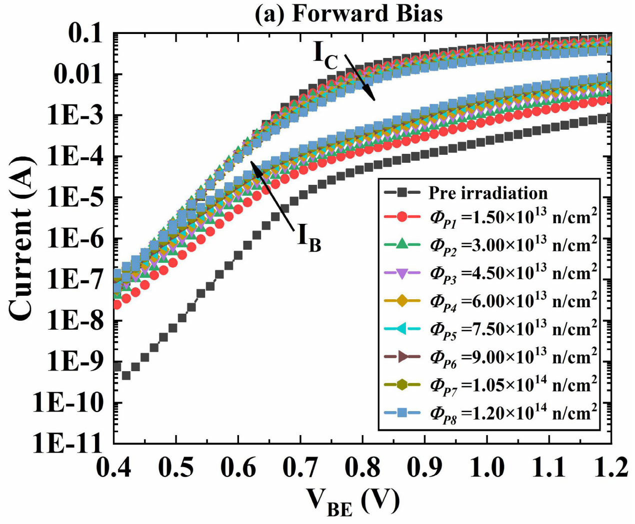
The Xi'an pulse neutron reactor operated in pulse mode in this experiment. The fluence was measured with the foil activation method, and the neutron pulse FWHM recorded with the reactor power sensor was ~9.4 ms. The 1-MeV equivalent neutron fluence of every neutron pulse was approximately 1.5×10^{13} n/cm^2 during one reactor pulse emission period. The ratio of the neutron fluence rate to the gamma dose rate was approximately $7.7 \times 10^9 \text{n}\cdot\text{cm}^{-2}\cdot\text{rad(Si)}^{-1}$. The gamma irradiation dose in one reactor pulse emission period was approximately 2 krad (Si). In this study, eight reactor pulse irradiation experiments were conducted on the DUTs, and the DC characteristics of the DUTs were measured by a semiconductor parameter analyzer (HP4156) immediately after every reactor pulse n-γ irradiation. The accumulated neutron fluence from the first reactor pulse to the last pulse was marked from $\hat{O}_{P1}$ to $\hat{O}_{P8}$. The DUTs under three bias conditions are annealed at room temperature during the short annealing process ($t_0 = 254$ s). Then, all DUTs are grounded during the later annealing process. The annealing characteristics were recorded at a short annealing time $t_0 = 254$ s after each pulse irradiation. The DC characteristics were measured for the relatively long annealing times $t_1 = 21$ h and $t_2 = 4.6$ days only after the first pulse irradiation ($\Phi_{P1} = 1.5 \times 10^{13}$ n/cm^2).

III. EXPERIMENTAL RESULTS AND ANALYSIS

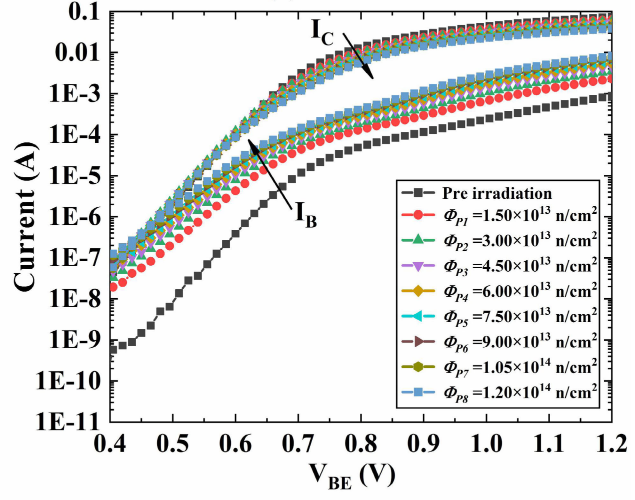
The forward Gummel characteristics of DUTs after eight pulse irradiation with a short annealing time ($t_0 = 254$ s) are displayed in Fig. 2. For all three bias conditions, the base current I_B gradually increased with increasing neutron fluence (1.5×10^{13} n/cm^2 to 1.2×10^{14} n/cm^2). Unlike previous gamma irradiation results [23]–[25] where the collector current I_C remains virtually unchanged, I_C seemed to slightly increase in the low V_{BE} range (approximately 0.4 V to 0.5 V) and decrease in the high-V_{BE} range (approximately $V_{BE} > 0.5$ V) after the reactor pulse irradiation as shown in Fig. 3. To achieve a clearer bias condition contrast, the normalized base and collector current as a function of neutron fluence at fixed voltages $V_{BE} = 0.4$ V and $V_{BE} = 0.7$ V are presented in Fig. 4 and Fig. 5, respectively. I_B significantly increased at low V_{BE} (0.4 V), while I_C increased at low V_{BE} voltage and decreased at high V_{BE} (0.7 V). Fig. 6 shows the current gain reciprocal $\Delta(1/\beta)$ under three bias conditions as a function of neutron fluence at $V_{BE} = 0.7$ V, since it has been effectively used to scale displacement damage considering different irradiation particles [26]–[28]. All three bias condition curves in Fig. 6 are linear with the irradiation dose, which corresponds to Messenger-Spratt equation [15], [29]. Although all DUTs are



(a) Forward Bias

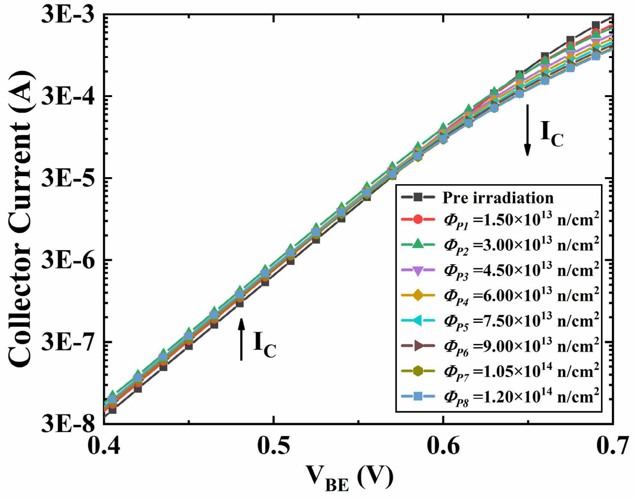


(b) Cutoff Bias

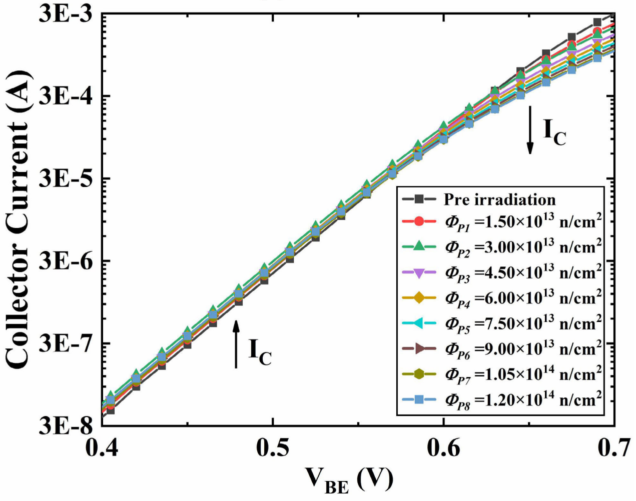


(c) Saturation Bias

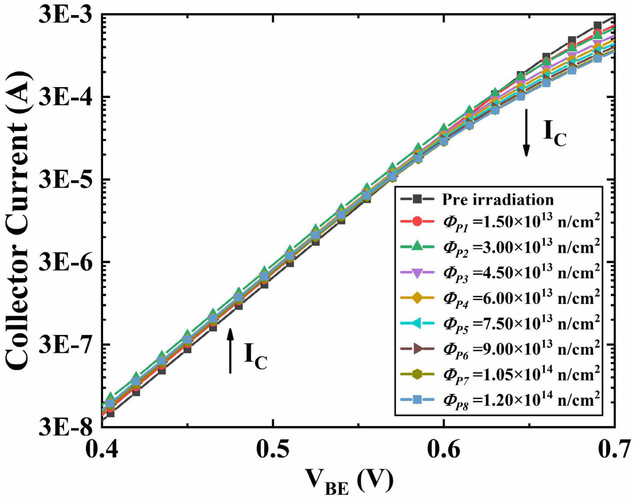
FIGURE 2. Forward Gummel characteristics of DUTs after eight pulses of irradiation with a short annealing time ($t_0 = 254$ s).



(a) Forward Bias



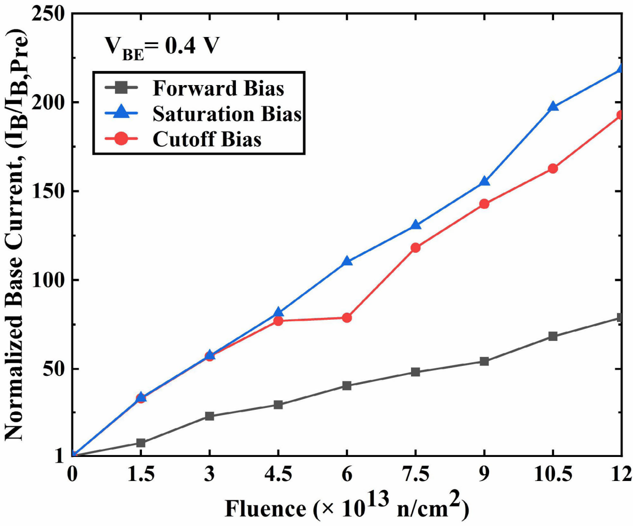
(b) Cutoff Bias



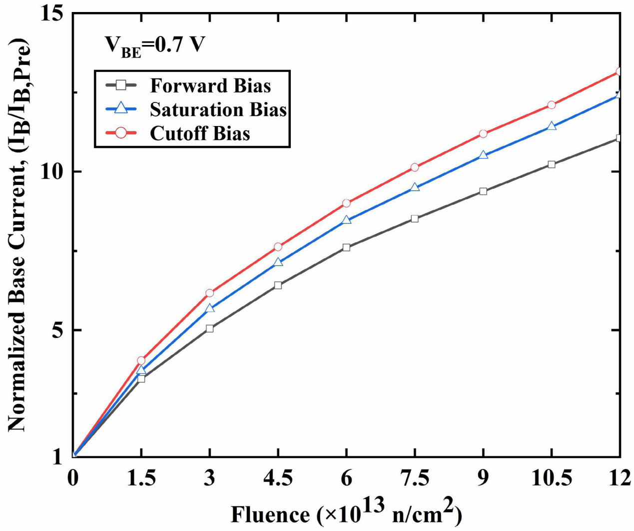
(c) Saturation Bias

FIGURE 3. Collector current I_C as a function of V_{BE} under three bias conditions.

irradiated with the reactor pulse neutron and gamma rays, the estimated gamma dose is relatively small, as mentioned above. In addition, the nonlinear response of $\Delta(1/\beta)$ is expected with increasing gamma dose, as reported in [22].



(a) Normalized $I_B/I_{B,Pre}$ at V_{BE}=0.4 V

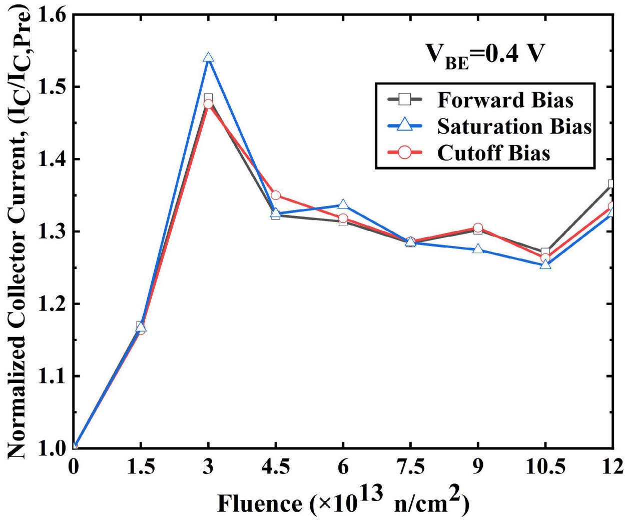


(b) Normalized $I_B/I_{B,Pre}$ at V_{BE}=0.7 V

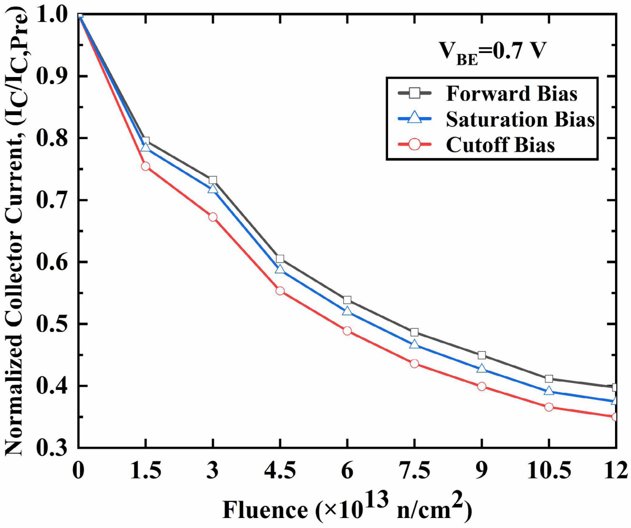
FIGURE 4. Normalized base current I_B as a function of the fluence at fixed voltages $V_{BE} = 0.4$ V and $V_{BE} = 0.7$ V.

Therefore, the degeneration of the DUTs can mainly be attributed to displacement damage.

Generally, incident high-energy neutrons can displace silicon lattice atoms from normal sites to form Frenkel defects, including vacancies and interstitials. The subsequent collision of the primary knock-on atom and other silicon atoms will create defect clusters [27], [30], [31]. The vacancies are very mobile at room temperature and can combine with other vacancies, dopants and oxygen impurity atoms to form divacancy, A center and E center defects. These defects can act as effective recombination and trapping centers, which mainly cause the decrease in carrier density, minority carrier lifetime, and carrier mobility [31]. In this case, the generation centres induced in the SiGe epitaxial layer in the base region, as well as the damages of interface between SiO_2 and SiGe epitaxial layer would increase the



(a) Normalized $I_C/I_{C,Pre}$ at V_{BE}=0.4 V



(b) Normalized $I_C/I_{C,Pre}$ at V_{BE}=0.7 V

FIGURE 5. Normalized collector current Ic as a function of the fluence at fixed voltages $V_{BE} = 0.4$ V and $V_{BE} = 0.7$ V.

recombination in the depletion region of the E-B junction and the neutral base region. This consequently leads to a decrease in the minority carrier lifetime, which will increase the base current [32], [33]. As reported in [26], the increase in base current and the decrease in collector current can be attributed to the electron capture levels, including interstitial boron in the base region as well as E centers and divacancy in the collector regions. Furthermore, recombination in the emitter-base depletion region has a larger impact on the base current response, particularly at lower V_{BE}, as noted in [29], which significantly increases I_B at low V_{BE}, as shown in Fig.4.

The slight increments in collector current I_C in the low V_{BE} region are mainly contributed by the generation current due to an increase in Shockley-Read-Hall (SRH) recombination in the space charge region of the collector-substrate and base-collector diode. The SRH recombination mechanism refers to the electrons and holes that use

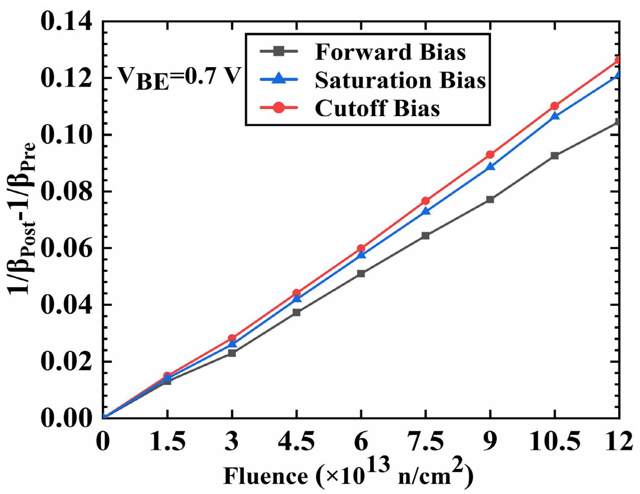


FIGURE 6. Current gain reciprocal $\Delta(1/\beta)$ as a function of the fluence at a fixed voltage $V_{BE} = 0.7$.

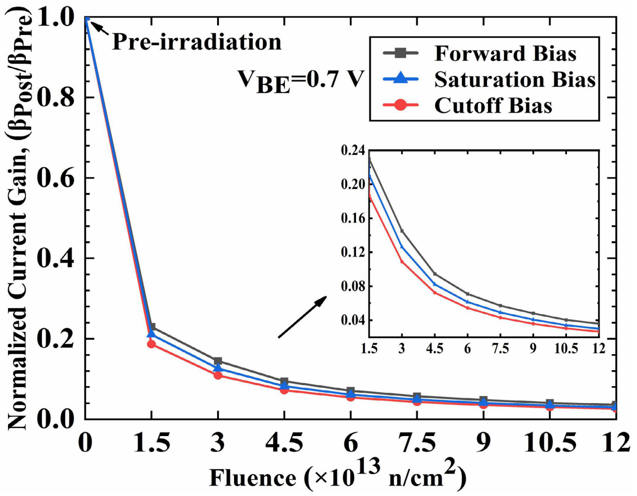


FIGURE 7. Normalized current gain β with a short annealing time ($t_0 = 254$ s) as a function of the fluence at a fixed voltage $V_{BE} = 0.7$.

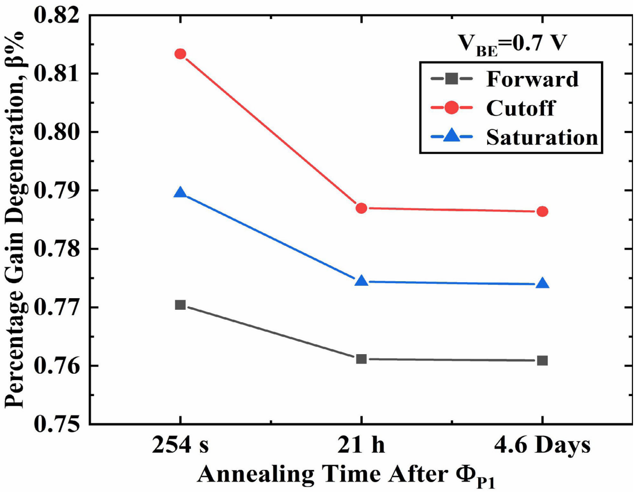
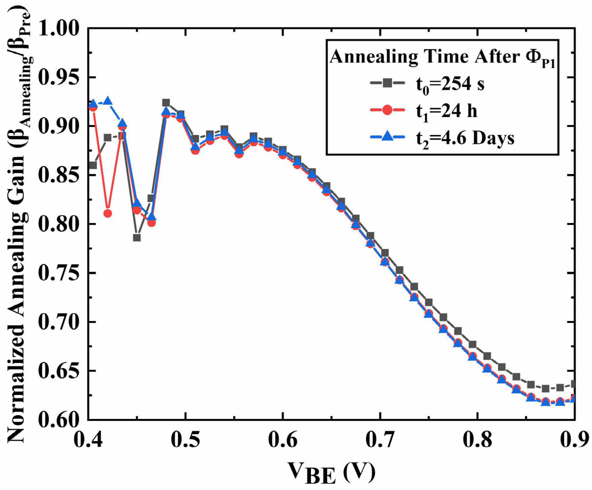


FIGURE 8. Variation in the percentage gain degradation β% for the three bias modes after long-term annealing.

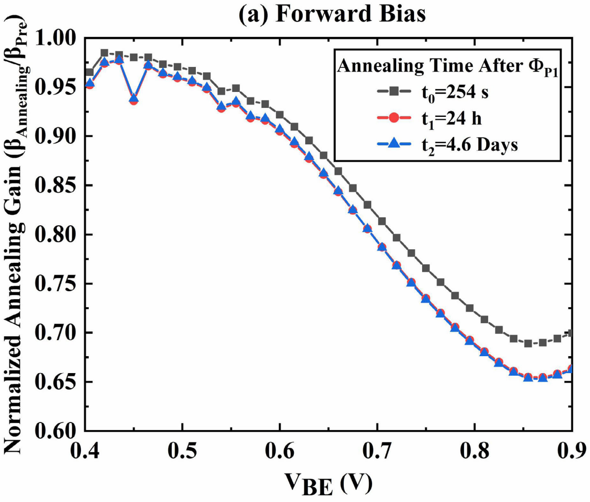
radiation-induced recombination centers for redirector and undergo recombination processes such as electron capture, electron emission, hole capture and hole emission. The radiation-induced displacement defects in the space charge region can become recombination centers for carriers, which decrease the lifetime of minority carriers. This behavior increases the electron-hole recombination rate. Therefore, the collector current will increase in the low voltage range. Similar results were found in [22], [34]. For the observed decline in I_C at high V_{BE}, the increase in collector resistance R_C and emitter resistance R_E is one of the reasons. With high neutron irradiation fluences (>10^{14} n/cm^2, 1 MeV equivalent), the accumulated trapping defect complexes will cause an increasing compensation of n-type dopants, which decreases the majority carrier concentration and mobility and consequently increases the series resistances in the n-type region, including the emitter and collector resistance for npn bipolar transistors [35]. The increased n-type resistance is also confirmed by reports [26], [36]. In addition, the high injection effect contributes to the decreased I_C in the high-V_{BE} region. With increasing V_{BE}, the injected electron from the emitter to the base makes the hole quasi-Fermi level gradually move toward the valence band and may even decrease some shallow acceptor defect levels in the base region. Then, these shallow acceptor defects are occupied with the desired charge state and act as effective recombination centers, which are similar to deep-level defects. Thus, when the injection level increases, both shallow-level and deep-level defects can decrease the carrier lifetime, which decreases I_C in the high-V_{BE} region [10], [22].

To investigate the effects of bias conditions on the gain degradation of SiGe HBTs, Fig. 7 presents the normalized current gain β with a short annealing time ($t_0 = 254$ s) under three bias conditions as a function of neutron fluence at $V_{BE} = 0.7$. In Fig. 7, at $V_{BE} = 0.7$ V, the cutoff condition shows the largest degradation, followed by the saturation bias and forward bias conditions. The same ranking results are observed from the current gain percentage degradation ($\beta\% = \Delta|\beta\text{Post}-\beta\text{Pre}|/\beta\text{Pre}$) at various biases as a function of annealing time and V_{BE}, as depicted in Fig. 8 and Fig. 9, respectively. The initial defects induced by pulse neutron irradiation are not stable, such as vacancies in bulk Si, which is notably mobile at room temperature [37]. Comparing the characteristics from a short annealing time t_0 to a long annealing time t_1 of the first pulse irradiation, slight recovery β is observed, which indicates an unstable defect reordering process, and β at annealing times t_1 and t_2 is nearly consistent, which suggests that the defects tend to be stable after long-term annealing. The degradation difference under three bias conditions is associated with the electronic occupation of the relevant traps [32], corresponding to the free charge injection annealing effect [37].

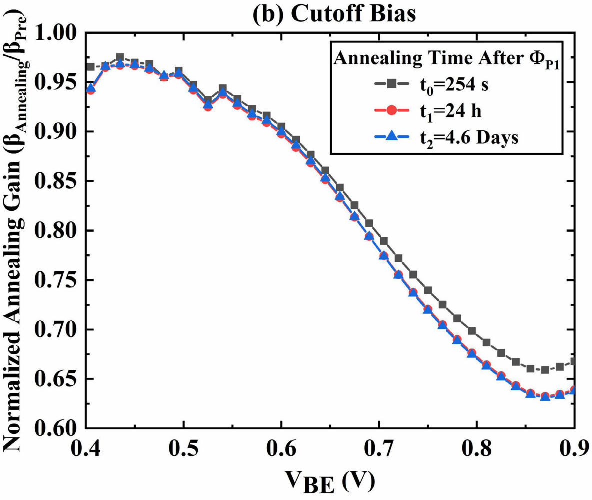
During the pulse n-γ irradiation, the charges injected into the Si bulk affects the defect reordering process by changing the defect charge state, which increases the defect



(a) Forward Bias



(b) Cutoff Bias



(c) Saturation Bias

FIGURE 9. **Short- and long-term annealing current gain percentage degradation ($\beta\% = \Delta|\beta_{Post}\text{-}\beta_{Pre}|/\beta_{Pre}$) for three bias conditions.**

mobility [37]. Deep level transient spectroscopy (DLTS) studies on neutrons irradiated on Si bipolar transistors have shown that point defect clusters such as vacancies and interstitials and defect-impurity complexes are introduced in bulk Si, which decreases the minority carrier lifetime [32]. Considering the forward bias state, the vacancy in the base region will change from neutral to negative with the increased vacancy mobility, which enhances the defect reordering and reduces displacement damage [22]. In addition, a review study [37] notes that a specific number of closely spaced or cluster defects has greater effectiveness than the same number of defects uniformly distributed throughout the lattice structure in terms of reducing the recombination lifetime. The primary Frenkel pairs induced by MeV neutrons in Si are not uniformly distributed, since the defects tend to form clusters [38]. Under forward bias, the charge state of the neutral vacancies will change to negative due to electron injection into the base region or base-emitter space charge region, which increases the vacancy mobility and promotes defect reordering. Less injection occurs under saturation bias, and even reverse extraction occurs under a cutoff bias. Therefore, the defect distribution throughout the lattice structure is more scattered for the forward bias than for the saturation bias, while the defects for the cutoff bias are more prone to aggregation. As a result, the difference in the distribution of the defects and effectiveness of displacement damage leads to the largest degradation for the cutoff bias state, followed by the saturation bias and forward bias state.

In addition, although the ionization damage caused by reactor gamma rays as mentioned above for the degeneration is small, its enhancement for displacement defects is reminded as a possible degeneration reason here. Previous studies indicate that the interface traps introduced by ionization damage will enhance displacement defects in the base-collector junction [39]–[41]. In [21], [42], the ionizing damage difference is mainly attributed to the effects of the fringe electric field in the SiO_2 layer and applied electric field. The forward V_{BE} mode weakens the fringe electric field, which results in more recombination of electron-hole pairs due to ionizing damage and fewer remaining holes in the SiO_2 layer. Hence, there are fewer net positive oxide trapped holes and interface defects compared with the reverse V_{BE} condition (cutoff bias). The larger number of interface traps under cutoff bias enhances the displacement defects. Furthermore, in [41], both positive oxide charge and interface trap charge spread the emitter-base depletion layer by reducing the majority carrier density near the base surface and in bulk Si, which enhances the displacement damage. Thus, the cutoff bias condition shows the largest degradation from this point of view. For the percentage of ionization damage under pulse n-γ irradiation and its effectiveness on displacement damage, more research is required in the future.

IV. CONCLUSION

The responses of SiGe HBTs at three common biases (forward, cutoff, saturation) induced by multiple-pulse n-γ irradiation were investigated. The results show that the device performance degradation after pulse n-γ irradiation was mainly caused by the significantly increased base current I_B. A slight increase in collector current I_C in the low-V_{BE}

region and a decrease in I_C at high V_{BE} were observed for multiple pulses.

The degradation degree and annealing characteristics of the test samples under different bias conditions (forward, cutoff, saturation) are investigated after pulse n-γ irradiation. The results show that the performance of the samples under the cutoff bias condition displayed the most serious degradation, followed by saturation bias and forward bias. The degradation difference under three bias conditions is mainly associated with the electronic occupation of the relevant traps, which corresponds to the free charge injection annealing effect.

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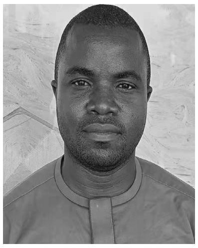

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