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Synergistic effect of total ionizing dose on single event effect induced by pulsed laser microbeam on SiGe heterojunction bipolar transistor*

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The synergistic effect of total ionizing dose (TID) on single event effect (SEE) in SiGe heterojunction bipolar transistor (HBT) is investigated in a series of experiments. The SiGe HBTs after being exposed to ^{60}Co γ irradiation are struck by pulsed laser to simulate SEE. The SEE transient currents and collected charges of the un-irradiated device are compared with those of the devices which are irradiated at high and low dose rate with various biases. The results show that the SEE damage to un-irradiated device is more serious than that to irradiated SiGe HBT at a low applied voltage of laser test. In addition, the γ irradiations at forward and all-grounded bias have an obvious influence on SEE in the SiGe HBT, but the synergistic effect after cutting off the γ irradiation is not significant. The influence of positive oxide-trap charges induced by TID on the distortion of electric field in SEE is the major factor of the synergistic effect. Moreover, the recombination of interface traps also plays a role in charge collection.

Keywords: SiGe HBT, synergistic effect, single event effects, total ionizing dose

PACS: 85.30.Pq, 61.80.Az, 73.40.Lq, 75.40.Mg **DOI:** 10.1088/1674-1056/27/10/108501

1. Introduction

Silicon–germanium heterojunction bipolar transistor (SiGe HBT), as a typical device of band gap engineering based silicon, not only possesses competitive high-speed and high-frequency capability, but also has a good integration with Si CMOS technology.[1,2] Particularly, SiGe HBT can operate in extreme environment (-180 °C$\sim$ $+200$ °C) especially at cryogenic temperature because of the band gap gradient of the base region.[3–5] Therefore, SiGe HBTs as active devices are possibly used outside the spacecraft, so that the volume and weight of the electronic system and launch costs will be greatly reduced.[6] The SiGe HBT has become a potential competitor in the space field. However, the electronic equipment outside the spacecraft will be placed in the complex space environment, which is composed of diverse particles and cosmic rays. Thus, the radiation damage shows a synergistic mechanism under the combined action of total ionizing dose (TID), single event effect (SEE), and displacement damage (DD).

The SiGe HBT has been demonstrated to have good tolerance of displacement damage, but it is very vulnerable to single-event effects.[7–9] In addition, our previous work found that the TID irradiation did not cause significant failure on the SiGe HBT, but showed complicated responses under different bias conditions.[10,11] In this case, the synergistic effect of TID on SEEs becomes a key issue for the space applications of SiGe HBTs. Nevertheless, at present, the anti-radiation capability of SiGe HBTs is mainly evaluated by independent tests based on different radiation effects. The synergistic radiation effect of SiGe HBT is rarely reported.

Based on our previous studies, in this paper the synergistic effect is investigated via a microbeam laser experiment to simulate SEE after TID tests by the irradiation of ^{60}Co γ on the SiGe HBTs. The transient current and the charge collection of the γ irradiated SiGe HBT with various biases are analyzed in order to discuss the mechanism of the influence of trapping defects induced by TID on the SEE. The results present some interesting phenomena and provide new ideas of radiation hardening technology.

2. Experiment details

2.1. SiGe HBT technology

Figure 1 shows the schematic diagram of the device cross section of the SiGe HBT employed in this work. The transistor is fabricated to be almost identical with Si BJT: just a little germanium is doped in the base region to form grading heterojunctions at the emitter/base (E/B) junction and base/collector (B/C) junction. The gradient bandgap of the base region im-

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proved the device performance because the gain and frequency were proportional to $\exp(\Delta E_g/kT)$.[12,13] In consequence, the doping concentrations of emitter and base are heavy, reaching to 1×10^{20} cm^{-3} and 1×10^{19} cm^{-3} respectively, to reduce resistance. A passivation oxide layer covers the top of the device, forming an EB Spacer near the E/B junction. A local oxidation of silicon (LOCOS)isolation surrounds the active region to form a beak region nearby B/C junction. A collector/substrate (C/S) junction is defined by an n/p interface with a large area of about 100 μm×100 μm. Figure 2 shows the top view of the layout of the SiGe HBT. The electrodes are threaded through the surface of the device: the electrode contacts of base and emitter are fabricated as an interdigital process with an area of about 40 μm×40 μm, and the substrate is not separately led out but is contacted with the emitter.

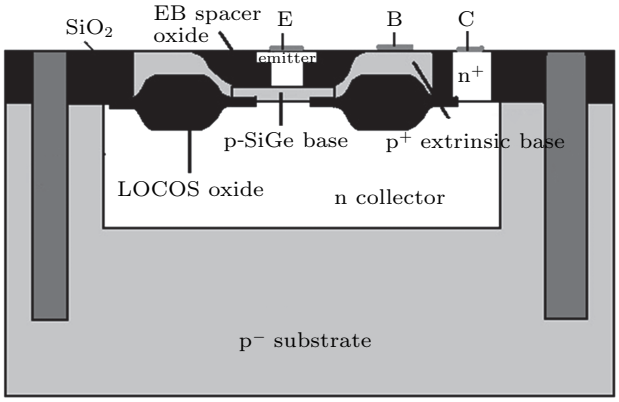


Fig. 1. Schematic diagram of device cross section of SiGe HBT.

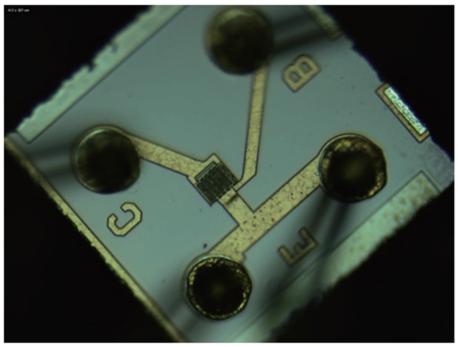


Fig. 2. (color online) Top view of layout of SiGe HBT.

2.2. Sample pre-treatment of γ irradiation

In order to investigate the mechanism of the synergistic effect, six SiGe HBT devices irradiated by ^{60}Co γ and an unirradiated device are chosen as samples for microbeam laser experiment. Three of these samples had been irradiated at a high dose rate of 80 rad(Si)/s, and set to be under three different biases in the irradiation exposure: (i) forward bias: $V_{BE}=0.8$ V, $V_{BC}=-1.8$ V; (ii) cutoff bias: $V_{BE}=0$ V, $V_{BC}=-2$ V; (iii) all-grounded bias: $V_E=V_B=V_C=0$ V. Other three samples are subjected to low dose rate irradiation with 0.1 rad(Si)/s under the same bias conditions. The TID tests are performed at the 3×10^6-Ci (1 Ci=3.7×10^{10} Bq) ^{60}Co γ-ray source platform in Xinjiang Technical Institute of Physics & Chemistry, Chinese Academy of Sciences. The total ionizing dose accumulates 1 Mrad(Si) in high and low dose rate irradiation.

2.3. Pulsed laser microbeam testing

The SEE test of the synergistic effect in the SiGe HBT is conducted by the pulsed laser microbeam system whose model is EKSMA PL2143 in the Northwest Institute of Nuclear Technology. The pulse width of the picoseconds laser is 25 ps that is similar to the characteristic time of SEE. The wave length is selected as 1064 nm so that the laser can reach the sensitive volume of the device to induce SEE. The spot diameter of the laser beam can be controlled within 1 μm∼ 3 μm.

The testing system of the SEE experiment consists of a test circuit and an oscilloscope. The test circuit is shown in Fig. 3. On the power supply side, two chip resistors with about 100 kΩ are respectively connected in series with base and emitter to avoid the breakdown; and two chip inductances are respectively placed in the same branch to filter high frequency noise signals. On the signal output side, the base and collector terminals are connected with a small capacitor for capturing single event transients (SET) with a pulse width of a nanosecond.[14] An Agilent oscilloscope with 20 GHz bandwidth and 50 GS/s sampling rate is used in this work. The base and collector outputs of the test circuit board are connected to the oscilloscope by a coaxial cable of 50 Ω. Thus, the impedance match of the oscilloscope is fixed at 50 Ω.

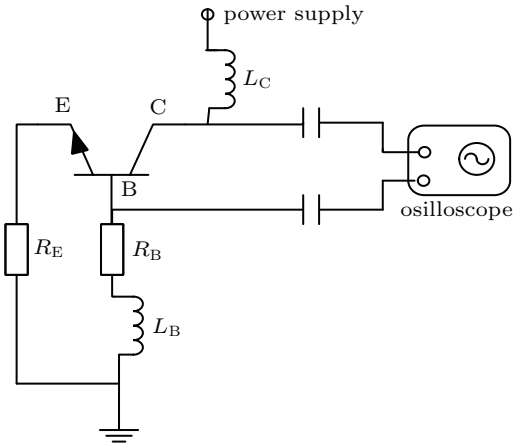


Fig. 3. Schematic diagram of test circuit in microbeam laser experiment.

Because there are only 1 to 3 layers of metal wiring in this SiGe HBT and the struck position can be determined by the device layout, the front of the device is selected to be struck by the laser. Thus, the front packages of all samples are decaped before the experiment. Referring to the SEE sensitive volume of the SiGe HBT obtained in our previous work,[15] a position outside the edge of the interdigital electrode is selected as the

point of laser striking, so that the SET signals can be captured, and was not affected by metal wiring. In the above section, we know the substrate did not have a separate electrode in the SiGe HBT. Consequently, the $V_C = +1.5$ V and $V_C = +3$ V are set during the laser irradiation test to form the worst bias under which the C/S junction is inversed. The laser energy is chosen from 0.1 nJ to 30 nJ.

The transient current and collected charges of emitter are too small to be neglected. The SET of the substrate cannot be obtained because the electrode is not individually led out. Therefore, the transient current and collected charges of collector and base are discussed in this paper. In addition, due to the excellent focusing and energy stability of the microbeam laser, the experimental data present good repeatability and identity.

3. Theory and mechanism

The ionizing of SEE induced by pulsed laser is different from the mechanism of heavy ion, which depends on the Coulomb interaction. When laser energy is greater than the band gap of semiconductor material, electrons will jump from the conduction band to the valence band and the carriers will be ionized by the photoelectric effect. Thus, the microbeam laser that strikes into the SiGe HBT sample ionizes a large number of electron–hole (e–h) pairs along the laser track. However, for the pulsed laser and heavy ion irradiation, the physics processes of charge transport are the same: a potential distortion is produced by the ionized excess carriers so that a funnel electric field is formed at the pn junction. A part of ionized carriers are collected by the drift effect of the funnel electric field, to form a large current transient in a few picoseconds. Subsequently, a large number of charges are further collected through the diffusion mechanism due to the doping gradient in the device.[16]

The TID damage is caused by two kinds of defects, i.e., oxide-trap charge and interface trap.[17] First, some metastable oxide-trap charges are captured by the intrinsic defect in oxide bulk with a shallow energy level and annealed easily. Then, the escaped holes and low probability protons react with $SiSiO_2$ strain bonds in nearly 10 nm range of the SiO_2 interface to form stable positive oxide-trap charges with a deep energy level. In addition, hydrogen is released under γ irradiation in the oxide layer, and reacts with the Si dangling bond to form an interface trap.[18–20]

According to the above mechanism, the synergistic effect of TID on SEE in the SiGe HBT is deemed to be dependent on the influences of oxide-trap charges and interface traps on the track of ion (laser) striking. 1) The positive oxide-trap charges of the deep energy level produce a space electric field from the SiO_2 layer to the pn junction. As shown in Fig. 4, a space electric field is applied to the B/C junction in the SiGe HBT. Then in the SEE laser test, a forward bias is set to be at collector and forms an applied electric field whose direction is opposite to the space electric field direction. Thus, the funnel distortion of electrostatic potential is partially offset by the space electric field. The drift effect on ionized carriers weakens near the B/C junction, resulting in the variation of transient current and charge collection. 2) A weak space electric field is formed near the E/B junction by the positive oxide-trap charges in EB Spacer, leading to a depletion layer expansion of E/B junction (Fig. 4). Hence in the SEE test, the recombination probability of ionized carriers will be slightly enhanced while the charges diffuse into the depletion layer. Sequentially, the charge collection is affected. 3) The interface traps at the Si/SiO_2 interface become a recombination center in the active region, thereby affecting the diffusion charge collection. However, the influence of interface traps on the synergistic effect is weak in the SiGe HBT because the number of excess carriers induced by SEE is much larger than the number of interface traps. The details are discussed in the following section with experimental data.

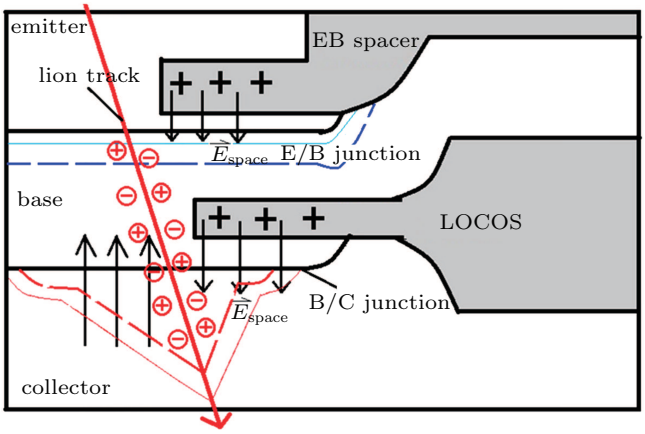


Fig. 4. (color online) Schematic diagram of synergistic effect of TID on SEE in SiGe HBT.

For high dose rate irradiation, the holes reach the interface before the protons, and the capture cross-section of the hole is also 1–2 orders of magnitude higher than that of proton. Therefore, these vast positive oxide-trap charges at the Si/SiO_2 interface generate an effective space electric field that offsets the SEE funnel potential of the B/C junction and influences the depletion layer of the E/B junction. Meanwhile, the space electric field prevents holes and protons from transporting so that a few interface traps are formed on the other side of the Si/SiO_2 interface far from the oxide-trap charges. When these interface traps are located in the region of funnel potential, a few ionized carriers are recombined, and thus reducing the charge collection in SEE. After γ irradiation at the low dose rate, the holes captured by oxygen vacancy decline because excess carriers ionized in the oxide layer are very small

per unit of time. Thus, the synergistic effect of the space electric field is relatively weak. In addition, under the weak space electric field, protons have enough time and greater probability to be released so that more interface traps are formed.[21,22] The TID of SiGe HBT is caused by the traps in the EB spacer layer and the beak region of the LOCOS layer. However, the quantity and distribution of oxide-trap charges and interface traps are different in these oxide layers due to the various biases near the pn junctions in γ irradiation as shown in Fig. 5. Therefore, the responses of the synergistic effect are different among the three biases, and the details are analyzed in the following.

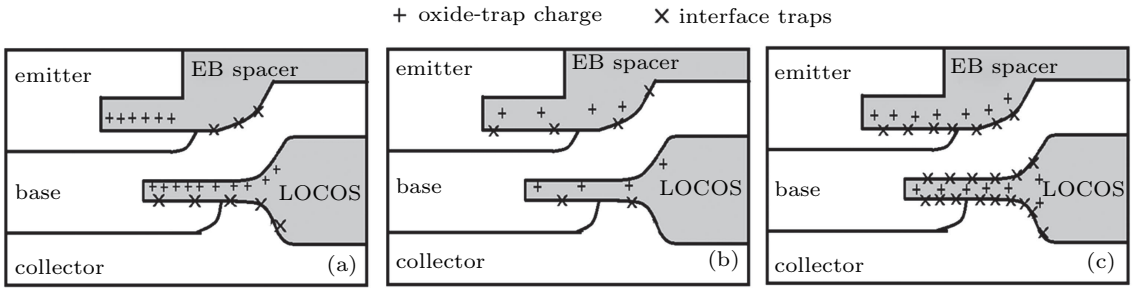


Fig. 5. Defect distributions subjected to γ irradiation at different biases in SiGe HBT: (a) forward bias, (b) cutoff bias, and (c) all-grounded bias.

4. Experimental results and discussion

The synergistic effect response of transient current and charge collection as a function of laser energy are shown in Figs. 6 and 17. All the curves increase sharply as the laser energy rises from 0.5 nJ to 5 nJ. Then the data tend to saturation until the laser energy increases to 30 nJ. This phenomenon depends on the number of injected carriers produced by the pulsed laser: as the laser energy gradually rises from the threshold, the ionized e–h pairs increase rapidly. So the carriers that are swept out of the electric field and the collected charges increase sharply in a short time. However, when the laser energy rises to a large enough value, the carriers are completely ionized due to the constant doping concentration in the device. Then, even if laser energy continues to increase, the number of ionized carriers increases slightly, and the peak values of the transient current and the collected charges are difficult to increase sufficiently. The carriers transport of SEE in SiGe HBT affects the local electric field and traps induced by TID. Thus, the synergistic effect of collector and base are different.

4.1. Response of synergistic radiation effect at collector

Figures 6–8 show the peak values of transient currents of the collector as a function of laser energy in the SiGe HBTs, which have been irradiated at forward, cutoff, and all-grounded bias, respectively. The left panels are for the results of laser test at $V_C = +1.5$ V, and the right panels are for the data at $V_C = +3$ V. As seen in these figures, the differences in SEE are not significant between the irradiated and un-irradiated devices as the laser energy is less than 5 nJ. However, when the laser energy exceeds 5 nJ, the SEE responses of the SiGe HBTs, which have been irradiated at high and low dose rate are both lower than those of the unirradiated sample at test bias of $V_C = +1.5$ V. However, the TID irradiation has little influence on the SEE for $V_C = +3$ V.

In addition, for the pulsed laser test at $V_C = +1.5$ V, the synergistic effect responses are different in the SiGe HBTs that have experienced TID irradiation with various biases: for the forward bias in Fig. 6, the peak values of current transient are the lowest in the SiGe HBT after being experienced by high dose rate irradiation, lower in the device after being experienced by low dose rate irradiation, and the highest in the un-irradiated sample. As shown in Fig. 7, the influence of TID at cutoff bias on the current transient of the collector is weak. Only when the laser energy is more than 20 nJ, will the current peak of the un-irradiated SiGe HBT be slightly larger than that of the irradiated sample. For the γ irradiation of all-grounded bias, the transient current of un-irradiated sample is the most serious, and the peak values of current are almost the same in the SiGe HBTs irradiated with low and high dose rates (Fig. 8).

According to our previous work[10] and the device structure shown in Fig. 1, the synergistic effect of the collector is deemed to relate with the TID defects in the LOCOS layer. The transient current is determined by the drift effect of funnel potential in the collector. Thus, the ionized carriers are affected by the space electric field, which is formed by positive oxide-trap charges at a deep level in the LOCOS.

During γ irradiation, an electric field pointing from collector to base is formed at the B/C junction by the forward bias in the SiGe HBT so that the ionized holes transit towards the base side in the LOCOS and generate stable positive oxide-trap charges near the base, forming space electric field (Fig. 5(a)). In the subsequent SEE laser test, this space electric field whose direction is from base to collector diminishes the applied voltage of $V_C = +1.5$ V. Consequently, the transient currents of the SiGe HBTs that have been experienced by TID irradiation are less than those of the un-irradiated sample (Fig. 6 (a)). However, because the space electric field is

weak, its influence is negligible as the applied voltage of the laser test rises to $V_C = +3$ V (Fig. 6(b)). After being experienced by high dose rate irradiation, the funnel potential is effectively offset by vast deep oxide-trap charges in LOCOS, but low dose rate irradiation induces few holes to form a weak space electric field. Thus, the peak value of the transient current in the sample irradiated by a high dose rate is smaller than that in the SiGe HBT irradiated by a low dose rate.

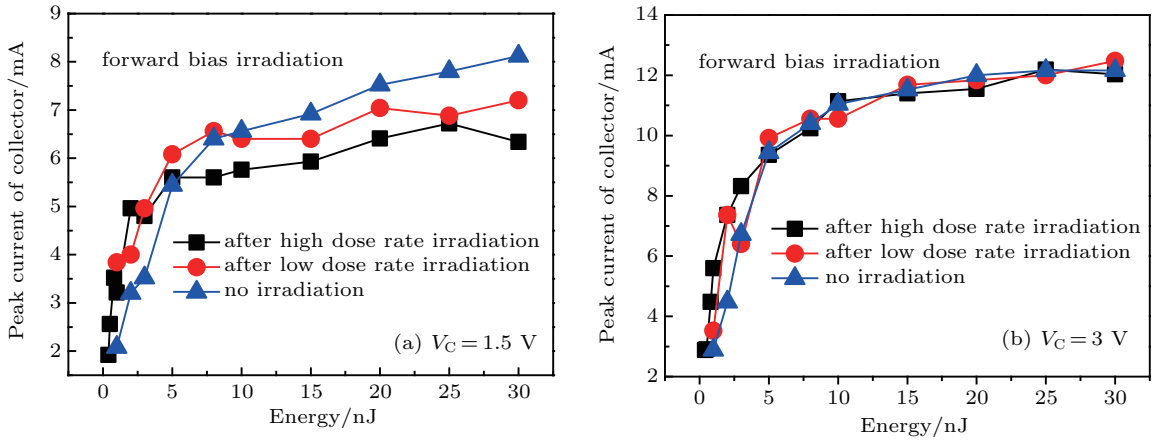


Fig. 6. (color online) Plots of peak value of transient current versus energy of the collector after being experienced by TID irradiation at forward bias with different dose rates.

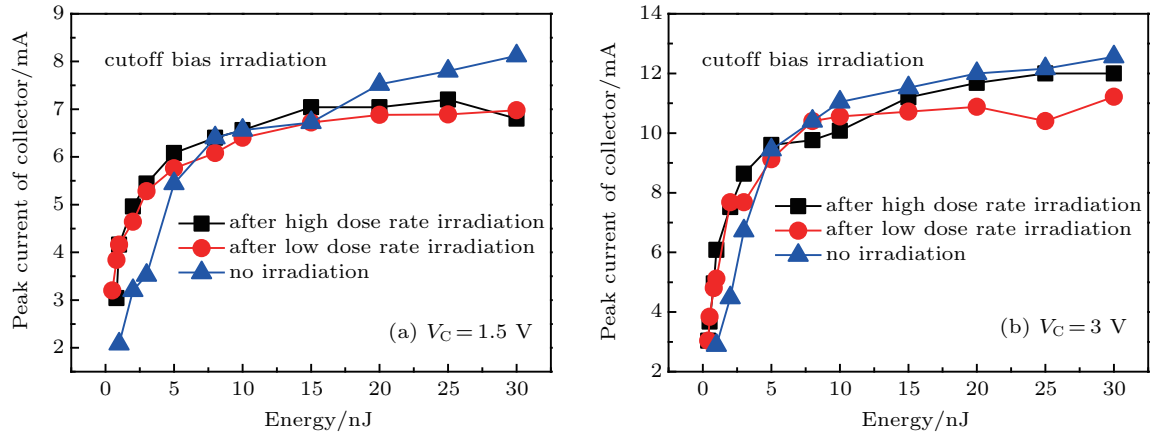


Fig. 7. (color online) Plots of peak value of transient current versus energy of collector after being experienced by TID irradiation at cutoff bias with different dose rates.

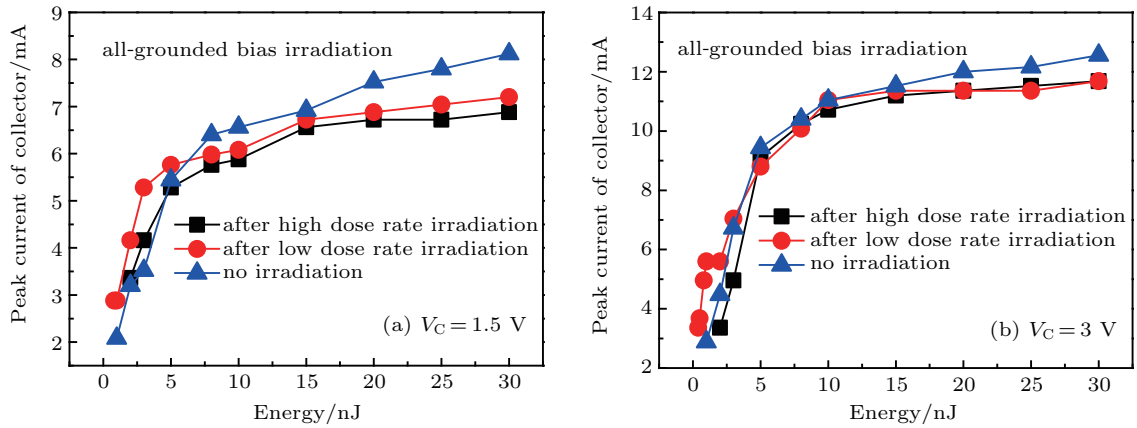


Fig. 8. (color online) Plots of the peak value of transient current versus energy of the collector after being experienced by TID irradiation at all-grounded bias with different doses.

Our previous research[11] shows that the γ irradiation of cutoff bias does not enhance the low dose rate sensitivity (ELDRS) in the SiGe HBT. It is considered that the ionized holes easily produce shallow level oxide-trap charges that are captured by the intrinsic oxygen vacancy in LOCOS during irradiation at cutoff bias (Fig. 5 (b)).These metastable space charges are gradually annealed so the effect of TID on transient current is not significant. However, part of annealed shallow oxide-

traps may still be captured by the deep level vacancy at the Si/SiO_2 interface during long time irradiation of the low dose rate, so the transient current is slightly small in the SiGe HBT irradiated by the low dose rate at cutoff bias (Fig. 7).

When the SiGe HBTs are subjected to TID irradiation at all-grounded bias, the ionized e-h pairs will not be affected by the applied electric field in the oxide layer. Thus during the irradiation and annealing, metastable holes escape from oxygen vacancies and transport slowly to form oxide-trap charges with a deep level in the LOCOS (Fig. 5 (c)). With the offsetting effect of the space electric field on the applied voltage of $V_C = +1.5$ V, the transient currents of irradiated SiGe HBTs are smaller than those of an un-irradiated device (Fig. 8).

The charge collections of the synergistic effect as a function of laser energy at the collector are given by Figs. 9–11. The curve characteristics of charge collection are similar to the representation of transient current in the above section. For all the three biases of forward, cutoff, and all-grounded, the charge collection is the largest in the un-irradiated SiGe HBT, but it is a minimum amount in the device irradiated with the high dose rate. The difference between the high and low dose rate is small in the samples irradiated at cutoff bias. The collected charges are almost the same in the SiGe HBTs that have been irradiated at all-grounded bias.

The ELDRS effect of the reverse mode in this SiGe HBT has been demonstrated in Ref. [11]. The interface traps induced by low dose rate irradiation are much more than that by the high dose rate irradiation in LOCOS. However, comparing Figs. 9–11 with Figs. 6–8, the responses of charge collection resemble the transient current for each bias. The collected charges do not decrease much in the low dose rate irradiated samples which have vast interface traps acting as recombination centers. The charge collection of the high dose rate irradiated device is even lower than that of the low dose rate irradiated device. The reason may be that the quantity of interface trap is relatively small compared with that of e–h pairs ionized by the SEE. Thus, the charge collection of the synergistic effect primarily depends on the drift of space electric field in the LOCOS for the collector so that the charges vary with transient current. Then, a few diffusion charges are recombined by the interface traps at LOCOS leading to the diversity of charge collection at various biases.

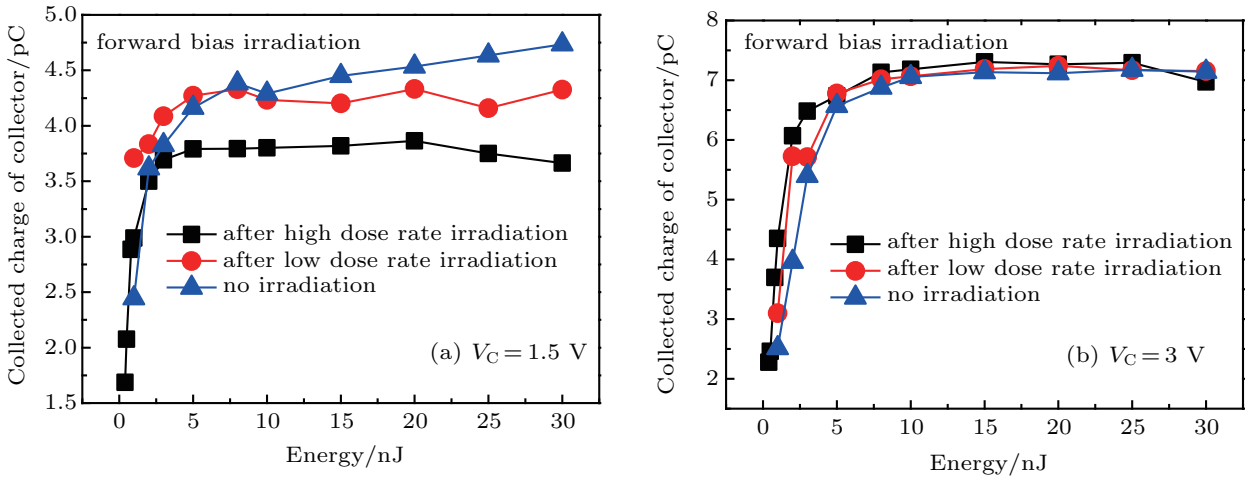


Fig. 9. (color online) Plots of charge collection versus energy of collector after TID irradiation at forward bias with different dose rates.

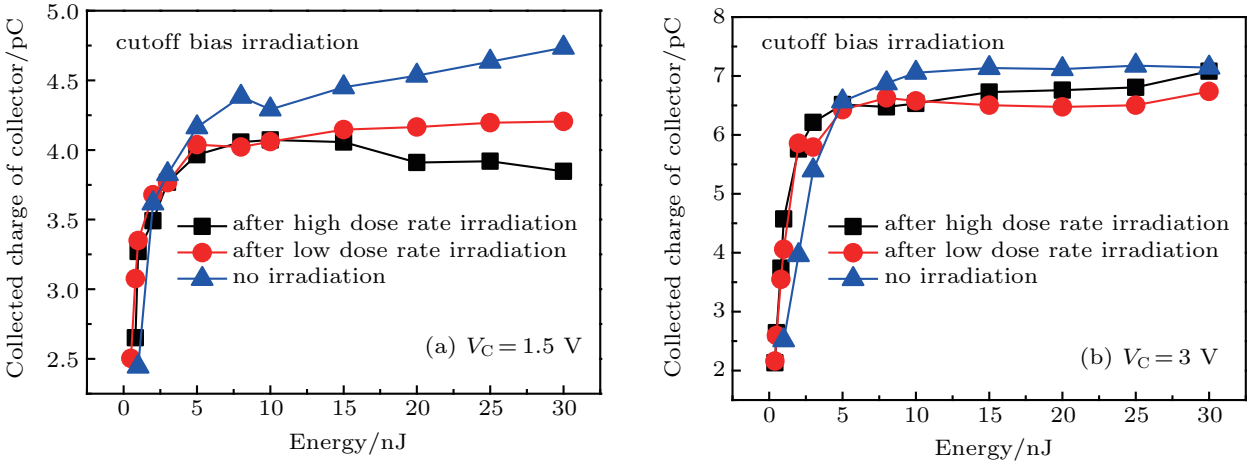


Fig. 10. (color online) (color online) Plots of charge collection versus energy of collector after TID irradiation at cutoff bias with different dose rates.

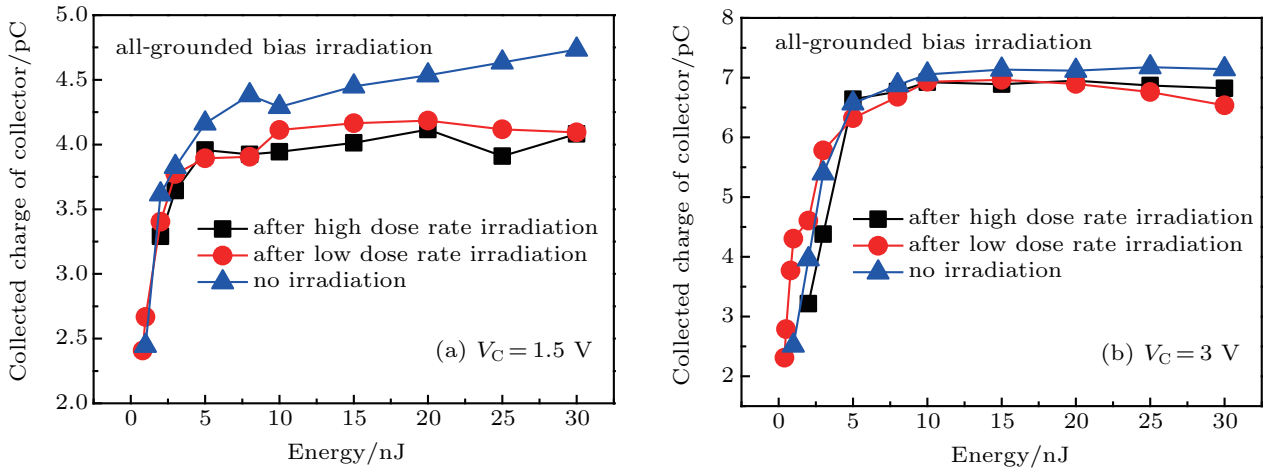


Fig. 11. (color online) Plots of charge collection versus energy of collector after being experienced by TID irradiation at all-grounded bias with different dose rates.

In the high dose rate γ irradiation at forward bias, the positive oxide-trap charges in the LOCOS on the base side prevent the protons from being transported, so the Si–H passivation bonds at the collector/LOCOS interface react with protons to form interface traps, which become the recombination center for diffusion electrons in the collector region (Fig. 5(a)). Therefore, the charge collection is least in the device irradiated by a high dose rate in Fig. 9. The cutoff bias produces a reverse pn junction of the B/C junction that is the same as the forward bias. So as shown in Fig. 10, the charge collection of the cutoff irradiated sample is similar to that of forward irradiation. In addition, due to the influence of the space electric field on drift charges near the LOCOS, the charge collections are very close in the SiGe HBTs irradiated with high and low dose rate at all-grounded bias (Fig. 11).

4.2. Response of synergistic radiation effect at base

The peak values of transient currents as a function of laser energy on the base of SiGe HBTs, which have been irradiated at forward, cutoff, and all-grounded bias are given by Figs. 12–14. Like the collector above, the left panels show the results of the pulsed laser test at $V_C = +1.5$ V, and the right panels display the responses at $V_C = +3$ V. The TID also has little influence on current transient of the base at $V_C = +3$ V. Interestingly, the synergistic effects of the base present various characteristics in different TID bias conditions when the laser energy exceeds 5 nJ for $V_C = +1.5$ V.

As shown in Fig. 12(a), after γ irradiation at forward bias, the transient current presents a maximum value in the un-irradiated SiGe HBT, a middle value in the low dose rate irradiated sample, and a minimum value in the high dose rate irradiated device. However, figure 13 indicates that the transient current of the irradiated device is slightly less than that of the un-irradiated device for cutoff bias irradiation. For the SiGe HBT irradiated at all-grounded bias in Fig. 14, the transient currents of low dose rate irradiated and un-irradiated samples are almost the same, and higher than those of the high dose rate irradiated device when the laser test is set to be at $V_C = +1.5$ V.

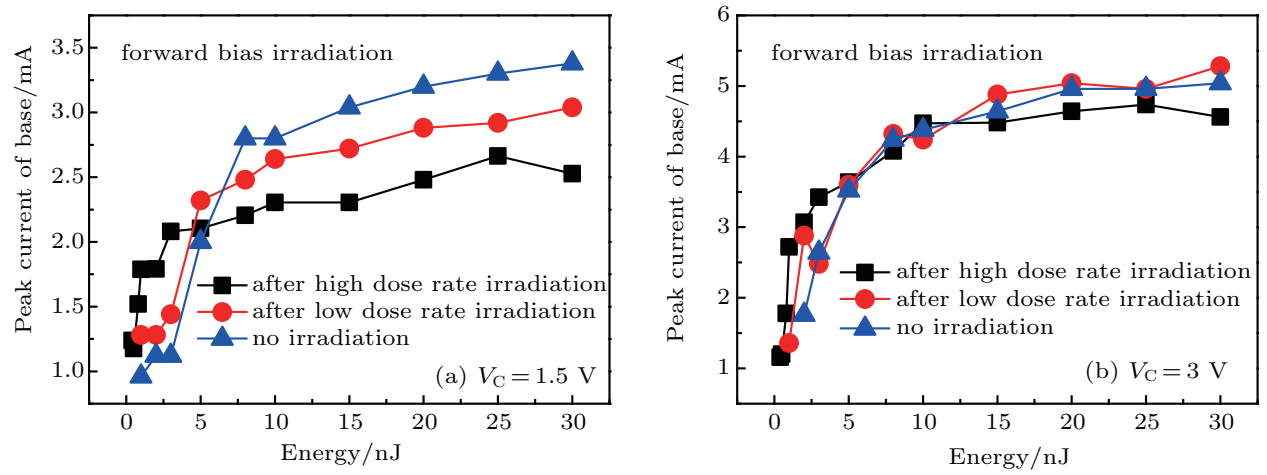


Fig. 12. (color online) Plots of peak value of transient current of base versus energy of collector after being experienced by TID irradiation at forward bias with different dose rates.

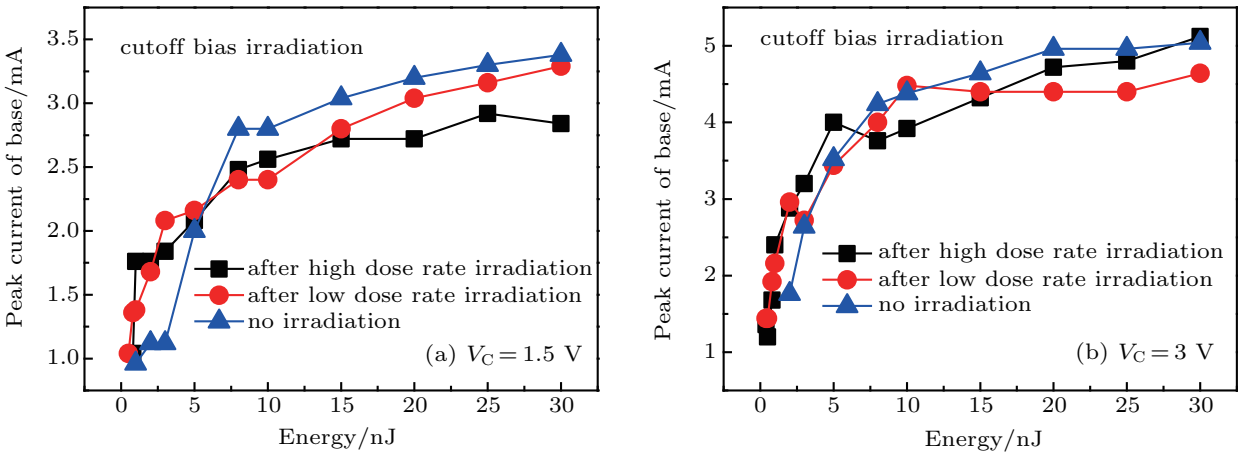


Fig. 13. (color online) Plots of peak value of transient current of base versus energy of collector after being experienced by TID irradiation at cutoff bias with different dose rates.

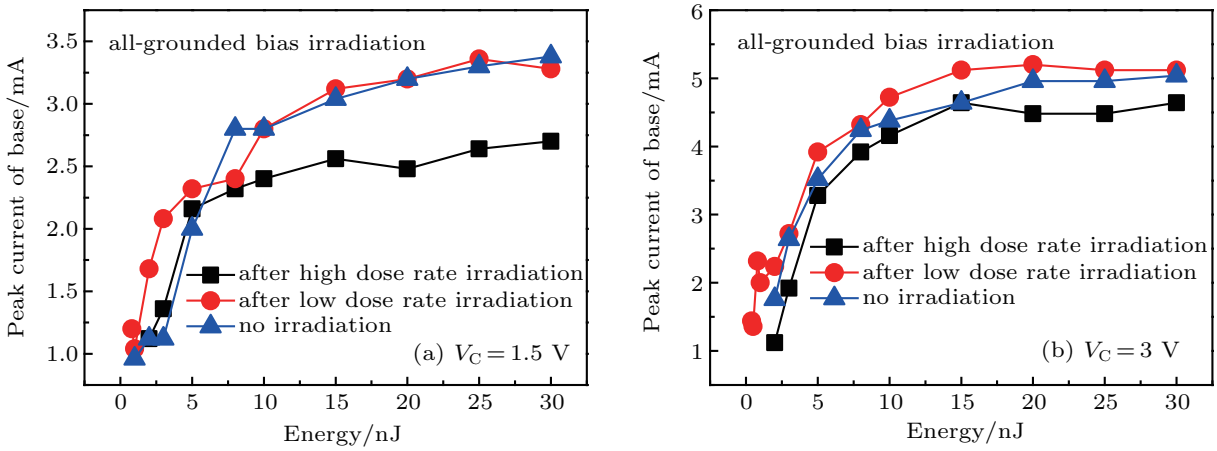


Fig. 14. (color online) Plots of peak value of transient current of base versus energy of collector after being experienced by TID irradiation at all-grounded bias with different dose rates.

The applied voltages of $V_C = +1.5$ V and $V_C = +3$ V create electric fields at C/S and B/C junctions, and thus affect the carrier transport in the base region. Besides, carriers tend to an equilibrium state inside the transistor. Hence, the electron transient current of the collector has the same effect on the base hole current, and becomes a factor of the synergistic effect in base current. On the other side, the space electric field induced by oxide-trap charges in EB Spacer also limits the transport of holes in the base region.

For the γ irradiation of forward bias, the synergistic effect of the collector (in Subsection 4.1) indicates that deep level oxide-trap charges are formed in LOCOS near the base side by reverse bias of the B/C junction. The space electric field also offsets the drift effect on holes by an applied voltage of $V_C = +1.5$ V in the base region. On the other hand, electron-holes need to be balanced inside transistors. Consequently, the response of base current transient (Fig. 12) is similar to that of the collector (Fig. 6) in the sample irradiated at forward bias. In the same way, the base transient current of cutoff bias irradiation exhibits the same pattern as that of the collector due to the equilibrium state of carriers. Our previous work found that the ELDRS is the most serious in the γ irradiation of all-grounded bias for this SiGe HBT.[11] So the low dose rate irradiation has little effect on transient current because of few positive oxide-trap charges. The offset effect of the space electric field in LOCOS and EB Spacer minimizes the transient current of the device irradiated with a high dose rate.

Figures 15–17 show the charge collection of the base as a function of laser energy in the synergistic effect. As seen in Fig. 15 for forward bias γ irradiation, the charge collection has a small difference among three samples at $V_C = +1.5$ V of SEE test. However, in the test of $V_C = +3$ V, the charge collections are the same between the un-irradiated device and the low dose rate irradiated device, which are more than that of the sample irradiated at the high dose rate. In Fig. 16, the γ irradiation at cutoff bias has little effect on the base charge collection. Figure 17 shows the charge collection of the base after irradiation at all-grounded bias. It is observed that the charge collection is the largest in the low dose rate irradiated sample, less in the un-irradiated device, and the least in the high dose rate irradiated SiGe HBT. The difference in the collection amount at $V_C = +1.5$ V is larger than that at $V_C = +3$ V.

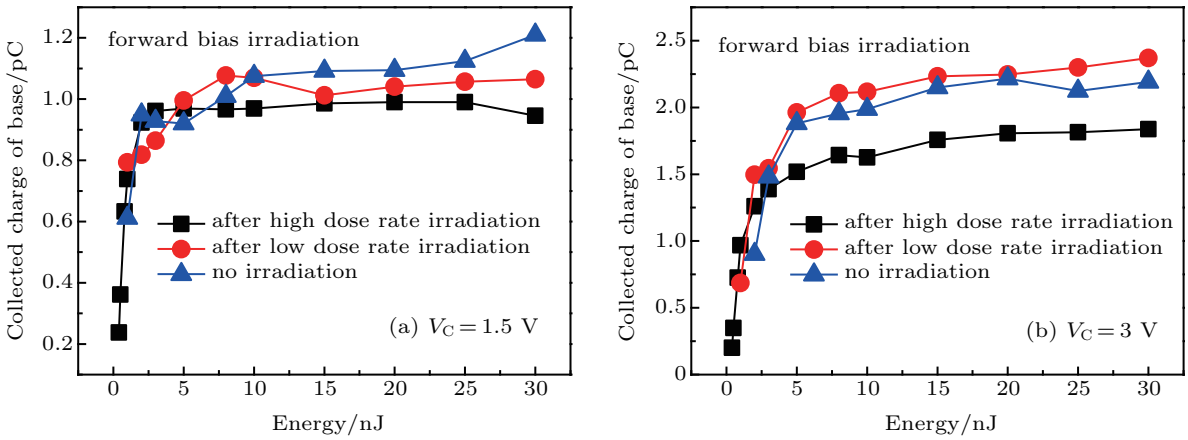


Fig. 15. (color online) Plots of charge collection of base versus energy of the collector after being experienced by TID irradiation at forward bias with different dose rates.

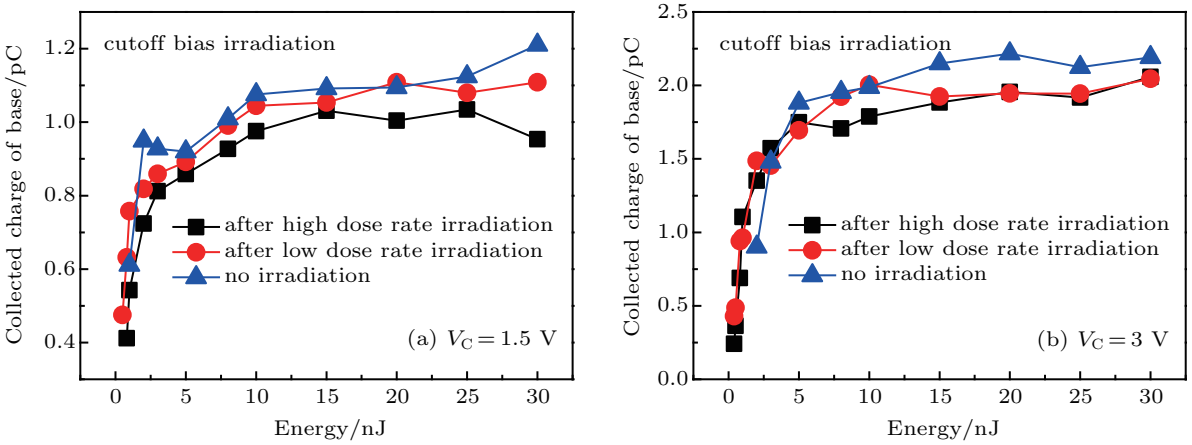


Fig. 16. (color online) Plots of charge collection of base versus energy of collector after being experienced by TID irradiation at cutoff bias with different dose rates.

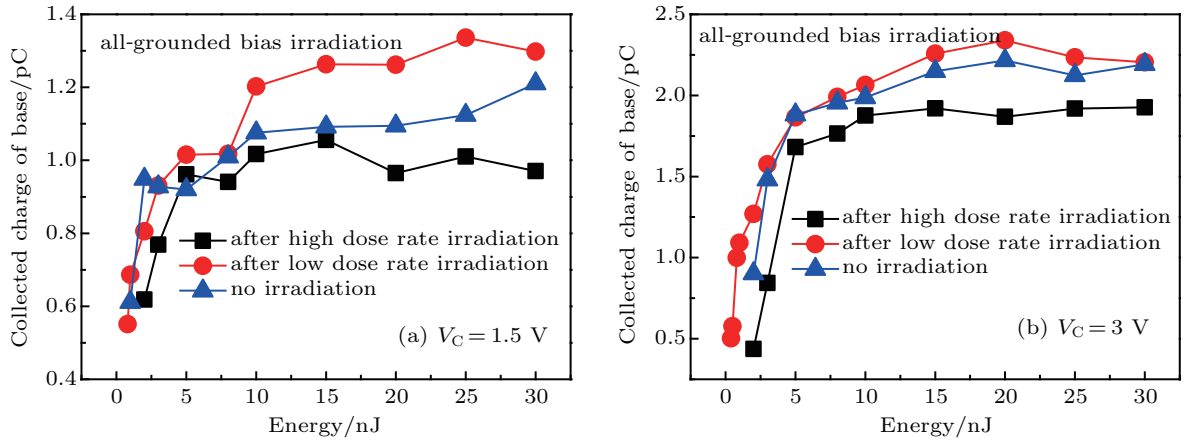


Fig. 17. (color online) Plots of charge collection of base versus energy of collector after being experienced by TID irradiation at all-grounded bias with different dose rates.

The base charge collection is primarily affected by the electric field at the B/C junction, resulting in the same response as the base current. In addition, in view of the very thin base region in the SiGe HBT, the defects induced by TID in the EB Spacer also have a nonnegligible effect on the transport of holes on the intrinsic base.

As seen in Fig. 15(b), the base charge collection of SiGe HBT irradiated at the high dose rate is less than those of the unirradiated sample and low dose rate irradiated sample. Under the forward bias at the E/B junction, the ionized holes transit towards the emitter side of the EB Spacer at high dose rate irradiation, and generate the deep level oxide-trap charges to form the space electric field near the Si/SiO_2 interface (Fig. 5(a)). Thus, the depletion layer of the E/B junction extends, and the

recombination of holes in the depletion region increases, leading to a small charge collection of the base after high dose rate irradiation.

Because there is no electric field in the SiGe HBT for all-grounded bias irradiation, the protons have a higher probability of being released to form interface traps while the ionized holes slowly transport at low dose rate irradiation (Fig. 5(c)). For the synergistic effect, these vast interface traps in the EB Spacer sufficiently influence the carriers in the base region since the area and volume of the base are much smaller than those of the collector. A large number of electrons that are produced by pulsed laser in the E/B junction are captured by these interface traps, so that the probability of holes recombined by electrons in the depletion layer decreases significantly in the base region, and the number of holes collected by the base electrode increases for the sample irradiated with the low dose rate (Fig. 17).

5. Conclusions

In this work, we have carried out the microbeam laser tests to simulate SEE in the SiGe HBT after being experienced by ^{60}Co γ irradiation with high and low dose rates, respectively. The synergistic effect of TID on SEE in SiGe HBT is investigated. The results show that the synergistic effect of SiGe HBT is not only related to bias conditions and dose rate of TID irradiation, but also is affected by the pulsed laser energy and applied voltage of SEE test. The characteristics of the synergistic effect in the SiGe HBT are as follows.

(i) The differences among synergistic effects in various samples are clearly observed when the applied voltage is small in the SEE test ($V_C = +1.5$ V), but are not significant when the applied voltage is large ($V_C = +3$ V).

(ii) The SEE response presents the difference between irradiated and un-irradiated SiGe HBTs when the pulsed laser energy is larger than 5 nJ.

(iii) In general, the transient current and charge collection of the un-irradiated SiGe HBT are more serious than those of γ irradiated devices. The γ irradiations at forward and all-grounded biases have an appreciable effect on SEE in the SiGe HBT, but the influence of TID irradiation at cutoff bias on the synergistic effect is not obvious.

(iv) The effect of positive oxide trap charges induced by TID on the distortion potential of SEE is the major factor for the synergistic effect. Moreover, the recombination of interface traps also plays a role in charge collection by diffusion.

The research results indicate that the γ irradiation has a possibility of mitigating the SEE damage in the SiGe HBT. Meanwhile, our previous researches have found that there is no apparent failure of the SiGe HBT when the total dose accumulates and reaches to 1 Mrad (Si). The TID damage of forward bias irradiation is weakest.[10] Consequently, this work also provides new ideas and research basis for the radiation hardening of SEE in the SiGeHBT.

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