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Sensitivity study of the SiGe heterojunction bipolar transistor single event effect based on pulsed laser and technology computer-aided design simulation

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The single event effect of a silicon–germanium heterojunction bipolar transistor (SiGe HBT) was thoroughly investigated. By considering the worst bias condition, the sensitive area of the proposed device was scanned with a pulsed laser. With variation of the collector bias and pulsed laser incident energy, the single event transient of the SiGe HBT was studied. Moreover, the single event transient produced by laser irradiation at a wavelength of 532 nm was more pronounced than at a wavelength of 1064 nm. Finally, the impact of the equivalent linear energy transfer of the 1064 nm pulsed laser on the single event transient was qualitatively examined by performing technology computer-aided design simulations, and a good consistency between the experimental data and the simulated outcomes was attained.

Keywords: silicon-germanium, heterojunction bipolar transistor, pulsed laser, single event effect, equivalent linear energy transfer (LET) value

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1. Introduction

A silicon–germanium heterojunction bipolar transistor (SiGe HBT) possesses excellent low noise, high frequency and high power gain performance. In addition, SiGe bipolar complementary metal–oxide–semiconductor technology combined with complementary metal–oxide–semiconductor technology provides a unique solution for the development of high-frequency integrated circuits.[1] However, the environmental conditions for operation in deep space are much worse than in a ground environment, while the operational cost is relatively high. Therefore, it is of great importance to enhance the robustness of such devices.

Extreme space environments include environments with extreme temperature and space radiation.[2] According to the literature, SiGe HBTs have strong resistance to the total dose-effect due to their unique structural characteristics.[3] However, by considering the large-area collector–substrate (CS) junction, a bulk silicon process SiGe HBT is more sensitive to the single event effect. This has become a severe problem restricting the space applications of SiGe HBTs.[4] Thus, it is necessary to gain a deep understanding of the mechanism of the single event effect and use various methods to alleviate such damage at the device, circuit or system level.[5] The most sensitive area was found according to the size of the single event transient generated after irradiation. This area was treated with anti-irradiation reinforcement to meet the normal operation of aerospace devices.[6]

In the field of microelectronics, pulsed lasers and heavy ions are two common tools used to evaluate single event effects.[7] Reed *et al.* studied charge collection induced by heavy-ion microbeams.[8] However, Wei *et al.* could not capture the bimodal response generated by the incident laser device. In the laser microbeam experiments conducted by Zhang *et al.*, only a laser with a wavelength of 1064 nm was selected. The minimum spot radius of a 1064 nm laser is large while the minimum spot radius of a 532 nm laser is small. A metal wiring layer is also frequently placed on the surface of the SiGe HBT device. Hence, a laser with a large spot radius will be blocked. Therefore, a laser with a wavelength of 532 nm was selected here. A pulsed laser has the advantages of high resolution, low experimental cost and convenient focusing, and no damage to the devices under test (DUT) was imposed. To a large extent, this makes up for the shortcomings of the ground simulation method and has become the preferred method for the rapid evaluation of the single event effect.[9,10]

For the SiGe HBT device used (model KT9041), it has been demonstrated that the worst biased state is induced when the emitter and base are connected to 0 V and the collector is connected to +3 V. So far there have been relatively few reports on the influence of the laser incident energy on the sensitivity of a SiGe HBT. Therefore, lasers of different wavelengths (1064 nm and 532 nm) and incident energy were used to study the collector transient current peak, cur-

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rent duration and charge collection under different applied bias conditions.[11,12] Finally, the equivalent linear energy transfer (LET) value relationship between the pulsed laser and the heavy ions was established by carrying out technology computer-aided design (TCAD) simulations. The single event transient induced by heavy-ion incidence was also studied.

2. Sample and experimental methods

2.1. Sample introduction

A model PL2210 picosecond laser with a pulse width of 21.8 ps, a lens with a numerical aperture of 0.7 and an oscilloscope with a bandwidth of 12.5 GHz and sample rate of 50 gigasamples·s^{-1} were used.[11] The laser can provide infrared light with a photon energy of 1.17 eV (wavelength 1064 nm) and a frequency-doubled green light component of 2.32 eV (wavelength 532 nm)[7], both of which are Gaussian beams. The incident depths of the 1064 nm and 532 nm wavelength lasers were about 500 μm and 2 μm, respectively. The DUT was a NPN SiGe HBT designed by Tsinghua University, and the vertical direction of the sensitive region was only a few microns. After scanning electron microscope imaging, a SiGe HBT was obtained with a lateral dimension of 240 μm and a longitudinal dimension of 175 μm; the lithographic node (or the emitter size) of the device is 0.4 μm × 20 μm. Because the bandgap width of Ge is smaller than that of Si, introduction of Ge into the base region could reduce the potential barrier height of the PN junction. The carrier injection of the emission junction could also be improved. Although the laser with a wavelength of 1064 nm can pass through the emitter, base and collector regions, this effect cannot be realized due to the coverage of the surface metal wiring layer. However, when the laser was incident from the gap between the emitter and the base, because the beam spot was too large, only part of the laser track could directly pass through the collector area and the CS junction. In addition, the repeatability of the laser experiment was poor. The goal of this work was to select three different sensitive nodes in the interdigital area where the gap was relatively large to examine the single event effect, as shown in Figs. 1(a) and 1(b).

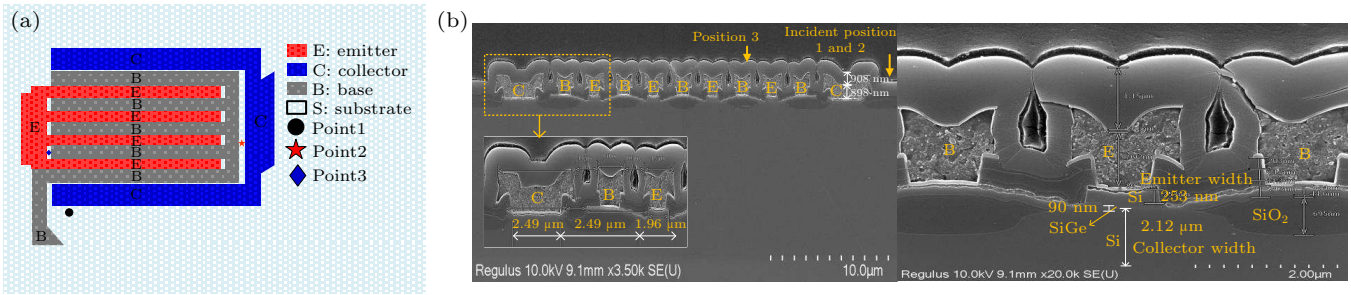


Fig. 1. (a) Simplified diagram of the interdigital area of the SiGe HBT. (b) Cross-sectional diagram of the interdigital area of the SiGe HBT.

2.2. Setting of experimental conditions

The wavelength of the pulsed laser microbeam and the size of the focused spot are considered to be the two main factors,[13] and pulsed lasers with wavelengths of 1064 nm and 532 nm were selected. Firstly, the interdigital region of the device was scanned by a pulsed laser to determine the more sensitive region. Three position points were selected, which were defined as Point1, Point2 and Point3, respectively.[14] The incident position of Point1 is near the outer side of the lateral collector of the interdigitated structure of the device, and the incident position of Point2 is near the inner side of the vertical collector of the interdigitated structure of the device. The incident position of Point3 was at the gap between the emitter and the base. At each sensitive point, the transient current and charge collection of each sensitive point were tested with an oscilloscope under different bias voltages.[12] To ensure the effectiveness of the experiment, the device was in the worst bias state. Since the SiGe HBT substrate does not directly lead out the electrode, the values of $V_E = V_B = 0$ were always maintained, and V_C was connected to a positive voltage. When the collector was placed in a forward bias voltage, a reverse-biased PN junction was also formed in the base–collector (BC) junction and the CS junction. The collector region became a potential well that facilitated the transport of electrons. Thereby, the device was switched to an off-biased state to enhance the funnel electric field caused by the incident photons (Table 1).

Table 1. Experimental parameter settings of the device's sensitive node position.

Sensitive location	Laser wavelength λ (nm)	Bias voltage (V)
Point1	1064/532	$V_C = 1$–3, $V_B = 0$, $V_E = 0$, $V_{STEP} = 1$
Point2	1064/532	$V_C = 1$–3, $V_B = 0$, $V_E = 0$, $V_{STEP} = 1$
Point3	1064/532	$V_C = 1$–3, $V_B = 0$, $V_E = 0$, $V_{STEP} = 1$

3. Discussion and analysis

3.1. The physical mechanism of the single event effect induced by the pulsed laser

When the laser was incident on the semiconductor devices, a host of electron–hole pairs were ionized. These pairs were collected by drift motion under the action of the electric field. When the amount of collected charge exceeds a certain

critical value, the logic state of the device will change, resulting in a single event effect.[15–18]

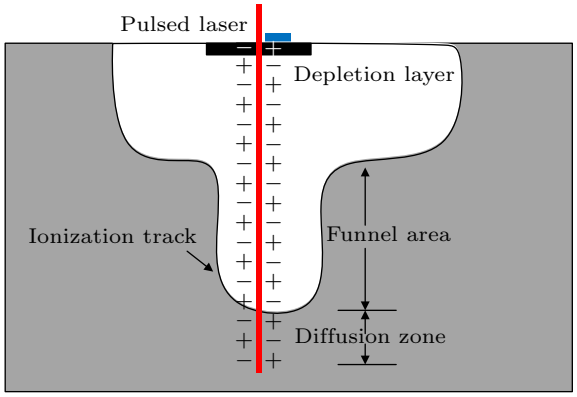


Fig. 2. Schematic diagram of a single event effect.

Equations (1) and (2) provide the expressions for the funnel length and the amount of collected charge that causes a single event effect, respectively:[19]

$$L_{\mathrm{F}} = \sqrt{\mu_{\mathrm{n}} V_0}\left[\frac{3N_0}{8\pi\beta N_{\mathrm{A}} \nu_{\mathrm{P}} D^{1/2}}\right]^{1/3}, \tag{1}$$

$$Q_{\mathrm{F}} = qN_0 L_{\mathrm{F}}, \tag{2}$$

where L_{F} is the funnel length, Q_{F} denotes the amount of charge collected and N_0 increases with increase in the LET value.[19]

3.1.1. Linear absorption

According to the Beer–Lambert law,[15,18] as the depth of the laser entering the semiconductor material is increased, its intensity I decays exponentially with the incident depth x

$$I(x) = I_0 \exp(-\alpha x), \tag{3}$$

where I_0 is the intensity of the laser light on the surface of the device, α represents the absorption coefficient of the material and x is the depth from the surface after the laser has entered the material.[20]

The wavelength is λ, NA is the numerical aperture and the surface of the DUT was placed on the focal plane of the lens. According to[15]

$$\omega_0 = \frac{2\lambda}{\pi \cdot \mathrm{NA}}, \tag{4}$$

the laser beams with wavelengths of 1064 nm and 532 nm have spot radii of 0.97 μm and 0.48 μm, respectively.

3.1.2. Impact of laser wavelength on the single event transient in the interdigital region of the device

The interdigital region of the SiGe HBT was scanned by lasers with an energy value of 3 nJ and wavelengths of 1064 nm and 532 nm, respectively. The captured pulse signal was processed to obtain the collector transient current peak;[17] the results are shown in Figs. 3 and 4. Area A contained in the dotted line depicts the position near the collector and outside of the interdigital area, and area B contained in the dotted line refers to the position where the emitters and bases inside the interdigital area are arranged across each other.

According to Figs. 3 and 4, the maximum transient current peak values generated by the lasers with wavelengths of 1064 nm and 532 nm were 8.8 mA and 33.3 mA, respectively. The reason for this is that although the incident depth of the 1064 nm laser was much deeper than that of the 532 nm one, the minimum spot radii of the 1064 nm and 532 nm lasers were 0.97 μm and 0.48 μm, respectively. Because the spot radius of the 1064 nm laser was large, a large part of the incident energy was blocked by the metal wiring layer. Therefore, the energy that can uniformly pass through the gap in the interdigital structure to cause a transient current was reduced. For the 532 nm laser, although it has a small incident depth, relatively more energy can pass through the gap in the interdigital structure. According to the Beer–Lambert law, due to the large absorption coefficient of the short-wavelength laser, the laser intensity decreased rapidly with increasing incident depth. The laser energy was quickly absorbed in the shallow sensitive area to ionize a large number of electron–hole pairs.

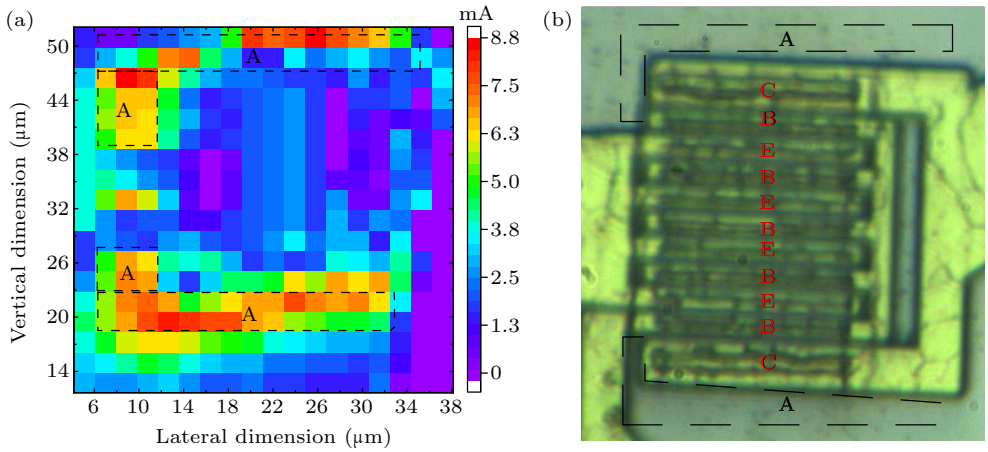


Fig. 3. Under the worst bias, transient current peak diagram (a) and physical diagram (b) of the various points in the interdigital region scanned by the laser with a wavelength of 1064 nm.

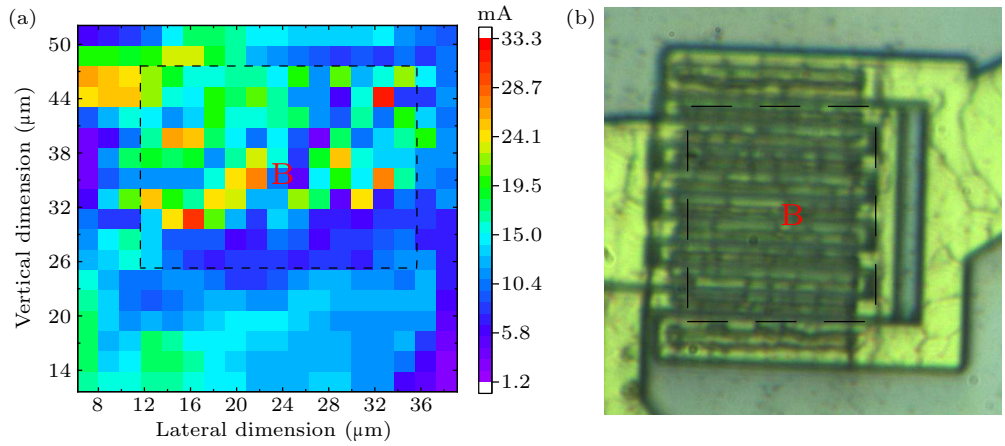


Fig. 4. Under the worst bias, transient current peak diagram (a) and physical diagram (b) of the various points in the interdigital region scanned by the laser with a wavelength of 532 nm.

Under the action of an electric field, the generated electron–hole pairs can be collected to form a transient current. However, the absorption coefficient of the laser with a wavelength of 1064 nm and the ionized carrier density along the incident track were relatively small compared with those of the 532 nm laser. In addition, although the incident depth of the 1064 nm laser was deep, the effective collection depth of the charges was much smaller than the incidence depth. Therefore, the transient current peak value generated by the laser with a wavelength of 1064 nm was reduced.

3.2. Impact of the bias voltage and laser energy on the single event transient and charge collection of the device

Under the same conditions of bias and laser incident energy, the pulsed lasers with wavelengths of 1064 nm and 532 nm were incident on Point1, Point2, and Point3, respectively. From the experimental results depicted in Figs. 5 and 6, when the bias voltage and laser incident energy were the same, the collector transient current lasted the longest when the 1064 nm wavelength laser was incident on Point1, while the transient current peak and the amount of charge collected were also the largest. A saturation value of 110 pC was attained after continuous collection for about 120 ns. When the laser with a wavelength of 532 nm was incident, the collector transient current duration of Point1 was also the longest, and the amount of charge collected reached the saturation value of 280 pC after 20 ns of continuous collection.

According to the charge formula, charge collection is mainly determined by the size and duration of the transient current. The peak value, duration and charge collection of the transient current caused by laser irradiation at different wavelengths at various points can be extracted: Point1 is the most sensitive node of the three, and the experimental phenomenon is consistent with Point2. When the 532 nm pulsed laser was used, the transient current peak value of Point3 was the largest.

The main reason for theses results is that Point1 was not covered by the metal wiring layer. The CS junction is also the most sensitive area of the SiGe HBT device and is connected with the collector area. Due to the large collector area, the ionization track passes through the CS junction. Most of the charges induced along the ionization track were collected in the collector area through drift and diffusion mechanisms to form a transient current. Although both Point1 and Point2 are near the CS junction, there is a metal wiring layer covering near Point2, and part of it will be blocked when the laser is incident. Therefore, under the same laser energy and bias voltage, the transient current peak value and the amount of charge collected at Point2 were less than at Point1. For Point3, although it is located near the emitter and base, due to the tight covering of the metal wiring layer around it when the 1064 nm laser was incident a large part of the energy was blocked.

In addition, although the incident depth of the 1064 nm laser was relatively deep, the effective charge collection depth was only about 20 μm.[21] Therefore, when the pulsed 532 nm wavelength laser was used, due to the small spot diameter, shallow incident depth and large absorption coefficient, the laser intensity reaching the incident surface was large. Therefore, the laser energy blocked by the metal wiring layer was less, and the transient current peak acquired its maximum value.

According to Fig. 5, the bimodal phenomenon was more obvious when the pulsed laser with a wavelength of 1064 nm was used since a small part of the depletion layer potential around the incident track is changed while most of the equipotential lines are confined inside the depletion layer. Only the excess carriers generated inside the depletion layer can be quickly collected under the action of a strong electric field.

Due to the narrow width of the depletion layer of the CS junction, the number of excess carriers deposited inside is limited. Therefore, the collector transient current formed by drift in the depletion layer quickly reaches its first peak. Under the

action of radial carrier diffusion, the ionization track continues to extend and the depletion region around the track produces obvious potential collapse. The electric field in the depletion region continues to extend along the track, resulting in a funnel effect similar to a funnel shape. Meanwhile, a large number of excess carriers were collected under the action of the funnel electric field, forming the second transient current peak. The funnel collection time lasted until the carrier concentration in the substrate was reduced to the initial doping concentration.

Under the same conditions, the single event transient peak and duration and the amount of the collected charge caused by the 532 nm laser were larger than for the 1064 nm laser. Thus, the pulsed laser with a wavelength of 532 nm was selected (Fig. 7). The sensitive node was irradiated with 3 nJ, 6 nJ, and 9 nJ laser energy, respectively. From the transient current peak value and the amount of charge collected it can be concluded that with an increase in laser incident energy, the collector transient current peak value, the transient current duration and the amount of charge collected amount also gradually increased.[12,22]

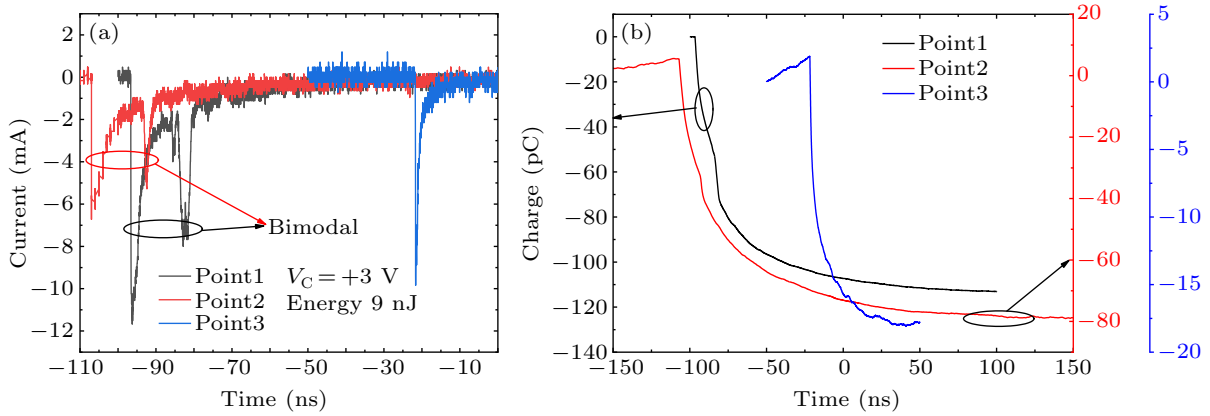


Fig. 5. Under the worst bias, the collector transient current (a) and charge collection (b) caused by the 1064 nm wavelength laser incident on different nodes.

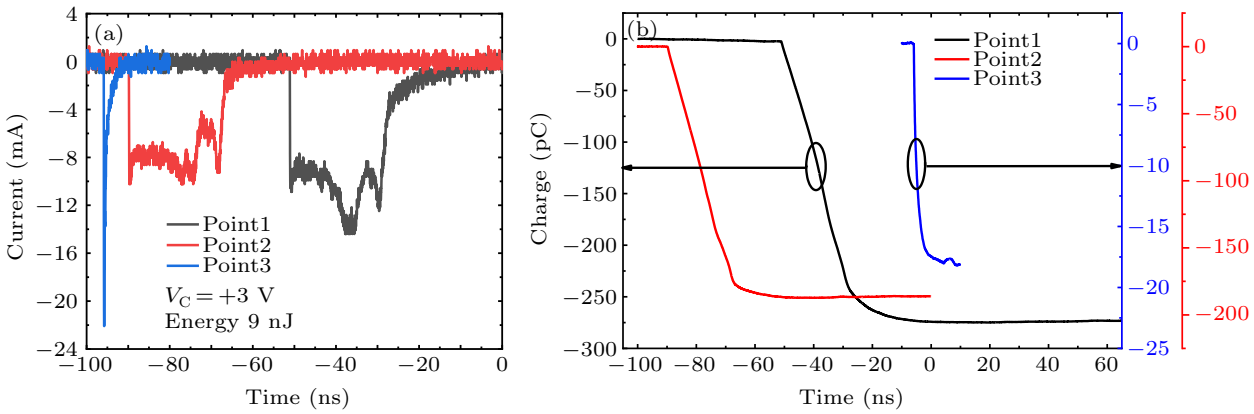


Fig. 6. Under the worst bias, the collector transient current (a) and charge collection (b) caused by the 532 nm wavelength laser incident on different nodes.

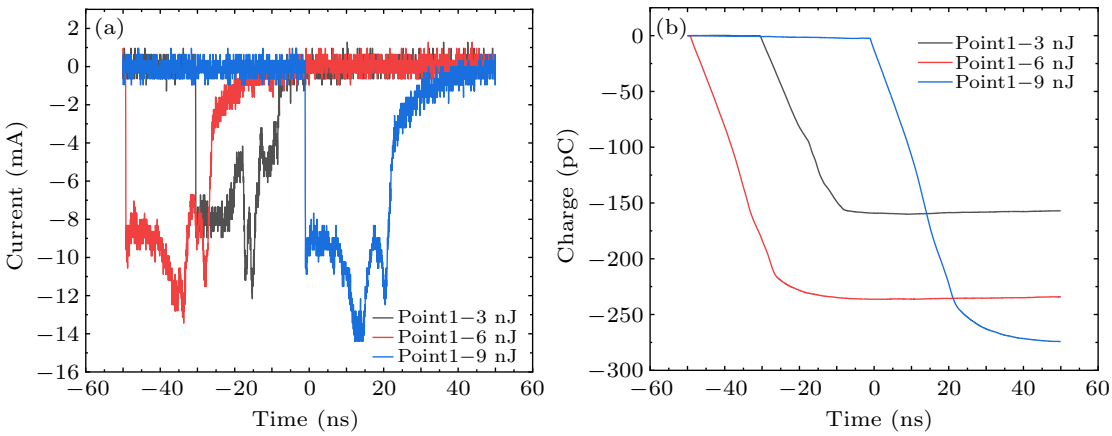


Fig. 7. Under the worst bias, the collector transient current (a) and charge collection (b) when the 532 nm wavelength laser and different energies were incident on Point1.

3.3. Influence of the laser energy and bias voltage on the single event transient peak of a SiGe HBT

According to the above-mentioned results, the single event transient of Point1 is more obvious. Therefore, for Point1, an experiment was carried out that involved changing the laser incident energy and applying different bias voltages to the collector,[3] as shown in Fig. 8.

Figures 8(a) and 8(b) show that the peak value of the collector transient current gradually increased with increasing laser incident energy and bias voltage. When the laser energy was less than 3 nJ, the transient current peak of the collector produced with 1064 nm laser irradiation increased more slowly with increase in the laser energy than the respective current peak with 532 nm irradiation. Nevertheless, with increase in the laser energy, the peak value of the transient current generated by the 1064 nm laser increased rapidly. When the incident energy of the 532 nm laser reached a value of 3 nJ, the transient current peak of the collector hardly increased.[22] The reason for this is that the increase in the laser irradiation energy enhanced the laser intensity. Hence, the linear carrier density N_0 along the incident particle track was increased. Moreover, the electron drift velocity became bigger with increase in the externally applied bias voltage. According to the charge formula, the collection of more charge at a certain time leads to a bigger transient current.[20]

When the laser was incident on Point1, the surface was not covered by the metal wiring layer. The 532 nm wavelength laser had a large absorption coefficient, so the incident depth was only about 2 μm,[15] and the minimum spot radius was half of the spot radius of the 1064 nm laser. When a laser with the same energy was used, the laser energy for the 532 nm wavelength was more concentrated and the laser intensity was higher. Therefore, under the same conditions, the carrier density ionized by the 532 nm wavelength laser was relatively large. These carriers were quickly collected by the collector to form a large transient current. When the collector bias voltage increased, the electric field intensity, the carrier drift velocity and the collection velocity all increased. Within a certain depth, when the laser energy was large enough, the carriers with a larger concentration were ionized, thus affecting the collection speed of the carrier. As a result, with increasing laser energy, the subsequent transient current peak increased slowly.[8]

Subsequently, the single event effect of the SiGe HBT was further studied by changing the laser incident energy at each sensitive node using the lasers with wavelengths of 1064 nm and 532 nm, respectively. As can be seen from Fig. 9, the collector transient current at the three incident points gradually increased with increase in the laser incident energy.

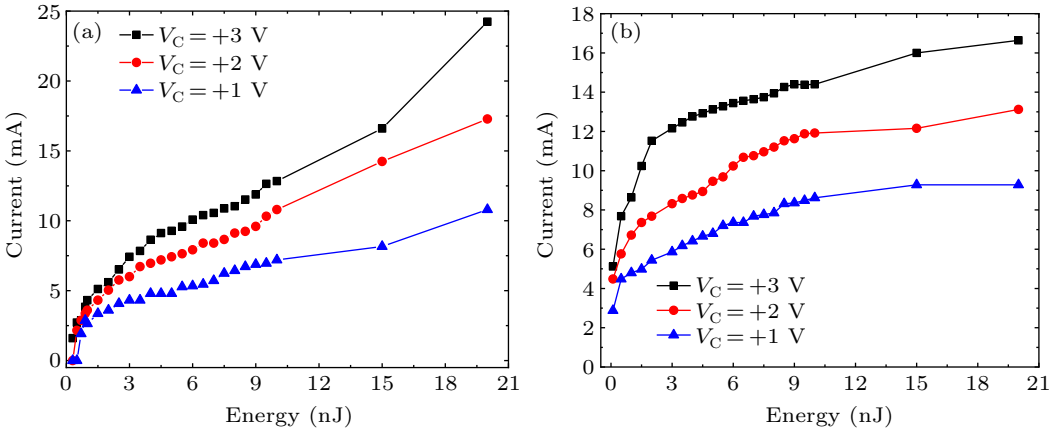


Fig. 8. Relationship between the laser incident energy and collector transient current peak under different bias voltages: (a) $\lambda = 1064$ nm and (b) $\lambda = 532$ nm.

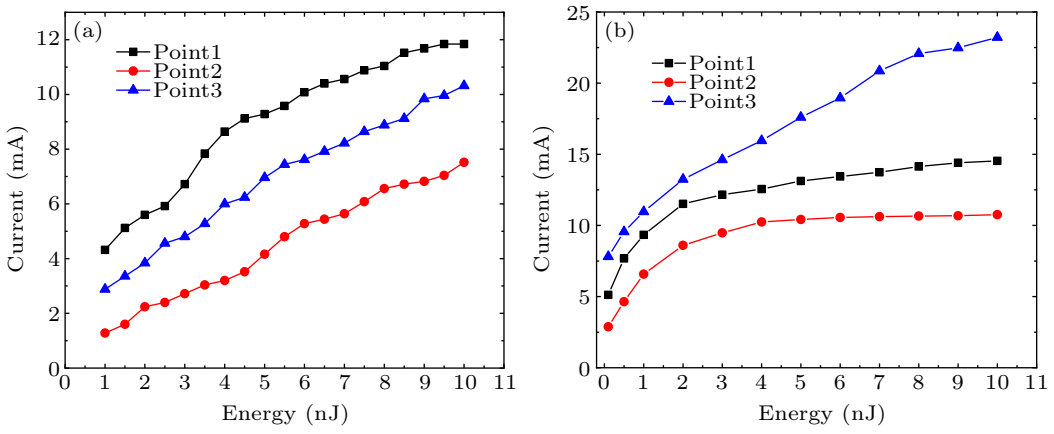


Fig. 9. Relationship between the laser incident energy and collector transient current peak at different nodes: (a) $\lambda = 1064$ nm and (b) $\lambda = 532$ nm.

Because a higher incident laser energy leads to a higher laser intensity, more electron–hole pairs are induced along the incident track. Under the action of the electric field, these electron–hole pairs are rapidly collected to form a larger transient current.[22] The collector transient current peak at Point1 was the largest when irradiated by the 1064 nm wavelength laser, whereas the collector transient current peak at Point3 was the largest when irradiated by the 532 nm wavelength laser, which was consistent with the experimental results in Figs. 5 and 6.

4. Study on the single event effect of SiGe HBT based on TCAD simulation

The TCAD simulation tool was used to explore the single event effect of heavy ions incident on the two-dimensional structure of the SiGe HBT.[30,31] The equivalent conversion was carried out for the heavy-ion LET value and the pulse laser energy. In the experiment, the single event transient caused by incidence of a pulsed laser was equivalent to that generated by the incidence of heavy ions. The number of charges deposited by the pulsed laser and equivalent heavy ions per unit length in semiconductor materials were assumed equal. Then, the LET value of heavy ions was calculated according to the attenuation relationship of the laser intensity I with incident depth x:[15,16]

$$\mathrm{LET}(x) = \mathrm{LET}_0\, \mathrm{e}^{-\alpha x}, \tag{5}$$

$$\mathrm{LET}_0 = 10^{-20} \times \frac{\alpha\lambda E_{\mathrm{ion}}}{\rho hc} E_\Lambda \ \ (\mathrm{MeV}\cdot\mathrm{cm}^2/\mathrm{mg}). \tag{6}$$

The calculated equivalent LET value of the laser with wavelength 1064 nm on the silicon surface is $\mathrm{LET}_0|_{1064} = 0.083E_\Lambda$, where E_Λ/pJ is the pulsed laser energy.[23] Pulsed laser energies of 3 nJ, 6 nJ, and 9 nJ were selected.[24] However, due to Fresnel reflection, when the pulsed laser passed through different materials, the change in refractive index at each interface will cause energy loss. By using Fresnel's equation, it was calculated that the reflectivity of a 1064 nm laser at the air/Si interface was 0.31.[25] Thus, the effective laser incident energies were 2.07 nJ, 4.14 nJ, and 6.21 nJ, respectively. Moreover, the laser equivalent LET values were 171.81 MeV·cm^2·mg^{-1}, 343.62 MeV·cm^2·mg^{-1}, and 515.43 MeV·cm^2·mg^{-1}, respectively. A high laser energy was selected in order to obtain clearer experimental results and reduce the influence of the metal wiring layer.

The potential distribution after ion irradiation for 30 ps on the device with heavy ions equal to the equivalent LET value of a pulsed laser is shown in Figs. 10 and 12. Only the carriers deposited in the depletion region can be collected by the electric field. Because the thickness of the depletion region is only a few microns, the number of deposited charges collected is limited, which makes the peak value of the first transient current higher and the duration shorter. Then, due to the radial diffusion of charge and the expansion of the ion track, the depletion region was deformed. When the electric field extended to the region of the lightly doped substrate, an obvious potential 'collapse' phenomenon occurred. Therefore, charge collection also expanded to form the second waveform of the transient current.[26–29]

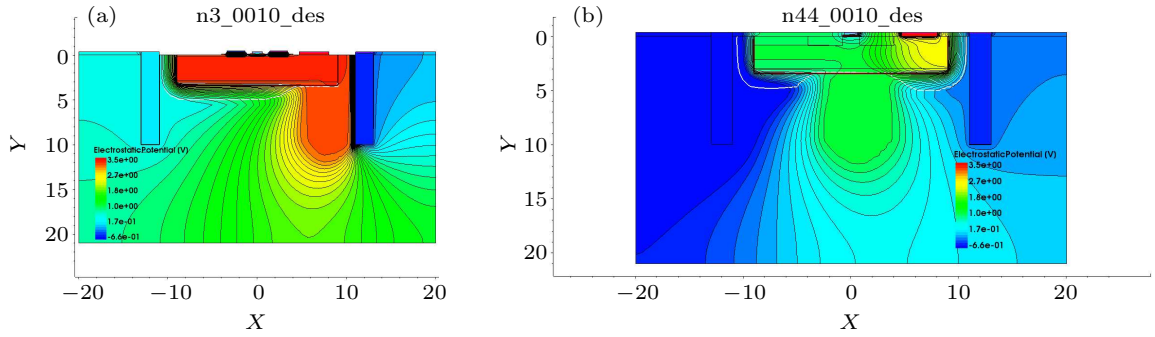


Fig. 10. Under the worst bias, the potential change when the laser equivalent LET value of 9 nJ was incident on the device for 30 ps: (a) incidence from near the collector and (b) incidence from near the emitter and base.

A large number of electron–hole pairs were ionized along the incident track of the heavy ions. These pairs were collected by the two poles of the PN junction under the action of the electric field. The first peak after 30 ps of ion incidence was due to charge collection in the depletion region. However, the duration of this peak was short, and charge collection was low compared with the total collected charge. The second transient current peak after 1.5 ns of ion incidence was caused by collection of the funnel charge.[21]

Firstly, the equivalent LET value when the laser reached the surface of the silicon device was obtained. Then, according to the diagram of variation of laser energy with incident depth,[15] the energy values at different depths were calculated. The incident position in Fig. 11(a) corresponds to Point1 in Fig. 5, while the incident position in Fig. 11(b) corresponds to Point3 in Fig. 5. After heavy ions with the same equivalent LET value to the pulsed laser were incident on the device, the simulated collector transient current exhibited a bimodal phenomenon as in the experiment. According to Figs. 11(a) and 11(b), when the incident energy was the same as the pulsed laser equivalent LET value, the duration of the single event transient current generated when incidence was near the emit-

ter and base was shorter, and no bimodal phenomenon was detected (Fig. 11(b)).

The impact of the pulsed laser equivalent LET value on the peak value of the collector transient current and pulse width was also studied. As can be seen from Fig. 13, the transient current was obviously bimodal when using different laser equivalent LET values. In addition, with increase in the laser equivalent LET value, the current peak value and pulse width were also gradually increased, which was consistent with the pulsed laser experiment.[26]

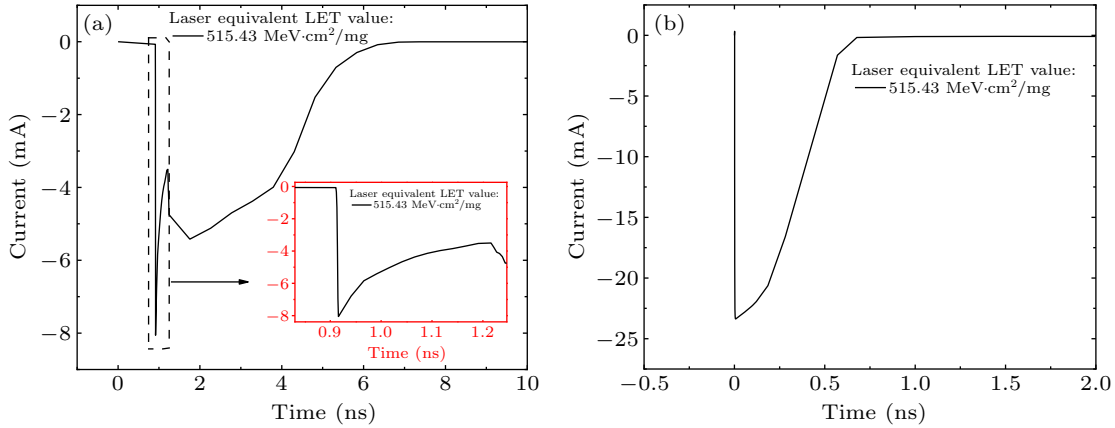


Fig. 11. Under the worst bias, the collector single event transient changes with time when the same laser equivalent LET value is incident: (a) near the collector and (b) near the emitter and base.

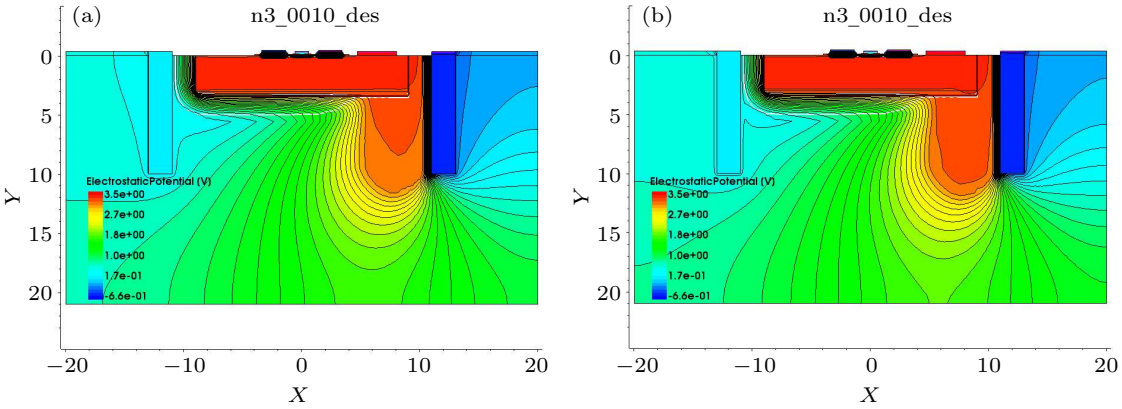


Fig. 12. Under the worst bias, the potential change when laser equivalent LET values of 3 nJ (a) and 6 nJ (b) were incident on the device for 30 ps.

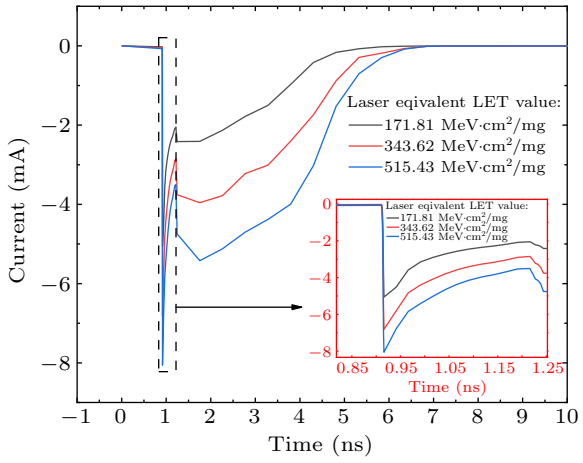


Fig. 13. Under the worst bias, the effect of the laser equivalent LET value on the peak value and the pulse width of transient current.

5. Conclusion

The goal of this work was to perform pulsed laser microbeam experiments and TCAD simulations to study the single event effect of a SiGe HBT. It was experimentally verified that there was a more pronounced effect when a laser with a wavelength of 532 nm was used. Meanwhile, the sensitivity of the SiGe HBT was examined under different bias voltages and laser energies. When the laser with a wavelength of 1064 nm was used near the area of the interdigital structure outside the edge of the collector that was not covered by the metal wiring layer, the sensitivity of the collector was higher than in other areas after laser irradiation. However, when the laser with a wavelength of 532 nm was used, the sensitivity was larger in the area with an interdigital structure. Finally, the single event effect of the device was simulated by under incidence of heavy ions equal to the laser equivalent LET value, yielding a good consistency with the experimental data.

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References

[1] Kasper E, Kissinger D, Russer P and Weigel R 2009 *IEEE Microwave Magazine* **10** 28

[2] Appaswamy A 2009 *Operation of inverse mode SiGe HBTs and ultra-scaled CMOS devices in extreme environments*, Ph. D. Dissertation (Georgia: Georgia Institute of Technoligy)

[3] Zhang J X, He C H, Guo H X, Tang D, Xiong C, Li P and Wang X 2014 *Acta Phys. Sin.* **63** 446453 (in Chinese)

[4] An H, Yang S S, Miao Y J, Yue Y X, Cao Z and Zhang C G 2017 *Nucl. Technol.* **23** 223

[5] Ferlet-Cavrois V, Pouget V, McMorrow D, Schwank J R, Fel N, Essely F, Flores R S, Paillet P and Gaillard M 2008 *IEEE Trans. Nucl. Sci.* **55** 2842

[6] Feng G Q, Ma Y Q, Zhang Z L and Han J W 2008 *Atomic Energy Science and Technology* **42** 36

[7] Xue Y X, Cao Z and Yang S Y 2006 *Spacecraft Environmental Engineering* **23** 98

[8] Buchner S P, Miller F, Pouget V and McMorrow D P 2013 *IEEE Trans. Nucl. Sci.* **60** 1852

[9] Sun Y B, Fu J, Wang Y D, Zhou W, Liu Z H, Li X J and Shi Y L 2016 *Microelectron. Reliab.* **6** 182

[10] Feng G Q, Ma Y Q, ShangGuan S H, Jiang Y G, Han J W, Chen R and Zhu X 2011 *The* 14*th National Symposium on Solar-Earth Space Physics*, Chongqing, China, October 25, p. 149

[11] Zhang J X, Guo H X, Pan X Y, Guo Q, Zhang F Q, Feng J, Wang X, Wei Y and Wu X Y 2018 *Chin. Phys. B.* **27** 108501

[12] Wei J N, He C H, Li P, Li Y H and Guo H X 2019 *Chin. Phys. B* **28** 076106

[13] Buchner S, Roche N, Warner J, McMorrow D, Miller F, Morand S, Pouget V, Larue C and Ferlet-Cavrois V 2012 *IEEE Trans. Nucl. Sci.* **59** 988

[14] Luo Y H, Guo H X, Chen W, Yao Z B, Zhang F Q and Wang Y H 2010 *Microelectron. Reliab.* **40** 464

[15] Huang J Y and Han J W 2004 *Sci. China* **34** 121

[16] Zhang C G, An H, Wang Y, Li C H, Cao Z, Wen X and Xue Y X 2020 *Nucl. Tech.* **43** 62

[17] Pouget V, Fouillat P and Lewis D 2007 *Radiation effects on embedded systems*. 259

[18] Du Y 2016 *Single event effect introduced by photons*, M. S. Dissertation (Cheng Du: University of Electronic Science and technology) (in Chinese)

[19] Huang J G, Han J W, Zhang Q X, Huang Z, Cheng D, Li X Y and Zhang Z L 2005 *The 11th National Society of Sun-Earth-Space Physics Symposium*. p. 132

[20] Melinger J S, McMorrow D and Campbell A B 1998 *Appl. Phys. Lett.* **84** 690

[21] Wei J N, He C H and Li P 2019 *Nucl. Instrum. Method A* **938** 29

[22] Xue Y X, Yang S S, Guo G, Ba D D, An H, Tian K, Cao Z, Shi S T and Shen D J 2012 *Nucl. Technology.* **35** 357

[23] Zhang J X, Wang X, Guo H X, Feng J, Lu L, Li P, Yan Y Y, Wu X X and Wang H 2022 *Acta Phys. Sin.* **71** 314324 (in Chinese)

[24] Zhang H, Guo H X, Zhang F Q, Pan X Y, Liu Y T, Guo C Q, Ju A A, Ouyang X P 2022 *Chin. Phys. B* **31** 018501

[25] Jonathan A 2008 *Bulk silicon-germanium heterojunction bipolar transistor process feature implications for single-event effects analysis and charge collection mechanisms*, Ph.D.Dissertation (Tennessee: Vanderbilt University)

[26] Wei J N, Li Y H, He C H, Li Y, Zhang H, Zhang J X and Guo G 2020 *Sci. China* **63** 851

[27] Ildefonso A, Tzintzarov G N, Nergui D, Omprakash A P, Goley P S, Hales J M, Khachatrian A, Buchner S P, McMorrow D, Warner J H and Cressler J D 2020 *IEEE Trans. Nucl. Sci.* **67** 71

[28] Fleetwood Z E, Lourenco N E, Ildefonso A, Warner J H and Wachter M T 2017 *IEEE Trans. Nucl. Sci.* **64** 398

[29] Buchner S P, Miller F, Pouget V and McMrrow D P 2013 *IEEE Trans. Nucl. Sci.* **64** 1852

[30] Li P, Guo H X, Guo Q, Zhang J X, Xiao Y, Wei Y, Cui J W, Wen L, Liu M H and Wang X 2015 *Chin. Phys. B* **24** 088502

[31] Wei J N, He CH, Li P, Li Y H and Guo H X 2019 *Microelectron. Reliab.* **95** 28