Three-dimensional simulation of fabrication process-dependent effects on single event effects of SiGe heterojunction bipolar transistor*

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The fabrication process dependent effects on single event effects (SEEs) are investigated in a commercial silicon–germanium heterojunction bipolar transistor (SiGe HBT) using three-dimensional (3D) TCAD simulations. The influences of device structure and doping concentration on SEEs are discussed via analysis of current transient and charge collection induced by ions strike. The results show that the SEEs representation of current transient is different from representation of the charge collection for the same process parameters. To be specific, the area of C/S junction is the key parameter that affects charge collection of SEE. Both current transient and charge collection are dependent on the doping of collector and substrate. The base doping slightly influences transient currents of base, emitter, and collector terminals. However, the SEEs of SiGe HBT are hardly affected by the doping of epitaxial base and the content of Ge.

Keywords: SiGe HBT, single event effects, fabrication process dependence, 3D simulation

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1. Introduction

Silicon–germainum heterojunction bipolar transistor (SiGe HBT) technology uses the established silicon manufacturing method bringing about good integration with complementary metal–oxide semiconductor (CMOS) and low cost.[1] SiGe HBT also has favorable transistor performances that speed and frequency is as high as III–V semiconductor devices because of doping Ge in the base region.[2] Importantly, SiGe HBT presents excellent temperature characteristics, which can operate reliably on the lunar surface, where temperature range is from −180 °C during the lunar night to +120 °C during the lunar day.[3–6] In addition, SiGe HBT shows outstanding robustness to total ionizing dose (TID) radiation and displacement damage effects. Thus, SiGe HBT has been emerged as a strong candidate for space applications in extreme environment.[7,8]

However, previous studies found that SiGe HBT is vulnerable to single event effects (SEEs),[9–11] and the charge collection behavior and SEEs mechanism of SiGe HBT also have been investigated.[12,13] Our team has been working on the SEEs of the SiGe HBT since 2010, including the influence of bias conditions, angle of ions striking, and extreme environment on SEEs.[14–16] According to these researches, it is inferred that the SEEs of SiGe HBT is likely related to the fabrication process information such as structure size and doping concentration. However, the SEEs of SiGe HBT for different processes are rarely reported. Furthermore, the device process should be adjusted according to different circuit applications. And the radiation hardening by process (RHBP) is one of the effective methods which achieve radiation tolerance for devices. Thus, it is necessary to study fabrication process dependence on SEEs of SiGe HBT to further investigation of SEEs mechanisms.

If the process dependence on SEEs is studied by using semiconductor processing line to fabricate devices with different process features, the time and costs will be very huge. However, the physical and electrical response of SiGe HBT induced by ions strike under different process conditions can be easily obtained via TCAD simulation, which can expediently change process parameters in the input file. Therefore, a 3-D model of SEE in SiGe HBT is built by TCAD tools in this paper. Then, different collector/substrate (C/S) junction size, different doping of each region and different content of Ge are carried out in SEE simulations. Finally, the current transient and collected charge induced by ions striking are analyzed.

2. Device simulation

2.1. Device structure

The prototype of the device in the simulation is based on the KT9041 SiGe HBT. First, the width of the emitter window is 0.4 μm, and the phosphorus doping of emitter region is 1.4×10^{20} cm^{-3}. Secondly, the base is constituted

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by gradient SiGe in the SiGe HBT. The content of Ge gradually changes from 0% at emitter/base (E/B) junction and base/collector (B/C) junction to 20% in the intrinsic base that forms grading heterojunctions. The thickness of intrinsic base is 0.08 μm. The epitaxial base uses boron doping of 1×10^{19} cm^{-3}. Thirdly, the arsenic doping of collector uses gaussian distribution which the maximum is 1×10^{18} cm^{-3} at the center and the minimum is 6×10^{15} cm^{-3} at the boundaries of the base region. The substrate is uniformly doped boron about 6×10^{14} cm^{-3}. The area of collector/substrate (C/S) junction is large about 18 μm×20 μm. According to the above information, the device structure model of the SiGe HBT is built by 3D TCAD tools as shown in Fig. 1. Figure 2 shows the internal structure and the impurities distribution of the SiGe HBT. In our previous work,[14–16] the Gummel characteristic and output characteristic calculated by simulation are compared with that characteristics measured by KEITHLEY 4200. The results show that the model is in relatively agreement with the actual device.

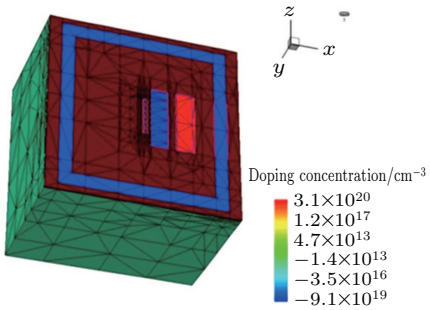


Fig. 1. (color online) 3D view of the SiGe HBT built by TCAD tools.

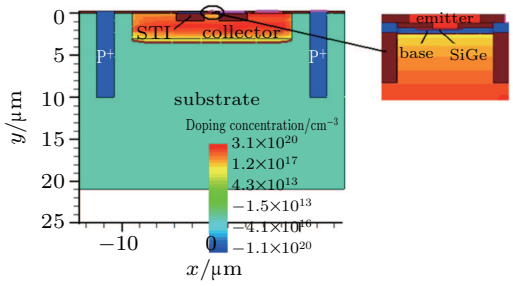


Fig. 2. (color online) The internal structure and the impurities distribution of the SiGe HBT.

2.2. Process conditions in SEE simulation

Our earlier works found that the large transient current and serious charge collection of collector and substrate were identified as the key mechanism of SEEs in this SiGe HBT.[14–16] These phenomena are caused by the funneling potential disturbance at the large C/S junction and in consequence the C/S junction is regarded as the sensitive volume of the SiGe HBT. In addition, through the microbeam laser experiment[17] and TCAD simulation,[18] the area of the C/S junction is inferred to be related to the SEEs of the SiGe HBT. Thus, five kinds of C/S junction sizes of 18 μm×20 μm, 16 μm×19 μm, 14 μm×18 μm, 12 μm×17 μm, and 10 μm×16 μm are selected for the device structure in the SEE simulation.

The previous study[15] shows that the ionization and transportation of carriers are influenced by the doping concentration of various regions in the SiGe HBT. Therefore, ten kinds of substrate doping concentration of 1×10^{13} cm^{-3}, 5×10^{13} cm^{-3}, 1×10^{14} cm^{-3}, 6×10^{14} cm^{-3}, 1×10^{15} cm^{-3}, 5×10^{15} cm^{-3}, 1×10^{16} cm^{-3}, 5×10^{16} cm^{-3}, 1×10^{17} cm^{-3}, and 1×10^{18} cm^{-3}, and eight kinds of collector doping concentration of 4×10^{17} cm^{-3}, 7×10^{17} cm^{-3}, 1×10^{18} cm^{-3}, 4×10^{18} cm^{-3}, 7×10^{18} cm^{-3}, 1×10^{19} cm^{-3}, 3×10^{19} cm^{-3}, and 6×10^{19} cm^{-3} are inputted for the device model in SEE simulations. In addition, the transient current of base induced by SEE is large to be on the same order of magnitude as the transient current of collector and substrate, so the influences of base doping and the epitaxial base doping also should be considered. The doping of 1.6×10^{17} cm^{-3}, 5.6×10^{17} cm^{-3}, 1.6×10^{18} cm^{-3}, 5.6×10^{18} cm^{-3}, 1.6×10^{19} cm^{-3}, 5.6×10^{19} cm^{-3}, and 1×10^{20} cm^{-3} for intrinsic base, and 1×10^{17} cm^{-3}, 5×10^{17} cm^{-3}, 1×10^{18} cm^{-3}, 5×10^{18} cm^{-3}, 1×10^{19} cm^{-3}, 5×10^{19} cm^{-3}, and 1×10^{20} cm^{-3} for epitaxial base are employed in SEE simulation. Moreover, the five percentages of Ge content about 13%, 17%, 20%, 23%, and 28% are used in the device model because the base current is affected by the component of Ge. The electrical characteristics of the SiGe HBT are operated properly with all these parameters.

3. SEE simulation

In essence, the SEE simulation is a calculation of electrical degradation which is induced by the interaction between striking ions and semiconductor materials.[19] Firstly, a reasonable physical method should be chosen on the basis of transistor characteristics in the 3D TCAD numerical simulation. Secondly, the mathematical equations are established under the guidance of the physical method. Finally, the electrical parameters are numerically solved. The high frequency and speed of SiGe HBT technology does not rely on the traditional method of reducing the feature size, but depend on the doped Ge in base region.[20,21] It follows that, the feature size of the SiGe HBT is in microns. Thus, the drift-diffusion model is used as the physical method. The physical process of drift-diffusion is described by the mathematical equations of Poisson's Equation, Continuity Equation, and Carrier Transport Equation. Then, the physical models including Phillips unified mobility, SRH recombination, Auger recombination, velocity saturation, and bandgap narrowing (BGN) are employed in the SEE numerical simulation.[12,13]

The changes of potential, current and charge of SEEs are determined by the generation rate of excess carriers which can be expresses as the follows:[22]

$$G(l,w,t) = G_{\mathrm{LET}}(l)R(w,l)T(t), \tag{1}$$

where $G_{\mathrm{LET}}(l)$ is the linear energy transfer (LET) generation density.[22] $R(w,l)$ and $T(t)$ describe carrier generation rate as a function of space and time respectively.[22] In order to investigate the most serious case of SEE in the SiGe HBT, the ions are assumed to pass through the entire device. Thus, the charge deposition of 0.2 pC/μm which is equivalent to LET = 20 MeV· cm^2/mg is selected in the simulation according to the results of SRIM. The ion track is generated using Gaussian waveform in which the 1/e characteristic time scale is 2 ps, the peak of the Gaussian distribution occurs at 5 ps and the 1/e characteristic radius is 0.1 μm. The striking position of ions is at the center of the device because ions can pass through emitter, base, collector and substrate leading to electrical disturbance for all terminals.

In the SEE simulation, the emitter, base, and collector are ground, and the p-type substrate was biased at reverse bias of −3 V, which provides the worst bias condition in the SiGe HBT on account of forming a reverse biased pn junction at C/S junction. In addition, the low potential of substrate can prevent breakdown of leakage current.

4. Results and discussion

For SEEs of the SiGe HBT, a mass of excess carriers are ionized along the ion track and then transport to the each terminal via drift and diffusion effects so that a large transient current is formed [Fig. 3(a)] and many charges are collected [Fig. 3(b)] at each terminal.[17] Therefore, the current transient and charge collection are the two important factors that should be focused by the simulation in this paper.

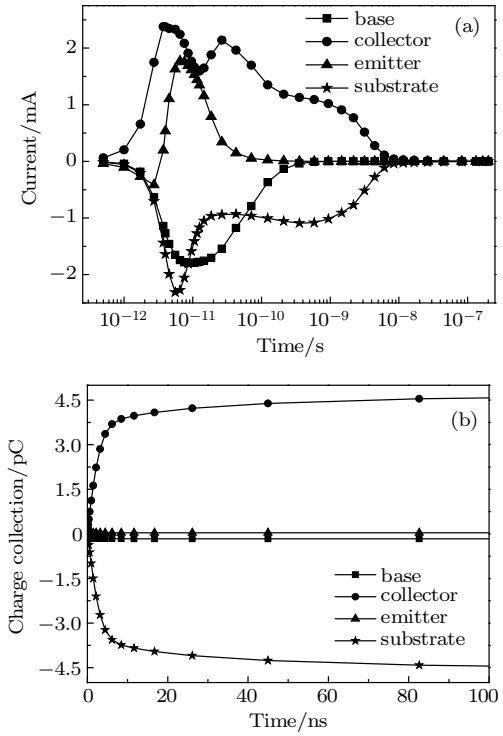


Fig. 3. Current and collected charges as a function of time at various terminals: (a) transient current as a function of time, (b) collected charges as a function of time.

4.1. C/S junction size dependence

Figures 4(a) and 4(b) show the peak of transient current and final collected charges versus the area of C/S junction at substrate and collector. As shown in Fig. 4(b), with the area of C/S junction increase, the collected charges induced by ions striking increase gradually and become saturated finally at substrate and collector. In the SEE of the SiGe HBT, the most of charges are collected via diffusion mechanism by the concentration gradient of carriers which is caused by the funnel potential field. Thus, the range of the funnel potential enlarges with the area of C/S junction increasing, resulting in increase of charge collection. Nevertheless, if the LET of striking ions is the same, the energy deposited along the ions track will be the same, and the influence of funnel electric field at the pn junction will be identical. Consequently, the charge collection tends to be saturated when the area of the C/S junction is larger than the range of the funnel effect. However, in Fig. 4(a), there is no significant dependence between the peak of transient current and the area of the C/S junction for the SEE of the SiGe HBT. It is because the peak of transient current is determined by the carriers which are ionized at the moment of ions strike. That is, the peak of transient current is only related to the drift mechanism caused by the distorted electric field near ions track, but does not depend on the diffusion in the C/S junction.

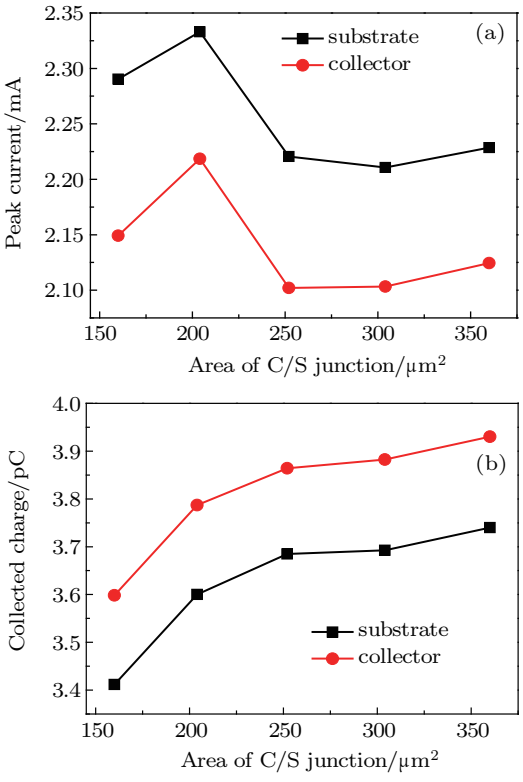


Fig. 4. (color online) Peak of transient current and charges collection versus the area of C/S junction at substrate and collector: (a) peak value of transient current, (b) final charge collection.

4.2. Substrate doping dependence

Figures 5(a) and 5(b) show the terminal currents induced by ions striking as function of time for the lowest doping (1×10^{13} cm^{-3}) and highest doping (1×10^{18} cm^{-3}) of substrate, respectively. The charge collections as function of time are given in Figs. 6(a) and 6(b).

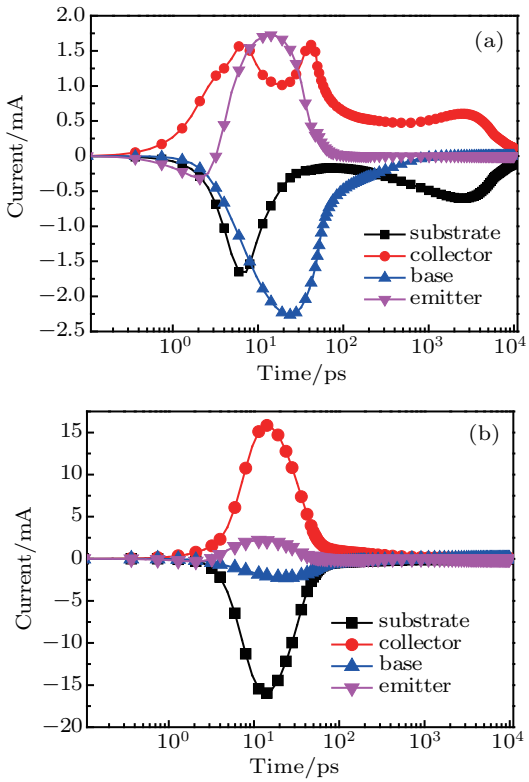


Fig. 5. (color online) Current versus time at various terminals for different substrate doping: (a) substrate doping concentration of 1×10^{13} cm^{-3}, (b) substrate doping concentration of 1×10^{18} cm^{-3}.

Firstly, the SEEs in the SiGe HBT with low substrate doping are discussed according to Fig.5(a) and Fig. 6(a). In Fig. 5(a), the curve shape of transient current contains a drift crest and a diffusion crest at collector and substrate, and the pulse widths are about 8 ns. But the transient currents of base and emitter are only induced by diffusion mechanism formed one crest. The peak values of transient current at all terminals are about 2 mA. In the case of low doping of substrate (1×10^{13} cm^{-3}) as shown in Fig. 6(a), the charge collection increase slowly at collector and substrate, and get close to saturated about 4 pC after 10 ns. If the light-dope is employed in substrate, the fewer electron-hole pairs can be ionized along the ion track so that the peak of transient current is small. However, the recombination rate of carriers becomes low due to lightly doped process. Thus, the carriers cannot be rapidly recombined so as to be slowly collected by diffusion in the funnel field, and resulting in a large crest of diffusion current.

Secondly, as shown in Fig. 5(b) and Fig. 6(b), the SEE characterization of the SiGe HBT with heavily doped substrate is quite different from that of lightly doped ones. When the doping concentration of substrate is as high as 1×10^{18} cm^{-3}, the transient currents of collector and substrate present only one pulse about 100 ps induced by drift mechanism, and the peak values of current are larger than 15 mA [Fig. 5(b)]. In addition, the collected charges of collector and substrate are less about 1 pC and begin to saturate after hundreds of picoseconds of ions striking [Fig. 6(b)]. When the heavily doped process is employed in substrate, a mass of carriers will be ionized along ion track leading to a serious funnel electric field. A fraction of the excess carriers are swept out of the electric field rapidly forming a large transient current. The rest of ionized carriers are recombined because of heavy doping. Therefore, the pulse of diffusion current is not formed and the charge collection is saturated quickly.

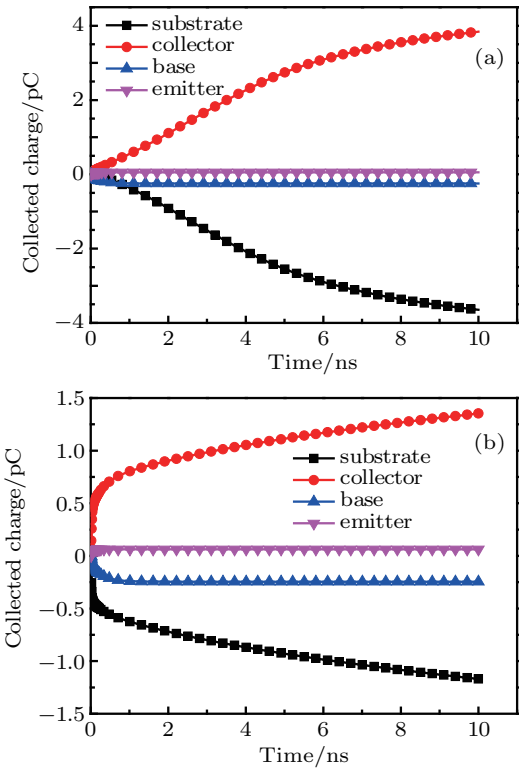


Fig. 6. (color online) Charge collection versus time at various terminals for different substrate dopings. (a) Substrate doping concentration of 1×10^{13} cm^{-3}, (b) substrate doping concentration of 1×10^{18} cm^{-3}.

Figures 7(a) and 7(b) show the peak values of the transient current and collected charges as function of the doping concentration of substrate at various terminals. As seen from the figures, the transient current and the charge collection of base and emitter are both insensitive to the doping concentration of substrate. However, the transient currents of collector and substrate increase linearly as substrate doping rising because the ionizable carriers increase in the funnel field. With the doping concentration of substrate increased by five orders of magnitude, the peak values of the transient current of collector and substrate increase by 15 mA [Fig. 7(a)]. In contrast, the collected charges of collector and substrate decrease by

3 pC as substrate doping rising [Fig. 7(b)]. The decline of charge collection of substrate is caused by the higher recombination rate in the heavily doped substrate. But the change of charge collection at collector is due to equilibrium between electrons of collector and holes of substrate. Therefore, the lightly doped substrate is suitable for using in the circuit that is sensitive to SET.[23–25] But in the circuit which is susceptible to charge collection, the doping concentration of substrate could be appropriately increased.

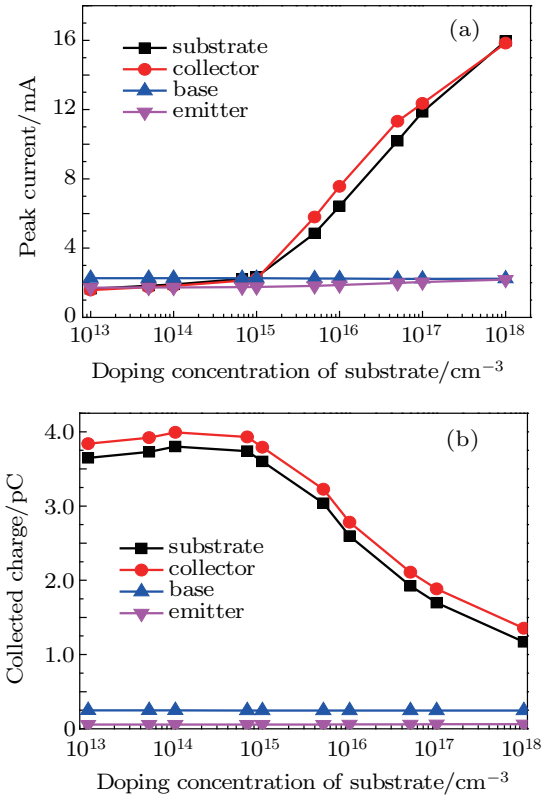


Fig. 7. (color online) Peak value of transient current and collected charges as function of doping concentration of substrate: (a) peak value of transient current, (b) final charge collection.

4.3. Collector doping dependence

Figures 8(a) and 8(b) respectively show the transient currents as function of time in the SiGe HBT of the lowest doping (4×10^{17} cm^{-3}) and the highest doping (6×10^{19} cm^{-3}) at collector. The charge collections as function of time are shown in Figs. 9(a) and 9(b). Comparing Fig. 8(a) with Fig. 8(b), when the collector doping concentration differs by two orders of magnitude, the current hardly change for emitter, base, and substrate. However, the transient currents of collector induced by drift are slightly different. The collector current peak of the SiGe HBT with the collector doping of 4×10^{17} cm^{-3} is 1mA larger than that of the device with the collector doping of 6×10^{19} cm^{-3}. In Figs. 9(a) and 9(b), the patterns of charge collection are similar in the SiGe HBT with various collector doping concentrations, but the charges collected by collector and substrate in the case of high collector doping are slightly more than that in the case of low doping.

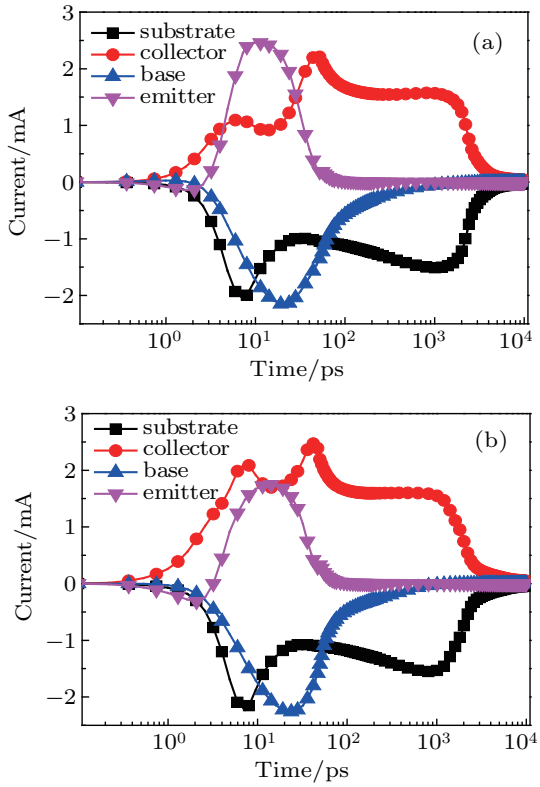


Fig. 8. (color online) Current versus time at various terminals for different collector dopings: (a) collector doping concentration 4×10^{17} cm^{-3}, (b) collector doping concentration 6×10^{19} cm^{-3}.

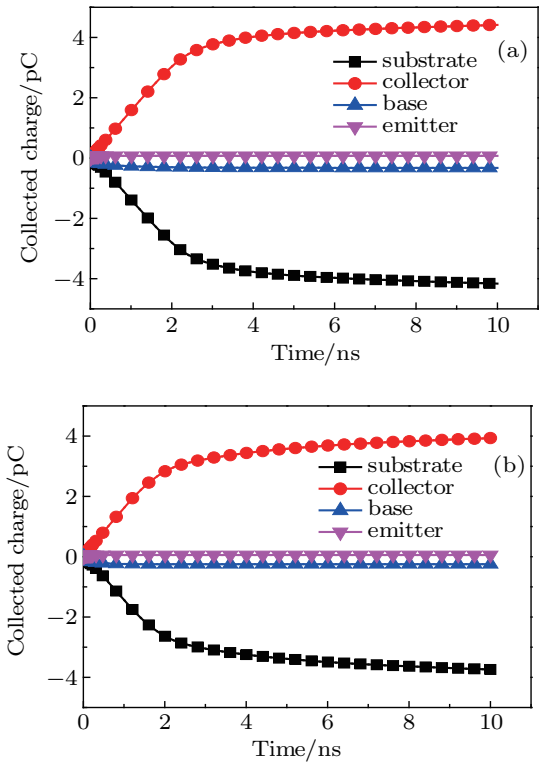


Fig. 9. (color online) Charge collection versus time at various terminals for different collector dopings: (a) collector doping concentration 4×10^{17} cm^{-3}, (b) collector doping concentration 6×10^{19} cm^{-3}.

The peak value of transient current and charge collection as function of doping concentration of collector are given in

Figs. 10(a) and 10(b). In Fig. 10(a), only collector current shows intense sensitivity to the collector doping. With the doping concentration of collector increased by two orders of magnitude, the peak value of transient current increases by 1 mA because more carriers are ionized for the heavily doped process. In view of the funnel electric field that penetrates deep into the substrate, the influence of collector doping on the SEE for substrate is not serious. Thus, the current transient at the substrate and the base is almost unchanged with the collector doping rising. Nevertheless, the transient current peak of emitter slightly decrease as collector doping rising so as to maintain the balance between electron current and hole current. In Fig. 10(b), the charges collected by collector and substrate decline with decrease of collector doping. This is due to the competition between recombination and diffusion in the region of funnel effect. The influences of collector doping concentration on the charge collection of emitter and base are negligible.

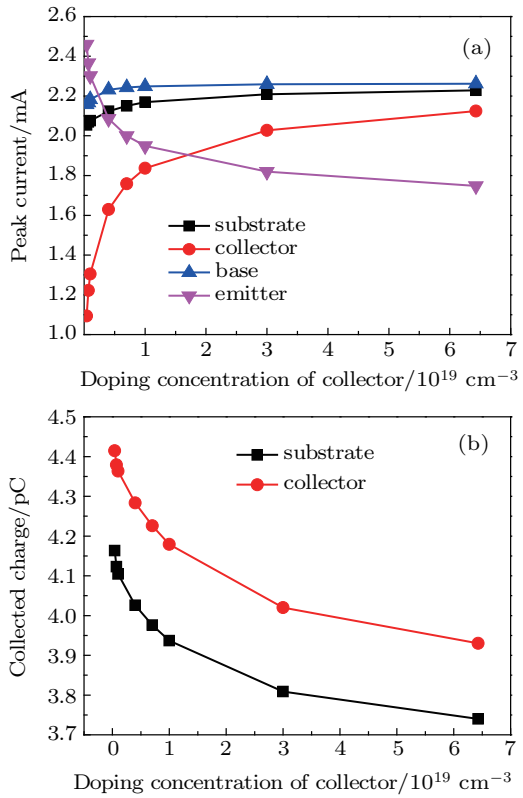


Fig. 10. (color online) Peak values of transient current and collected charges as a function of doping concentration of collector: (a) peak value of transient current, (b) final charge collection.

4.4. Base doping dependence

The ion path passes through emitter, base, collector, and substrate in sequence for an ion striking at the center of device, resulting in a large current transient of base that is even higher than it of substrate. Especially for the SiGe HBT at cutoff bias, the base current transient cannot be ignored for SEE.[17] Figures 11(a) and 11(b) show the transient currents as function of time in the SiGe HBT with lowest base doping (1.6×10^{17} cm^{-3}) and highest base doping (1×10^{20} cm^{-3}), respectively. In Fig. 11, the transient currents of emitter and base are large as 2 mA and 5 mA respectively in the case of heavily doped of base. In contrast, the peak currents are just 0.5 mA at emitter and base under lightly doping of base. In addition, the peak value of collector current is 5 mA and the width of current pulse is about 3 ns when the heavy doping of base is 1×10^{20} cm^{-3}. But the transient current of collector is less than 2 mA at the light base doping of 1.6×10^{17} cm^{-3}.

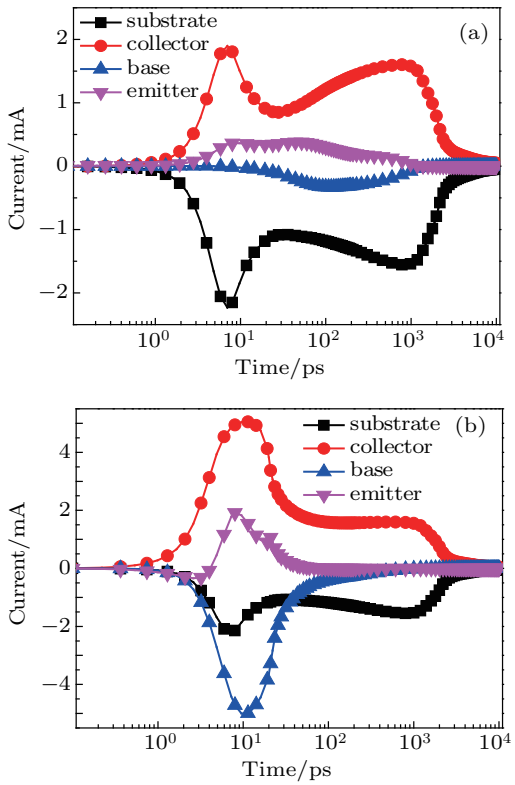


Fig. 11. (color online) Currents versus time at various terminals for different base doping: (a) base doping concentration 1.6×10^{17} cm^{-3}, (b) base doping concentration 1×10^{20} cm^{-3}.

The dependence of base doping on transient current is discussed according to Fig. 12. Firstly, the transient current of substrate remains constant with base doping rising, because the potential in substrate is hardly affected by variation of base doping. Secondly, as doping concentration of base increased, the peak value of collector current stays the same at first and then increases rapidly after the doping of base larger than of 5.6×10^{18} cm^{-3}. When the heavily doped base is employed, a built-in electric field will be formed at B/C junction because of a large concentration difference between base region and collector region. The built-in electric field gives rise to a perturbation of the electrostatic potential in the collector region so that transient current of collector increases. Thirdly, the current peaks of base and emitter increase as base doping increasing. The reason is that the number of ionized carriers per unit time induced by striking ions increase on account of the rising of

base doping. With the base doping rising, the slow increasing of emitter current is due to the balance between positive and negative current.

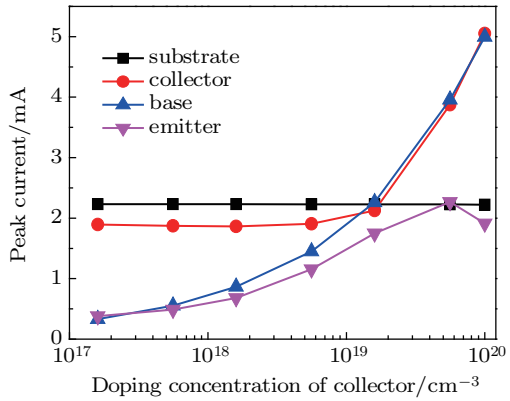


Fig. 12. (color online) Peak values of transient current as function of doping concentration of base.

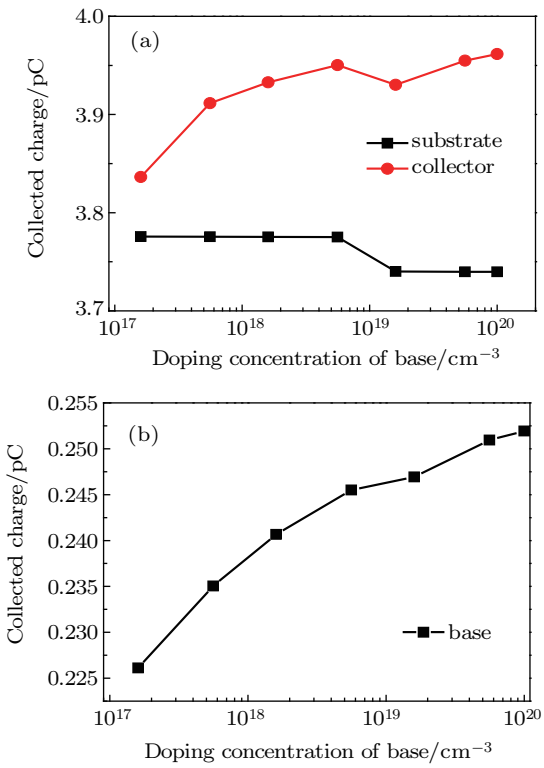


Fig. 13. (color online) Collected charges as a function of doping concentration of base: (a) substrate and collector, (b) base.

Figure 13 shows the final charge collection as function of the base doping. As shown in Fig. 13(a), the charge collection of substrate is invulnerable to the base doping. The collected charges of collector only increase by 0.2 pC with the base doping increased by three orders of magnitude. In addition, the collected charges of base increase by 0.03 pC as base doping rising (Fig. 13(b)). Because there is no applied electric field at E/B and B/C junctions, the perturbation of funnel field along the ion path is not serious in the base region, and the excess carriers are collected rapidly by diffusion mechanism in the base region of small volume. In summary, the charge collection is insensitive to the base doping in the SEE of SiGe HBT.

4.5. Epitaxial base doping dependence

Figure 14 shows the peak values of transient currents versus doping concentration of epitaxial base for all terminals. The results show that the peaks of transient current at base and emitter increase by 0.6 mA with epitaxial base doping rising perhaps because of small resistance of epitaxial base region by heavily-doped. The peaks of transient currents of collector and substrate increase less than 0.1 mA as epitaxial base doping increased by three orders of magnitude. The collected charges as a function of epitaxial base doping at various terminals are shown in Fig. 15 (The few charge collection of emitter is not given in the figure). In the two figures, the collected charges

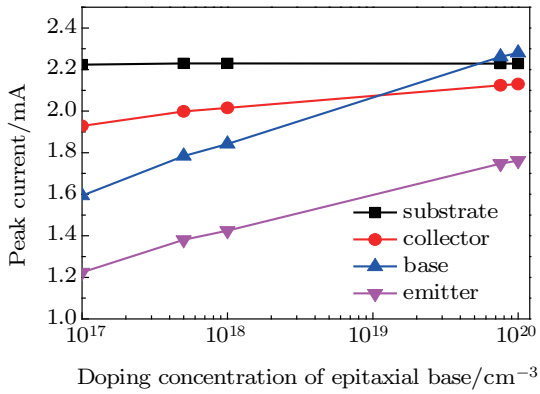


Fig. 14. (color online) Peak values of transient current as a function of doping concentration of epitaxial base.

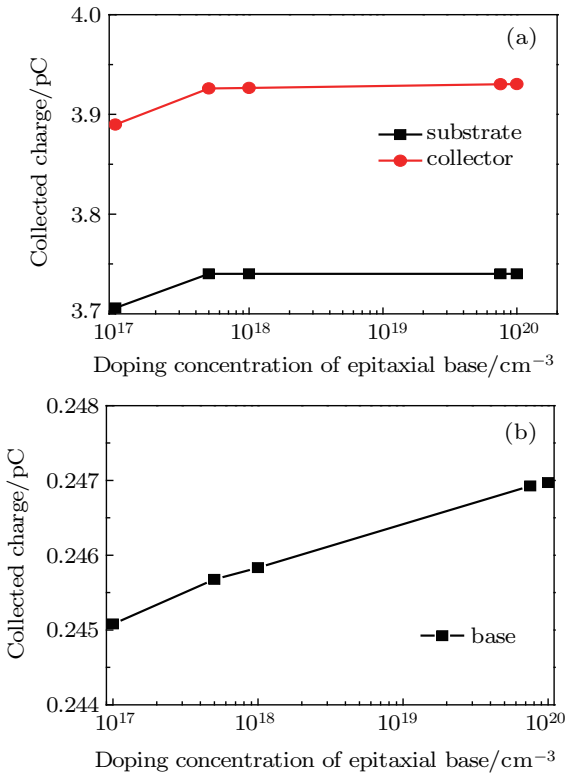


Fig. 15. (color online) Collected charges as a function of doping concentration of epitaxial base: (a) collector and substrate, (b) base.

increase about 0.05 pC at collector and substrate and only increase 0.002 pC at base with epitaxial base doping increasing. These results indicate that the charge collection does not depend on the doping concentration of epitaxial base. Therefore, it is considered that the epitaxial base doping has little effect on the SEE of the SiGe HBT.

4.6. Ge content dependence

The doped Ge in the base region is the key technology to achieve the excellent electrical performances of SiGe HBT, consequently the impact of Ge content on SEEs is investigated in this paper. Figure 16 shows the peak values of transient current versus Ge content at all terminals. The transient currents of substrate and collector are hardly changed with the variation of Ge content. However, the peak values of transient current decrease by 0.2 mA and 0.3 mA for base and emitter respectively, as Ge content increased by 15%.

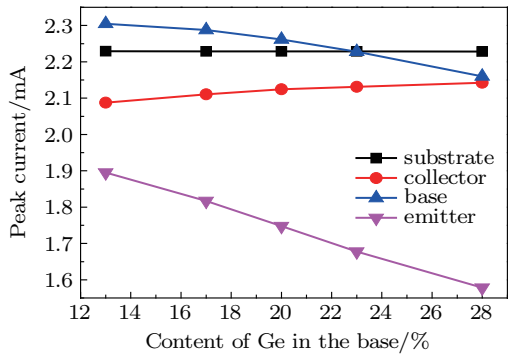


Fig. 16. (color online) Peak value of transient current as a function of content of Ge.

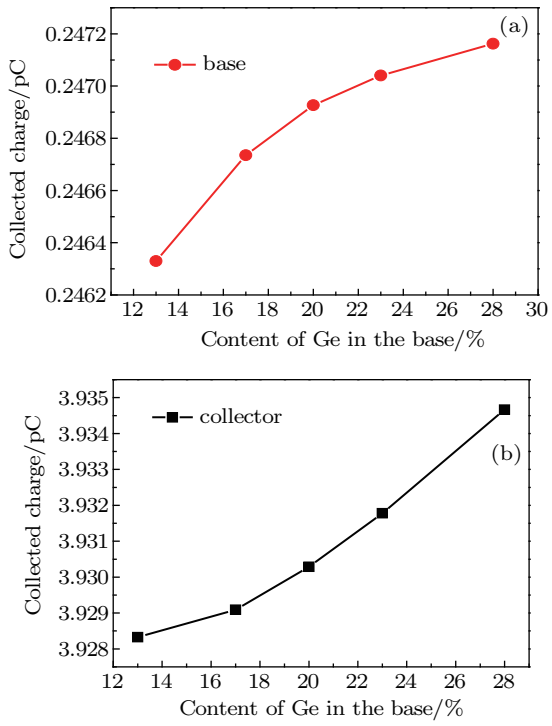


Fig. 17. (color online) Collected charges as a function of content of Ge: (a) base, (b) collector.

The reason may be that the transit time declines due to the increasing of Ge content, leading to the decreased of diffusion current. In Figs. 17(a) and 17(b), the collected charges slightly increase with Ge content rising at base and collector (the collected charges of substrate remain constant, and the charges collected by emitter are negligible). These data lead us to conclude that the Ge content is not the sensitive factor for the SEE of SiGe HBT.

5. Conclusion

The influence of process conditions on the SEE of SiGe HBT is investigated in this paper. The dependences of area of C/S junction, doping concentration, and Ge content on SEE induced by ions striking are simulated. The charge collection is strongly dependent on the area of C/S junction in a certain range, but the transient current has nothing to do with the area of C/S junction. The doping concentration dependence presents different characteristics for transient current and charge collection at various terminals. The transient current of substrate and collector is serious in the case of heavily doped of substrate. Thus, the heavily doped substrate should be avoided in the circuit that is vulnerable to SET. In contrast, the charge collection of substrate and collector are sensitive to the low doping of substrate. The doping concentration of collector only affects the SEE at collector. Interestingly, the base doping has a great influence on the transient current of base and collector. The peak values of the transient currents increase by several milliamperes as base doping increased by a thousand times. Nevertheless, the heavily doped base is used to reduce the area resistance so that the performance and SET need to be weighed up for the SiGe HBT in the design. Finally, the dependences of the epitaxial base doping and Ge content on the SiGe HBT SEE are weak.

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