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Model of transit time for SiGe HBT collector junction depletion-layer*

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The transit time through collector junction depletion-layer is an important parameter that influences AC gain and frequency performance. In SiGe heterojunction bipolar transistor (HBT) collector junction, the depletion-layer width is given in three cases. The models of collector depletion-layer transit time, considering the collector current densities and base extension effect, are established and simulated using MATLAB. The influence of the different collector junction bias voltage, collector concentration of As or P dopant and collector width on collector junction transit time is quantitatively studied. When the collector junction bias voltage, collector doping concentration and collector width are large, the transit time is quite long. And, from the results of simulations, the influence of the collector depletion-layer transit time on frequency performance is considerable in SiGe HBT with a thin base, so it could not be ignored.

Keywords: SiGe HBT, collector depletion-layer transit time
PACC: 6185, 8160C, 9240C

1. Introduction

The collector depletion-layer transit time is an important parameter influencing AC gain and frequency performance. When the base-width becomes narrower and the concentration of the As or P doped in the collector becomes lower, the collector depletion-layer transit time strongly influences AC gain. Especially, when the collector current density is high and the collector depletion-layer width is large, the collector depletion-layer transit time will be the crucial parameter for determining AC gain and frequency performance.[1,2]

The base-width can be very small for an SiGe heterojunction bipolar transistor (HBT). Meanwhile, the self-building electric field that can accelerate minority carriers is established due to the graded Ge and impurity profile. Therefore, the base layer transit time of SiGe HBT can be reduced compared to the general Si bipolar junction transistor (BJT). The hetero-emitter-junction of HBT can restrain the minority carriers injected from base to emitter, which might reduce the emitter layer transit time. Based on the above factors, the effect of the collector depletion-layer transit time on the frequency performance in SiGe HBT is more significant than in BJT. Accordingly, it is very useful to quantitatively study the collector depletion-layer transit time for the design of SiGe HBT.

Based on the transportation process of the carriers in npn-type bi-heterojuction SiGe HBT, the models of the collector depletion-layer transit time are established by considering the collector current densities and base extension effect. The influence of the structure parameters and collector current density on the collector depletion-layer transit time of the SiGe HBT are simulated and analysed. The model is also suitable for the sole-heterojuction SiGe HBT if the material parameters of the collecting region are changed.

2. Models of the collector depletion-layer transit time

The collector depletion-layer transit time is given by

$$\tau_{\mathrm{d}} = \frac{x_{\mathrm{d}}}{2v_{\mathrm{s}}}, \tag{1}$$

where v_{s} is the saturation velocity, x_{d} is the width of depletion-layer, which varies with the collector current

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density. The collector depletion-layer transit time is proportional to the depletion-layer width.

When the collector current density is small, the width of the collector junction space charge region will get wider with increasing collector current density. The region will become fully depleted when the width of the collector junction space charge region increases until it equals the width of the collector. Then the collector junction space charge region meets the substrate with the continuous increase of the collector current density. The base extension effect emerges with the increase of the collector current density, and the collector junction moves to the interface between the collector and substrate. From Eq.(1), it may be found that the collector depletion-layer transit time is proportional to the width of depletion-layer. The influence of the collector current density on the collector depletion-layer transit time will be discussed for three situations: part-depletion, full-depletion and base widening.

2.1. Part-depletion

When the collector current density is small, the collector layer is part-depleted, and the electric field in the space charge region on the two sides of the collector junction is shown in Fig.1 for $x_{\rm n} < w_{\rm C}$ here.

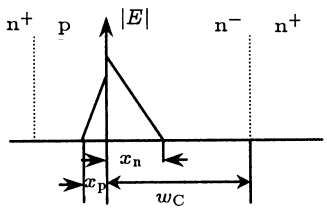


Fig.1. The electric fields of the space charge region on the two sides of the collector junction in SiGe HBT part-depletion layer.

In Fig.1, $w_{\rm C}$ is the width of collector, $x_{\rm p}$ is the width of collector junction depletion layer on the base side, and $x_{\rm n}$ is the width of collector junction depletion layer on the collector side. $x_{\rm n}$ and $x_{\rm p}$ are given in Eqs.(2) and (3) respectively,[1]

$$x_{\rm n} = \left\{ \frac{2\varepsilon_{\rm Si}\varepsilon_{\rm SiGe}(V_{\rm CB}+\phi_1)\left(qN_{\rm B}+\dfrac{J_{\rm C}}{v_{\rm s}}\right)}{\left[\varepsilon_{\rm Si}\left(qN_{\rm C}-\dfrac{J_{\rm C}}{v_{\rm s}}\right)^2+\varepsilon_{\rm SiGe}\left(qN_{\rm C}-\dfrac{J_{\rm C}}{v_{\rm s}}\right)\left(qN_B+\dfrac{J_{\rm C}}{v_{\rm s}}\right)\right]} \right\}^{\frac{1}{2}}, \tag{2}$$

$$x_{\rm p} = \frac{\left(N_{\rm C}-\dfrac{J_{\rm C}}{qv_{\rm s}}\right)}{\left(N_B+\dfrac{J_{\rm C}}{qv_{\rm s}}\right)}x_{\rm n}. \tag{3}$$

In Eqs.(2) and (3), $N_{\rm C}$ is the collector doping concentration, $N_{\rm B}$ is the base doping concentration, $v_{\rm s}$ is the electron saturation velocity, $V_{\rm BC}$ is the applied voltage across the BC junction,$J_{\rm C}$ is the collector current density, $\varepsilon_{\rm Si}$ is the dielectric constant of Si. $\varepsilon_{\rm SiGe}$ is the dielectric constant of $\rm Si_{1-y}Ge_y$ in the base region, and is given as follows:[3]

$$\varepsilon_{\rm SiGe} = 11.9 + 4.9y, \tag{4}$$

where y is the content of Ge in the base region. ϕ_1 is the Fermi potential difference between the base and collector, which may be given by

$$\phi_1 = \frac{kT}{q}\ln\left(\frac{N_{\rm C}N_{\rm B}}{n_{\rm i}^2}\right) - \Delta E_{\rm V}. \tag{5}$$

In Eq.(5), $n_{\rm i}$ is the intrinsic carrier density of Si, and $\Delta E_{\rm V}$ is the valence band offset between the base and collector[3]

$$\Delta E_{\rm V} = 0.96y - 0.43y^2 + 0.17y^3. \tag{6}$$

Then the collector depletion-layer transit time is given by

$$\tau_{\rm d} = \frac{x_{\rm p}+x_{\rm n}}{2v_{\rm s}}. \tag{7}$$

2.2. Intrinsic collector full-depletion

From Eq.(2), there is an enhancement in $x_{\rm n}$ with increasing collector current density. The collector layer is fully depleted when $x_{\rm n} = w_{\rm C}$. The collector junction depletion layer will extend towards the substrate with the continuous increase of the collector current density. Then the space charge region consists of three parts: the base part $x_{\rm p}$, the collector part $w_{\rm C}$ and the substrate part $x_{\rm n}^+$. After the intrinsic collector layer is fully depleted due to the continuous increase of the collector current density, the collector part of

the collector junction depletion layer will be changed from positively charged to electrical neutral, and then becomes a negatively charged region.

As the collector part of the collector junction depletion layer becomes a positively charged region, we have $qN_{\mathrm{C}} - \dfrac{J_{\mathrm{C}}}{v_{\mathrm{s}}} > 0$. The electric field of the space charge region on two sides of the collector junction is shown in Fig.2, in which x_{n}^{+} is the width of the substrate part of the collector junction depletion layer.

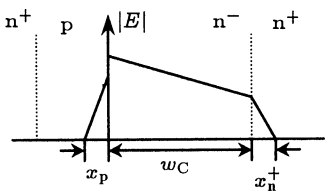


Fig.2. The electric field of the space charge region on the two sides of the collector junction in full-depletion, with the collector part of the collector junction depletion layer being positively charged.

Poisson equations of space charge region are given by

$$\frac{\mathrm{d}E_{21}(x)}{\mathrm{d}x} = -qk_1 \quad -x_{\mathrm{p}} \le x < 0, \tag{8a}$$

$$\frac{\mathrm{d}E_{22}(x)}{\mathrm{d}x} = qk_2 \quad 0 \le x < w_{\mathrm{C}}, \tag{8b}$$

$$\frac{\mathrm{d}E_{23}(x)}{\mathrm{d}x} = qk_3 \quad w_{\mathrm{C}} \le x < w_{\mathrm{C}} + x_{\mathrm{n}}^{+}. \tag{8c}$$

In Eq.(8), E_{21} is the electric field of depletion layer in the base, E_{22} is the electric field of depletion layer in the collector, E_{23} is the electric field of depletion layer in the substrate, and

$$k_1 = \frac{\dfrac{J_{\mathrm{C}}}{qv_{\mathrm{s}}} + N_{\mathrm{B}}}{\varepsilon_{\mathrm{SiGe}}}, \tag{9a}$$

$$k_2 = \frac{N_{\mathrm{C}} - \dfrac{J_{\mathrm{C}}}{qv_{\mathrm{s}}}}{\varepsilon_{\mathrm{Si}}}, \tag{9b}$$

$$k_3 = \frac{N_{\mathrm{C}}^{+} - \dfrac{J_{\mathrm{C}}}{qv_{\mathrm{s}}}}{\varepsilon_{\mathrm{Si}}}. \tag{9c}$$

According to the boundary conditions

$$E_{21}(x)\big|_{x=-x_{\mathrm{p}}} = 0, \tag{10a}$$

$$E_{22}(x)\big|_{x=0} = E_{21}(x)\big|_{x=0}, \tag{10b}$$

$$E_{23}(x)\big|_{x=w_{\mathrm{C}}+x_{\mathrm{n}}^{+}} = 0, \tag{10c}$$

by solving Eq.(8), three electric field equations are obtained for the three parts of the depletion layer

$$E_{21}(x) = -qk_1(x + x_{\mathrm{p}}) \quad -x_{\mathrm{p}} \le x < 0, \tag{11}$$

$$E_{22}(x) = qk_2 x - qk_1 x_{\mathrm{p}} \quad 0 \le x < w_{\mathrm{C}}, \tag{12}$$

$$E_{23}(x) = qk_3\left(x - x_{\mathrm{n}}^{+}\right) \quad w_{\mathrm{C}} \le x < w_{\mathrm{C}} + x_{\mathrm{n}}^{+}. \tag{13}$$

The potential difference between two sides of the space charge region is the sum of the applied voltage V_{BC} across the BC junction, the built-in potential ϕ_1 of BC junction and the Fermi potential difference between the collector and substrate ϕ_2, and can be obtained by integrating over the space charge region

$$\begin{aligned} &V_{\mathrm{CB}} + \phi_1 + \phi_2 \\ &= -\left(\int_{-x_{\mathrm{p}}}^{0} E_{21}(x)\,\mathrm{d}x + \int_{0}^{w_{\mathrm{C}}} E_{22}(x)\,\mathrm{d}x \right. \\ &\quad \left. + \int_{w_{\mathrm{C}}}^{w_{\mathrm{C}}+x_{\mathrm{n}}^{+}} E_{23}(x)\,\mathrm{d}x\right). \end{aligned} \tag{14}$$

In Eq.(14), ϕ_2 is the Fermi potential difference between the collector and substrate

$$\phi_2 = \frac{kT}{q}\ln\left(\frac{N_{\mathrm{C}}^{+}}{N_{\mathrm{C}}}\right). \tag{15}$$

Under the condition that positive charges must be equal to negative charges in the space charge region, we have

$$q\varepsilon_{\mathrm{SiGe}}k_1 x_{\mathrm{p}} = q\varepsilon_{\mathrm{Si}}k_2 w_{\mathrm{C}} + q\varepsilon_{\mathrm{Si}}k_3 x_{\mathrm{n}}^{+}. \tag{16}$$

By solving Eqs.(14) and (16), expressions of x_{n}^{+} and x_{p} are obtained.

$$\begin{aligned} x_{\mathrm{n}}^{+} = \frac{\left[2k_3 w_{\mathrm{C}} - \dfrac{k_1 w_{\mathrm{C}}\varepsilon_{\mathrm{Si}}^2 k_2 k_3}{\varepsilon_{\mathrm{SiGe}}^2 k_1^2} - 2k_1 w_{\mathrm{C}}\left(\dfrac{\varepsilon_{\mathrm{Si}}k_3}{\varepsilon_{\mathrm{SiGe}}k_1}\right)\right]}{2\left[k_1\left(\dfrac{\varepsilon_{\mathrm{Si}}k_3}{\varepsilon_{\mathrm{SiGe}}k_1}\right)^2 + k_3\right]} \\ + \frac{\left\{\begin{array}{l} +\left[2k_3 w_{\mathrm{C}} - \dfrac{k_1 w_{\mathrm{C}}\varepsilon_{\mathrm{Si}}^2 k_2 k_3}{\varepsilon_{\mathrm{SiGe}}^2 k_1^2} - 2k_1 w_{\mathrm{C}}\left(\dfrac{\varepsilon_{\mathrm{Si}}k_3}{\varepsilon_{\mathrm{SiGe}}k_1}\right)\right]^2 - 4\left[k_1\left(\dfrac{\varepsilon_{\mathrm{Si}}k_3}{\varepsilon_{\mathrm{SiGe}}k_1}\right)^2 + k_3\right] \\ \times\left[k_1 w_{\mathrm{C}}^2\left(\dfrac{\varepsilon_{\mathrm{Si}}k_2}{\varepsilon_{\mathrm{SiGe}}k_1}\right)^2 + 2k_1 w_{\mathrm{C}}^2\left(\dfrac{\varepsilon_{\mathrm{Si}}k_2}{\varepsilon_{\mathrm{SiGe}}k_1}\right) - k_2 w_{\mathrm{C}}^2 - \dfrac{2(V_{\mathrm{CB}}+\phi_1+\phi_2)}{q}\right] \end{array}\right\}}{2\left[k_1\left(\dfrac{\varepsilon_{\mathrm{Si}}k_3}{\varepsilon_{\mathrm{SiGe}}k_1}\right)^2 + k_3\right]}, \end{aligned} \tag{17a}$$

$$x_{\rm p} = \frac{k_2\varepsilon_{\rm Si}w_{\rm C} + k_3\varepsilon_{\rm Si}x_{\rm n}^{+}}{k_1\varepsilon_{\rm SiGe}}. \tag{17b}$$

Then the collector depletion-layer transit time is given by

$$\tau_{\rm d} = \frac{x_{\rm p} + w_{\rm C} + x_{\rm n}^{+}}{2v_{\rm s}}. \tag{18}$$

2.3. Base-widening

As the collector current density increases continuously, the base extends towards the collector, and the collector junction moves to the region between the collector layer and the substrate. Then the space charge region consists of two parts: the collector part $x_{\rm p}$ and the substrate part $x_{\rm n}^{+}$. The electric field of the space charge region on two sides of the collector junction is shown in Fig.3.

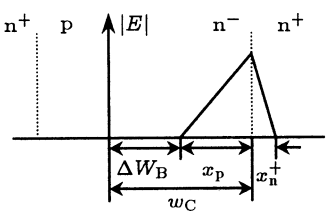


Fig.3. The electric field of the space charge region on two sides of the collector junction in full-depletion after base widening.

The expression of $x_{\rm p}$ is given by

$$x_{\rm p} = w_{\rm C} - \Delta w_{\rm B}, \tag{19}$$

where $\Delta w_{\rm B}$ is the width of the base widening[4]

$$\Delta w_{\rm B} = w_{\rm C}\left[1 - \left(\frac{J_{\rm CR} - qv_{\rm s}N_{\rm C}}{J_{\rm C} - qv_{\rm s}N_{\rm C}}\right)^{1/2}\right]. \tag{20}$$

In Eq.(20), $J_{\rm CR}$ is the critical current density for the start of base widening[5]

$$J_{\rm CR} = qv_{\rm s}\left(N_{\rm C} + \frac{2\varepsilon_{\rm Si}V_{\rm CB}}{qw_{\rm C}^2}\right). \tag{21}$$

Since positive charge is equal to negative charge in the space charge region, the following expression can be obtained

$$x_{\rm n}^{+} = x_{\rm p}\left(\frac{\dfrac{J_{\rm C}}{v_{\rm s}} - qN_{\rm C}}{qN_{\rm C}^{+} - \dfrac{J_{\rm C}}{v_{\rm s}}}\right). \tag{22}$$

So, with the base widening the collector depletion-layer transit time is given by

$$\tau_{\rm d} = \frac{x_{\rm p} + x_{\rm n}^{+}}{2v_{\rm s}}. \tag{23}$$

3. Results of simulation and analysis

In this paper, the models established are simulated and analysed using MATLAB. The relation between the collector depletion-layer transit time $\tau_{\rm d}$ and the collector current density $J_{\rm C}$ is plotted in Fig.4, for different applied voltages across the BC junction, with the doping concentrations in the base layer and the collector layer, and the width of the collector layer being fixed.

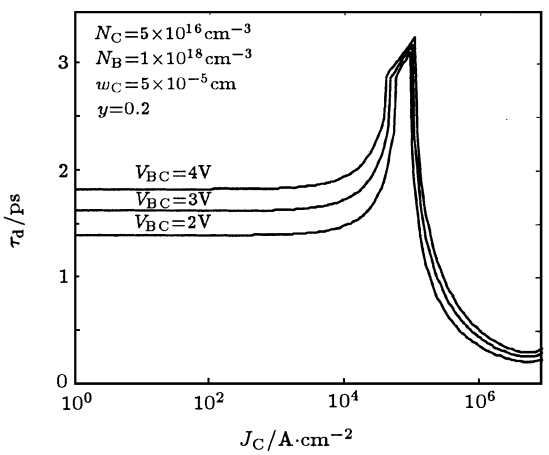


Fig.4. Relations between the collector depletion-layer transit time $\tau_{\rm d}$ and the collector current density $J_{\rm C}$ for different applied voltages across BC junction.

From Fig.4, it can be seen that the influence of the collector junction reverse voltage on the collector depletion-layer transit time is remarkable. When the collector junction reverse voltage is large, the transit time is quite long, and can be longer than the base transit time, because the order of magnitude of the base transit time is about ps for transistors with thin base layer. In order to obtain high frequency performance, the collector junction reverse voltage and the collector layer doping concentration must be synthetically considered when designing transistors. In Fig.4, there are two turnover points in every curve. At the first turnover point, the collector layer is fully depleted. And at the second turnover point, the base extending towards the collector layer starts.

The relation between the collector depletion-layer transit time $\tau_{\rm d}$ and the collector current density $J_{\rm C}$ is plotted in Fig.5 for different doping concentrations of collector layer, with the width of collector layer, the doping concentration of the base and applied voltage of BC junction being fixed.

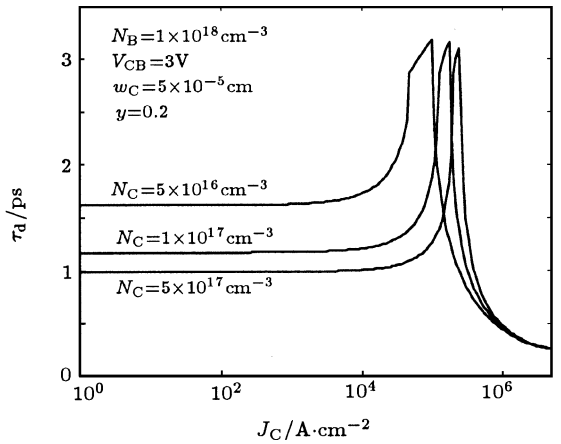


Fig.5. Relations between the collector depletion-layer transit time and the doping concentration of the collector layer.

From Fig.5, it can be seen that increasing doping concentration of collector layer could cut down the collector depletion-layer transit time, but this would influence the performance of BV_{CBO}. So, the device is designed according to the requirement of applications. The higher the doping concentration of the collector layer, the larger the current density for generating full-depletion of the collector layer, and the higher the critical current density for generating base-widening. These can all be seen from Fig.5.

The relation between the collector depletion-layer transit time τ_d and the collector current density J_C is plotted in Fig.6 for different widths of the collector layer, with the doping concentration of the base and collector layer and the applied voltage across BC junction being fixed.

From Fig.6, when the collector layer is full-depleted, the collector depletion-layer transit time τ_d is significantly influenced by the width of the collector layer.

According to Ref.[6], for SiGe HBT with the base width of 0.22μm and the base doping concentration of $10^{17}cm^{-3}$, the base layer transit time is about 10ps, when the device is operating in linear work. From Figs.5, 6 and 7, the collector depletion-layer transit time is less than 2ps, so it has only slight influence on the frequency performance.

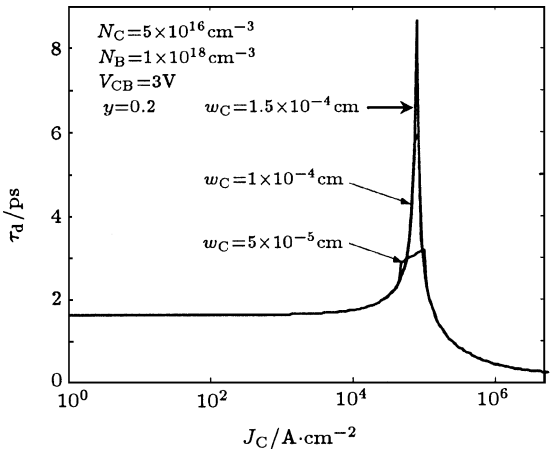


Fig.6. Relations between the collector depletion-layer transit time and the width of the collector layer.

But the cut-off frequency of SiGe HBT used at high frequency is dozens of GHz. According to Ref.[7], the SiGe HBT's base width is 45nm, its base doping concentration is $8\times10^{18}cm^{-3}$, so its base layer transit time is 2.2ps, and the influence of the collector depletion-layer transit time on frequency performance is considerable. Therefore, in designing SiGe HBT for high frequency applications, the influence of the collector depletion-layer transit time on frequency performance must be fully taken into consideration.

4. Conclusion

Based on the transportation process of the carriers in npn-type bi-heterojunction SiGe HBT, the models of the collector depletion-layer transit time, taking into account the collector current densities and base extension effect, have been established. The influences of the structure parameters and collector current density on the collector depletion-layer transit time of the SiGe HBT are simulated and analysed. The collector depletion-layer transit time is quantitatively studied by considering the effect of the base-collector voltage, doping concentration and the width of the collector layer.

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