A device model for thin silicon-on-insulator SiGe heterojunction bipolar transistors with saturation effects*

Xu Xiao-Bo(徐小波)†, Xu Kai-Xuan(徐凯选), Zhang He-Ming(张鹤鸣), and Qin Shan-Shan(秦珊珊)

Key Laboratory of Ministry of Education for Wide Band-Gap Semiconductor Materials and Devices, School of Microelectronics, Xidian University, Xi'an 710071, *China*

(Received 1 April 2011; revised manuscript received 9 May 2011)

In this paper, we describe the saturation effect of a silicon germanium (SiGe) heterojunction bipolar transistor (HBT) fabricated on a thin silicon-on-insulator (SOI) with a step-by-step derivation of the model formulation. The collector injection width, the internal base–collector bias, and the hole density at the base–collector junction interface are analysed by considering the unique features of the internal and the external parts of the collector, as they are different from those of a bulk counterpart.

Keywords: saturation effect, heterojunction bipolar transistor, SiGe, silicon-on-insulator

PACS: 85.30.Pq, 85.30.De, 85.30.–z **DOI:** 10.1088/1674-1056/20/9/098501

1. Introduction

The silicon germanium heterojunction bipolar transistor (SiGe HBT) fabricated on a thin silicon-on-insulator (SOI) has been integrated with the latest 0.13 μm mm-wave SiGe SOI BiCMOS technology and shown decent device performances, including higher Early voltage, weaker avalanche multiplication effect, better trade-off between the base–collector breakdown voltage and the characteristic frequency, better proton radiation effect, smaller parasitic parameters, and improved immunity to the substrate noise and crosstalk.[1]

As the SOI SiGe HBT has both vertical and horizontal current flow paths, the electrical behaviour change makes the conventional models insufficient to describe the device. Although many models are reported to describe various electrical parameters, such as the base transit time, the collector resistance, the depletion capacitance, the Early voltage, and the avalanche current,[2−6] they are only suited to the case of low current situation. We take saturation effects into account and describe the device under the large current situation by focusing on the unique features of the SOI device. The collector is in the injection mode if the transfer current is large enough to make the internal base–collector junction forward biased, specifically in the saturation condition. Saturation models of the bulk device have been reported,[7−9] and our models of the SOI device are derived step by step similar to that of the bulk one. The current is vertical and horizontal, therefore the collector current density parallel to the base–collector junction is non-uniform, and the voltage drop across the collector region is different from that of the bulk one. So the saturation effects of the SiGe SOI device should be analysed carefully. In this paper, we model the saturation effects of the SOI SiGe HBTs for the first time.

The remainder of this paper is organized as follows. In Section 2, we provide information about the investigated transistor and derive the employed models including the collector injection width, the injected hole density, and the internal base–collector bias. In Section 3, the simulation results are demonstrated and the observations are discussed. Finally, the conclusions drawn from the obtained results are given in Section 4.

*Project supported by the National Ministries and Commissions, China (Grant Nos. 51308040203 and 6139801), the Fundamental Research Funds for the Central Universities, China (Grant Nos. 72105499 and 72104089), and the Basic Natural Science Research Program in Shaanxi Province, China (Grant No. 2010JQ8008).

†Corresponding author. E-mail: wavychina@hotmail.com

© 2011 Chinese Physical Society and IOP Publishing Ltd

2. Model derivation for SOI SiGe HBT

Figure 1 shows the schematic diagram of a SiGe HBT on a thin SOI. The width of the collector is about 150 nm,[1] therefore the current flows vertically and makes a turn horizontally to the N^+ collector contact region. The zero point of the x axis is located at the base side edge of the base–collector depletion region at zero bias, and the zero point of the y axis at the edge of the intrinsic base. The analysis is constrained to the left half of the device, and a similar analysis can be made on the other half. We consider just the saturation effect in the hard saturation case, for simplicity, most of the collector region is assumed to be quasi-neutral.

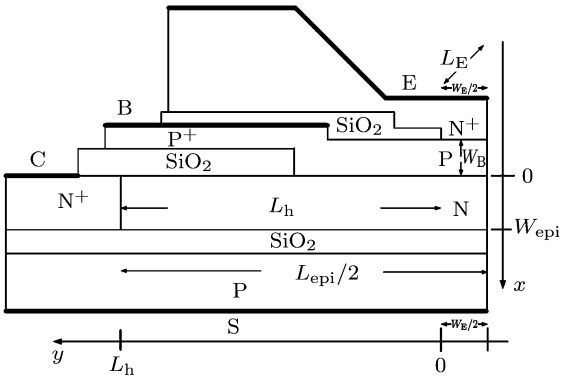


Fig. 1. Schematic of SiGe HBT on thin SOI.

First, the collector injection width is considered. The abrupt base–collector junction ($N_B \gg N_{epi}$, where N_B and N_{epi} are the base and the collector doping concentrations, respectively, and are assumed to be constants) and the depletion approximation are made. The one-dimensional Poisson's equation is given by[10]

$$\frac{\mathrm{d}E}{\mathrm{d}x} = \frac{1}{\varepsilon_{Si}}\left(qN_{epi} - \frac{J_{epi}}{v_{sat}}\right), \tag{1}$$

where ε_{Si} is the dielectric coefficient of silicon, J_{epi} is the collector current density, v_{sat} is the electron saturation drift velocity, and q is the charge of an electron. The term $(qN_{epi} - J_{epi}/v_{sat})$ represents the modulation of the space charge by the electrons in transit.

Equation (1) is integrated twice with boundary conditions

$$E(x_i) = -v_{sat}/\mu_n, \tag{2}$$

$$-\int_{x_i}^{W_{epi}} E(x)\,\mathrm{d}x = V_{CB} + V_d - I_{epi}R_{ch}, \tag{3}$$

where $I_{epi} = A_{em}J_{epi}$ is the collector current, with A_{em} being the emitter area; μ_n is the electron mobility; R_{ch} is the Ohmic resistance of the horizontal part of the external collector, which will be discussed in more detail below; W_{epi} is the collector epilayer width; x_i is the collector injection width; V_{CB} is the reverse base–collector junction bias; and $V_d = V_T\ln(N_{epi}^2/n_i^2)$ is the built-in potential of the base–collector junction, with V_T the thermodynamic potential and n_i the intrinsic carrier concentration. The relation between I_{epi} and x_i is obtained as

$$\begin{aligned} &V_{CB} + V_d \\ &= I_{epi}R_{ch} + \frac{v_{sat}}{\mu_n}(W_{epi} - x_i) \\ &\quad - \frac{1}{2\varepsilon_{Si}}\left(qN_{epi} - \frac{I_{epi}}{A_{em}v_{sat}}\right)(W_{epi} - x_i)^2. \end{aligned} \tag{4}$$

The collector horizontal resistance can be modeled directly, as the current passing through the region is uniform,

$$R_{ch} = \frac{L_h}{2q\mu_n N_{epi}L_E W_{epi}}, \tag{5}$$

where 2 arises from the symmetry, $L_h = (L_{epi} - W_E)/2$ is the collector external horizontal length, W_E and L_E are the emitter width and the emitter length, respectively, and the current flow area is $L_E \times W_{epi}$.

Substituting Eq. (5) into Eq. (4), the final collector injection width for the saturation condition is obtained.

Next, the internal reverse collector–base bias V_j is considered. Here we use the collector quasi-neutrality ($N_{epi} + p = n$, where p and n are the collector hole and electron densities, respectively) and the following basic relation

$$pn = n_i^2\exp[(\phi_n(x) - \phi_p)/V_T], \tag{6}$$

where $\phi_n(x)$ and ϕ_p are the electron and the hole quasi-Fermi potentials, respectively. The ϕ_p is assumed to be independent of x, which has been verified by the numerical simulation by Kull *et al.*,[7] as the collector hole density is relatively small under the saturation condition. Their difference equals the bias applied over the junction, specifically $\phi_n(x) - \phi_p = -V(x)$, where $V(x)$ is the voltage drop from point x to the base. Equation (6) is rewritten as

$$p(x)(p(x) + N_{epi}) = n_i^2\exp(-V(x)/V_T). \tag{7}$$

Apparently $V(0) = V_j$. The problem is in principle solved if the hole density at the base–collector junction

interface $p(0)$ is obtained. In fact, we just calculate another relevant parameter $K(0) = 2p(0)/N_{\rm epi} + 1$ from collector current $I_{\rm epi}$ and collector injection width x_i, which will be discussed below.

The $I_{\rm epi}$ should be analysed by applying the continuity equation in the collector. For the device under the saturation condition, the internal base–collector junction is forward biased, and holes are injected into the collector epilayer. Assuming no recombination, the collector hole current can be given by the continuity equation

$$J_{\rm p} = q\mu_{\rm p}\varepsilon_{\rm BI}p - qD_{\rm p}\frac{{\rm d}p}{{\rm d}x} = 0, \tag{8}$$

where μ_p is the hole mobility, $\varepsilon_{\rm BI}$ is the base built-in electric field for large current, and D_p is the hole diffusion coefficient. The $\varepsilon_{\rm BI}$ can be obtained as

$$\varepsilon_{\rm BI} = \frac{D_{\rm p}}{\mu_{\rm p}}\frac{1}{p}\frac{{\rm d}p}{{\rm d}x} = \frac{KT}{q}\frac{1}{p}\frac{{\rm d}p}{{\rm d}x}, \tag{9}$$

where the Einstein relation is used. The electron continuity equation is

$$J_{\rm n} = q\mu_{\rm n}\varepsilon_{\rm BI}n + qD_{\rm n}\frac{{\rm d}n}{{\rm d}x}, \tag{10}$$

where $D_{\rm n}$ is the electron diffusion coefficient. Substituting Eq. (9) into Eq. (10) and assuming the collector quasi-neutrality again, we obtain the transfer current density as

$$J_{\rm epi} = -J_{\rm n} = -qD_{\rm n}\left(2 + \frac{N_{\rm epi}}{p}\right)\frac{{\rm d}p}{{\rm d}x}. \tag{11}$$

Multiplying both sides of Eq. (11) by ${\rm d}x$ and then integrating the resulting equation from 0 to $W_{\rm epi}$, we have

$$J_{\rm epi} = \frac{qD_{\rm n}}{W_{\rm epi}}\left(2p(0) - 2p(W_{\rm epi}) + N_{\rm epi}\ln\frac{p(0)}{p(W_{\rm epi})}\right). \tag{12}$$

The collector current $I_{\rm epi}$ can be evaluated by combing Eqs. (7) and (12) and multiplying both sides of Eq. (12) by emitter area $A_{\rm em}$, and is expressed as

$$I_{\rm epi} = \frac{1}{R}\left[V_{\rm T}\left(K(0) - K(W_{\rm epi}) - \ln\frac{K(0)+1}{K(W_{\rm epi})+1}\right) + V_{\rm CB} - I_{\rm epi}R_{\rm ch} - V_{\rm j}\right], \tag{13}$$

where

$$R = \frac{W_{\rm epi}}{q\mu_{\rm n}N_{\rm epi}A_{\rm em}}, \tag{14}$$

$$K(0) = \sqrt{1+4n_{\rm i}^2/N_{\rm epi}^2\exp[-(V_{\rm j}+V_{\rm d})/V_{\rm T}]}, \tag{15}$$

$$K(W_{\rm epi}) = \sqrt{1+\frac{4n_{\rm i}^2}{N_{\rm epi}^2}\exp(I_{\rm epi}R_{\rm ch}-V_{\rm d}-V_{\rm CB})}, \tag{16}$$

with R being the low current Ohmic resistance of the vertical collector region, $K(0) = 2p(0)/N_{\rm epi} + 1$, and $K(W_{\rm epi}) = 2p(W_{\rm epi})/N_{\rm epi} + 1$. If the device is under the low current condition, $V_{\rm CB} > 0$ and $K(0) = K(W_{\rm epi})$, equation (13) reduces to Ohm's law

$$I_{\rm epi} = (V_{\rm CB} - I_{\rm epi}R_{\rm ch} - V_{\rm j})/R. \tag{17}$$

With Eq. (7), we obtain

$$p(0)(p(0) + N_{\rm epi}) = n_{\rm i}^2\exp(-V_{\rm j}/V_{\rm T}). \tag{18}$$

By combining Eqs. (13) and (18), $K(0)$ and $V_{\rm j}$ can be calculated from $I_{\rm epi}$, x_i, and $K(W_{\rm epi})$, so can $p(0)$.

3. Verification and discussion

Numerical simulations are performed to investigate the ranges of x_i, $p(0)$, and $V_{\rm j}$ achievable with the variation of $I_{\rm epi}$. For these simulations, a 0.17 μm × 2 μm transistor with a collector length $L_{\rm epi}$ of 800 nm, a collector width $W_{\rm epi}$ of 150 nm, and a base width of 50 nm is established. Doping concentration $N_{\rm epi}$ is 1×10^{17} cm^{-3} for the collector, 2×10^{18} cm^{-3} for the base, 5×10^{19} cm^{-3} for the emitter, collector–base bias $V_{\rm CB}$ is 2.3 V. To analyse the influence of the saturation effect, collector current $I_{\rm epi}$ is varied between 0.1 mA and 10 mA.

Figure 2 shows normalized collector injection width $x_{\rm i}/W_{\rm epi}$ varying with collector current $I_{\rm epi}$. The injection width increases with the increase of $I_{\rm epi}$. There are two reasons for this. First, the voltage drop across the collector resistance can be ignored at low collector current. However with the increase of collector current $I_{\rm epi}$, the voltage drop further increases, and the internal base–collector junction is forward biased at certain $I_{\rm epi}$, which makes the holes in the base injected into the collector. The injected holes accumulate at the boundary of the base–collector space charge region. With the continuous increase of $I_{\rm epi}$, the holes in the collector increase further. Finally, the base region spreads, and the collector injection width increases. Second, at low collector current, the carriers can be ignored. With the increase of $I_{\rm epi}$, the carriers increase, and the pure space charge density in the collector turns to be reversed at certain $I_{\rm epi}$. The

injection width increases with the continuous increase of $I_{\rm epi}$.

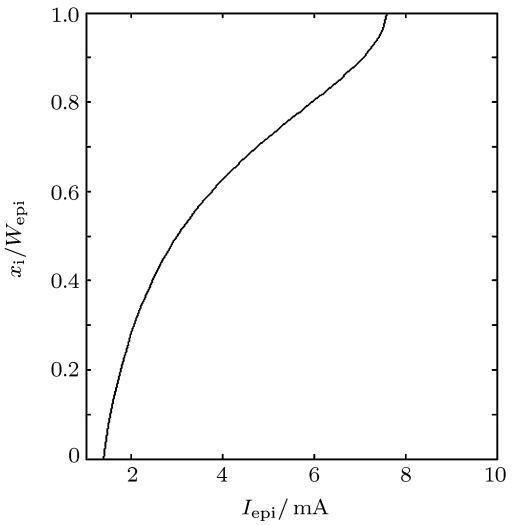


Fig. 2. Relation between normalized collector injection width x_i and collector current.

Figure 3 shows the change of the hole density at the base–collector junction interface with the increase of collector current $I_{\rm epi}$. As can be seen from the figure, the hole density $p(0)$ is tiny and can be ignored for not too large current and increases rapidly at the high current mode. With the increase of the collector current, the HBT operates in a saturation state, and the internal base–collector junction becomes forward biased, which makes the holes injected into the collector. The forward bias increases with the continuous increase of $I_{\rm epi}$, therefore the hole density at the base–collector junction interface further increases.

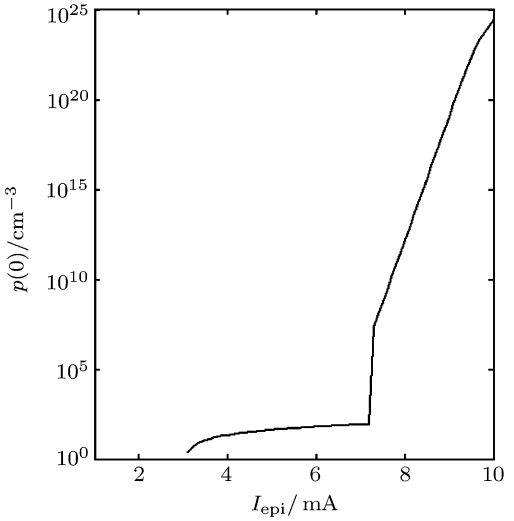


Fig. 3. The relation between hole density at the base–collector junction interface $p(0)$ and collector current $I_{\rm epi}$.

Figure 4 shows internal reverse collector–base bias $V_{\rm j}$ varying with the collector current. The internal reverse collector–base bias decreases with the increase of the collector current. The applied collector–base bias drops mostly on the corresponding base–collector junction due to the fact that the voltage drop across the collector resistance is small and can only make a small contribution to the total applied bias at the low current mode. The increase of collector current $I_{\rm epi}$ causes the voltage drop across the collector resistance to increase, and hence leading to the decrease of the internal collector–base junction voltage. At the point the voltage drop across the collector resistance increases to the applied bias, $V_{\rm j}$ equals zero. The $V_{\rm j}$ is below zero and decreases further, as $I_{\rm epi}$ further increases, which is the case that the base–collector junction is forward biased.

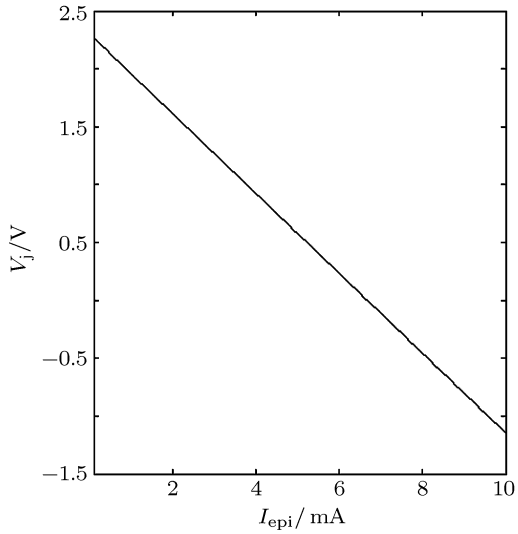


Fig. 4. The relation between internal reverse collector–base bias $V_{\rm j}$ and collector current $I_{\rm epi}$.

4. Conclusion

The saturation effect of an SOI SiGe HBT is analysed with a step-by-step derivation of the model formulation. The collector injection width, the injected hole density, the internal base–collector bias, and the hole density at the base–collector junction interface are described by considering the unique features of the internal and the external parts of the collector, as they are different from those of a bulk counterpart. The presentation of the saturation effect can be employed as a compact model for the design and the simulation of the high performance SOI SiGe devices and circuits.

References

[1] Avenier G, Fregonese S, Chevalier P, Bustos J, Saguin F, Schwartzmann T, Maneux C, Zimmer T and Chantre A 2008 *IEEE Trans. Electron Devices* **55** 585

[2] Fregonese S, Avenier G, Maneux, C, Chantre A and Zimmer T 2006 *IEEE Trans. Electron Devices* **53** 296

[3] Xu X B, Zhang H M, Hu H Y, Xu L J and Ma J L 2011 *Acta Phys. Sin.* **60** 078502 (in Chinese)

[4] Xu X B, Zhang H M, Hu H Y, Ma J L and Xu L J 2011 *Chin. Phys.* B **20** 018502

[5] Xu X B, Zhang H M, Hu H Y and Qu J T 2011 *Chin. Phys.* B **20** 058503

[6] Xu X B, Zhang H M, Hu H Y and Ma J L 2011 *Chin. Phys.* B **20** 058502

[7] Kull G M, Nagel L W, Lee S W, Lloyd P, Prendergast E J and Dirks H 1985 *IEEE Trans. Electron Devices* **32** 1103

[8] de Graaff H C and Kloosterman W J 1995 *IEEE Trans. Electron Devices* **42** 274

[9] Paasschens J C J, Kloosterman W J, Havens R J and de Graaff H C 2001 *IEEE J. Solid St. Circ.* **36** 1390

[10] Kirk C T Jr. 1962 *IRE Trans. Electron Dev.* **9** 164