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Early effect of box, triangular and trapezoidal Ge profiles for SiGe HBTs

Xiaobo Xu*, Wenping Gu, Si Quan, Zan Zhang, Lin Zhang

School of Electronic and Control Engineering, Chang'an University, Xi'an 710064, PR China

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ABSTRACT

This paper deals with the Early effect of SiGe HBTs. Simple, analytical expressions are derived for forward and reverse Early voltages, considering different Ge profiles in the base, including box, triangular, and trapezoidal profiles. The SiGe parameters of the electron diffusion coefficient and the intrinsic carrier concentration are adopted to modify the traditional model. It is predicted that the triangular and box Ge shapes in the base of SiGe HBTs correspond to the best forward and reverse Early voltages, respectively.

1. Introduction

Ge incorporation induced bandgap engineering in the base of silicon bipolar transistors enhances the device performances and becomes more popular in wireless and broadband communications, with the recent record of 505 GHz f_T, 702 GHz f_{max} and a minimum of ring oscillator gate delays of 1.34 ps [1], however the corresponding model about SiGe in the base should be modified to describe SiGe HBTs more accurately for better circuit design and simulation results, one of which is the Early effect. In SiGe HBTs, the Early effect should be carefully analyzed as the Ge introduction makes the traditional SPICE-Gummel-Poon (SGP) model invalid [2]. The Early effect corresponds to the modulation of the quasi-neutral base width by the base-emitter voltage or the base-collector voltage. The theory of the Early effect in SiGe HBTs presented in recent solutions applies only to two extreme cases, including box and triangular Ge shapes in the base [3–5], while the general case of the trapezoidal Ge distribution has not been reported yet. In this paper, a universal model of the Early effect of SiGe HBTs for the above three cases has been proposed, and the influences of different Ge profiles and contents on Early voltages have been discussed carefully. To simplify the derivation, the high injection effect is neglected, and the base doping concentration is constrained to be constant.

2. Model derivation

The collector current of the SiGe HBT is given as [5]

$$I_C = I_S(\exp(V_{BE}/V_T) - \exp(V_{BC}/V_T))/(G_B/G_{B0}) \quad (1)$$

* Corresponding author.
E-mail address: xuxiaobo@chd.edu.cn (X. Xu).

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$$G_{B(B0)} = \int_{-x_E(0)}^{x_C(W_{B0})} \frac{N_B n_{i0}^2}{D_{n,SiGe}(x) n_{i,SiGe}^2(x)} dx \tag{2}$$

where *Is* is the reverse saturation current, $V_{BE(C)}$ is the base-emitter (collector) voltage, V_T is the thermodynamic voltage, $G_B(_{B0})$ is the Gummel number at arbitrary (zero) bias, $x_{E(C)}$ is the change of the base-emitter (collector) depletion layer width, W_{B0} is the quasi-neutral base width at zero bias. $n_{i,SiGe}$ (n_{i0}) is the intrinsic carrier concentration of SiGe (Si). $D_{n,SiGe}$ is the electron diffusion coefficient of SiGe, N_B is the base doping density.

To keep the Early voltage consistent with the SGP model, the effective reverse (forward) Early voltage $V^{eff}_{ER(F)}$ can be defined as [4]

$$V_{ER(F)}^{eff} = G_{B0}\left(\frac{\partial G_{E(C)}}{\partial V_{BE(C)}}\right)^{-1}\Bigg|_{V_{BC(E)}=0} \tag{3}$$

$$G_{E(C)} = \int_{-x_E(W_{B0})}^{0(x_C)} \frac{N_B n_{i0}^2}{D_{n,SiGe}(x) n_i^2(x)} dx \tag{4}$$

For SiGe HBTs, $D_{n,SiGe}$ is approximated by the empirical fit as [6–8]

$$D_{n,SiGe}(x) = (1 + 3y_{ave}) M_n N_B^{-m_n} \tag{5}$$

with $\mu_{n,SiGe}$ (μ_n) the mobility of SiGe (Si), y_{ave} the average Ge content in the base, $M_n = 2.86 \times 10^8 \mathrm{cm\ s^{-1}}$, and $m_n = 0.42$. y_{ave} is the average Ge content in the base.

The intrinsic SiGe concentration $n_{i,SiGe}$ is given as

$$n_{i,SiGe}^2(x) = \gamma n_{i0}^2 \exp\left(\Delta E_{g,eff}(x)/kT\right) \tag{6}$$

where γ is the ratio of the effective state density of SiGe to that of Si, k is the Boltzmann constant, T is the absolute temperature, $\Delta E_{g,\ eff} = \Delta E_{g,\ Ge} + \Delta E_{g,\ dop}$ is the effective band gap narrowing, including the Ge and the base doping contributions.

Fig. 1 shows box, triangular and trapezoidal Ge profiles [6,9], where $y_{c\Delta}$ is the Ge content at the collector edge for the triangular shape, y_e is the Ge content at the emitter edge, X_T is the transition point. Apparently the low ($X_T = 0$) and high ($X_T = 1$) limits of X_T correspond to the box and the triangular shapes, respectively. The average Ge dose is assumed constant, and the bandgap reduction of SiGe can be expressed as follows by assuming linear correlation with the Ge fraction [2,10]

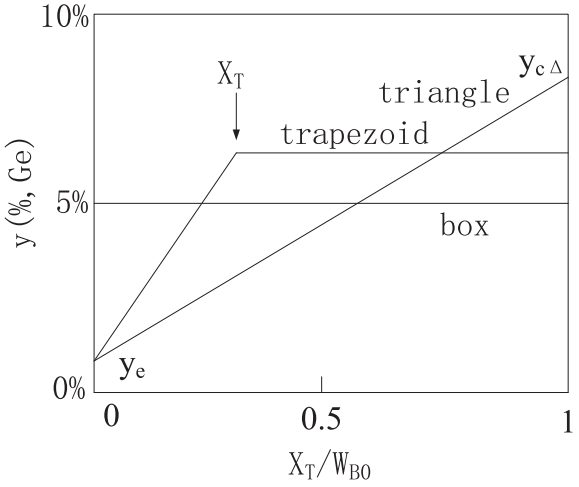

Fig. 1. Ge profiles for box, trapezoidal and triangular shapes.

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