Paper

Optimization of selected parameters of SiGe HBT transistors

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Abstract — SiGe-base HBTs with Gaussian doping distribution are modeled including the effect of the drift field and variable Ge concentration in the base on the diffusion coefficient. Two different Ge distributions in the base are considered: a triangular one and a box one.

Keywords — heterojunction bipolar transistor, base transit time, current gain.

1. Introduction

The past few years have seen significant progress in SiGe heterojunction bipolar transistor (HBT) technology. Today, the use of SiGe-base HBTs is becoming increasingly popular in wireless and high-speed digital communications. In these transistors, band gap grading gives rise to a drift field which aids the minority carrier transport through the base. This fact has been used to realize devices with high cut-off frequency f_T (over 100 GHz).

The design of Ge profile and base doping profile to minimize the base transit time in SiGe HBTs has been studied extensively in the literature [1–5]. The triangular Ge profile is effective in optimizing the band gap grading in the base to minimize t_{BSiGe} (base transit time-the dominant factor in f_T).

Since the exponential base doping profiles and similar ones have already been examined [4, 5] our purpose was to investigate the Gaussian distribution of dopants in the base. In conventional devices such a distribution resulted in a decreased base transit time [6], therefore it would be useful to estimate its influence on the SiGe HBT. Moreover, in real transistors the doping profiles are closer to a Gaussian distribution than to an exponential one.

Two important parameters of the SiGe HBT are modeled, i.e. base transit time and current gain. The model incorporates not only high-doping effects but also the dependence of the diffusion coefficient on the drift field and the variable Ge concentration along the base.

Two types of Ge distribution in the base are examined: the triangular one and the box one [4, 7].

2. Theory

2.1. The base transit time

The base transit time t_{BSiGe} of a n-p-n SiGe HBT may be expressed as [8]

$$t_{\mathrm{BSiGe}} = \int_0^{W_B} \frac{n^2_{i\mathrm{SiGe}}(y)}{N_A(y)} \left(\int_z^{W_B} \frac{N_A(x)}{n^2_{i\mathrm{SiGe}}(x) D_{n\mathrm{SiGe}}(x)} dx \right) dy \,, \quad (1)$$

where W_B – base width, N_A – base doping, $n_{i\mathrm{SiGe}}$ – intrinsic carrier concentration of the SiGe base given as [8]

$$n^2_{i\mathrm{SiGe}}(x) = n^2_{i0} \exp\left(\frac{\Delta E_g}{\mathrm{k}T} \frac{x}{W_B}\right) , \quad (2)$$

where n_{i0} – intrinsic carrier concentration in undoped Si, k – the Boltzmann constant, T – temperature [K], ΔE_g – effective band gap reduction in the base due to the presence of Ge ($\Delta E_{g\mathrm{Ge}}$) and due to heavy doping effects (ΔE_{gDOP}):

$$\Delta E_g(x) = \Delta E_{g\mathrm{Ge}}(x) + \Delta E_{gDOP}(x) \,. \quad (3)$$

The band gap narrowing due to the presence of Ge is assumed to have a linear dependence on Ge concentration: 7.5 meV per 1% of Ge [5] and the Slotboom – de Graff band gap narrowing model [9] is used to model (ΔE_{gDOP}):

$$\Delta E_{gDOP} = \\ = 9\ \mathrm{meV} \left(\ln\left(\frac{N_A(x)}{10^{17}}\right) + \sqrt{\ln^2\left(\frac{N_A(x)}{10^{17}}\right) + 0.5} \right) . \quad (4)$$

The model of electron mobility in a SiGe base used in our analysis is as follows [4]

$$\mu_{n\mathrm{SiGe}}(x) = \left(1 + 3y_{\mathrm{Ge}}(x)\right) \mu_{n\mathrm{Si}}(x) \,, \quad (5)$$

where $\mu_{n\mathrm{SiGe}}(x), \mu_{n\mathrm{Si}}(x)$ – electron mobility in the SiGe base and in silicon, respectively and $y_{\mathrm{Ge}}(x)$ – Ge concentration in the base.

The model of the impurity-concentration-dependent and the electric-field-dependent electron mobility in silicon proposed in [6] has been used

$$\mu_{n\mathrm{Si}} = \frac{\mu_{nc}}{\sqrt{1 + \dfrac{\left(\dfrac{\mu_{nc}|E(x)|}{\nu_c}\right)^2}{\left(\dfrac{\mu_{nc}|E(x)|}{\nu_c} + G_n\right)} + \left(\dfrac{\mu_{nc}|E(x)|}{\nu_S}\right)^2}} \,, \quad (6a)$$

$$\mu_{nc} = \mu_{n1} + \frac{\mu_{n0}}{1 + \dfrac{N_A(x)}{N_{ref}}} \,, \quad (6b)$$

where: $\mu_{n1} = 232$ cm^2/Vs, $\mu_{n0} = 1180$ cm^2/Vs, $\nu_c = 4.9 \cdot 10^6$ cm/s, $\nu_S = 1.04 \cdot 10^7$ cm/s, $G_n = 8.8$,

$N_{ref} = 8 \cdot 10^{16}$ cm^{-3}. Using Einstein's relation, the electron diffusion coefficient may be obtain from the following equation:

$$D_{n\mathrm{SiGe}}(x) = \frac{\mathrm{k}T}{q}\mu_{n\mathrm{SiGe}}(x)\,. \tag{7}$$

To express the base doping profile we introduced a Gaussian-type function

$$N_A(x) = N_0 \exp\left(-\ln\left(\frac{N_0}{N_C}\right)\left(\frac{x}{W_B}\right)^2\right). \tag{8}$$

This function satisfies the boundary conditions

$$N_A(0) = N_0\,, \tag{9a}$$

$$N_A(W_B) = N_C\,. \tag{9b}$$

Additionally, we assume that the drift field at the base-collector junction is large enough to saturate the electron velocity. The transit time through the neutral base region is thus given by

$$\mathrm{t}_{\mathrm{BSiGe}} = \int_0^{W_B} \frac{n_{i\mathrm{SiGe}}^2(y)}{N_A(y)}\left(\int_z^{W_B} \frac{N_A(x)}{n_{i\mathrm{SiGe}}^2(x)D_{n\mathrm{SiGe}}(x)}dx\right)dy + \\ + \frac{1}{\nu_S}\int_z^{W_B} \frac{N_A(W_B)n_{i\mathrm{SiGe}}^2(x)}{n_{i\mathrm{SiGe}}^2(W_B)N_A(x)}dx\,, \tag{10}$$

where ν_S is the saturation velocity of electrons. Comparing (1) and (10) one may easily see that the base transit time is higher in the latter case.

2.2. The current gain

The influence of the variations of the band gap, Eq. (3) and electron diffusion coefficient, Eq. (7) on the dc terminal properties of the SiGe HBT may be expressed in a closed-form for a Gaussian base doping profile, Eq. (8) using the generalized Moll-Ross formula [8]:

$$J_{C\mathrm{SiGe}} = \frac{q\left(\exp\left(\frac{qU_{BE}}{\mathrm{k}T}\right)-1\right)}{\int_0^{W_B}\frac{N_A(x)}{n_{i\mathrm{SiGe}}^2(x)D_{n\mathrm{SiGe}}(x)}dx} = \\ = J_{C0\mathrm{SiGe}}\left(\exp\left(\frac{qU_{BE}}{\mathrm{k}T}\right)-1\right), \tag{11}$$

where all parameters have been defined above. Incorporation of the carrier velocity saturation effects to $J_{C0\mathrm{SiGe}}$ yields the following expression [10]

$$J_{C0\mathrm{SiGe}} = \frac{q}{\int_0^{W_B}\frac{N_A(x)}{n_{i\mathrm{SiGe}}^2(x)D_{n\mathrm{SiGe}}(x)}dx + \frac{N_A(W_B)}{n_{i\mathrm{SiGe}}^2(W_B)\nu_S}}\,. \tag{12}$$

For identically constructed devices, the ratio of β between SiGe HBT and Si BJT can be determined from the equation [7]

$$\left.\frac{\beta_{\mathrm{SiGe}}}{\beta_{\mathrm{Si}}}\right|_{U_{BE}} \approx \left.\frac{J_{C0\mathrm{SiGe}}}{J_{C0\mathrm{Si}}}\right|_{U_{BE}}\,. \tag{13}$$

3. Results

In the present study, we have considered a SiGe-base HBT transistor with the neutral base width of 50 nm and the Gaussian doping profile with the peak concentration $N_0 = 10^{19}$ cm^{-3} and minimum concentration $N_C = 10^{17}$ cm^{-3}.

First of all we have examined transistor with triangular Ge profile with concentration at the emitter edge of base $y_{E\mathrm{Ge}} = 0\%$ and varying concentration of Ge at the collector edge $y_{C\mathrm{Ge}}$.

The ratio of the base transit time $t_{\mathrm{BSiGe}}/t_{\mathrm{BSi}}$ (for identically constructed HBT and BJT) is plotted in Fig. 1 as a function of $y_{C\mathrm{Ge}}$. To illustrate the influence of the drift field

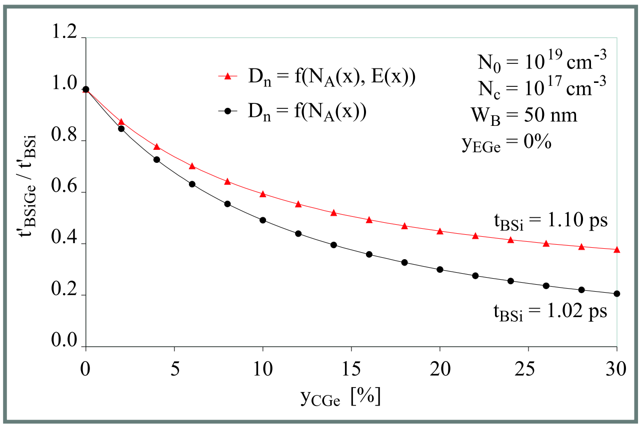

Fig. 1. Normalized base transit time versus Ge concentration at the collector edge of the base for cases: diffusion coefficient dependent and independent on the drift field.

the base transit time was calculated in two ways: with the diffusion coefficient either dependent or independent of the field. The high-doping effects were taken into account in both cases. As seen calculation of the base transit time assuming diffusion coefficient independent on the field underestimates the value of this parameter.

The current gain β was studied in a similar (Fig. 2). This time assumption that the diffusion coefficient is independent on the drift field results in a severe overestimation of the gain.

For the purposes of comparison we have repeated the above mentioned analysis calculating the diffusion coefficient as a function of $y_{tot\mathrm{Ge}} = \frac{y_{C\mathrm{Ge}} + y_{E\mathrm{Ge}}}{2}$ [4] rather than as a function of the position-dependent Ge concentration. It turned out that the base transit time was not sensitive to the change, while in the case of the current gain the simplified method yields overestimated values (Fig. 2).

The effect of finite velocity saturation on the base transit time is illustrated in Fig. 3. It is obvious that this effect increases the transit time. On the other hand, the changes of the current gain are almost imperceptible.

Moreover, we have modeled the parameters of a transistor with a box Ge profile and the proposed Gaussian doping profile. All effects mentioned above have been incorporated. A comparison of the normalized base transit times

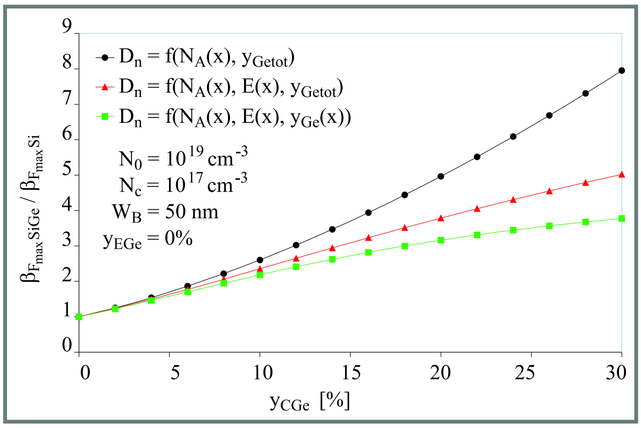

Fig. 2. Normalized current gain versus Ge concentration at the collector edge of the base for cases: A. diffusion coefficient dependent and independent on the drift field; B. diffusion coefficient dependent on constant $y_{totGe} = \frac{y_{CGe}+y_{EGe}}{2}$ or variable Ge concentration along the base.

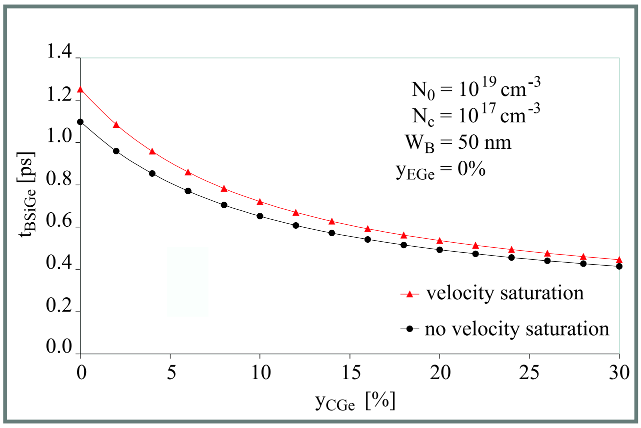

Fig. 3. Base transit time versus Ge concentration at the collector edge.

in the case of box and triangular Ge profiles in the base is show in Fig. 4 as a function of the total Ge concentra-

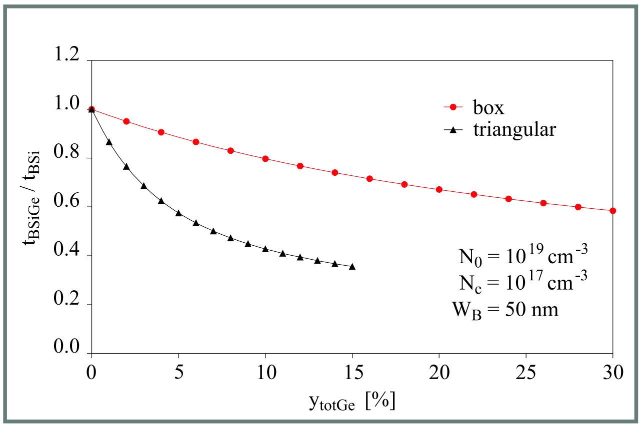

Fig. 4. Normalized base transit time versus total Ge concentration for box and triangular Ge profile.

tion in the base. A similar plot of the normalized current gain is presented in Fig. 5. As seen the reduction of t_B in the box case is not as significant as in the triangular case, however β is much higher in the box case than in the other one (Fig. 5).

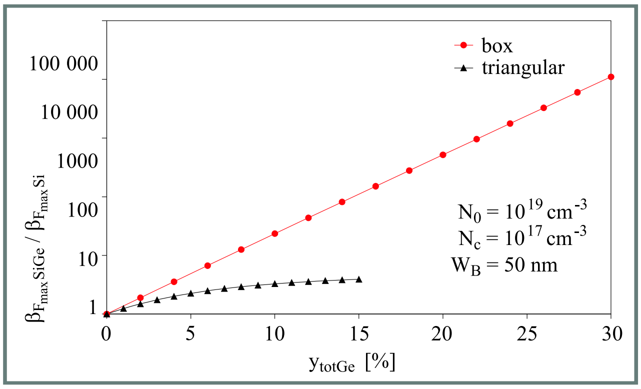

Fig. 5. Normalized current gain versus total Ge concentration for box and triangular Ge profile.

4. Conclusions

The results of numerical modeling of parameters of SiGe-base HBT transistor with the Gaussian base doping profile and different Ge profiles are presented for the first time. The importance of including the dependence of minority carrier diffusion coefficient on the drift field and variable Ge concentration along the base is demonstrated.

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