Modelling two SiGe HBT specific features for circuit simulation

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ABSTRACT

We present compact model formulations for the description of two effects seen in SiGe HBT's, but not in pure-Si transistors. One of them is the influence on the Early effect of a graded Ge-content in the base. The other is the neutral base recombination due to the high base doping levels in some SiGe transistors. Both formulations have been implemented as options in a publicly available compact model.

1 Introduction

SiGe HBT's have found their way into the production processes of many companies. For versatile circuit design in these new processes one needs an accurate compact model (SPICE model) in circuit simulators. Most models used are based on the physics of pure-Si transistors. Without modifications these models are in general capable of modelling SiGe transistors as well, unless some effects specific for SiGe HBT's are important.

Here we discuss two effects present in SiGe transistors that do not play a role in pure-Si transistors. The first is the Early effect in the case of a graded Ge-content in the base [1, 2, 3]. From a process point of view this graded Ge-profile is easier to make than a constant Ge-profile. An advantage of using Ge is that higher base doping levels can be achieved at still acceptable gain levels. These high doping levels may lead to increased Auger recombination in the neutral base. This affects the forward base current, which becomes collector voltage dependent [4, 5].

Our approach is aimed at developing formulations that on the one hand are simple enough to be implemented as options in a complete compact model, but on the other hand capture all the relevant changes in the characteristics of SiGe HBT's. We do not aim at modelling the effects in full physical detail. We introduced only one extra parameter for each effect. The formulations for a graded Ge-content and for neutral base recombination have been incorporated in the publicly available model Mextram 504 [6], that has already been implemented in a number of commercial simulators. For comparison with measurements we have selected data from processes in which one, but not both effects are present.

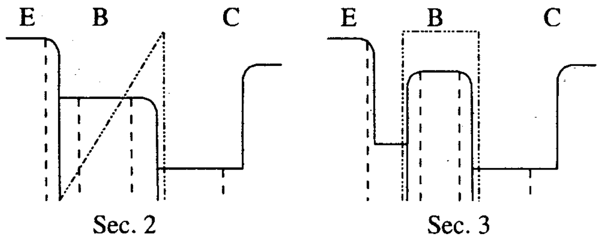

Figure 1: *Schematic view of typical doping profiles (solid lines) and Ge-content (dash-dotted line) of the intrinsic transistor. We have also shown the positions of the depletion layers (dashed).*

2 Graded-Ge base

The collector current of a bipolar transistor is modulated by the total Gummel number in the base, which in the case of pure-Si transistors is proportional to the hole charge in the base. For a SiGe transistor, however, those parts of the base with a high Ge-content add less to the Gummel number than those parts with a low Ge-content. When the Ge-content is constant all parts add equally to the Gummel number, as in pure-Si transistors. For many SiGe processes the concentration of the Ge is not constant within the base, but has a gradient, schematically sketched in the left part of Fig. 1. (Note that our own Philips processes [7] are more like the one sketched in the right part of Fig. 1.) In that case those parts with a low Ge-content become dominant in the Gummel number. A change in base-emitter depletion layer width (reverse Early effect) than has a larger influence on the total Gummel number and hence on the collector current, then in a pure-Si transistor.

2.1 Theory

Let us consider only the intrinsic part of a compact model for a bipolar transistor. The collector current can be given by [8, 9]

$$I_C = \mathsf{I_S} \left(e^{V_{BE}/V_T} - e^{V_{BC}/V_T}\right) \frac{G_{B0}}{G_B}. \tag{1}$$

Here V_{BE} and V_{BC} are the base-emitter and base-collector biases of the intrinsic transistor, $V_T = kT/q$ is the thermal voltage and $\mathsf{I_S}$ is the saturation current. The last factor is the ratio of the total base Gummel number G_B and the base Gummel number at zero bias G_{B0}. For our presentation here, we only consider the Early effect and neglect any high-injection effects (i.e., we assume that the hole concentration in the quasi-neutral base equals the doping N_A). The effect of the bandgap narrowing due to a Ge profile is very large. We therefore neglect the position dependence of the doping concentration and the diffusion constant, since these effects are much smaller. We can then write for the Gummel number.

$$G_B = \frac{N_A}{D_n} \int_{-x_E}^{W_B + x_C} \frac{n_{i0}^2}{n_i^2(x)} dx. \tag{2}$$

Here x_E (x_C) is the increase of the quasi-neutral base width due to a change in the base-emitter (base-collector) depletion layer width. The $n_i(x)$ is the intrinsic carrier concentration. At zero bias we have $G_{B0} = G_B(x_E{=}x_C{=}0)$.

When n_i is fairly constant, as in a pure-Si BJT, the Gummel number and the base charge are proportional to each other. Let us therefore consider the base charge. (Note that for a complete model we need an expression for the charge as well as for the current.) The difference between the total base charge and the charge at zero bias is due to the change in the two depletion regions, their ratio being

$$\frac{Q_B}{Q_{B0}} = 1 + \frac{x_E}{W_B} + \frac{x_C}{W_B} = 1 + \frac{V_{depl,BE}}{\mathsf{V_{er}}} + \frac{V_{depl,BC}}{\mathsf{V_{ef}}}. \tag{3}$$

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The bias dependent voltages used in this formulation can be found from the depletion charges (defined to vanish at zero bias) as

$$V_{depl,BE} = Q_{depl,BE}/C_{j_E}, \tag{4}$$

$$V_{depl,BC} = Q_{depl,BC}/C_{j_C}, \tag{5}$$

where C_{j_E} and C_{j_C} are the zero-bias depletion capacitances. We have also introduced the forward and reverse Early voltages V_{er} and V_{ef}. Note that these are related, at least for a one-dimensional transistor, by $V_{er}\,C_{j_E} = V_{ef}\,C_{j_C} = Q_{B0}$.

Up to here the theory is fairly standard. Next we want to include the effect of a gradient in the Ge-profile in the base. We are looking for a reasonably simple but adequate formulation for use in compact models. Hence we assume that the intrinsic carrier concentration only depends on the bandgap narrowing due to the Ge present in the base, and we take this bandgap narrowing to be a linear function of position. We can then write

$$n_i^2 \propto \exp\left(\frac{x}{W_B}\,\frac{\Delta E_g}{kT}\right) \tag{6}$$

The parameter ΔE_g is the difference between the bandgap at the collector depletion edge and that at the emitter depletion edge (both at zero bias).

It is now simple to calculate the ratio of Gummel numbers using Eq. (2). For the endpoints of the integral we need expressions for x_E and x_C. These can be found from the charge description, given in Eq. (3). The final result is then

$$\frac{G_B}{G_{B0}} = \frac{\exp\left(\left[\frac{V_{depl,BE}}{V_{er}}+1\right]\frac{\Delta E_g}{kT}\right) - \exp\left(\frac{-V_{depl,BC}}{V_{ef}}\,\frac{\Delta E_g}{kT}\right)}{\exp\left(\frac{\Delta E_g}{kT}\right)-1}. \tag{7}$$

This expression must be used in the formulation of the current, Eq. (1).

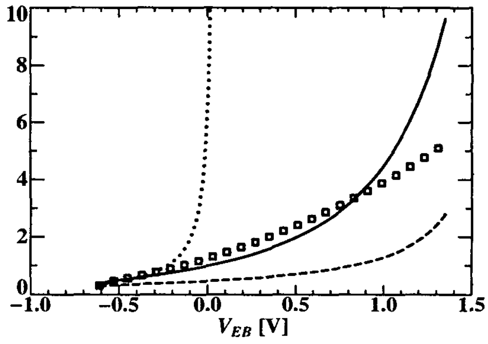

Figure 2: *Emitter current in the reverse Early measurement at $V_{BC} = 0.65$ V. The markers are the measurements. The solid line is from simulations results including our new model. The dashed and dotted lines are from simulations without the new model (i.e., taking $\Delta E_g = 0$), but with slightly different parameter sets (see text).*

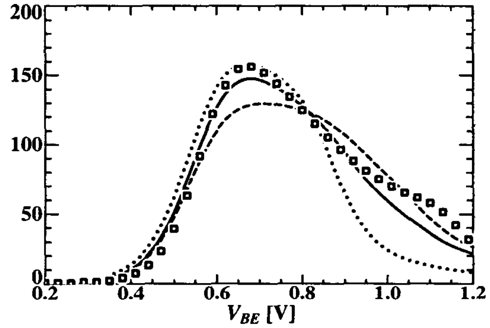

Figure 3: *Forward current gain at $V_{BC} = 0$ V. The markers are from measurements. The lines are from three different simulations (see Fig. 2 and text).*

2.2 Experimental results

For our experimental results we made use of measurement data on the 75 GHz SiGe Bipolar production technology B7HF from Infineon Technologies [10]. The data was kindly made available to us by P. Brenner. The DUT is a SiGe transistor from this BiCMOS process with an effective emitter area of $0.25\times5.75\,\mu\text{m}^2$. We have fully characterised this transistor, including temperature scaling, for the bipolar model standardisation effort of the CMC [11].

Let us look at the reverse Early effect in the two measurements where we can clearly observe it. First of all we have of course the reverse Early measurement, as shown in Fig. 2. Here the transistor is biased in reverse, and one looks at the variation of the emitter current as function of the emitter-base bias. The other measurement is the forward current gain, shown in Fig. 3. The steep decrease of this gain after its peak [1] denotes a small (effective) reverse Early voltage.

First consider what happens if we do not use our new model, i.e., taking $\Delta E_g = 0$. (All simulations presented here are done using the compact model Mextram, level 504 [6]. This model contains much more than just the intrinsic part discussed here.) We normally extract the reverse Early voltage from the reverse Early measurement (Fig. 2). In this case we find $V_{er} = 1.5$ V. We then optimise the saturation current I_s, the current gain β_f and the parameters of the non-ideal base current from the forward Gummel plot and the current gain. We find $I_s = 6$ aA and $\beta_f = 219$. The simulation results are shown in the Figs. 2 and 3 as dashed lines. With this method we are not able to get the correct absolute value for the emitter current in reverse, although the effective reverse Early voltage (the *relative* slope of the emitter current) is correct.

Since we have a fairly large V_{er} the slope of the current gain is not steep enough. To improve the modelling of h_{fe} we can include V_{er} in the optimisation of the current gain, resulting in the dotted line. In this case we do indeed find a small reverse Early voltage: $V_{er} = 41.5$ mV. We also find new values for the other parameters: $I_s = 85$ aA and $\beta_f = 3400$. Note that due to the sharp decrease of h_{fe} with base-emitter bias the parameter β_f (the zero-bias value of h_{fe}) becomes very large. Also the value of I_s depends very much on the reverse Early voltage.

Although we are now able to model the higher values of h_{fe} we still have two problems. First the values of the current gain at larger V_{BE} are still not correct (note that this has nothing to do with high-injection effects or quasi-saturation). Furthermore, in the reverse characteristics we see a very sharp increase of the emitter current. This is due to punch-through (at least in the model), which happens when $Q_B \to 0$.

As one can see we are not able to model this SiGe transistor with a pure Si-based compact model. We really need to include

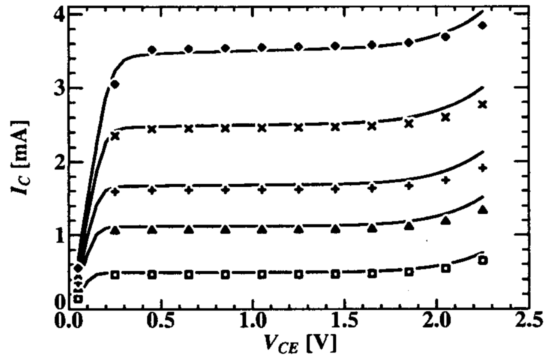

Figure 4: *The collector current versus collector-emitter bias. Markers are the measurements. Solid lines are the model, including the formulation in Eq. (7). The base currents are* $I_B = 4.3\,\mu$A, $11\,\mu$A, $17\,\mu$A, $28\,\mu$A, *and* $43\,\mu$A.

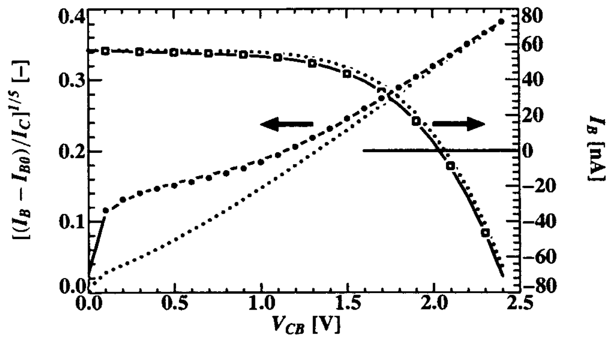

Figure 5: *Base current for constant* $V_{BE} = 0.635$ V *as function of* V_{CB} *(right axis). The markers are from measurements (some have been left out for clarity). The lines are from model simulations (solid for full model, dotted for model with* $\mathsf{X}_{\mathrm{rec}} = 0$*). The axis on the left shows the plot based on the ideas in Ref. [4].*

the fact that the bandgap in the base is not constant. When we include our new model we find the solid lines in Figs. 2 and 3. For these results we used as parameters: $\Delta\mathsf{E}_\mathrm{g} = 35\,\mathrm{mV}$, $\mathsf{I_s} = 10\,\mathrm{aA}$, $\beta_\mathrm{f} = 430$, and $\mathsf{V_{er}} = 1.3\,\mathrm{V}$. With these parameters we are now able to model both the forward and reverse characteristics.

For the determination of the parameter $\Delta\mathsf{E}_\mathrm{g}$ one can either use process knowledge, use the method described in Ref. [12], or use the measurements as described above to estimate its value. We used the last method, since the others were not available. The value of $\Delta\mathsf{E}_\mathrm{g} = 35\,\mathrm{mV}$ that we found corresponds to about 5% difference in Ge concentration between the two depletion regions (at zero bias). This value is low, but not unrealistic. As can be seen in Fig. 1, $\Delta\mathsf{E}_\mathrm{g}$ must be smaller than the (process-dependent) maximum value of the Ge content.

The differences that still exist between the measurements and the model are due to complicating effects, like for instance a non-constant doping profile. Our approach here is to get the bulk part of the effects correct in a simple way.

In Fig. 4 we have shown the collector current versus collector bias. The forward Early voltage parameter we found is $\mathsf{V_{ef}} = 31\,\mathrm{V}$. This is the value that corresponds to a transistor with the same doping profile but without Ge. The effective Early voltage due to the graded-Ge is much higher [5] (larger than 100 V).

3 Neutral base recombination

The base current as function of base-emitter bias normally can be seen as a sum of a non-ideal part (dominant at low V_{BE}) and an ideal part (dominant at higher V_{BE}). We will consider here only the ideal part, not as function of base-emitter bias, but as function of collector-base bias. We have shown an example in Fig. 5. For pure-Si transistors this base current is constant until the avalanche current causes it to decrease. In SiGe transistors, however, one can sometimes observe a decrease, even before avalanche becomes important [4]. This decrease should be modelled, since it can have a large impact on design [5], especially on the output conductance (see Fig. 6). Quite elaborate models have been published [13], but these can not be incorporated simply in existing compact models.

Generally the decrease in the base current is attributed to neutral base recombination. This recombination can normally be neglected in pure-Si transistors. In SiGe transistors the base-dope is sometimes much higher (see right part of Fig. 1), which leads to increased Auger-recombination in such a way that this recombination can become important. Also the barrier between base and collector can play a role in this recombination [14]. Note that neutral base recombination is not seen in all SiGe processes [15].

A method to discriminate between avalanche and neutral base recombination is given in Ref. [4]. One plots $[(I_B - I_{B0})/I_C]^{1/5}$ (a root of the multiplication factor), as in Fig. 5. A straight line through the origin indicates pure avalanche (like the dotted line). For $V_{CB} \gtrsim 1.5\,\mathrm{V}$ we see that avalanche dominates. Below that value another effect is also present: neutral base recombination.

3.1 Theory

We are interested in the collector-base dependence of the base current. This is a kind of Early effect. We model it, therefore, in a similar way as the normal Early effect given in Eq. (3), and write

$$I_B = \frac{\mathsf{I_s}}{\beta_\mathrm{f}}\left(e^{V_{BE}/V_T} - 1\right)\left(1 + \mathsf{X}_{\mathrm{rec}}\,\frac{V_{depl,BC}}{\mathsf{V_{ef}}}\right). \tag{8}$$

The new parameter $\mathsf{X}_{\mathrm{rec}}$ determines the amount of the base current that is due to neutral base recombination (as opposed to hole injection into the emitter). The effective Early voltage of the base current is $\mathsf{V_{ef}}/\mathsf{X}_{\mathrm{rec}}$. This formulation should suffice to model the collector-bias dependence of the forward base currents at not too high base-emitter biases.

Of course we do need to model this recombination current not only at small biases, but also at higher biases. The total electron concentration in the base not only depends on the electron density at the base-emitter junction (proportional to e^{V_{BE}/V_T}), but also on the electron density at the base-collector junction (proportional to e^{V_{BC}/V_T}). This latter term can not be neglected in the case of quasi-saturation (including Kirk-effect) or hard saturation. In principle these electron densities have a knee, determined by the knee-current, just as the collector current. Neutral base recombination is, however, only important in the case of a very high base-doping. In that case the knee current should be very high, and we need not take it into account here.

Our final formulation for the base current is then

$$\begin{aligned} I_B \;=\; & \frac{\mathsf{I_s}}{\beta_\mathrm{f}}\Big[(1 - \mathsf{X}_{\mathrm{rec}})\,\left(e^{V_{BE}/V_T} - 1\right) & (9)\\ & + \mathsf{X}_{\mathrm{rec}}\left(e^{V_{BE}/V_T} + e^{V_{BC}/V_T} - 2\right)\left(1 + \frac{V_{depl,BC}}{\mathsf{V_{ef}}}\right)\Big]. \end{aligned}$$

From this formulation one can clearly observe a $1 - X_{\rm rec}$ part belonging to hole-injection into the emitter and the $X_{\rm rec}$ part of neutral base recombination.

When looking at Eq. (9) it seems logical to also include a term $V_{depl,BE}/V_{\rm er}$, as was done in Eq. (3). The reason we do not include it is two-fold. First of all the expression is not meant as a way to model any non-idealities in the base-current at $V_{BC} = 0\,\rm V$. By not including it the base current remains ideal. The second reason has to do with parameter extraction. By not including any extra V_{BE} dependence the parameter extraction at $V_{BC} = 0\,\rm V$ is not influenced by neutral-base recombination. This includes the parameters $\beta_{\rm f}$ and those of the non-ideal forward base current (see for instance the previous section). The parameter $X_{\rm rec}$ has an influence only on the collector bias dependence. In this way different parts of the total compact model (and their parameters) are kept independent of each other.

3.2 Experimental results

The experimental results are from a commercially available SiGe process from Atmel [16], which has a doping profile similar to that in the right part of Fig. 1. The emitter area is $4 \times 1.2{\times}13\,\mu{\rm m}^2$.

In Fig. 5 we have plotted the base current. The solid lines are our model with $V_{\rm ef} = 120\,\rm V$ and $X_{\rm rec} = 8$. The avalanche current is modelled according to Ref. [17]. The dotted line is found by taking $X_{\rm rec} = 0$. The decrease in the base current due to neutral base recombination is small. The effect on the derivative, which is important for designs [5], is much bigger. For instance, the effect on the output conductance can be observed in Fig. 6. The output conductance in the absence of neutral base recombination is, in the region where avalanche is not important, the same for voltage drive or bias drive conditions (solid and dotted lines). For constant base current drive, neutral base recombination increases the output conductance by a factor of ten (dashed line), which means that the effective Early voltage has been reduced by the same amount.

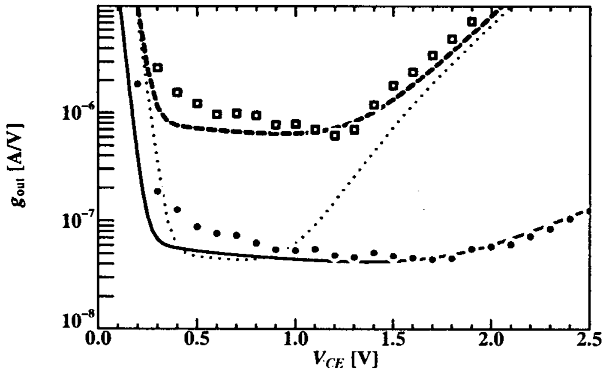

Figure 6: *Output conductance* $g_{\rm out} = {\rm d}I_C/{\rm d}V_{CE}$ *for constant base emitter voltage* $V_{BE} = 0.635\,\rm V$ *(filled markers, solid line) and for constant base current* $I_B = 57\,\rm nA$ *(open markers, dashed line). The dotted line is the simulation for the same constant base current, but with with* $X_{\rm rec} = 0$. *The simulation for constant* V_{BE} *and* $X_{\rm rec} = 0$ *is indistinguishable from the solid line.*

In Fig. 7 we have shown the Gummel plot at higher biases. Before quasi-saturation (in this case for $V_{BE} \lesssim 0.95\,\rm V$), the high-injection effect of neutral base recombination is not visible (the solid lines and dotted lines overlap). Beyond that there is a clear difference between the two.

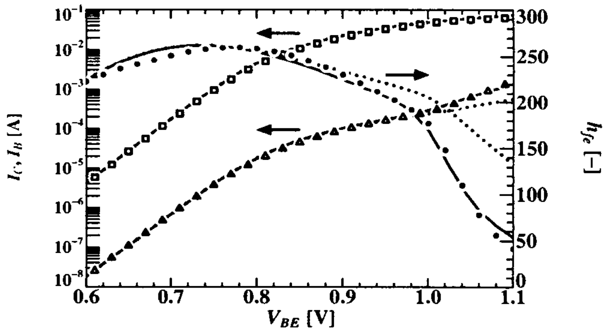

Figure 7: *Gummel plot at* $V_{CB} = 0$. *The markers are from measurements. The lines are from model simulations (dotted lines again are with* $X_{\rm rec} = 0$. *Also shown is the current gain.*

4 Conclusions

We present two formulations dedicated to SiGe processes that have been implemented in a publicly available compact model Mextram 504. One of them describes the Early effect in case of a graded Ge-content in the base and the other describes neutral base recombination. These formulations are not needed in pure Si-transistors, and not even in all SiGe processes. If these effects *are* present they have a profound effect on characteristics and design. In that case the formulations developed here are essential.

Acknowledgements

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