On the Optimisation of SiGe-Base Bipolar Transistors
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Abstract
Extensive computer simulations of NPN SiGe-base bipolar transistors were performed to examine the effect of the Ge profile in the electrical characteristics. It is shown that extra charge storage in the emitter-base (E-B) junction, caused by the Ge profile, affects the device performance considerably. In addition, it is shown that an abrupt Ge profile in the middle of the base region is optimal for a given critical layer thickness of approximately 600 A.

1 Introduction
Advanced epitaxial growth of strained SiGe on a Si substrate offers a wide variety of Ge profiles in the base region of SiGe-base bipolar transistors. Different research groups have their own approach on the Ge profile to obtain high figures-of-merit, such as a high cutoff frequency ($f_t$), a maximum frequency of oscillation ($f_{max}$), a high breakdown voltage ($BV_{CEO}$) and a high Early voltage ($V_A$). One group [1], for instance, focusses on SiGe HBTs with a uniform Ge profile in the base, while another group [2] uses graded Ge profiles. However, both strategies are very sensitive to enhanced boron outdiffusion during a thermal anneal later on in the processing. In this paper it is shown that an abrupt Ge profile in the middle of the base region (see fig. 1) offers a good compromise and has high figures-of-merit. This optimum was found from calculating $f_t$, $h_{fe}$, $BV_{CEO}$ and $V_A$ for different Ge profiles and taking into account a critical layer of approximately 600 A [3].

2 Results
In particular the position of the raising edge of the abrupt Ge profile was varied over a distance $d$ from the E-B-junction (see fig. 1). Extensive simulations (MEDICI [4]) were done with physical parameters extracted from measurements. In figure 1, the vertical doping profile of the SiGe heterojunction bipolar transistor (HBT) is shown. The main concern appears to be the optimisation of the Ge profile position near the E-B space charge region. The position of the falling edge of the Ge profile is rather insensitive and was kept constant in the B-C space charge region. In figure 2 $f_{t,\text{max}}$ and current gain $h_{fe,\text{max}}$ are shown as a function of the raising edge position of the Ge profile relative to the E-B metallurgical junction. Three regions of operations can be seen. In region 1 the Ge edge is in the E-B space charge region. Here, the Ge causes extra bandgap narrowing (BGN) which reduces $f_{t,\text{max}}$.

BGN increases the storage time in the E-B space charge region, which is part of the total transit time $\tau_{ec}$ that determines the cutoff frequency (in quasi-static approach) by

$$f_t = \frac{1}{2\pi \cdot \tau_{ec}}$$

where $\tau_{ec}$ can be divided according to:

$$\tau_{ec} = \tau_{eb} + \tau_b + \tau_c$$
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and where

\[ \tau_{eb} = r_e \cdot (C_{eb} + C_N) \]
\[ \tau_b = \frac{W^2_t}{2D_n} \]
\[ \tau_c = \frac{W_c}{2v_{\text{sat}}} + R_c \cdot C_{bc} + r_e \cdot C_{bc} \]

where \( \tau_{eb}, \tau_b \) and \( \tau_c \) are the emitter-base, base and collector transit times. The emitter-base transit time is both depends on the compensated and uncompensated carrier charge in the E-B space-charge region. The base transit time depends on compensated carrier charge in the base region and the collector transit time depends on uncompensated carrier charge in the base-collector (B-C) space charge region. \( C_{eb} \) and \( C_{bc} \) are the emitter-base and base-collector depletion capacitances per unit area. \( W_t \) and \( W_b \) are the B-C space charge layer thickness and neutral base thickness. \( C_N \) is the neutral or the storage capacitance per unit area, that is caused by compensation of free charge carriers and \( R_c \) and \( v_{\text{sat}} \) are the collector resistance and the electron saturation velocity. The emitter differential resistance can be described by

\[ r_e = \frac{kT}{q} \]

where \( k \) is Boltzmann’s constant, \( T \) the temperature and \( q \) the electron charge. Hence, the total transit time depends strongly on the collector current density.

As mentioned in [6] the storage capacitance takes the form

\[ C_N = \frac{U_i}{a} \cdot n_i \cdot \exp\left[\frac{3}{4} \cdot \left(\frac{qV_{be}}{kT}\right)\right], \]

where \( a \) depends on the slope of the emitter profile, \( n_i \) is the intrinsic carrier concentration and \( U_i \) is the normalized potential in the E-B space charge region formulated as

\[ U_i = \frac{q}{kT} \cdot \left\{ \psi - \frac{1}{2} \cdot (\phi_n + \phi_p) \right\}, \]

where \( \psi \) is the potential and \( \phi_n, \phi_p \) are the quasi-fermi levels of the electrons and holes, respectively.

For \( n_i \) the Maxwell-Boltzmann approximation is used according to

\[ n_i^2 = (N_c N_v)_{Si} \cdot \exp\left(\frac{-E_g}{kT}\right) \cdot \frac{(N_c N_e)_{SiGe} \cdot \exp(\Delta E_g/kT)}{(N_c N_e)_{Si} \cdot \exp(\Delta E_g/kT)} = n_i^2 \cdot \frac{(N_c N_e)_{SiGe} \cdot \exp(\Delta E_g/kT)}{(N_c N_e)_{Si} \cdot \exp(\Delta E_g/kT)} \]

where \( E_g \) is the bandgap and \( N_c \) and \( N_v \) are the effective densities-of-states (DOS) and \( \Delta E_g \) is BGN in SiGe.

Equation (6) shows that BGN in SiGe increases \( n_i \) considerably although the effective DOS reduce and according to equation (4) \( C_N \) increases. Consequence is that the storage time increases resulting to a lower \( f_{\text{t,\text{max}}} \) (see figure 2). Notice that the space charge layer width also affects the charge storage which is determined by \( a \). Increasing the space charge layer (or decreasing \( a \)) enhances the charge storage and therefore reduces \( f_{\text{t,\text{max}}} \). Therefore we can conclude that when the germanium profile reaches into the E-B space charge region, \( f_{\text{t,\text{max}}} \) is considerably reduced.
Shifting the profile edge to region 2 increases $f_{t, \text{max}}$ and decreases $h_{f_{r, \text{max}}}$, but the base Gummel number is very sensitive to the bias condition $V_{be}$. Here, the profile causes an enhancement in the Gummel number that is given by

$$G_b = \int_0^L \left( \frac{P}{D_n} \right) \cdot \left( \frac{n_{\text{be}}^2}{n_i^2} \right) \, dx,$$

where $L$ is the device length, $P$ the hole concentration and $D_n$ the electron diffusion coefficient. This enhancement reduces the collector current density according to

$$J_c = \frac{-q n_{\text{be}}^2}{G_b} \cdot \left\{ \exp\left( \frac{q V_{be}}{kT} \right) - 1 \right\}.$$

In region 3 the profile edge enters deeper into the base region causing a considerable reduction in the collector current density $J_c$. Consequently, $f_{t, \text{max}}$ reduces, which is caused by the storage time that depends on $G_b$. By the enhancement of $G_b$ according to equation (8) $J_c$ reduces. Hence, for reaching $f_{t, \text{max}}$ and therefore the same $J_c$, a higher applied $V_{be}$ is necessary. Consequently, according to equation (4) a high $C_N$ is incorporated reducing $f_{t, \text{max}}$.

There is a tradeoff between two different values of $h_{f_r}$ for obtaining the same $f_{t, \text{max}}$. In summary, the optimal point of the Ge profile is in the middle of the neutral base region (hence, region 3), because the SiGe thickness is low (600 Å), $h_{f_r}$ is relatively low (80), hence $BV_{ce}$ is high (3.5 V) and $f_{t, \text{max}}$ is high (50 GHz). The transistors were grown by Atmospheric Pressure Chemical Vapour Deposition (APCVD) in the ASM epsilon-1. In figure 3 the SIMS depth profile of the fabricated optimised device is shown. (The boron pile-up at the raising edge of the Ge profile is probably due to segregation [5].) The main concern in the 2D transistor design was the reduction of the base resistance, the collector-base capacitance and the sidewall effects. In figure 4 is shown that the simulated collector current agrees well with measurements. The base current, however, shows some non-ideality due to recombination at the oxide surface. In figure 5 the simulated cutoff frequencies are shown for both the optimised SiGe HBT and the Si BJT. The maximum cutoff frequency is lower in the latter case due to a high base Gummel number.

3 Conclusion
In summary, it appears that the optimum Ge profile is located in the middle of the neutral base region. The base Gummel number and the extra charge storage in the E-B space charge region play a key role in the results.

Part of this work was supported by Stichting Toegepaste Wetenschappen (STW), the Netherlands.
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Fig. 1: The vertical doping profile. The distance is relative to the poly/mono interface. The base top concentration is \(2.2 \times 10^{18}\) cm\(^{-3}\).

Fig. 2: The maximum cutoff frequency \(f_{\text{t,max}}\) and the current gain \(h_{\text{fe}}\) as a function of the distance \(d\) shown in figure 1. This so called technical window can be divided into three regions: 1, 2 and 3. The collector-base voltage \(V_{\text{cb}} = 1\) V. The maximum values are for \(f_{\text{t,max}} = 52\) GHz and for \(h_{\text{fe}} = 400\). The optimal position is indicated with a circle (*).

Fig. 3: The SIMS depth profile of the epitaxial layer structure. The Ge profile is shown in the figure. Notice the slight boron pile-up at the Si/Ge interface.

Fig. 4: The measured Gummel plot (dense marks) of the optimised HBT structure compared with MEDICI [4] (2D) simulations (open marks) for \(T = 294\) K and \(V_{\text{cb}} = 0\) V.

Fig. 5: The simulated cutoff frequency vs. the collector current density for both the HBT and the BJT (\(V_{\text{ce}} = 1.0\) V).

REFERENCES


