Novel Ge-profile design for high-speed SiGe HBTs: modelling and analysis

V.S. Patri and M. Jagadash Kumar

Abstract: The authors investigate the optimisation of the Ge profile in SiGe HBTs, with the aim of enhancing current gain without degrading the base transit time at different ambient temperatures and points of film stability. Using a new box-triangular Ge profile, they show that a current gain enhancement of ~3 is achievable at $T = 300$ K for $y_{col} = 14$% Ge without degrading the base transit time corresponding to that of a triangular Ge profile. The effect of an electric field on the base transit time is also studied. It is shown that for $W_{b} = 50$ nm, the limiting base electric field is ~40 kV/cm, beyond which any reduction in the base transit time is offset by the electron mobility degradation.

1 Introduction

High values of current gain and cut-off frequencies have been achieved using SiGe heterojunction bipolar transistors (HBTs) by approximately tailoring the base bandgap profile [1–8]. Further, unlike Si bipolar transistors, SiGe HBTs show enhanced performance at reduced temperatures, making them viable candidates for operation at liquid nitrogen temperature (LNT) [9, 10]. The design of the Ge content profile in SiGe HBTs for optimising the device performance has been investigated in the literature [11–13]. It has been demonstrated that a linear Ge grading in the base is optimal for reducing the base transit time [1, 2, 4, 9–11]. In [9, 11, 12] the reduction in the base transit time was traded off for increased Ge concentration at the emitter edge of the neutral base. However, such an approach results in an increase in the base transit time in comparison with the triangular Ge profile. Also, the resultant collector current is strongly dependent on the slope of the Ge profile at the emitter edge of the base [12].

It is of interest to examine the design of the Ge profile for optimising both current gain and base transit time. To our knowledge, the bandgap engineering problem of optimisation of the Ge content profile with the objective of maximising the current gain enhancement, without degrading the base transit time from that of the triangular Ge profile, has not been investigated. Such an optimised profile would make it possible to minimise both emitter and base transit times, thereby improving the high-frequency performance of the device. In the present work, we studied the design of the Ge profile using an analytical model of the base transit time, with the objective of maximising the emitter edge Ge concentration without degrading the base transit time. The optimisation of the base bandgap profile was investigated at different ambient temperatures and points of film stability. Further, the enhancement in current gain obtained using the optimised Ge profile was studied by developing an analytical model for the current gain increase. Also, the limits on the reduction in the base transit time, obtainable for a given base width and temperature, were investigated using a triangular Ge profile.

![Fig. 1 Ge composition profiles under study for total Ge content $y_{col} = 10\%$ Ge and the neutral base width $W_{b} = 50$ nm.

(i) Triangular Ge profile ($y_{b} = 0$% Ge, $x_{b} = 0$, $y_{col} = 20$% Ge).
(ii) Shifted-triangular Ge profile ($y_{b} = 0$% Ge, $x_{b} = 0.19W_{b}$, $y_{col} = 20$% Ge).

$y_{b}$ is the Ge content at the emitter edge of the neutral base and $y_{col}$ is the Ge content on the collector side of the neutral base.

2 Ge profiles considered

The Ge profiles, in the present study, for investigating the optimisation of a SiGe HBT's performance are shown in Fig. 1. The triangular Ge profile (curve (i) of Fig. 1) is used to investigate the effect of electric field on the base transit time. We studied the design of the base bandgap profile for minimising the base transit time using a shifted-triangular Ge profile (curve (ii) of Fig. 1), which has 0% Ge concentration up to a point $X_{b}$ in the base and a line-
early increasing Ge concentration from $X_B$ to $W_B$. A new Ge-content profile, referred to as the box-triangular Ge profile (curve (ii) of Fig. 1) is proposed for enhancing current gain without degrading the base transit time. The box-triangular Ge profile has a constant non-zero Ge concentration up to a point $X_B$ in the base and a linearly varying Ge concentration beyond $X_B$. The Ge concentration for a box-triangular Ge profile at any point $x$ in the base can be expressed as

$$y(x) = y_e \quad 0 \leq x \leq X_B$$

$$= \left(y_e(X_B) - y_e \right) \frac{x - X_B}{W_B - X_B} + y_e \quad X_B \leq x \leq W_B$$

(1)

where $y_e$ is the Ge concentration at the emitter edge of the neutral base and $y_e(X_B)$ is the Ge content at the collector edge, which is dependent on $X_B$ if the total Ge content, i.e., the stability point [13, 14] is fixed. The Ge mole fraction at the collector edge is given by

$$y_c(X_B) = \frac{y_{eA} - 2y_{eD}}{1 - \frac{X_B}{W_B}} + y_e \quad 0 \leq X_B \leq W_B$$

(2)

where $y_{eA}$ is the Ge concentration at the collector edge of the neutral base for the triangular Ge profile and is expressed as $y_{eA} = 2y_{eD}$ where $y_{eD}$ is the integrated Ge concentration in the base. When $y_e = 0$% Ge, for $X_B > 0$, eqns. 1 and 2 describe a shifted-triangular Ge profile and for $X_B = 0$ eqns. 1 and 2 reduce to those of the triangular Ge profile.

3 Modelling the base transit time and the current-gain enhancement

3.1 Mobility models used in the analysis

In order to facilitate the derivation of closed-form analytical models for the base transit time $\tau_{b,SiGe}$ and the current gain enhancement for the Ge profiles considered, it is necessary to make a judicious choice of models for the base transport parameters, such as majority carrier diffusivity $D_{n,SiGe}$, bandgap narrowing and effective intrinsic carrier concentration $n_{i,SiGe}$.

In the present analysis, the low-field electron mobility in Si is modelled using Klaassen’s temperature-dependent minority carrier mobility model [15, 16]. The electric field dependence of the carrier mobility is taken into account using a modified Caughey–Thomas electric field dependent mobility model [17, 18] given by

$$\mu_n(E_n) = \frac{\mu_n}{\left[1 + \left(\frac{\mu_n E_n}{v_n}\right)^2\right]^{\frac{3}{2}}}$$

(3)

where $\beta_n = 2$ for electrons and

$$E_n = \frac{k_B T}{q} \left\{ \frac{1}{N_A(x)} \frac{\partial N_A(x)}{\partial x} - \frac{\partial}{\partial x} \left[ \ln n_i^2(x) \right] \right\}$$

(4)

is the electric field in the quasi-neutral region. For a uniformly doped SiGe base, the electric field $E_n$ in the base given by eqn. 4 reduces to

$$|E_n| = \frac{k_B T}{q} \frac{1}{n_i^2(SiGe)(x)} \frac{\partial}{\partial x} n_i^2(SiGe)(x)$$

$$= \frac{\partial}{\partial x} \left[ \frac{\Delta E_{p,Ge}(x)}{q} \right]$$

(5)

where the position-dependent effective intrinsic carrier concentration $n_{i,SiGe}$ is modelled using [19]

$$n_i^2(SiGe)(x) = \gamma n_{i,Ge}(x) \exp \left[ \frac{\Delta E_{p,Ge}(x)}{k_B T} \right]$$

(6)

where $\gamma = (N_{e,Ge} - N_{i,Ge}) / (N_{e,Ge} - N_{i,Ge})$ accounts for the reduction in effective density of states owing to the presence of Ge [20] and $\Delta E_{p,Ge}(x)$ is the bandgap reduction due to Ge given by [19]:

$$\Delta E_{p,Ge}(x) = C y(x)$$

(7)

where $y(x)$ is the Ge mole fraction at a point $x$ in the base and $C = 688$ meV. The dopant-induced bandgap narrowing in the SiGe base $\Delta E_{p,Ge}(x)$ is assumed to be identical to that in Si [13].

If the bandgap in the base is wider at the emitter edge of the base than at the collector edge, the electric field aids the electron transport in the p-type base. The triangular Ge profile shown in Fig. 1 (curve (i)) introduces a constant accelerating electric field in the base region. For a triangular Ge profile, an increase in the electric field is achieved by increasing the base bandgap grading, or equivalently, by increasing the total Ge content. If the accelerating electric field is large, the carrier mobility degrades due to increased phonon scattering [17, 18]. Therefore the relationship between the electric field and base transit time is not straightforward and needs to be understood.

The carrier mobility in strained SiGe films has been reported to be higher than that for Si [13]. This enhancement may be attributed to the reduction in the hole effective mass. Experimental data suggests a linear variation in mobility with Ge concentration [13]:

$$\mu_{n,SiGe}(y) = [1 + K y]\mu_{n,SI}$$

(8)

where $\mu_{n,SI}$ is the electron mobility in strained SiGe, $\mu_{n,SI}$ is the electron mobility in Si and $K (= 10)$ is a fitting parameter. For simplicity, we have used an average value $\bar{y}$ for $y(x)$ in eqn. 8 in the regions where the Ge concentration varies with distance. For a box-triangular Ge profile, the average value $\bar{y}$ is defined as

$$\bar{y} = \frac{1}{2} \left[ y_e(X_B) + y_c \right] \left( 1 - \frac{X_B}{W_B} \right)$$

(9)

In the case of a triangular Ge profile, the average Ge content $\bar{y} = y_{eD}$.

3.2 Base transit-time model

For an n–p–n SiGe HBT, the base transit time is given by [21, 22]

$$\tau_{b,SiGe} = \tau_{b,SiGe}^e + \tau_{b,SiGe}^e$$

(10)

where

$$\tau_{b,SiGe}^e = \int_{0}^{W_B} \frac{n_i^2(SiGe)(x)}{N_A(x)} \int_{x}^{W_B} \frac{\Delta E_{p,Ge}(x)}{e q x} \, dx \, dx$$

(11)

and $\tau_{b,SiGe}^e$ is the increase in the base transit time due to the finite velocity of the carriers in the base-collector depletion region [21, 22] and is given by (see Appendix)

$$\tau_{b,SiGe}^e = \int_{x}^{W_B} \frac{N_A(W_B)}{N_A(x)} \int_{0}^{W_B} \frac{n_i^2(SiGe)(x)}{e q x} \, dx \, dx$$

(12)
If uniform base doping is assumed, eqns. 11 and 12 reduce to

\[ \tau_{b, SiGe}^b = \int_0^{n_{2, SiGe}^b} \int_0^{n_{2, SiGe}^b} \frac{1}{D_{n, SiGe}(x) n_{2, SiGe}^b(x)} \, dz \, dx \]  
(13)

\[ \tau_{b, SiGe}^e = \frac{1}{v_a} \int_0^{n_{2, SiGe}^b} \frac{1}{n_{2, SiGe}^b(x)} \, dz \, dx \]  
(14)

Substituting eqns. 3 and 6-9 in eqns. 13 and 14, the temperature-dependent analytical model of the base transit time for a box-triangular Ge profile can be obtained as

\[ \tau_{b, SiGe} = \tau_{b, SiGe}^b + \tau_{b, SiGe}^e \]

\[ = \frac{W_B}{2V_T \mu_{n, SiGe}^b} F_1(\chi) + \frac{W_B}{2V_T \mu_{n, SiGe}^e} F_2(\chi) + \frac{W_B}{\nu_a} F_3(\chi) \]  
(15)

where

\[ \chi = \frac{X_B}{W_B} \quad V_T = \frac{k_B T}{q} \]

\[ \mu_{n, SiGe}^b = (1 + K y_e) \mu_{n, Si} \]

\[ \mu_{n, SiGe}^e = (1 + K y_e) \mu_{n, Si} \]

\[ y_e = \frac{1}{2} \left( y_e(X_B) + y_e(1 - \chi) \right) \quad \text{and} \quad y_e(X_B) + y_e(1 - \chi) \]

\[ F_1(\chi) = \chi^2 \]

\[ F_2(\chi) = \chi(1 - \chi) \left[ \Gamma(X_B) \Delta(X_B, y_e) + e^{-C_{2 y_e}(X_B)} \right] + (1 - \chi) \Delta(X_B, \tilde{y}) \]  

\[ F_3(\chi) = \chi e^{-C_{2 y_e}(X_B)} + (1 - \chi) \Gamma(X_B) \]

where

\[ C_2 = C/(k_B T) \]

\[ y_e(X_B) = y_e(X_B) - y_e \]

\[ \Gamma(X_B) = \frac{1 - e^{-C_{2 y_e}(X_B)}}{C_{2 y_e}(X_B)} \]

\[ \Delta(X_B, \tilde{y}) = \left\{ 1 + \left[ \frac{(1 + K \tilde{y}) \mu_{n, Si} C_{2 y_e}(X_B)}{(W_B - X_B) \nu_a} \right] \right\} \]  
(16)

For uniform base doping, after substituting eqn. 17 in eqn. 16, the enhancement in the current gain is obtained as

\[ \frac{\beta(X_B, y_e)}{\beta} \frac{W_B}{G_{B, \Delta}} \]  

\[ = \frac{X_B}{\mu_{n, SiGe}^b n_{2, SiGe}^b(x)} \int_0^{X_B} \frac{dz}{\mu_{n, SiGe}^b n_{2, SiGe}^b(x)} \]  

where

\[ \mu_{n, SiGe}^b = (1 + K y_e) \mu_{n, SiGe}(T) \]

Solving eqn. 18 using eqns. 3 and 6-9 and further simplification yields the model for the enhancement in current gain for the box-triangular Ge profile as

\[ \frac{\beta(X_B, y_e)}{\beta} \frac{W_B}{G_{B, \Delta}} \]  

\[ = e^{-\frac{y_e(1 + y_e \Delta) \Gamma_0(1, \Delta) \Delta(X_B, \tilde{y})}{\Gamma_0(1, \Delta) \Delta(X_B, \tilde{y})}} \]  
(19)

where \( \chi \), \( y_e \), and \( \tilde{y} \) are the reduction in effective density of states [20] for an average Ge concentration of \( y_{tot} \) and \( y_e \), respectively.

4 Results and discussion

4.1 The effect of electric field on base transit time

Using a gradually reduced bandgap in the quasi-neutral base region, an accelerating electric field may be introduced for decreasing the base transit time. However, a large electric field in the base can be counter-productive as a result of mobility degradation in the high-field regions [17, 18]. Therefore it is of interest to examine whether there exists a limiting electric field above which the base transit time does not decrease appreciably. We have chosen the triangular Ge profile to study the effect of electric field in the present analysis, because of the simple relationship that exists between the electric field \( E_r \) and the total Ge content \( y_{tot} \) obtained by substituting the expression for \( \Delta E_{SiGe}(x) \) given by eqn. 7 in eqn. 5

\[ |E_r| = \frac{2 C y_{tot}}{W_B} \]  
(20)

Using eqn. 15 with \( X_B = 0 \) and \( y_e = 0 \% \) Ge, the base transit time \( \tau_{b, SiGe} \) is plotted as a function of \( y_{tot} \) in Fig. 2 for the triangular Ge profile with \( W_B = 50 \mu m \) at different ambient temperatures. We have defined the optimum value for \( y_{tot} \), as the value of total Ge content above which the reduction in \( \tau_{b, SiGe} \) is < 2%.

As shown in Fig. 2, for a triangular Ge profile the optimum total Ge concentration at \( T = 300 \) K is ~14% Ge, which gives a base transit time of about 0.6 ps. The electric field corresponding to this optimum value of \( y_{tot} \) is evaluated using eqn. 20 as ~40 kV/cm. Above this value of \( E_r \), the degradation of the minority carrier mobility at high electric fields offsets any reduction in the base transit time due to composition grading. If \( y_{tot} \) is increased beyond ~14% Ge, as can be seen in Fig. 2, there is no significant reduction in \( \tau_{b, SiGe} \) (0.1 ps reduction in \( \tau_{b, SiGe} \) if \( y_{tot} \) is increased by 10% Ge). However, higher values of \( y_{tot} \) can
affect the film stability [13, 14]. Therefore, it is desirable to keep the total Ge content $y_{tot}$ at its optimum value. Our calculations show that the optimum $y_{tot}$ is lower at reduced temperatures.

![Figure 2](image)

**Fig. 2** Base transit time against total Ge content $y_{tot}$ at different ambient temperatures for neutral base width $W_B = 300nm$ for a triangular Ge profile

$T = 300K$

$T = 200K$

$T = 100K$

distinct minimum for $X_B > 0$ at different ambient temperatures. The reduction in base transit time obtained using the shifted-triangular Ge profile can be traded off for a higher Ge content at the emitter edge of the base. The resulting profile is a box-triangular Ge profile shown in curve (iii) of Fig. 1. This approach has two-fold advantages over other optimised Ge profiles viz.,

- $\tau_{S,SIGE}$ of the triangular Ge profile is not compromised for an increase in current gain; and
- the collector current is relatively less sensitive to the change in the emitter-base junction space charge-layer width because of the constant value of the Ge content profile near the edge of the base (cf. curve (iii) of Fig. 1).

In Fig. 4, the optimum values of the co-ordinate of the base of the shifted triangular profile $X_B$ and Ge concentration at the emitter edge $y_e$ are plotted as functions of $y_{tot}$ at different ambient temperatures. We note from the figure that for $W_B = 50nm$, the optimum value of $y_e$ is close to half the value of $y_{tot}$. This is a consequence of the saturation of the base transit time at high values of $y_{tot}$ because of which a large fraction of $y_{tot}$ can be located at the emitter edge without significantly affecting $\tau_{S,SIGE}$. It is of interest to note from Fig. 4 that the optimum value of $X_B$ decreases with decreasing temperature for a given $y_{tot}$. This implies that the peak Ge concentration $y_e(X_B)$ at the collector edge of the base is lower at reduced temperatures for a given $y_{tot}$.

![Figure 3](image)

**Fig. 3** Base transit time against $X_B/W_B$ for the total Ge content $y_{tot} = 10\%$ Ge at different ambient temperatures for neutral base width $W_B = 300nm$, $y_e = 0\%$ Ge

$T = 300K$

$T = 200K$

$T = 100K$

4.2 Ge profile optimisation

A shifted triangular Ge profile (curve (ii) of Fig. 1) increases the average electric field in the base for a given total Ge content $y_{tot}$. This results in a decrease in $\tau_{S,SIGE}$ as $X_B$ is increased. However, as $X_B$ is further increased, the base transit time begins to rise as a result of the increase in the length of the zero-field region. The degradation of carrier mobility at high electric field strengths also contributes to the rise in $\tau_{S,SIGE}$. This behaviour is evident in Fig. 3, where the plot of $\tau_{S,SIGE}$ against $X_B/W_B$, obtained using eqn. 15 for $y_{tot} = 10\%$ Ge and $y_e = 0\%$ Ge, shows a

![Figure 4](image)

**Fig. 4** Optimum values of $X_B$ and $y_e$ (Ge content at the emitter edge of the neutral base) as functions of the total Ge content $y_{tot}$ at different ambient temperatures for neutral base width $W_B = 50nm$

$T = 300K$

$T = 200K$

$T = 100K$

4.3 Current gain enhancement for the optimised Ge profile

In Fig. 5, the current gain enhancement obtained for a box-triangular Ge profile, is plotted as a function of $y_{tot}$ at different ambient temperatures. It is of interest to note that a current-gain enhancement of ~3 is achievable at $T = 300K$ for $y_{tot} = 14\%$ Ge. At reduced temperatures, the enhancement in current gain is very high as the effect of non-zero $y_e$ is accentuated at low temperatures. It appears that the optimised Ge profile (curve (iii) of Fig. 1) presented in this work is better than the trapezoidal Ge profile proposed in [9, 10] for devices operated at LNT. This is a consequence of the two-fold advantage described earlier, that the box-triangular Ge profile (curve (iii) of Fig. 1)
offers over any Ge profile which has a finite amount of composition grading near the emitter edge of the base.

![Graph showing current gain enhancement vs. Ge content for different temperatures for neutral base width W_B = 50nm.](image)

**Fig. 5** Current gain enhancement $\beta \times X_B$ vs. $Y_{Ge}$ at different ambient temperatures for neutral base width $W_B = 50nm$

<table>
<thead>
<tr>
<th>$T$ (K)</th>
<th>$Y_{Ge}$, % Ge</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>0.1</td>
</tr>
<tr>
<td>700</td>
<td>0.2</td>
</tr>
</tbody>
</table>

5 Conclusions

The design of the Ge profile for enhancing the current gain in SiGe HBTs, without degrading the base transit time from that of the triangular Ge profile, has been investigated at different ambient temperatures and stability points. It has been found that a shifted-triangular Ge profile (curve (ii) of Fig. 1) has a lower $t_{90,Ge}$ than the triangular Ge profile at a given $Y_{Ge}$. Trimming off this reduction in $t_{90,Ge}$ for higher Ge concentrations at the emitter edge of the base results in an enhancement of current gain. The optimized Ge profile presented here has a base transit time identical to that of the triangular Ge profile with high current gain. We have also investigated the effect of electric field on the base transit time. Our analysis shows that, beyond a limiting value of electric field (~40 kV/cm at $T = 300 K$ for $W_B = 50nm$), the degradation in electron mobility is large enough to offset any reduction in $t_{90,Ge}$.

6 References


18. THOMAS, K. K.: 'Relation of drift velocity to low field mobility and high field saturation velocity', *J. Appl. Phys.*, 1979, 51, pp. 2127-2134


7 Appendix: Integral relation for $n$ of shallow-base bipolar transistors including the velocity saturation effects

As a result of the finite velocity of carriers in the collector-base depletion region, the minority carrier concentration in the base increases [22]. The effect of this increase in minority carrier concentration on the base transit time becomes important for small base widths. If the effect of the finite carrier velocity in the collector depletion region is taken into account, the minority carrier concentration at the collector edge of the base is given by:

$$n(W_B) = \frac{J_n}{q \nu_e}$$  \hspace{1cm} (21)

where $n(W_B)$ is the electron concentration at the collector edge of the base. In terms of the carrier concentrations $n$ and $p$, we can now write:

$$\frac{n}{n_B^2} = \frac{p}{p_B^2} = \frac{J_n}{q \nu_e} \frac{p}{p_B^2}$$

$$\frac{J_n}{q \nu_e} \frac{p}{p_B^2} = \frac{J_n}{q} \int_{W_B}^{W_B + p} \frac{p}{D_n \nu_e^2} \, dx$$  \hspace{1cm} (22)
Assuming quasi-neutrality in the base, i.e. \( p(x) = N_A(x) \), the expression for minority carrier concentration at any point \( x \) in the base can be written using eqn. 22 as:

\[
n(x) = -\frac{J_n}{q} \left( \frac{n_i^2(x)}{N_A(x)} \right) \times \left[ \int_x^{W_B} \left( \frac{N_A(z)}{D_n(z)n_i^2(z)} \right) dz + \frac{1}{v_s} \frac{N_A(W_B)}{n_i^2(W_B)} \right] \tag{23}
\]

The second component in eqn. 23 is due to the effect of velocity saturation in the collector-base depletion region.

The base transit time is the average time taken by the minority carriers to travel across the neutral base region and is given by

\[
\tau_b = \int_0^{W_B} \frac{dx}{|v_n(x)|} = \int_0^{W_B} \frac{-q n(x)}{J_n} dx \tag{24}
\]

where \( v_n(x) = -q n(x) \) is the velocity of electrons at a point \( x \) in the base. Substituting eqn. 23 in eqn. 24 gives the total base transit time as [22]

\[
\tau_b = \tau_5^v + \tau_6^v = \int_0^{W_B} \frac{n_i^2(x)}{N_A(x)} \int_x^{W_B} \frac{N_A(z)}{D_n(z)n_i^2(z)} dz dx + \frac{1}{v_s} \frac{N_A(W_B)}{n_i^2(W_B)} \int_0^{W_B} \frac{n_i^2(x)}{N_A(x)} dx \tag{25}
\]