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Base Transport Limited Current Gain Analysis for Low-Noise SiGe DHBTs

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Abstract: An analysis of current gain and cutoff frequency for very high maximum oscillation frequency NPN Si/SiGe/Si double heterojunction bipolar transistors (SiGe DHBTs) has been performed. The simulation results for a Box-Germanium and a Box-triangular-Germanium profile in the base of SiGe DHBT are compared while the Ge profile is kept under the critical thickness limit constraint in both the cases. The Box-triangular-Germanium profile SiGe DHBT shows a superior current gain and cut-off frequency owing to an improved base transport limited current gain.

Key words: SiGe DHBTs, base transport, low-noise, current gain, base recombination

INTRODUCTION

The development in silicon germanium (SiGe) process technology and its compatibility with silicon (Si) technology, has led to the realization of Si/SiGe/Si NPN double heterojunction bipolar transistors (DHBTs) with extremely high cut-off frequency (f_t) and maximum frequency of oscillation (f_{max})[1]. The f_{max}, unity power gain frequency, is a good measure of transistor performance for power gain, wideband analog amplifiers and nonsaturating logic gates[2]. The requirements for a high f_{max} are high f_t, low base-collector capacitance (C_{jc}) and low base resistance (R_B). Low R_B could be achieved by an increase in base doping (N_B). The present work investigates the SiGe HBT performance at maximum possible N_B, defined by the maximum solid solubility limit of a p-type (Boron) doping in silicon (at 800°C, which is approx. maximum temperature for present day SiGe device processing). SiGe DHBTs with very high β, f_t and f_{max} fits the role for realizing very low-noise, high-speed transistor circuits. However, an increase in N_B would increase the neutral base region recombination. This would adversely affect β and f_t of SiGe DHBT. The current gain and cut-off frequency performance of SiGe DHBTs with two different Germanium profiles in the base region were analyzed. This analysis brings out the dominance of the base region recombination in very high f_{max} DHBTs and proposes a box-triangular Ge profile in base region to minimize the effect of base recombination and exploit the Ge concentration of SiGe base in efficient way.

The major advantage of using Ge in the base of the SiGe HBT is to increase β of the transistor for the fixed bias in comparison with a silicon (Si) bipolar junction transistor (BJT). The ratio of β between a SiGe HBT and a Si BJT is given as[3]:

$$\frac{\beta_{SiGe}}{\beta_{Si}} \cong \gamma\eta \frac{\frac{\Delta E_{G(BC-BE)}}{KT} \exp\left(\frac{\Delta E_{G(BE)}}{KT}\right)}{1 - \exp\left(\frac{\Delta E_{G(BC-BE)}}{KT}\right)} \quad (1)$$

where, $\beta_{Si} \approx \frac{W_E D_{nb} N_E}{W_B D_{pe} N_B}$

here W_E and N_E are the emitter region thickness and doping, respectively. D_{nb} and D_{pe} are the electron and hole diffusion coefficients in the base and emitter regions, respectively. The parameter γ accounts for the reduction in the effective density of states with increasing Ge at%, η is the strain induced increase in electrons mobility with increased Ge content. The Ge induced reduction in the bandgap of SiGe base at emitter-base (e-b) junction of the quasi-neutral base is given as $\Delta E_{G(BE)}$. The grading of the Ge across the neutral base is given as $\Delta E_{G(BC-BE)}$ ($=\Delta E_{G(BC)}-\Delta E_{G(BE)}$), where $\Delta E_{G(BC)}$ is the Ge induced reduction in the bandgap of SiGe base at base-collector (b-c) junction of the quasi-neutral base. The term K is Boltzmann's constant and T is the absolute temperature. We have not included the effect of heavy doping induced apparent band gap narrowing in base, in the expression for β_{Si} for keeping the expression simple. For constant base doping, the ratio of base transit time (t_{BB}) for SiGe HBT (t_{BBSiGe}) and Si BJT (t_{BBSi}) devices can be given as[3]:

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$$\frac{t_{BBSiGe}}{t_{BBSi}} \cong \frac{2KT}{\eta \Delta E_{G(BC-BE)}}\left[1 - \frac{KT}{\Delta E_{G(BC-BE)}}\left(1 - \exp\left(-\frac{\Delta E_{G(BC-BE)}}{KT}\right)\right)\right] \qquad (2)$$

where, $t_{BBSi} \quad \frac{1}{2}\frac{W_B^2}{D_{nb}}\left[1 \quad \frac{2D_{nb}}{v_d W_b}\right]$

here v_d is the drift velocity of minority carriers.

The development of Si/Si$_{1-x}$Ge$_x$/Si HBTs has historically followed two different approaches. One approach (Triangular-Ge at%) starts with a Ge at% of x=0 at the e-b junction, then increases 'x' towards the collector till it reaches the b-c junction, thus introducing a strong drift field in the base. This increases the f_t (reduced t_{BB}) of triangular-Ge HBT as:

$$f_t \quad \left[\frac{1}{2\pi\left\{\frac{V_t}{I_C}(C_{je} \quad C_{jc}) \quad t_{BB} \quad t_t\right\}}\right] \qquad (3)$$

where, $t_t = t_{scl} + t_{em} + t_{qbe} + R_C\,C_{jc}$.

Here C_{je} and C_{jc} are the e-b and b-c junction capacitances. R_C is the collector resistance and t_{scl}, t_{em} and t_{qbe} are the delay terms associated with the, base-collector space-charge layer, charge in the emitter and free carrier charge in emitter-base space-charge layer, respectively. The maximum oscillation frequency f_{max} is given as:

$$f_{max} \quad \sqrt{\frac{f_t}{8\pi R_B C_{jc}}} \qquad (4)$$

Unfortunately, the triangular Ge% approach produces a homojunction transistor at e-b junction. Therefore, β of the transistor is only slightly increased and the increase in N_B is limited to preserve the emitter injection efficiency. The alternative approach of Box-Germanium (B-GE) profile DHBT uses a Ge% x>0 at the e-b junction to improve the emitter injection efficiency. This approach allows N_B to be increased by orders of magnitude over that of emitter doping N_E. An increase in N_B reduces R_B, and a low N_E reduces C_{je} (for improved f_t). Hence, this configuration is ideally suited for high f_{max} and superior high-frequency noise performance, when compared to conventional Si BJTs. The current gain $\beta_{SiGebox}$ for such a B-GE HBT (with $\Delta E_{G(BC-BE)}$ =0) would become:

$$\beta_{SiGebox} \cong \beta_{Si}\gamma\eta \exp\left(\frac{\Delta E_{G(BE)}}{KT}\right) \qquad (5)$$

We have used a two-dimensional MEDICI device simulator known for its authenticated results at the device level for SiGe HBT structures[4] to study the current gain and f_t performance for a B-GE (x=30at% Ge) SiGe DHBT. The device dimensions and doping profile have been chosen to match the typical configuration of SiGe HBT with high f_{max} and very low noise figure. The results show a reasonably high f_t and f_{max} for the device, however, the current gain of the device is found to be quite low, contrary to the expected value from Eq. (1). This reduced current gain is detrimental for the device high frequency low-noise performance. Further, a reduced β would have an adverse effect on f_t due to dependence of f_t on I_C (and hence β).

To investigate the current gain behavior of high N_B transistors, it have been taken into account the factors responsible for base recombination, which are neglected for the low N_B Si BJTs. The effect of base region recombination effects could be included in the current gain as:

$$\beta_0 \quad \frac{1}{\frac{1}{\beta_{SiGebox}} \quad \frac{1}{\beta_{brec}}} \qquad (6)$$

Where, β_0 is the dc current gain and β_{brec} is the common emitter current gain limited by the base transport factor (or base recombination effects). β_{brec} strongly depends on N_B and W_B and reduces significantly at high N_B and W_B. As mentioned earlier, a high f_{max} requires very high N_B and therefore, such transistors are prone to suffer from the β_{brec} as a bottleneck for overall dc current gain considerations. We have not included emitter-base space-charge region recombination and high level-injection effects on current gain in order to isolate the effects of increased base recombination. Using the base minority carrier charge divided by the base lifetime τ_B as the base current I_B, the expression for β_{brec} could be given as:

$$\beta_{brec} \quad \frac{\tau_B}{t_{BB}} \qquad (7)$$

where, $\tau_B \quad \frac{D_{nb}\, n_{ie}^4}{C_s^2 N_B^2}$

Where, n_{ie} is the intrinsic carrier concentration and C_s is a fitting constant in the range 1.4×10^6 cm^{-2} s^{-1} to 5.4×10^6 cm^{-2} s^{-1}[2]. The typical values of τ_B lies in the range of 10^{-10} sec for the base doping N_B of order of

10^{19} cm^{-3}. For a B-GE DHBT, the base transit time can be approximated as[2,3]:

$$t_{BBSiGebox} \quad \frac{1}{\eta}\frac{W_B^2}{D_{nb}}\left[1 \quad \frac{2D_{nb}}{v_d W_B}\right] \tag{8}$$

An insight into the current gain performance of B-GE SiGe HBT could be gained by putting Eq. (5), (7) and (8) in (6) and rearranging the terms as:

$$\beta_0 \quad \frac{1}{\dfrac{1}{\gamma\eta\dfrac{W_E D_{nb} N_E}{W_B N_B D_{pe}}\exp\left(\dfrac{\Delta E_{G(BE)}}{KT}\right)} \quad \dfrac{1}{\eta\dfrac{D_{nb}^2 n_{ie}^4}{W_B^2 N_B^2 C_s^2}\left[1 \quad \dfrac{2D_{nb}}{v_d W_B}\right]^{-1}}} \tag{9}$$

As is evident from (9), β_0 of a typical B-GE SiGe DHBT would be dominated by the maximum of the two terms in the denominator. Therefore, The lower of the two ($\beta_{SiGebox}$ and β_{brec}) would bring down the β_0. Further insight into transistor current gain behavior at very high N_B could be found by comparing the base Gummel Number (G_B=N_BW_B) terms for $\beta_{SiGebox}$ and β_{brec}. The emitter injection efficiency dependent current gain $\beta_{SiGebox}$ is inversely proportional to G_B, whereas the base transport limited current gain β_{brec} is inversely proportional to G^{2}_{B} This effectively means that the reduction in current gain with increasing G_B (or N_B) would be more severe for the case of β_{brec} component. This would lead to a base transport limited (base recombination limited) overall current gain β_0, as the N_B is increased for achieving high f_{max}. The dominance of β_{brec} would also negate the advantage of high emitter injection efficiency obtained by SiGe base-emitter heterojunction in B-GE HBTs at very high N_B. Any reduction in β_0 would severely degrade the high-frequency NF_{min} in SiGe HBT. The simulation results confirmed the above theoretical formulation and points out the need of increasing the β_{brec} simultaneously with $\beta_{SiGebox}$, to achieve improved high-frequency noise performance along with the high f_{max}. One of the options available to increase β_{brec} is to reduce the base transit time t_{BB} for minority charge carriers. This could be achieved by using a triangular-Ge profile in base as shown in Eq. (2). However, going for an all out triangular-Ge ramp in base would again reduce the β_0 as the exp ($\Delta E_{G(BE)}$)/KT term in (1) would become unity.

A better approach would be to use a box-triangular Germanium (BT-GE) profile i.e. a reduced germanium profile at e-b junction (in comparison with pure B-GE HBT) and then to use the remaining germanium concentration for a Ge ramp inside the base up to b-c junction. An important aspect of such an approach would be to keep the total germanium concentration and base thickness well within the critical thickness limit for SiGe layers. Moreover, the best-optimized BT-GE profile would be a strong function of N_B (G_B) as N_B defines the individual dominance of $\beta_{SiGebox}$ and β_{brec}. The optimization criteria for the Ge profile in base region could be expressed as:

$$\left[\frac{1}{\beta_{SiGebox}} \quad \frac{1}{\beta_{brec}}\right]_{B-GE} > \left[\frac{1}{\beta_{SiGeBT}} \quad \frac{1}{\beta_{brecBT}}\right]_{BT-GE} \tag{10}$$

Where, β_{SiGeBT} and β_{brecBT} are the emitter injection efficiency dependent current gain and base transport limited current gain, respectively, for box-triangular BT-GE DHBT. We have simulated numerous SiGe BT-GE DHBT structures and one of the results is given in the present work.

RESULTS AND DISCUSSION

The current gain, cut off frequency and maximum oscillation frequency performance of the B-GE NPN DHBT and proposed BT-GE NPN DHBT is compared for identical device dimensions, doping densities and bias conditions. Base doping concentration and base width for SiGe DHBTs as used in conventional microwave frequency SiGe bipolar transistors were chosen[5]. The surface emitter doping of 2×10^{20} cm^{-3} and its thickness of 0.1 μm is chosen to provide ohmic contact. The emitter doping of 5×10^{18} cm^{-3}and its thickness of 0.1 μm is selected to lower the emitter-base capacitance for improved frequency performance. The base thickness of 0.03 μm with a uniform base doping of 9×10^{13} cm^{-3} is chosen in both the structures. The collector doping of 1×10^{17} cm^{-3} and thickness of 0.35 μm has been chosen in both the structures. The Ge profile in base region of B-GE DHBT and BT-GE DHBT structures is shown in (Fig. 1) An optimized mole fraction of germanium has been chosen to

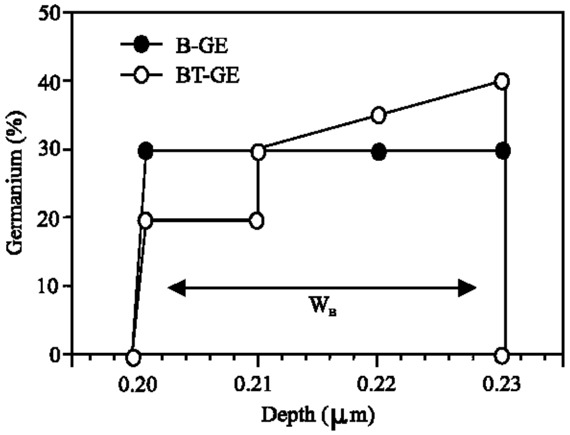

Fig. 1: Germanium concentration in the base region for Box-Germanium (B-GE) and Box Triangular-Germanium (BT-GE) profile DHBTs

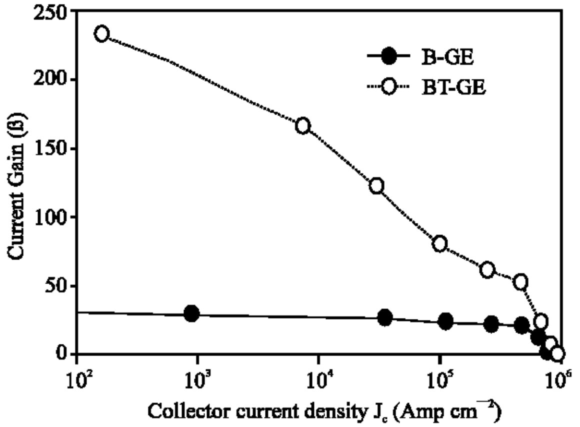

Fig. 2: Common emitter DC current gain for Box-Germanium (B-GE) and Box-Triangular-Germanium (BT-GE) profile DHBTs

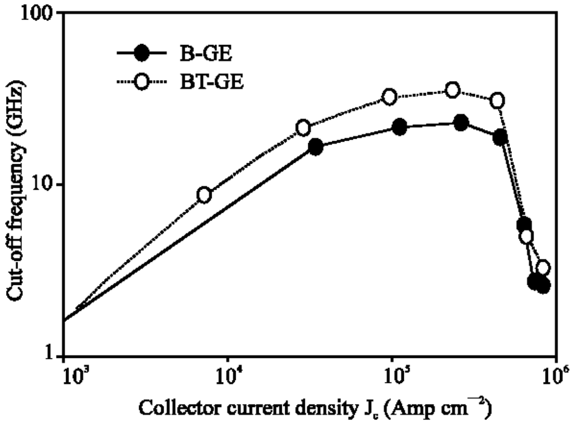

Fig. 3: Cut-off Frequency curves for Box-Germanium (B-GE) and Box-Triangular-Germanium (BT-GE) profile DHBTs

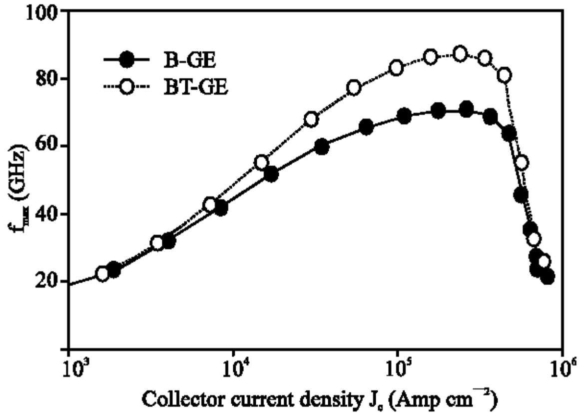

Fig. 4: Maximum Oscillation frequency for Box-Germanium (B-GE) and Box-Triangular-Germanium (BT-GE) profile DHBTs

retain the strained behavior and stability of SiGe layers[6]. A uniform 30% Ge has been chosen in the base of B-GE DHBT structure. The BT-GE DHBT has 20% Ge at the emitter-base heterojunction and a Ge ramp inside the base region to 40% Ge at the b-c junction.

Figure 2 shows the current gain vs. Collector current density plot for B-GE and BT-GE DHBT structures. A better optimization of Ge profile in BT-GE DHBT leads to a superior dc current gain β_0 of ≈ 81 in comparison to a very low current gain of ≈ 22 in B-GE DHBT at a collector current density of $\approx 1\times10^5$ Amp cm^{-2}. The β_0 value for B-GE DHBT is typically the value controlled by β_{brec}, which is found to be approx. in the range of 30-40 for the chosen bias, device dimensions and doping profiles. On the other hand, the BT-GE with higher β_0 would show a reduced NF_{min} in comparison with B-GE DHBT and hence would be better suited for high-frequency low noise applications. Similarly, the BT-GE DHBT shows a superior performance in terms of cut-off frequency and maximum oscillation frequency in comparison with B-GE DHBT. In Fig. 3, the BT-GE DHBT shows a peak f_t of ≈ 36 GHz in comparison with a peak f_t of ≈ 23 GHz in B-GE DHBT. In Fig. 4, the BT-GE DHBT is showing an improved peak f_{max} of ≈ 86 GHz in comparison with the peak f_{max} of ≈ 70 GHz in B-GE DHBT. The reduced f_{max} in B-GE is a consequence of reduction in f_t as given in Eq. (4). And, the reduction in f_t is fallout of reduced current gain in B-GE in comparison with BT-GE, as expressed in Eq. (3). This effectively leads to the conclusion that in order to exploit the advantage of reduced base resistance in high f_{max} SiGe DHBTs, it is important to avoid the degradation in current gain. Further, an improved current gain and cutoff frequency in BT-GE HBT would lead to better high frequency noise performance[7], which is important in low-noise amplifiers and mixers.

The present work gives a theoretical base of understanding the dominance of base transport limited current gain in the expression of total dc current gain for a SiGe DHBT. The degradation of current gain in high f_{max} SiGe DHBT at very high N_B should be avoided to fully exploit the advantages of SiGe base. This calls for an optimized Ge profile in the base, which includes a combination of box- and triangular- Ge profile region. A high f_{max} could be achieved by optimizing the current gain and f_t with the use of suitable BT-GE DHBT.

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