Performance Analysis of a SiGe/Si Heterojunction Bipolar Transistor for Different Ge-composition

Mukul K Das [1] , N. R. Das [2] and P. K. Basu [2]
[1] Computer Centre, [2] Institute of Radio Physics and Electronics
University of Calcutta, 92 Acharya P. C. Road,
Kolkata – 700009, India, Email: nrd@ieee.org

ABSTRACT:

In this paper, the common-emitter forward current gain, Early voltage and total transit time of a SiGe heterojunction bipolar transistor (HBT) have been calculated and computed for different composition of Ge in the base. The results show that using suitable Ge-composition in the uniformly doped base, the transit time of the HBT can be significantly increased. The calculated cut-off frequency (f_T) of the HBT increases with the increase in the total Ge-content, and for the same Ge-content, it increases with the change in profile gradually from 'box' to 'trapezoidal', and then to 'triangular' type.

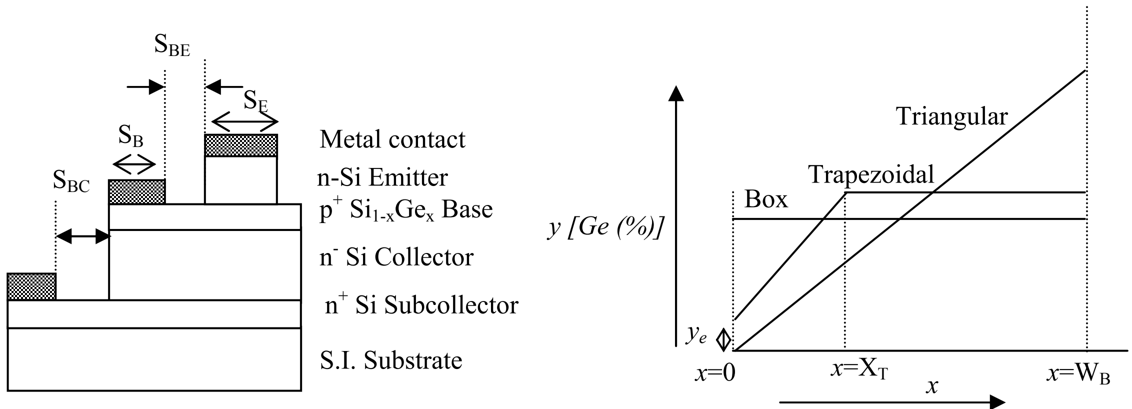
1. INTRODUCTION:

Recently, Si-based monolithically integrated photoreceiver has attracted a great deal of interest among researchers around the world [1-2]. Because of low-cost, high reliability and the potential for very large scale integration, Si-based devices have got an edge over their III-V counterparts, even though the latter shows superior high frequency performance. The two key components of a photoreceiver are a photodetector and an amplifier in which the state-of-the-art heterojunction bipolar transistor (HBT) is used as the active device [3-5]. In the Si photoreceiver, the amplifier is usually constructed from the state-of-the-art SiGe/Si heterojunction bipolar transistor (HBT). The smaller band gap of base layer at SiGe HBT causes an increase in the collector current for the same forward bias, and the bandgap grading results in rapid transport of the minority carriers through the base [6]. The absorption at longer wavelengths (e.g. 1.3µm, 1.55µm) can be enhanced with the addition of more Ge [7], but this leads to a strained SiGe base layer and the strain is tolerable if the layer thickness is less than a critical value [8]. Thus, the Ge-profile and the total Ge-content in the base of a HBT have critical roles in the high frequency performance of the HBT.

In the present paper, the effect of Ge-composition on the performance parameters of a SiGe HBT has been investigated. The common-emitter current gain, the Early voltage, the transit time and, hence, the cut-off frequency (f_T) of the SiGe HBT have been calculated and computed for different composition of Ge in the base considering uniform base doping. The remaining sections of this paper are organized as follows. The structure of the SiGe-base HBT is described in section 2. In section 3, a theoretical aspect of the SiGe-base HBT has been discussed to study the above-mentioned performance of the transistor. The results and analysis are discussed in section 4. Finally, in section 5, a conclusion is given.

2. DEVICE STRUCTURE:

The schematic layer structure of a SiGe-HBT is shown in Fig.1(a). The structure shown in this figure is suitable for an integrated circuit where the photodetector and HBT amplifier are monolithically grown on the Si substrate. The base of the HBT is formed by the graded band-gap SiGe layer, where the grading depends on the Ge content incorporated into Si layer. The profile of Ge in the base along x is shown in Fig.1(b). The profile starts at x=0, i.e. at the emitter-base junction and ends at x=W_B, i.e. at the base-collector junction. In this figure, three different types of Ge profiles are shown assuming total Ge content in the base to be the same in all the cases. In case of 'box' profile, Ge content remains same throughout the base while in case of 'triangular' profile, Ge content varies linearly from emitter to collector junction. In a more general profile, called 'trapezoidal' profile, the Ge content increases linearly from an initial value y_e at the emitter to a maximum at a point X_T within the base and then remains constant for the rest of the base region. In the two extreme cases, i.e X_T =0, y_e = 0 and X_T =1, y_e = 0, the profile converges to 'box' and 'triangular' profiles respectively.



(a) (b)

Fig. 1 (a) Schematic structure of a SiGe/Si HBT, (b) Ge-profile in the base.

3. THEORETICAL ASPECTS:

The performance of the SiGe-base HBT with respect to the forward current gain (β), Early voltage (V_A), Transit time (τ) and the unity current gain cut-off frequency (f_τ) will be discussed in the present analysis.

The forward current gain for SiGe HBT will be expressed as a ratio of current density in SiGe to that in Si BJT. Denoting β_{SiGe} (β_{Si}) as the forward current gain in HBT with SiGe (Si) base it can be shown from the Moll-Ross relationship [7] that

$$\left.\frac{\beta_{SiGe}}{\beta_{Si}}\right|_{V_{BE}} \approx \left.\frac{J_{c,SiGe}}{J_{c,Si}}\right|_{V_{BE}} = \bar{\eta} W_B \bar{\gamma} \left\{ \frac{1}{\dfrac{X_T}{e^{\Delta E_{g,Ge}^{(0)}/kT}}} \frac{1-e^{-\Delta E_{g,Ge(grade)}^{(X_T)}/kT}}{\Delta E_{g,Ge(grade)}^{(X_T)}/kT} + \frac{W_B - X_T}{e^{\Delta E_{g,Ge}^{(X_T)}/kT}} \right\}, \quad \ldots(1)$$

where $J_{c,SiGe}$ ($J_{c,Si}$) is the collector current density in the SiGe (Si)– base HBT. The β's are calculated using typical values of several physical constants of Si,Ge and conversion factors [7]. From Eq.(1), we can calculate β_{SiGe} using β_{Si} for a similarly constructed BJT.

Physically Early voltage accounts for the amount of base width modulation for arbitrary values of Collector-Base reverse bias (V_{CB}). Starting from the Moll-Ross equation [7] the following expression for Early voltage is found.

$$\frac{V_{A,SiGe}}{V_{A,Si}} = \frac{\exp\left[\Delta E_{g,Ge(grade)}^{(X_T)}/kT\right]-1}{\Delta E_{g,Ge(grade)}^{(X_T)}/kT} X_T + (1-w) \quad , \quad \ldots(2)$$

where $V_{A,SiGe}$ ($V_{A,Si}$) is the Early voltage for HBT with SiGe (Si) base and $w = X_T/W_B$.

The reduction in bandgap due to incorporation of Ge into the base of SiGe HBT gives rise to a drift field Causing rapid transport of minority carrier through the base, with the consequent reduction in base transit time. A closed form analytical model for base transit time is used [9] to calculate base delay ($\tau_{b,SiGe}$) assuming 75meV reduction in band gap per 10% change in Ge content [6]. The other time delays such as, emitter delay (τ_e), collector-space charge layer delay (τ_{cscl}) and the RC time delay due to the collector capacitance(τ_c) can also be calculated in the same way as given elsewhere[10]. The unity current gain cut-off frequency (f_τ) which is given by

$$f_\tau = \frac{1}{2\pi\tau}, \quad \ldots(3)$$

3. RESULTS AND DISCUSSIONS:

The forward current gain (β), the Early voltage(V_A) for SiGe HBT are shown in Table1 for different Ge Profile. The Table shows that forward current gain (β) and the Early voltage (V_A) increases as the slope of the Ge profile increases.

Table 1 Performance parameters of SiGe HBTs for different Ge profile

Ge profile	V_A (volt)	β	τ_{total}(ps)	fτ(GHz)
3%-8%	49.53	149.1	2.36	67.3
3%-15%	199.12	296.7	2.1	76
3%-22%	984.90	477	1.97	80.8
3%-33%	15231.92	786.9	1.88	84.9

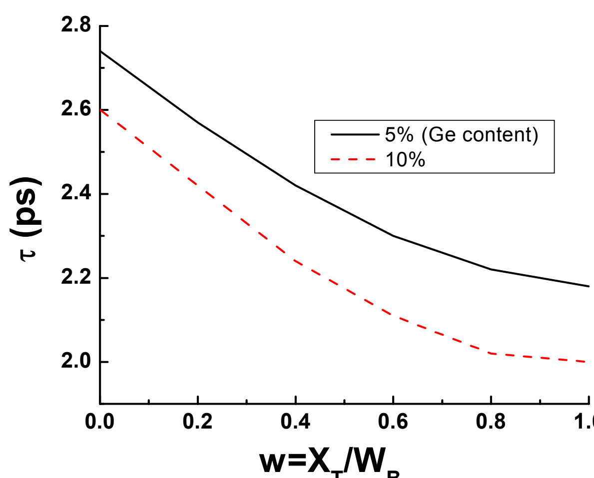
Variation of the transit time in a SiGe HBT with peak-position (w) of the trapezoidal Ge profile measured from the base-emitter junction is shown in Fig.2(a) for two different values of the total Ge-content. It can be seen from this figure that the transit time decreases with the shifting of the peak position towards the collector junction. Thus the time delay due to transit through base is minimum when the triangular Ge profile is chosen, i.e. $w = X_T/W_B = 1$. It may also be noted that for the same profile that high values of total Ge-content reduces the transit time. This can be seen more clearly from Fig.2(b).

Variation of cut-off frequency (f_τ) with the peak position of Ge profile is shown in Fig.3(a) for two different values of total Ge-content. This figure shows that the cut-off frequency increases as one moves gradually from box towards the triangular profile and also as the total-Ge content is increased. Variation of cut-off frequency with total Ge-content is shown more clearly in Fig.3.(b). The rate of increase of cut-off frequency is higher for lower values of total Ge content and also for triangular type of profile. It is observed that a high value of f_τ can be achieved for Ge content as low as 10% and further increase in Ge content does not introduce significant increase in f_τ values. The lower value of Ge content to achieve high value of f_τ is advantageous as the base layer thickness may easily be kept below critical layer thickness.

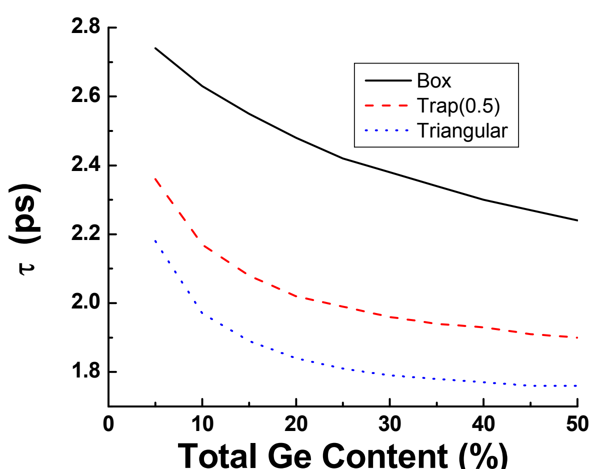
4. CONCLUSION

In this paper a detailed investigation has been made to study the effect of Ge profile as well as total Ge content in the SiGe-HBT base on the performance of the HBT. A general type of trapezoidal Ge profile has been employed, the two extreme cases of which are box and triangular profiles. The HBT parameters studied include the Early voltage, forward current gain, transit time and cut-off frequency. The study shows that the forward current gain and transit time decrease as the profiles change from box to triangular types while Early voltage increases for the similar change. The decrease in transit time results in increase of f_τ.

In case of box profile, the band gap reduction at B-E junction and at B-C junction is same and hence there is no drift field due to band gap grading. As a consequence the reduction of transit time in case of a box profile is absent, while the reduction is the most significant in case of a triangular profile. On the other hand to achieve enhancement of forward current gain (β), one should increase the Ge content at B-E junction and slope of Ge profile also. The present study shows that a trapezoidal profile with controlled peak position and total content of Ge in the base can give rise to a design of the SiGe-base HBT for both high gain and high frequency.

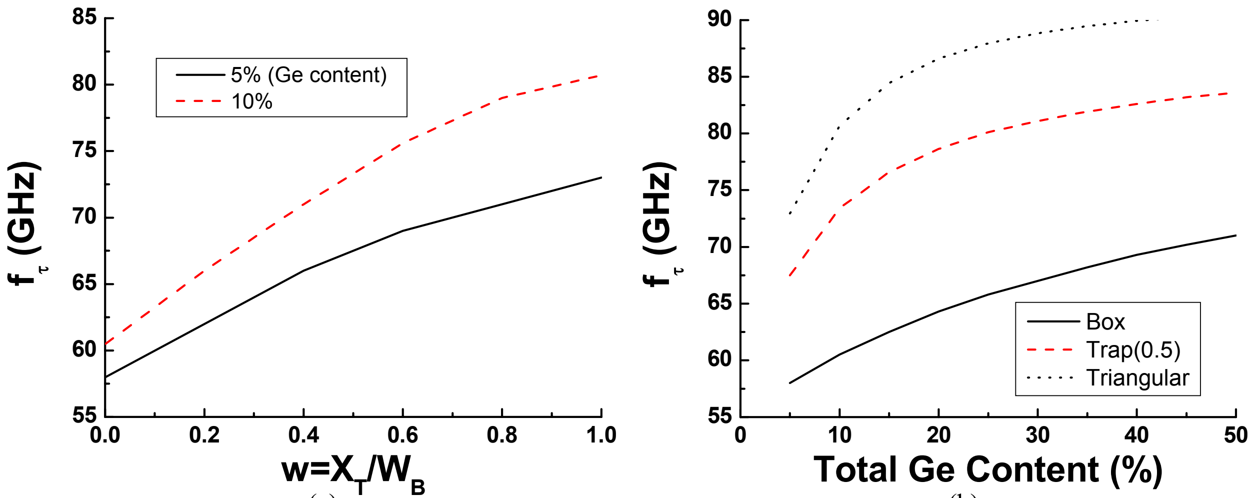


(a)



(b)

Fig.2 (a)Total transit time(τ) vs. peak position (*w*) of Ge-content for different total Ge content for different Ge profiles. (b) Total transit time (τ) vs. total Ge-content for different Ge profiles.



(a) (b)

Fig.3 (a) Plot of cut-off frequency (f_τ) vs peak position (w) of Ge content for different total Ge content. (b) Cut-off frequency (f_τ) vs total Ge content for different Ge profile.

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