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Analytical Modeling of AlGaAs/GaAs and Si/SiGe HBTs Including the Effect of Temperature

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Abstract: A semi-empirical analytical model of AlxGaAs1-x/GaAs and Si1-xGex heterojunction bipolar transistor is presented in this paper. Current gain (β) and forward transit time(τF) are two important factors for determining the performance of a transistor. Variations of current gain and forward transit time with temperature and other device parameters are predicted with the help of this model. Comparison of performance characteristics of these two devices are made for different composition and doping concentration in the emitter and base regions and for a wide range of temperature. Performance characteristics of these devices are also compared with Si homojunction bipolar transistor.

Keywords: Heterojunction Bipolar Transistor, AlGaAs/ GaAs heterojunction, Si/SiGe heterojunction, current gain, transit time

I. INTRODUCTION

Recent advances in communication, digital signal processing and computational systems demand very high performance electronic circuits. Heterojunction Bipolar Transistors (HBTs) have the potential of providing a more efficient solution to many key system requirements through intrinsic device advantages[1]. In a HBT the emitter region has wider band gap than base and this feature is primarily responsible for better performance of HBTs. Most of the developments of HBT technology has been made for Al_xGaAs_{1-x}/GaAs material system. The lattice constants of these materials are very close and this leads to excellent heterointerface quality with very few dislocations and interface states [2]. Another important HBT structure is made of Si emitter and $Si_{1-x}Ge_x$ base.

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This structure has similar advantages like Al_xGaAs_{1-x}/GaAs HBT. Moreover compatibility with standard Si technology makes it much attractive for HBT fabrication. Both of these devices have widely been studied in literature [3,4,5,6,7,8,9]. A semiempirical analytical model is developed in the present paper to compare the performance of these two competing structures. Current gain and forward transit time are two important factors for determining the performance of HBTs .This model is used to study the variation of current gain and forward transit time different parameters like temperature , composition and doping concentration. The performance characteristics of these HBTs are also compared with Si Bipolar Junction Transistors.

II. THEORY

The current gain of an npn HBT having uniform doping concentration in the base and emitter region is given by [10]

$$\beta = N_{DE}W_E D_n(T)\exp(\Delta E_g / kT) / \left[N_{AB}W_B D_P(T)\right] \quad (1)$$

where, N_{DE} and N_{AB} are emitter and base doping concentrations, W_E and W_B are emitter and base widths, D_n, and D_p, are diffusion constants of minority carriers in the base and the emitter regions respectively, ΔEg is the band gap difference between emitter and base regions, k is Boltzmann constant and T absolute temperature in degree Kelvin. Assuming Einstein's relation holds good D_n and D_p are given by

$D_n = (kT/q)\,\mu_n$
$D_p = (kT/q)\,\mu_p$

Forward transit time (τ_F) which is an important factor for determining switching speed of a transistor is the sum of emitter and base transit times(τ_E and τ_B) and is given by [11]

$$\tau_F = \tau_E + \tau_B$$

where,

$$\tau_E = W_E^2 / [2D_p(T)\beta] \text{ and}$$
$$\tau_B = W_B^2 / [2D_n(T)] \quad (2)$$

A. *Al_xGaAs_{1-x}/GaAs HBT:*

From (1) the current gain of *Al_xGaAs_{1-x}/GaAs* HBT having uniform doping concentration in the base and emitter region is given by

$$\beta = N_{DE}W_E D_{n,\,GaAs}(T)\exp(\Delta E_g / kT) / \left[N_{AB}W_B D_{p,\,AlGaAs}(T)\right] \quad (3)$$

Temperature dependence of mobility is given by [12]

$$\mu_{n,GaAs} \;\alpha\; T^{-2.1} \text{ or } \mu_{n,GaAs} = K_1\, T^{-2.1} \quad (4)$$

where K_1 is proportionality constant. K_1 is determined considering $\mu_{n,GaAs}$ =8500cm^2/V-s at 300k. For $Al_xGa_{1-x}As$ [2] at T=300k

$$\mu_{p,AlGaAs} = 370-970x+740x^2 \quad (5)$$

where, x is the mole fraction of Al in the compound. Temperature dependence of hole mobility in GaAs is $\mu_{p,GaAs}\;\alpha\; T^{-1}$ [12]. Assuming the same dependence in AlGaAs for low value of mole fraction x one can write

$$\mu_{p,AlGaAs}\;\alpha\; T^{-1} \text{ or } \mu_{p,AlGaAs} = K_2\, T^{-1} \quad (6)$$

For a given value of x, $\mu_{p,AlGaAs}$ is calculated from (4) at 300k and constant K_2 can easily be determined. Again band gap difference between $Al_xGa_{1-x}As$ emitter and GaAs base is given by[2],

$$\Delta E_g = 1.25x \qquad \text{for } x < 0.4 \quad (7)$$

Using (1)-(7) variation of current gain and forward transit time is determined for $Al_xGa_{1-x}As$/ GaAs npn HBTs with different parameters like temperature, mole fraction of composition of emitter and doping concentration of base region.

B. *$Si/\,Si_{1-x}Ge_x$ HBT:*

In order to compare the performance of similar *$Si/\,Si_{1-x}Ge_x$* HBTs following equations are used.

$$\beta = N_{DE}W_E D_{n,\,SiGe}(T)\exp(\Delta E_g / kT) / \left[N_{AB}W_B D_{p,\,Si}(T)\right] \quad (8)$$

$$\Delta E_g = .43x - .0206{*}x^2 \text{ [2]}$$
$$\mu_{n,,Si}\;\alpha\; T^{-2.42} \text{ or } \mu_{n,Si} = K_3\, T^{-2.42} \quad (9)$$

$$\mu_{,n,Ge}\;\alpha\; T^{-1.66} \text{ or } \mu_{n,Ge} = K_4 T^{-1.66}$$

Proportionality constants K_3 and K_4 are determined considering $\mu_{n,,Si}$ = 1350 cm^2/V-s and $\mu_{,n,Ge}$= 3900cm^2/V-s at T=300k.

$$\mu_{n,,SiGe} = \mu_{n,,Si}(1-x) + \mu_{,n,Ge}\,x \quad (10)$$

Temperature dependance of $\mu_{p,Si}$ is given by $\mu_{p,Si} = K_5 T^{-2.2}$ where K_5 is determined considering $\mu_{p,Si}$=500cm^2/V-s at T=300k.Using (8) to (10) and (2)current gain and forward transit time of $Si/ Si_{1-x}Ge_x$ HBTs are determined.

III. RESULTS AND DISCUSSIONS

Variations of current gain β with temperature as obtained from (3) and (8) considering temperature dependences of different parameters used in these equations are shown in Fig.1and 2. It is seen that only with x=0.1 in the Al_xGaAs_{1-x} emitter of $Al_xGaAs_{1-x}/GaAs$ HBT high current gain of the order of a few thousand is possible even with equal doping concentration and equal width of the emitter and base regions . However, for $Si/ Si_{1-x}Ge_x$ HBTs gain is only of the order of few tens for x=0.1 and a few hundreds for x=0.2. Better performance is obtained at lower temperature range for both of these HBT structures. Current gain less than 10 is obtained for comparable Si BJT [Fig.2]. Fig.3 shows forward transit time less than one tenth of pico second is possible for $Al_xGaAs_{1-x}/GaAs$ HBT for x= .05 only and as x is increased forward transit time reduces further. However, not much improvement is obtained for x greater than 0.1. For $Si/ Si_{1-x}Ge_x$ HBTs forward transit time is at least one order of magnitude less than that for comparable $Al_xGaAs_{1-x}/GaAs$ HBT with identical values of x [Fig.4]. For both of these structures forward transit time reduces with decrease in temperature. Fig. 5 shows at room temperature in order to get a gain of 100, x value less than .08 is required for $Al_xGaAs_{1-x}/GaAs$ HBT, whereas, to get same value of gain, x equals to about 0.2 is required for $Si/ Si_{1-x}Ge_x$ HBT . Fig.6 shows current gain with doping concentration in the base region for $Al_xGaAs_{1-x}/GaAs$ HBT and $Si_{1-x}Ge_x$ HBT for constant value of N_{DE} and equal base and emitter widths . Even for N_{DE} less than N_{AB} current gain of a few hundred is obtained for $Al_xGaAs_{1-x}/GaAs$ HBT for x=0.1. For $Si/ Si_{1-x}Ge_x$ HBT for x=0.3 and under similar conditions current gain is much less than that for $Al_xGaAs_{1-x}/GaAs$ HBT. Fig.1 to Fig.6 suggest that performance of $Al_xGaAs_{1-x}/GaAs$ HBT in terms of current gain and forward transit time is much better than that of $Si/ Si_{1-x}Ge_x$ HBT and Si BJT specially when doping concentration in emitter and base region is moderate and almost equal.

III. CONCLUSIONS

Results obtained from the analytical modeling of the $Al_xGaAs_{1-x}/GaAs$ HBT and $Si/ Si_{1-x}Ge_x$ HBT structures shows that good performance characteristics like high gain and low forward transit time are possible with the introduction of only a very small amount of Al in the emitter region of $Al_xGaAs_{1-x}/GaAs$ HBT structure . It shows better performance characteristics than that of comparable $Si/ Si_{1-x}Ge_x$ HBT and of Si BJT over a wide temperature range and with moderate doping concentration in both emitter and base regions. High gain and low forward transit time are possible even with higher doping concentration in the base region than in the emitter region for both of these structures.

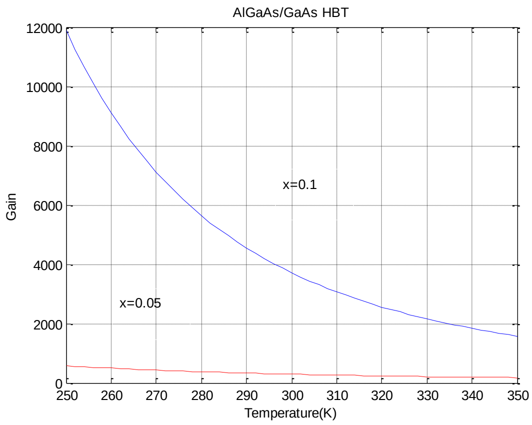

Fig.1 Variation of current gain with temperature for an $Al_xGaAs_{1-x}/GaAs$ HBT. $N_{DE}=N_{AB}=7.5x10^{15}/cm^3, W_E=W_B=60nm$.

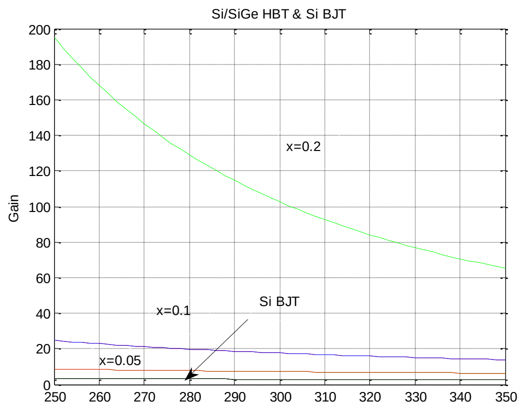

Fig.2 Variation of current gain with temperature for a $Si_{1-x}Ge_x$ HBT. $N_{DE}=N_{AB}=7.5x10^{15}/cm^3, W_E=W_B=60nm$.

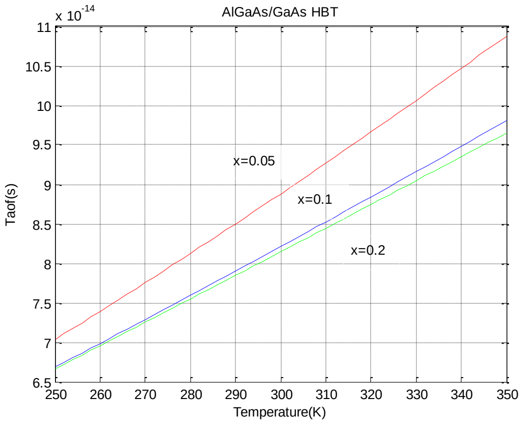

Fig.3 Variation of forward transit time with temperature for an $Al_xGaAs_{1-x}/GaAs$ HBT. $N_{DE}=N_{AB}=7.5x10^{15}/cm^3, W_E=W_B=60nm$.

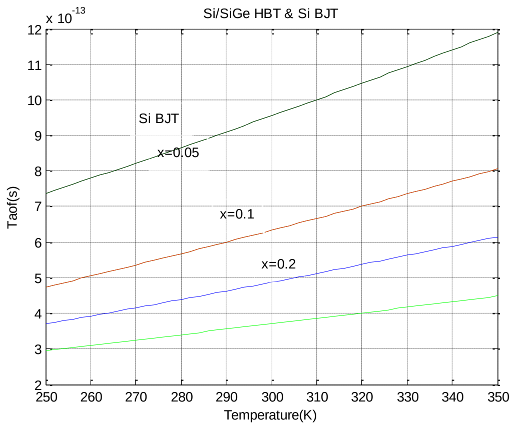

Fig.4 Variation of forward transit time with temperature for a $Si_{1-x}Ge_x$ HBT and Si BJT. $N_{DE}=N_{AB}=7.5x10^{15}/cm^3, W_E=W_B=60nm$.

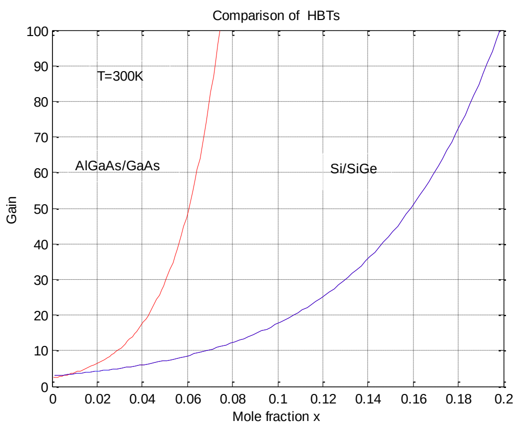

Fig.5 Variation of current gain with mole fraction xfor an $Al_xGaAs_{1-x}/GaAs$ HBT and $Si_{1-x}Ge_x$ HBT. $N_{DE}=N_{AB}=7.5x10^{15}/cm^3$, $W_E=W_B=60nm$.

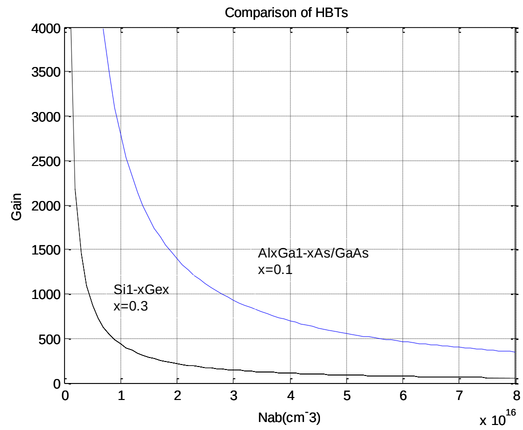

Fig.6 Variation of current gain with doping concentration in the base region for an $Al_xGaAs_{1-x}/GaAs$ HBT and $Si_{1-x}Ge_x$ HBT. N_{DE} $7.5x10^{15}/cm^3$, $W_E=W_B=60nm$.

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