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A STUDY OF BASE TRANSIT TIME AND GAIN OF INP-INGAAS HBTS FOR UNIFORM AND NEARLY GAUSSIAN BASE DOPING PROFILES

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ABSTRACT

A detailed study on Inp-InGaAs Heterojunction Bipolar Transistor is presented in this paper. Two important factors for determining the performance of a transistor are base transit time (τ_b) and current gain (β). Variations of base transit time and gain with temperature and other device parameters for both uniform and non uniform base doping profiles are studied here. Dependence of diffusion constant on temperature and doping concentration are taken into account in this study.

Keywords: InP/InGaAsHBT, Base Transit time; Current Gain.

I. INTRODUCTION

Heterojunction bipolar transistors (HBTs) using III-V compounds are of great importance in high frequency and power applications. Among these HBTs GaAs based systems are much studied in literature[1],[2],[3]. InP based technology has numerous advantages over GaAs technologies for many applications and the rapidly expanding demand for broadband telecommunications provides a strong market pull for the enabling performance. Recently, remarkable advances of InP-InGaAs HBTs and InGaAs based HEMTs have been achieved [4],[5],[6],[7] and they have become important due to their excellent current handling capability, superior frequency performance (provided by InP microelectronics) and high speed performance, which is obtained due to high electron mobility in the p type InGaAs base region. Further improvement in speed performance of these devices can be obtained by reducing base resistance which requires high doping concentration. On the other hand low doping concentration reduces junction capacitance and tunneling leakage current of either the BE or CB junction. The doping profile (nearly Gaussian) considered here meets both of these requirements. Moreover linear grading of the In content across the base can create a built-in field which can further decrease τ_b. Again mobility of carrier is another important factor on which both transit time and current gain are dependent. Mobility of carriers through base depends on temperature as well as on doping concentration and composition of base. In the present paper, effect of base doping profile and composition of base material on base transit time and gain is analyzed including the effect of temperature variation.

II.THEORY

Base transit time of InP/InGaAs HBTs by Kroemer's double integration formula is given by [8]

$$\tau_b=\int_0^{W_b}\frac{n_i^2(x)}{N_a(x)}\left[\int_x^{W_b}\frac{N_a(y)\,dy}{D_n\,n_i^2(y)}+\frac{N_a(W_b)}{V_{sat}n_i^2(W_b)}\right]dx \quad (1)$$

where W_b is the neutral base width, Na is the p type base doping concentration, Dn is the electron diffusion coefficient in the InGaAs base, n_i is the intrinsic carrier concentration of the InGaAs base and V_{sat} is the saturation velocity of minority carrier in base. Ballistic transport of carriers is not considered in (1) since clear ballistic behavior is observed only when base width is a small fraction of mean free path of carriers[9].

Assuming Einstein's relation holds good

$$D_n=\frac{KT}{q}\,\mu_{n(InGaAs)} \quad (2)$$

where $\mu_{n(InGaAs)}$ is the electron mobility in the InGaAs base , K Boltzmann constant, T absolute temperature and q electronic charge .Mobility in InGaAs is related to mole fraction of In by the relation [10]

$$\mu_{n(InGaAs)} = y_t\,\mu_{n(InAs)}+(1-y_t)\,\mu_{n(GaAs)} \quad (3)$$

where , y_t is the total In content in the base , $\mu_{n(InAs)}$ is the electron mobility in InAs , $\mu_{n(GaAs)}$ is the electron mobility in GaAs .Here the values of $\mu_{n(InAs)}$ and $\mu_{n(GaAs)}$ are considered as 22600 cm^2/v-s and 8500 cm^2/v-s respectively [11].

Mobility is dependent on temperature (T) as well as on doping concentration and is given by the relation [12]

$$\mu=\mu_{min}+\frac{\mu_{max(300K)}(300/T)^{\theta_1}-\mu_{min}}{1+\left(\frac{N_a}{1.3\times10^7\times(T/300K)^{\theta_2}}\right)^{\lambda}} \quad (4)$$

For InGaAs μ_{min} and $\mu_{max\ (300K)}$ are 300 cm^2/v-s and 14000 cm^2/v-s respectively. N_{ref} at 300K is 1.3x 10^{17} cm^{-3}. Θ_1=1.59, Θ_2=3.68, λ=0.48 [12].

Using these values mentioned above mobility in InGaAs can be found.

Current Gain of InP/InGaAs HBT is given by [13]

$$\beta=\frac{2v_B}{W_b f_R\left[1+\left(\frac{v_B}{V_{sat}}\right)\right]}=\frac{1}{f_R\left[\left(\frac{W_b^2}{2D_n}\right)+\left(\frac{W_b}{V_{sat}}\right)\right]} \quad (5)$$

where, v_B is effective electron velocity through the neutral base region, f_R is recombination factor. f_R is given by [13]

$$f_R = C_{AP}N_a^2 + (C_{BB} + C_{SRH})N_a \quad (6)$$

where, C_{AP} is Auger coefficient for holes, C_{BB} is band-to-band radiative coefficient; C_{SRH} is Shockley-Read-Hall coefficient. Here f_R is calculated as 1.6×10^9 s^{-1}[13] considering N_a as 10^{19} cm^{-3}, base width (W_b) is taken as 50nm and V_{sat} is taken as 8×10^6 cm /s[15].

From (1) base transit time for uniform base doping profile can be written as

$$\tau_b = W_b^2/2\, D_{n(InGaAs)} \quad (7)$$

II.1. Base transit time and gain for nonuniform base doping profiles without considering variation of electron diffusion constant with doping concentration

Following base doping profile (fig: 1) is considered here [14].

$$N_a(x) = N_p \sin\left(\frac{(3.12-\alpha)x}{W_b} + \alpha\right) \quad (8)$$

where $0 \le x \le W_b$ and

α *varies from* 0.1 *to* 1.57 *and* $\alpha = \sin^{-1}\frac{N_0}{N_p}$.

No is the doping concentration near the emitter, Np the peak concentration in the base, W_b the base width. At the base-emitter junction (i.e. at x=0), No=$N_p\sin(\alpha)$ and at the base-collector junction (i.e. at x=W_b) the doping concentration is $N_p\sin(3.12)=0.22N_p$.

By using (1) the base transit time for the profile in(8)can be written as

$$\tau_b = \frac{-1.998W_b^2\log\left(\sin\frac{\alpha}{2}\right)}{D_n(3.12-\alpha)^2} + \frac{0.043W_b}{V_{sat}(3.12-\alpha)} + \frac{-0.022W_b\left(\log\left(\tan\frac{\alpha}{2}\right)\right)}{V_{sat}(3.12-\alpha)} \quad (9)$$

The first term inside the bracket of (5) represents base transit time for uniform profile .The current gain of Inp-InGaAs HBT for non uniform base doping profile of (8) can be calculated from equation (5) by replacing the first term inside the bracket by the expression for transit time (τ_b) obtained in (9).

II. 2. Transit time and Gain for non uniform base doping profile taking electron diffusion coefficient as function of base doping concentration and temperature

Here diffusion coefficient is function of base doping concentration and temperature. So, diffusion coefficient is included in the integration. The transit time is calculated using (1) as,

$$\tau_b = \int_0^{W_b}\frac{n_i^2(x)}{N_a(x)}\left(\int_x^{W_b}\frac{N_a(y)\,dy}{D_n(N_a(x))\,n_i^2(y)}\right)dx + \int_0^{W_b}\frac{n_i^2(x)}{N_a(x)}\frac{N_a(W_b)\,dx}{V_{sat}\,n_i^2(W_b)}$$

$$= \int_0^{W_b}\frac{1}{N_a(x)}\left(\int_x^{W_b}\frac{N_a(y)\,dy}{D_n(N_a(x))}\right)dx + \int_0^{W_b}\frac{N_a(W_b)}{N_a(x)}\frac{dx}{V_{sat}} \quad (10)$$

where μ_n and D_n are functions of $N_a(x)$ and T. By using (4) and the values of $\mu_{min}, \mu_{max(300K)}$, θ_1 for InGaAs we obtain:

$$\mu_{InGaAs} = 300 + \frac{\left(\frac{121549400}{T^{1.59}} - 300\right)(6763.8T^{1.77})}{6763.8T^{1.77} + N_a(x)^{0.48}} \quad (11)$$

Now, for the ease of calculation some replacements are made like 300 as A, $\left(\frac{121549400}{T^{1.59}} - 300\right)(6763.8T^{1.77})$ as B and $6763.8T^{1.77}$ as C.

Then Eq. (11) can be written as

$$\mu_n(N_a(x)) = A + \frac{B}{C+N_a(x)^{0.48}}. \quad (12)$$

Diffusion coefficient can be written using (12) as

$$D_n(N_a(x)) = \frac{KT}{q}\mu_n(N_a(x)) \quad (13)$$

where base doping profile is taken as (8).Here for the purpose of simplification, the term B+A(C+$N_a(y)^{0.48}$) is replaced by 8.2A(C+$N_a(y)^{0.48}$) in the calculation of τ_b in equation (10) .The average value of the above terms are nearly equal. After the calculation A, B, C were replaced by their original values.

Now from (8),(10) and (13) we get,

$$\tau_b = \frac{W_b^2\left(\log\left(\sec^2\frac{\alpha}{2}\right)\right)}{0.213T(3.12-\alpha)^2} + \frac{0.02W_b\left(1.97-\log\left(\tan\frac{\alpha}{2}\right)\right)}{V_{sat}(3.12-\alpha)} \quad (14)$$

and Gain is calculated from (5).

II.3. Base transit time and gain for the non uniform base doping profile and linear grading of composition.

Intrinsic carrier concentration of InGaAs base is written as

$$n_{i(InGaAs)}^2 = N_c N_v \exp\left[\frac{-E_{g(InGaAs)}}{KT}\right] \quad (15)$$

where N_c,N_v are the effective density of states in the conduction band and valance band respectively, .$E_{g(InGaAs)}$ is the energy gap of InGaAs base which is in the form $E_{g(InGaAs)} = y_t\, E_{g(InAs)} + (1-y_t)\, E_{g(GaAs)}$, and E_g of InGaAs is given by [10].

Using linear variation of composition:

$E_{g\,(InGaAs)}$ = -A x+ B (16)

where A=[1.07x(y_{tc}-y_{te})/W_b] and B =[1.43-(y_{te}x1.07)], y_{te} and y_{tc} are the mole fractions of In at the emitter end of the base and the collector end of the base respectively.

$$n_{i(InGaAs)}^2 = N_c N_V \exp[\left(\frac{A}{KT}\right)x - \left(\frac{B}{KT}\right)] \quad (17)$$

Using (1) base transit time for the profile in (8) can be written as

$$\tau_b = a+b+c \quad (18)$$

where $a = \dfrac{0.11 W_b^{\,2}\left(\frac{AW_b}{KT} - 0.7\right)}{D_n\left(1+\frac{A^2 w_b^2\, 0.11}{(KT)^2}\right)}$,

$$b = -\left(\frac{0.33 W_b\left(0.01\frac{AW_b}{KT} - 1\right)\left(46.3 - 10\exp\left(-\frac{AW_b}{KT}\right)\right)}{\frac{AD_n\left(1+\frac{0.11A^2W_b^2}{(KT)^2}\right)}{KT}}\right) \text{ and}$$

$c = \dfrac{\left(0.9 - 0.2\exp\left(-\frac{AW_b}{KT}\right)\right)}{\frac{AV_{sat}}{KT}}$ and here the composition variation the electron diffusion coefficient has been taken as independent of composition variation; the expression of $n_{i(InGaAs)}^2$ in (17) is substituted in (1) to find the transit time.

Here KT=26 meV= 0.026 eV, A= [1.07× $\frac{(y_{tc}-y_{te})}{W_b}$] and delz is taken as $(y_{tc} - y_{te})$ and the gain can be calculated by (5).

III.RESULTS AND DISCUSSION

In Fig. 1, the non uniform base doping profile of InP-InGaAs has been shown, which is nearly Gaussian in nature when $\propto$ is taken as 0.1 and $N_p = 10^{19}$ cm^{-3}. When $\propto$ is taken as 1.57 the starting doping concentration is the peak concentration which occurs at the base-emitter junction.

In Fig. 2, using the base doping profile in (8) and with the help of (1), (5), (9) base transit time and gain are calculated and plotted against the fraction ($\propto$) which indicates the pattern of the base doping profile. It shows that transit time decreases and gain increases with the increase of α. Fig. 3 shows that as the doping concentration near emitter (N_0) increases the base transit time decreases and gain increases. Fig. 4 shows that as the base width (W_b) increases, the base transit time increases and the gain decreases. Using (5) and (9) the gain and transit time are calculated. Figure 5 shows that transit time decreases and gain increases with an increase in temperature from 250K to 350K. In Fig. 6, using the base doping profile in (8) and with the help of (1), (5), (11), the base transit time and gain are calculated and plotted against the base width. Here with the increase of base width the gain decreases and the transit time increases. In Fig. 7, the effect of In mole fraction grading on τ_b and β is shown. Here the In grading is varied from 0%-10% (delz=0.1) to 0%-30 % (delz=.30). As the gradient of mole fraction of In in the base increases the base transit time decreases and the gain increases. Fig. 8 and Fig. 9 show the comparison of gain and transit time's dependence on temperature for uniform and non uniform base doping profile. It is easily seen that the gain curve of non uniform doping profile is located higher in the gain axis than the curve for the uniform doping profile and transit time curve of non uniform doping profile is located lower in the transit time axis than the curve for the uniform doping profile. The temperature has not much effect the transit time of a non uniform doping profile.

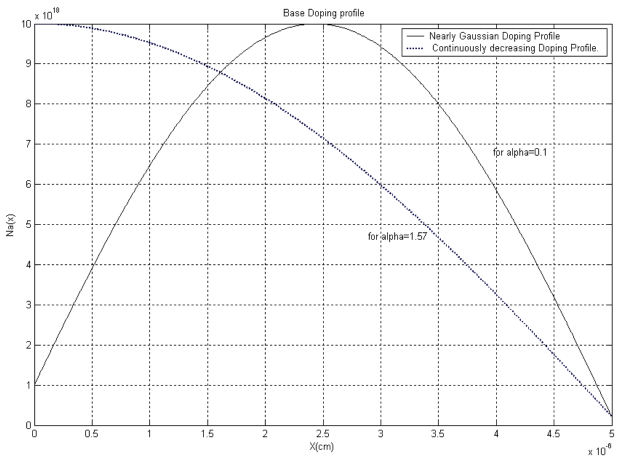

Fig. 1: Nearly gaussian base doping profile (∝=0.1) and continuously decreasing doping profile for ∝ =1.57.

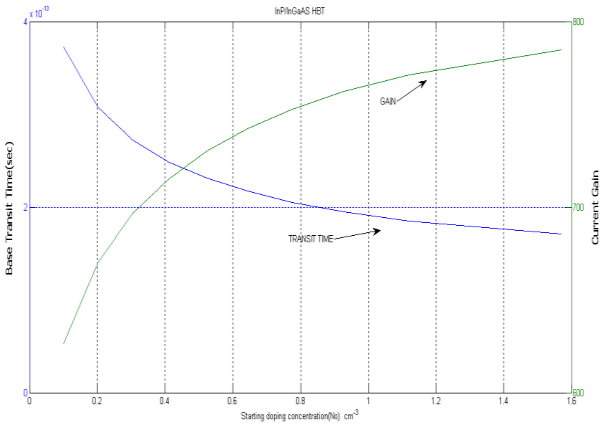

Fig. 2: Transit time /gain vs profile fraction (∝).D_n=415 cm^2/s, y_t=0.53.

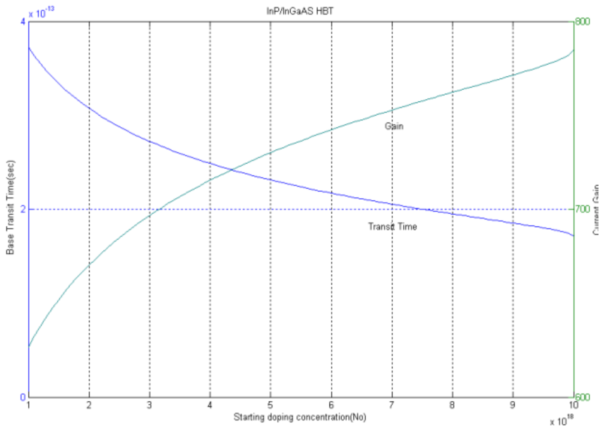

Fig. 3: Transit time /gain vs starting doping concentration(N_0), D_n=415 cm^2/s. y_t=0.53.

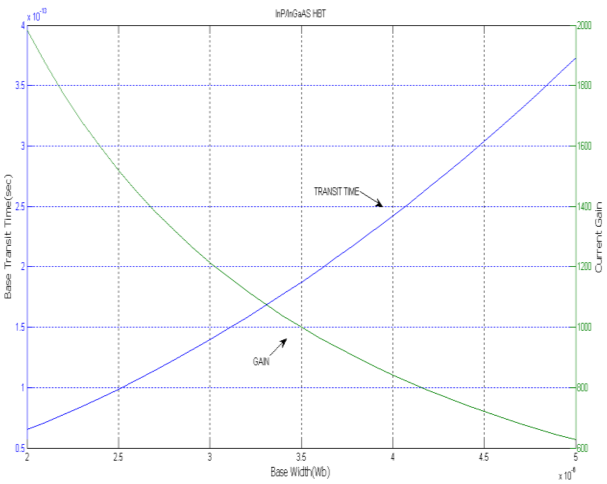

Fig. 4: Transit time /gain vs base width, Dn=415 cm^2/s, y_t =0.53.

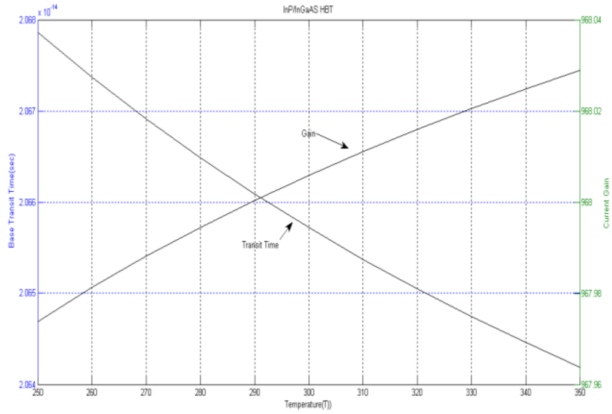

Fig. 5: Transit time /gain vs temperature .Diffusion coefficient is function of doping concentration and temperature.

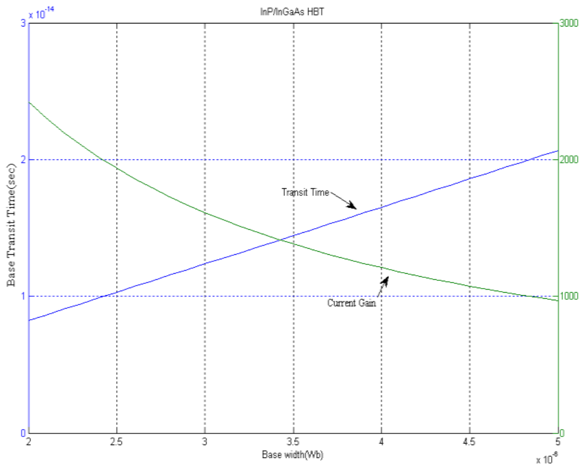

Fig. 6: Transit time /gain vs base width. .Diffusion coefficient is function of base doping concentration .i.e function of x and temperature, T=300K.

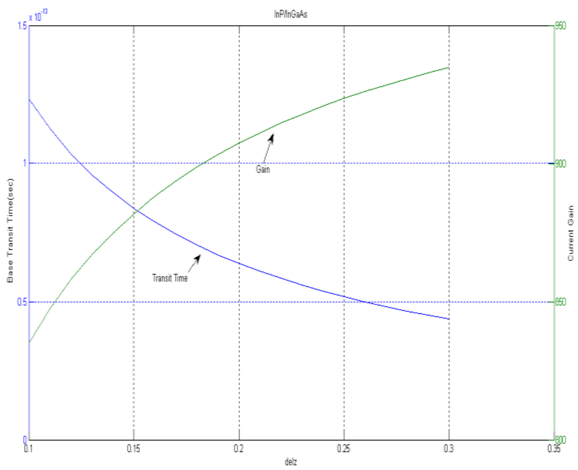

Fig. 7: Transit time /gain vs delz, D_n=415 cm^2/s, y_t=0.53.

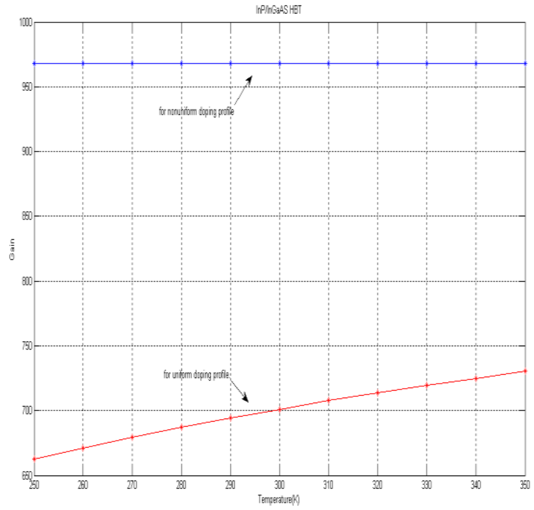

Fig. 8: comparison between gain vs temperature plot for uniform and non uniform nearly Gaussian doping profile.

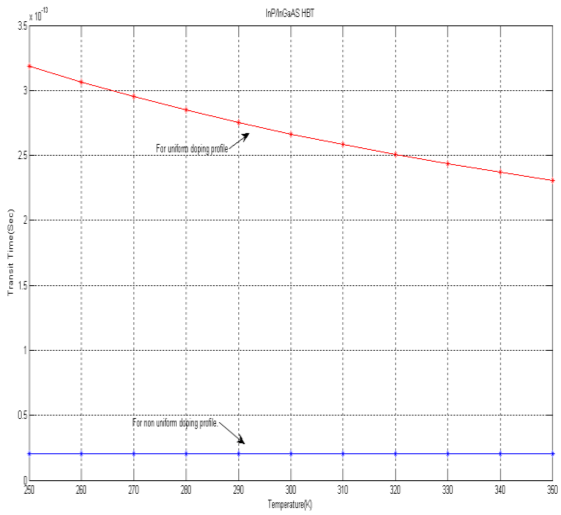

Fig.9: Comparison between transit time vs temperature plot for uniform and non uniform nearly Gaussian doping profile.

IV. CONCLUSION

Results obtained from the analytical model of the Inp/InGaAs HBT shows that higher current gain can be achieved from nonuniform base doping profile (here which is nearly Gaussian in nature) than the uniform base doping profile. High Temperature and low doping concentration (N_{p}) give low base transit time. It is found that rate of decrease of τ_b and rate of increase of β become lower as N_o, approaches N_p. The τ_b increases considerably and gain decreases with the increases in base width (w_b). But τ_b decreases considerably and gain increases with the increases in gradient of mole fraction of In (Indium) in the base. When diffusion coefficient is function of doping concentration and temperature then their contribution is taken into account for the calculation. Moreover when the profile has the highest concentration at the base–emitter junction (α= 1.57), the gain is more than when the profile has the peak value at the middle of the base (α= 0.1). But, in order to reduce junction capacitance and tunneling leakage current of the base emitter junction, doping concentration should be low at both the junctions. The base doping profile which has been taken here (Nearly Gaussian, α= 0.1.), gives the optimum base transit time and moderate current gain.

References

[1] Sukla Basu, Parijat Sarkar, "Analytical Modeling of AlGaAs/GaAs and Si/SiGe HBTs Including the Effect of Temperature", Journal of Electron Devices **9**, 325-329, (2011).

[2] Gourab Dutta,Sukla Basu, "Analysis of the electrical characteristics of GaInP/GaAs HBTs including the recombination effect", Journal of Semiconductors **33**, 5, (2012).

[3] Byoung-Gue Min,Hyung Sup Yoon, Jong-Min Lee, Seong-Il Kim , Hae Cheon Kim, "Dependences of the Characteristics of an InGaP/GaAs HBT for Applicationsin Power Amplifiers on the Structural Parameters", Journal of the Korean Physical Society **59**, 435-438, (2011).

[4] H-F Chau, H-Q Tserng, E.A. Beam, "Ka-Band Power Performance ofInP/InGaAs/InP Double Heterojunction Bipolar Transistors," IEEE Trans. Microwave and Guided Wave Letters. **6**, 129-131 (1996).

[5] Song J-I, Chough K B, Palmstrom C J, Van der Gaag B P, and Hong WP, "Carbon –doped base InP/InGaAs base HBTs with fT=200GHz" in Proc. IEEE Device Research Conf. 97-98, (1994).

[6] Subhra Chowdhury, Sukla Basu,"Effect of Device Parameters on Current Voltage Characteristics and Current Gain of InP/InGaAs HBTs", Journal of Electron Devices **9**, 362-366 (2011).

[7] U P Gomes, K Takhar, S Rathi and D Biswas," Impact of aspect ratio on the logic performance of strained In0.53Ga0.47As metamorphic HEMT", Journal of Electron Devices, **13**, 939-944 (2012).

[8] P. Rinaldi and H. SchÄattler "Minimization of the base transit time in semiconductor devices using optimal control," in Proc 4th Int. conf. Dynamical systems and differential equations. Wilmington, NC, USA 742-751, (2002).

[9] M. S. Lundstrom, P. E. Dodd, M. L. Lovejoy,E. S. Harmon, and M. R.Melloch "Electron Transport in Thin-Base InP/InGaAs HBTs", IEEE Trans. on Electron Devices **39**, 2658, (1992).

[10] P.Bhattacharya, "Elemental and Compound Semiconductors" in Semiconductor Optoelectronic Device, 2nd ed. Delhi, India: Prentice-Hall, ch. 1, sec. 1.1, 5 (2007)

[11] B.G. Streetman and S.Banerjee, Appendix III, in "*Solid State Electronic Device*," 2nd ed. New Delhi, India: Prentice Hall. 443, (1986).

[12] M. Sotoodeh, A. H. Khalid, and A. A. Rezazadeh, "Empirical low-fieldmobility model for III–V compounds applicable in device simulation codes", J. Appl. Phys. **87**, 2890-2900 (2000).

[13] Juan M. LoÂ pez-GonzaÂ lez, Pau Garcias-SalvaÁ, LluõÂs Prat "Bulk recombination in the neutral base region of abrupt InP/InGaAs HBTs", Solid-State Electronics Letter **43**, 1307-1311 (1999).

[14] W. Zhang, Z. Zheng, W. Wu, J. Luo, "Effects of doping and Ge Fraction Grading in the base on the base transit time and early voltage of Si/SiGe HBTs" in Proc. 4th Int. Conf. Solid State and Integrated Circuit Technology, Beijing, China. 450-452 (1995).

[15] S. M. Frimel and K. P. Roenkera, "Gummel–Poon model for Npn heterojunction bipolar photo-transistors", J. Appl. Phys. **82**, 3581-3592 (1997).