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EFFECT OF DEVICE PARAMETERS ON CURRENT VOLTAGE CHARACTERISTICS AND CURRENT GAIN OF InP/InGaAs HBTs

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Abstract— **An analytical model for predicting current voltage characteristics and current gain of InP-InGaAs Heterojunction Bipolar Transistors is presented in this paper. Dependence of carrier diffusion constants on composition, doping concentration and temperature as well as dependence of intrinsic carrier concentration (n_i) on temperature are incorporated in the model. Effects of base doping concentration (N_B) and mole fraction (y_t) of In in the InGaAs base region on collector current (I_C) and base current (I_B) are investigated using this model. Dependence of current gain (β) on temperature is also studied here.**

*Keywords— **HBT; InP/InGaAs HBT; Base current; Collector current; Current Gain***

I. INTRODUCTION

Heterojunction bipolar transistors (HBTs) using III-V compounds are of great importance in high frequency and power applications [1]. Among these HBTs AlGaAs/GaAs systems are much studied in literature. Recently, InP-InGaAs HBTs have become important due to their high speed performance, excellent current handling capability and superior frequency performance [2]. 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 provided by InP microelectronics [3]. In the present paper a compact analytical model for predicting electrical characteristics of InP/InGaAs HBTs is developed. Since effects of temperature (T), base doping concentration (N_B) and mole fraction of In in InGaAs base (y_t) on base current-base emitter voltage and collector current-base emitter voltage characteristics of InP-InGaAs HBTs have not been discussed much in literature [1-5] , these are considered in the present paper. Current gain, an important performance parameter for HBTs, is also considered in this study and its variation with temperature is included.

II. THEORY

A. *Dependence of collector current of InP/InGaAs HBTs on mole fraction, base doping concentration and temperature*

Collector current density of InP/InGaAs HBTs is given by [6]

$$J_C = \frac{q\, n_{iB}^2 D_n}{N_B W_B}\left[\exp\left(\frac{qV_{BE}}{KT}\right)-1\right] \qquad (1)$$

Intrinsic carrier concentration is related to temperature by the relation given below [6]

$$n_{iB}^2 = N_{CB} N_{VB} \exp\left(-\frac{qE_g}{KT}\right) \qquad (2)$$

where, N_{CB} and N_{VB} are conduction and valence band densities of states in the base respectively. E_g is the energy gap in the InGaAs base.

N_{CB} and N_{VB} are related to temperature by the relations given below [7]

$$N_{CB} = 2\left(\frac{2\Pi\, m_{nb}^* KT}{h^2}\right)^{3/2} \text{ and}$$

$$N_{VB} = \left(\frac{2\Pi\, m_{pb}^* KT}{h^2}\right)^{3/2}$$

where, m_{nb}^* and m_{pb}^* are electron and hole effective masses in in InGaAs base respectively.

Assuming Einstein's relation holds good

$$D_n = \frac{KT}{q}\mu_{n(InGaAs)} \qquad (3)$$

where, $\mu_{n(InGaAs)}$ is the electron mobility in the InGaAs base.

Mobility in InGaAs is related to mole fraction of In in the InGaAs base by the relation [8]

$$\mu_{n(InGaAs)} = y_t\, \mu_{n(InAs)} + (1-y_t)\mu_{n(GaAs)} \qquad (4)$$

where, y_t is total In content in the base, $\mu_{n(InAs)}$ and $\mu_{n(GaAs)}$ are the electron mobilities in InAs and GaAs respectively.

Mobility is dependent on temperature (T) as well as on doping concentration (N), μ as a function of doping concentration and temperature is given by the relation (5) [9].

TABLE I
Fitting parameters for the low-field mobility model in (5) [9]

Material	Electron or hole	μ_{min} (cm^2/v-s)	$\mu_{max(300K)}$ (cm^2/v-s)	$N_{ref(300K)}$ (cm^{-3})	θ_1	θ_2	λ
InAs	Electron	1000	34000	1.1×10^{18}	1.57	3	0.32
GaAs	Electron	500	9400	6×10^{16}	2.1	3	0.394
InP	Hole	10	170	4.87×10^{17}	2	3	0.62

$$\mu = \mu_{min} + \frac{\mu_{max(300K)}(300/T)^{\theta_1} - \mu_{min}}{1+\left(\frac{N}{N_{ref(300K)}(T/300K)^{\theta_2}}\right)^{\lambda}} \qquad (5)$$

Using (3) and (4) electron diffusion coefficient in InGaAs base is given by

$$D_n = \frac{KT}{q}\left[y_t\,\mu_{n(InAs)} + (1-y_t)\,\mu_{n(GaAs)}\right] \qquad (6)$$

Using (5), (6) and TABLE I, D_n as a function of temperature, mole fraction of In in InGaAs base and base doping concentration can be obtained.

Using (1),(2) and (6) collector current is given by

$$I_C = A\frac{q\,N_{CB}N_{VB}\exp\left(-\frac{q\,E_g}{KT}\right)}{N_B W_B}\left[\exp\left(\frac{qV_{BE}}{KT}\right)-1\right]\times\frac{KT}{q}\times\left[y_t\,\mu_{n(InAs)} + (1-y_t)\mu_{n(GaAs)}\right] \qquad (7)$$

where, A is the emitter base junction area.

B. Dependence of base current of InP/InGaAs HBTs on mole fraction, base doping concentration and temperature

Base current of InP/InGaAs HBTs is given by

$$I_B = I_{diff} + I_{bulk} + I_{ther} \qquad (8)$$

where, I_{diff} is the hole diffusion current from base to emitter, I_{bulk} is the bulk recombination current in the neutral base region and I_{ther} is the hole injection current with thermionic emission current from base to emitter.

Diffusion current density is given by [6]

$$J_{diff} = \frac{q\,n_{iE}^2\,D_p}{N_E W_E}\left[\exp\left(\frac{q\,V_{BE}}{KT}\right)-1\right] \qquad (9)$$

Considering temperature dependence of various terms of (9), following equation is obtained

$$J_{diff} = \frac{q\,N_{CE}N_{VE}\exp\left(-\frac{q\,E_{ge}}{KT}\right)}{N_E W_E}\left[\exp\left(\frac{qV_{BE}}{KT}\right)-1\right]\times\frac{KT}{q}\,\mu_{p(InP)} \qquad (10)$$

N_{CE} and N_{VE} are conduction and valence band densities of states in emitter respectively. E_{ge} is the energy gap in the InP emitter. N_{CE} and N_{VE} are given by the following relations [7]

$$N_{CE} = 2\left(\frac{2\Pi\, m_{ne}^{*}KT}{h^2}\right)^{3/2} \text{ and } N_{VE} = \left(\frac{2\Pi\, m_{pe}^{*}KT}{h^2}\right)^{3/2}$$

where, m_{ne}^{*} and m_{pe}^{*} are electron and hole effective masses in InP emitter respectively.

Bulk recombination current density in the neutral base can be written as [10]

$$J_{Bulk} = q\frac{W_B}{2}n_0\exp\left(\frac{qV_{BE}}{KT}\right)f_S\left[1+\frac{(D_n/W_B)}{(D_n/W_B)+V_{sat}}\right]f_R \qquad (11)$$

where, n_0, f_S, V_{sat} and f_R are the minority carrier electron concentration in the base at thermal equilibrium, spike factor, saturation velocity of minority carrier in base and recombination factor respectively. f_R is given by [10]

$$f_R = C_{AP}\,N_B^2 + (C_{BB}+C_{SRH})N_B \qquad (12)$$

where, C_{AP} is the Auger coefficient for holes, C_{BB} is the band-to-band radiative coefficient, C_{SRH} is the Shockley-Read-Hall coefficient.

Thermionic emission current density is given by [11]

$$J_{ther} = A^{*}T^2\exp\left(-\frac{q\,\phi_p}{KT}\right)\left[\exp\left(\frac{q\,V_{BE}}{KT}\right)-1\right] \qquad (13)$$

where, $q\,\phi_p$ is the hole barrier height between the hole quasi-Fermi level and valence band edge at the interface in Fig. 1.

$$q\,\phi_p \cong E_g + \Delta E_v - q\,\varphi_p \qquad (14)$$

where, $q\,\varphi_p$ is the energy difference between the electron and hole quasi-Fermi levels under bias at the interface, ΔE_v is valence band offset at the heterojunction.

A^{*} is hole Richardson's constant which is given by [12]

$$A^{*} = \frac{4\Pi q\,K^2\,m_{pb}^{*}}{h^3} \qquad (15)$$

C. *Current gain of InP/InGaAs HBTs*

Current gain in terms of base current and collector current can be written as

$$\beta = I_C / I_B \tag{16}$$

Using (7),(8),(10),(11) and (13) current gain can be written as

$$\beta = \frac{\dfrac{q\,N_{CB}\,N_{VB}\exp\left(-\dfrac{q\,E_g}{KT}\right)}{N_B W_B}\left[\exp\left(\dfrac{qV_{BE}}{KT}\right)-1\right]\times\dfrac{KT}{q}\times\left[y_t\,\mu_{n(InAs)}+\left(1-y_t\right)\mu_{n(GaAs)}\right]}{\left\{\dfrac{q\,N_{CE}\,N_{VE}\exp\left(-\dfrac{q\,E_{ge}}{KT}\right)}{N_E W_E}\left[\exp\left(\dfrac{qV_{BE}}{KT}\right)-1\right]\times\dfrac{KT}{q}\,\mu_{p(InGaAs)}\right\}+\left\{q\dfrac{W_B}{2}n_0\exp\left(\dfrac{qV_{BE}}{KT}\right)f_S\left[1+\dfrac{\left(D_n/W_B\right)}{\left(D_n/W_B\right)+V_{sat}}\right]f_R\right\}+\left\{A^* T^2\exp\left(-\dfrac{q\phi_p}{KT}\right)\left[\exp\left(\dfrac{qV_{BE}}{KT}\right)-1\right]\right\}} \tag{17}$$

III. RESULTS AND DISCUSSIONS

With the help of (1) to (15) collector current and base current for InP/InGaAs HBTs are calculated. Current gain can be determined from (17). Values of m^*_{nb}/m_0, m^*_{pb}/m_0, m^*_{ne}/m_0 and m^*_{pe}/m_0 for npn InP/InGaAs HBTs are 0.041, 0.47, 0.077 and 0.50 [13] respectively. f_R is taken as 2.7×10^{10} s^{-1}[10] for $N_B = 5\times10^{19} cm^{-3}$.Using (15) A^* is calculated as 56.534 $Acm^{-2}K^{-2}$. Value of ΔE_v is taken as 0.34 ev [13]. In Fig. 1 $q\varphi_p$ is taken as 0. Fig. 2 shows the variation of collector current and base current with emitter-base junction voltage (V_{BE}) for y_t =0.53, since this composition gives good lattice matching with InP. In the same Fig. contributions from different components of base current are also shown. This Fig. indicates that contribution of bulk recombination current in the neutral base region is higher than other components. In Fig. 3 variation of I_C with T and V_{BE} is shown. This Fig. shows that when junction voltage is below ~0.83V collector current increases with increasing temperature and junction voltage. However, for higher values of V_{BE} collector current reduces with increasing T. Fig. 4 shows variation of collector current with base doping concentration for different V_{BE} values. This Fig. illustrates that as base doping concentration increases I_C decreases for constant value of V_{BE}. But for fixed value of N_B collector current increases with increasing emitter-base junction voltage. In Fig. 5 variation of I_C with mole fraction of In in base is shown. This Fig. shows that variation of y_t does not have much effect on I_C for a fixed value of V_{BE}. Variation of base current with T and V_{BE} is shown in Fig. 6. This Fig. shows that rate of increase of base current with base emitter voltage is lower at higher temperature than that at higher temperature. For values of V_{BE} above ~0.93V base current reduces for increasing temperature. Fig. 7 shows the effect of N_B and V_{BE} on base current. This Fig. indicates that as base doping concentration increases base current decreases for a constant emitter-base junction voltage. In Fig. 8 effect of mole fraction of In in base and emitter-base junction voltage on base current is shown. This Fig. indicates that base current is not affected by y_t. Fig. 9 shows the variation of current gain with temperature and junction voltage. This Fig. indicates that current gain increases when $T \leq$ 300K, after 300K it decreases with increasing temperature.

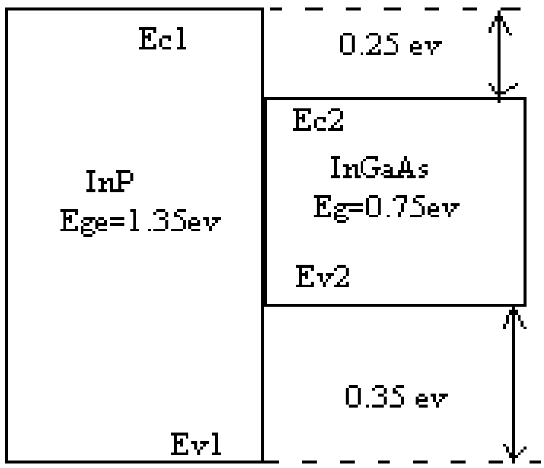

Fig. 1. Band diagram of InP/InGaAs heterojunction bipolar transistors.

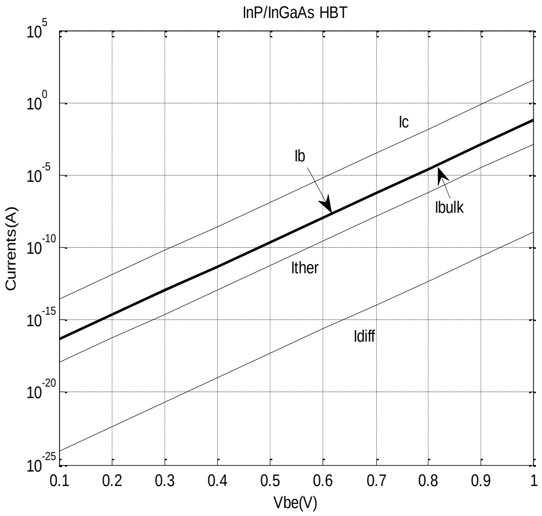

Fig. 2. Variation of collector current and base current with emitter-base junction voltage. T =300K, y_t =0.53, W_E =40nm, W_B =30nm, N_E =5×10^{17} cm^{-3}, N_B =5×10^{17} cm^{-3} and A =1μm^2.

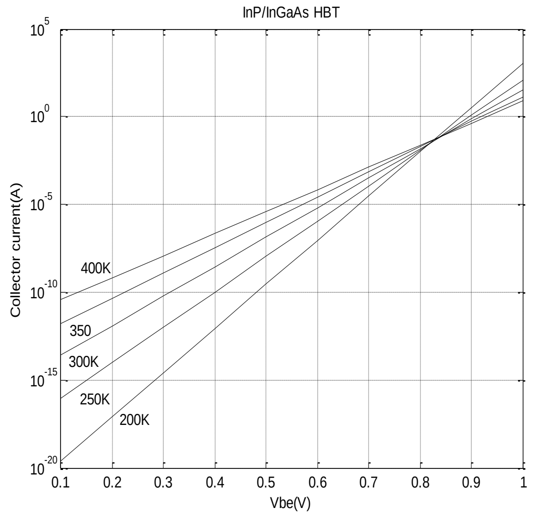

Fig. 3. Variation of I_C with V_{BE} for different temperature. y_t =0.53, W_E =40nm, W_B =30nm, N_E =5×10^{17} cm^{-3}, N_B =5×10^{17} cm^{-3} and A =1μm^2.

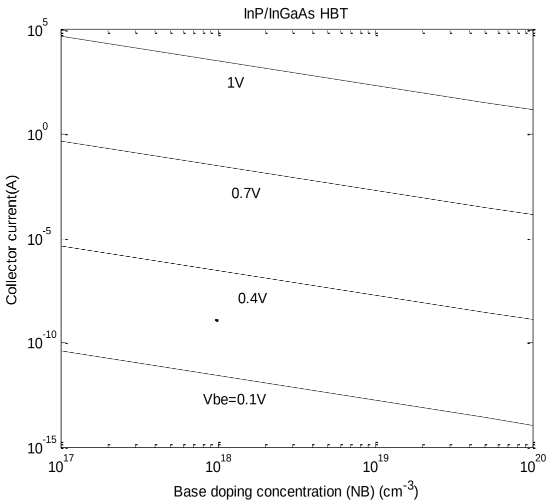

Fig. 4. Variation of collector current with N_B for different V_{BE}. T =300K, y_t =0.53, W_E =40nm, W_B =30nm, N_E =5×10^{17} cm^{-3} and A =1μm^2.

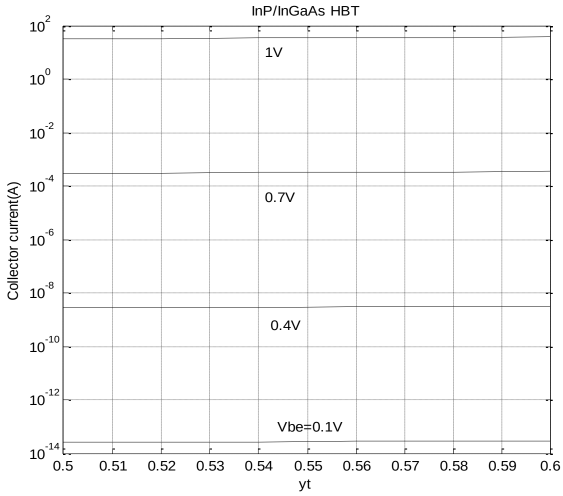

Fig. 5. Effect of mole fraction of In in base and V_{BE} on I_C. T =300K, W_E =40nm, W_B =30nm, N_E =5×10^{17} cm^{-3}, N_B =5×10^{17} cm^{-3} and A =1μm^2.

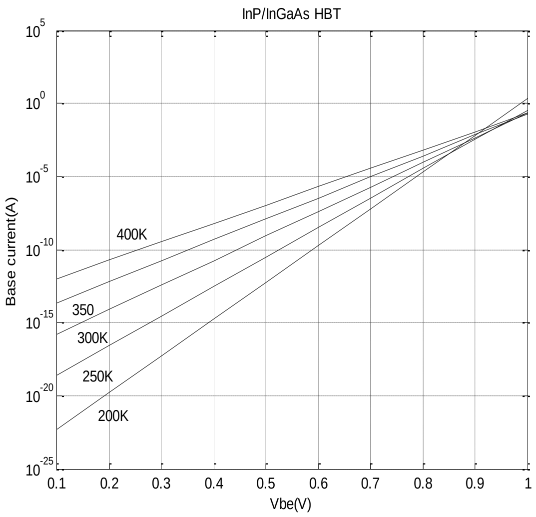

Fig. 6. Variation of base current with V_{BE} for different temperature. y_t =0.53, W_E =40nm, W_B =30nm, N_E =5×10^{17} cm^{-3}, N_B =5×10^{17} cm^{-3} and A =1μm^2.

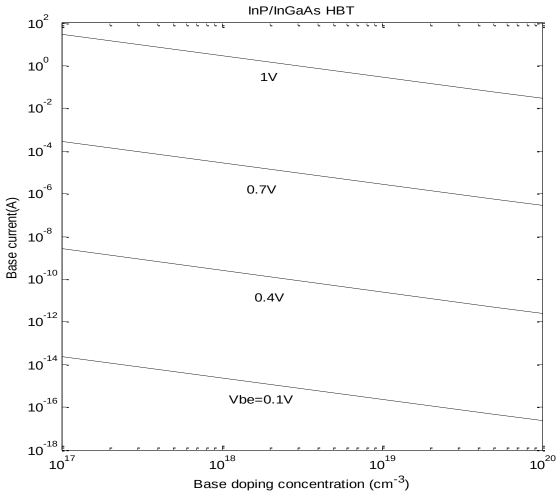

Fig. 7. Effect of base doping concentration and V_{BE} on I_B. T =300K, y_t =0.53, W_E =40nm, W_B =30nm, N_E =5×10^{17} cm^{-3} and A =1μm^2.

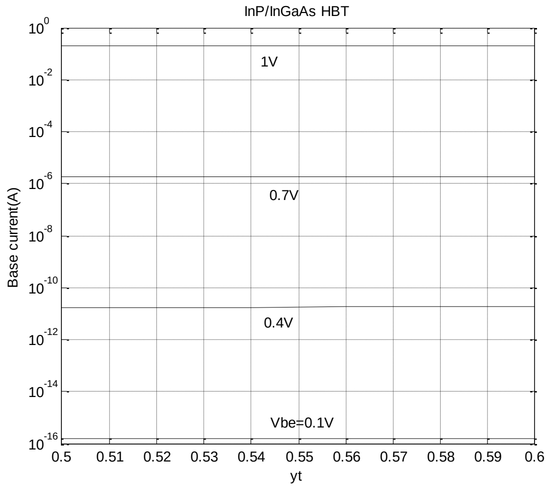

Fig. 8. Mole fraction of In in base versus I_B for different V_{BE}. T =300K, W_E =40nm, W_B =30nm, N_E =5×10^{17} cm^{-3}, N_B =5×10^{17} cm^{-3} and A =1μm^2.

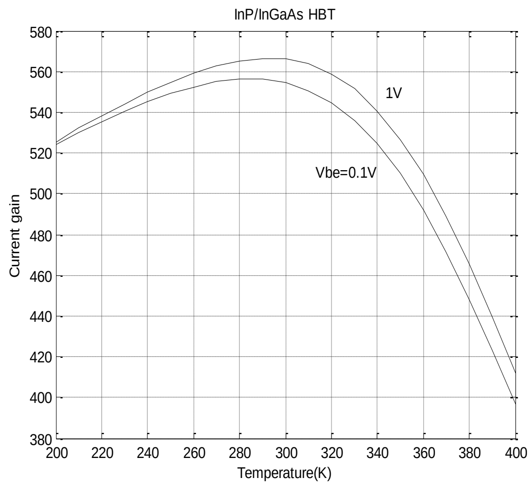

Fig. 9. Variation of current gain with T and V_{BE}. y_t =0.53, W_E =40nm, W_B =30nm, N_E =5×10^{17} cm^{-3}, N_B =5×10^{17} cm^{-3} and A =1μm^2.

IV. CONCLUSION

An analytical model for base current (I_B), collector current (I_C) and current gain (β) is developed in this paper. From the above analysis it is found that high value of collector current can be obtained for low base doping concentration and low base current for high base doping concentration. So depending on base emitter voltage optimum value of base doping concentration must be chosen. Results show that small change of mole fraction of In in InGaAs base does not have much effect on I_B and I_C. Small variation of composition is considered here in order to maintain lattice matching of hetero interface. Current gain has maximum value for T~300K and reduces in both higher and lower temperature range. However, between 200K and 340K variation of current gain with temperature is only ~ 10% .This small variation of current gain with temperature is a distinct advantage of these HBTs.

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