

A Physics-Based InP/InGaAs SHBT Model for SPICE simulation

Suchat Osaklang⁽¹⁾ and Chiranut Sa-ngiamsak⁽²⁾

⁽¹⁾ Graduate School, Department of Electrical Engineering, Faculty of Engineering, KKU, Thailand

⁽²⁾ Department of Electrical Engineering, Faculty of Engineering, KKU, Thailand

Email: g4880070@eestud.kku.ac.th and chiranut@kku.ac.th

Abstract- A physics-based, large-signal SPICE model for an abrupt-junction uniform-base InP/InGaAs SHBT is reported. This work was developed from the physics-based model for AlGaAs/GaAs SHBT. The SPICE parameters for this model are directly and automatically calculated from the transistor profile. A specific InP/InGaAs SHBT was studied. The simulations of the IV characteristics were compared with the measurements. The results show a good agreement between this work and the measurements. The comparison between the DC characteristics of InP-based HBT and of GaAs-based HBT demonstrates better suitability of this model to InP-based HBT due to the reduction of a deviation of the V_{CE} offset voltage (ΔV_{CE} offset). That of InP-based and GaAs-based SHBTs are $\sim 0.16V$ and $\sim 0.30V$, respectively.

I. INTRODUCTION

Full-custom IC design is usually carried out by first choosing an IC manufacturing technology and then circuit development is conducted until it reaches satisfactory. This conventional IC design has the restriction upon the choices of transistor technologies and its profile. This restriction became an inspiration for a newly proposed way to design ICs. This new approach is called “Physical ICs Design” [1]. “Physical IC Design” offers a door of opportunity for circuit designers to modify and to investigate the impacts of changes of a transistor profile upon circuit performance. The new idea requires a physics-based transistor model which can provide a monitoring tool for electrical effects resulted from changes in transistor profile. This physics-based transistor model was initially begun with AlGaAs/GaAs Single Heterojunction Bipolar Transistors (SHBTs). Lately, due to an emerging of new III-V semiconductors such as InP-based HBTs casts a light into this research by reapplying the physics-based model for AlGaAs/GaAs SHBTs into InP-based HBTs. For high-speed ICs designs, InP-based HBTs are generally favorable comparing with GaAs-based HBTs because InP-based HBTs show the superior in microwave characteristics. Hence InP-based HBTs become an excellent candidate for high-speed and high-frequency applications [2].

Consequently, the purpose of this work is to investigate the possibility for reapplying the Physical ICs design principle designed for AlGaAs/GaAs SHBTs to InP-based SHBTs. The set of SPICE parameters is directly calculated from the given profile. An accuracy of this model was verified by comparing the simulations with the measurements.

List of Symbols

D_{pE}	Hole diffusivity at emitter ($\text{cm}^2 \text{s}^{-1}$)
$\Delta E_C, \Delta E_V$	Conduction and valence band discontinuities (eV)
$\Delta E_n, \Delta E_p$	Electron and hole back barrier heights (eV)
E_{gB}, E_{gE}	Band-gap energy at the base and the emitter (eV)
\hbar	Planck's constant divided by 2π (J-s)
J_C, J_E	Collector and emitter current density (A/cm^2)
L_E	Diffusion length of hole at emitter (cm)
k	Boltzmann's constant ($= 1.38 \times 10^{-23} \text{ J/K}$)
m_n^*	Electron effective mass at emitter (in unit of m_0)
\bar{n}_{B0}	Electron density at thermal equilibrium (cm^{-3})
n_{in}, n_{ip}	Intrinsic carrier density at the emitter and the base (cm^{-3})
N_B, N_E	Doping density at the base and the emitter layers (cm^{-3})
\bar{p}_E	Equilibrium hole concentration in emitter (cm^{-3})
q	Electron charge ($= 1.6 \times 10^{-19} \text{ C}$)
T	Absolute temperature (K)
V_{bi}	Built-in voltage (V)
V_{bc}	Applied voltage across the B-C junction (V)
V_{be}	Voltage across the B-E junction (V)
V_T	Thermal voltage ($= kT/q$) (V)
V_{TnE}, V_{TpE}	Electron and hole thermal velocity at the emitter (cm/s)
W_E	Emitter layer thickness (cm)
X_{ne}, X_{pe}	Depletion region at the emitter and the base (cm)
γ_n	Tunneling factor
ϵ_B, ϵ_E	Dielectric constant of the base and the emitter layers
χ_B, χ_E	Electron affinity of the base and the emitter (eV)

II. DEVICE STRUCTURE

Table 1 shows a doping profile of an InP/InGaAs SHBT grown by MOVPE (Metal Organic Vapor Phase Epitaxy). This profile is obtained from Topaloglu S. [3] and the electrical properties for this device are referred to [4] and [5].

Table 1
Transistor profile of InP/InGaAs SHBT
for the emitter area (A_E) of $1 \times 15 \mu\text{m}^2$ [3]

Emitter-cap	n++ InGaAs	1E19cm-3	100nm
Emitter contact	n++ InP	1E19cm-3	50nm
Emitter	n+ InP	2E17cm-3	50nm
Base	p++ InGaAs	3E19cm-3	50nm
Collector	n- InGaAs	1E17cm-3	600nm
Stop Etch	InP		10nm
Subcollector	n++ InGaAs	8E18cm-3	300nm
Buffer	InP		50nm
S.I InP Substrate			

III. HBT MODEL

A. Abrupt-Junction Uniform-Base HBTs model

This work focuses on a large-signal InP/InGaAs HBT model [6] for the case of an abrupt-junction uniform-base structure only. The specific AlGaAs/GaAs SHBTs model development for “physical IC design” was proposed by Sa-ngiamsak C. [1]. The report of Sa-ngiamsak C. shows a good agreement between the I-V characteristic of the simulations and the measurements; Her work becomes an initiation for this work to investigating on reapplying this model to an InP/InGaAs SHBT due to its superior properties over GaAs/AlGaAs HBTs.

Reapplying the existing model of GaAs/AlGaAs HBTs to InP-based HBTs is not a straight forward task. The following investigations have to be carried out:

1. Linearity of electron back barrier high(ΔE_n)
2. Linearity of hole back barrier high(ΔE_p)
3. Effects of tunneling factor (γ_n)

The details and reasons for this condition checkout are thoroughly explained in [1] and [6]

B. Voltage dependency parameters of an InP/InGaAs HBTs model

According to [1], [6] and [7], the SPICE-based HBT model can be represented by using the Ebers-Moll (E-M) BJT model when A_{ij} parameters are constant only.

The emitter and the collector currents for the E-M BJT model are written as:

$$\begin{aligned} J_E &= -A_{11}(e^{qV_{bc}/kT} - 1) + A_{12}(e^{qV_{bc}/kT} - 1) \\ J_C &= A_{21}(e^{qV_{bc}/kT} - 1) - A_{22}(e^{qV_{bc}/kT} - 1) \end{aligned} \quad (1)$$

Reapplying the E-M model to represent a SHBT cannot be directly accomplished due to the A_{ij} parameter for SHBTs are not constant.

For example, the A_{11} parameter of a SHBT is shown below:

$$A_{11} = \frac{u_n y_n \bar{n}_{B0}}{1 + \frac{u_n y_n}{z_n}} + \frac{J_{PE}}{R_E} \cosh\left(\frac{W_E}{L_E}\right) \quad (2)$$

where $J_{PE} = qD_{pE} \bar{p}_E / L_E \sinh(W_E / L_E)$ and $R_E = 1 + (J_{pE} / qV_{TpE} \bar{p}_E) \exp(-\Delta E_p / kT) \cosh(W_E / L_E)$ [7]

The first and the second terms reflect the electron and the hole currents, respectively. The first term of A_{11} can be simplified as: $\bar{n}_{B0} Z_n$ where $u_n y_n / z_n \gg 1$ in case of an abrupt junction

[6] and $z_n = qv_{TnE} \gamma_n e^{-\Delta E_n / kT}$. Moreover, the electron back barrier height (ΔE_n), the hole back barrier height (ΔE_p) and tunneling factor (γ_n) are all a voltage dependency parameter. Overcoming this matter, if the $\gamma_n e^{-\Delta E_n / kT}$ term of an InP/InGaAs SHBT can be proven as an exponential, then there is a possibility to define this term in a single diode equation.

The investigation of the linearity of the electron and hole back barrier height are shown in Fig.1 & Fig.2.

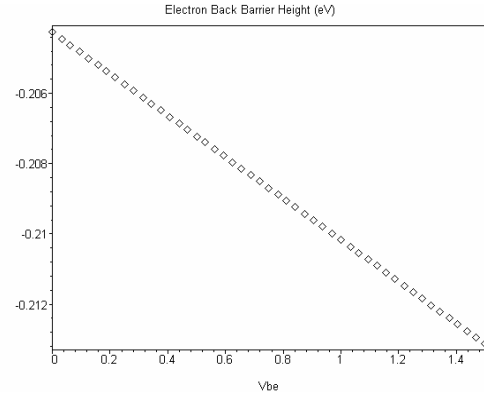


Fig. 1 Electron back barrier height in the emitter-base junction of InP/InGaAs HBTs.

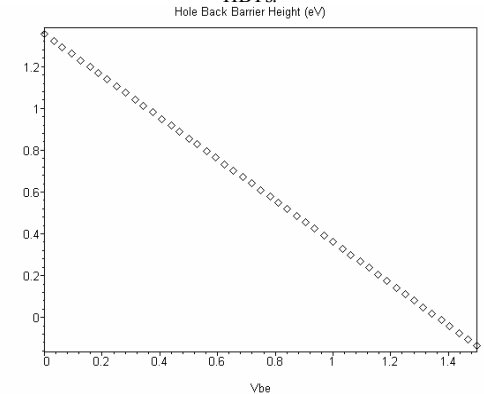


Fig. 2 Hole back barrier height in the emitter-base junction of InP/InGaAs HBTs

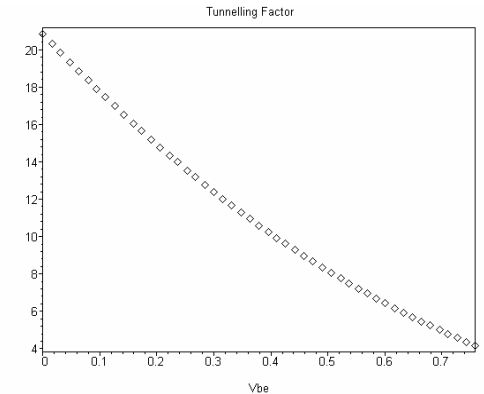


Fig. 3 Tunneling factor in the emitter-base junction of InP/InGaAs HBTs

Fig.1 demonstrates that the simulation result of the relation between ΔE_n and a bias voltage (V_{be}) is linear and so that of ΔE_p and V_{be} as shown in Fig.2. Hence, the $e^{-\Delta E_n/kT}$ term located in z_n parameter can be expressed in a diode-like format and merging the effects of ΔE_n into the E-M model in Eq.(1).

Regarding the characteristic of the tunneling factor (γ_n) shown in Fig.3, it depicts that the tunneling factor for the case of an InP/InGaAs HBT possessed an exponential relation with the bias voltage (V_{be}). So that, the $\gamma_n e^{-\Delta E_n/kT}$ terms in z_n can be exponentially expressed. In conclusion, $A_{ij}(e^{qV_{be}/kT} - 1)$ and $A_{ij}(e^{qV_{bc}/kT} - 1)$ of Eq.(1) can be defined in a single diode equation.

C. Verification of Assumptions in the Model

The assumption of $(u_n y_n / z_n) + 1 \approx (u_n y_n / z_n)$ which was applied to Eq.(1) is proven in Fig.4

Fig.4 is a plot of $(u_n y_n / z_n)$ of the InP/InGaAs SHBT profile shown in Table 1. This figure clearly demonstrates that $(u_n y_n / z_n) \gg 1$ for the normal mode operation range of V_{be} (0.4-1.0 Volt).

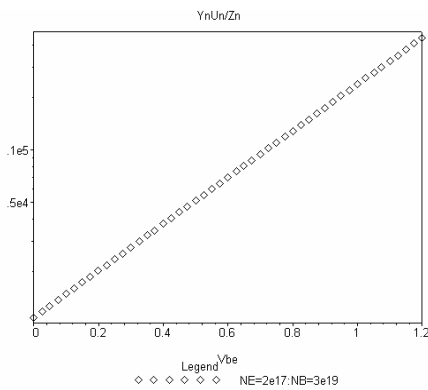


Fig. 4 The estimation result of $u_n y_n / z_n$ term in case of InP/InGaAs SHBT, for the doping profile listed in Table 1

An exponential expression of the voltage-dependent term ($\gamma_n e^{-\Delta E_n/kT}$) describes the carrier transport across a heterojunction. The $\gamma_n e^{-\Delta E_n/kT}$ term which consists of physics-based equations of the device is fitted to $A^* e^{-V_{be}/SV_t}$ where A^* and S are constant. The results of the best fit for the InP-based SHBT profile given in Table 1 are show in Fig.5. The best-fit

parameters (A^* and S) for a range of doping concentration were calculated and listed in Table 2.

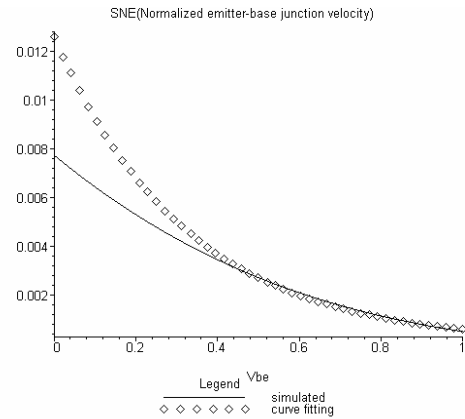


Fig. 5 The product $\gamma_n e^{-\Delta E_n/kT}$: comparison of the result from computation and the best-fit, over the bias range 0.4-1.0 V. for the uniform-base InP/InGaAs SHBT

Table 2
Fitting parameter of InP/InGaAs SHBT with different doping profile

N_B (cm^{-3})	N_B (cm^{-3})	A^*	S
1×10^{17}	1×10^{19}	0.006099	13.766864
2×10^{17}	1×10^{19}	0.022011	9.697101
2×10^{17}	3×10^{19}	0.012584	12.540796

IV. RESULTS AND DISCUSSIONS

This section presents the comparisons of the DC characteristic obtained from the simulation and the measurements [3] of the InP/InGaAs SHBT profile given in Table 1. The simulation results were generated by using PSpice where the list of the calculated SPICE parameters is in Table 3. The simulation results (dashed-lines) and the measurements (solid-lines) are depicted in Fig.6.

Table 3
SPICE parameters of InP/InGaAs SHBT [6]

SPICE parameter	Value
β_f	49.485
β_r	0.0228
I_s	3.069E-22
I_{se}	8.56E-28
I_{sc}	1.476E-28
N_f	1.0866
N_r	1
N_e	1
N_c	1
R_e	0.86
R_b	18.5
R_c	4.4

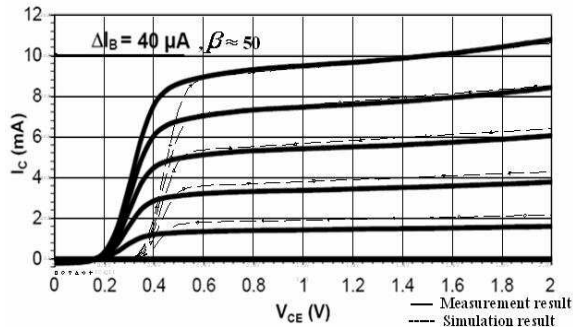


Fig. 6 Comparison of the DC characteristics between measurements (solid-lines) and simulations (dashed-lines) of the InP/InGaAs SHBT

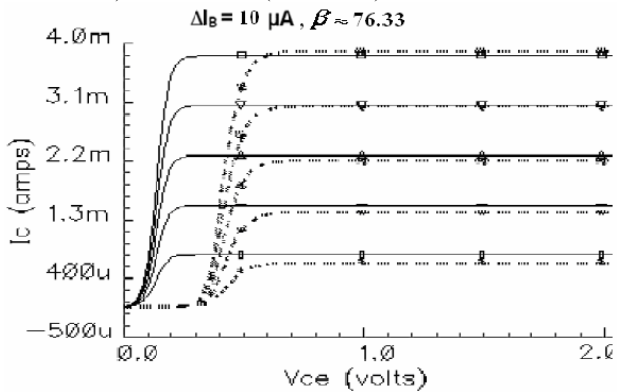


Fig. 7 Comparison of the DC characteristics between measurements (dashed-lines) and simulations (solid-lines) of the AlGaAs/GaAs HBTs where [1]

Fig.6 demonstrates a nice agreement of extending this model into InP/InGaAs SHBT devices. However, the deviation increases with smaller I_b due to the influence of the surface recombination effect being ignored at the low-level injection of carrier into emitter-base heterojunction [8].

Moreover, this model is proven to be more suitable to InP/InGaAs SHBT devices than AlGaAs/GaAs SHBT due to a smaller deviation of the V_{CE} offset voltage between the simulations and the measurements. The comparison of this figure between InP/InGaAs SHBTs (Fig.6) AlGaAs/GaAs SHBTs (Fig.7) listed in Table 4.

Table 4
Deviation of the offset voltage between the simulations and measurements of InP/InGaAs HBT vs AlGaAs/GaAs HBT

ΔV_{CE} offset	
InP/InGaAs SHBTs (Fig.6)	AlGaAs/GaAs SHBTs (Fig.7)
~ 0.16 V	~ 0.30 V

V. CONCLUSION

The extension of the physics-based HBT model for AlGaAs/GaAs HBTs has been successfully applied to InP-based HBTs. The set of SPICE parameters for a given transistor profile was calculated; and the accuracy of this approach was verified by comparing the simulations with the measurements of the specified transistor for the case of an abrupt-junction uniform-base InP/InGaAs SHBTs. The results show a good agreement in DC characteristics and an

improvement in the reduction of an error regarding to knee voltage. This work can benefit to further study on the finding of a suitable InP-based SHBT profile for a specific-purpose integrated circuits which is the core of “physical ICs design” approach.

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Appendix: Electron and hole back barrier heights ($\Delta E_n, \Delta E_p$) [1]

From the energy band diagram of a heterojunction is shown

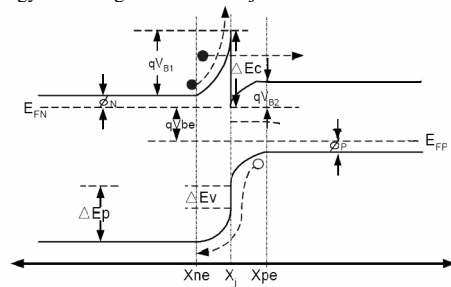


Fig.A1 Energy band diagram of an abrupt-junction and graded base HBT

The electron barrier height (ΔE_n) of an abrupt heterojunction is given by

$$\Delta E_n = qV_{B2} - \Delta E_C \quad (A1)$$

where

$$qV_{B2} = \frac{qN_B}{2\epsilon_B} X_{pe}, \quad X_{pe} = \sqrt{\frac{2N_E \epsilon_E \epsilon_B (V_{bi} - V_{be})}{qN_B (N_E \epsilon_E + N_B \epsilon_B)}}$$

$$\Delta E_C = \chi_B - \chi_E, \quad V_{bi} = \Delta E_C - \frac{E_{gE}}{2} + \frac{E_{gB}}{2} + \frac{kT}{q} \left(\frac{N_E N_B}{n_n n_p} \right)$$

The hole barrier height (ΔE_p) is defined as a level of energy which holes need to travel from the heterojunction to the emitter area. The function of the hole barrier height is given by

$$\Delta E_p = qV_{B1} - \Delta E_V \quad (A2)$$

where

$$qV_{B1} = \frac{qN_E}{2\epsilon_E} X_{ne}, \quad X_{ne} = \sqrt{\frac{2N_B \epsilon_E \epsilon_B (V_{bi} - V_{be})}{qN_E (N_E \epsilon_E + N_B \epsilon_B)}}$$

$$\Delta E_V = \Delta E_G - \Delta E_C$$

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