**VBIC MODEL APPLICABILITY AND EXTRACTION PROCEDURE FOR InGaP/GaAs HBT**

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In this paper the applicability of VBIC-95 for InGaP/GaAs HBTs modelling is examined. Extraction procedure is presented for parameters responsible for saturation currents, thermal resistance, internal base resistance and forward transit time. Resulting VBIC model was verified against large-signal DC and AC measurements.

1 **Introduction**

The VBIC model for bipolar transistors [1] is an extension of the SPICE Gummel-Poon (SGP) model for Si bipolar transistors. Questions remain whether it is applicable to GaAs HBTs. Among the possible concerns are: 1) The thermal resistance of HBTs is often reported to be temperature dependent, which is not modeled by VBIC. 2) The ideality factors of base-collector and base-emitter current components in HBT were found to change with temperature, which are not modeled by VBIC. 3) Relatively light collector doping and relatively high operation current densities make HBTs very susceptible to the base push-out (Kirk) effect. It is not clear whether SGP-like formula for base transit time in VBIC can account for this effect. 4) Modulation of base-collector depletion capacitance by collector current is not modeled in VBIC. Furthermore, VBIC model extraction procedures published to date either deal with only DC or AC part of the model [2, 3], or rely on extensive use of numerical optimisation [4].

In this paper the extraction procedure of major VBIC model parameters is presented for InGaP/GaAs HBTs. Model applicability is verified throughout the extraction and by comparison with large signal DC and AC measurements. Transistors studied were single-heterojunction 3×20 μm single-emitter HBTs with base width of 0.1 μm, collector doping of $10^{16}$ cm$^{-3}$, and unity-gain frequency of 40 GHz.

2 **Simplified VBIC model**

The topology of VBIC model is shown in Fig. 1. Note that several parts of VBIC equivalent circuit are omitted in Fig. 1: thermal sub-circuit, excess phase delay sub-circuit, base-emitter and base-collector overlap capacitors and base-collector breakdown current source. The full model is complex and contains 86 parameters, however, specific of HBT make it possible to consider a simplified version (Fig. 2). Transformation from VBIC to the simplified model is justified by the following: 1) The formulas derived for epi-layer resistance and charge ($R_{CE}$ and $Q_{CE}$) did not take into account the base push-out effect and therefore may be incorrect when Kirk effect occurs. In addition, there is no direct procedure known to extract the associated parameters. For these reasons both $R_{CE}$ and $Q_{CE}$ can be dropped. 2) The HBT topology naturally calls for SGP-like separation of both DC and AC base-collector currents into internal and external components. This can be accomplished by connecting together the "substrate" and "collector" terminals in the VBIC model and using $I_{CCE}$, $I_{ECE}$, and $Q_{ECE}$ to model the external base-collector current. 3) There is no parasitic $pnp$ transistor in $nnp$ HBT, therefore $I_{SCP}$, $Q_{SCP}$, $R_{SP}$, and $R_{S}$ can be eliminated. 4) Topologically, only non-ideal component of $I_{BEX}$ may contribute to DC external base-emitter current in HBT. For DC current there is no significant difference whether it is internal or external since DC voltage drop across $R_{B}$ is typically small. The whole external base-emitter branch therefore can be eliminated. 5) For HBTs with ordered InGaP/GaAs base-emitter heterojunction forward and reverse transport currents should be equal for equal base-emitter and base-collector potentials. It means that the same set of parameters can be used.
Fig. 1. VBIC model topology. Note: the thermal sub-circuit is not shown.

Fig. 2. Simplified SGP-like sub-model used for extraction.

for both of them. 6) The ideal component of base-emitter current mostly arises from bulk recombination and therefore can be modelled as forward transport current divided by forward current gain $\beta_e$. This current gain is assumed to be temperature-independent. 7) On the other hand, the ideal component of base-collector current is dominated by electron transport from external collector through external base directly to base contact. This is not very different from transport of electrons through internal base into emitter, which is essentially reverse transport current. The ideal component of base-collector current therefore can be modelled as a scaled reverse transport current. This scale is approximately equal to external/internal base ratio and for this reason is also assumed temperature-independent.

All DC current sources in the simplified model are defined in terms of three basic functions: $I_T(V)$, $I_{BC}(V)$ and $I_{BE}(V)$. They represent three primary conduction mechanisms: transport currents, and base-emitter and base-collector non-ideal currents, respectively. Each basic function has the same form as VBIC transport current sources:

$$I(V) = I_S e^{\frac{qE_d}{N_0 k T_J}} \left( \frac{T_J}{T_0} \right)^{\frac{qV}{N_0 (1+\alpha_d (T_J-T_0)) k T_J}} - 1, \tag{1}$$

where $I_S$, $E_d$, $N_0$ and $\alpha_d$ are the parameters to be extracted (different for each basic function); $V$ is the bias voltage; $T_J$ is the internal temperature; $T_0$ is the reference temperature (VBIC model parameter $TNOM$), $k$ is the Boltzmann constant; and $q$ is the electron charge. Parameter $XBC = 0.35$ in the sub-model was estimated from geometry.

The AC part comprises capacitors $C_{BC}$, $C_{BCN}$, $C_{BCI}$ and phase delay $\tau_p$. All capacitors include depletion and diffusion contributions. Base-collector barrier capacitance is divided between internal and external parts using SGP-like parameter $XBC$.

3 DC parameters extraction
The parameters of basic functions $I_s(V)$, $I_{(v)}(V)$ and $I_{be}(V)$ were extracted using forward and reverse Gummel characteristics (FGC and RGC) measured at different temperatures. At each temperature, the saturation currents and ideality factors ($I_{sat}$ and $n$) for $I_s$, $I_{be}$, and $I_{bc}$ were extracted together with forward and reverse current gains $\beta_F$ and $\beta_R$. This was done by first, extracting $I_{sat}$ and $n$ for $I_T$ using collector current of FGC. Then $I_{sat}$ and $n$ for $I_{be}$ were extracted together with $\beta_F$ by fitting log of base current of FGC to $\log(I_{be}(V_{be}) + I_T(V_{be})/\beta_F)$. Finally, $I_{sat}$ and $n$ for $I_{bc}$ and $\beta_R$ were extracted by fitting log of base current of RGC to $\log(I_{bc}(V_{bc}) + I_T(V_{bc})/\beta_R)$. Temperature dependencies of $I_{sat}$ and $n$ were then examined for each basic function to determine parameters $I_s$, $E_a$, $N_0$ and $\alpha_0$. Ideality factors were first fitted with straight lines to obtain the $N_{sat}$ and $\alpha_{sat}$. The pre-exponential factors ($I_{sat}$) and activation energies ($E_{act}$) were then extracted from Arrhenius plots of saturation currents. Forward and reverse current gains were just averaged over all temperatures.

Transition from sub-model back to VBIC is trivial for transport currents since they have exactly the same form as Equation (1). The rest of current sources in VBIC have $\alpha_0$ equal to zero. For them extracted activation energy $E_a'$ was modified as follows: $E_a' = E_a - T_0 \nu \alpha_0 N$. This transformation makes the temperature response of Equation (1) with activation energy $E_a'$ close to that with $E_a$ and $\alpha_0 = 0$ for biases close to $V$. Characteristic voltage $V$ was selected as 1.3 and 1.1 V for base-emitter and base-collector currents, respectively. Note that while the non-ideal component of $I_{be}$ was used to implement $I_{be}^{CC}$, the $I_{bc}^{CC}$ was implemented as $I_{bc}^{CC}$. This was done to account for base-collector diffusion charge.

Thermal resistance was extracted by measuring a series of constant power characteristics $I_s(V_{ce})$. For each power level $P$ collector voltage $V_{ce}$ was swept from 1.5 to 4 V and at each $V_{ce}$ the base current was adjusted so that $I_C = P/V_{ce}$. The saturation current of $I_T$ was extracted from $\ln(I_C)$ vs. $V_{be}$ plot at each power level. Knowing dependence of saturation current on temperature (through parameters of $I_T$ extracted earlier) the junction temperature was calculated and plotted vs. power (Fig. 3). From Fig. 3 it is clear that the thermal resistance is not constant. Since there is no way to implement this dependence in VBIC, a low-power value (dotted line in Fig. 3) was taken as the model parameter $RTH$ in VBIC.

The extracted VBIC model was verified against measured $I-V$ characteristics (Fig. 4).
Parameters extracted in this section include internal base resistor ($R_{bb}$), excess phase delay ($\tau_F$), reverse transit time ($\tau_R$) and those responsible for bias dependence of forward transit time ($TF$, $ITF$, $XTF$). All of them (except for $\tau_R$) were extracted from small-signal $S$-parameters measured in active regime. Fig. 5 shows the small-signal equivalent circuit of the simplified model. First, $Z_{bb}$ was extracted at small $I_C$ (before onset of base push-out) using known $X_{bc}$. At each frequency $R_{bb}$ was calculated according to:

$$ R_{bb} = \frac{Y_{11} + Y_{21} + X_{bc}(Y_{12} + Y_{22}) Y_{12} + Y_{22}}{(Y_{11} Y_{22} - Y_{12} Y_{21}) (1 - X_{bc}) Y_{11} + Y_{21}}. $$

where $Y_0$ are Y-parameters calculated after de-embedding all external elements. The value of $R_{bb}$ was then averaged over all frequencies. At high $I_C$ the value of $X_{bc}$ may change (decrease) because of two-dimensional distribution of pushed-out holes in collector. On the other hand, $R_{bb}$ is not expected to vary with bias because of very high base doping. The $R_{be}$ extracted at small $I_C$ was therefore used to calculate $G_{be}$ and $G_F$ at all biases and frequencies according to:

$$ G_F = \frac{A}{1 - Y_{11} + Y_{12}}, \quad G_{be} = \frac{A}{1 - Y_{11} + Y_{12}}, $$

$$ A = \frac{Y_{11} + Y_{21} + Y_{12} + Y_{22}}{(1 - R_{bb} Y_{11} + Y_{12}) (1 - Y_{11} + Y_{21})}. $$

From this data, $C_{bed}$ and $\tau_F$ were calculated for each bias as follows:

$$ C_{bed} = \frac{\text{Im}(G_{be})}{\omega}, \quad C_{bed} = \frac{\text{Im}(G_F)}{\omega}, \quad \tau_F = \frac{\text{arg}(G_F)}{\omega}, $$

where $C_{bed}$ is the base-emitter barrier capacitance. Extracted bias dependence of $C_{bed}$ is shown in Fig. 6. In the active regime forward diffusion charge can be written as $\tau_F I_C$, where $\tau_F$ is the bias dependent forward transit time. In VBIIC this dependence is:

$$ \tau_F = TF \cdot (1 + QTF q) \left[ 1 + XTF \left( \frac{I_C}{I_C + ITF} \right)^2 \frac{V_{bc}}{I_C} e^{1.44ITF} \right]. $$

Parameter $QTF$ accounts for base width modulation, which is negligible in HBT. Parameter $VTF$ accounts for suppressed electron extraction by collector electric field as $V_{bc}$ increases. This is also hardly the case in HBT, so both $QTF$ and $VTF$ are omitted (set to zero) in this study. $C_{bed}$ can therefore be expressed as:

**Fig. 5.** Small signal equivalent circuit of sub-model in active regime.

**Fig. 6.** Diffusion capacitance $C_{bed}$ (symbols) extracted and (lines) calculated using (7). $TF=2.5$ ps, $XTF=6$ and $ITF=100$ mA.

**Fig. 7.** Excess phase delay $\tau_F$ extracted according to Equation (4).
Fig. 8. (lines) Simulated vs. (symbols) measured (a) harmonic output power and (b) DC collector current. Class B, 1 GHz, 125 Ω load, 1 mA quiescent current, 400 Ω bias resistor in series with base. (a) fundamental frequency at 1 GHz, (○) 2nd, and (△) 3rd harmonics

\[ C_{BED} = \frac{d(y_{TR} I_C)}{dV_{BE}} = G_m \cdot TF \left( 1 + XTF \left( \frac{I_C}{I_C + ITF} \right) \left( 1 + \frac{2ITF}{I_C + ITF} \right) \right). \]  

(6)

Here \( G_m \) is the DC transconductance \( I_C / (n \cdot q_T) \). Parameters TF, ITF and XTF were extracted by fitting (6) to \( C_{BED} \) from (4). Results of this extraction are also plotted in Fig. 6 confirming that (6) can be used to account for the Kirk effect.

Extracted bias dependence of \( \tau_D \) is shown in Fig. 7. The dramatic increase of \( \tau_D \) after onset of the Kirk effect is because of the way the transconductance is implemented in VBIC and the simplified model: \( G_T = G_m e^{-j \omega T \tau} \). Theoretically however this should be \( G_T = G_m e^{-j \omega T (\tau_p + \tau_T)} \), where \( \tau_p \) and \( \tau_T \) are yet another bias-dependent time constants related to the collector transit time and base transit time, respectively. The overall phase shift \( \omega \tau_p \) therefore equals to \( \omega (\tau_p + \tau_T) \), which explains enormous growth of \( \tau_D \) in Fig. 7. Since there is no way to implement such bias dependence of \( \tau_D \) in VBIC, the low-current \( \tau_p \approx 6 \) ps was selected as the model parameter \( TD \).

The reverse transport time (parameter TR) in VBIC accounts for the charge of reverse transport electrons. However, in HBT this may not be the dominant charge when base-collector junction becomes forward biased. Calculations show that the charge of holes accounting for the non-ideal component of base-collector current is several orders of magnitude higher than that of reverse transport electrons. To account for this effect the charge sources \( \tau_T \cdot I_{BCD} \) and \( \tau_T \cdot I_{BCCD} \) (where \( \tau_T \) is the recombination time for holes in collector) connected in parallel with corresponding current sources are required. This is not possible in terms of VBIC model through. A possible workaround is to use reverse transport current component of \( I_{CC} \) to model \( \tau_T \cdot I_{BCCD} \) and use reverse transport current component of \( I_{CCD} \) to model \( \tau_T \cdot I_{BCD} \). The substrate terminal in this case should be connected to the collector. This approach was implemented and \( TR \) was adjusted to fit large-signal data. Since reverse transport currents are usually smaller than \( I_{BCD} \) and \( I_{BCCD} \), the resulting value of parameter \( TR \) (~50 ns) significantly overestimates what is typically reported \( \tau_p \approx 1 \) ns. Extracted VBIC model was verified against large-signal measurement as shown in Fig. 8.

5 Conclusion

In this work the key part of VBIC model was successfully extracted for InGaP/GaAs HBT. Throughout the extraction applicability of the model was analysed. It was found that, in spite of being unable to model non-linear thermal resistance, temperature dependent ideality factors and bias-
dependent excess phase delay, VBIC is suitable for InGaP/GaAs HBT modelling at least up to several GHz.

References

