A Practical Method of Parameter Extraction for the VBIC Model used on a GaAs HBT.

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ABSTRACT
This paper shows a simple practical method of extracting the major parameters in the VBIC model used on a GaAs HBT. The method was developed mainly for the circuit designer, who want to have an easy practical way of extracting good model parameters from a few simple measurements, and due to the lack of such simple methods for the VBIC model used on GaAs HBT. The extraction method is based on a semi-analytic approach. The method includes a simple analytic extraction of the non-ideal current sources $I_{ben}$, $N_{en}$, $I_{bcn}$ and $N_{cn}$. The algorithm for the parameter extraction is presented. To verify the method, measurements from Caswell Technology were used. The extracted model shows good agreement with measurements.

I. INTRODUCTION
In the last few years, many papers describing new models for the Hetero-junction Bipolar Transistor (HBT) have been published. The main drawback is that the models are not implemented in commercial simulator software like Agilent ADS. One exception is the VBIC model by McAndrew et al (1). The VBIC model is discussed by Najm (2). In order to use this model in a practical circuit, one must extract the values for many of the numerous parameters of the model. This paper describes a practical method of using a few simple measurements to extract the major parameters. The extraction of the self-heating parameter $R_{th}$ is based upon Marsh (3). Cao et al (4) shows a method of parameter extraction for silicon BJT.

II. PARAMETER EXTRACTION
The VBIC model is shown in Figure 1. The symbols used for the model parameters are all taken from the model implementation in Agilent ADS (there are 86 parameters that can be extracted). The model includes effects like self-heating, non-ideal current-sources, and distributed base- and collector modeling effects. This model also includes a parasitic substrate transistor, which may be important in silicon technology, but can be neglected in GaAs design due to low substrate losses and high isolation. This parasitic will not be discussed any further, and its parameters $R_{sp}$, $I_{sop}$, $I_{sp}$, $I_{sop}$, $I_{sp}$, $X_{sop}$, $C_{jep}$, $C_{jcp}$, $W_{sp}$, $N_{sp}$, $N_{sp}$ and $N_{sp}$ are all set to the default values.

A. FORWARD GUMMEL MEASUREMENT

Low current region: From this region we can extract the saturation currents and the emission coefficients. The base current $I_b$ can be written (including the non-ideal currents) as shown in equation 1:

$$I_b = I_{bei} \cdot (e^{\frac{qV_b}{kT}} - 1) + I_{ben} \cdot (e^{\frac{qV_b}{kT}} - 1)$$  \hspace{1cm} (1)

This gives two asymptotic lines (line C, given by $V_b$ approaching zero and line B where the slope is maximum) in a logarithmic plot as illustrated in Figure 2. We get the ideal base-emitter saturation current $I_{bei}$ where the asymptotic line (B) crosses the y-axes ($V_b=0$). The ideal base-emitter emission coefficient $N_{ei}$ is then given by equation 2:

$$N_{ei} = \frac{q}{\ln(10) \cdot kT \cdot \text{SlopeB}}$$  \hspace{1cm} (2)

We find the non-ideal saturation current $I_{ben}$ and the emission coefficient $N_{en}$ of the base-emitter the same way using the asymptotic line (C). The transport saturation current $I_s$ and the forward emission coefficient $N_f$, are found the same way using the asymptotic line (A) fitted to the measurement of $I_c$. If higher accuracy is needed, these six parameters ($I_{bei}$, $N_{ei}$, $I_{ben}$, $N_{en}$, $I_s$, $N_f$) should be optimized to fit the $I_b$ and $I_c$ measurements.

High current region: In this region many parameters have influence on the behavior of the currents. Therefore an iterative approach is the most convenient approach. The most dominant parameter here is the emitter resistance $R_e$. This should be optimized to the measurements of $I_b$ and $I_c$.

B. REVERSE GUMMEL MEASUREMENT

Low current region: When applying the same method as for the forward Gummel plot, we find from the measured base-collector current $I_{bc}$ the ideal and non-ideal saturation currents $I_{bc}$ and $I_{bcn}$, and emission coefficients $N_{ci}$ and $N_{cn}$ of the base-collector. Again, if higher accuracy is needed, these four parameters should be optimized to fit the $I_{bc}$ measurements. In the VBIC model it is recommended to set the reverse emission coefficient $N_r = N_f$ to ensure convergence.
**High current region**: In this region many parameters have influence on the behavior of the currents, equivalent to the forward Gummel measurements. The most dominant parameter here is the total resistance in the base-collector junction \((R_b + R_c)\). This should be fitted by optimization, to the measurements.

The reverse knee current \(I_{kr}\) could have been optimized in this region, but in HBT's the reverse knee current is usually very high and can be set to infinity (in ADS \(I_{kr} = 0\)).

**C. DC MEASUREMENT**

The DC-measurements include \(I_c\) versus \(V_{ce}\) curves for different base currents \(I_b\), and if possible at different temperatures.

**Self-heating**: If measurements of the \(I_c-V_{ce}\) curves are available at different temperatures, the thermal resistance \(R_{th}\) can be calculated from an excellent method given by Marsh (3), or from another method given by Bovolon et al (5). If no temperature measurements are available, the thermal resistance \(R_{th}\) must be estimated from material properties and the geometry of the device. The thermal capacitance \(C_{th}\) can be calculated from the material properties and the geometry of the device, or by pulsed measurements.

**Temperature dependent parameters**: The three most important parameters are: \(X_{is}\), the temperature exponent of \(I_s\), \(X_{ii}\), the temperature exponent of \(I_{sei}\), \(I_{bci}\), \(I_{beip}\) and \(T_{nf}\), the temperature coefficient of \(N_f\). These parameters are found by optimization of the IV curves at two or more temperatures. Increased accuracy can be obtained by including measurements of the \(V_{be}\) versus \(V_{ce}\) curves. If no temperature measurements are available, the best results are obtained by optimizing \(X_{is}\) and leaving \(T_{nf}\) at their default value.

**Collector resistance**: The total collector resistance \(R_c\) can be found directly from the IV-curves as shown by Lu et al (6). The emitter resistance \(R_e\) was found in the high current region of the forward Gummel plots.

The temperature exponent of the emitter, base and collector resistances \(X_{re}\), \(X_{rb}\), and \(X_{rc}\) can be set to zero when found in the high current region of the forward Gummel plots. The total collector resistance \(R_c\) (\(R_{ci} + R_{cx}\)) can be found directly from the IV-curves. \((R_c + R_e)^{-1}\) is the maximal slope in the triode region of the IV-curves as shown by Lu et al (6). The emitter resistance \(R_e\) was found in the high current region of the forward Gummel plots.

**Forward knee current**: The forward knee current \(I_{kf}\) can be optimized in this region to ensure the best fit to the \(I_c-V_{ce}\) curves. However, in HBT's the forward knee current is usually very high and can often be set to infinity (in ADS \(I_{kf} = 0\)).

**D. COLD-CAPACITOR MEASUREMENT**

The cold-capacitor measurements are s-parameter measurements at different base voltages, i.e. \(V_b = -2.5 \rightarrow 1.1 V\), with \(V_c=0\). Optimization in ADS is used to extract the parameters.

**Bias independent parameters**: The s-parameter measurement at zero bias \((V_b = 0)\) is used to find almost all the passive, bias independent parameters. These parameters are the zero-bias base-emitter and base-collector capacitances \(C_{be}\) and \(C_{bc}\), and the extrinsic base-emitter and base-collector capacitances \(C_{beo}\) and \(C_{bco}\). (If extrinsic inductors \((L_b, L_c\) and \(L_e\)) are included at the base, collector and emitter, these parameters are also found here).

**Bias dependent parameters**: The bias dependence of base-emitter and base-collector capacitances \(C_{je}\) and \(C_{jc}\) is found by optimizing the measured s-parameters to the best fit as follows:
1) At negative bias (i.e. \(V_b = -2.5V\)), optimize the base-emitter/base-collector junction exponents \(M_e\) and \(M_c\).
2) At moderate positive bias (i.e. \(V_b = 0.5V\)), optimize the base-emitter/base-collector grading coefficient \(P_e\) and \(P_c\).
3) At positive bias (i.e. \(V_b = 0.9V\) or higher), optimize the forward bias junction capacitance threshold \(F_c\).

At this step it is also possible to find the distributed effect of the base, which is given by \(W_{be}\) (the portion of \(I_{be}\) that runs through the distributed current source \(I_{beo}\)), and the distribution of the base resistance \(R_b\) between the intrinsic and extrinsic base resistance \(R_{bi}\) and \(R_{bx}\). If the fit to the measured s-parameters in this step are satisfactory without these parameters, the distributed effect of the base can be neglected i.e. \(W_{be} = 1, R_{bx} = 0\). If necessary, repeat these three steps for the best results.

**E. ACTIVE S-PARAMETER MEASUREMENT**

The s-parameter measurement for an active forward bias is used to find the forward transit time \(T_f\), and to find the distribution of \(R_e\) between \(R_{ei}\) and \(R_{ex}\), by optimization. This measurement can also be used to fine-tune other parameters like the resistors found in the DC part of the extraction.

If s-parameters for several bias points are measured, the bias dependent parameters \(Q_{df}\), \(X_{df}\), \(V_{df}\), and \(I_{df}\), of the forward transit time \(T_f\) can be found. This has not been analyzed here.

**F. OTHER PARAMETERS**

The activation energy parameters \(E_{ais}, E_{aie}, E_{aic}, E_{ais}, E_{anc}, E_{ans}\) are all set to 1.42 eV for GaAs. Noise parameters are not included in this method, and should be set to the simulator defaults. The forward and reverse Early voltages \(V_{ef}\) and \(V_{er}\) are set to infinity (0 in ADS), due to the fact that the GaAs HBT is nearly ideal in that respect. All other parameters should be set to the default values.
III. THE ALGORITHM

In this algorithm, when a parameter has been extracted, its value is used in all the consequent steps.

1. From the low current region of the forward Gummel plot, \( I_{be} \), \( N_{ei} \), \( I_{ben} \), \( I_s \), and \( N_t \) are extracted.
2. From the low current region of the reverse Gummel plot, \( I_{bec} \), \( N_{ci} \), \( I_{bcn} \), and \( N_{cn} \) are extracted.
3. From the self-heating part of the DC-measurement, \( R_{th} \) and \( C_{th} \) are extracted.
4. From the high current region of the forward Gummel plot, \( R_e \) is extracted.
5. From the high current region of the reverse Gummel plot, the \( R_b + R_c \) (if needed \( I_{kr} \)) are extracted.
6. From the collector resistance part of the DC-measurement, \( R_c \) and if necessary \( X_{rc} (= X_{rb} = X_{re}) \) are extracted.
7. From the Temperature dependent parameters part of the DC-measurements, \( X_{is} \), \( X_{ii} \) and \( T_{nf} \) are extracted.
8. Steps 4 to 7 are repeated until the best fits are obtained.
9. From the Bias independent parameters of the cold-capacitor measurements, \( C_{je} \), \( C_{jc} \), \( C_{beo} \) and \( C_{bco} \) (and if included \( L_b \), \( L_c \), \( L_e \)) are extracted.
10. From the Bias dependent parameters of the cold-capacitor measurements, \( M_e \), \( M_c \), \( P_e \), \( P_c \) and \( F_c \) (and if needed \( W_{be} \) and the distribution of \( R_b \) between \( R_{bh} \) and \( R_{bh} \)) are extracted.
11. From the active s-parameter measurement, \( T_f \) and the distribution of \( R_c \) between \( R_{ci} \) and \( R_{cx} \) are extracted. If necessary this s-parameter measurement can be used to fine-tune the resistances \( R_c \), \( R_b \) and \( R_c \).
12. If parameters for distributed base are used in Step 10, or some of the resistors have been fine-tuned in Step 11, then Step 4 to 11 should be repeated for the best possible fit. Steps 4 to 6 do not extract new values for the resistors that have been fine-tuned in Step 11.

IV. RESULTS

The algorithm described above is verified by applying it to measurements provided by Caswell Technology, Marconi Caswell Limited. The measurements referred to in Figure 3, 4 and 5 are all statistical mean values of about 40 single finger transistors. Figure 3 and 4 show the simulated forward and reverse Gummel curves respectively. Solid lines are simulated results and dots are measurements. Figure 5 shows an example of the simulated and measured results for all four s-parameters at a bias point, \( V_{ce} = 5V \) and \( I_c = 20mA \). Similar results are seen at different bias points. Overall, we see that the model predicts the measured results very well.

V. CONCLUSION

In this paper a practical method of parameter extraction for the VBIC model applied on a GaAs HBT is proposed. The method extracts all major parameters for the model, including self-heating and the non-ideal parameters. Only a few simple measurements are necessary to extract the parameters (forward and reverse Gummel, DC-curves, cold capacitor s-parameters and s-parameters for a ‘normal’ bias are needed). Simulations with the extracted parameters for the VBIC model show good agreement with the measured results.

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REFERENCES

1.05
1.1
1.15
1.2
1.25
1.3
1.35
1.4
1.45
1.5

-10
-8
-6
-4
-2
0
2
4

Forward Gummel plot

Figure 1: The VBIC model

Figure 2: Forward Gummel plot and asymptotic lines

Figure 3: Forward Gummel plot: Simulated and measured.

Figure 4: Reverse Gummel plot: Simulated and measured.

Figure 5: S-parameters at $V_{ce} = 5V$, $I_c = 20mA$: Simulated (solid lines) and measured (magnitude: circles, phase: triangles).