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_s, I_{sp}, I_{beip}, I_{benp}, I_{bcip}, I_{bcnp}, I_{kp}, X_{rs}, C_{jep}, C_{jcp}, W_{sp}, N_{fp}, N_{cip} and N_{cnp} 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:

$$I_b = I_{bei} \cdot (e^{\frac{qV_{be}}{N_{ei}kT}} - 1) + I_{ben} \cdot (e^{\frac{qV_{be}}{N_{en}kT}} - 1) \tag{1}$$

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:

$$N_{ei} = \frac{q}{\ln(10) \cdot kT \cdot SlopeB} \tag{2}$$

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_{bci} 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.

<u>*High current region*</u>: 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.

<u>*Self-heating*</u>: 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.

<u>*Temperature dependent parameters*</u>: The three most important parameters are: X_{is}, the temperature exponent of I_s, X_{ii}, the temperature exponent of I_{bei}, I_{bci}, I_{beip}, I_{bcip} 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_{ii} and leaving X_{is} and T_{nf} at their default value.

The temperature exponent X_{in} of the non-ideal saturation currents I_{ben}, I_{bcn}, I_{benp} and I_{bcnp} is set to simulator default values. The effect of this parameter is very small.

<u>*Collector resistance*</u>: 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.

The temperature exponent of the emitter, base and collector resistances X_{re}, X_{rb}, and X_{rc} can be set to zero when operating in a limited (normal) temperature range. When this is not the case and when temperature measurements are available the X_{rc} can be calculated by finding R_c, as described above, at different temperatures. Then, for all practical purposes, $X_{re} = X_{rb} = X_{rc}$ is set.

<u>*Forward knee currents*</u>: 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_{ce}=0. Optimization in ADS is used to extract the parameters.

<u>*Bias independent parameters*</u>: 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_{je} and C_{jc} 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).

<u>*Bias dependent parameters*</u>: The bias dependence of base-emitter and base-collector capacitances C_{je} and C_{jc} are found by optimizing the measured s-parameters to the best fit as follows:

1) At negative bias (i.e. $V_b = -2.5$V), optimize the base-emitter/base-collector junction exponents M_e and M_c.
2) At moderate positive bias (i.e. $V_b = 0.5$V), optimize the base-emitter/base-collector grading coefficient P_e and P_c.
3) At positive bias (i.e. $V_b = 0.9$V 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_{bei} that runs through the distributed current source I_{bex}), 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_c between R_{ci} and R_{cx}, 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_{tf}, X_{tf}, V_{tf}, and I_{tf}, of the forward transit time T_f can be found. This has not been analyzed here.

F. OTHER PARAMETERS

The activation energy parameters E_a, E_{aie}, E_{aic}, E_{ais}, E_{ane}, E_{anc}, and 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_{bei}, N_{ei}, I_{ben}, N_{en}, I_s, and N_f are extracted.
2. From the *low current region* of the reverse Gummel plot, I_{bci}, 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_{bi} and R_{bx}) 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_e, 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.

ACKNOWLISHMENT

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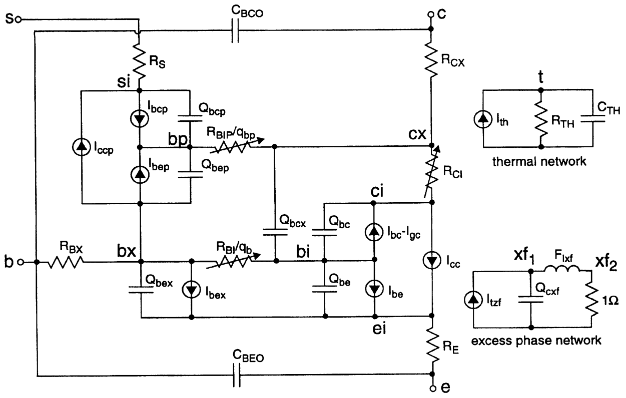

Figure 1: The VBIC model

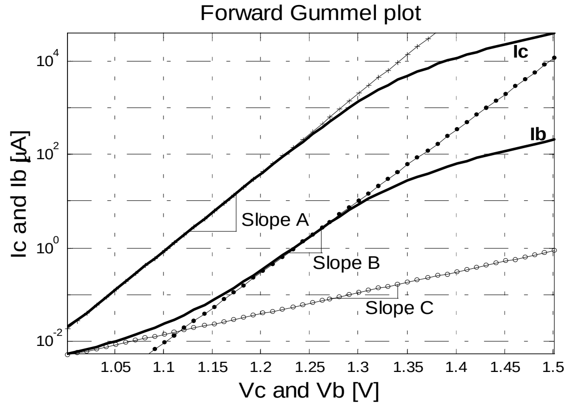

Figure 2: Forward Gummel plot and asymptotic lines

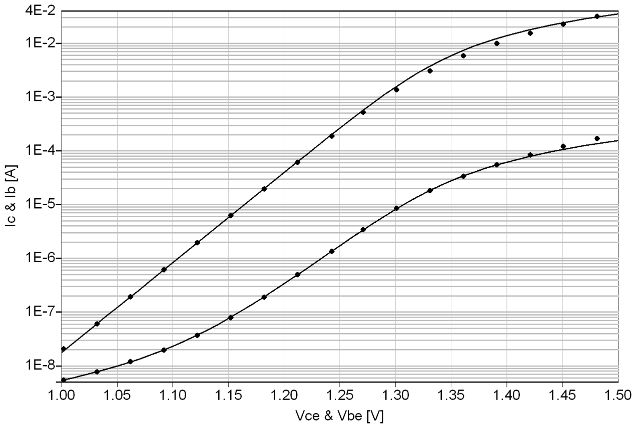

Figure 3: Forward Gummel plot: Simulated and measured.

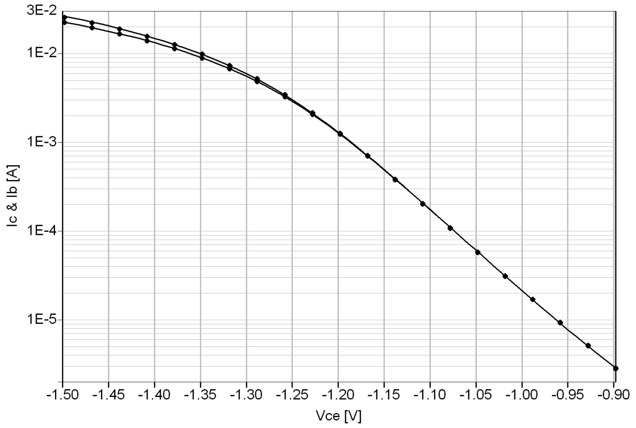

Figure 4: Reverse Gummel plot: Simulated and measured.

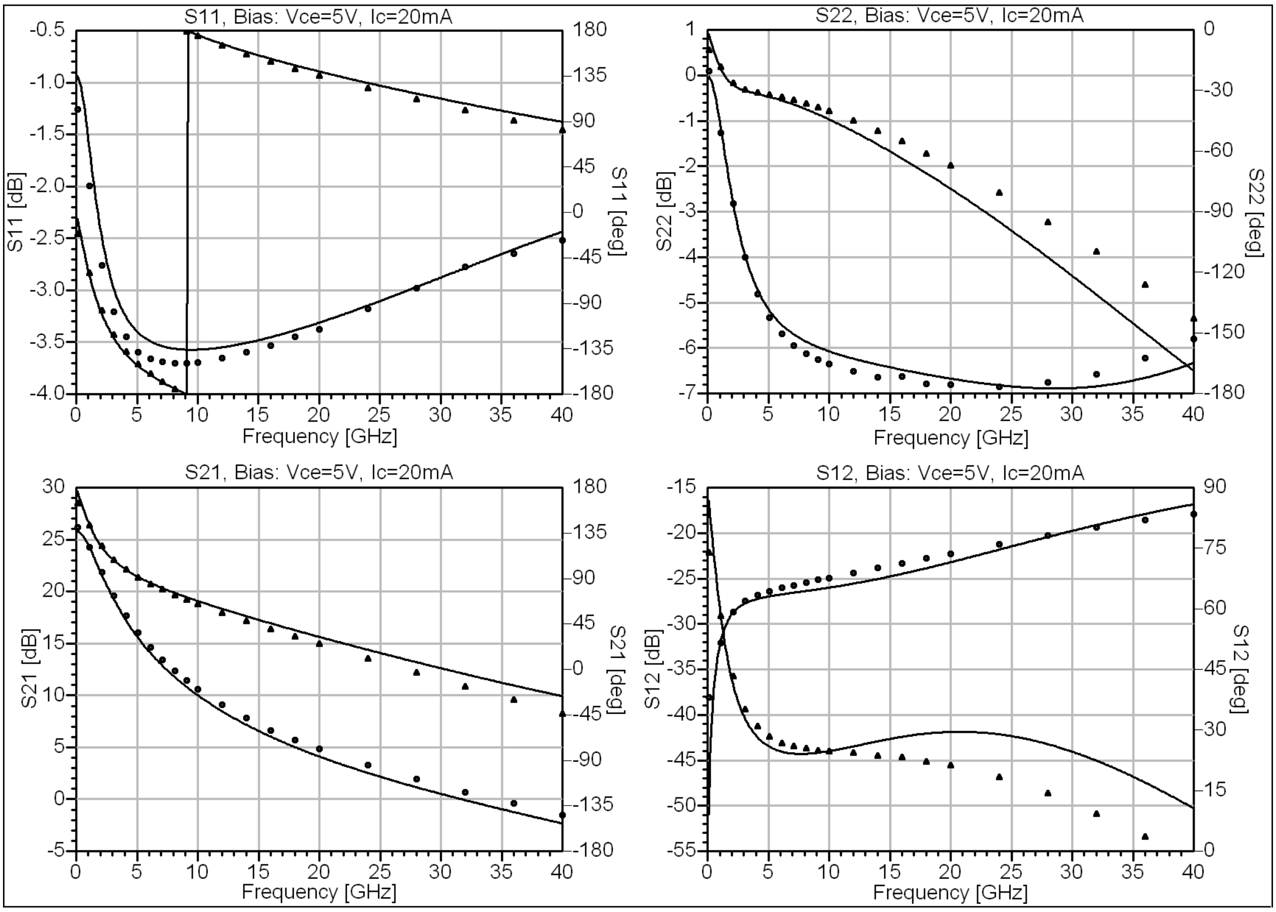

Figure 5: S-parameters at V_{ce} = 5V, I_c = 20mA: Simulated (solid lines) and measured (magnitude: circles, phase: triangles).