Optimal Parameter Extraction Scheme of Current Sources and Bias Dependent Elements for HBT by searching the whole unknown Parameter Space

Youngsuk SuH[1], I. S. Kim[2], and J. S. Song[2]

[1]Yeungnam University, Department of EECS, Kyongsan, 712-749, South Korea, 82-53-810-2585
[2] Korea Electrotechnology Research Institute, Electric & Magnetic Device Research Group, ChangWon, 641-600, South Korea, 82-55-280-1675

Abstract - **New analytical expressions for the dynamic resistance, transconductance, base-collector internal capacitance, and base-emitter internal capacitance are derived. And a new scheme, to extract the current source parameters, thermal parameter, and small signal parameters at multiple bias points on the normal active region, is developed. The proposed parameter extraction method is robust and very fast. Based on these equations, we propose a new scheme to find out the optimal solution by searching for a full-unknown parameter space. The search space corresponds to 1.17x10^8 points on the error surface, and it takes 12.6 hours to get an optimal model parameters using a 2GHz-desktop PC. This scheme is helpful for the modeling of HBT excluding the local minimum problem in the gradient optimization method and the inaccuracies in the direct extraction methods**

I. INTRODUCTION

Large signal CAD-models for HBTs are essential for the design of RF and microwave circuits. Optimization and direct extraction method for the model parameters are typical procedures for the small signal and large signal equivalent modeling of HBTs [1].

Many direct extraction methods for the model parameters (Lb, Le, Lc, Cpb, Cpbc, Cpc, Rb1, Rb2, Re in Fig. 1) are developed [2][3]. The accuracies of parameters are dependant on the extraction conditions, methods, and type of data. For example, the parasitic resistances (Rb1, Rb2, and Re) extractions are strongly related with the s-parameters, the measured voltage and current, current source model parameters, and even the thermal resistance values. Those initially extracted values from the specific data by the specific method should be trimmed and optimized to predict all the measured DC and AC data on all the bias points.

The gradient optimization of the model parameters from the initial values is typical procedure in the modeling. However, this method has the local minimum problem. The results are dependant on the initial values.

The most reliable method is to search the whole unknown parameter space around the initial values. The only problem is computation time. To reduce the computation time, the number of variables should be reduced. Conventional large signal models have several tens of parameters such as the current sources parameters, thermal resistance, resistances, inductances, and capacitances those need to be trimmed.

In this paper the new analytical expressions for the dynamic resistance, transconductance, base-collector internal capacitance, and base-emitter internal capacitance are derived. These expressions enable the very fast extractions of parameters. And the whole searching scheme of the parameter values is proposed instead of the gradient optimization. In the following section, we introduce the analytical expression for the four parameters and the whole searching procedure around the initially extracted parameter values.

II. ANALYTICAL EXPRESSIONS FOR CURRENT SOURCE MODEL AND CAPACITANCE PARAMETERS

A. Analytical Expressions for the Current Sources and the Corresponding Small Signal Parameters

The parameters of current source model (I_A, I_B, I_C, I_E in fig. 1) and thermal resistance should be determined to predict the measured voltage and current data. Under the given values of (Re, Rb1, Rb2, and Rc), the current source parameters (A_0~A_2, B_0~B_2, C_0~C_2, E_0~E_2) and the thermal resistance (R_{th}) can be calculated analytically by the method in reference [4] minimizing the least square errors between the model and the measured DCIV data.

The current source model I_B and I_C those have a dominant role on the normal active region should predict the measured s-parameter and DCIV data, simultaneously. The corresponding small signal models for the current sources are the base-emitter dynamic resistance r_π and transconductance g_m.

The base-emitter dynamic resistance r_π can be derived differentiating of the current source I_B with respect to the base-emitter junction voltage V_{be},

$$r_\pi = \left(\frac{dI_B}{dV_{be}}\right)^{-1} = \frac{1}{I_{bt}B_1} \qquad (1)$$

where I_{bt} is measured base terminal current. The transconductance g_m is derived differentiating of the current I_C w.r.t V_{be}

$$g_m = \frac{dI_C}{dV_{be}} = I_{ct}C_1 \qquad (2)$$

where I_{ct} is measured collector terminal current on the normal active region.

B. Analytical Expression for Bias Dependent Capacitances

The bias dependent capacitances Cu1, Cu2, and Cπ extracted from the measured s-parameters are very important for the junction capacitance and transit time modeling. De-embedding the values of (Le, Lc, Re, Cpb, Cpbc, Cpc, Rb1, Re, and Rc) from the measured data, we can make the values of the z-parameter [Zi] for the boxed circuit in fig 1. Two analytical expression as a function of [Zi] are derived,

$$\omega(C_{u1} + C_{u2}) = imag\{(Z_{i22} - Z_{i21})^{-1}\} \quad (3)$$

$$\frac{C_{u2}}{C_{u1} + C_{u2}} = \left[R_{b2} real\{(Z_{i11} - Z_{i22})^{-1}\}\right]^{-1} \quad (4)$$

The capacitance Cu1 and Cu2 at each bias points are calculated using the equation (3) and (4), analytically.

An analytical expression for term "g_m^{-1} Yπ" can be derived as a function of the internal Z-parameters [Zi],

$$g_m^{-1} Y_\pi = \frac{Z_{i22} - Z_{i12}}{Z_{i12} - Z_{i21}} \quad (5)$$

where $Y_\pi \equiv (r_\pi^{-1} + j\omega C_\pi)$. The base-emitter internal capacitance Cπ can be extracted using the eq. (5) putting the extracted g_m value by the eq. (2).

III. Optimization Procedure and Results

All the current source parameters and small signal parameters should be extracted to predict the measured DCIV and the s-parameters at multi-bias points, simultaneously. The modeling procedure is shown in the flow chart of figure 2.

Step1; The initial values of the parasitic components Lb, Le, Lc, Cpb, Cpbc, Cpc, Re, Rc, Rb1, Rb2 are extracted from the measured s-parameters by the conventional method [2].

Step2; The discrete search space is constructed from the initial values of (Lb, Le, Lc, Cpb, Cpbc, Cpc, Rb1, Rb2, Re). For example, the 10 discrete values (60%, 70%, 80%, 90%, 100%, 110%, 120%, 130%, 140%, 150%) from the initial values of (Rb1, Rb2, Re) are stored, respectively.

Step3; All the current source model parameters (A_0~A_2, B_0~B_2, C_0~C_2, E_0~E_2), thermal resistances (Rth), the corresponding r_π's, and gm's are calculated using the equation (1), equation (2), and the method in ref. [4],.

Step4; The internal z-parameters [Zi]'s at each bias points are calculated.

Step5; The parameter Cπ, Cu1, Cu2 are calculated using the linear equation (3), (4), and (5).

Step6; The small signal models are constructed using all the parameters and the errors between the model and the measured data are calculated.

We applied this extraction scheme to the 2 finger 2x20 um HBT. The measured DCIV and 11 s-parameter sets are selected from the marked bias points in fig. 3. We tested the three cases of variable combinations. The number of unknown parameter combinations for the case A, B, and C in the table 1 is equal to 10^3x5^6, 10^3x6^6, and 10^3x7^6, respectively. Using a 2GHz-desktop personal computer, it take 1.67hr., 5hr., and 12.6 hr. of computation time, respectively. Through this procedure, all of unknown parameter combinations in 9-dimensional error surface (Lb, Le, Lc, Cpb, Cpc, Cpbc, Rb1, Rb2, Re) are considered in the computation of optimal solution. And the current source model parameters including thermal resistance are calculated automatically minimizing the least square errors. Figure 3 shows the modeled and measured DCIV curves. The cross section of the error profile for the s-parameters around the initial extracted values is shown in fig.4 on the domain of emitter resistance and external base resistance variables.

IV. Conclusion

New dynamic resistance, transconductance, base-collector internal capacitance, and base-emitter internal capacitance equations are derived. Using these equations a new scheme to extract the current source parameters, thermal parameters, and small signal parameters at multiple bias points on the normal active region, is developed. This very fast and robust parameter extraction scheme is applied to the computation of 10^3x7^6 combinations around the initial values of the parameters to search for the optimal model parameters. It takes 12.6 hours of computation time. This proposed, fast, and robust extraction method will be helpful for the modeling of HBT, excluding the local minimum problem in the gradient optimization method and the inaccuracies in the direct extraction method.

Acknowledgement

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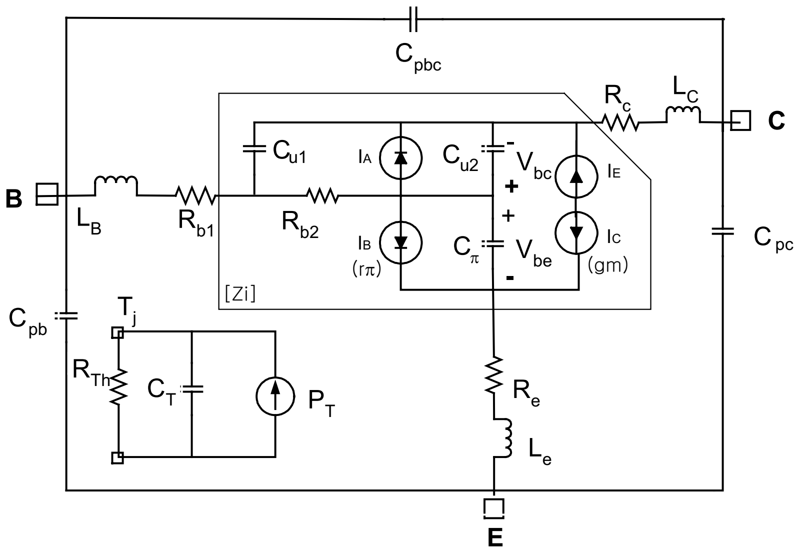


$$I_A = \exp\left(A_0 + A_1 V_{bc} + A_2 dT_j\right)$$
$$I_B = \exp\left(B_0 + B_1 V_{be} + B_2 dT_j\right)$$
$$I_C = \exp\left(C_0 + C_1 V_{be} + C_2 dT_j\right)$$
$$I_E = \exp\left(E_0 + E_1 V_{bc} + E_2 dT_j\right)$$
$$dT_j = (T_a - T_{a0}) + R_{th} P_d$$

Figure 1 Equivalent Circuit of HBT

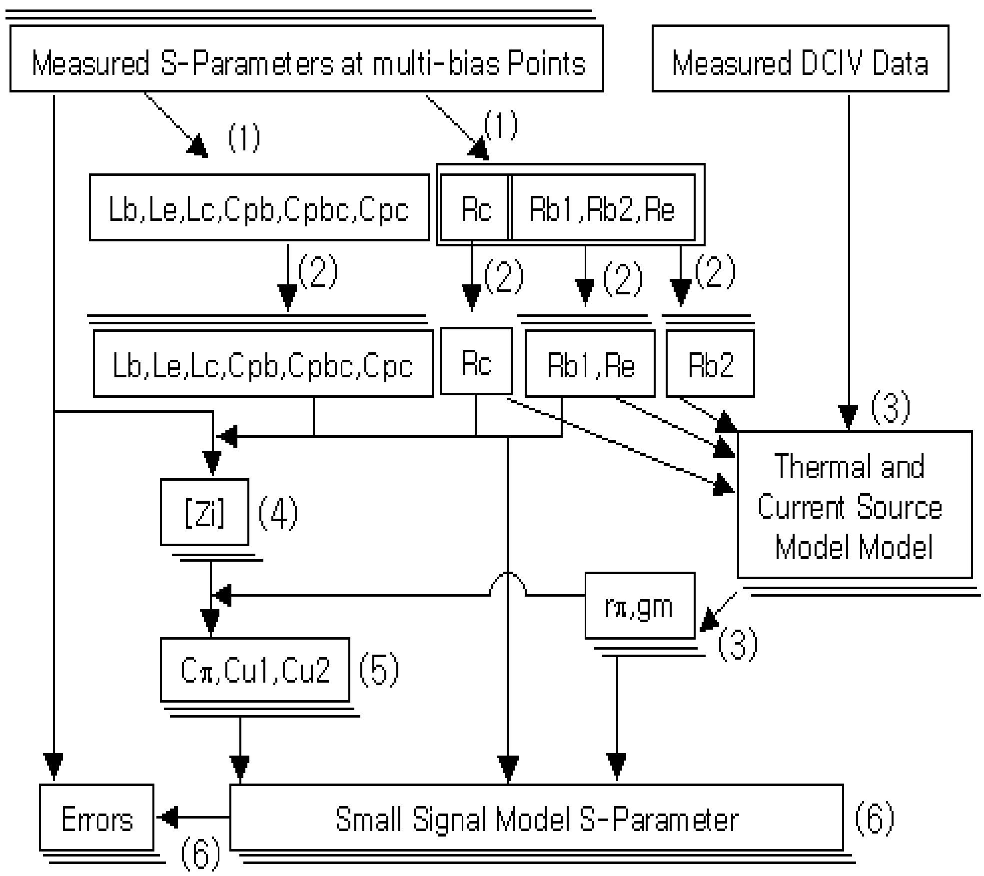


Figure 2 Bias Dependent Small Signal, Current Source, and Thermal Modeling Procedures

Table 1 Sweep points for the variables and Computing time in 2.4GHz speed of PC

	CASE A	CASE B	CASE C
Sweep Points	Re:10 pt. Rb1:10 pt. Rb2:10 pt.	Re:10 pt. Rb1:10 pt. Rb2:10 pt.	Re:10 pt. Rb1:10 pt. Rb2:10 pt.
	(Lb,Le,Lc, Cpb,Cpc, Cpc) : 5 pt. each	(Lb,Le,Lc, Cpb,Cpc, Cpbc) : 6 pt. each	(Lb,Le,Lc, Cpb,Cpc, Cpbc) : 7 pt. each
Cpu Time	1.67hr	5hr	12.6hr

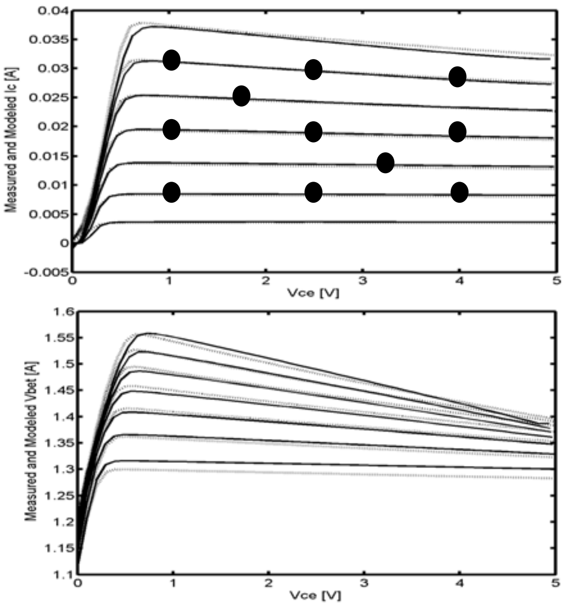
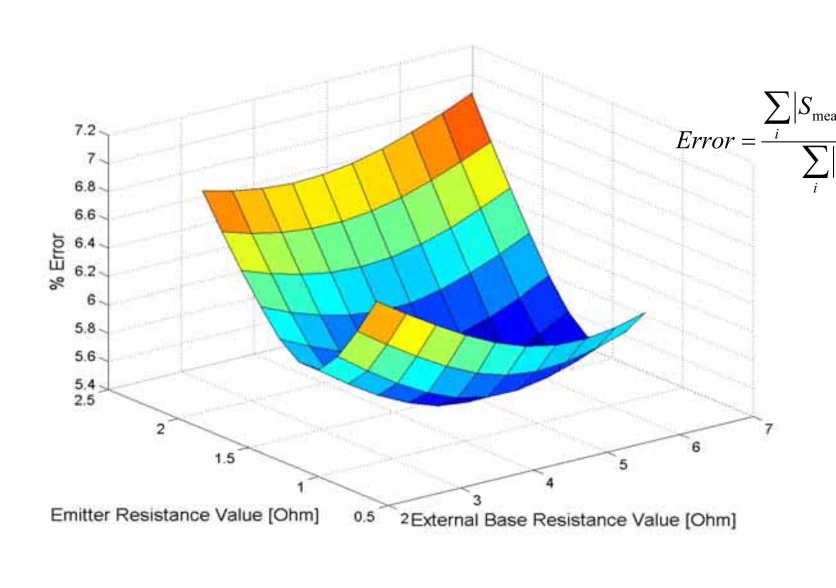


Fig. 3 Measured (dotted line) and Modeled (line) Collector Currents (Ic), the sampling bias points for S-parameters( ), and Base-Emitter Terminal Voltages (vbet)



$$Error = \frac{\sum_i \left| S_{\text{measured}} - S_{\text{model}} \right|}{\sum_i \left| S_{\text{measured}} \right|}, i = \text{all sampled bias points}$$

Figure 4 Percent S-Parameter Errors of the Model vs. Measured Data with the Variations of Model Parameters Re and Rb1 from the 1.3Ω and 4.1Ω of the initial values, respectively