Direct Extraction and Modeling Method for Temperature Dependent Large Signal CAD Model of Si-BJT

Y. Suh*, D. Heo, A. Raghavan, E. Gebara, S. Nuttnick, K. Lim, and J. Laskar

Yamacraw Design Center, School of ECE, Georgia Institute of Technology, 791 Atlantic Drive, Atlanta, GA, 30332, *School of ECE, YeungNam Univ., KyongSan 712749, Korea.

***Abstract* — A new Si-BJT CAD model and the corresponding direct extraction method are presented. An exact analytical expression for the total distributed base resistance is developed. Several exact analytical solutions for the thermal resistance and the current source models are derived. The model based on the new analytical expressions can predict the measured data minimizing the least square errors between measured and modeled data. This current source modeling method requires no optimization or trimming process. The parameters are extracted self consistently to minimize the error in modeling. We applied this method to 5 finger 0.4x20 μm^2 Si-BJT and verified the model over the temperature range 273°K ~ 333°K and up to 15GHz. The model shows good correlation with the measured data.**

I. Introduction

Many studies have been performed on large signal modeling of HBTs in the microwave range [1]. The recent growth of commercial RF applications of Si-BJTs up to 25 GHz [2] has created the need for an improved large signal Si-BJT model and modeling method. Physics based large signal RF models and modeling methods such as VBIC have been developed [3]-[5].

A robust model is one that can predict all measured data and has many physical parameters over a broad range of frequency, ambient temperature, and bias levels. It needs a few tens of parameters, and a lot of measured data at several temperatures. The parameter extraction procedure is complex and requires some optimization to obtain the desired accuracy [6].

In the current source modeling, many physical factors are involved, such as the ideality factor, reverse saturation current, thermal resistance, Early voltage, and Kirk effect that are not so simple to extract [7].

In this paper, a large signal RF CAD model for Si-BJT based on a novel parameter extraction procedure is proposed. A new analytical expression for total base resistance is derived. And exact analytical expressions for the current source modeling are introduced. The model based on these expressions can accurately predict the measured voltage and current data in the normal active region, minimizing the error between the measured and modeled data.

II. Parasitic and Access Parameter Extraction

Fig. 1 shows the typical equivalent circuit model of Si-BJT that has the distributed base-collector elements and thermal resistance. We will discuss the temperature dependent current source modeling in detail.

First, the parasitic capacitances (C_{pb}, C_{pc}), the emitter elements (R_e, L_e), and collector parasitic components (R_c, L_c) are extracted through the hot and cold measurements method [8].

The total base resistance extraction is very important for internal current source modeling. In the simple equivalent circuit that has a single base resistance, the base resistance can be extracted using the simple analytical expression $\mathrm{Re}\{z_{11}-z_{12}\}$. In the equivalent circuit that has the distributed base elements, the resistances (R_{bext}, R_{bint}) can be extracted through several steps of procedure using measured data at several bias points. Based on the procedure described in [9], we present a simple and accurate analytical expression for the calculation of the total base resistance.

$$R_{btot} \approx \mathrm{Re}\left\{\tilde{z}_{11} - \tilde{z}_{12}\frac{\tilde{z}_{12}-\tilde{z}_{21}}{\tilde{z}_{22}-\tilde{z}_{12}}\right\}_{at\ high\ freq.} \quad (1)$$

where $\tilde{Z}_{ij}$'s are the Z-parameters after de-embedding C_{pb}, C_{pc}, L_e, and R_e. The 5x0.4x20μm^2 size Si-BJT is measured at several bias levels. Figure 2 shows the frequency behavior of equation (1) at several bias points. The base resistance is seen to be 9.2 ohm from the high frequency range. This total base resistance and the extracted emitter resistance are used in the current source modeling.

III. Thermal Resistance, Current Source, and Capacitances Modeling

To accurately express the measured voltage and currents from the region dominated by space-charge-region recombination current to the region dominated by diffusion current, a number of physical parameters need to be resolved. Most of these parameters are temperature dependent. Their extraction is complex and requires a lot of data. We propose a simple current source model to reduce the complexity. This simple model accurately predicts the measured DC-IV curves in the normal active region below the Kirk current level over the broad range of ambient temperature.

A. Current Source and Thermal Models

The four voltage dependent current sources in the Fig. 1 can be expressed as

$$I_{CC} = I_{SCC}\left[\exp\left(\frac{V_{bei}}{NV_{TCC}}\right)-1\right]\left(1+\frac{V_{bci}}{V_A}\right) \quad (2)$$

$$I_{EE} = A_r I_{SBC}\left[\exp\left(\frac{V_{bci}}{NV_{TBC}}\right)-1\right] \quad (3)$$

$$I_{BE} = I_{SBE}\left[\exp\left(\frac{V_{bei}}{NV_{TBE}}\right)-1\right] \quad (4)$$

$$I_{BC} = I_{SBC}\left[\exp\left(\frac{V_{bci}}{NV_{TBC}}\right)-1\right] \quad (5)$$

where V_A is early voltage, V_{xyi}'s are internal voltages, and I_{SXY}'s are the temperature dependent parameters given by

$$I_{SXY} = I_{SXY0}\exp\left[A_{XY}\left(R_{th}P_d + T_A - T_{A0}\right)\right] \quad (6)$$

where, P_d is the power dissipation, T_A the actual ambient temperature, T_{A0} the reference ambient temperature, R_{th} the thermal resistance, and A_{XY}'s the parameters for the temperature dependency of I_{SXY}'s.

B. Parameter Extraction Procedure

The early voltage is extracted from the slope of DC-IV curves. The parameters in the expression (2) and (4) can be extracted from the measured terminal currents and voltages. The current source I_{CC} and I_{BE} are dominant in the normal active region of the DC-IV curves above the knee voltage. In this region, I_{CC} and I_{BE} represent most of collector and base terminal currents; I_{ct} and I_{bt}, respectively ($I_{ct} \approx I_{CC}$ and $I_{bt} \approx I_{BE}$). The equation (2) can be converted to a linear equation, using n number of sampled data

$$AX = B \quad (7)$$

where

$$A \equiv \begin{bmatrix} 1 & V_{bei,1} & P_{diss,1} & \left(T_{A,1}-T_{A0}\right) \\ 1 & V_{bei,2} & P_{diss,2} & \left(T_{A,2}-T_{A0}\right) \\ \vdots & \vdots & \vdots & \vdots \\ 1 & V_{bei,n} & P_{diss,n} & \left(T_{A,n}-T_{A0}\right) \end{bmatrix}_{n\times 4},$$

$$X \equiv \begin{bmatrix} \ln(I_{SCC}) \\ NV_{TCC}^{-1} \\ R_{th}A_{CC} \\ A_{CC} \end{bmatrix}_{4\times 1}, \quad B \equiv \begin{bmatrix} \ln\left[\dfrac{I_{ct,2}}{1+V_A^{-1}V_{cei,2}}\right] \\ \ln\left[\dfrac{I_{ct,2}}{1+V_A^{-1}V_{cei,2}}\right] \\ \ln\left[\dfrac{I_{ct,n}}{1+V_A^{-1}V_{cei,n}}\right] \end{bmatrix}_{n\times 1}$$

Where V_{cei} and V_{bei} are the internal junction voltage of base-emitter and base-collector junctions, respectively. Matrix A is n x 4 and B is n x 1 and there are four unknowns in X. The equation (7) can be constructed from the measured DC-IV data in the normal active region at several ambient temperatures. For $n>4$, the equation (7) is an over-determined linear equation. Its solution can be obtained using $X=(A^TA)^{-1}A^TB$, which predicts the sampled data minimizing the error between the measured and modeled data. Using the equation (7), the parameters NV_{TCC}, I_{SCC0}, A_{CC}, and R_{th} are extracted.

By a similar procedure, a linear equation for the current source I_{BE} can be constructed

$$CY = D \quad (8)$$

where

$$Y \equiv \begin{bmatrix} \ln(I_{SBE}) \\ NV_{TBE}^{-1} \\ A_{BE} \end{bmatrix}_{3\times 1}, \quad D \equiv \begin{bmatrix} \ln(I_{bt,1}) \\ \vdots \\ \ln(I_{bt,m}) \end{bmatrix}$$

and

$$C \equiv \begin{bmatrix} 1 & V_{bei,1} & R_{th}P_{d,1} + T_{A,1} - T_{A0} \\ \vdots & \vdots & \vdots \\ 1 & V_{bei,1} & R_{th}P_{d,1} + T_{A,1} - T_{A0} \end{bmatrix}_{m\times 3}$$

Using the equation (8), the parameters NV_{TBE}, I_{SBE0}, and A_{BC} are extracted. Even if there are small perturbations in the parasitic resistances, the solutions based on the equation (7) and (8) return self consistently the exact parameter values to predict the measured voltage and currents. The parameters in equations (3) and (5), that are dominant in the reverse bias mode, are extracted from the reverse-Gummel plot.

All the parameters for the current sources are listed in table 1. Fig. 3 and 4 show the measured and modeled collector currents and base-emitter terminal voltages at 273, 299, and 333 °K.

Table 1. Extracted parameters for current source modeling

C_{pb}	116×10^{-15}	NV_{TBC}	0.0307815433
C_{pc}	158×10^{-15}	A_{CC}	0.042457
Re	6.1	A_{BE}	0.041891
Le	21×10^{-12}	A_{BC}	0.041421
R_{btot}	9.2	I_{SCC0}	1.1743×10^{-13}
Rc	2.6	I_{SBE0}	1.5077×10^{-16}
T_{A0}	299°K	I_{SBC0}	2.1219×10^{-15}
VA	15.625	A_r	0.366
NV_{TCC}	0.03453336	R_{th}	231.3271
NV_{TBE}	0.03148644		

All the parameters in table 1 are determined without any optimization or trimming process, and are extracted directly from the measured data. The resulting modeled data agree accurately with the measured data at several ambient temperatures as shown in Fig. 3 and 4.

C. Capacitance Model and Parameter Extraction.

With the constructed current source models, the corresponding small signal parameters such as base-emitter dynamic resistance and trans-conductance can directly be calculated. The ratio of the internal and external base resistance is calculated. The base-emitter and base-collector capacitances are extracted using the small signal parameter extraction method described in [7] at all bias points and temperatures. The capacitance values are fitted into the polynomials as a function of internal junction voltages and currents.

Fig. 5 shows the measured and modeled S-parameters at the bias Ibt=80μA, Vce=2.5V, and an ambient temperature of 333 °K.

To verify the large signal model, load and source pull measurements were performed at several ambient temperatures. As shown in Fig. (6) there is a good correlation between the measured and modeled power, gain and efficiencies.

VI. CONCLUSION

A new temperature dependent large signal CAD model for Si-BJT and the corresponding direct extraction method are presented. The proposed current source model is simple and can accurately predict the measured data. To extract the thermal resistance and current source parameters analytically, linear algebraic equations are derived. From the solutions of the equations, thermal resistance and current source parameters can be extracted. From the sampled data, over-determined linear equations are constructed and the solution predict the measured data minimizing the least square errors. The large signal model based on this modeling procedure can predict the measured current, voltage, s-parameters, and load pull data at different ambient temperatures.

ACKNOWLEDGEMENT

The authors wish to acknowledge the assistance and support of National Semiconductor and Yamacraw Design Center. Y. Suh thanks the support of KOSEF.

REFERENCES

[1]. C. Snowden, "Large-signal microwave characterization of AlGaAs/GaAs HBT's based on a physics-based electrothermal model," *IEEE Trans. Microwave Theory and Tech.*, vol. MTT-45, no. 1, pp. 58-71, January 1997.

[2] G. Puma, et al, "A RF transceiver for WDCT in a 25GHz Si Bipolar technology," *2000 IEEE MTT-Digest*, pp.273~275.

[3]. C. McAndrew et al, "VBIC95, the vertical bipolar intercompany model," *IEEE journal of solid state circuit* vol. 31, no. 10, pp.1476~1483, Oct. 1996.

[4]. X. Cao, et al, "Comparison of the new VBIC and conventional Gummel-Poon bipolar transistor models," *IEEE Trans. Elec. Dev.*, Vol. 47, no. 2, pp.427~433 February 2000.

[5]. M. Schroter, et al, "Physics and process based bipolar transistor modeling for integrated circuit design," *IEEE Jouranl of Solid state circuit,* vol. 34, no. 8, pp. 1136~1149, 1999.

[6]. K. Garwacki, "Extraction of BJT Model Parameters Using Optimization Method," *IEEE Trans. CAD.*, Vol. 7, no. 8, pp. 850~854, 1988.

[7]. D. Zweidinger, et al, "Compact modeling of BJT self-heating in SPICE," *IEEE Trans. CAD.*, vol. 12, no. 9, pp. 1368~1375, 1993.

[8]. Y. Govert, et. Al, "A physical yet simple small signal equivalent circuit for the heterojunction bipolar transistor," *IEEE Trans. MTT.*, vol.45, no. 1, pp. 149~153, 1997.

[9]. Y. Suh, E. Seok, D. Heo, A. Raghavan, and J. Laskar, " Direct extraction method for internal equivalent circuit parameters of HBT small-signal hybrid-pi model," *2000 IEEE MTT-s Digest*, pp. 1235.

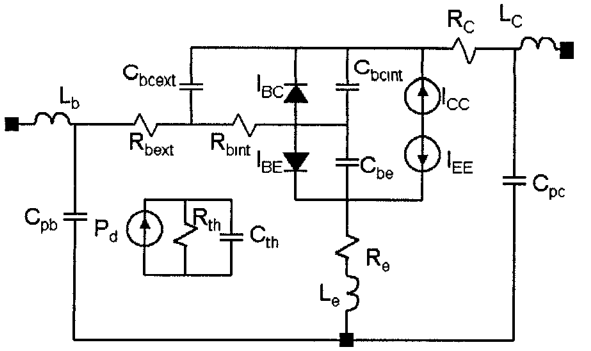

Fig.1 Large signal equivalent circuit of Si BJT

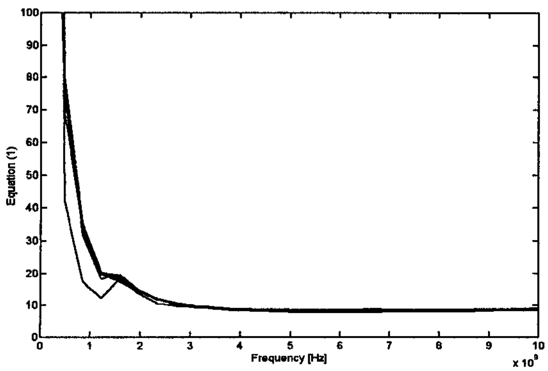

Fig. 2 The real parts of equation (1) at the bias points of Ibt=35μA, 60μA, 85μA, 110μA, 135μA, and 160μA, Vce=2.5V

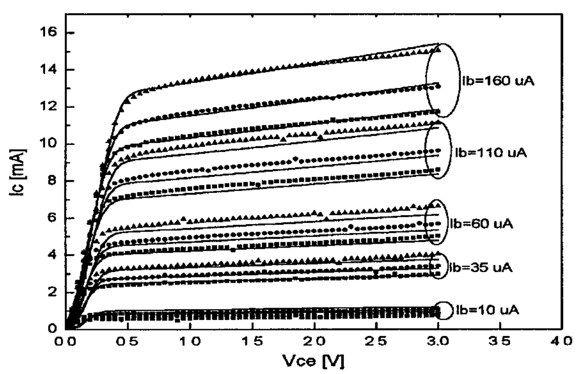

Fig. 3 Modeled and measured (rectangle;273°K, circle;299°K and triangule;333°K) collector currents curves.

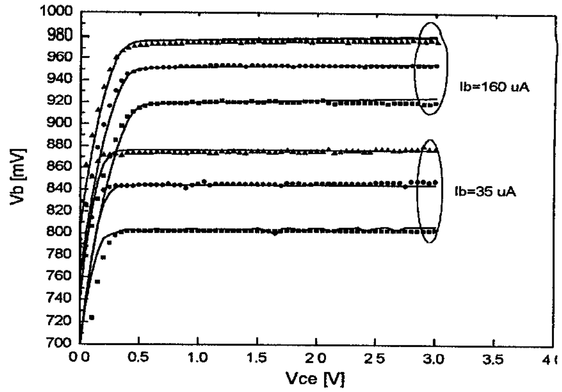

Fig. 4 Modeled and measured (triangule;273°K, circle;299°K and rectangle;333°K) voltage curves.

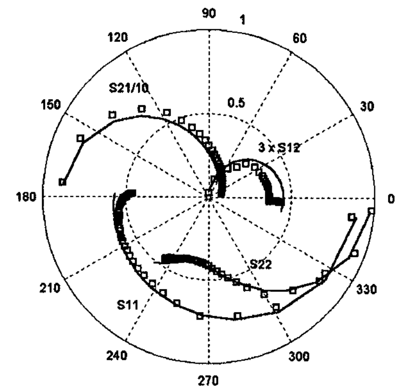

Fig. 5 Modeled (line) and measured (rectangle)S-parameters at the bias Ib=80uA, Vce=2.5V, at the temperature of 333°K

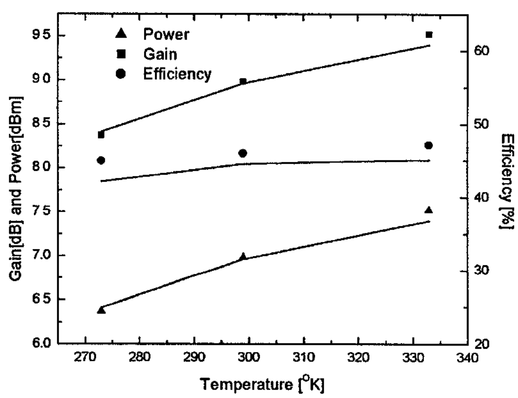

Fig. 6 Modeled and measured power, efficiency, and gain at the bias Ib=70μA, Vce=2.5V, at 273°K, 299°K, 333°K, and Pin = -2dBm at 2.4GHz.