Scalable Large Signal Modeling of InGaP/GaAs HBT for CAD Tools

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A new HBT current source model and the corresponding direct parameter extraction methods are presented. Exact analytical expressions for the current source model parameter are derived. This method is applied to scalable modeling of HBT. Some techniques to reduce redundancy of the parameters are introduced. The model based on this method can accurately predict the measured data for the change of ambient temperature, size, and bias.

INTRODUCTION

Scalable large signal CAD-models for HBTs are very useful for designing of circuits that needs the change of device periphery. The simple linear scale model is good in case of the devices that have large size of emitter periphery comparing thickness of wafer or sufficient thermal shunt. In case of the devices that have insufficient thermal shunt or small area the linear scaling rule cannot predict all the behaviors of HBTs. Because many complex and nonlinear physical properties, including nonlinear thermal interaction, are involved (1)(2).

Current source model based on Gummel-Poon model have the parameters of reverse saturation current and ideality factor. These parameters are extracted from slope and magnitude of (over low current level) the Gummel-Plot and give very useful information for the physical properties of devices. However, the extracted values cannot predict the current and voltage in the normal active bias region (high current level) due to the nonlinear thermal resistance and electrical resistance effects. These initially extracted parameters should be optimized in the high current region. This optimization process cannot guarantee monotonous trends of parameter values for the various sizes of HBTs that have insufficient thermal shunt or small emitter area comparing the wafer thickness.

We propose a new current source models and direct parameter extraction method. These current source modeling method is applied to 1~4 finger size of 2um x 20um emitter and 100um of thickness InGaP/GaAs HBTs that have no via hole and have not the linear scaling properties.

CURRENT SOURCE MODEL AND PARAMETER EXTRACTION METHOD

We use of the equivalent circuit topology in figure 1. We will discuss the temperature dependent current source model in detail and comment briefly on the other parts.

Current Source Model

We propose a new current source model to accurately predict the data on the normal active region and the corresponding direct parameter extraction method. All current source models are

$$I_{cc} = \exp\left(A_0 + A_1 V_{be} + A_2 (R_{th} P_d + \Delta T_a)\right) - \exp\left(A_0\right) \quad (1)$$

$$I_{be} = \exp\left(B_0 + B_1 V_{be} + B_2 (R_{th} P_d + \Delta T_a)\right) - \exp\left(B_0\right) \quad (2)$$

$$I_{bc} = \exp\left(C_o + C_1 V_{bc} + C_2 (R_{th} P_d + \Delta T_a)\right) - \exp\left(C_0\right) \quad (3)$$

$$I_{ee} = \exp\left(D_o + D_1 V_{bc} + D_2 (R_{th} P_d + \Delta T_a)\right) - \exp\left(D_0\right) \quad (4)$$

Where A_0~D_0 are constants related to the reverse saturation currents, R_{th} is thermal resistance, P_d; electrical power dissipation of HBT, ΔT_a; ambient temperature deviation from the reference temperature (T_{a0}) (normally room temperature). The thermal behaviors of current source are represented through the parameters; A_2, B_2, C_2, and D_2. Junction voltage (Vbe and Vbc) dependencies of terminal currents are expressed by the parameters; A_1, B_1, C_1, and D_1.

Parameter Extraction

The current source Icc and Ibe make a dominant role in the normal active region of the DC-IV curves above the knee voltage. In this region, the term "-exp(A_0)" in eq. (1) can be neglected, and Icc represent most of collector terminal currents; Ict

$$I_{ct} \approx I_{cc} = \exp\left(A_0 + A_1 V_{be} + A_2 (R_{th} P_d + \Delta T_a)\right) \quad (5)$$

To extract the parameter A_0, A1, A2, and R_{th}, the equation (5) can be converted to a linear equation, using n number of sampled data from the measured DC-IV curves.

$$\begin{bmatrix} 1 & V_{be,1} & P_{d,1} & (T_{a,1}-T_{a,0}) \\ 1 & V_{be,2} & P_{d,2} & (T_{a,2}-T_{a,0}) \\ \vdots & \vdots & \vdots & \vdots \\ 1 & V_{be,n} & P_{d,n} & (T_{a,n}-T_{a,0}) \end{bmatrix} \begin{bmatrix} A_0 \\ A_1 \\ a_2 \\ A_2 \end{bmatrix} = \begin{bmatrix} \ln\left(I_{ct,1}\right) \\ \ln\left(I_{ct,n}\right) \\ \vdots \\ \ln\left(I_{ct,n}\right) \end{bmatrix} \quad (6)$$

Where, $a_2 = A_2 R_{th}$, the junction voltage(Vbe) can be calculated using the measured base-emitter terminal voltage(Vbet), base terminal current(Ibt), collector terminal current(Ict), total base resistance (Rb1+Rb2), and emitter resistance(Re); Vbe=Vbet-(Rb1+Rb2)Ibt-Re(Ibt+Ict). The total base resistance(Rb1+Rb2) and emitter resistance(Re) are calculated using the method described in reference (3)(4).

We measured the the DC-IV data of 1~4 finger of 2um x 22um InGaP/GaAs HBT at 300^oK and 310^oK. Equation (6) have 4 unknowns. We sampled 8 points of DC-IV data at several values of Vcet, ibt, and ambient temperature ($T_a = 310^oK$ and $T_a = 300^oK$) on the normal active bias region. From the over-determined linear equation (8 sampled data), the 4 unknowns are exactly calculated using the pseudo-inverse of the linear equations whose solution minimize the least square errors between model and measured data. The thermal resistance is calculated using the equation $R_{th}=a_2/A_2$ from the solution of (6).

By similar procedure, a linear equation can be constructed for the base current source model. Using the extracted constant thermal resistance,

$$\begin{bmatrix} 1 & V_{be,1} & R_{th}P_{d,1}+T_{a,1}-T_{a,0} \\ 1 & V_{be,2} & R_{th}P_{d,2}+T_{a,2}-T_{a,0} \\ \vdots & \vdots & \vdots \quad \vdots \\ 1 & V_{be,n} & R_{th}P_{d,n}+T_{a,n}-T_{a,0} \end{bmatrix} \begin{bmatrix} B_0 \\ B_1 \\ B_2 \end{bmatrix} = \begin{bmatrix} \ln\left(I_{bt,1}\right) \\ \ln\left(I_{bt,n}\right) \\ \vdots \\ \ln\left(I_{bt,n}\right) \end{bmatrix} \quad (7)$$

By the linear equation (7), the parameters B_0, B_1, B_2 can be calculated directly.

The current source model Ibc and Iee is not dominant role in the normal active region. These model affect on the current and voltages about the knee voltage of Vcet (<1V). The model Ibc an Iee with only the parameter C_0, C_1, D_0, and D_1, extracted from the reverse Gummel-Plot, can predict the curves below the knee voltage of Vcet sufficiently well.

The current source models based on the solution of the equation (6) and (7) predict the measured DC-IV curves minimizing the least square errors between model and measured data.

SCALABLE CURRENT SOURCE MODELING

The proposed current source model and direct parameter extraction method is applied to the scalable modeling. The proposed method has no optimization or trimming process. This guarantees monotonous trends of parameter values for the different size of HBTs.

To reduce the redundancies of the parameters for different size of HBTs, we set "A_2/A_1" as a constant value as shown in fig. 6. Meaning of A_2/A_1 is the base-emitter voltage change per junction temperature change (;dVbe/dTj) under the constant collector currents (cf. dVbe/dTj under the constant base current is B_2/B_1, shown fig. 6). The parameter A_2/A_1 is independent on the size of HBT. It is dependent only on the physical properties of InGaP/GaAs wafer. The value of $-1.18mV/^oC$, calculated by eq.(7) for 1 finger 2um x 20um HBT, is applied on the other size of HBTs. With the constrain, all the other parameters are calculated for 1 ~ 4 finger of 2x 20um InGaP/GaAs HBTs. Figure 5 shows A_0,B_0,A_1, and B_1. Figure 6 shows A_2, B_2, and R_{th}. The calculated parameters show the constant, linear, or monotonous behaviors. These parameters are fitted as polynomial functions.

The parasitic impedances and internal capacitances are extracted by the method in reference [3][4]. These parameters are fitted as a function of bias and size. All models and parameters are implanted in ADS from Agilent. Figure 2, 3, 4 shows the modeled and measured currents and voltages for the different size of devices and at two ambient temperatures. Figure 7 shows the measured and modeled S-parameters for 2 and 4 finger of HBTs. The model can predict all of the data very well.

CONCLUSION

A new large signal current source model for InGaP/GaAs HBTs and the corresponding direct extraction methods without any optimization or trimming process are presented. This modeling method is applied to the scalable InGaP/GaAs HBT model. The calculated parameters for the several sizes of HBTs show constant, linear, or monotonous behaviors. Using the property of dVbe/dTj=constant, the redundancies of the parameters are removed. The constructed compact scalable model shows very accurate prediction of the measured data for the change of ambient temperature, periphery, voltage, and current on the normal active bias region.

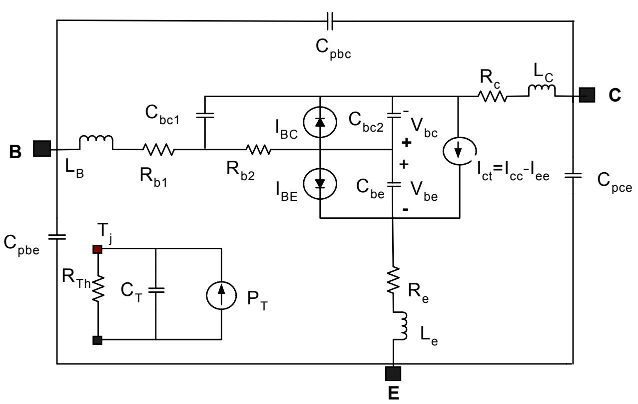

Figure 1: Large Signal Model of InGaP/GaAs HBT.

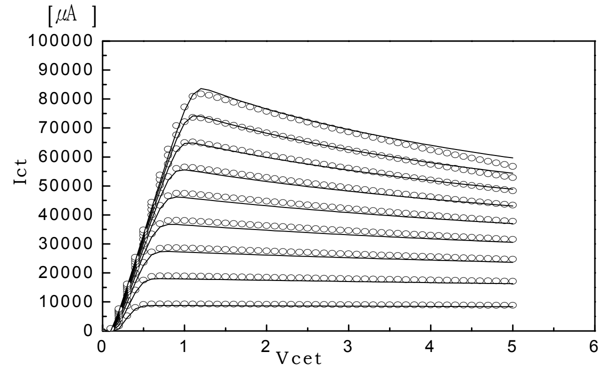

Figure 2: Measured and Modeled Ict-Vcet curves of InGaP/GaAs HBT, 4 finger 2x20um, Ibt=200uA~1.8mA

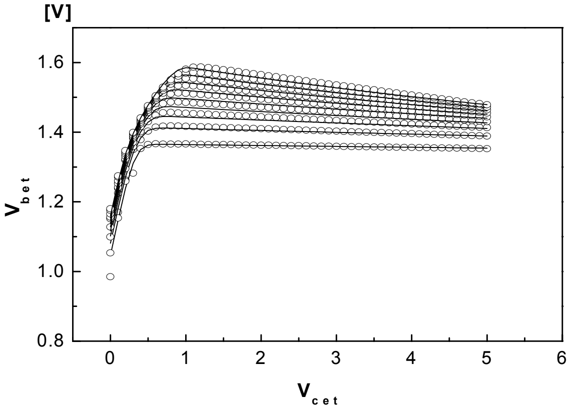

Figure 3: Measured and Modeled Vbet-Vcet curves, 1finger 2x20um HBT Ibt=50uA~450uA, 50uA Step

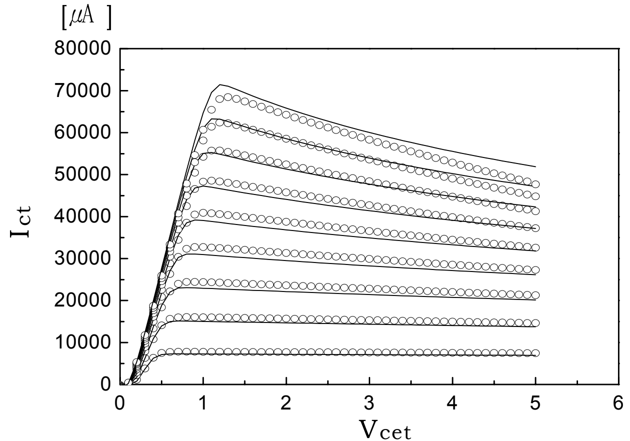

Figure 4: Measured and Modeled Ict-Vcet curves of HBT, 3 finger 2x20um, Ibt=150uA~1350uA, 150uA Step, At the ambient temperature of Ta=310°K.

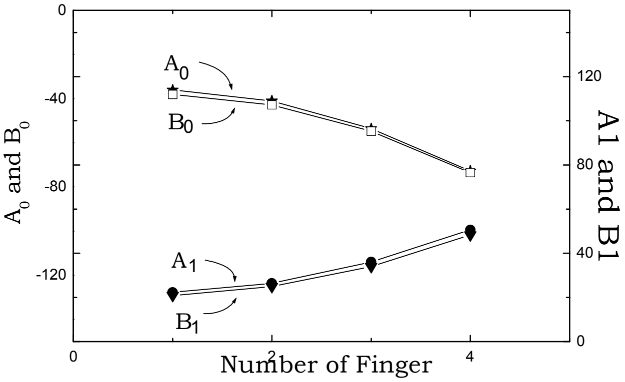

Figure 5: Calculated A0,B0,A1,B1 for the 1~4 finger of InGaP/GaAs HBTs

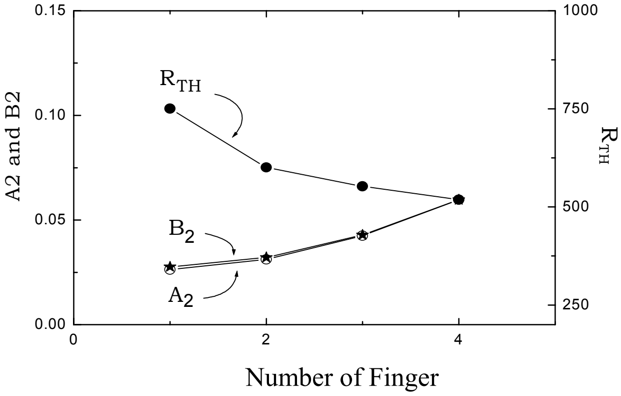

Figure 6a: Calculated A2,B2,Rth for the 1~4 finger of 2x20um InGaP/GaAs HBTs

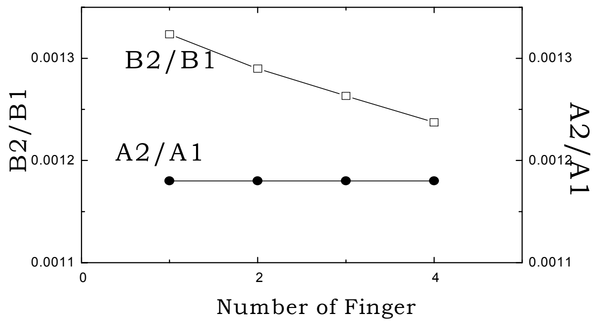

Figure 6b: Calculated A2/A1 and B2/B1 for the 1~4 finger of 2x20um InGaP/GaAs HBTs

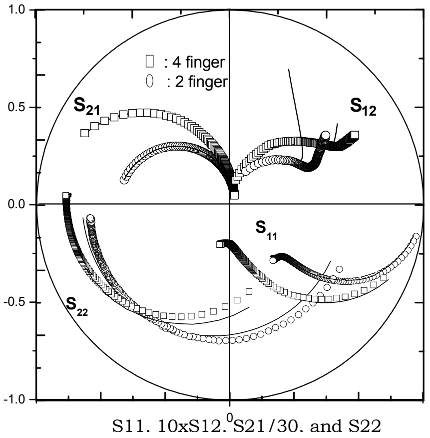

Figure 7: Modeled and Measured S parameter for the 2 finger (Ib=600uA) and 4 finger (Ibt=1.2mA) of 2x20um HBT, at Vcet=3.0V.

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