A Novel Extraction Method for a Fully Electro-Thermal Large-Signal Model of HBT

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***Abstract* — A large-signal modeling of power HBT is demonstrated for an accurate simulation of self-heating and ambient temperature effects and nonlinear behaviors such as output power, gain expansion, and IMD. The extraction was done for in-situ output-stage device from power amplifier circuit. The physical relationship between the device current and the rate of change in the built-in potential with respect to the device temperature has been utilized for a fully electro-thermal modeling. Measurements and simulations are compared for the verification of the model under DC condition at various temperatures. Also the gain expansion and the sweet spot under large-signal two-tone condition have been characterized at the various harmonic load conditions to assess the accuracy of the model.**

I. INTRODUCTION

Heterojunction bipolar transistors (HBT's) have attained maturity as power devices in wireless communication area due to their intrinsic high power density, linearity and efficiency. For a successful circuit design exploiting the full potentials of the device with minimum design-to-production cycles, an accurate large-signal model generated from the measured characteristics of the device under the various conditions is in critical demand.

Despite the superior RF performances, the current gain of HBT exhibits a severe dependency over the junction temperature, which is inherent for the power devices operating under the high current density. This is known as a self-heating effect. Moreover, the power amplifier circuit employing HBT's should work successfully over the specified ambient temperature range to meet the commercial need. It is strongly recommended that these two effects should be predictable by the large-signal model for a reliable circuit design.

The parameter extraction procedure including self-heating effect for the medium-size device with GSG probable patterns is described in [1]. The model is described by a conventional Gummel-Poon component and a thermal subcircuit [2]-[3]. In this paper, the large-signal modeling of the output device in the two-stage power amplifier circuit for a full electro-thermal simulation is described. The model is extended to include the ambient temperature effect by a simple relationship between the device current and the temperature dependence of the built-in potential. The extraction procedure greatly simplifies by this approach and the required parameters can be easily achieved from measurement data. The device was wire-bonded to the test jig for consistent I-V, small-signal S-parameter, and power sweep measurements.

II. PARAMETER EXTRACTION PROCEDURE

The device used in this study is InGaP/GaAs HBT with an emitter area of 5400 μm^2. It has a thick collector metal for uniform heat distribution among the fingers. The device has an output prematching capacitance and a set of series-connected diodes in each pad for ESD protection. These are all lumped into the equivalent circuit diagram in Fig. 1. The temperature effects are described by two feedback elements, $V_{J,T}$ and $V_{PE,T}$ which are used to model the change of the built-in potential and the current gain, respectively.

For DC characterization, I-V data were measured at five ambient temperatures (T_{amb}). To model self-heating effect, the thermal resistance is extracted from I_C-V_{CE} data under constant I_B condition [4] as shown in Fig. 2. The value increases with T_{amb} and is fitted to the 2[nd]-order polynomial.

$$R_{th} = 30.7 + 0.053 \cdot T_{amb} - 0.00029 \cdot T_{amb}^{2} \qquad (1)$$

The model parameters for DC characteristics such as ideality factor and saturation current are extracted from forward Gummel data measured at room temperature. The parasitic resistances are extracted from open collector measurements under DC [5] and AC [6] conditions. The temperature dependence of the built-in potential (dV_{BE}/dT) is extracted from V_{BE}-V_{CE} curve initially.

It is well known that the saturation current and the ideality factor changes with T_{amb}. This change is fitted to the exponential function in the conventional Gummel-Poon model. But if we assume that the saturation current and the ideality factor remain constant at their room temperature values, the associated temperature dependence can be attri-

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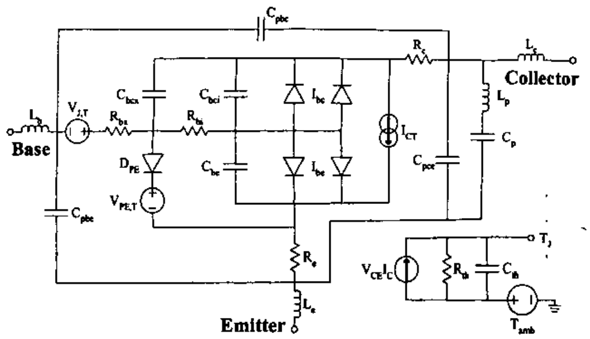

Fig. 1. Equivalent circuit diagram of the large-signal model.

buted to the shift in the built-in potential required to turn on some predetermined current level.

This rate of change with T_{amb} can be extracted from multi-temperature forward Gummel plots at the various emitter currents. The value is linearly related to the logarithmic of I_E below several mA's since the device operates in the ideal region where I_E is governed by the exponential law of the junction device. However, it saturates to −1.24 mV/°C afterwards with the increase of the device current when the self-heating and the extrinsic resistance effects start to occur as shown in Fig. 3. The extracted dV_{BE}/dT is fitted to the 5th-order polynomial.

$$\begin{aligned} dV_{BE}/dT = &-0.00123 - 4.01e^{-5}\cdot\log I_E \\ &-9.55e^{-5}\cdot(\log I_E)^2 - 1.55e^{-5}\cdot(\log I_E)^3 \\ &-1.13e^{-6}\cdot(\log I_E)^4 - 3.04e^{-8}\cdot(\log I_E)^5 \quad (2) \end{aligned}$$

When dV_{BE}/dT is determined from the above equation for a certain I_E, the multiplication with the difference between the device temperature and the room temperature will produce the required shift in the built-in potential. On the other hand, dV_{BE}/dT is constant at −1.24 mV/°C for high

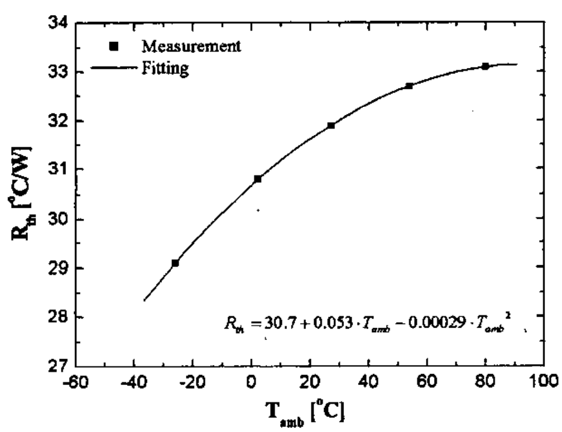

Fig. 2. Temperature dependence of the thermal resistance.

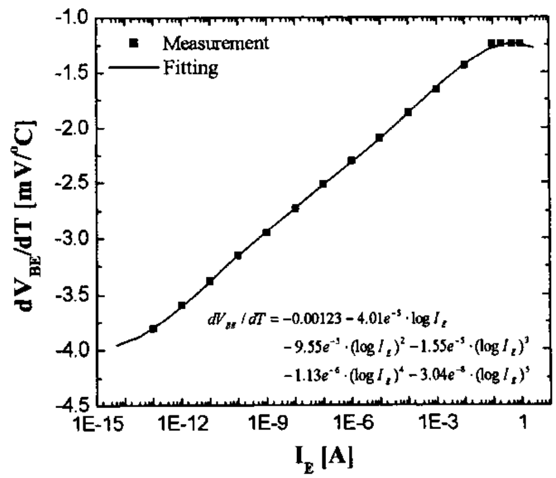

Fig. 3. Extraction of dV_{BE}/dT at various emitter currents.

current region, and the device temperature increase is from self-heating. The multiplication at this time will produce the decrease in the built-in potential due to mainly self-heating.

The measured and the simulated Gummel plots are shown in Fig. 4 at T_{amb} = −26, +2, +27, +54, and +80 °C. The correlation is impressive from high current level down to leakage current level. It is found out that the self-heating and the ambient temperature effects can be explained by one equation. Moreover, the remaining DC parameters are fixed constant during simulation, which means the extraction needs to be done only once at room temperature.

For S-parameter measurements, ICM's TRL1004A calibration kit was used to deembed the test structure from 0.5 to 5.5 GHz. The capacitance-voltage characteristics of both junctions are extracted for V_{BE} < 1.0 V and V_{BC} < 1.0 V. The base-collector junction exhibited a full depletion for V_{BC} < −1.0 V, which is a desirable property for minimum phase distortion under large-signal operation.

Finally, S-parameter optimization is performed at 16 different bias points simultaneously until the best fit is obtained. Before the optimization, the previously extracted parameters for the terminal currents are fixed constant. This avoids iterations between DC and small-signal parameters in the extraction flowchart.

III. SIMULATION VS. MEASUREMENT

The extracted parameters for 5400 μm² device are listed in Table I. To verify how the model works for the temperature effect, the comparisons between the simulated and the measured I-V characteristics are displayed in Fig. 5 and 6 for constant I_B and V_{BE} conditions, respectively. The fitting is excellent from T_{amb} = −26 °C to +80 °C for both conditions. The correlation in I_C-V_{CE} under constant V_{BE} operation is very good, which has been ignored by some temperature-dependent models.

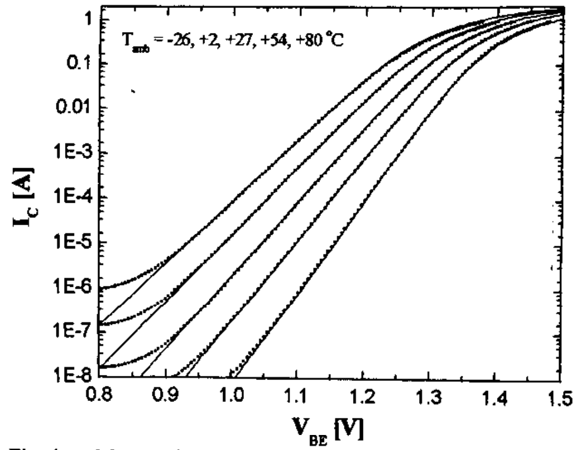

Fig. 4. Measured and simulated forward Gummel plots at various T_{amb} (symbol–measurement, line–simulation).

The model was also verified by comparisons with power sweep measurements under two-tone condition. The device was measured with Focus passive tuners at 1.95 GHz with a frequency spacing of 100 KHz. It was biased at V_{CE} = 3.4 V and I_C = 40 mA. The source reflection coefficient at the fundamental frequency (Γ_{S1}) was 0.80∠–147.5, the second harmonic frequency Γ_{S2} = 0.93∠97.1, and the third harmonic frequency Γ_{S3} = 0.88∠67.6, respectively. The load was tuned to Γ_{L1} = 0.85∠–171.6 at the fundamental frequency. At the second harmonic Γ_{L2} was 0.79∠124.3 and at the third harmonic Γ_{L3} was 0.74∠18.3. For base-band frequency region covering the beat frequency, the measurement setup presented very low impedance to the device due to the bias path. All these harmonic conditions are reflected in the harmonic balance simulator.

Fig. 7 shows the measured and the simulated Pout, Gain, IMD_3, and TOI. The match is very good up to the saturated output power level. The measurement showed a sweet spot around Pin = 14 dBm where IMD performance suddenly improves. It is very interesting to see that the input drive level for the sweet spot is at the vicinity of the point where the gain maximizes. Since the device is biased for class-AB operation, it experiences an appreciable amount of gain expansion with the increase of Pin. This phenomenon is known to improve the linearity performance of the device [7]. As a result, TOI improves with Pin until it peaks at the maximum gain point and then decreases with the further increase of Pin, which leads to a heavy saturation.

In order to verify the applicability of the model again, the device was tuned to a different load condition (Γ_{L1} = 0.76∠180.0, Γ_{L2} = 0.87∠108.1, and Γ_{L3} = 0.82∠46.5). The comparisons are given in Fig. 7(b). The device showed a slightly higher gain and TOI at low Pin region. It showed a sweet spot again around Pin = 12 dBm. This point also corresponds to the maximum point of gain expansion. The shift of the sweet spot means that the nonlinear behavior of HBT is heavily dependent on the load condition. The model tracks the measured behavior for different load conditions very well. It is concluded that the model is very effective in predicting nonlinear behavior of the large area device.

TABLE I
EXTRACTED PARAMETERS OF 5400 μm² HBT

Parameter	Value	Parameter	Value
IS	4.9078×10^{-23} A	MJE	0.35
BF	279	TF	7.459 ps
NF	1.0119	XTF	-0.45
VAF	∞	VTF	1.80 V
IKF	∞	ITF	0.367 A
ISE	6.8157×10^{-23} A	CJC	2.80 pF
NE	1.1129	VJC	0.05 V
BR	0.1	MJC	0.10
NR	1.0119	XCJC	0.913
VAR	∞	EG	1.42 eV
IKR	∞	FC	0.63
ISC	2.8420×10^{-12} A	$\Delta V_{BE}/\Delta T$	-1.24 mV
NC	1.9854	Lb	1.167 nH
RBI	1.5 Ω	Lc	0.281 nH
RBX	1.0 Ω	Le	0.024 nH
IRB	∞	Cpbe	0.50 pF
RBM	0 Ω	Cpbc	0.08 pF
RE	0.092 Ω	Cpce	1.20 pF
RC	0.29 Ω	Lp	0.862 nH
CJE	9.716 pF	Cp	2.76 pF
VJE	0.75 V		

IV. CONCLUSION

A large-signal modeling of the power HBT is presented for an accurate characterization of self-heating and ambient temperature effects. These effects have been successfully merged into one physical equation to simplify the extraction procedure. The model predicts the output power and the distortion performance at the various load conditions very well. The model was extracted for in-situ device from two-stage amplifier circuit. Consequently, it is expected to produce a ready-to-use solution for nonlinear simulation of power amplifier circuit.

ACKNOWLEDGEMENT

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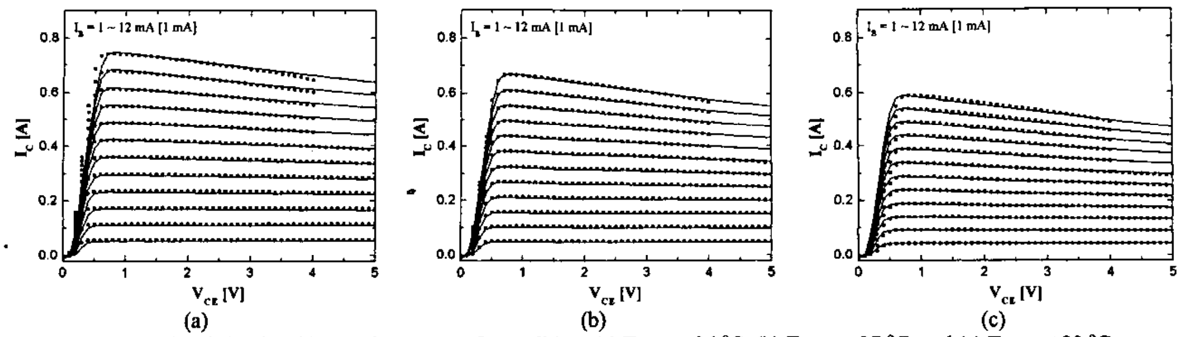

Fig. 5. Measured and simulated I-V under constant I_B condition: (a) $T_{amb} = -26$ °C, (b) $T_{amb} = +27$ °C, and (c) $T_{amb} = +80$ °C.

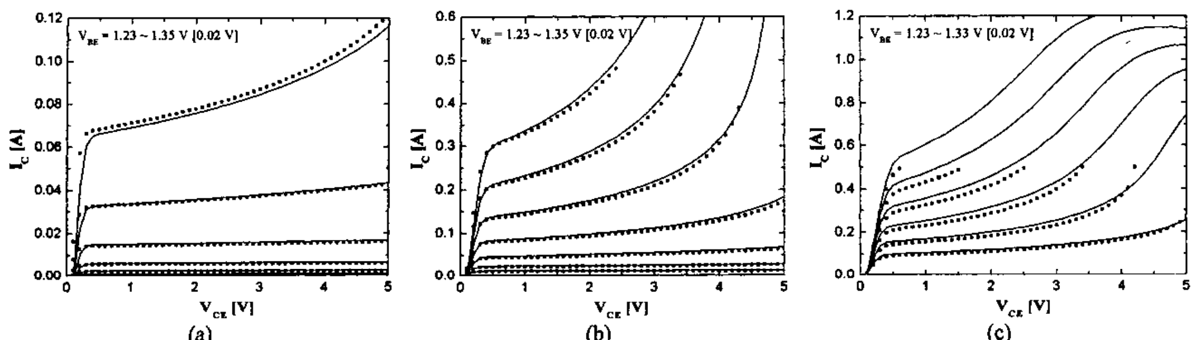

Fig. 6. Measured and simulated I-V under constant V_{BE} condition: (a) $T_{amb} = -26$ °C, (b) $T_{amb} = +27$ °C, and (c) $T_{amb} = +80$ °C.

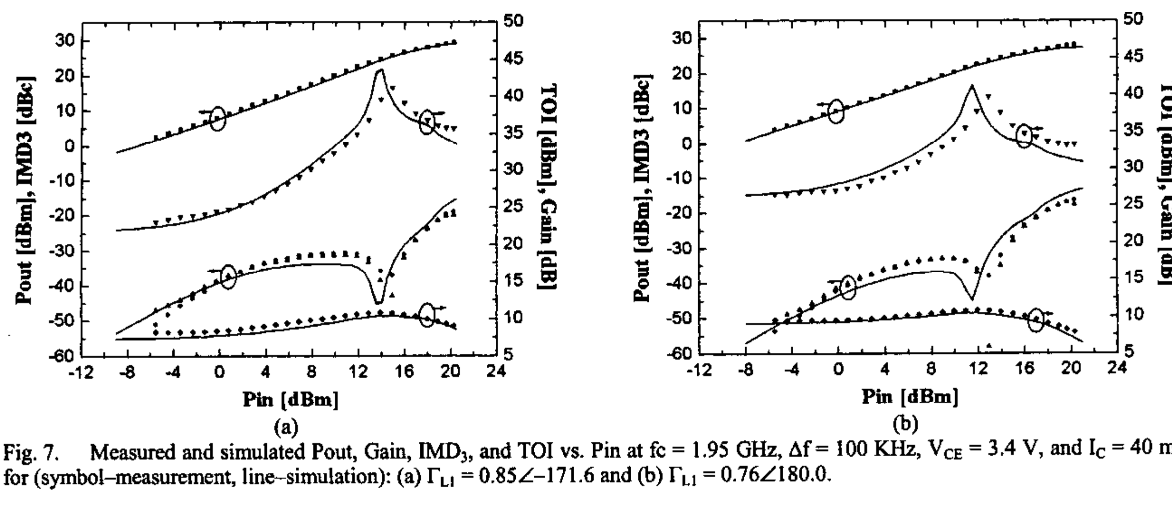

Fig. 7. Measured and simulated Pout, Gain, IMD_3, and TOI vs. Pin at fc = 1.95 GHz, Δf = 100 KHz, $V_{CE} = 3.4$ V, and $I_C = 40$ mA for (symbol–measurement, line–simulation): (a) $\Gamma_{L1} = 0.85\angle{-171.6}$ and (b) $\Gamma_{L1} = 0.76\angle 180.0$.