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Large Signal Evaluation of Nonlinear HBT Model

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SUMMARY The performance of recently developed Large Signal (LS) HBT model was evaluated with extensive LS measurements like Power spectrum, Load pull and Inter-modulation investigations. Proposed model has adopted temperature dependent leakage resistance and a simplified capacitance models. The model was implemented in ADS as SDD. Important feature of the model is that the main model parameters are taken directly from measurements in rather simple and understandable way. Results show good accuracy despite the simplicity of the model. To our knowledge the HBT model is one of a few HBT models which can handle high current & Power HBT devices, with significantly less model parameters with good accuracy.

key words: *HBT, large signal model, bipolar transistor models, nonlinear circuits*

1. Introduction

1.1 HBT Thermal Dependence

The characteristics of all HBT are quite sensitive to the temperature changes [1]–[24]. A careful thermal layout design, use of good quality and properly placed via, thick air bridges improves the thermal stability and reduces some problems like current collapse. The thermal modelling problem in CAD is becoming difficult when the dissipating power is more than 0.5 W and very few HBT models can handle this at all [1], [2], [4], [6], [13], [27], [28]. This is reflected in the published literature- we rarely see results of modelling HBT devices with currents above 0.5A and powers above 1 W in published papers [1], [4], [8], [9].

Very important parts of temperature dependence of HBT currents are:

1. Temperature dependence of the junction voltage when junction current is fixed.
2. Leakage temperature dependence
3. Temperature dependence of BETA

Often HBT is biased with fixed base current as shown in Fig. 1. The devices with small number of fingers are thermally stable up till the maximum dissipated power they can handle from reliability (junction temperature) point of view. With fixed I_{be}, I_{ce} is gradually decreasing at high dissipating power. This decrease is small for low dissipated power

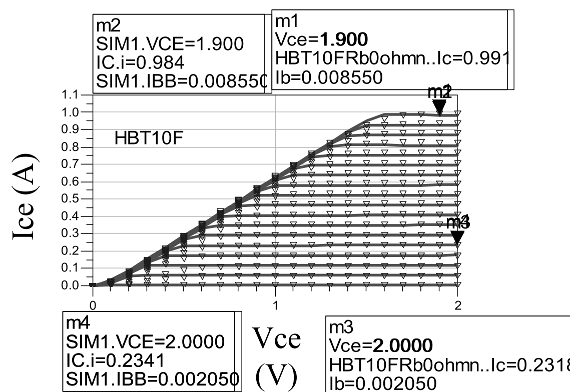

Fig. 1 Measured and simulated I_{ce}(A) vs. V_{ce}(V), I_b = 0.1 mA to 8.55 mA.

P_{dc} < 100 mW and can be substantial for high dissipating powers and high thermal resistance. The bipolar transistors are voltage control devices with exponential dependence on the controlling voltage V_{be} [10]–[12]. When current source is used for I_{be}, the base voltage required to sustain the base current is reduced when the dissipated power or temperature is increased, Fig. 2(a).

If the device is biased with a voltage source V_{be}, increasing the dissipated power will change the junction temperature and we will observe exponential increase of I_{ce} due to this feedback. The slope of I_{ce} vs. V_{ce} is determined by the thermal coefficient of V_{be} (material dependent) and thermal resistance: i.e. the junction temperature dependence for fixed base current is critical for device operation.

In high power RF applications, when we swing the device from pinch off to high currents, biasing with voltage source V_{be} can be beneficial to obtain high output power and efficiency. This biasing mode can be used in the final stages to boost the efficiency, but biasing and protection circuits should be designed carefully. Additional problem with high power HBT devices (from operational and simulation point of view) is that thermal resistance R_{therm} is a function of the temperature [25], [26] by itself. That is why, in this implementation, the thermal resistance was arranged to be temperature dependent with temperature coefficient $T_{cRtherm}$:

$$R_{thermT} = R_{therm} * (1 + T_{cRtherm} * (T_{chanK} - T_{refK}))$$

The CAD tool can be used directly to refine the temperature coefficients and provide the best fit at high dissipated power.

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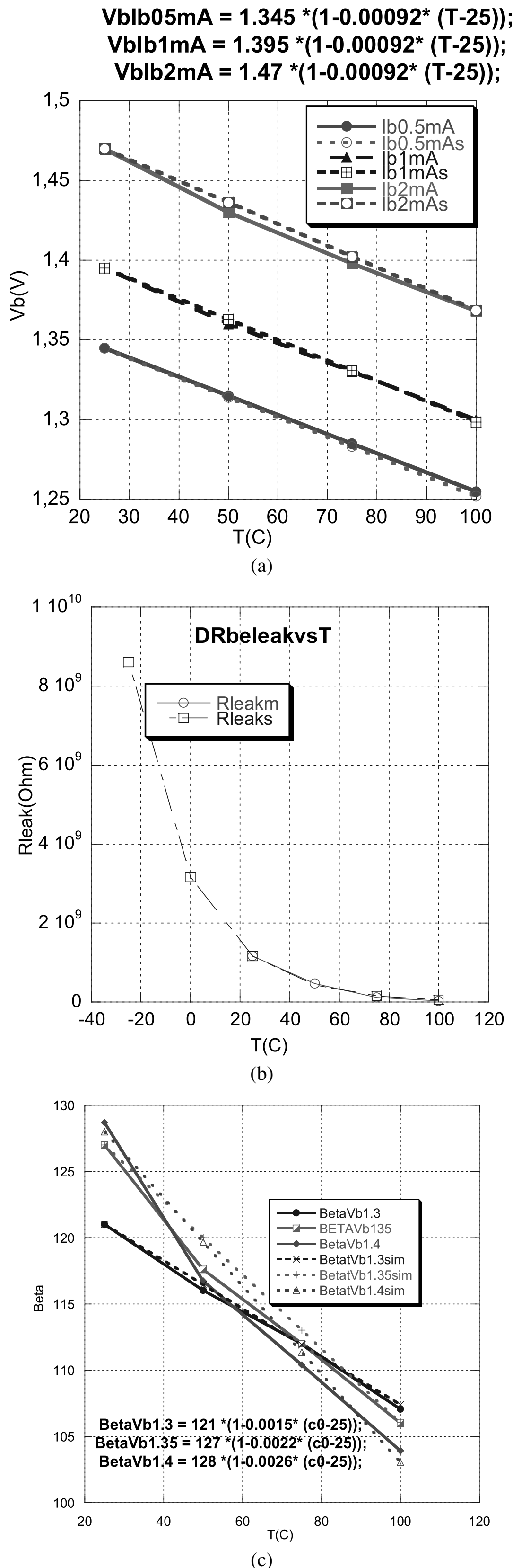

Fig. 2 (a) Measured and simulated temperature dependence of V_{be} at fixed I_b. Solid line shows experimental data, and dashed line shows simulation results. (b) Measured and simulated Leakage FG vs. Temperature. (c) Measured and simulated temperature dependence of BETA.

1.2 Leakage Temperature Dependence

When the device is biased at the pinch-off, due to the fact that materials are not ideal, we will always have some residual small currents I_{res} i.e. some leakage resistance $R_{leak} = 1/I_{res}$. Residual currents I_{res} for good quality process are less than 1×10^{-10} A, and their temperature dependence is exponential.

Figure 2(b) show measured (points) and modeled (lines) leakage resistance extracted from Forward Gummel (FG) and Reverse Gummel (RG) measurements at different temperatures. This dependence can be modeled as addition or modification of the current sources, but it is more stable in the simulations and easier to understand & extract if we model the leakage as a temperature dependent resistor.

Following equations are proposed as extension of previously published HBT model [23], [24] and implemented in ADS to model the leakage:

$$\begin{aligned} DT_{JL} &= T_{chanK} - T_{refK} \\ R_{leakti} &= R_{leaki} * (1/(0.00001 + \exp(-T_{cRleaki} * DT_{JL}))) \end{aligned} \quad (1)$$

The R_{leaki} are the corresponding leakages at room temperature for BE, BC, CE junctions and $T_{cRleaki}$ is the temperature coefficient. A small number is added in the denominator to improve the numerical stability.

1.3 Temperature Dependence of BETA

It is known that current parameter Beta is temperature dependent, as shown in Fig. 2(c), and this should be implemented in the simulator. In the practical temperature range, linear dependence provides satisfactory fit [25], [26]. In addition, we can use these temperature dependences to extract the thermal resistance [25], [26].

2. Model Implementation in ADS

$$\begin{aligned} & y = (V_{bec}/VJC) - 1; z = (V_{bcc}/VJC) - 1 \\ & C_{bedepl} = ((m + y \wedge 2) \wedge (-1 - MJC)) \\ & \qquad * (m + (1 - 2 * MJC) * y \wedge 2) \\ & C_{bcdepl} = ((m + z \wedge 2) \wedge (-1 - MJC)) \\ & \qquad * (m + (1 - 2 * MJC) * z \wedge 2) \\ & C_{bcdepl1} = C_{bcdepl} * (1 + 1 * (C_{dep1}/(\exp(V_{bec} - V_{cmin})) \\ & \qquad + C_{dep2} * \exp((19.347/N_{cf1}) * \tanh(V_{bec} - VJC)))) \\ & th1 = ((1.00001 + \tanh(P_{11} * (V_{bec} - P_{10})))) \\ & C_{be} = C_{be0T} * (A * th1 + C_{bedepl}) + C_{bepi}; C_{bcdif} \\ & \qquad = C_{bc0T} * th2 \\ & th2 = ((1.00001 + \tanh(P_{21} * (V_{bcc} - P_{20})))) \\ & C_{bc} = C_{bc0T} * (A * th2 + C_{bcdepl}) + C_{bcpi} \end{aligned} \quad (2)$$

The main purpose of this study was extensive LS evaluation of the HBT model. The HBT model and model parameters are described in details [23], [24], but several changes were made in the previous implementation to reflect refined temperature dependencies and to improve the model. First addition was implementation of temperature dependent

leakage and temperature dependent thermal resistance. The capacitance model as it is described in [23] includes many of the features of other capacitance models [2], [6], [27], but it is defined from $-\infty$ to $+\infty$ without any poles, conditions etc. For user convenience, the capacitance model is arranged to have the same names and values for common parameters like MJC, VJC, but it is more stable in Harmonic Balance simulations. In this study, it was found that simpler depletion capacitance model C_{bedepl}, C_{bcdepl}, provides a good fit for actual devices and capacitance equations [23] are simplified as Eq. (2). For user convenience, they can switch for the complete capacitance model [23] if required. In addition, some small adjustments were made to improve convergence like adding small numbers in the denominators etc.

3. S-Parameters Evaluation

The following figures show some results from the S-parameter evaluation for 2 finger devices with emitter sizes of $80\,\mu\text{m}^2$. In all graphs in this paper, measured data are shown by points and simulations are shown by lines. Similar results are obtained for 8-finger devices. The 2 finger device shows better accuracy, as it is expected -it is simpler, the thermal distribution is better. The model is able to predict details as loops in S12 and S22 shown in Fig. 3 at high V_{ce}.

The topic of HBT small signal equivalent circuit extraction is covered extensively in the literature and only few references are listed [12], [14]–[19]. The initial extraction of basic model parameters like Re, Rc, Rb, capacitances is made using standard blocks and procedures in ICCAP for HBT. These results provide very good starting values for the optimization with the CAD tool and limit the expected tolerance of the model parameters.

Additional benefit is that main current parameters like V_{bep}, I_{pkc}, Beta, BetaR, N_{cf1}, N_{be1}, N_{bc1} are taken directly from the measurement.

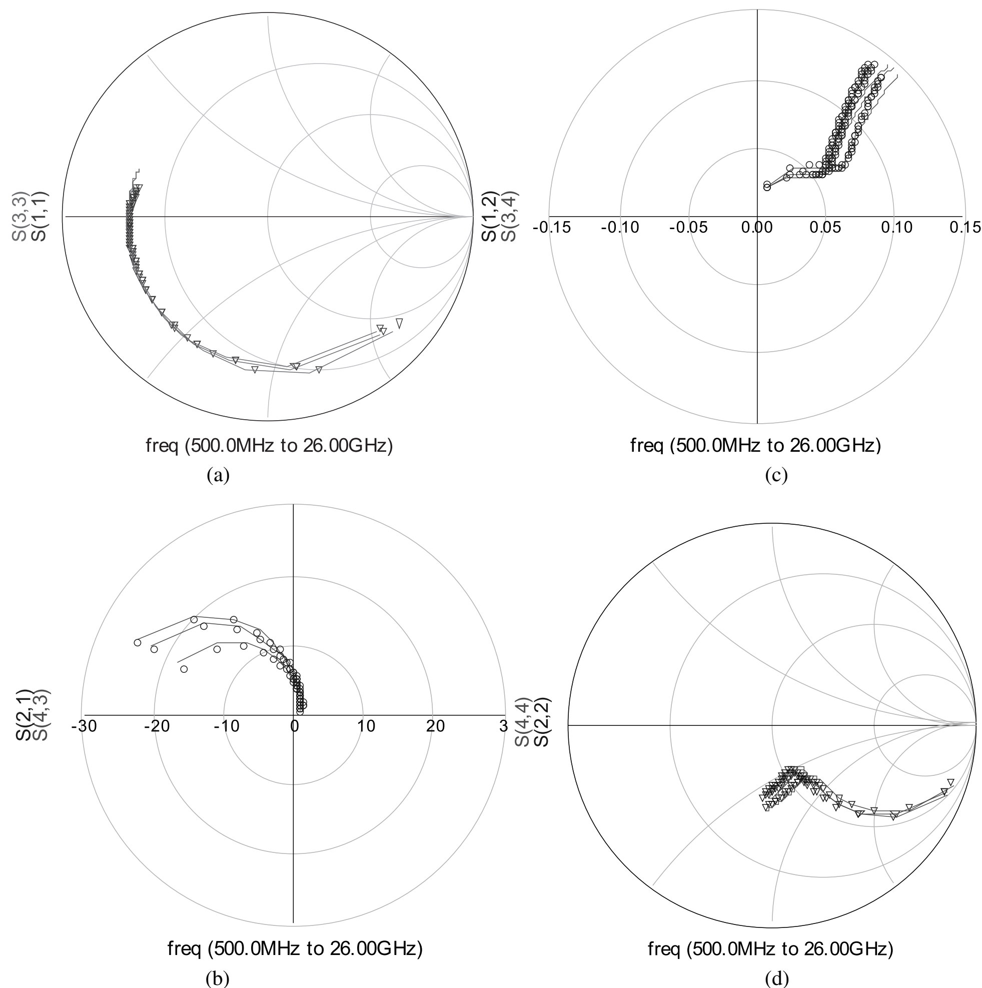

Fig. 3 (a) S11. 2 finger; $V_{\text{ce}} = 3\,\text{V}$; I_{b}: 0.1, 0.2, 0.3 mA. (b) S21. 2 finger; $V_{\text{ce}} = 3\,\text{V}$; I_{b}: 0.1, 0.2, 0.3 mA. (c) S12. 2 finger; $V_{\text{ce}} = 3\,\text{V}$; I_{b}: 0.1, 0.2, 0.3 mA. (d) S22. 2 finger; $V_{\text{ce}} = 3\,\text{V}$; I_{b}: 0.1, 0.2, 0.3 mA.

4. Evaluation of the Model with Power Spectrum (PS) Measurements

The model behavior in power spectrum, load pull circuits and IMD test combined with load pull circuit is a severe test for every kind of LS model and this was the main goal in this study. Quite often, we can observe convergence problems, if the model is not constructed and implemented properly. The correspondence between measurements and simulations, especially for harmonics, was the main focus of the study.

Power spectrum measurement, Fig. 4, is very important tool for evaluation of large signal models. It is rather easy to assemble the PS measurements set-up. It consists of general measurement equipment like signal source (synthesizer) and harmonics measurements equipment like spectrum analyzer (or power meter & filter). It is important to provide good 50 ohm match for the fundamental and harmonics, and that is why it is recommended to use decoupling attenuators connected directly at the bias tees close to the device. Following figures, Fig. 5–7, show results from the measurements and simulations.

If the model provides a good accuracy in modeling IV characteristic, this is a good sign, which means that the model should be able to predict accurately the fundamental power. The harmonic content is much more difficult to model accurately for various reasons.

Harmonics generation in HBT is critically dependent on the intrinsic junction voltage, leakage and device junction temperature, ideality factor, capacitance shape, thermal resistance, etc. If for some reasons there is a change in some parameters- this will lead to very different results in the measurements. As a result, the correspondence between measured and simulated harmonics will not be good. The simplest reason for the difference will be that one device is used for model extraction and the other device was measured for harmonics test.

Figure 5–7 show measured and simulated PS, i.e. P1-st, P2-nd and P3-rd harmonics for different bias conditions for the 2 and 8 finger devices. Generally, the model describes the PS with accuracy adequate for practical purposes.

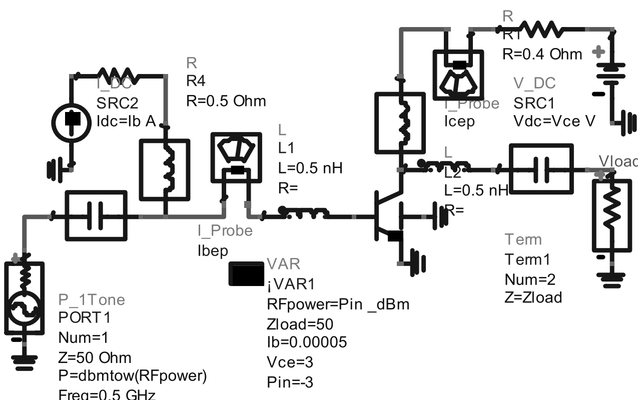

Fig. 4 Power spectrum measurement set up.

For the smaller device, as expected, the accuracy is better. To our knowledge, there exists no simple HBT model which can describe the PS with better accuracy. The accuracy is comparable with what can be obtained from FET

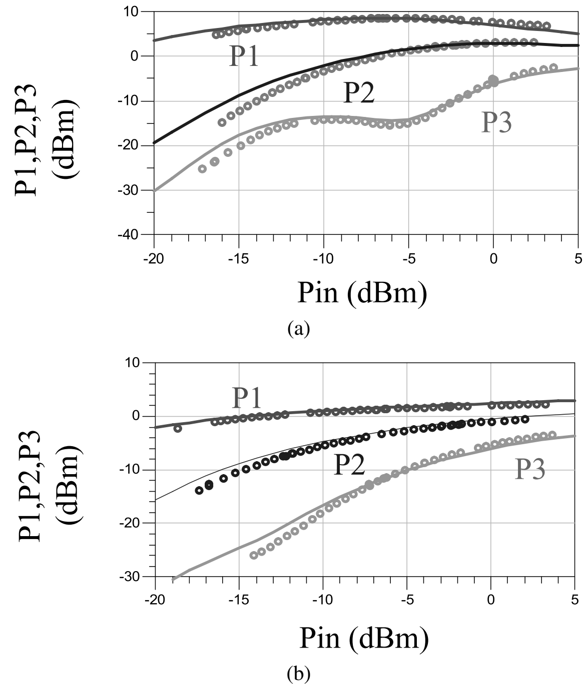

Fig. 5 (a) PS of 2 finger device P1, P2, P3 (dBm) vs. Pin (dBm) meas. and simulated. V_{ce} = 1.5 V; I_{be} = 100 μA; Pin: −20 to 5 dBm. (b) PS of 2 finger device P1, P2, P3 (dBm) vs. Pin (dBm) meas. and simulated. V_{ce} = 1.5 V; I_b = 40 μA; Pin: −20 to5 dBm.

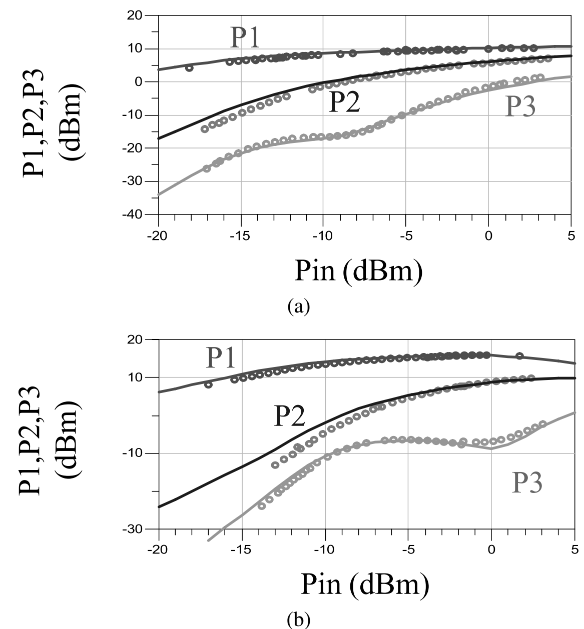

Fig. 6 (a) PS of 2 finger device P1, P2, P3 (dBm) vs. Pin (dBm) meas. and simulated. V_{ce} = 3 V; I_b = 100 μA; Pin −20 to5 dBm. (b) PS of 2 finger device P1, P2, P3 (dBm) vs. Pin (dBm) meas. and simulated. V_{ce} = 3 V; I_b = 220 μA; Pin −20 to5 dBm.

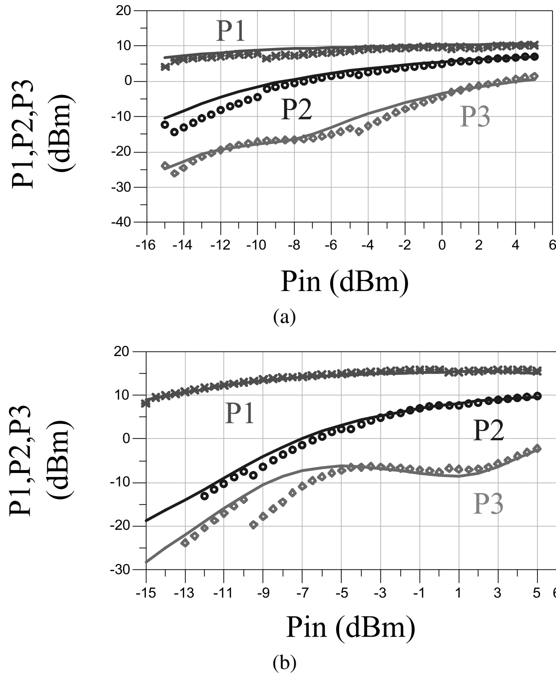

Fig. 7 (a) PS of 8 finger device P1, P2, P3 (dBm) vs. Pin (dBm) meas. and simulated. V_{ce} = 3 V; I_b 50 μA; Pin: −15 to5 dBm. (b) PS of 8 finger device P1, P2, P3 (dBm) vs. Pin (dBm) meas. and simulated. V_{ce} = 3 V; I_b 220 μA; Pin: −15 to5 dBm.

models, but FET is easier to model, because it is more stable from thermal point of view.

5. Load Pull Evaluation of the Model

Load-pull measurements are more sensitive to the actual temperature, thermal resistance, biasing conditions and device parameter tolerances, because the impedance is very different from 50-ohm at fundamental and harmonics.

In order to improve the accuracy of the harmonics measurements and evaluate the sensitivity of the generated harmonic content to the impedance which device actually faced, a new set of measurements was performed. The impedances at the input and output were measured and later used in the simulations. I.e. in the corrected PS simulation set-up, Figs. 8–10, measured input and output impedance were used. As expected, the accuracy is much better with corrected impedances with accuracy surpassing what we have seen in published HBT models.

Device is biased in two modes- with voltage source at the input and outputs and with current source at the output and floating base at the input. The bias conditions in the current mode are difficult to reproduce in the simulator, but for the voltage source biasing quite reasonable results are obtained.

6. Inter-Modulations Measurements and Simulations

Figures 11 and 12 show measured and modeled response with 2-tone set-up i.e. IMD3 evaluations for two collector

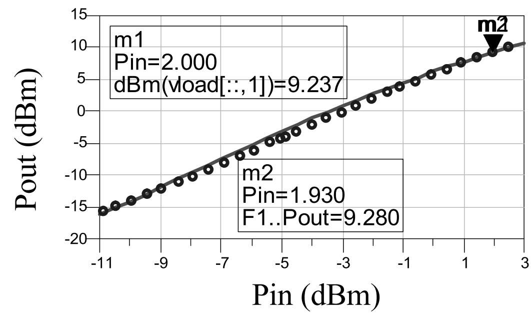

Fig. 8 Pout (dBm) vs. Pin (dBm) load-pull evaluation for 2 finger device. V_{ce} = 1.5 V, V_{be} = 1.15, RF = 2.1 GHz.

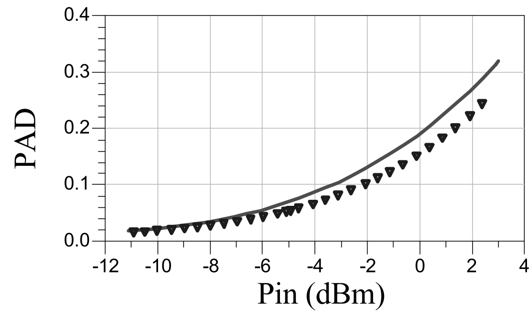

Fig. 9 PAD (= P1/Pdc) vs. Pin (dBm) load-pull evaluation for 2 finger device. V_{ce} = 1.5 V, V_{be} = 1.15: Pin; −11 to 3 dBm, RF = 2.1 GHz.

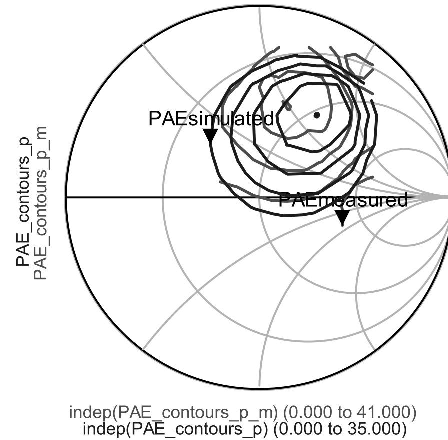

Fig. 10 Load-pull evaluation of 2 finger device. V_{ce} = 1.5 V; V_{be} = 1.15 V; RF = 2.1 GHz, Fspacing 50 kHz.

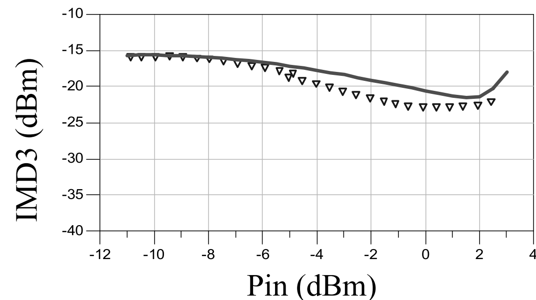

Fig. 11 IMD3 evaluation of 2 finger device. Pin; −11 to 3 dBm, IMD3 (dBm); V_{ce} = 1.5 V; V_{be} = 1.15 V; RF = 2.1 GHz, Fspacing 50 kHz.

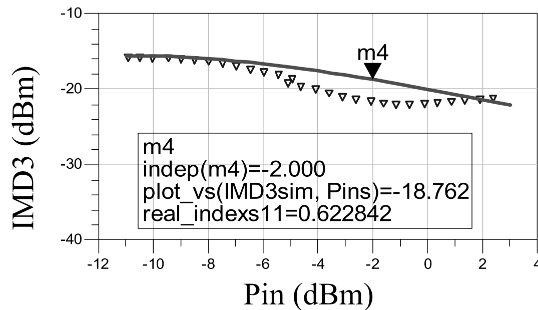

Fig. 12 IMD3 evaluation of 2 finger device. Pin; −11 to 3 dBm, IMD3 (dBm); V_{ce} = 3 V; V_{be} = 1.15 V; RF = 2.1 GHz, Fspacing 50 kHz.

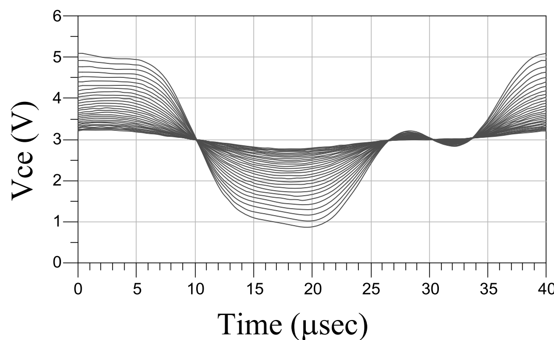

Fig. 13 Simulated waveforms of 2 finger device. V_{ce} = 3 V, V_{be} = 1.15 V; Pin; −11 to 3 dBm.

voltages. The accuracy of IMD simulations is better than the typical accuracy one can get from the IMD3 simulations for HBT. The reason for this is that the currents in our model are accurately defined, derivatives are exponential, as they should be, and the capacitance models are accurate and converge well. As can be seen from the simulated waveforms, Fig. 13, the voltage swing is rather high and reaches nearly 5 V. This means that, if we want our model to be more accurate, some data should be available for high V_{ce} or LSVNA measurements. The convergence of the HBT model is good, considering that quite often there are convergence problems with IMD simulations with any LS model. For IMD simulations in load pull environment the convergence is even more critical. We can greatly improve the accuracy of our predictions if we use on-wafer measurements to verify the IMD3 generated. This way we can exclude the bonding inductances and pads from elements creating uncertainty & sacrificing accuracy.

The junction temperature Tj is very important for the IMD3 measurements and simulations. Tj is influenced by the thermal resistance of mounting structure and power dissipation. The respective first harmonic P_{1st}, DC current & power P_{dc} and Tj depend on the load and mounting structure & transistor parameter tolerances, and this will influence the PAD = P_{1st}/P_{dc}. Even simple combination of small tolerances can change the shape of IMD3 dependence and produce error more then 3 dB. A problem which can critically influence the reliability and affect the accuracy of the simulations is the temperature distribution in the chip and difference in the temperature of the fingers. If at high dissipated power hot spots are formed, this will critically influence the accuracy of simulated IMD products. Probably, the lower accuracy in the simulations is not as important as the fact that when hot spots are formed, this can be critical for the device reliability.

7. Conclusions

The HBT model developed jointly between Chalmers and Mitsubishi was evaluated at different temperatures with extensive DC, S-parameter and large signal measurements. The measurements and simulations were performed on several device sizes. Using these results, model parameters like temperature dependencies were refined. Temperature dependent leakages and capacitance model implementation were improved. The model is very compact, with minimum model parameters, but shows very good accuracy despite its simplicity. To our knowledge, this is one of very few models that can handle large current & power devices with similar accuracy. The reason for this good accuracy is that the model is mathematically defined in the bias range we practically use the device.

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Shinsuke Watanabe was born in Saitama, Japan in 1978. He received B.S. and M.S. degrees in physics from Osaka University, Japan, in 2002 and 2004, respectively. Since joining the High Frequency & Optical Device Works, Mitsubishi Electric Corporation, Itami, Japan, in 2004, he has been engaged in the design of GaAs millimeter-wave MMICs such as voltage controlled oscillator. His present research interests include the extraction of device parameter such as HBTs. He is also working on the investigation of millimeter-wave application, and electromagnetic field analysis for mobile communications.