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Fully Functional Nonlinear Table-Based HBT Model With Explicit Thermal Feedback

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Abstract—A fully functional table-based nonlinear model of the heterojunction bipolar transistor (HBT) is presented which includes explicit thermal feedback. The model uses four table-based nonlinear functions: I_c , Q_c , V_{be} , and Q_b , all defined versus I_b and V_{ce} by using a nonuniform bias grid. Thermal modeling (self-biasing and environment temperature dependence, T_a) is done by linearly mapping the table-based current functions versus T_a coupled with explicit thermal feedback. Four table-based nonlinear coefficients are required to accurately predict the device behavior versus temperature. Excellent results have been obtained under dc, small, and large signal excitations for InGaP/GaAs HBTs in the range 10 °C to 110 °C.

Index Terms—Heterojunction bipolar transistor (HBT), modeling.

I. INTRODUCTION

MANY heterojunction bipolar transistor (HBT) nonlinear models proposed so far are extended versions of [1]. The poor thermal conductivity of III–V materials combined with the high power densities of HBT operation makes thermal modeling compulsory in III–V based HBTs [2]–[4]. As a consequence, empirical HBT models present a complex formulation and time consuming extraction procedure, which involves many parameters and multiple optimization steps. As in the field effect transistor (FET) case [5], table-based approaches could be used to simplify model formulation and extraction, and to improve its generality. HBT table-based models proposed so far are, to our knowledge, mixed analytical/table-based approaches for either the nonlinear current or charge functions (with the other function purely analytical), hence are only partially table-based [6], [7]. This may be related to difficulties in accounting for thermal behavior in a pure table-based approach. In this letter, we propose a fully functional HBT modeling approach, in which all nonlinear intrinsic functions at both ports are table-based, that takes into account the first-order modeling of self-heating and environment-ambient temperature effects.

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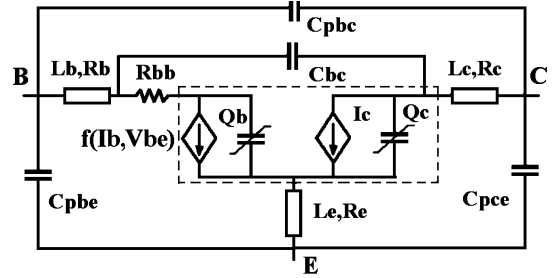


Fig. 1. HBT table-based nonlinear model.

II. TABLE-BASED HBT MODEL FORMULATION WITH THERMAL FEEDBACK

A. Table-Based HBT Model Basic Formulation

Fig. 1 shows the model topology, including extrinsic and intrinsic elements. The goal is to model the nonlinear I – V and Q – V relationships at the HBT intrinsic ports by means of nonlinear table-based functions which will be spline interpolated during simulation time. In the output, we use the nonlinear relations I_c and Q_c . In the input, because V_{be} can be measured when doing I_b driven measurements, we do not use an explicit I – V function, but an implicit one, $f(I_b, V_{be}) = 0$. Implicit functions can be directly managed by some simulators, e.g., ADS. In this case, the table-based function is V_{be} . This approach avoids the use of analytical approximations (e.g., the diode equation, as in [3]) which decrease accuracy and imply a conventional parameter optimization procedure to fit the equations with temperature and voltage. Nonlinear charge at the base terminal is modeled by the table-based nonlinear function Q_b . All four previous table-based nonlinear functions are defined versus I_b (input port current) and V_{ce} , as in [3], because these are the actual independent variables typically used during HBT device characterizations. In addition, they allow for a wider and safer dc voltage-current characterization.

B. Thermal Modeling

To predict device thermal behavior at different ambient temperatures, T_a , we studied how the measured I_c and V_{be} functions map over T_a , and searched for an analytical function with the minimum number of parameters. A linear dependence with T_a as considered in (1) and (2) is a good approximation for most bias points

$$I_c(I_b, V_{ce}, T_a) = tc_1 \cdot T_a + I_{c0} \quad (1)$$

$$V_{be}(I_b, V_{ce}, T_a) = tc_2 \cdot T_a + V_{be0} \quad (2)$$

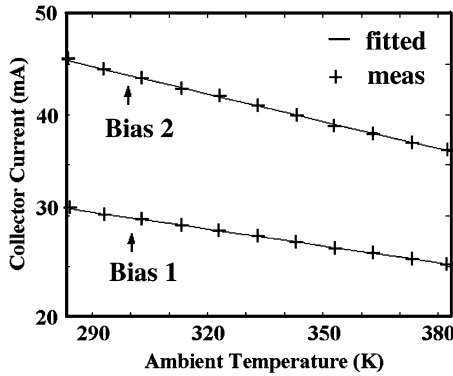


Fig. 2. Measured and fitted with (1) dc collector current versus T_a . Bias point 1: $I_b = 0.52$ mA, $V_{ce} = 3$ V. Bias point 2: $I_b = 0.72$ mA, $V_{ce} = 0.5$ V.

tc_1 , tc_2 , V_{b0} , and I_{c0} are nonlinear table-based thermal coefficients versus I_b and V_{ce} . The coefficients V_{b0} and I_{c0} could be understood as the corresponding functions at 0 K.

Equation (1) is a simplification of a previous static thermal approach developed by the authors [8]. In that approach, a Gaussian-like function was used for thermal modeling of I_c at all bias points. While the Gauss-like function improves this modeling at the cut-off region for low T_a , the linear approach (1) provides better results at high T_a for all bias points. Under radio frequency (RF) large signal operation, we have found that for the devices studied in this work the linear approximation provides more accurate results.

From (1) and (2) versus T_a , it is possible to dynamically extract the internal device temperature, T_j , at each bias point (using a conventional one-pole thermal feedback network with R_{th} and C_{th} as parameters to calculate the dissipated power and temperature rise). Taking that into account, we have coupled in the model (1) and (2) with a thermal feedback network, dynamically calculating T_j during simulation time and effectively using this new variable to drive the nonlinear intrinsic functions I_c and V_{be} . Linear temperature dependence has also been applied to R_{bb} and C_{bc} .

III. MODEL EXTRACTION AND RESULTS

This approach has been applied to InGaP/GaAs HBT devices. Results shown in this letter are on the same $2\ \mu\text{m} \times 3\ \mu\text{m} \times 25\ \mu\text{m}$ HBT. Device parasitic values, R_{bb} and C_{bc} have been obtained from small signal data. R_{th} and C_{th} have also been extracted by conventional methods. I_c and V_{be} nonlinear functions were extracted from dc I - V measurements versus I_b , V_{ce} and T_a . Coefficients in (1) and (2) were obtained at each bias point by linearly fitting the measured dc I - V s versus T_a . For this purpose, on-wafer dc I - V measurements were performed with a HP4142 and a thermally controlled probe station in the range 10 °C–110 °C. Fig. 2 shows the fit of I_c to (1) in the case of saturation and active region bias points. Fig. 3 shows the improved behavior in dc operation by using the linear approach (1) with respect to the gauss-like approach [8] in the active region at 100 °C.

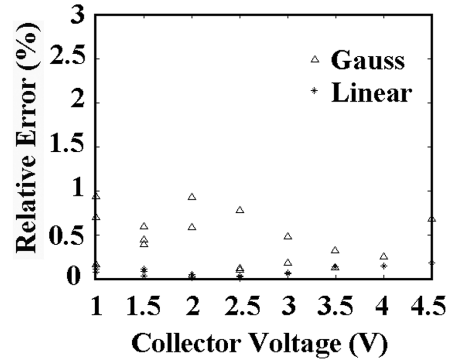


Fig. 3. Relative error in dc collector current at $T_a = 100^\circ\text{C}$ by applying (1) for different base current values (0.521, 0.621, and 0.721 mA) and collector voltages in the active device I - V region.

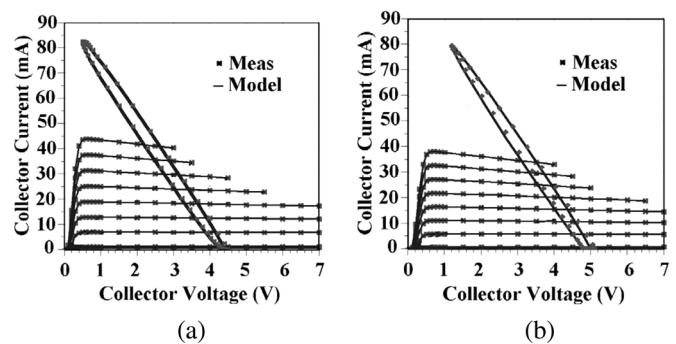


Fig. 4. Measured and modeled dc collector current and dynamic load line (Fundamental Frequency = 1 GHz) (a) $T_a = 30^\circ\text{C}$ Class AB: $V_{be} = 1.32$ V $V_{ce} = 2.5$ V $P_{in} = -9.6$ dBm $P_{out} = 17.3$ dBm, (b) $T_a = 100^\circ\text{C}$ Class A: $I_b = 0.62$ mA $V_{ce} = 3.5$ V $P_{in} = -8.1$ dBm $P_{out} = 16.3$ dBm.

Q_b and Q_c are obtained from small signal s -parameter measurements versus bias, at 5 GHz and $T_a = 30^\circ\text{C}$, by using an integration procedure similar to [5] and based, in this case, on smoothing B-splines (MATLAB algorithms). In this work, the required on-wafer small signal and large signal measurements were performed by using a Maury LSNA (system bandwidth 0.6 to 50 GHz) and the thermally controlled probe station.

Model accuracy will be dependent on the measurements quality, the bias grid used and the type and behavior of the simulator spline routines. In the boundary cutoff-active region a denser bias grid has been used to avoid spline oscillations.

The model has been implemented in ADS simulator by using Symbolically Defined Devices and validated under dc, small and large signal operation. Figs. 4–6 show the excellent results obtained at different ambient temperatures, $T_a = 10^\circ\text{C}$, 30°C , 80°C , and 100°C , under dc and large signal excitations (Class A and AB operation). In Fig. 4, it is shown the measured dc I - V range (at a given T_a) used for model extraction along with the predicted and measured RF current swing observed well into gain compression. The results clearly show the model accurately predicts RF performance even under RF drive conditions that require extrapolation beyond the measured dc I - V range. Fig. 7 shows also excellent model behavior in small signal operation at two different bias points.

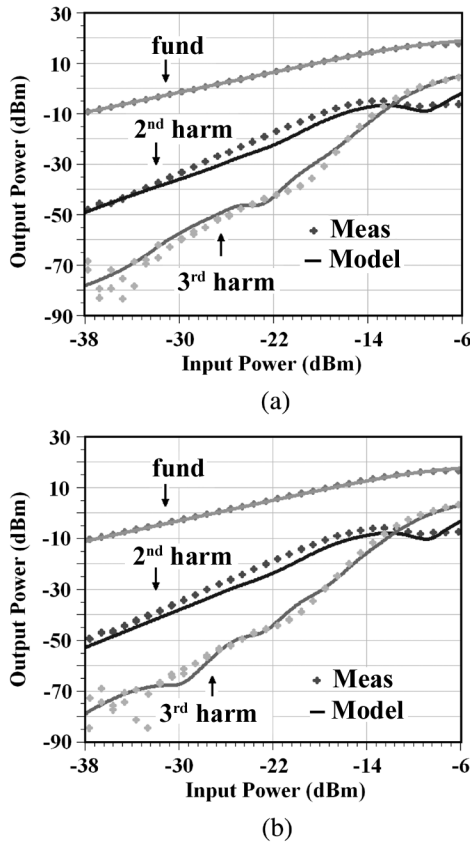


Fig. 5. Measured and modeled large signal Class AB behavior Fundamental Frequency = 1 GHz: (a) $T_a = 10^\circ\text{C}$, $V_{be} = 1.34\text{ V}$, $V_{ce} = 2.5\text{ V}$. (b) $T_a = 80^\circ\text{C}$, $V_{be} = 1.27\text{ V}$, $V_{ce} = 2.3\text{ V}$.

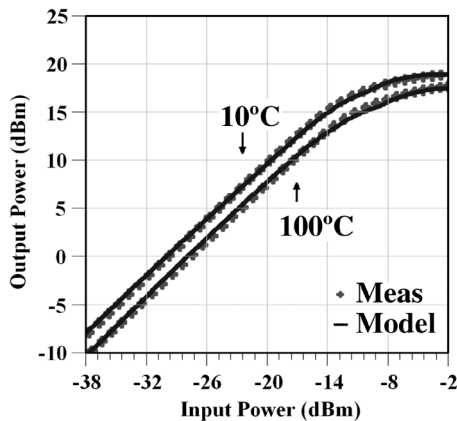


Fig. 6. Measured and modeled large signal Class A behavior Fundamental Frequency = 1 GHz, $T_a = 10^\circ\text{C}$ and 100°C , $I_b = 0.62\text{ V}$, $V_{ce} = 3.5\text{ V}$.

IV. CONCLUSION

In this letter we propose a fully functional HBT modeling approach in which all nonlinear intrinsic functions at both ports are table-based taking into account the first order modeling of

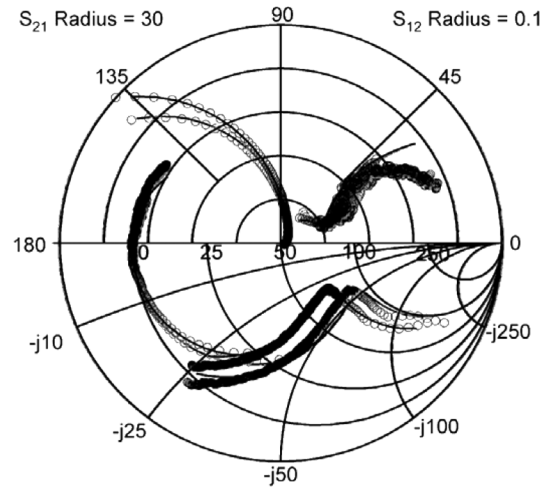


Fig. 7. Measured and modeled s -parameters at $T_a = 30^\circ\text{C}$. Bias points: $I_b = 0.421\text{ mA}$, $V_{ce} = 2.5\text{ V}$ and $I_b = 0.321\text{ mA}$, $V_{ce} = 3.5\text{ V}$.

self-heating and environment-ambient temperature effects. Excellent results were obtained under dc, small, and large signal operation in the range $10\text{--}110^\circ\text{C}$.

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