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A NEW TOOL FOR BIPOLAR TRANSISTOR CHARACTERIZATION BASED ON HICUM

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Abstract.

This paper presents a tool for the characterization of bipolar transistors through the extraction of the main parameters of the bipolar model HICUM, one of the most advanced physics-based model for strongly non-linear and high-frequency operating conditions. The extraction flow for a single transistor geometry considers specific bias regions of the device allowing simplifications of HICUM equations able to obtain the desired device parameters. Device data have been obtained from simulations using a specific parameter set, while the tool utilizes the default parameter set for internal issues. The procedure is fully automated and has been successfully tested on simulated data.

Keywords: bipolar transistor; characterization; HICUM model; parameter extraction

1. Introduction

Compact bipolar transistor models, such as MEXTRAM,[5] VBIC[9] and HICUM, have been developed to overcome some important deficiencies of older models, like SGPM and ST-SGPM, dealing with advanced bipolar or BiCMOS technologies. These new models are more physics-based, more complicated and require more parameters. On the other hand, they are more accurate and allow complex device behavior to be modeled. Each device is characterized by a unique set of parameters that have to be determined by means of proper parameter extraction procedures. HICUM compact bipolar model is suitable for very high frequency operating devices and for strongly non linear behaviours. The university nature of this model makes its state under continuous development. Many HICUM versions have been presented and, lastly, researchers have been focused on treatment of temperature dependence and geometrical scaling. In this paper a tool is presented for the characterization of bipolar transistors through the extraction of the main parameters of the bipolar model HICUM; in addition the efficiency and robustness of the implemented extracting procedures for the HICUM are discussed and important extraction issues have been identified and solved. The paper is structured as follows: in Section 2 main HICUm features are illustrated; in Section 3 the extraction procedure is described; in Section 4 the results obtained by using the developed procedure are discussed; authors' conclusions follw in section 5.

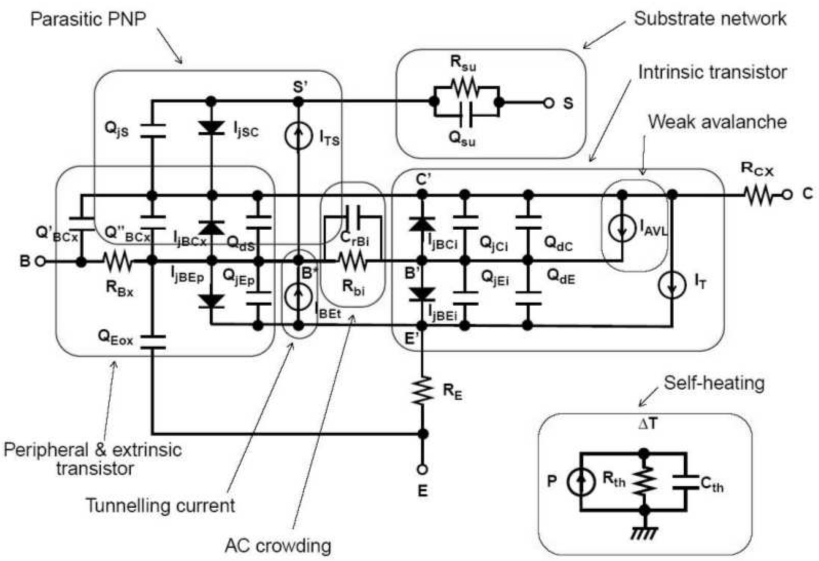

Fig. 1. HICUM small signal equivalent circuit for veritcal NPN transistors with its thermal network.

2. Main HICUM's Features

HICUM is a physics-based compact model dedicated to vertical BJTs and HBTs. Its small signal equivalent circuit is given in Fig. 1. It is composed of 5 internal nodes (B*, B', E', C', S') and 4 external nodes (B, E, C, S) to take into account the internal, emitter periphery and extrinsic transistor regions. One additional node T_j enables modeling of self-heating. This topology reflects the main relevant effects occurring in modern bipolar transistors such as:

- emitter periphery injection;
- distributed nature of the base-collector region;
- weak avalanche breakdown in the base-collector region;
- self-heating;
- the current flowing through the parasitic substrate transistor in saturated mode and the substrate coupling effect;
- the tunneling current in the base-emitter junction.

Including all physical effects, the model equations feature about 100 parameters. The extraction procedure presented in this paper allows the determination of the main parameters (59) for a single transistor geometry. One of the most important improvements in HICUM is the expression of the transfer current I_T, based on the generalized integral charge control relation (GICCR)[4,6]

(1) $$I_T = I_{TF} - I_{TR} = \frac{C_{10}}{Q_{PT}} \cdot \left[\exp(\frac{V_{B'E'}}{V_T}) - \exp(\frac{V_{B'C'}}{V_T})\right]$$

in which:

(2) $$Q_{PT} = Q_{P0} + h_{jEi} \cdot Q_{jEi} + h_{jCi} \cdot Q_{jCi} + Q_F + Q_R$$

and the expression of the forward transit time, given by

$$\tau_F = \tau_{F0} + \Delta\tau_F \quad (3)$$

in which:

$$\tau_{F0} = \tau 0 + \Delta\tau_{0h} \cdot (c-1) + \tau_{BVL} \cdot (c^{-1} - 1) \quad (4)$$

and

$$\Delta\tau_F = \tau_{EF0} \cdot (\frac{I_{TF}}{I_{CK}})^G_{TFE} + \tau_{HCS} \cdot w^2 \cdot \left(1 + \frac{2I_{Ck}}{I_{TF}\sqrt{(1-\frac{I_{CK}}{I_T F})^2 + A_{LHC}}}\right) \quad (5)$$

3. Extraction Strategy

The extraction flow can be splitted into several steps corresponding to specific bias regions of the device that allow simplifications of HICUM equations. The procedure follows step by step the entire flow and is fully automated. Device data have been obtained from simulations using a specific parameter set while the tool utilizes the default parameter set for internal issues. In HICUM, according to device physics, the AC and DC characteristics are strongly coupled. This coupling makes the parameter extraction more difficult in comparison with other bipolar transistor models and requires a careful selection of the extraction sequence.

3.1. *Step 1 (Capacitances)*

The first step is the extraction of the parameters related to the depletion capacitances. This is done by applying a linear regression on their logarithmic values.[1] Then the BE and BC junction capacitances are splitted between the internal and external transistor defining the parameters X_{jBC} and X_{jBE}. The former is obtained from high-frequency measurements (as described in Ref. 2), while the latter derives from geometrical considerations:

$$X_{jBE} = \left(1 + \frac{\pi}{2} \cdot r_j \cdot \frac{P_E}{A_E}\right)^{-1} \quad (1)$$

in which r_j takes into account the border effects, and PE and AE are the perimeter and area of the emitter window, respectively. This first step allows the extraction of 17 model parameters.

3.2. *Step 2 (Avalanche Current)*

Once the internal BC capacitance parameters are known, extraction of the avalanche parameters (F_{AVL} and Q_{AVL}) can be performed (see Ref. 3) using a simple linear regression on the equation:

$$\ln(\frac{M-1}{V_j}) = \ln(F_{AVL}) - \frac{Q_{AVL}}{C_{jCi0} \cdot V_{DCi}^{ZCi}} \cdot V_j^{Z_{Ci}-1} \quad (2)$$

where $V_j = V_{DCi} - V_{B'C'}$ and M is a multiplication factor.

3.3. *Step 3 (Saturation Current)*

This step deals with the extraction of the saturation current parameters (at low injection levels) $I_S = C_{10}/Q_{p0}$ from the collector current at $V_{BC} = 0$ and very low collector current densities. Using a linear regression on the following equation (derived from 1 and 1 under the above assumptions):

$$Q_{jEi} = -\frac{Q_{P0}}{h_{jEi}} + \frac{C_{10}}{h_{jEi} \cdot I_C} \cdot \exp(\frac{V_{B'E'}}{V_T}) \tag{3}$$

provides the auxiliary parameters $C'_{10} = C_{10}/h_{jEi}$ and Q'_{P0}/h_{jEi} as the slope and intercept, respectively. Their ratio gives the saturation current parameter which is independent from h_{jEi}.

3.4. *Step 4 (Base Currents)*

The extraction flow now deals with the determination of the base current parameters. In HICUM the BE current equation is given by:

$$I_{jBEi} = I_{BEiS} \cdot \left[\exp(\frac{V_{B'E'}}{M_{BEi} \cdot V_T}) - 1\right] + I_{REiS} \cdot \left[\exp(\frac{V_{B'E'}}{M_{REi} \cdot V_T}) - 1\right] \tag{4}$$

At medium values of V_{BE}, (8) can be rewritten as:

$$I_{jBEi} \approx 2 \cdot I_{BEiS} \cdot \left[\exp(\frac{V_{B'E'}}{M_{BEi} \cdot V_T}) - 1\right] \tag{5}$$

from which the parameters I_{BEiS} and M_{BEi} can be obtained through a logarithmic regression. Knowing this direct current we have to find the region in which:

$$I_{BEiS} \cdot \left[\exp(\frac{V_{B'E'}}{M_{BEi} \cdot V_T}) - 1\right] \approx I_{REiS} \cdot \left[\exp(\frac{V_{B'E'}}{M_{REi} \cdot V_T}) - 1\right] \tag{6}$$

so that

$$I_B \approx 2 \cdot I_{BEiS} \cdot \left[\exp(\frac{V_{B'E'}}{M_{BEi} \cdot V_T}) - 1\right] \tag{7}$$

From this condition we extract the "'knee voltage"' V'_{BE}. Now, for $V_{BE} < V'_{BE}$ we can apply a logarithmic regression to (8)3 extracting I_{REiS} and M_{REi}. The same procedure is then used for the extraction of the base-collector and collector-substrate current parameters without the recombination part (16 parameters extracted in this step).

3.5. *Step 5 (External Resistances)*

This step deals with the extraction of external resistance parameters.[7] The series resistance R_E is derived from the inverse of the transconductance $1/g_m$ vs $1/I_C$ characteristic, while the collector resistance R_{Cx} is obtained through curve fitting of the $I_C(V_{CE}, I_B)$ characteristics in hard saturation.

3.6. *Step 6 (AC/DC Coupling)*

The AC and DC couplingrequires extracting the correction factor h_{jEi}. The extraction is performed through an optimization of the β_f characteristic:

$$\beta_f^{-1} = \beta_{max}^{-1} \cdot (1 + I_C/I_{Keff}) \tag{8}$$

in which the effective knee current is given by $I_{Keff} = Q_{p0}/\tau_0$ when $V_{BC} = 0$. Hence the necessity to extract the parameter τ_0. An ad-hoc function has been created with the purpose of an easy and fast extraction of an approximated value of the parameter.[1] In a successive step a precise evaluation of this parameter will be performed through a more complex and accurate methodology.

3.7. *Step 7 (Base Resistance)*

The base resistance is determined using the modified input impedance circle method.[10] Plotting the imaginary part of the parameter h_{11} as a function of its real part for different frequencies an approximate circle arc is graphically obtained. This allows the extraction of the base resistance value. The characteristic relationships $R_B(V_{BE}, I_C)$ are obtained by repeating the above computation for a number of bias points. Starting from these values an optimization procedure leads to the extraction of the four base resistance parameters.

3.8. *Step 8 (Higher Frenquencies)*

The most complicated step of the procedure concerns the extraction of the transit time parameters. The 14 transit time parameters are evaluated by performing 3 successive optimization procedures. This strategy has been chosen in order to maximize parameters accuracy, even if it leads to a more complex analysis. The equation of the transit time, as described in Ref. 8, can be written in the low injection region:

$$\tau_{fx} = \frac{1}{\omega} \cdot \Im \left\{ \frac{(y_{11} + y_{12} - r_{cx} \cdot Y)}{y_{21} - y_{12}} \right\} \tag{9}$$

Performing the optimization of $\tau_{fx}(V_{BE})$ for a fixed value of V_{BC} we extract a first evaluation of τ_0, τ_{BVL} and $\Delta\tau_{0h}$. The second optimization regards the high-injection region employing the following equation:

$$\Delta\tau = \tau_{fx} - \tau_0 - f_\tau \left(y, C_{jEi}, C_{jEp}\right) / g_m(I_C) \tag{10}$$

This optimization leads to the extraction of a first evaluation of the parameters A_{LjEi}, R_{Cio}, V_{CES}, V_{PT}, V_{LIM}, T_{EF0}, G_{TFE}, T_{HCS}, A_{LHC}, L_{ATB} and L_{ATL}. Finally the third and last optimization considering the whole τ_{fx} characteristic and using as starting values of all the 14 parameters the results of the previous 2 optimizations has the purpose of computing more accurate estimates of all the 14 parameters.

3.9. *Step 9 (NQS Effects)*

The last step concerns the extraction of the parameters related to non-quasi-static effects (A_{LQF} and A_{LIT}). The analysis is carried out at high frequencies on the base of the phase of the h_{21_e} parameter.

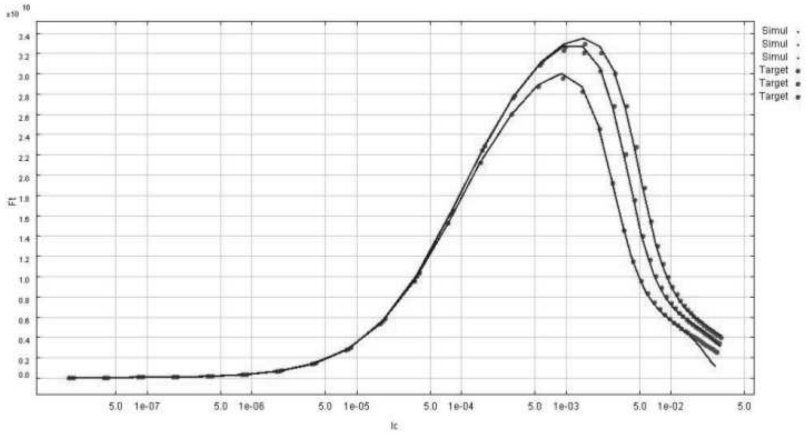

Fig. 1. Transition frequency as a function of collector current.Dots represent target data while lines are simulated data (using extracted parameters and for null base-collector potential).

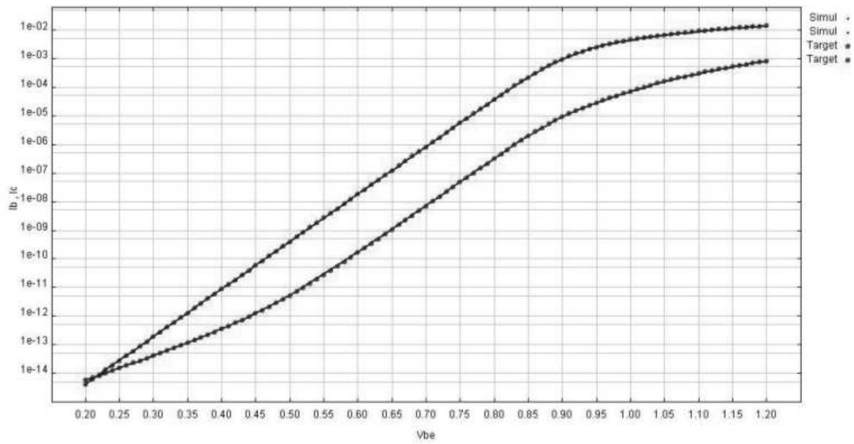

Fig. 2. Collector and base currents as a function of the base-emitter voltage. Dots represent target data while lines are simulated data (using extracted parameters and for null base-collector potential).

4. Results and conclusions

The extraction procedure has been successfully tested using simulated data. For this purpose a certain number of full data sets has been generated on the base of parameter sets suitably chosen to represent typical devices. In all the examined cases the procedure succeeded in the parameters extraction. Two examples of the extracted parameters are shown in fig. 1 and in fig. 2. The first shows the accuracy of transition time parameters extraction, the latter shows a perfect match between the simulations taken out from extracted parameters and target data. It is worth noticing that the good accuracy of the extracted parameters has also been observed using experimental data given by measurements by real devices.

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