Efficient Parameter Extraction for the MEXTRAM Model

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Abstract

A very fast, robust and accurate parameter extraction method for bipolar compact models has been developed. Using a combination of simplified expressions and selected measurements the iterative solution of the full model equations (e.g. using a circuit simulator) is avoided. The method is applied to the bipolar compact model MEXTRAM.

1 Introduction

Reliable simulation of bipolar circuits requires that a large number of physical phenomena has to be described accurately by the bipolar compact model used. This leads inevitably to the increase of the complexity of the compact model: e.g. the Gummel-Poon model uses three internal nodes, while the more accurate and sophisticated MEXTRAM model has five internal nodes [1, 2]. The presence of internal nodes implies that the full model equations can only be solved by iteration. The cpu time needed for this solution increases at least linearly with the number of internal nodes. During automated parameter extraction the model equations may have to be evaluated for unrealistic parameter values, which slows down the speed of the iterative solution even further. Moreover, if the compact model is not implemented directly in the extraction program, but only in a circuit simulator interfaced to the extraction program, versatile parameter extraction may become unfeasible.

Bipolar parameter extraction methodology and related issues are reported in [3,4]. In this paper we present a new method for parameter extraction, in which the iterative solution of the full model equations is avoided. The total set of parameters, that has to be determined, is divided into subsets, each containing only a small number of parameters. The guideline for this division is that the parameters in a subset all have to relate to a very specific part of the transistor characteristics, which can be translated in a corresponding set of bias conditions. If for the extraction of the parameters in this subset only data measured at these bias conditions are used, the solution of the model equations can be approximated by a reduced set of expressions. As the iterative solution of the full model equation is no longer necessary, the speed of the parameter extraction is improved more than an order of magnitude. An additional advantage is that this procedure leads to a robust and unambiguous parameter extraction strategy.

In principle this method can be applied to any compact model. However, the degree of success and accuracy depends on the physical basis of the compact model used. In the following we will discuss how this method has been applied successfully to all relevant parameters of the MEXTRAM model.

2 Phenomena, parameters and characteristics

The following physical phenomena are modelled in the bipolar compact model MEXTRAM [1, 2]:

1. charge storage effects
2. high-injection effects
3. built-in electric field in base region
4. bias-dependent Early effect
5. low-level non-ideal base currents
6. hard and quasi-saturation
7. hot-carrier effects in collector epilayer
8. weak avalanche
9. explicit modelling of inactive regions
10. substrate effects and parasitic pnp
11. split base-collector depletion capacitance
12. base resistance: current crowding and conductivity modulation
13. intrinsic base: hf current crowding and excess phase-shift
14. temperature effects

In order to account accurately for all these effects five internal nodes have proven to be necessary. The MEXTRAM model has 62 parameters. Of these parameters 10 refer to model flags, noise and the reference temperature, 13 refer to temperature scaling. From the remaining 39 parameters, 4 parameters are given by the transistor design. Consequently 35 parameters have to be determined by fitting the model to the transistor characteristics of a specific device (at a specific temperature). In table 1 the division of the MEXTRAM parameters into subsets is shown. For each subset it is indicated also from which transistor characteristic the parameters can be obtained. For each of these characteristics we are able to derive approximate analytical expressions, which replace the iterative solution of the full set of MEXTRAM equations.

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	characteristic	parameters	phen.
#1	b-e capacitance	Cj_e, Vd_e, P_e	1
#2	b-c capacitance	Cj_c, P_c, X_p	1
#3	c-sub capacitance	Cj_s, Vd_s, P_s	1
#4	reverse Early effect	Qb_o	4
#5	forward Early effect	XCj_c	4, 11
#6	forward Gummel at low Vbe	I_s	
#7	reverse Gummel at low Vbc	I_{ss}	10
#8	avalanche at small I_c, high Vcb	AVL	8
#9	β_F up to medium currents	B_f, Ib_f, Vl_f	5
#10	β_R up to medium currents	B_{ri}, Ib_r, Vl_r, (Ik_s)	5
#11	open collector, slope of I_e at high $Vbe > 1.5V$	R_e	
#12	forward Gummel at high Vbe	Rb_c, (Rb_v)	12
#13	reverse Gummel at high Vbc	Ik_s, R_{cc}, $XEXT$	2, 9, 10, 11
#14	quasi-sat., $I_c < I_{hc}$, low V_{ce}	R_{cv}, (Vd_c)	2, 6
	quasi-sat., $I_c > I_{hc}$, high V_{ce}	SCR_{cv}, I_{hc}, (SF_h, I_k)	6, 7
#15	f_T curve up to the top	$Taun_e$, M_{tau}, (M_c)	1

Table 1: Division of MEXTRAM parameters into subsets. The number in the last column refers to the physical phenomenon described (see section 2).

The fittings of these analytical expressions to their corresponding characteristics have to be performed in such an order that other parameters appearing in these expressions are either already known or negligible. This is most difficult for the charactersistics influenced by a combination of several physical phenomena (see last column of table 1).

For the parameter extraction program IC-CAP from Hewlett-Packard, a total of 15 transforms are written. Using the built-in optimizer from IC-CAP all MEXTRAM parameters can be extracted directly. Consequently for the parameter extraction the evaluation of the full MEXTRAM model implemented in one of the built-in circuit simulators of IC-CAP or implemented in an external circuit simulator interfaced with IC-CAP is not necessary anymore!

As an example two of these subsets of parameters, the analytical approximations involved and their application will be discussed in some detail (#9 and #14). To demonstrate the general applicability of the method, for the first subset also the analogon for the more familiar Gummel-Poon model is discussed.

3 Forward current gain (#9)

3.1 The Gummel-Poon model

The forward current gain, β_F, is defined as

$$\beta_F = \frac{I_c}{I_b} \;, \tag{1}$$

where the collector current, I_c, without high injection, is given in the Gummel-Poon model by

$$I_c = I_s \left(\exp\left(\frac{Vbe_i}{n_F V_t}\right) - 1\right)\left(1 - \frac{Vbe_i}{VAR} - \frac{Vbc_i}{VAF}\right) \;, \tag{2}$$

and the base current, I_b, is given by

$$I_b = \frac{I_s}{B_f}\left(\exp\left(\frac{Vbe_i}{n_F V_t}\right) - 1\right) + I_{se}\left(\exp\left(\frac{Vbe_i}{n_E V_t}\right) - 1\right) . \tag{3}$$

The parameters I_s, n_F, VAR and VAF in these expressions have already been determined from other characteristics following a similar sequence as given in table 1. In the correction of the collector current for the Early effect the internal base-emitter voltage, Vbe_i, and base-collector voltage, Vbc_i, can be replaced by their external values, Vbe and Vbc, respectively,

$$I_c \approx I_s \left(\exp\left(\frac{Vbe_i}{n_F V_t}\right) - 1\right)\left(1 - \frac{Vbe}{VAR} - \frac{Vbc}{VAF}\right) . \tag{4}$$

Now Vbe_i can be calculated from measured values of I_c. This step, which can be executed as pre-processing, eliminates the effects of the base and emitter resistances. Once the Vbe_i values are known, the forward current gain β_F can be calculated from eqs. 1 and 3 and the measured values of I_c. Fitting the values for β_F obtained to the measurements, the parameters B_f, I_{se} and n_E can be determined. From the dashed line in fig. 1 it can be seen that this expression gives a good description of the experimental data up to the region where the current gain decreases due to high-injection or quasi-saturation. Of course only data below this region should be used in the fit.

3.2 The MEXTRAM model

The expression for the collector current, I_c, without high injection in the MEXTRAM model reads

$$I_c = \frac{I_s\left(\exp\left(\frac{Vbe_i}{V_t}\right) - 1\right)}{1 + \frac{Q_{TE}(Vbe_i) + Q_{TC}(Vbc_i)}{Qb_o}} \;, \tag{5}$$

where the depletion charges $Q_{TE}(Vbe_i)$ and $Q_{TC}(Vbc_i)$ account for the reverse and forward Early effect. The base current, I_b, is given by

$$I_b = \frac{I_s}{B_f}\left(\exp\left(\frac{Vbe_i}{V_t}\right) - 1\right) + \frac{Ib_f\left(\exp\left(\frac{Vbe_i}{V_t}\right) - 1\right)}{\exp\left(\frac{Vbe_i}{2\,V_t}\right) + \exp\left(\frac{Vl_f}{2\,V_t}\right)} \tag{6}$$

The parameters I_s and Qb_o as well as the voltage dependency of Q_{TE} and Q_{TC} in these expressions have already been determined from other characteristics (see table 1). Again in the correction of the collector current for the Early effect Vbe_i and Vbc_i can be replaced by their external values, Vbe and Vbc, respectively,

$$I_c \approx \frac{I_s\left(\exp\left(\frac{Vbe_i}{V_t}\right)-1\right)}{1+\frac{Q_{TE}(Vbe)+Q_{TC}(Vbc)}{Qb_o}} \quad . \qquad (7)$$

Now Vbe_i can be calculated from measured values of I_c as a pre-processing step. Once the Vbe_i values are known, the forward current gain β_F can be calculated from eqs. 1 and 6 and the measured values of I_c. Fitting the values for β_F obtained to the measurements, the parameters B_f, Ib_f and Vl_f can be determined. From the solid line in fig. 1 it can be seen that this expression gives a good description of the experimental data up to the region where the current gain decreases due to high-injection or quasi-saturation $V_{be} \approx 0.9\ V$. Of course only data below this region should be used in the fit.

4 Output characteristic (#14)

The topology of the relevant parts in the equivalent circuit of MEXTRAM is given in fig. 2. At node c_2 we have to fulfil the Kirchhoff law, which yields in good approximation

$$I_n = I_{epi} \quad . \qquad (8)$$

Now I_n [1] is a function of Vbe_i and Vbc_i

$$I_n \equiv I_n\,(Vbe_i,\, Vbc_i) \quad , \qquad (9)$$

containing the unknown parameter I_k, that is to be determined. The current through the epi-layer I_{epi} [2] is a function of Vbc_i and Vbc_x

$$I_{epi} \equiv I_{epi}\,(Vbc_i,\, Vbc_x) \quad , \qquad (10)$$

containing the unknown parameters R_{cv}, SCR_{cv}, I_{hc} and Vd_c, that are to be determined. If now the following conditions are satisfied:

1. $I_{ex} \ll I_b$ or "no hard saturation" and
2. $I_{avl} \ll I_b$ or "no avalanche",

for both Vbe_i and Vbc_x quite good approximative expressions are obtained. From measured values of I_b we can calculate Vbe_i

$$Vbe_i = V_t \ln\left(\frac{B_f\, I_b}{I_s}\right) \quad . \qquad (11)$$

From measured values of I_c and I_b we can calculate Vbc_x

$$Vbc_x = Vbc + I_c\, R_{cc} - I_b\left(Rb_c + Rb_v\,\frac{I_c}{B_f\, I_b}\right) \quad . \qquad (12)$$

From eqs. 11 and 12 the values of Vbe_i and Vbc_x can be calculated in pre-processing. Substitution of these values in the expressions for I_n and I_{epi} (see eqs. 9 and 10), followed by equating them according to eq. 8, yields a non-linear equation for Vbc_i. This equation has to be solved by iteration. Once Vbc_i is known, the value of $I_n = I_{epi}$ can be calculated. Fitting this value to the measured I_c, the parameters I_k, R_{cv}, SCR_{cv}, I_{hc} and Vd_c can be determined. From fig. 3 it can be seen that this procedure gives a good description of the experimental data for $0.5\ V < V_{ce} < 7.0\ V$. Outside this region the necessary conditions mentioned above are not satisfied. For $V_{ce} < 0.5\ V$ one has $I_{ex} \neq 0$ and for $V_{ce} > 7.0\ V$ one has $I_{avl} \neq 0$. Of course only data between these boundaries should be used in the fit.

5 Accuracy of final parameter set

By executing the 15 transforms indicated in table 1, a complete MEXTRAM parameter set is obtained in a straightforward manner. Despite the fact that in the transforms #13, #14 and #15 an iterative procedure is used, this new extraction method is very fast compared to the conventional method. With the conventional method the equivalent electrical circuit (fig. 2) has to be solved for each model evaluation. The values of the parameters obtained with this new method are in good agreement with the conventional method. This is demonstrated by the fact that solving the full model equations using the parameters extracted with our new method, yields an excellent description of the measured cut-off frequency (see fig. 4).

6 Conclusion

We propose a very fast and accurate parameter extraction method for bipolar compact models. The procedure leads to a robust and unambiguous parameter extraction strategy. This method avoids iterative solution of the full model equations and the use of a circuit simulator. Applied to the MEXTRAM model, the new method yields a parameter set which describes all bipolar characteristics with excellent accuracy.

References

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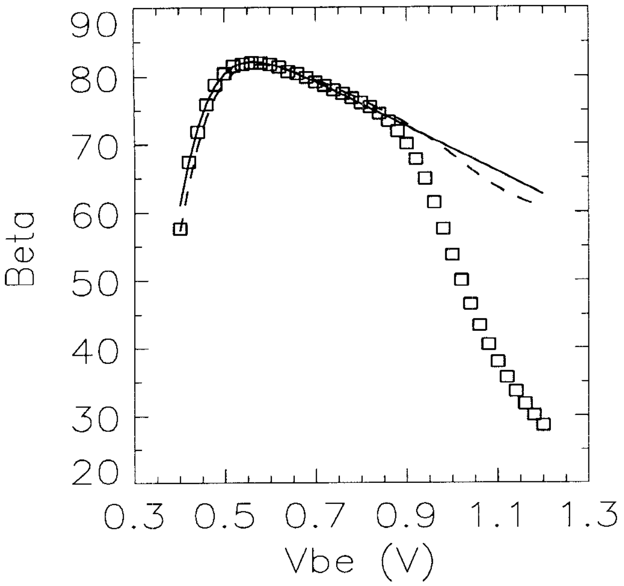

Figure 1: Forward current gain as a function of base-emitter voltage. Symbols represent the measurements; the dashed line represents the approximation for the Gummel-Poon model and the solid line represents the approximation for the MEXTRAM model (transform #9) valid for $V_{be} < 0.9\ V$.

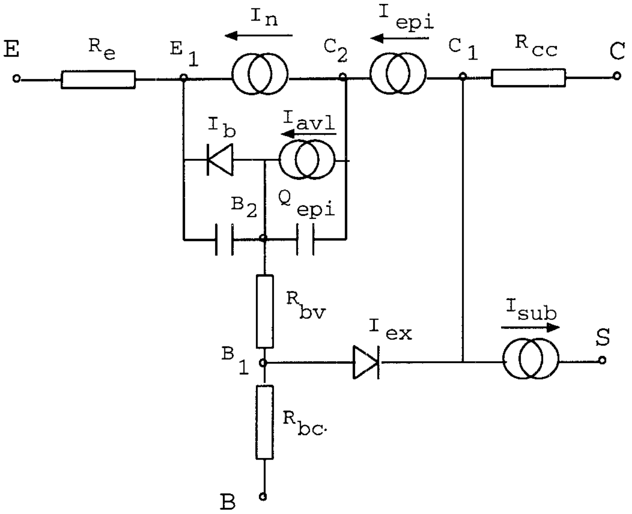

Figure 2: Simplified topology of the MEXTRAM equivalent circuit for the determination of the epilayer related parameters and high injection of the base. In the text Vbe_i is the voltage between nodes B_2 and E_1, Vbc_i the voltage between nodes B_2 and C_2 and Vbc_x the voltage between nodes B_2 and C_1 respectively.

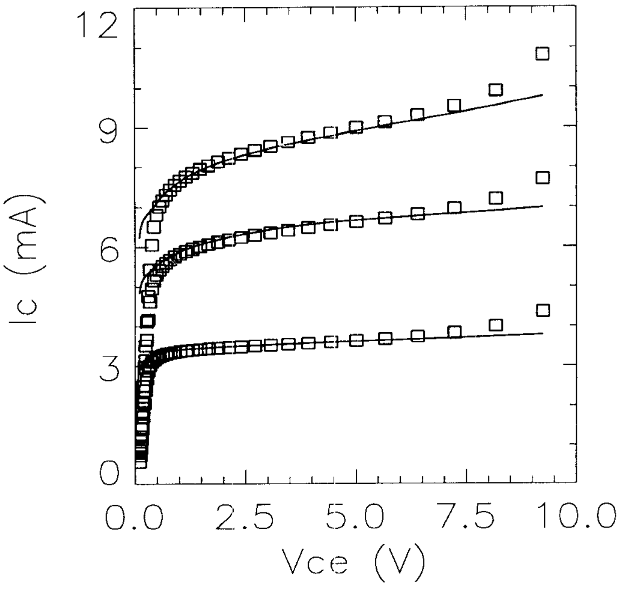

Figure 3: Output characteristics at base currents of 0.05, 0.10 and 0.15 mA, respectively. Symbols represent the measurements; the solid lines represent the approximation for the MEXTRAM model (transform #14) valid for $0.5\ V < V_{ce} < 7.0\ V$.

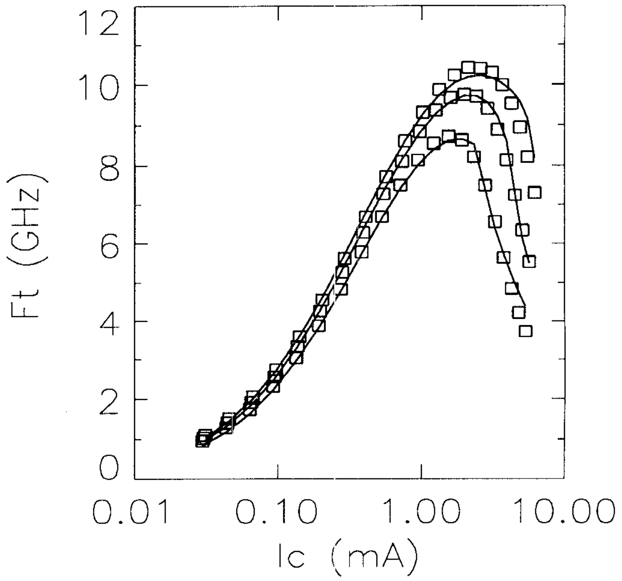

Figure 4: Cut-off frequency at Vbc of 0, −1 and −3 Volts, respectively. Symbols represent the measurements; the solid lines represent the full MEXTRAM model calculations using the parameters extracted with our new method.