NEW LARGE SIGNAL ELECTROTHERMAL HBT MODEL WITH ORIGINAL PARAMETERS EXTRACTION PROCEDURE

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ABSTRACT

A new large signal electrothermal Heterojunction Bipolar Transistor (HBT) model with original parameters extraction procedure is reported. The model, which is implemented in Hewlett-Packard MDS software, is based on a physical description and includes the high order effects of HBT operation. The extraction process requires only conventional DC and microwave measurements and does not need any numerical optimisations. In order to demonstrate the accuracy of the model, simulations performed without convergence problems are compared to measurements data for a 2x30μm^2 GaInP/GaAS HBT.

INTRODUCTION

Recent advancement in HBT fabrication technology promises to HBT excellent future in particularly in monolhitic microwave high power amplifiers. The industrial development of these applications needs an accurate and reliable model with efficient parameters extraction procedure. Although there are not fundamental differences in HBT basic operating principles compared to the Bipolar Junction Transistor (BJT), conventional BJT model is not suitable to HBT principally because HBT and BJT thermal effects are very different and the device self heating is not taking into account. We propose in this paper a new large signal electro-thermal HBT model with original parameter extraction procedure. This physically based model includes all the principal high order effects of the HBT operation such as self heating, Kirk effect, avalanche breakdown, transconductance delay.

Simulations which are performed at all bias conditions and for small and large signal operation agree well with the corresponding measurements. This good agreement demonstrates that the proposed model is able to predict linear and non linear dynamic behaviour of the HBT with reasonable CPU time and it is important to point out that all the calculated responses of the HBT are obtained without convergence problems.

MODEL

As shown in fig. 1, we have used Gummel-Poon model topology which results from a good trade-off between simplicity and accuracy. On the other hand we have excluded the use of complex topologies due to parameters extractability convenience. Very non linear HBT operations need to take into account the high order physical effects such as Kirk effect and avalanche breakdown which can not be neglected in high current regimes and for high voltage levels respectively. These two effects are included in current generators I_{CN} and I_A respectively (Fig. 1). Because of very high base doping levels, Early and Webster effects are ignored, and the base series resistance is assumed bias independent. Typical HBT base current characteristic is collector current independent thereby Gummel-Poon model current gain parameters BF and BR are replaced by independent Boltzmann relations.

Accurate self heating modelling needs bidimentionnal or tridimentionnal calculation which is unrealistic for CAD circuit models. Nevertheless it is possible to analytically calculate the junction temperature assuming that thermal flow is homogeneous under emitter fingers which are assumed the unique thermal source. In this condition the temperature can be determined using thermal impedance and dissipated power. Due to the dependence of semiconductor thermal conductivity with temperature, the equivalent thermal resistance is temperature dependant and it is described in our model using an analytical expression which is derived from the theory proposed by Cooke (1). Equivalent thermal capacitance C_{TH} is not an important parameter, for microwave circuit simulation its value is choosed to get a thermal constant time a few order of magnitude than electric constant time.

Each saturation current of the model is directly related to junction temperature. Base current may have many physic origins and may be located in both semiconductor material (ref. (2)), thereby the thermal parameters of each current generator may be different, and each current generator is governed by independent laws in our model.

The transit time and charge storage mechanisms are modelled by capacitors. Base emitter diffusion capacitance account for base collector space charge transit time which is modulated by both base collector intrinsic voltage and collector current. In the expression which describes the base collector intrinsic junction capacitance, effect of mobile carriers in the space charge region is taken into account by a phenomenological law. To model high frequency behaviour, a delay time τ was introduced in collector current I_{CN}.

Equation of non linear elements of the model are given below. In theese equations junction potentials Vbi are intrinsic potentials exept for base collector extrinsic junction capacitance.

Current generators:

$$I_{CN} = \frac{I_{SCN}}{F_K}\left(EXP\left(\frac{V_{BE}(t-\tau)}{N_{CN}.V_T}\right)-1\right) \qquad \text{with} \qquad F_K = 1 \qquad \text{if} \qquad I_{CN} \leq I_2 = I_K + \alpha_{I2}\left(\Phi_{BC} - V_{BC}\right)$$

and

$$F_K = 1 + \alpha_{K1}\left(1 - \sqrt{\frac{I_2 - I_K}{I_{CN} - I_K}}\right) \qquad \text{else;}$$

and

$$\tau = \tau_0 . COTH\left(\alpha_\tau . V_{CB}\right) \tag{1}$$

$$I_{CR} = I_{SCR}\left(EXP\left(\frac{V_{BC}}{N_{CR}.V_T}\right)-1\right) \tag{2}$$

$$I_{BEi} = I_{SBEi}\left(EXP\left(\frac{V_{BE}}{N_{BEi}.V_T}\right)-1\right) \tag{3}$$

$$IA = (M-1)ICN \quad \text{with} \quad M = \left(1 - \left(\frac{V_{BC}}{B_{VCB0}}\right)^m\right)^{-1} \tag{4}$$

Thermal dependence:

$$I_{Si} = I_{Si0}\left(EXP\left(\frac{E_{Gi}}{K.T}\left(\frac{T}{T_0}-1\right)\right)\right)\left(\frac{T}{T_0}\right)^{Xi} \tag{5}$$

$$E_{Gi} = E_{Gi0} - \alpha_i \frac{T^2}{T - \beta_i} \tag{6}$$

$$R_{TH} = \alpha_R . R_{TH0} \frac{\left(T - T_H\right)\left(T_H - 273\right)^{-0.26}}{\left(T - 273\right)^{0.74} - \left(T_H - 273\right)^{0.74}} \tag{7}$$

where T_H is the heatsink temperature.

Non linear reactive elements:

$$C_{BE} = C_{JBE0}\left(1 - \frac{V_{BE}}{V_{JBE}}\right)^{m_{jbc}} + \left(\tau_B + \tau_{BC}\sqrt{1 - \frac{V_{BC}}{\Phi_{BC}}}\right)\frac{I_{CN}}{N_{CN} V_T} \tag{8}$$

$$C_{BCi} = C_{JBCio}\left(1-\frac{V_{BC}}{V_{JBCi}}\right)^{m_{jbci}} + \alpha_{cjbci}.EXP\left(-\beta_{cjbci}.I_{CN}\right) + \tau_{Ri}\frac{I_{CR}}{N_{CR}V_T} \qquad (9)$$

$$C_{BCe} = C_{JBCeo}\left(1-\frac{V_{BCe}}{V_{JBCe}}\right)^{m_{jbce}} + \tau_{Re}\frac{I_{CR}}{N_{CR}V_T} \qquad (10)$$

PARAMETER EXTRACTION AND RESULTS

The parameters extraction procedure is illustrated by the example of a 2x30um2 HBT. This extraction procedure include five steps:

1) The linear parasitic elements L_E, L_B, L_C, R_E, R_B, R_C are first extracted from S parameters using direct extraction of HBT linear equivalent circuit proposed in ref. (3). Inductance values are fixed for the whole procedure and resistor values are used as starting conditions in the next steps.

2) Thermal resistance R_{TH0} is calculated from technological data from ref. (1), or extracted from static electrical measurements proposed in ref. (4).

3) Static bias-dependent parameters are extracted from different section on the normal and reverse Gummel plots. Leakage currents which dominate the low current range are modelled by parasitic resistors not reported in Fig.1, but included in the model during static parameters extraction procedure for more extraction accuracy.

In section 2 (Fig. 2), junction temperature increase is less than 1 degree and voltage drop across parasitic resistors is negligible. Room temperature saturation currents and non ideality factors are extracted in this section by classical BJT methods (5). Collector current parameters which can be precisely determined are now fixed but base current parameters may be slightly tune in step 4.

In section 3 (Fig. 2) self heating leads to important increase of saturation currents, and thermal parameters influence is important in this region. This section may be separated in two parts: - the first part, where the influence of parasitic resistors RE and RB is weak, is used to determine thermal parameters. - the second part, which corresponds to the high current range where both thermal parameters and parasitic resistors influence is important, is used to adjust parasitic resistors around their initial values. Initial values of thermal parameters are computed from physical material properties.

Then a similar determination of reverse current parameters is then carry out from reverse gummel plot.

4) At this step all the static parameters are known, and model accuracy is examined by comparing measured and simulated values on both current gain and output characteristics (Fig. 3 and Fig. 4). All the static parameters are then slightly tuned around the precedent values to get a good fit between modelled and experimental values.
The use of separate bias ranges with a few dominant parameters allow manual fitting and avoid global numerical optimisation.

5) Finally direct extraction of HBT linear equivalent circuit under several sets of bias conditions gives bias dependence capacitances. All capacitance expression parameters are then extracted from these dependencies.

Fig.2 to Fig.6 show a comparison between measured and simulated data for dc, broad band small-signal S parameters and large signal power sweep measurements. Model parameters obtained by the full parameter extraction process are fixed for the whole simulations and are given in table (1).

CONCLUSION

A new large-signal model which includes self-heating and all the important high order effects of the HBT operation has been developed and tested. This model is implemented in the Hewlett Packard CAD software and ensures good convergence. An accurate extraction procedure for the model parameters allows good agreement between measured and simulated data over a wide range of operating biases and frequencies.

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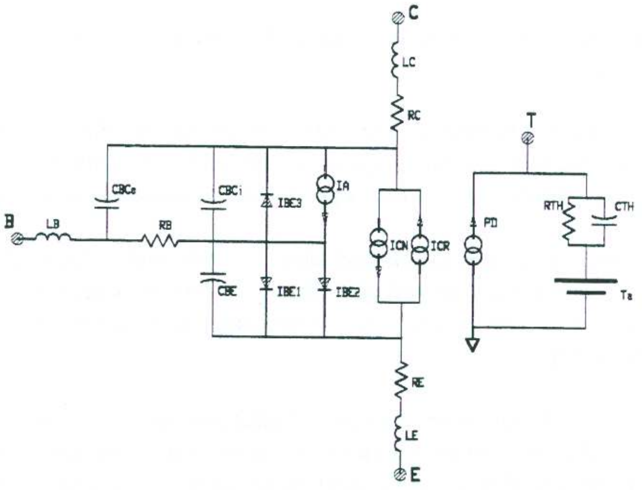

Figure 1 Non-linear electrothermal model's HBT

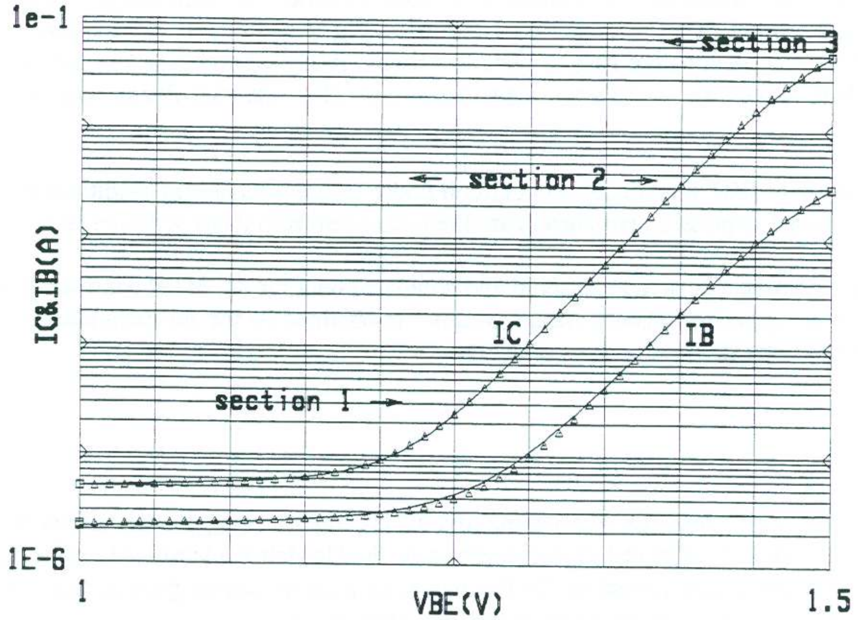

Fig.2 Comparison of the measured (solid lines) and simulated (triangles) Gummel plots.

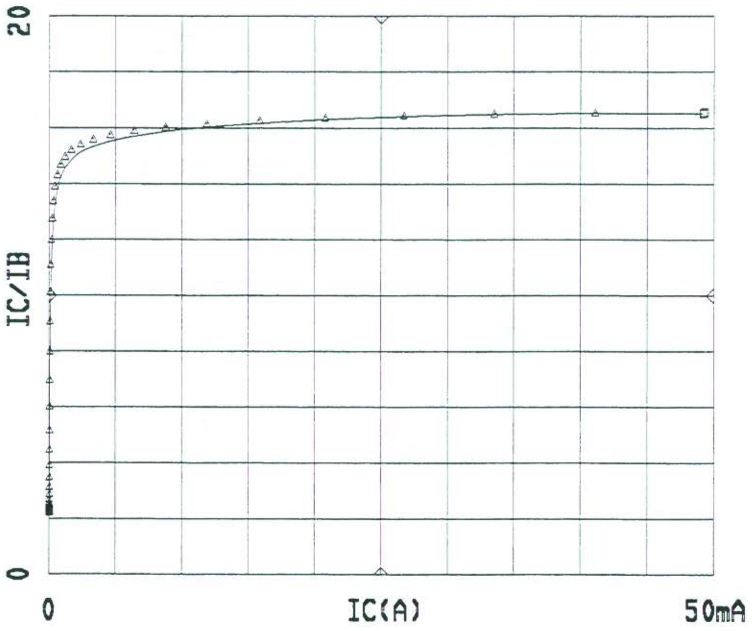

Fig.3 Comparison of the measured (solid lines) and simulated (triangles) current gain at VBC=0V.

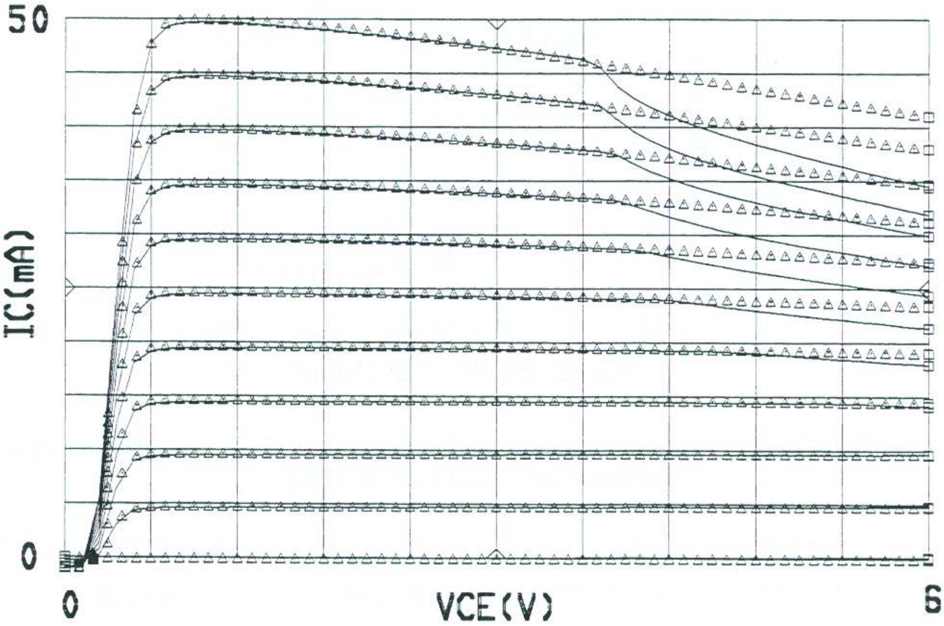

Fig.4 Comparison of the measured (solid lines) and simulated (triangles) output characteristics.

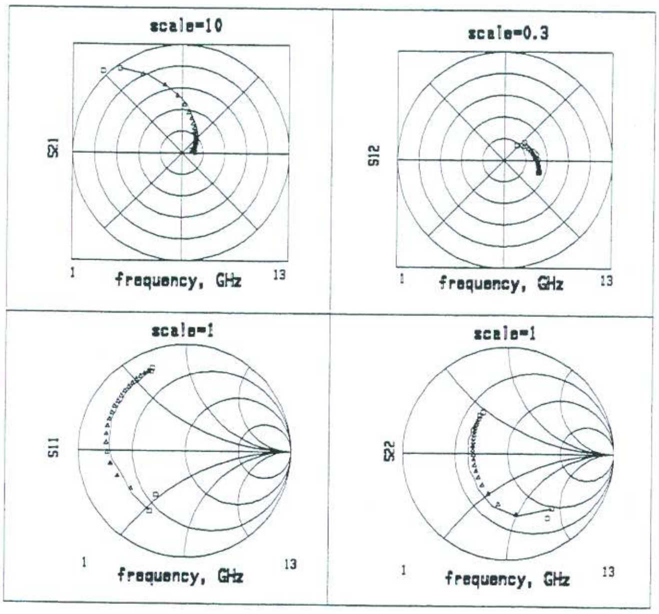

Fig.5 Comparison of the measured (solid lines) and simulated (triangles) S parameters. VCE=2V, IB=1mA.

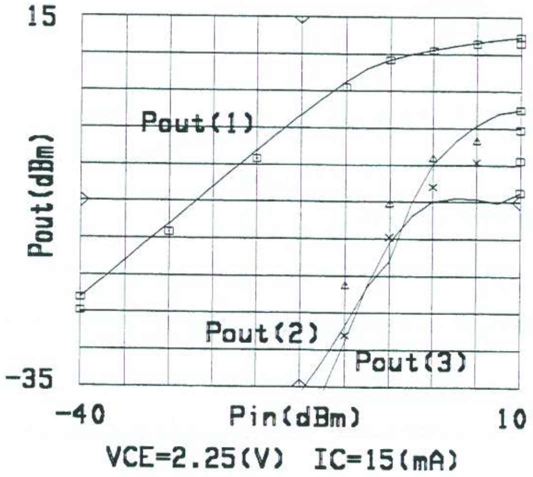

Fig.6 Fundamental and harmonics power measurement (labels) performed on spectrum analyser compared to simulated data (solid lines) at 2GHz.

N_{CN}=1.11	N_{CR}=1.055	N_{BE1}=1.13	N_{BE3}=1.85	I_{SCN}=2.2E-24	I_{SCR}=1.5E-24
I_{SBE1}=3.52E-25	I_{SBE2}=0	I_{SBE3}=3.05E-14	E_{GCN}=1.45	E_{GCR}=1.45	E_{GBE1}=1.55
E_{GBE3}=1.45	X_{CN}=1.5	X_{CR}=1.5	X_{BE1}=3	X_{BE3}=1.5	R_{TH0}=500
α_R=0.74	Φ_{BC}=1.15	I_K=1E5	R_B=13	R_C=2.5	R_E=0.1
L_B=390E-12	L_C=380E-12	L_E=1E-12	C_{JBE0}=143E-15	C_{JBCi0}=20.E-15	C_{JBCe0}=191E-15
mjbe=0.5	mjbci=0.5	mjbce=0.5	V_{JBE}=1.15	V_{JBCi}=1.15	V_{JBCe}=1.15
α_{CJBCi}=159E-15	β_{CJBCi}=200	τ_B=2.4E-12	τ_{BC}=1E-12	τ_{Ri}=50E-12	τ_{Re}=50E-12
τ_0=4.8E-12	α_τ=0.8				

Table 1: non linear model parameters.