A User Compiled Large Signal Model for GaAs Heterojunction Bipolar Transistors

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Abstract — **This paper presents a nonlinear circuit simulation model for III-V Heterojunction Bipolar Transistors (HBTs), implemented using C code in the Agilent ADS circuit simulator as a User Compiled Model (UCM). The UCM is based-on a recently developed compact large-signal model, which includes all physical effects taking place in power III-V based HBT devices. The validity and the accuracy of the UCM are assessed by comparing its simulation results to both measurements and Symbolically Define Device (SDD) simulations in DC, multi-bias small-signal S-parameters and large-signal microwave power characteristics for a 2x20 μm^2 emitter area InGaP/GaAs transistor.**

I. INTRODUCTION

Heterojunction Bipolar Transistors (HBTs) based-on III-V materials in particular GaAs have played a major role in power amplification for microwave and millimeter-wave applications such as handset phones and wireless local area networks, during these last years. For designers of these circuits, it is imperative to use a reliable large-signal model, developed from the measurements under various bias conditions of the device, for accurate predictions of the circuit performances such as gain and distortion. Also, accurate nonlinear models reduce the number of iterations in the product development cycle and give a wider insight of the working of the device and of its fabrication process. A correct prediction of gain and of transition frequency requires an accurate DC model including self-heating effect, Early and Kirk effects and the variation of the model parameters with temperature as well as a good modeling of the variation of the base emitter capacitance with bias. A true perdition of distortion is related to the quality of the modeling of the inner and the outer base collector capacitances with bias. The Spice Gummel-Poon (SPG) model [1] has served the industry as a modeling standard of silicon bipolar junction transistors (BJT), since the early 1970. However, it is not sufficiently accurate for a low-risk design involving modern BJTs. The vertical bipolar inter-company (VBIC) [2] model has been developed for modern bipolar junction transistors and to be as compatible as possible to the SGP model but improved over it in various aspects. Hence, the VIBC model satisfies to some extent the first requirement of an accurate device model but stills lack the description of the bias dependent elements with both current and voltage biasing. In most existing circuit simulators, these are the only available two models for BJT and HBT devices. This is why most system designers try to predict the large signal behavior of GaAs-based HBT's using these two models although Si-based semiconductors differ in various aspects than the III-V compound semiconductors and this difference is reflected at the device level. In GaAs-based HBTs, there is no parasitic substrate transistor and the maximum operating current density is limited by the device thermal properties to region where the quasi-saturation effect is not significant and the thermal runaway effect does not occur. To take advantage of the VBIC model's ability to capture the self-heating effect in GaAs-based HBTs, circuit designers usually simplify it until it becomes similar to the SGP model. This explains in part why the SGP model is still in active use for GaAs-based HBT modeling. This lack of accurate HBT models in circuit simulators despite the relatively important body of literature suggesting quite accurate such models may be attributed to the implementation complexity of such models which in turn is due to the many complicated physics based formulas and to the large amount of the required work much of it is tedious and error-prone. Nevertheless, due to HBT applications, a development of a specific nonlinear model capable of reproducing the behavior of III-V devices is of a great practical importance. A few months ago, Agilent has advertised a development of a dedicated model for HBT devices [3] based-on III-V materials to be included in the ADS 2003C. However, this model version does not include the self-heating effect, which is crucial for HBTs. Recently a new compact large-signal model, developed specifically to describe GaAs based HBT devices, was described in [4]-[6]. The DC performances of the model have been compared to the VBIC model in [4], and it has been shown that they exceed those of the VBIC model. Expressions capable of describing the small-signal behavior of the device with bias of the AC HBT electrical equivalent circuit elements were developed in [5]. The eight-port symbolically define device large signal performances of the constructed model based-on equations developed in [4] and [5] were shown in [6].

The purpose of this paper is to present the performances of the nonlinear HBT simulation model implemented as user-compiled model (UCM) in Agilent ADS simulator. The UCM is based-on the recently developed compact large-signal model, which accounts for all physical phenomena taking place in modern III-V HBT devices including charge accumulation implemented as transcapacitances. The validity and the accuracy of the UCM are assessed by comparing its simulation results to both measurements and Symbolically Define Device (SDD) simulations in DC, multi-bias small-signal S-parameters and large-signal microwave power characteristics for a 2x20 μm^2 emitter area InGaP/GaAs transistor.

II. THE MODEL

Fig. 1 presents the electrical equivalent circuit of the large signal model on which the user-compiled model is based as well as the physical representation of each circuit element. The schematic of the developed user-compiled model is shown in Fig. 2. It consists of only 45 parameters, whereas VBIC model has 95 parameters and it is capable of describing fully the large signal behavior of the III-V HBT devices. The equations upon which is built are differentiable everywhere for insuring robustness of the model convergence. The DC modeling equations are based on the simplified relations presented in [4]. These relations are revised and are made more accurate and more appropriate for large signal modeling by including the temperature as well as the Kirk and Early effects. An electrothermal circuit for self-heating, and modified equations for the ideality emission coefficients, thermal resistance and band gap energy versus temperature are also included. In small signal mode, the model captures the variation of various AC capacitances with both bias voltage and bias current [5]. The total transit time (τ_d) and the distributed base resistance (Rbb) are implemented using their mean values. The 45 model parameters can be extracted from DC and multi-bias s-parameters measurements [6], using a simple and systematic extraction procedure implemented in Matlab programming language.

III. EXAMPLE OF SIMULATION RESULTS

The UCM is designed in the same spirit as the VIBIC model in such a way, if we neglect the improvements of the model; it can reproduce the reduced VBIC simulations commonly used to describe HBTs [4]. As examples of simulation results, Figs. 3 to 6 present comparisons between measurements, SDD and UCM simulations in DC, small-signal and large signal modes of operation for a 2x20 μm^2 emitter area transistor. Fig. 3 shows the Ic-Vce curves comparison between DC model predictions and the measured data at T_o=27°C. Figs. 4 and 5 show the small-signal comparison between model predictions and measurements over 1 - 20 Ghz frequency range. Fig. 6 compares the measured power added efficiency and the power gain with the simulation results from the model implemented in SDD and in UCM forms, at 3 Ghz, as function of a single-tone input power.

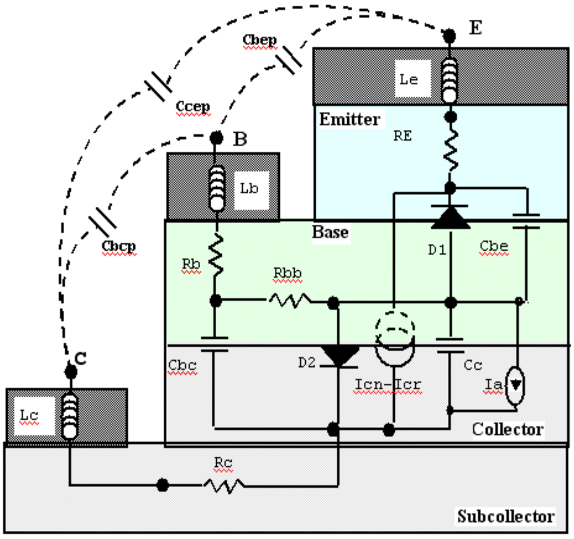
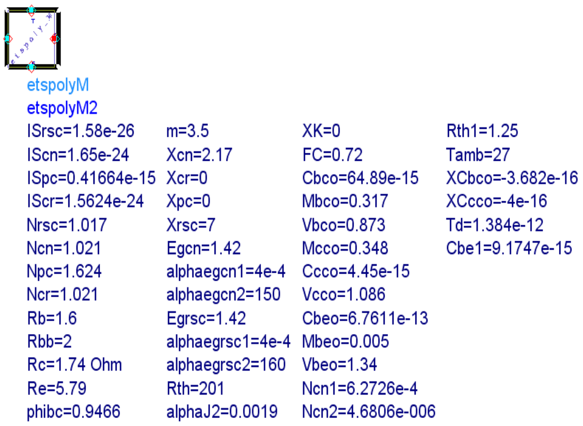


Fig. 1. Large-signal electrical equivalent circuit elements and their physical representation.



etspolyM
etspolyM2
ISrsc=1.58e-26
IScn=1.65e-24
ISpc=0.41664e-15
IScr=1.5624e-24
Nrsc=1.017
Ncn=1.021
Npc=1.624
Ncr=1.021
Rb=1.6
Rbb=2
Rc=1.74 Ohm
Re=5.79
phibc=0.9466
m=3.5
Xcn=2.17
Xcr=0
Xpc=0
Xrsc=7
Egcn=1.42
alphaegcn1=4e-4
alphaegcn2=150
Egrsc=1.42
alphaegrsc1=4e-4
alphaegrsc2=160
Rth=201
alphaJ2=0.0019
XK=0
FC=0.72
Cbco=64.89e-15
Mbco=0.317
Vbco=0.873
Mcco=0.348
Ccco=4.45e-15
Vcco=1.086
Cbeo=6.7611e-13
Mbeo=0.005
Vbeo=1.34
Ncn1=6.2726e-4
Ncn2=4.6806e-006
Rth1=1.25
Tamb=27
XCbco=-3.682e-16
XCcco=-4e-16
Td=1.384e-12
Cbe1=9.1747e-15

Fig. 2. UCM HBT circuit simulation model baptized etspoly model

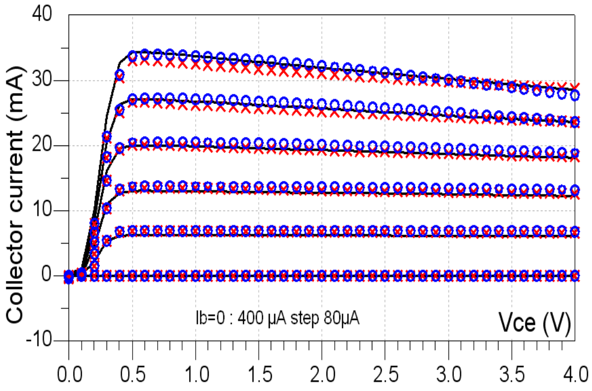


Fig. 3. Forward current-voltage characteristics at constant Ib.
(—) Measurements,
(x) Simulations from SDD form
(o) Simulations from UCM form

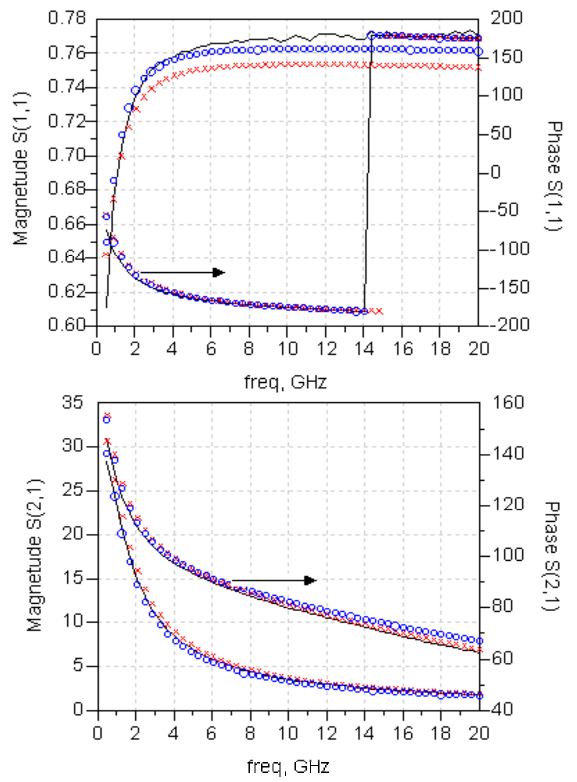


Fig. 4. S11 and S21 at Vce=1v Ib=320µA bias point, from 1Ghz to 20Ghz.

(—) Measurements

(x) Simulations from SDD form,

(**o**) Simulations from UCM form.

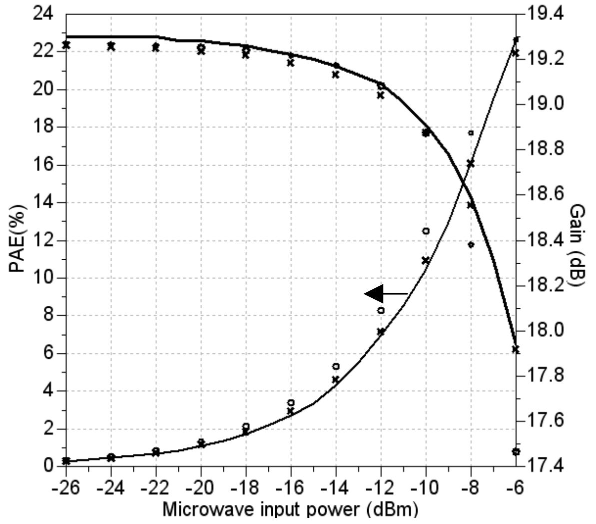


Fig. 6. Power gain and power added efficiency (PAE) vs. single-tone input power, at 3 Ghz for a bias condition of Vce=3 V and Ib=250 µA.

(—) Measurements,

(x) Simulations from SDD form,

(**o**) Simulations from UCM form.

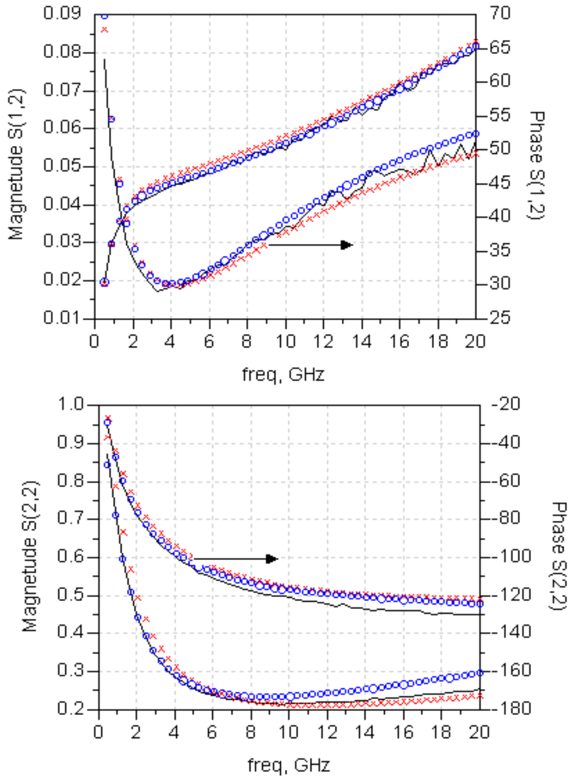


Fig. 5. S12 and S22 at Vce=1v Ib=320µA bias point, from 1Ghz to 20Ghz.

(—) Measurements,

(x) Simulations from SDD form,

(**o**) Simulations from UCM form.

IV. CONCLUSIONS

A nonlinear circuit simulation model for III-V Heterojunction Bipolar Transistors based on a new complete simple but accurate large-signal model is implemented using C code in the Agilent ADS circuit simulator as a User Compiled Model (UCM). This model accounts for self-heating, Kirk and Early effects and the temperature dependence of the diode ideality coefficients, of the band-gap energy and of the thermal resistance. The model is verified by comparing the simulated and measured data in DC, multi-bias small-signal S-parameters and large-signal microwave power characteristics for a 2x20 µm^2 emitter area transistor. The obtained excellent results show the robustness and the effectiveness of the model.

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