Comparison of a New Modified Gummel-Poon Model and VBIC for AlGaAs/GaAs HBTs

A. Issaoun[1], D. Dousset[2], A. B. Kouki[1], F. M. Ghannouchi[2]

[1]Ecole de Technologie Supérieure, 1100 Notre-Dame St. W., Montréal, Canada, H3C 1K3
[2]Ecole Polytechnique de Montréal, P.O. Box 6090, su. Centre-ville, Montréal, Canada, H3C 3A7

***Abstract* — A new modified Gummel-Poon (MGP) based model has been developed and tested on heterojunction bipolar transistors (HBTs). This paper focuses on the comparison of the new MGP and the VBIC models under DC and small-signal operations. The DC parameters of the two models are extracted from Gummel forward and reverse measurements at various junction temperatures and Ic-Vce measurements. The small-signal intrinsic elements are extracted from multi-bias s-parameter measurements. DC comparisons between the two model predictions and measurements reveal that the new MGP model surpasses the VBIC DC performances. The s-parameter comparisons of simulated and measurements at various bias points, from 1Ghz to 30Ghz, show that the two models are equivalent.**

I. Introduction

Heterojunction bipolar transistors (HBTs) have become very promising devices for future applications at microwave- and millimeter-wave frequencies. A critical precondition for any successful design is the availability of accurate large-signal model capable of describing the device over a broad bias range and signal frequencies. This is subjected to an accurate DC model, from one part, and to a precise description of the variation of the small-signal intrinsic elements with bias and signal frequencies, from the other part. The VBIC [1] model has been developed for bipolar junction transistors and to be as similar as possible to the SPICE Gummel-Poon model but improved over it in the following aspects [2], [3]:

- Improved Early effect
- Quasi-saturation
- Parasitic substrate
- Parasitic fixed (oxide) capacitance
- Avalanche multiplication
- Temperature
- Decoupled base current from collector current
- Electrothermal (self-heating effect) modeling

Due to the completeness and to the availability on commercial simulators of the VBIC, many authors [3]-[10] have investigated its applicability in HBTs modeling. From these studies, it comes out that VBIC is applicable for HBT modeling within certain acceptable error and deleting of several equivalent circuit parts to fit HBTs requirements:

- Epi-layer resistance and charge
- Parasitic transistor
- No quasi-saturation effect
- Ideal components
- Same forward and reverse transport currents

The reduced VBIC equivalent circuit matches the new MGP equivalent circuit but the modeling equations are different. The MGP model satisfies all the HBTs requirements including the performances of the VBIC model and thermally improved to it in the following aspects:

- Thermal resistance
- Emission coefficients
- Band-gap energy
- Kirk effect
- Charge modulation (Cbc(Ic,Vbc); Cc(Ic,Vbc); Cbe(Ic,Vce) and intrinsic base resistance)

These improvements are crucial for modern HBT modeling in particular for power applications [3], [4].

In the following, comparisons are conducted, for a 2*25 μm^2 emitter area AlGaAs/GaAs transistor, between measurements and the model simulations using VBIC from one side and using MGP from the other side.

II. Modeling Equations

The large-signal model for AlGaAs/GaAs HBT's, which is developed based on the conventional Gummel-Poon large-signal BJT model, is shown in Fig. 1. The extrinsic capacitances and inductances are not shown on the figure for the sake of clarity; they are bias independent and they can be removed using an electromagnetic or any de-embedding technique.

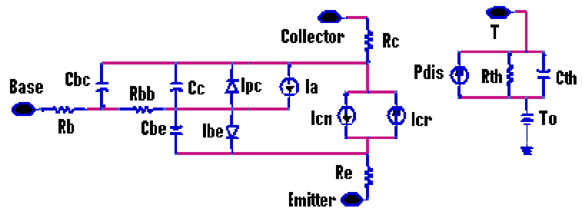

Fig. 1. Equivalent circuit diagram of the large-signal MGP model without parasitic elements

Icn is the electron current injected from the emitter to the base in the forward bias condition. Icr is the electron current injected from the collector to the base in the reverse bias condition. Ibe is the direct base current representing all recombination processes taking place in the base emitter junction in the forward bias condition. Ipc is the base current in reverse bias; hole current injected from the base to the collector sometimes increased by the recombination current in the depletion region. Ia is the Avalanche current, added for the sake of model completeness. Except Ia, these currents follow a same type of modeling equation:

$$I = Is\, e^{\frac{Egcn(T)}{Vt}\left(\frac{T}{T_o}-1\right)}\left(\frac{T}{T_o}\right)^X (e^{\frac{Vbe}{N\,.\,Vt}} - 1) \qquad (1)$$

where T_o is the reference absolute temperature, Is is the saturation current at T, Vbe is the applied base emitter potential, X is a temperature coefficient, N is an ideality factor, T is the junction absolute temperature, Vt is the thermal voltage and Egcn(T) defines the temperature dependence of the bend gap energy given by:

$$Egcn(T) = Egcn(0) - (\alpha_{egcn1}.T^2)/(T + \alpha_{egcn2}) \qquad (2)$$

Early and Kirk effects are introduced in the model by dividing Icn current by factors Fe and Fk respectively; described by the following equations.

$$Fe = \begin{cases} 1 - \alpha_e\sqrt{\varphi_{bc} - V_{bc}} & \text{if } V_{bc} < \varphi_{bc} \\ 1 & \text{else} \end{cases} \qquad (3)$$

φ_{bc} and V_{bc} are the built-in and the applied potentials between the base and collector junction. α_e is the Early parameter.

$$Fk = \begin{cases} 1 & \text{if } Ic < I2 = I1 + \alpha_{I2} * \left|\varphi_{bc} - V_{bc}\right| \\ 1 + \alpha_k * (Ic - I2)^{Xk} * \left(1 - \sqrt{\dfrac{I2 - I1}{Ic - I1}}\right) & \text{else} \end{cases} \qquad (4)$$

with α_k, and, α_{I2}, I1 are Kirk parameters.
In the above equations, the junction temperature is computed from:

$$T = T_o + Rth\,(T) * Pdiss \qquad (5)$$

where Pdiss is the total dissipated power in the junction and Rth(T) is the thermal resistance at junction temperature T. The thermal resistance Rth(T) is given by:

$$Rth(T) = Rth(T_o) * (T/T_o)^n \qquad (6)$$

Where $Rth\,(T_o)$ is the thermal resistance at the reference temperature T_o and n is a temperature coefficient depending on fabrication material.

The intrinsic circuit elements are coupled to the DC model as shown in Fig. 1 to construct the large-signal equivalent circuit used in this study, as the VBIC does. The characterizing equations used for these elements are the standard ones.

III. Parameter extraction

The DC parameter extraction procedure starts by extracting ideality factors and saturation currents from forward and reverse Gummel data measured at reference temperature T_o. Second, we repeat the first step for forward ideality factors and saturation currents from forward Gummel data measured at temperatures T_i. From the obtained data, we extract the variation of these parameters to temperature. The third step consists on the extraction of the parasitic resistances from Fly_back measurements. Third, we evaluate Kirk, and Early parameters and $Rth(T_o)$ and n from theoretical relations and optimize these values in the high region of the forward Gummel data measured at temperature T_o.

The VBIC parameters are extracted from the same measurements using the procedure given in [4].

IV. Results and discussion

We have applied the extraction procedure to various HBT transistors. Tables I and II list the obtained parameters for an AlGaAS / GaAs 2*25 μm^2 emitter area transistor for the MGP and for the VBIC models, respectively. The non-mentioned VBIC parameters are set to values giving no influence on simulation results.

Iscno	3.03 e-24	Xcn	2.17
Iscro	12.4 e-24	Xrsc	9.6
Ispco	3 e-15	$Rth(T_o)$	84
Isrsco	1.16 e-23	n	1.24
Npc	1.6225	Egrsco	1.65
Ncn	1.0677	α_e	0.078
Nrsc	1.219	α_{egcn1}	4e-4
Ncr	1.017	α_{egcn2}	150
φ_{bc}	0.95	Xk	1.11
α_k	11.58	α_{I2}	0.0019
Egcno	1.54	I1	0.0178
Re	0.6	Rc	9.4
Rb	5.6		

TABLE I
EXTRACTED PARAMETERS FOR THE NEW MGP MODEL

Parameter	Value	Parameter	Value
NPN	yes	Iben	1.4e-23
PNP	no	Nen	1. 219
Tnom	25	Is	4.1e-24
Rci	9.4	Ibci	3.5e-15
Vo	1kV	Nci	1.622
Gamma	0	Ncn	2.064
Hrcf	0	Vef	20
Rbx	0	Ikf	0.8
Rbi	5.6	Ea	1.45
Nf	1.0677	Eane	1.65
Nr	1.07	Re	0.6
Ibei	1.16e-24	Eaie	1.65
Nei	1.219	Xii	3
Xin	1.93	Rth	50

TABLE II
EXTRACTED PARAMETERS FOR VBIC MODEL

Forward current-voltage characteristics and forward Gummel plots obtained from MGP are compared to measurements and to those obtained from VBIC in Figs 2 and 3, respectively. The superior performances of the MGP model are clearly seen from the observation of Fig. 2, in particular at high currents. The MGP model reproduces VBIC performances when we neglect the variations of the bad gap energy, emission coefficients and thermal resistance with temperature as shown in Figs 4 and 5. As AC performances are related to the DC model, the large-signal shown in Fig. 1 was constructed in HP-ADS simulator using SDD and simulated at fixed bias points with intrinsic elements extracted using procedure [11]. As an example of the obtained results, the measured and the simulated S-parameters are compared in Fig. 6 at two bias points from 1 Ghz to 30 Ghz; notice the very good agreement obtained.

The values of the intrinsic elements as extracted and used in simulations of Fig.6 are listed in Table III.

Cbe (pF)	Cbc(fF)	Cc (fF)	τd (ps)	Rbb (Ω)	Ic (mA)
0.76	14.58	14.44	1.58	6.7	5
1.38	13.76	11.78	1.49	7.0	10

TABLE III

EXTRACTED INTRINSIC PARAMETERS AT VCE=2.5 V

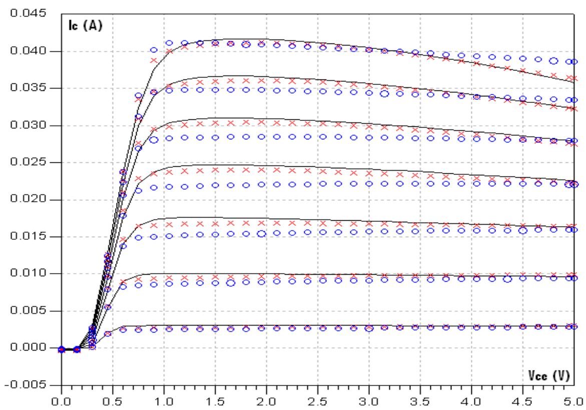

Fig. 2. Forward current-voltage characteristics obtained from measurements (—), from VBIC model (o) and from MGP (x).

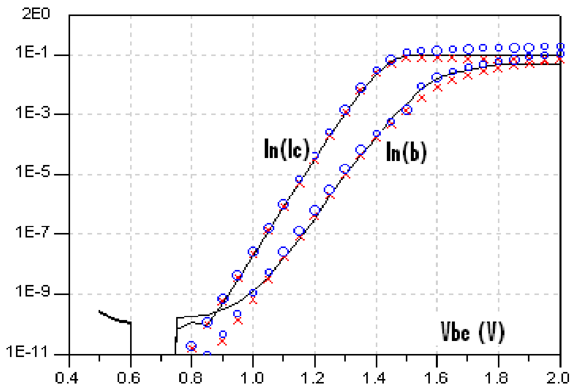

Fig. 3. Forward gummel plots obtained from measurements (—), from VBIC model (o) and from MGP (x).

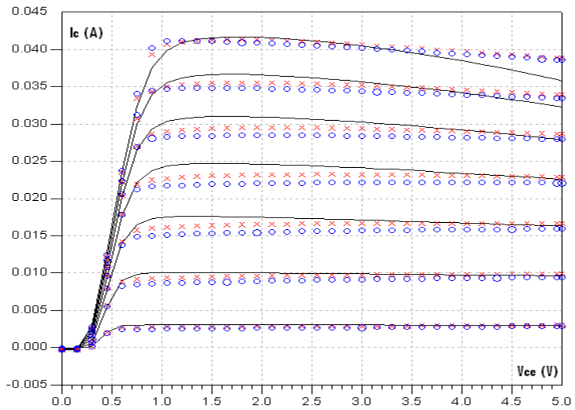

Fig. 4. Forward current-voltage characteristics obtained from measurements (—), from VBIC model (o) and from MGP (x), Rtho and Ns are not varying with temperature and Rth(T_o)=57, Xk=1 and αk=4.5; I1=0.005

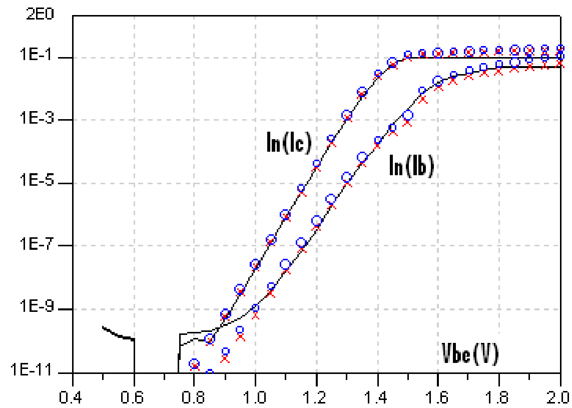

Fig. 5. Forward gummel plots obtained from measurements (—), from VBIC model (o) and from MGP (x), Rtho and Ns are not varying with temperature.

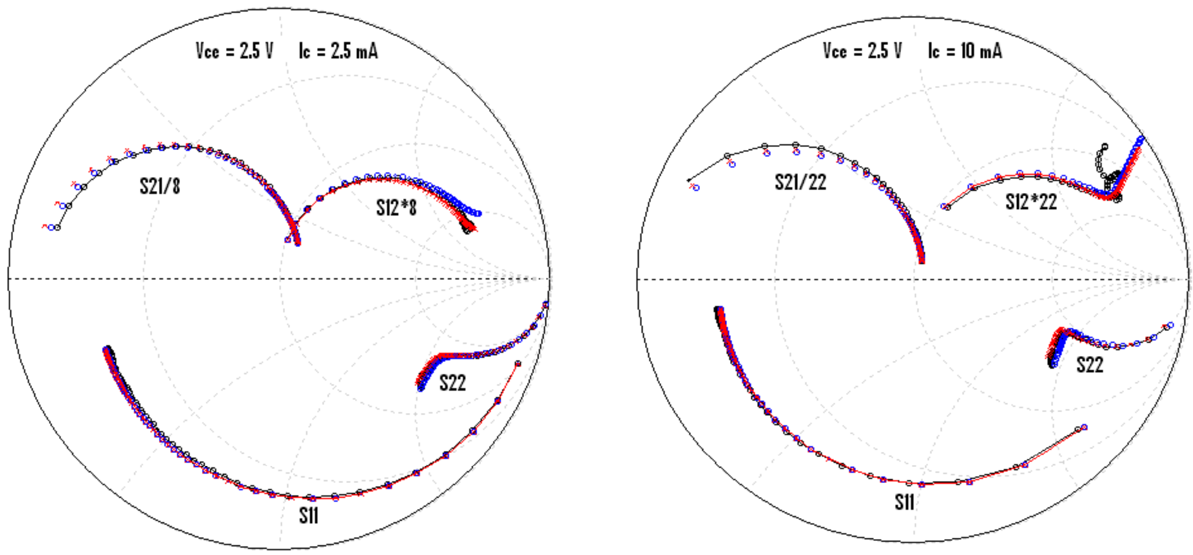

Fig. 6. Small-signal comparison between measurements (—) and model predictions from VBIC (o) and from MGP (x), at two bias points, from 1 Ghz to 30 Ghz.

IV. Conclusion

The new modified Gummel-Poon (MGP) based model was compared to the VBIC under DC and small-signal operations. The MGP performances are clearly seen when comparing simulations resulting from this model to those resulting from the VBIC one, simultaneously to measurements. The MGP performances are due to the improvement of the modeling of the following effects:

- Thermal resistance
- Emission coefficients
- Band-gap energy
- Kirk effect

Acknowledgement

The authors would like to acknowledge R. Surridge and A. St. Denis, Nortel Networks, Ottawa Canada, for providing the measurements and for the helpful discussions. This research was supported by the National Science and Engineering Research Council of Canada (NSERG) with financial contribution from Nortel Networks.

References

[1] C. C. McAndrew, J. A. Seitchik, D. F. Bowers, M. Dunn, M. Foisy, I. Getreu, M. McSwain, S. Moinian, J. Parker, D. J. Roulston, M. Schroter, P. Wijnen, L. F. Wagner; "VBIC95, the vertical bipolar inter-company model," IEEE *Journal of Sld. Stat. Ckt*., vol. 31, no. 10, Oct. 1996, pp. 1476 –1483.

[2] P. Layman, J. J. Liou, J. Mcmacken, S. Moinian, A. Oritz-Conde, K. Stiles, C. Xiaochong; "Comparison of the new VBIC and conventional Gummel-Poon bipolar transistor models", *IEEE Transactions on Electron Devices*, vol. 47, no. 2, Feb 2000, pp. 427-433.

[3] C.K. Maiti, B. Senapati, "Advanced SPICE modelling of SiGe HBTs using VBIC model," *IEE Proceedings Circuits, Devices and Systems*, vol. 149 no 2, Apr. 2002, pp. 129-135.

[4] S.V. Cherepko, J.C.M. Hwang, "VBIC model applicability and extraction procedure for InGap/GaAs HBT," *Asia-Pacific Microwave Conference*, APMC 2001, vol.2, pp. 716-721.

[5] C.J. Wei, J. gering, S. Sprinkle, A. Klimahsoe and Y. A. Tkachenko; "Modified VBIC-model for InGaP/GaAs HBTs"; *Asia-Pacific Microwave Conference*, WEOF-10, 2002, pp. 354-357.

[6] M. Tutt, "GaAs based HBT large signal modeling using VBIC for linear power amplifier applications," *Proceedings of the Bipolar/BiCMOS Circuits and Technology Meeting*, 2000, pp. 58-61.

[7] F. X. Sinnesbichler, G. R. Olbrich, "Accurate large-signal modeling of SiGe HBTs," *Microwave Symposium Digest, IEEE MTT-S International*, vol.2, 2000, pp. 749 -752.

[8] X.Cao, P. Layman, J.J. Liou, J. McMacken, S. Moinian, K. Stiles, A. Sun, "Parameter extraction and optimization for new industry standard VBIC model," *Second International Conference on Advanced Semiconductor Devices and Microsystems*, ASDAM '98, 5-7 Oct 1998, pp. 107-116.

[9] K. M.Chen, D. Y. Chiu, Y. M. Deng, G. W. Huang, J. F. Kuan, M. T. Wang, S. Y. Wen, "Silicon BJT modeling using VBIC model," *Asia-Pacific Microwave Conference*, vol. 1, 2001, pp. 240 –243.

[10] D. L. Harame, K. M. Newton, M. Ramana Murty, D. C. Sheridan, S. L. Sweeney, "Implementation of a scalable and statistical VBIC model for large-signal and intermodulation distortion analysis of SiGe HBTs," *Microwave Symposium Digest, IEEE MTT-S International*, IF-TH-46, 2002, pp.2165-2168.

[11] D. Dousset, A. Issaoun, A. B. Kouki, F. M. Ghannouchi, "A Novel Method for a Direct Extraction of HBT Small-Signal Parameters Using Analytical Expressions,'' *Asia-Pacific Microwave Conference*, WEOF-15, 2002, pp. 374-377.