Critical discussion of emitter capacitance modeling

R. Amador, A. Nagy, M. Alvarez, A. Polanco
Centro de Investigaciones en Microelectrónica,
Ciudad Habana 10800, Cuba, Fax: 53-7-558939
Email: ramador@electrica.ispjae.edu.cu

Introduction

Bipolar transistors are presently, due to superior performance at high frecuencies, the most widely used active semiconductor devices in electronic circuits for communications technology [1].The model of the bipolar transistor used in the design of these circuits has been characterized by the continuous increase of its complexity beginning with the first generation Ebers-Moll [2] and Gummel-Poon [3] models up to the more sophisticated HICUM [4] and Mextram 504 [5] compact models. Modeling the emitter capacitance Ce is important not only at high frecuencies but also at direct current to model the emission coefficient with temperature as required in the design of temperature sensors and bandgap references [6,7,8]. In this work the measurement results of emitter capacitance under forward bias of a bipolar transistor are analyzed. Measurement results show an unexpected exponential increase of emitter capacitance under significant forward bias. The measurement method of emitter capacitance used has been proposed by Getreu [2]. The variations of Ce as a function of emitter-base voltage have been simulated using Poon-Gummel [9] and HICUM [4] emitter capacitance models, showing a noticeable difference with experiment.

Experimental measurements of Ce

Emitter capacitance was measured in an open collector common-base configuration [2] using a 1 Mhz Boonton Capacitance Meter bridge at 29.3 ^{0}C and 39.3 ^{0}C.

The MAT-01 pair of bipolar transistors used, has a very high stability in its Ic(Vbe) characteristics [10]. The relatively high intrinsic emitter capacitance of this transistor allows to neglect lateral parasitic extrinsic capacitance present in small RF BJT devices [4]. A Haake liquid bath thermostat guaranteed temperature stability better than 0.05 ^{0}C. The DC measurements of Vbe were performed with a 6 1/2 digits Agilent multimeter.

Graphical plotting of Ce measurements in the transistor active region (450 to 550 mV) at 29.3 ^{0}C in semilog paper showed excellent straight line goodness of fit as expected in an exponential function.

It was verified also that Ce measurement error in the bridge due to parallel base-emitter diode conductance was negligible except near the maximum value of Ce where it is only 2 %. Therefore no corrections were introduced in the experimental values of Ce shown in Figures 1 and 2.

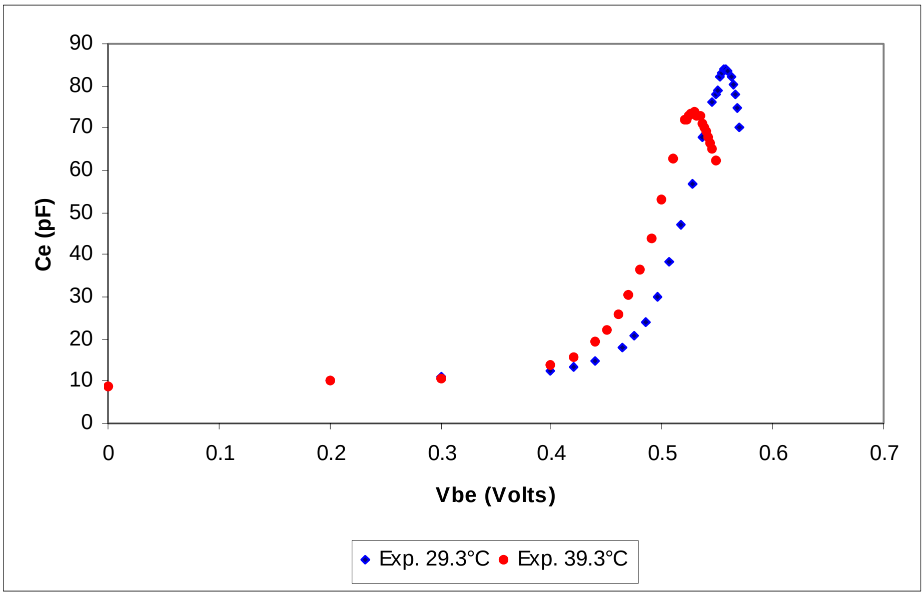

Fig.1 Experimental measurements of Ce in MAT01 transistor

Modeling of Ce

The experimental results are modelled using Poon-Gummel's model [9] and HICUM [4] model.

An analysis of the emitter capacitance model development shows that up to 1969, when the Poon-Gummel model was published, the three parameter space charge model (Ideal) had been used:

$$C_e = \frac{C_o}{\left[1 - \frac{V_{BE}}{V_{DE}}\right]^{z}} \qquad (1)$$

whose three parameters are,

V_{DE}: diffusion or built-in voltage
C_0: zero bias emitter capacitance
z: grading coefficient

Under significant forward bias, emitter capacitance increases to a maximum value that can not be explained with expression (1).

The Poon-Gummel model [9], that uses four parameters, improved the description of emitter capacitance under forward bias up to the "built-in" voltage (at Ce_{max}), and was used in all Mextram 503 models [11],

$$Ce = \frac{Co}{(x^2+b)^{n/2}}\left(1 + \frac{n}{1-n} * \frac{b}{x^2+b}\right) \qquad (2)$$

where $\mathbf{x}=\frac{V_{be}-V_1}{V_1}$, n of the Poon-Gummel model is equal to the grading coefficient z, b is emitter peak capacitance coefficient , Co is approximately the zero bias emitter capacitance and V_1 is the “built-in voltage”.

In HICUM compact model [4] the expression (1) has been modified with a four parameters expression that also includes a smoothing function,

$$\mathbf{C_{je}=\frac{C_{je0}}{(1-V_j/V_{DE})^z}\frac{e}{1+e}+a_{je}C_{je0}\frac{1}{1+e}} \qquad \mathbf{(3)}$$

where **e, V_j, V_f** and the fourth parameter $\mathbf{a_{je}}$ are given by the expressions,

$$\mathbf{e=\exp\left(\frac{V_j-V_{be}}{V_T}\right)} \qquad \mathbf{(4)}$$

$$\mathbf{V_j=V_f-V_T\ln(1+e)} \qquad \mathbf{(5)}$$

$$\mathbf{V_f=V_{DE}\left[1-a_{je}{}^{-(1/z)}\right]} \qquad \mathbf{(6)}$$

$$\mathbf{a_{je}=\frac{C_{jemax}}{C_{je0}}} \qquad \mathbf{(7)}$$

The experimental values of Ce and their simulation using expressions (1), (2) and (3) are shown in Fig.2.

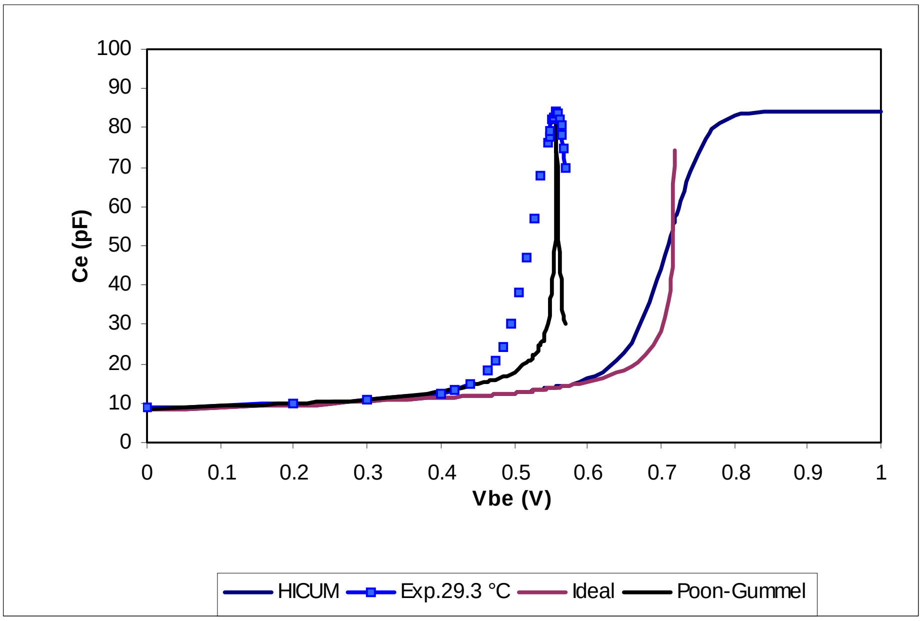

Fig.2 Experimental and simulated values of Ce at 29.3 °C

In Fig.2 a noticeable difference with experiment is observed, especially in the exponential increase region of Ce, that has not been considered in these models. This exponential behaviour was theoretically predicted by Shockley through the concept of neutral capacitance Cn [12,13] and has not been included in any compact model.

Conclusions

Compact models of the Bipolar Junction Transistor introduce significant errors of emitter capacitance Ce in the active region of the transistor. Careful measurements of Ce in this region show an exponential increase with Vbe that was theoretically predicted by Shockley but has not been included in any compact model.
Accurate modeling of Ce in this region will be required to improve modeling of the emission coefficient n as a function of Ce, which has been recently considered of interest in the design of temperature sensors and voltage bandgap references.

References

[1] S. Mijalkovic, H. C. de Graaff, Mextram 504 for SiGe HBT Applications, Proc. 4 th Workshop on Semiconductor Advances for Future Electronics, Veldhoven, Netherlands, November (2001) 115-122

[2] Ian E. Getreu, Modeling the bipolar transistor, Elsevier, New York, 1978

[3] H. K Gummel, H. C. Poon, An integral charge control model of bipolar transitors, BSTJ, May-June (1970) 827-852.

[4] M. Schroter, HICUM, A scalable physics-based compact bipolar transistor model, available on the web: http://www.iee.et.tu-dresden.de/iee/eb/comp_mod.html

[5] J. C. J. Paasschens, W. J. Kloosterman, The Mextram Bipolar Transistor Model – Level 504, Nat. Lab. Unclassified Report, NL –UR 2000/811, Koninklijke Philips Electronics N.V. 2000/2001

[6] R. Amador, A. Nagy, M. Alvarez, A. Polanco, Influence of Emitter Capacitance on Emission Coefficient at Constant Bias Current, Proc. XVII Conference on Design of Circuits and Integrated Systems (DCIS'2002), Santander, Spain, November (2002) 649-653

[7] G. Wang, G. C. M. Meijer, The temperature characteristics of bipolar transistors fabricated in CMOS temperature sensors, 13 th European Conference on Solid-State Transducers, The Hague, Netherlands, September (1999) 553-556

[8] G. Wang, G. C. M. Meijer, The temperature characteristics of bipolar transistors fabricated in CMOS technology, Sensors and Actuators, 87 (2000) 81-89

[9] H. C. Poon, H. K. Gummel, Modeling of emitter capacitance, Proc. IEEE, Dec. (1969) 2181-2182

[10] G. C. M. Meijer, Thermal sensors based on transistors, Sensors and Actuators, 10 (1986) 103-125

[11] J. C. J. Paasschens, W. J. Kloosterman and R. v.d. Toorn, Model derivation of Mextram 504, Nat. Lab. Unclassified Report, NL –UR 2002/806, Koninklijke Philips Electronics N.V. 2002

[12] W. Shockley, The Theory of p-n Junctions in Semiconductors and p-n Junction Trnasistors, BSTJ 28, (1949) 435-489

[13] B.C. Bouma, A.C. Roelofs, An experimental determination of the forward-bias emitter-base capacitance, Solid-State Electronics, 21 (1978) 833-836.