Transient Analysis of Collector Current Collapse In Power HBTs

R. Sommet, D. Lopez, R. Quéré

I.R.C.O.M. - C.N.R.S. U.M.R. n° 6615,I.U.T. G.E.I.I.,7, rue Jules Vallès 19100 Brive la Gaillarde

sommet@brive.unilim.fr

This paper describes the dynamic of the current collapse phenomenon that can occur in a multifinger power HBT. The electrothermal model used is a self consistent model based on an electrical distributed Ebers Moll model coupled to a thermal subcircuit derived from Ritz vector reduction technique of 3D thermal finite element simulation. Simulation of static as well as dynamic collector current collapse for HBT has been performed and allows to optimize the ballast resistor.

INTRODUCTION

Many efforts have been made to push the limits of InGaP/GaAs HBT technology towards high power densities in order to face to HFET or PHEMT power technology. Nowadays whereas only medium HPA are available in catalogue, due essentially to the limiting factor of the reliability, new advances in term of thermal management, reliability [1], electrical behavior and topology have been pushed ahead tending to the ultimate predicted 10W/µm² as figure of merit [2]. The thermal management of the devices is one of the key points of the success. In general the HBT technology use an integrated emitter ballast resistance to prevent a thermal runaway. Thus, the risk of hot spot in the emitter is reduced or can be mastered. Moreover, in order to improve the thermal resistance of the devices, many techniques can be applied such as the use of an heat spreader to connect fingers [3], flip chip mounting technology [4], or the use of thick copper or diamond materials on top of the emitter finger [5]. The model we have developed allows getting very precise information about the thermal behavior of the device and allows predicting instability phenomenon such as the collector current collapse phenomenon. It is very interesting in order to optimize the ballast resistance for a specified application.

ELECTROTHERMAL MODEL

The electrothermal model is a self-consistent model that is presented in figure 1. According to this figure, this model is split into two parts, an electrical one and a thermal one. A distributed nonlinear modified Ebers Moll circuit composes the electrical part of the model. One cell of this electrical circuit is depicted in figure 2. Each elementary electrical model corresponding to a finger is derived from the global model of the transistor that is extracted from pulse measurements [6]. Scale rules are applied to extract electrical model parameters. The electrical non-linear model accounts for the temperature dependence of the physical parameters such as saturation currents, current gain…

The thermal behavior of the device is represented by a multi ports inputs and outputs SPICE thermal circuit. The inputs correspond to the dissipated powers and the outputs to the temperatures for each elementary device. Temperature acts like an electrical command for the device.

The originality of the thermal part of the model relies on the fact that it is computed from a full 3D thermal physical analysis [7][8][9].

As a matter of fact, thermal measurements of temperature profile are very difficult to obtain for small devices. Moreover when these devices have many fingers and when their active area are under thick gold heat spreader it is impossible to extract temperature for each finger precisely. It is why we have chosen a simulation approach.

The device temperature is governed by the heat equation:

$$div(\kappa(T)\cdot gradT) + g = \rho C_p \frac{\partial T}{\partial t} \qquad (1)$$

where κ is the thermal conductivity, T the temperature, ρ the density, C_p the specific heat and g is the heat generation rate by unit volume.

Assuming κ constant and equal to the conductivity at 300°K, the Finite Element formulation of equation (1) leads to the semidiscrete heat equation:

$$\mathbf{M}\dot{T} + \mathbf{K}T = \mathbf{F} \qquad (2)$$

where the **K** and the **M** matrices are called respectively the stiffness and mass matrix. These matrices are symmetric and positive-definite. **T** is the temperature vector at mesh nodes and F the load vector that takes into account of the power generation and the boundary conditions for the device. This system can be solved and the temperature profile of the device determined by a static analysis as well as a dynamic analysis. The mathematical model represented by a large system of linear differential equations is not suited for circuit simulation because on one hand of the large number of mesh nodes (more than 20000) and on the other hand of the difficulties to distribute the electrical part of the model for connection with the thermal part.

It is why a technique based on the Ritz vectors approach [10] [11] has been used in order to extract a fully functional and accurate model.

The main advantages of such a model rely on its precision that can be nearly the same provided by the 3D FE model, but also the low CPU simulation time and the very simplified implementation in circuit simulator because of the SPICE format. The generation of the SPICE model is fully automatic when you provide K, M, F, and the list of the fixed nodes corresponding to the limit conditions applied on baseplate of the device or example.

A free version of this software developed under GNU Public License and a documentation is available at the web address http://www.brive.unilim.fr/~raph.

The model has been successfully experimented with the Advanced Design System (ADS) simulator and validated on several HBT structures [9].

RESULTS

The transient analysis of the current collapse phenomenon has been performed on an eight finger HBT of 2*40µm²: the CEPD 824 of the United Monolithic Semiconductors (UMS) foundry. The 3D thermal model has been first realized with MODULEF Finite Element software from INRIA and reduced to a SPICE subcircuit with fifty time constants and eight ports which correspond to the maximum temperature on each elementary finger of the device. We can see a very good agreement between simulation and its model reduction in figure 3 for the transient behavior of the device. The electrical part of the model is extracted from measurements. We show in figure 4 the IV output curves for a dissipated power of 600mW.

In order to simulate the current collapse phenomenon, the emitter ballast of the transistor has been set to 2 Ohms. This small value of ballast resistor as it can be seen in figure 5 on IV static curves authorizes the current collapse phenomenon [12] to occur.

The simulated circuit for the current collapse is presented in figure 6. The bias Vce point corresponds to 10V and a current step of 5.5 mA is applied to the base of the device.

The time domain response of global current, finger current and finger temperature is computed during 100µs.

Figures 7 to 10 show that there are several stages in the current collapse phenomenon. This phenomenon starts in the outer finger and progress to the center finger. Before 4µs, all fingers have the same behavior. After 4µs, the outer finger temperature as well as its finger current decrease, which correspond to the beginning of the current collapse phenomenon. Then it is up to the second finger and so on. The whole current in the device is mainly due to the center finger after 40µs. Figure 10 shows in 3D the temperature increase versus time for each device finger.

This value of 4µs seems to correspond to the necessary duration for the heat to reach the heat spreader. Before this date, the device fingers are thermally uncoupled. After this date, they are all coupled together. The more fingers are coupled together the more the thermal time constants of the thermal reaction will be reduced, the temperature distribution more uniform and the current collapse phenomenon pushed back. One objective of the thermal optimization of the device would be to reduce the duration for the heat to reach the thermal shunt.

CONCLUSION

A finger distributed electrical model coupled to a reduced thermal equivalent model has been used for accurate prediction of static or dynamic collector current collapse instability. The reduction process based on Ritz vector approach leads to the generation of a SPICE format subcircuit file that can be easily implemented in many circuit simulators. This model allows optimizing emitter ballast resistance but also by its very high precision exhibits very good properties to simulate the slow dynamic effects of temperature in power amplifiers for radar applications.

Moreover reduced models will be a very good way to thermally optimize device structure and circuit. The reduction method has been illustrated with HBT devices but model reduction can be also performed on any kind of devices.

ACKNOLEDGEMENTS

The authors would like to thank D. Floriot of THALES TRT (France), Ph. Auxemery of UMS (France) for technical support and for providing the devices, and the French DGA for financial support of D. Lopez’s Ph.D.

REFERENCES

(1) H. Blanck and al “Industrial GaInP/GaAs Power HBT MMIC process”, GAAS 2000 Paris, 2-3 Oct. 2000, p 113

(2) B. Bayraktaroglu “HBT power Devices and circuits”, Solid State Electronics, vol 41, n°10,p1657,1997

(3) S.Delage, D. Floriot, H. Blanck, M. Di Forte Poisson, C. Brylinski, Y. Perreal, D. Pons, “Power GaInP/GaAs HBT MMIC’s,” EuMC Cannes 94, Vol. 2, pp 1143-1148.

(4) D. Hill and al,“28V Low Thermal Impedance HBT with 20W CW Output Power” IEEE MTTS 1997, p137

(5) D. Floriot, S. Delage, S. Piotrowicz, E. Chartier, Ph Auxemery “High Power HBT Technology : Present and Trends”, GAAS 2001 London, 24-24 Sep. 2001, p57

(6) T. Peyretaillade, M. Perez, S. Mons, R. Sommet, Ph. Auxemery, J.C. Lalaurie, R. Quéré "A Pulsed-Measurement based Electrothermal Model of HBT with Thermal Stability Prediction Capabilities" IEEE, MTT-S 97, DENVER, june 1997

(7) R. Sommet, D. Lopez, R. Quere, “Electrothermal Harmonic Balance Simulation Of An InGaP/GaAs HBT Based On 3D Thermal and Semiconductor Transport Models”, GAAS 2000 Paris, 2-3 Oct. 2000, pp. 516-519

(8) D. Lopez, R. Sommet, R. Quere, “ Spice Thermal Subcircuit of Multifinger HBT derived from Ritz Vector Reduction Technique of 3D Thermal Simulation for electrothermal modeling”, GAAS 2001 London, 24-24 Sep. 2001, pp. 207-210

(9) D. Lopez , “Intégration d’un modèle électrothermique de transistor bipolaire à hétérojonction issu de simulation thermiques tridimensionnelles dans un environnement de simulation circuit »

(10) Jia Tzer Hsu, Loc Vu-Quoc, “A Rationnal Formulation of thermal circuit Models for Electrothermal Simulation - Part I & II,” IEEE Trans. Circuits Syst., vol. 43, NO. 9, pp. 721-743, Sept. 1996.

(11) E.L. Wilson, M.W. Yuan, “Dynamic Analysis by direct superposition of Ritz vectors” Earthquake Eng. Structural Dynamics, vol. 10, NO. 6, pp. 813-821, Nov. 1982.

(12) W. Liu, A. Khatibzadeh “The Collapse of Current Gain in Multi-Finger Heterojunction Bipolar Transistors : its Substrate Temperature Dependence, Instability Criteria, and Modelling”, IEEE Trans. On Electron Devices N° 10, oct.1994

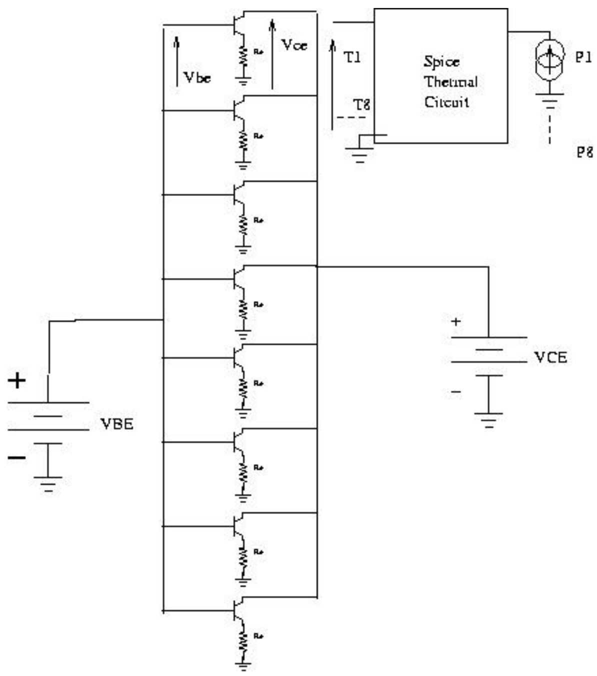

Fig. 1 : Schematic of the simulated electrothermal model

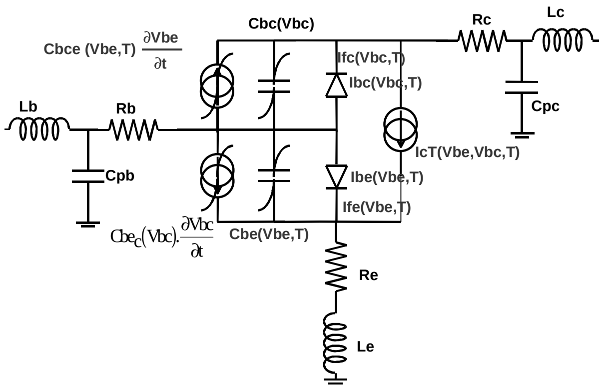

Fig. 2: One cell of the electrical model

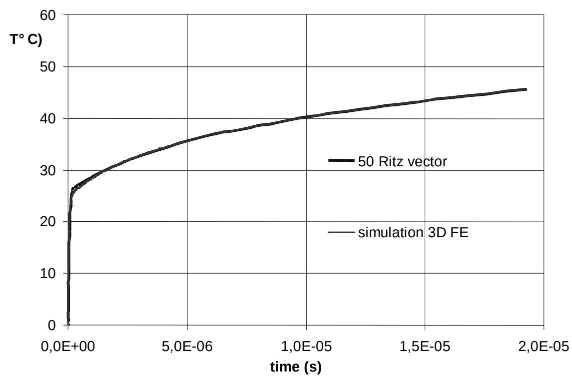

Fig. 3: Comparison between transient 3D FE simulation and 50 Ritz vector reduced model

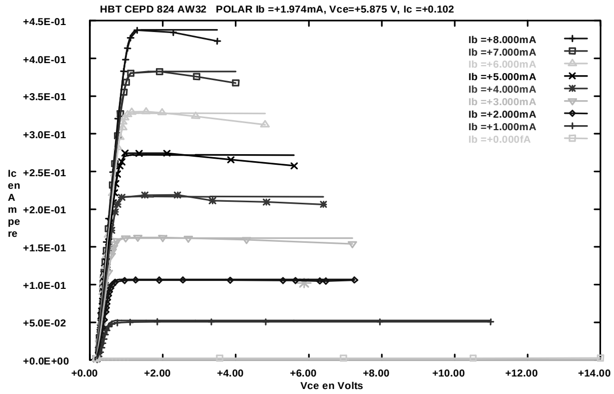

Fig. 4 :IV output curves for a dissipated power of 600mW

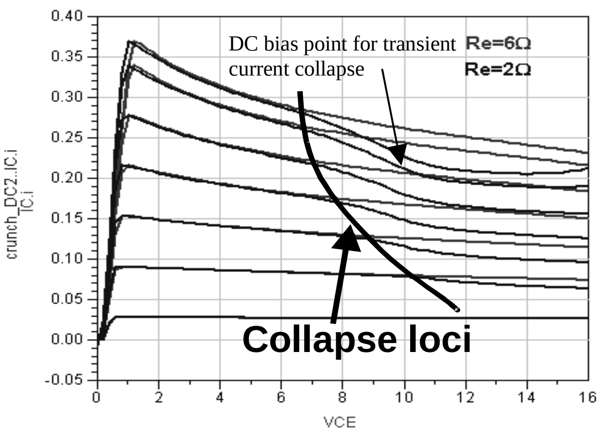

Fig 5: IV output for different values of emitter ballast

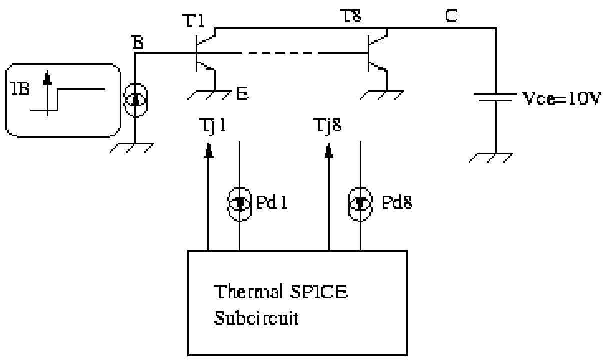

Fig. 6: Simulated circuit

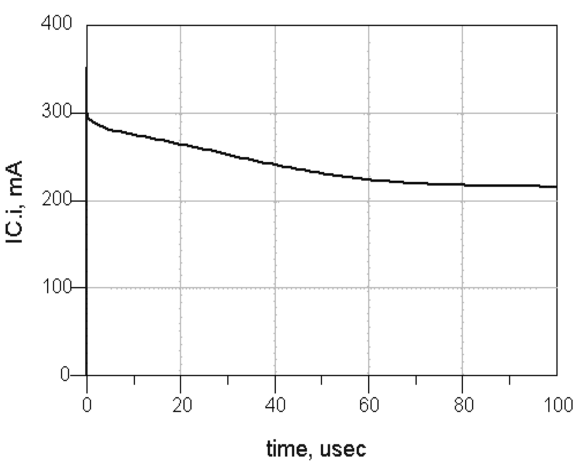

Fig. 7 : Global current versus time

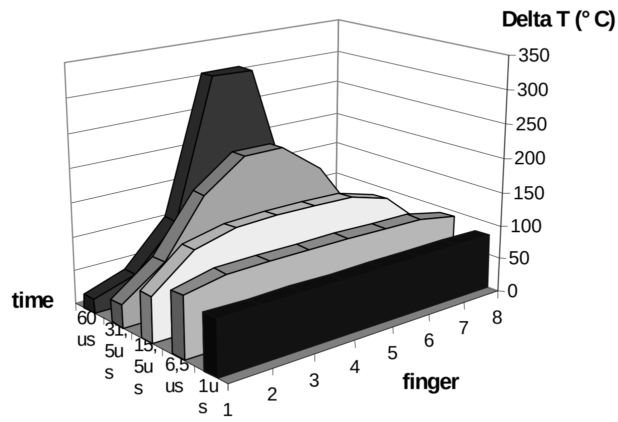

Fig. 8:Current collapse phenomenon

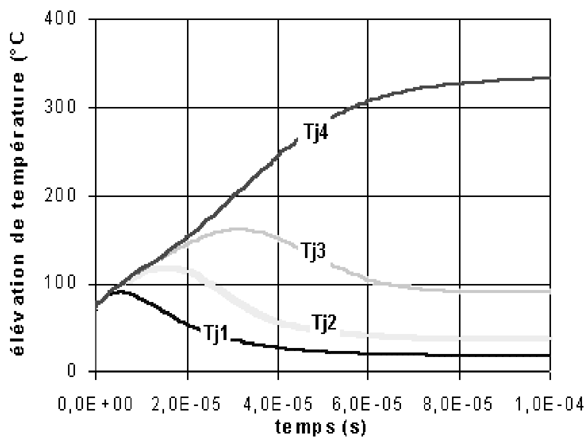

Fig. 9: Finger temperature versus time

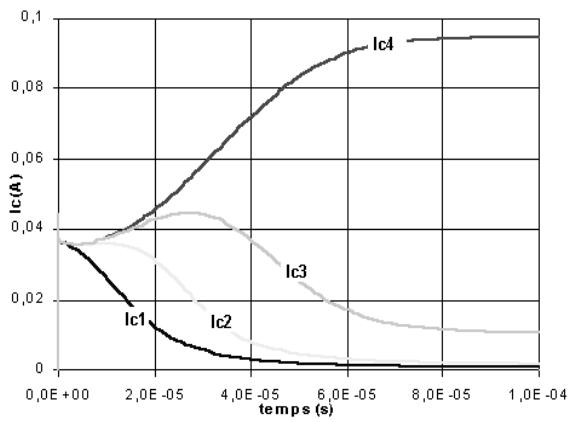

Fig.10 Finger current versus time