Self consistent electrothermal modeling of multifingers HBTs for power application

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INTRODUCTION :

The purpose of this paper is to present a self consistent approach for the development of an elctrothermal model of multifinger power devices. It has been applied to multifinger GaInP/GaAs HBT devices and circuits. This model can describe complex coupled thermal and electrical phenomenons such as the "crunch effect" (current collapse) or the RF power saturation.

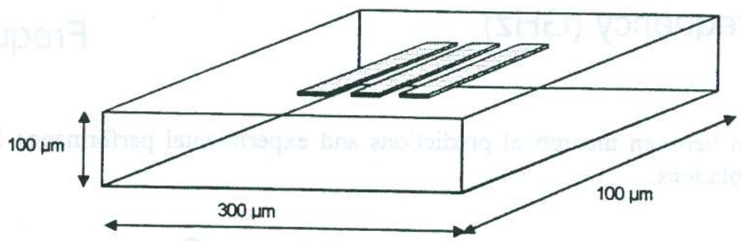
1) Thermal study of multifingers HBTs

The well known heat equation that describes the heat flow in a solid is [1]:

$$\nabla.(k.\nabla T) + q''' = \rho c \frac{\partial T}{\partial t}$$

Where k is the thermal conductivity of the material ($Wm^{-1}K^{-1}$)
T is the temperature (°K)
q''' is the generated heat (Wm^{-3})
ρ is thermal density
c is the specific heat ($J\,°K^{-1}\,Kg^{-1}$)

This formulation can be used either under steady state or transients conditions. A 3D solution based on a finite difference scheme is used for the steady state operation via an iterative process, while a direct 2D solution is used for transient operation also based on a FD scheme.



3 Fingers HBT structure.

We consider a non linear GaAs thermal conductivity given by : $K_{AsGa}=44*(To/T)^{1.25}$ ($Wm^{-1}°K^{-1}$)
It strongly depends on the temperature, that involves a strong dependence of thermal resistances versus temperature.

The boundary conditions over the bottom of the substrate is taken as a constant temperature T=To. A radiation coefficient is used to describe the heat exchanged between the air and the metallizations on the top of the device [3] [4] .

In HBT structures, the heat is essentially generated close to the base-collector junction. The dissipated power at each point of the BC junction depends on the current density and so on the temperature in this area so we have introduced an injection law in this model to describe the current concentration phenomenon.
Pulsed measurements have been carried out to fit the injection law as [2]:

$$Jc = Jo\left(1-\frac{Vbe}{Vbi}\right)*\exp\left(\frac{qVbe}{kT}-1\right) \quad \text{with} \quad Js = 1.53910^{9}\ A/m^{2}$$

$$Vbi = 1.579\ V$$

$$\text{where} \quad Jo = Js*q*T*\frac{Vbi}{k}*\exp\left(\frac{qVbi}{kT}\right) \quad k = 13.806\ 10^{-24}\ J.K^{-1}$$

$$q = 1.602\ 10^{-19}\ C$$

The 3D mesh consists of more than 200,000 elementary cells, in which we resolve the heat flow conservation equation : $\Sigma q_{exchanged} + q_{generated} = 0$.
Our model gives the temperature and current density everywhere in the component as illustrated figures 1 to 4.

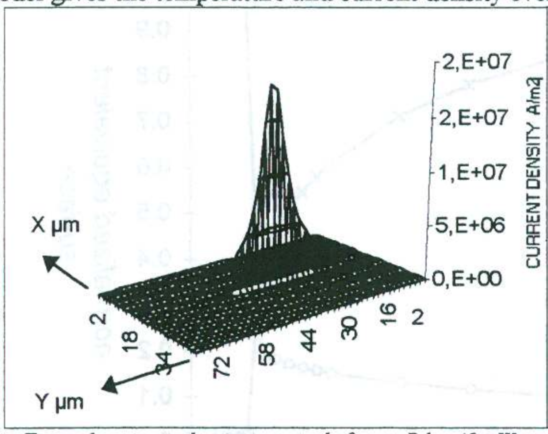


Figure 1 : current density in a single finger Pd = 45 mW

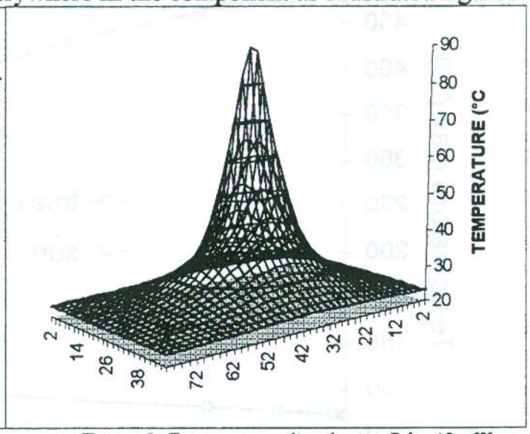


Figure 2 :Temperature distribution Pd =45 mW

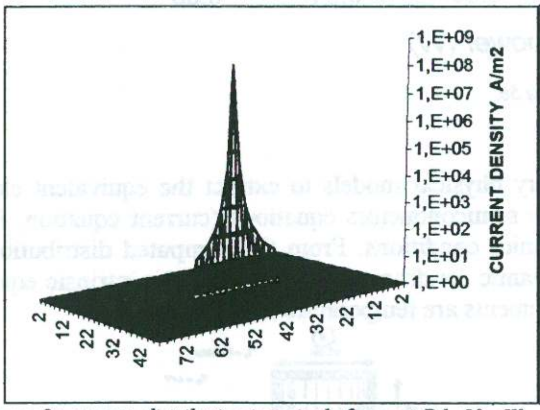


Figure 3 : current distribution in a single finger at Pd=50 mW

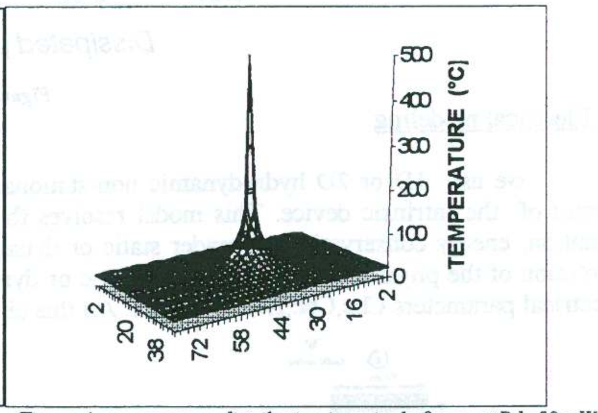


Figure 4 : temperature distribution in a single finger at Pd=50 mW

Figures 1&2 show the current and temperature distribution over a single finger ($2*30\ \mu m^2$) in a $50*100 \mu m^2$ area with a dissipated power of 45 mW. Figures 3&4 show the thermal runaway effect when a power of 50 mW is dissipated.

Because of the important temperature gradient in high injection conditions we can not use so easily the definition of the thermal resistance : $Rth = \dfrac{T_{junction} - T_{substrate}}{Pdissipated}$.

To describe this phenomenon we have used a normalized equivalent area that is : $Aeq = \dfrac{\sum_{finger} dx * dy * Jc(T = T_{i,j})}{Surf_{finger} * Jc(T = T\max)}$. This means that we have assumed a constant temperature distribution (and so for the current) over a smaller finger with a temperature T=Tmax and an equivalent area as illustrated figure 5a.

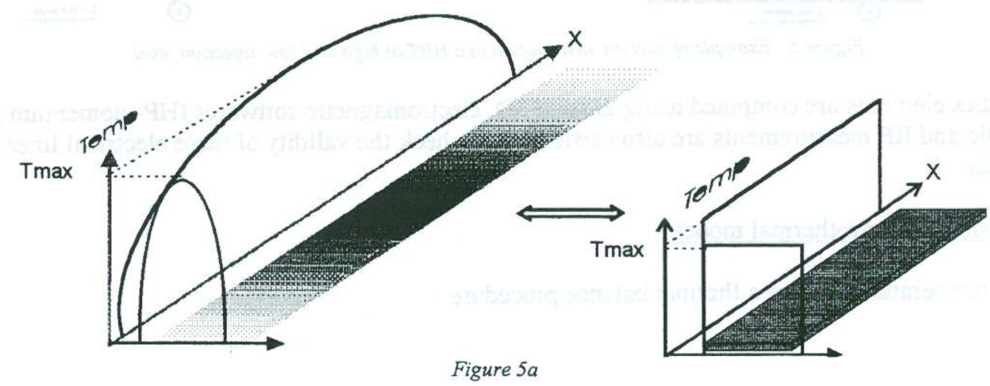


Figure 5a

The normalized equivalent surface for a single 2µm*30µm finger is :

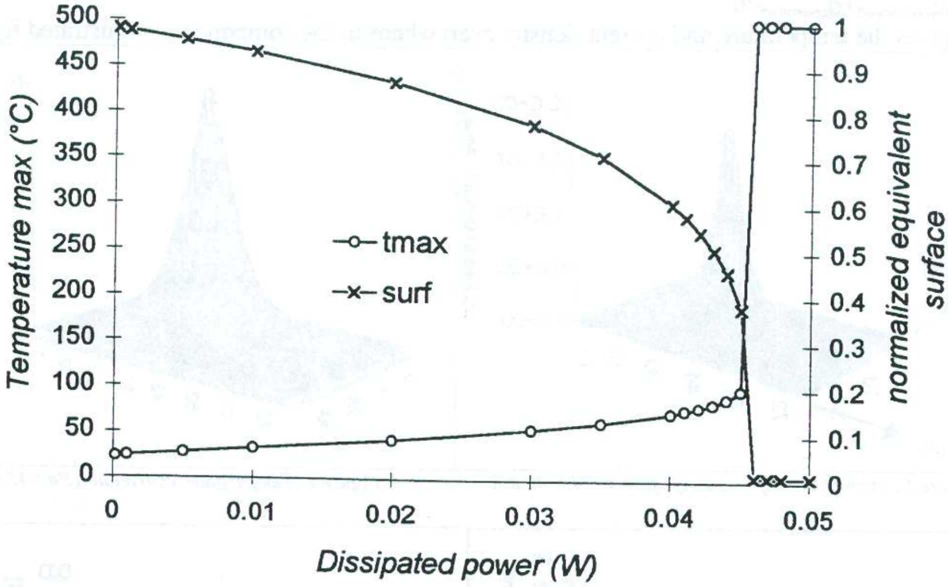


Figure 5b.

2) Electrical modeling

we use 1D or 2D hydrodynamic non-stationary physical models to extract the equivalent electrical circuit of the intrinsic device. This model resolves the semiconductors equations (current equation, Poisson equation, energy conservation ...) under static or dynamics conditions. From the computed distribution and evolution of the physical parameters under static or dynamic conditions we can derive the intrinsic equivalent electrical parameters Cbc,Cbe,Rbe,Rbc,Gm... All this elements are temperature dependent.

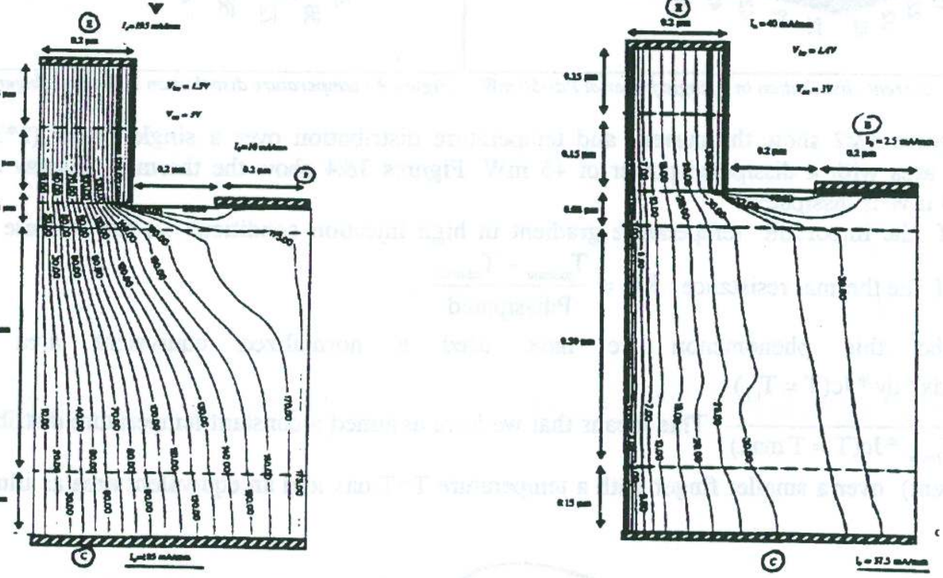
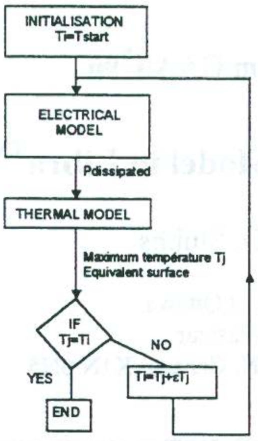


Figure 6 : Example of current distribution in a HBT at high and low injection level

The parasistics elements are computed using 2D and 3D electromagnetic softwares (HP-momentum and HP-HFSS). Static and RF measurements are also carried out to check the validity of these electrical linear and non-linear models.

3) Self-consistent electrothermal model

To find the temperature, we use a thermal balance procedure :



The maximum temperature and equivalent area of each finger in the HBT is computed by this procedure, using the convergence algorithm of the CAD software.

This model is implemented in the commercial CAD software HP-MDS.

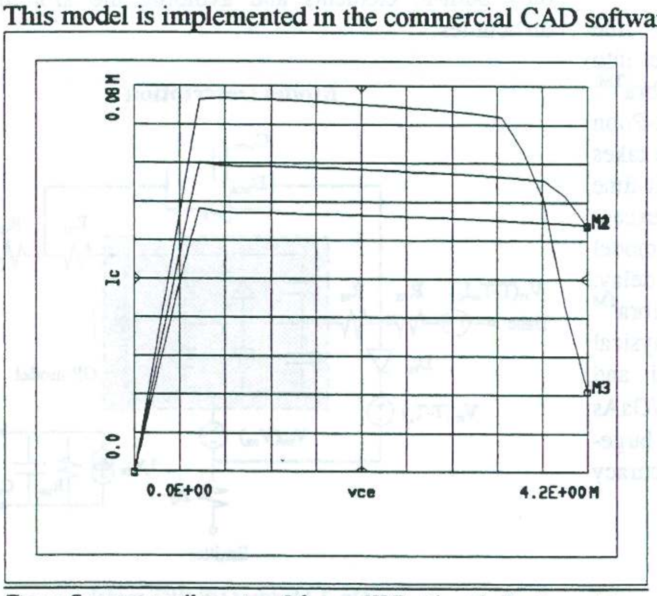
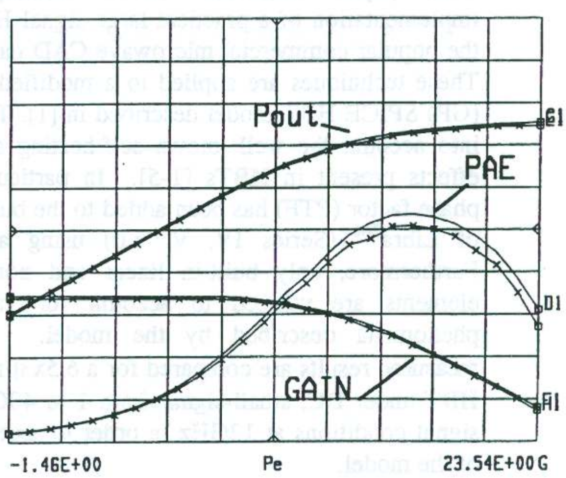


Figure 7 :current collpase in a 5 fingers HBT without ballasting resistor



- Simulated results
** experimental results*

figure 8 : example of an simulated amplifiers

It allows us to compute in a self consistent manner the thermal and electrical properties of the device under static or RF operating conditions. As an example this approach provides a realistic description of the crunch effect either in a single or multi-finger HBTs as illustrated figure 7 in the case of a 5 fingers GaInP/GaAs HBT. Figure 8 gives another example concerning a comparison between theoretical and experimental results on a power amplifier.

CONCLUSION :

This self consistent electrothermal model of multi fingers HBT which run under a commercial CAD software provides a precious tool for HBT devices and circuits optimization. Since it is based on physical modelling it can predict the behavior of new device structures thus saving time and money.

REFERENCES :

[1] W.M.Rohsenow,J.P.Hartnett and E.N Ganic "Hand book of heat transfer fundamentals" MacGraw-Hill Company

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[4] LL.Liou, B.Bayraktaroglu and C.I.Huang "Thermal Stability of multiple emitter finger microwave AlGaAs/GaAs HBT" IEEE MTT-S Digest 1993, pp281-284