# 3D SELF HEATING MODELING FOR ELECTRO-THERMAL CHARACTERISATION OF SiGe HBTs

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5th European HICUM Workshop
STMicroelectronics Crolles, France June 6-7, 2005

# Outline

I. Introduction

II. Modeling

III. Measurement verification

IV. Conclusions

# Introduction

SiGe heterojunction bipolar transistors (HBT SiGe) technologies are of great importance for the semiconductor market to produce high speed devices :

- Low cost and mature Technology
- High RF performances ( Ft, Ftmax, current gain)
- Low noise

→ High frequency performance
High current density

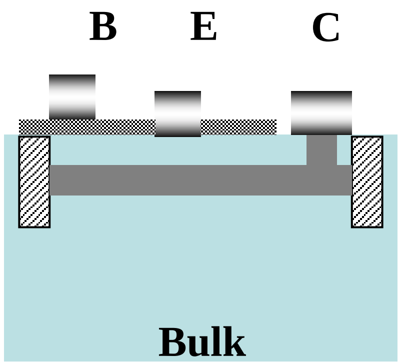
➢ High power effect : self heating

➢ Modification of the electrical parameters ( $I_B\uparrow$) …….$V_{BE}\downarrow$…performances drop

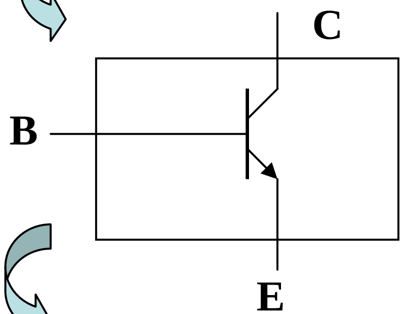
Work → Better understanding and Modeling electrical devices : HBT SiGe

# Modeling

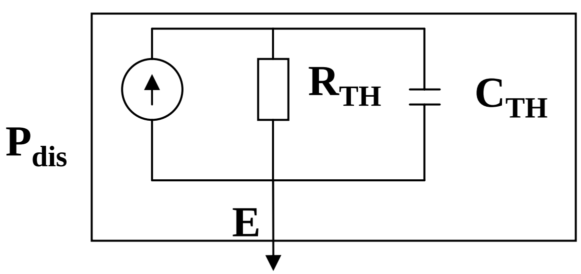
## Geometrical structure NPN




## Electrical représentation




## THERMAL Network




## Compact Models (Mextram, VBIC, HICUM) based on the equation [1]

$$\rho c \frac{\partial T(M,t)}{\partial t} = \nabla.\left(\lambda\left(T(M,t)\right)\nabla T(M,t)\right) + H$$

T(M,t) = Temperature [K]

λ(T(M,t)) = Heat conductivity [$Wm^{-1}K^{-1}$]

c = Heat capacity [$Jkg^{-1}K^{-1}$]

ρ = Density [$kgm^{-3}$]

H = Heat source : intrinsic transistor (Joule heat of phonons, electrons and holes, recombination heat, Peltier Thomson heat – Thermoelectric powers variation , radiation)

## Thermal network sub circuit

$$R_{TH} C_{TH} \frac{\partial T_j}{\partial t} = -(T_j - T_{amb}) + R_{TH} P_{dis}(t)$$

$$P_{dis}(t) \approx i_c(t) \times v_{ce}(t)$$

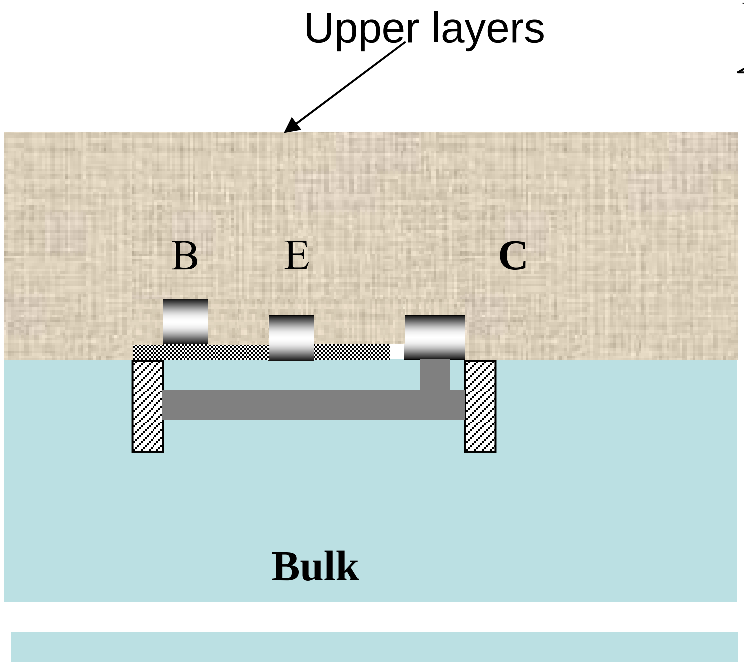
## Analytical solution

$$(T_j - T_{amb}) = R_{TH} P_{dis} \left[ 1 - \exp\left(\frac{-t}{R_{TH} C_{TH}}\right) \right]$$

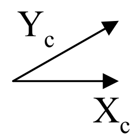

[1] – G. K. Wachutka – "Rigorous thermodynamic treatment of heat generation and conduction  in semiconductor device modeling" – IEEE Transactions oncomputer Aided Design, Vol.9,N°11,November 1990

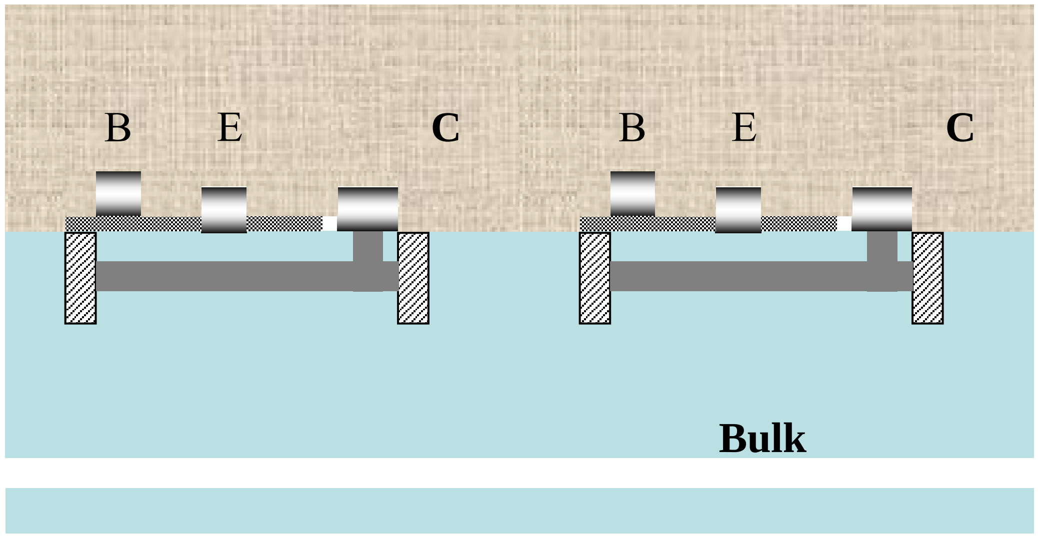
# Modeling

**Compact Model**




**Periodicity**




Experiment : $X_c$ and $Y_c$ ↑

Model validation

Real geometry : $X_c$ and $Y_c$ limited

Simulation

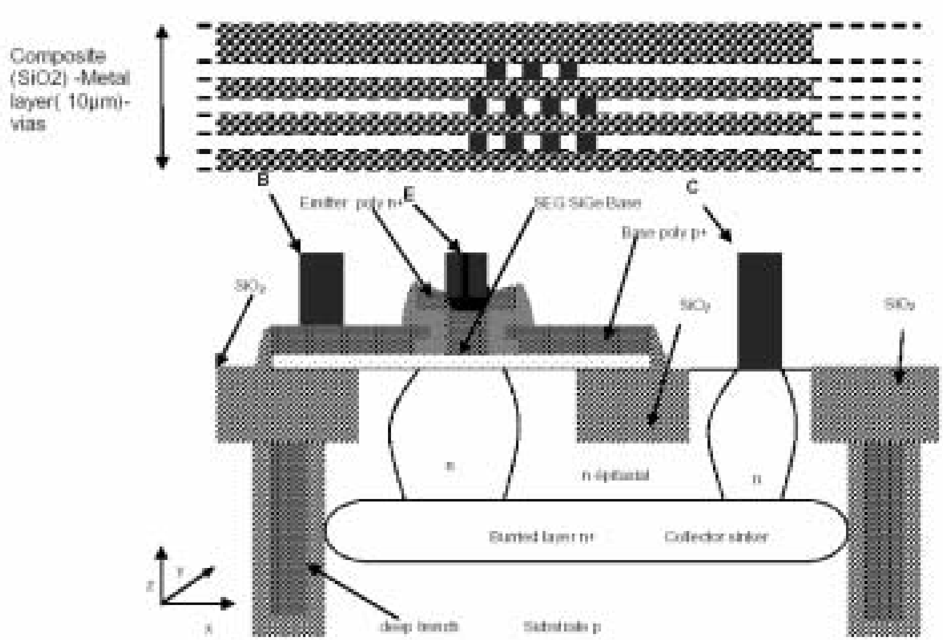
$R_{TH}$

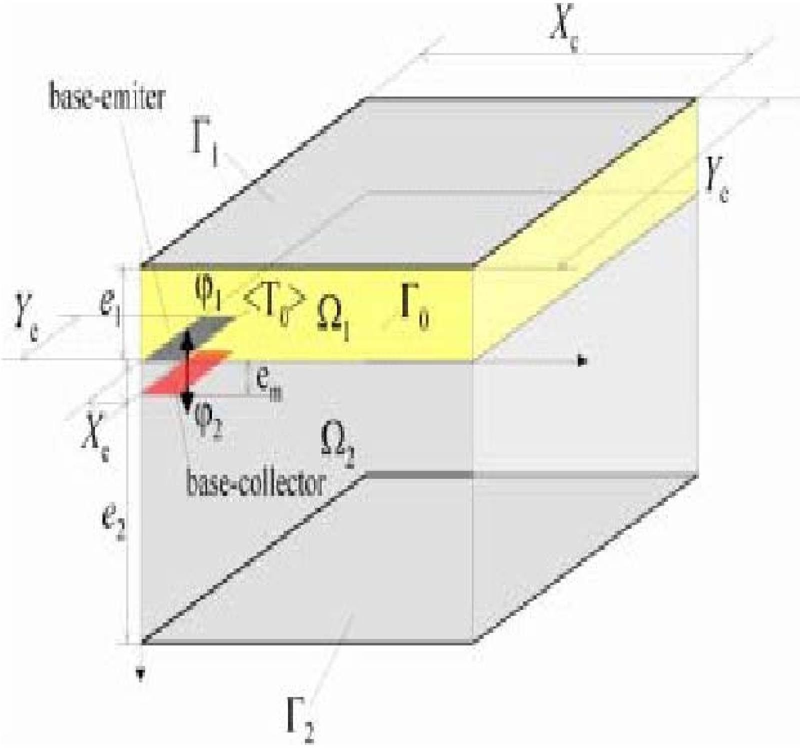
$C_{TH}$

# Modeling

## Compact Model

## Homogenization




Schematic cross section of the HBT SiGe

Transistor representation

<u>Layer 1</u>

Composite $SiO_2$ metal homogenized

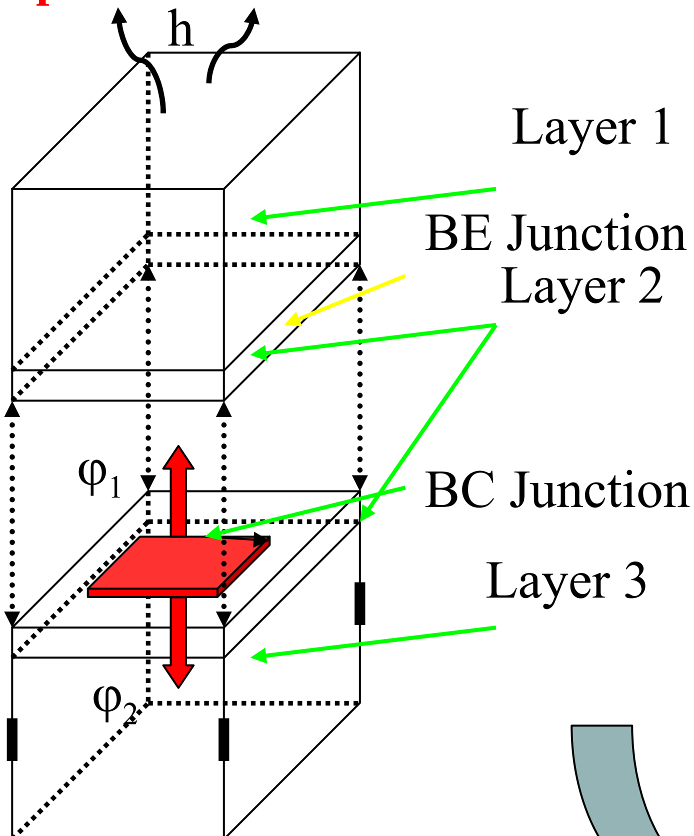
<u>Layer 2</u>

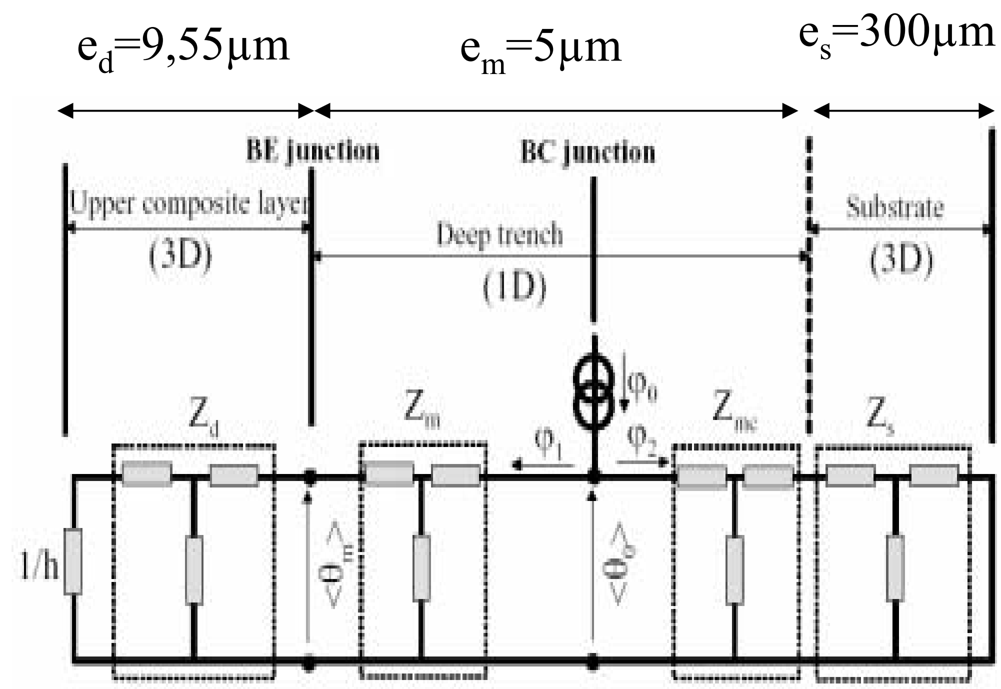
Deep trench and active transistor

<u>Layer 3</u> Substrate

# Modeling

**Compact Model**




HBT SiGe thermal network

Transistor representation

Layer 1

Composite $SiO_2$ metal homogenized

Layer 2

Deep trench and active transistor

Layer 3 Substrate

Composite $SiO_2$ metal homogenized parameters

$$\lambda_d = f\left(e_d, \frac{e_{Al}}{\lambda_{Al}}, \frac{e_W}{\lambda_W}, \frac{e_{SiO_2}}{\lambda_{SiO_2}}\right)$$

$$(\rho C_p)_d = g\left(e_d, (\rho C_p)_{Al} e_{Al}, (\rho C_p)_W e_W, (\rho C_p)_{SiO_2} e_{SiO_2}\right)$$

# Modeling

**Compact Model** **General resolution**

3D Heat diffusion equation

+

Heat generated BC junction H Heaviside function

$$\varphi = \varphi_0(t)\left[H(x) - H(x - X_e)\right]\left[H(y) - H(y - Y_e)\right]$$

+

Initial condition

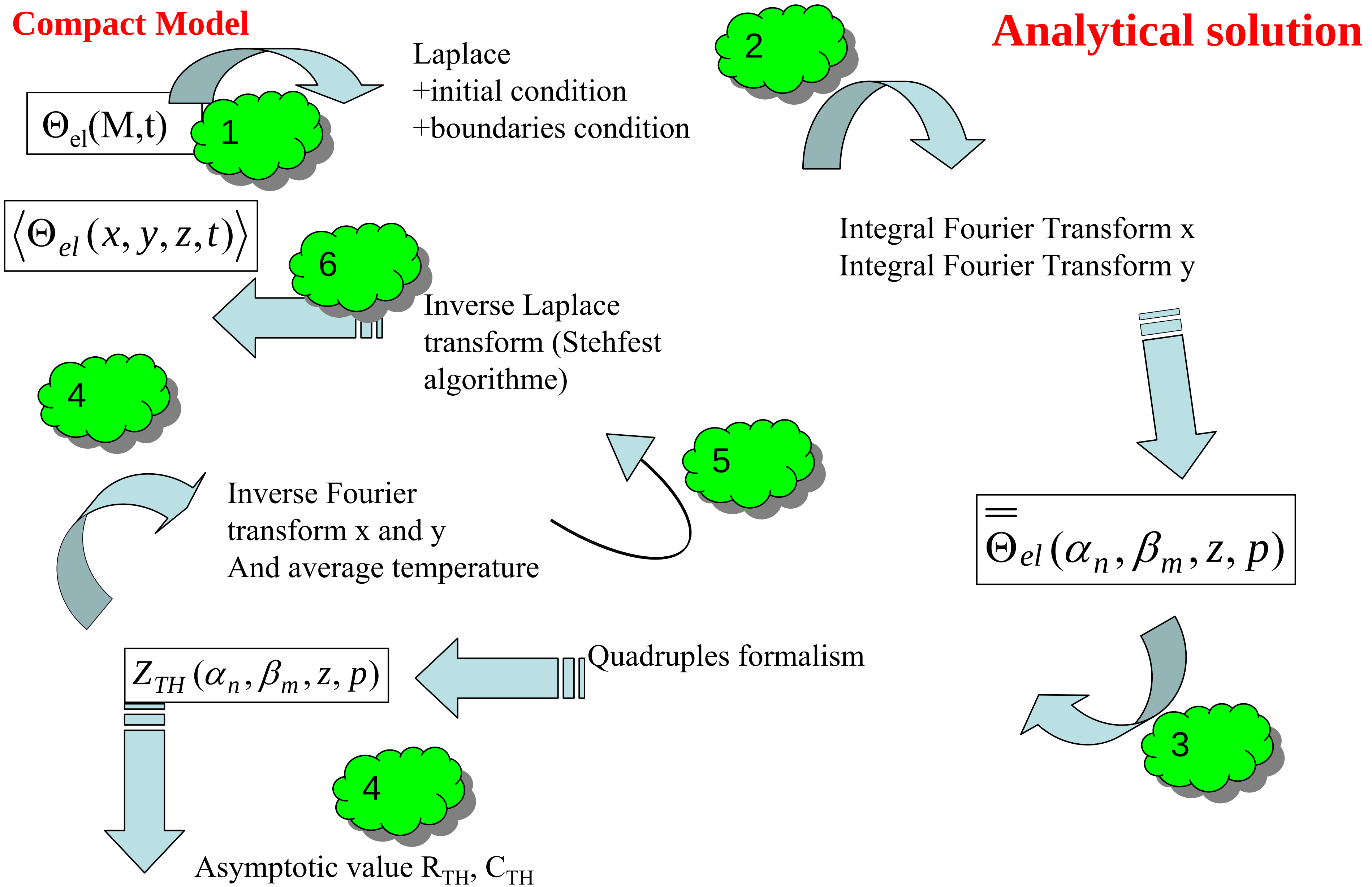
Boundaries conditions

+

Spatial periodicity
$x=0, y=0; x=X_c, y=Y_c$

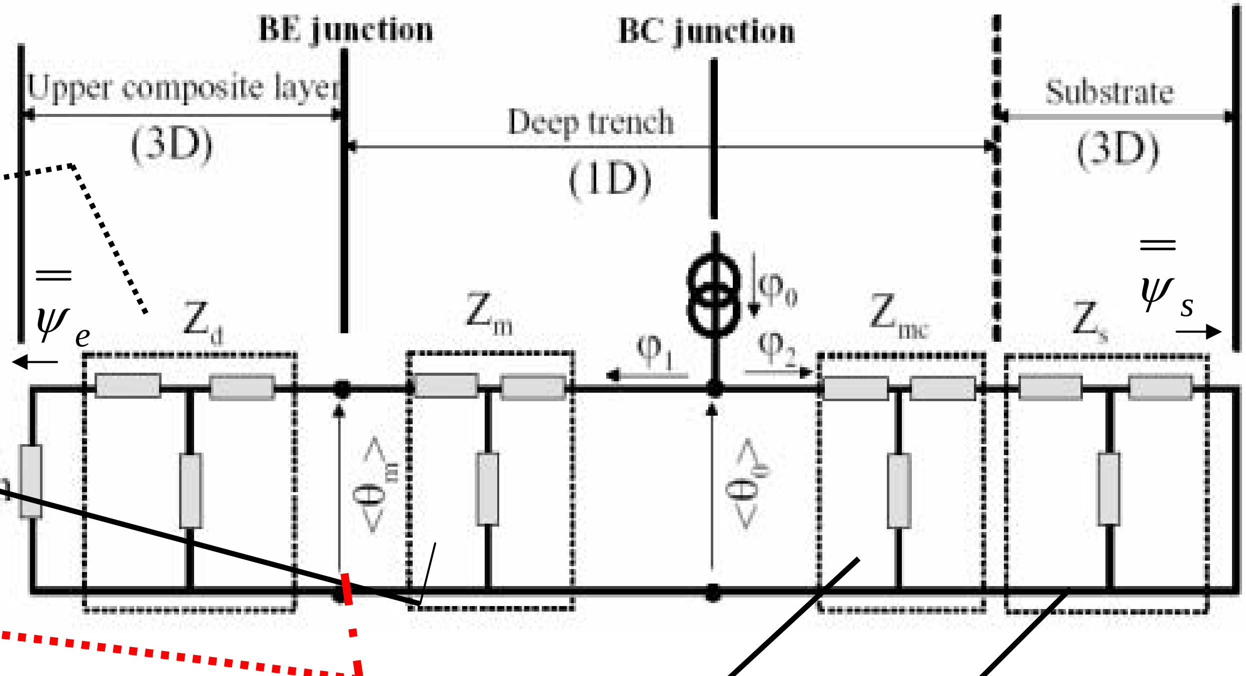
Analytical solution

# Modeling


Compact Model
Analytical solution
$\Theta_{el}(M,t)$
1
Laplace
+initial condition
+boundaries condition
2
Integral Fourier Transform x
Integral Fourier Transform y
$\overline{\overline{\Theta}}_{el}(\alpha_n, \beta_m, z, p)$
3
Quadruples formalism
$Z_{TH}(\alpha_n, \beta_m, z, p)$
4
Asymptotic value $R_{TH}$, $C_{TH}$
4
Inverse Fourier
transform x and y
And average temperature
5
$\langle \Theta_{el}(x, y, z, t) \rangle$
6
Inverse Laplace
transform (Stehfest
algorithme)

# Modeling

## Compact Model




$$\begin{bmatrix}\overline{\overline{\Theta}}_0\\ \overline{\overline{\psi}}_1\end{bmatrix}=\begin{bmatrix}A_m & B_m\\ C_m & D_m\end{bmatrix}\begin{bmatrix}A_d & B_d\\ C_d & D_d\end{bmatrix}\begin{bmatrix}\overline{\overline{\Theta}}_e\\ \overline{\overline{\psi}}_e=h\overline{\overline{\Theta}}_e\end{bmatrix}$$

$$\overline{\overline{\psi}}_e \qquad \overline{\overline{\psi}}_s$$

$$\overline{\overline{\Theta}}_m=\left(A_m-\frac{B_m}{Z_1}\right)Z_0\overline{\overline{\psi}}_0$$

$$Z_0=\frac{1}{\frac{1}{Z_1}+\frac{1}{Z_2}}\ ;\ \overline{\overline{\psi}}_0=\overline{\overline{\psi}}_1+\overline{\overline{\psi}}_2$$

$$Z_1=\frac{\overline{\overline{\Theta}}_0}{\overline{\overline{\psi}}_1}\quad ;\ Z2=\frac{\overline{\overline{\Theta}}_0}{\overline{\overline{\psi}}_2}$$

$$\begin{bmatrix}\overline{\overline{\Theta}}_0\\ \overline{\overline{\psi}}_2\end{bmatrix}=\begin{bmatrix}A_{mc} & B_{mc}\\ C_{mc} & D_{mc}\end{bmatrix}\begin{bmatrix}A_s & B_s\\ C_s & D_s\end{bmatrix}\begin{bmatrix}\overline{\overline{\Theta}}_s\\ \overline{\overline{\psi}}_s=h\overline{\overline{\Theta}}_s\end{bmatrix}$$

Quadruples formalism

# Modeling

**Compact Model** **Asymptotic behavior**

$$\overline{\overline{\Theta}}_m = \left( A_m - \frac{B_m}{Z_1} \right) Z_0 \overline{\overline{\psi}}_0$$

$$Z_{TH}(p) = \left( A_m - \frac{B_m}{Z_1} \right) Z_0$$

Asymptotic thermal resistance

$$\boxed{\mathrm{Z}_{\mathrm{TH}}(\mathrm{p} \to 0) \to \mathrm{R}_{\mathrm{TH}}}$$

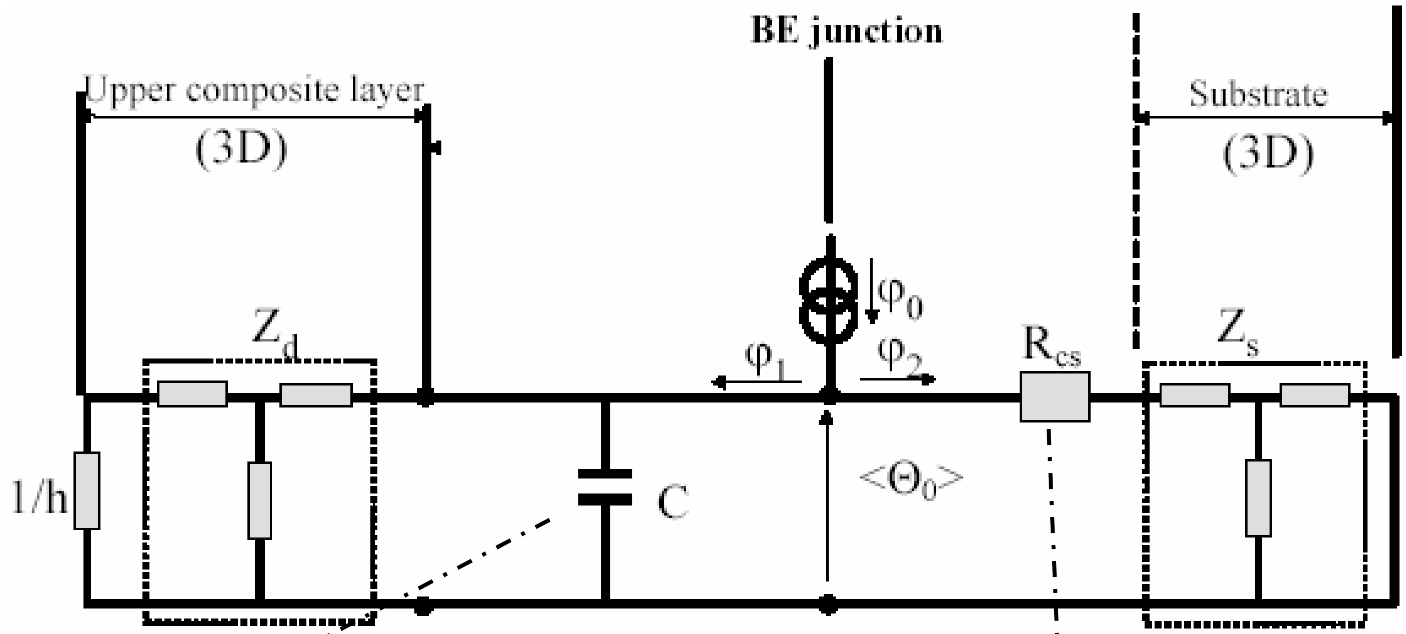
Asymptotic thermal capacitance

$$\boxed{Z_{TH}(p \to \infty) \to C_{TH}}$$

# Modeling

**Compact Model**

**Volume source assumption**




$$C = h\left(\left(\rho C\right)_m, e_m, \frac{S_D}{S_e}, S_e\right)$$ Volume source term

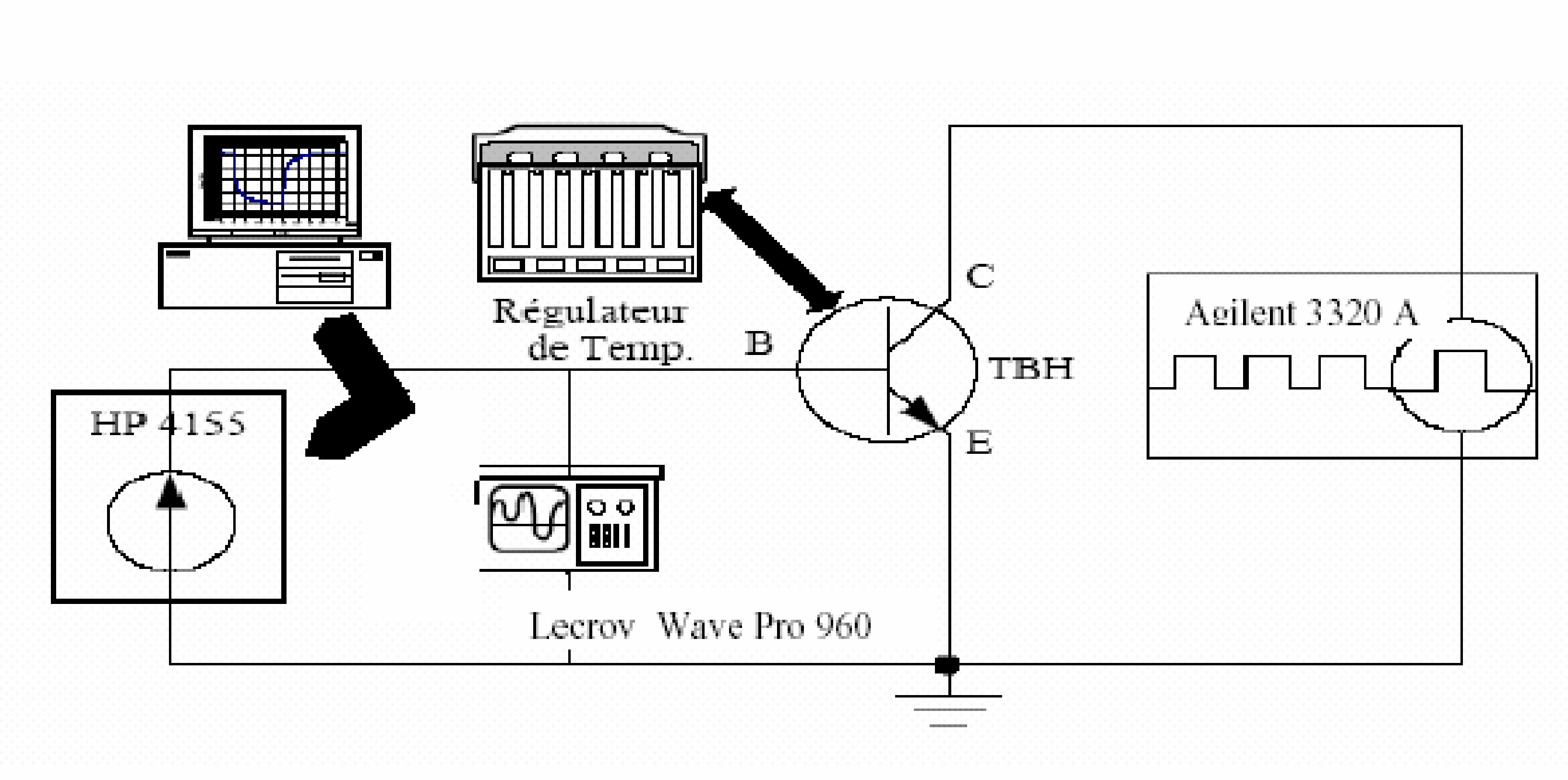
$$R_{cs} = \frac{e_m}{\lambda_m}$$

Asymptotic thermal resistance $\boxed{\mathrm{Z_{TH}}\left(\mathrm{p} \to 0\right) \to \mathrm{R_{TH}}}$

Asymptotic thermal capacitance $\boxed{Z_{TH}\left(p \to \infty\right) \to C_{TH} = R_{TH} \times \left(\sqrt{\lambda_d \left(\rho C\right)_d} + \sqrt{\lambda_s \left(\rho C\right)_s}\right)^2 + C}$

# Measurements verification

Five steps experimental verification

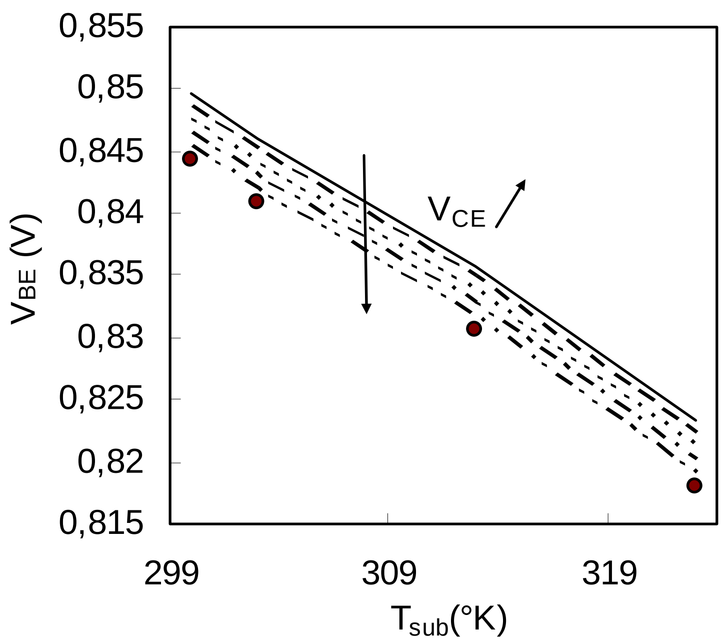



**General measurement set up**

# Measurements verification

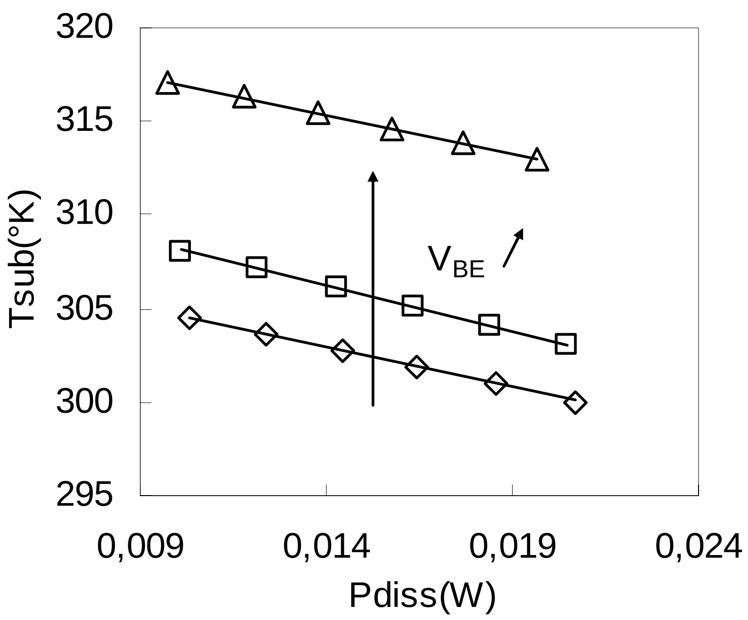
## DC

1




Calibration
$V_{BE}=f(T_i)$
$A_e$= cte ; $I_b=c^{te}$

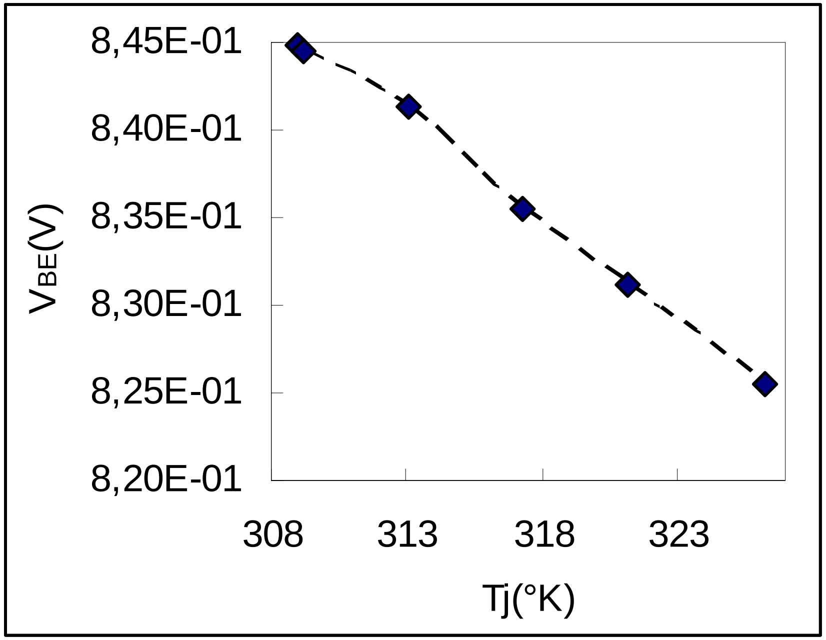
2




$T_{sub}=f(P_{diss})$
$A_e$= cte ; $V_{BE}=c^{te}$ ; $I_b=c^{te}$

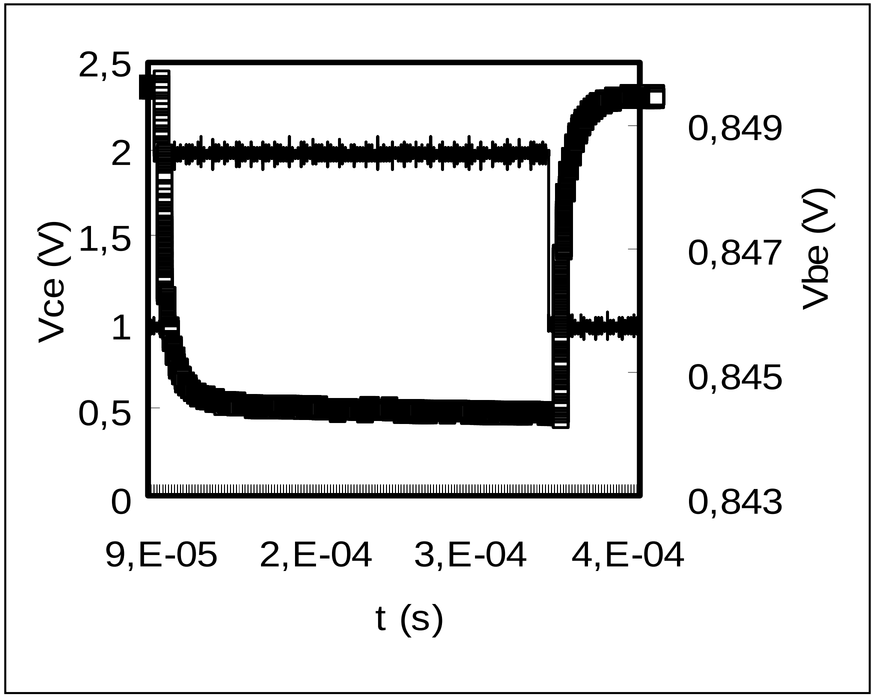
# Measurements verification

## DC 3




$V_{BE}=f(T_j)$
$A_e$=cte ; $V_{BE}=c^{te}$ ; $I_b=c^{te}$

## Transient 4

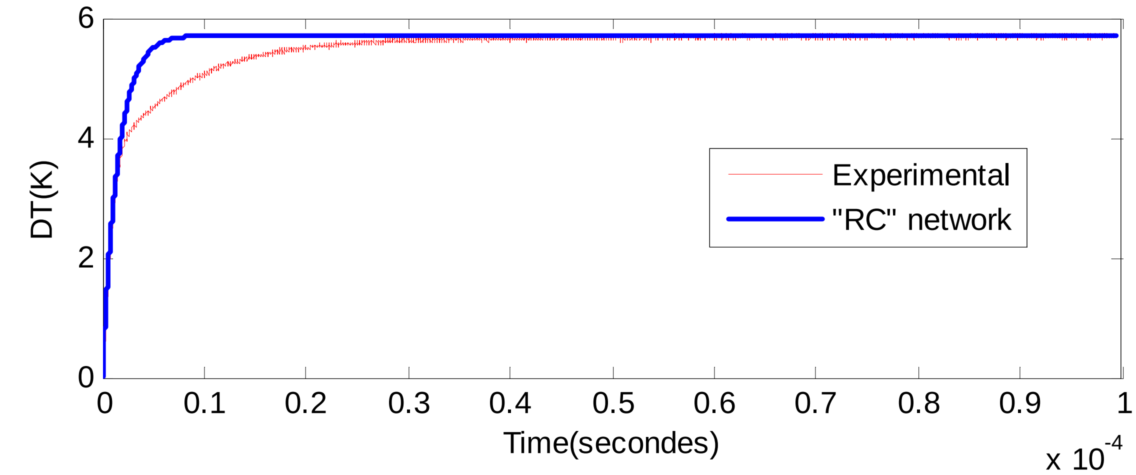


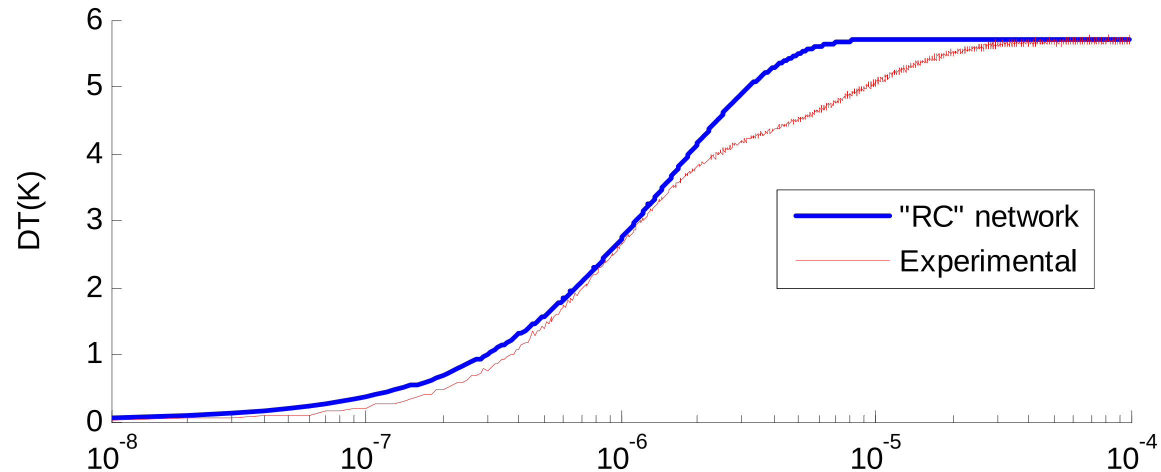

Measured
$V_{be}=f(t)$
$A_e$= cte ; $V_{CE}$=pulse[1;2]volts ; $I_b=c^{te}$

# Measurements verification

## Transient

5




$$DT = \mathrm{Pdis} \times \mathrm{R}_{\mathrm{TH}} \left(1 - e^{\left(-\frac{t}{\mathrm{R}_{\mathrm{TH}}\mathrm{C}_{\mathrm{TH}}}\right)}\right)$$

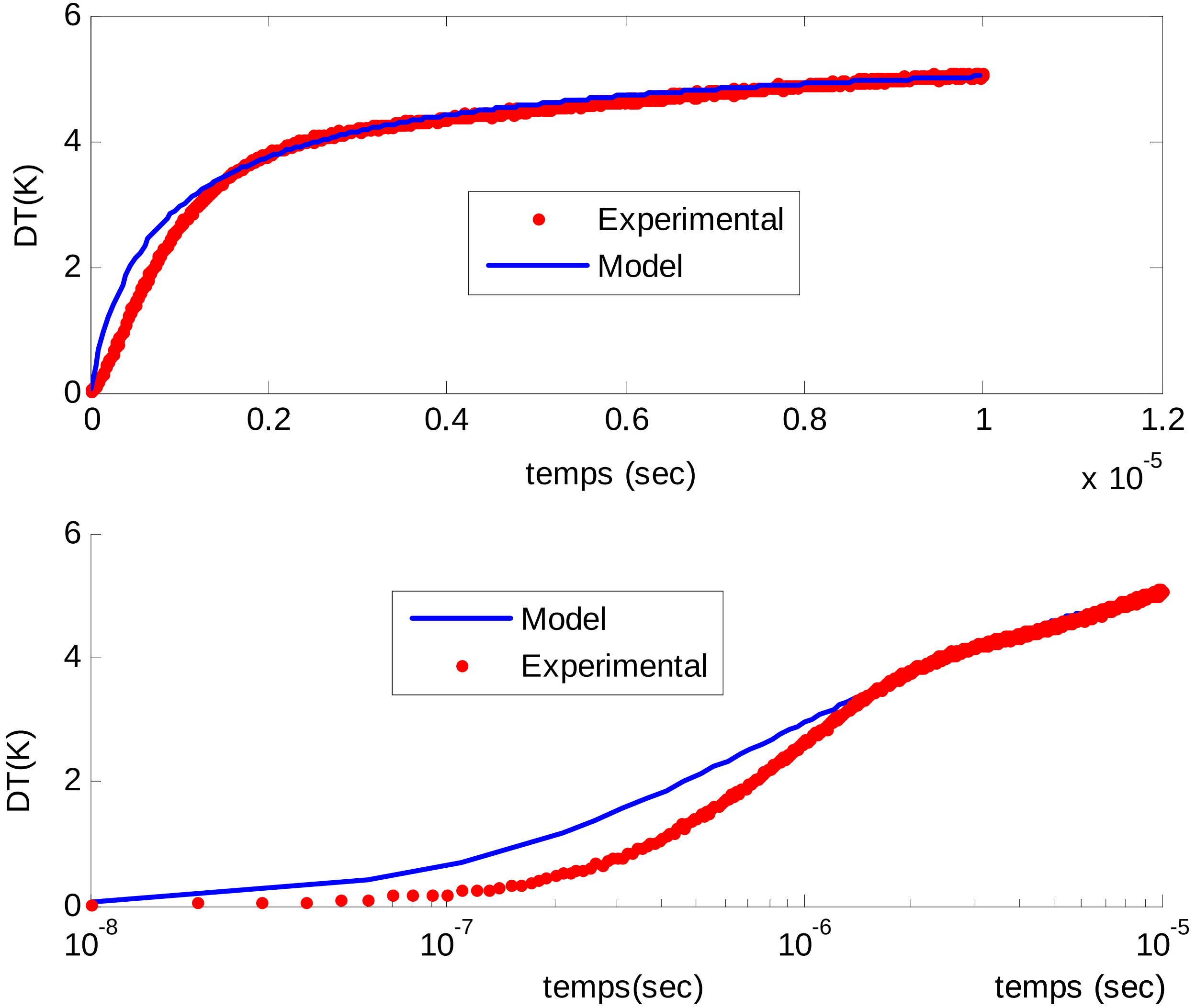
Thermogram :Tj=f(t) ; $A_e$=6,56µm²

# Measurements verification

**Measurements**

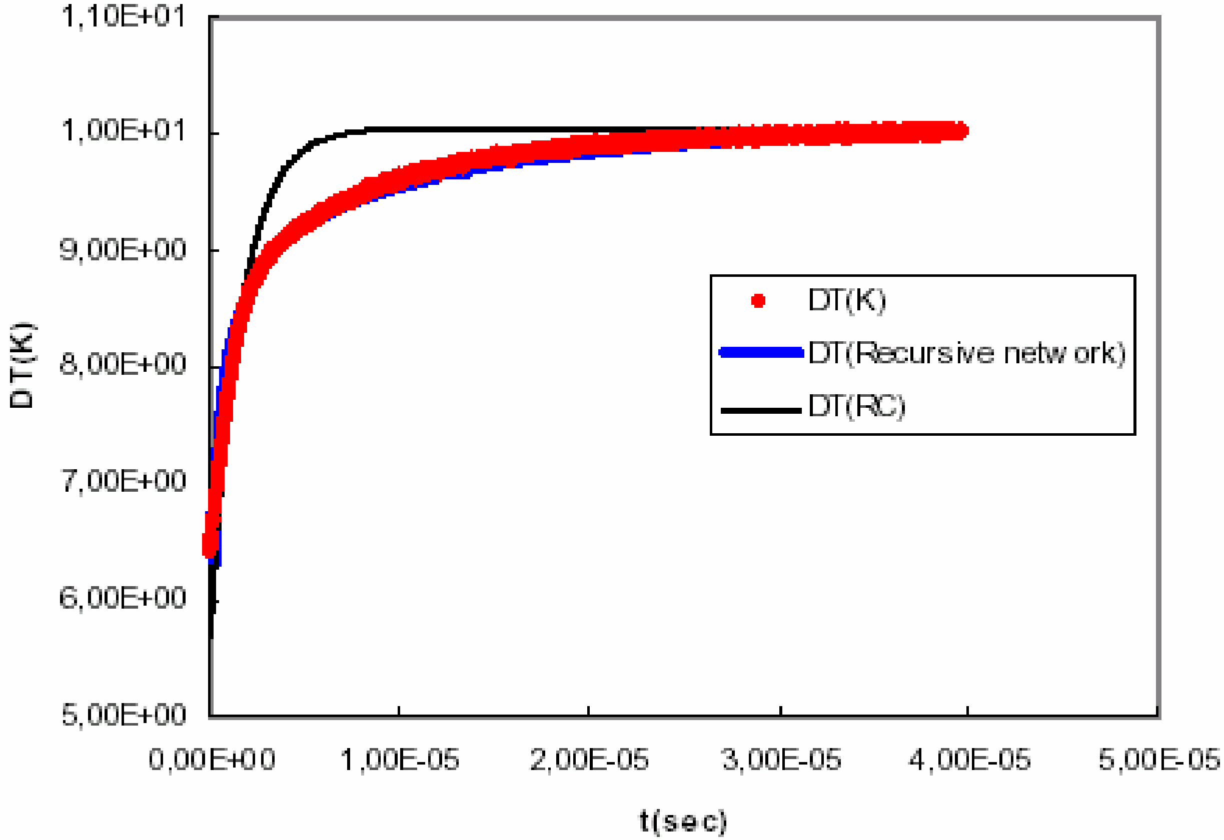
**Compact Model**

Thermogram –
Tj=f(t) $A_e$=6,56µm²



# Measurements perspectives

**Comparison**
**RC Network/Recursive Network**




Thermogram –
Tj=f(t) $A_e$=5*3,16µm²

# Conclusions

***Self Heating at a glance***

➢**Resolution of the heat equation in a real 3D HBT SiGe by a new dynamic model, with short calculations time**

➢**Determination of the thermal network parameters $Z_{TH}$ ($R_{TH}$ and $C_{TH}$) for standard self heating compact models**

➢**Very good agreement with experimental results**

➢**Simple thermal compact model to describe self heating phenomenon in electrical devices**

***Some perspectives***

**Simulation for smaller $X_C$ and $Y_C$ – $R_{TH}$ $C_{TH}$ dependence of ($X_C$ , $Y_C$ ) – Coupling phenomena structure**

➢**Developing the thermal model for HBT SOI technology**

➢**Development of the equivalent recursive network**

**Thanks for your attention**

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