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

P-Y. SULIMA, J-L BATTAGLIA, T. ZIMMER, H. BEKRICH, D. CELI

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

I. Introduction
II. Modeling
III. Measurement verification
IV. Conclusions
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, Fmax, current gain)
- Low noise

High frequency performance
High current density

- High power effect: self heating
- Modification of the electrical parameters (I_B↑) ……V_BE↓…performances drop

Better understanding and Modeling electrical devices: HBT SiGe
Modeling

**Geometrical structure NPN**

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

\[
\rho c \frac{\partial T(M,t)}{\partial t} = \nabla \cdot (\lambda(T(M,t)) \nabla T(M,t)) + H
\]

- \(T(M,t)\) = Temperature [K]
- \(\lambda(T(M,t))\) = Heat conductivity [Wm\(^{-1}\)K\(^{-1}\)]
- \(c\) = Heat capacity [Jkg\(^{-1}\)K\(^{-1}\)]
- \(\rho\) = 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**

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

Modeling

Compact Model

Upper layers

Periodicity

Yc
Xc

Experiment: $X_c$ and $Y_c \uparrow$

Model validation

Real geometry: $X_c$ and $Y_c$ limited

Simulation

$R_{TH}$  $C_{TH}$

Sulima Pierre-Yvan
Modeling

Compact Model

Schematic cross section of the HBT SiGe

Homogenization

Transistor representation
Layer 1
Composite SiO$_2$ metal homogenized
Layer 2
Deep trench and active transistor
Layer 3 Substrate

Sulima Pierre-Yvan
Modeling

Transistor representation

Layer 1
Composite SiO₂ metal homogenized

Layer 2
Deep trench and active transistor

Layer 3 Substrate

Compact Model

HBT SiGe thermal network

Composite SiO₂ metal homogenized parameters

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

\[
\left(\rho C_p\right)_d = g\left(e_d, \left(\rho C_p\right)_{Al} e_{Al}, \left(\rho C_p\right)_{W} e_W, \left(\rho C_p\right)_{SiO_2} e_{SiO_2}\right)
\]
Modeling

Compact Model

General resolution

3D Heat diffusion equation

Heat generated BC junction \( H \) Heaviside function

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

Initial condition

Boundaries conditions

Spatial periodicity
\( x=0,y=0;x=X_e,y=Y_e \)

Analytical solution
Modeling

Compact Model

\[ \Theta_{el}(M,t) \]

Laplace
+ initial condition
+ boundaries condition

\[ \langle \Theta_{el}(x, y, z, t) \rangle \]

Inverse Laplace transform (Stehfest algorithm)

Inverse Fourier transform x and y
And average temperature

\[ Z_{TH}(\alpha_n, \beta_m, z, p) \]

Asymptotic value \( R_{TH}, C_{TH} \)

Analytical solution

\[ \Theta_{el}(\alpha_n, \beta_m, z, p) \]

Integral Fourier Transform x
Integral Fourier Transform y

Quadruples formalism
Modeling

Compact Model

\[
\begin{bmatrix}
\Theta_0 \\
\psi_1
\end{bmatrix} =
\begin{bmatrix}
A_m & B_m \\
C_m & D_m
\end{bmatrix}
\begin{bmatrix}
A_d \\
C_d
\end{bmatrix}
= \Theta_e
\]

\[
\psi_e = h\Theta_e
\]

\[
\Theta_m = \left(A_m - \frac{B_m}{Z_1}\right)Z_0 \psi_0
\]

\[
Z_0 = \frac{1}{\frac{1}{Z_1} + \frac{1}{Z_2}}; \quad \psi_0 = \psi_1 + \psi_2
\]

\[
Z_1 = \frac{\Theta_0}{\psi_1}; \quad Z_2 = \frac{\Theta_0}{\psi_2}
\]

Quadruples formalism

\[
\begin{bmatrix}
\Theta_0 \\
\psi_2
\end{bmatrix} =
\begin{bmatrix}
A_{mc} & B_{mc} \\
C_{mc} & D_{mc}
\end{bmatrix}
\begin{bmatrix}
A_s \\
C_s
\end{bmatrix}
= \Theta_s
\]

\[
\psi_s = h\Theta_s
\]
Modeling

Compact Model

Asymptotic behavior

\[ \Theta_m = \left( A_m - \frac{B_m}{Z_1} \right) Z_0 \psi_0 \]

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

Asymptotic thermal resistance

\[ Z_{TH}(p \to 0) \to R_{TH} \]

Asymptotic thermal capacitance

\[ Z_{TH}(p \to \infty) \to C_{TH} \]

Sulima Pierre-Yvan
Modeling

Compact Model

Volume source assumption

\[ C = h((\rho C)_m, e_m, \frac{S_D}{S_e}, S_e) \]

Volume source term

Asymptotic thermal resistance

\[ Z_{TH} (p \to 0) \to R_{TH} \]

\[ R_{cs} = \frac{e_m}{\lambda_m} \]

Asymptotic thermal capacitance

\[ Z_{TH} (p \to \infty) \to C_{TH} = R_{TH} \times (\sqrt{\frac{\lambda_d}{\rho C_d}} + \sqrt{\frac{\lambda_s}{\rho C_s}})^2 + C \]

Sulima Pierre-Yvan
Measurements verification

Five steps experimental verification

General measurement set up
Measurements verification

DC

1

![DC graph]

Calibration

\[ V_{BE} = f(T_i) \]

\[ A_e = \text{cte} ; I_b = e^{cte} \]

2

![DC graph]

\[ T_{sub} = f(P_{diss}) \]

\[ A_e = \text{cte} ; V_{BE} = e^{cte} ; I_b = e^{cte} \]

Sulima Pierre-Yvan
Measurements verification

**DC**

\[ V_{BE} = f(T_j) \]
\[ A_e = \text{cte} ; \quad V_{BE} = c^e ; \quad I_b = c^e \]

**Transient**

\[ V_{be} = f(t) \]
\[ A_e = \text{cte} ; \quad V_{CE} = \text{pulse}[1;2] \text{volts} ; \quad I_b = c^e \]

Sulima Pierre-Yvan
Measurements verification

Transient

5

\[ DT = P \text{dis} \times R_{TH} \left( 1 - e^{-\frac{t}{R_{TH}C_{TH}}} \right) \]

Thermogram: \( T_j = f(t) \); \( A_e = 6.56 \mu m^2 \)

Sulima Pierre-Yvan
Measurements verification

Measurements

Compact Model

Thermogram –
$T_j=f(t)$ $A_c=6.56\mu m^2$

Sulima Pierre-Yvan
Measurements perspectives

Comparison
RC Network/Recursive Network

Thermogram –
\[ T_j = f(t) \ A_c = 5 \times 3,16 \mu m^2 \]
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

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

Sulima Pierre-Yvan