Investigation of transient intra-device thermal coupling


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Outline

• Temperature issues in multifinger SiGe HBTs
• Transient thermal coupling modeling
• TCAD thermal simulations
• Measurement of thermal coupling in pulsed operation
• Conclusions
Temperature issues in multifinger SiGe HBTs

High current densities and high internal electric fields at the BC junction that can be considered as a heat source.

INTRA-device thermal issues

Increase of device SELF HEATING and MUTUAL HEATING between the emitter stripes that shift the device DC and AC electrical characteristics. These effects are worsened by the presence of positive electro-thermal feedback.

To achieve high speed performances SiGe HBTs undergo an aggressive shrinking of device dimensions.

To achieve high power at high frequencies the transistors are often designed in a multiple finger layout.

http://users.ece.gatech.edu/cressler/
Thermal instability in multifinger SiGe HBTs

Complex mutual thermal interaction between the emitters

Formation of hot spot: may lead to thermal runaway and performance degradation

3D TCAD thermal simulation: 24mW power dissipation on the emitter stripes

Need to include these effects into compact models for an optimized design of circuits at mmW
It is possible to model a multifinger component using one transistor model element per finger.
Network to model DC thermal coupling

The new thermal network takes into account the thermal interaction between the emitter stripes as expressed by:

\[ T_1 = R_{th1}P_{d1} + R_{th2}P_{d2} = R_{th1}P_{d1} + c_{12}R_{th2}P_{d2} = R_{th1}P_{d1} + c_{12}\Delta T_2 \]
\[ T_2 = R_{th_{21}}P_{d1} + R_{th2}P_{d2} = c_{21}R_{th1}P_{d1} + R_{th2}P_{d2} = c_{21}\Delta T_1 + R_{th2}P_{d2} \]

- \( P_{d_x} \) dissipated power on finger \( x \)
- \( \Delta T_x \) temperature rise of finger \( x \)
- \( C_{xy} \) coupling coefficient of finger \( y \) on finger \( x \)
- \( R_{th_{in}} \) thermal resistance

Measurements for the verification of the DC thermal coupling model (INTRA-device)

Measurements on special test structures:

- fingers are thermally coupled, but electrically separated

It is possible to use each finger as a heater, turning it on, or as a temperature sensor, measuring the shift in its $I_E(V_{BE})$ characteristics

$C_{xy}$ coupling coefficients are measured and used in the thermal coupling network

Improvement of the accuracy of the DC curves considering the mutual thermal coupling

Modeling of transient mutual thermal coupling

case of pulses of power dissipation: the transient temperature doesn’t reach the
steady state value (like in switching applications)

- Model by Zimmermann et al.

Physical analysis of the structure

The zone below the heat sources has spherical isothermal contours

An infinite number of RC poles is theoretically needed

Thermal resistance and capacitance are given by:

\[
\Delta R(T) = \frac{1}{k(T) A(\xi)} \Delta \xi
\]

\[
\Delta C(T) = \frac{k(T)}{\alpha} A(\xi) \Delta \xi
\]
The model proposed for transient mutual thermal coupling

1. The model we propose

\[
\begin{align*}
R_{th_{jn}} &= k_r^n R_j \\
C_{th_{jn}} &= k_c^n C_j
\end{align*}
\]

- \( k_r < 1 \)
- \( k_c > 1 \)

• 3 time constants RC circuit

• Delay network: takes into account the delay in the propagation of heat from one heat source to another

• Temperature dependency of thermal conductivity with:

\[
R_{th}(T) = R_{th}(T_0) \left( \frac{T}{T_0} \right)^\alpha
\]

Validation of the model with 3D TCAD thermal simulations

Structure reproduces a 5x(CBEBC) SiGe HBT component

- DTI and STI isolation
- emitters are assumed to be the heat sources
- drawn emitter area $A_E = 0.18 \times 5 \ \mu m^2$
- pulses of power dissipation: 10mW per finger

2 different cases are considered:

- all the emitters are dissipating power
- just one emitter is dissipating power
Thermal distribution along the x axis when just one source is heating

Calculation of the coupling coefficients for different distances

The model can predict the temperature at various distances from the heat source

Thermal distribution along the x axis when just one source is heating
Modeled and simulated temperature evolution vs time

• Just finger 1 heating

It is possible to quantify the delay in the time response.
Effect of the DTI and of the thermal coupling: finger 3 is the hottest

Modeled and simulated temperature evolution vs time

• All the 5 fingers heating
Effect of the thermal coupling on the temperature evolution of the finger

- when all the fingers are heating (included finger 3)
- when it is the only heater in the structure

Temperature evolution of the central finger:

- when all the fingers are heating (included finger 3)
Pulsed measurements

On-wafer measurements on a 5x(CBEBC) in STMicroelectronics BiCMOS 55 technology

- SÜSS MicroTec probing station with thermal chuck at 300°K
- probing with 2 differential GSGSGG probes (SÜSS) and 2 GSG probes (Picoprobe)
- common collector constantly biased using an HP4155A DC analyzer
- DC analyzer Keithley 4200 containing a 4225-PMU module to generate the pulses on the heating finger and measure the response on the sensing finger

The temperature increase of the heating finger will induce a shift in the DC characteristics of the sensing finger (current increases)
Results from the measurements and comparison with the model

Current increase on fingers 1, 4 and 5 due to heat generated by finger 2
The sensing finger dissipates a small amount of power, which gives a small increase on the current of the heating finger.
Conclusions

• A netlist based model has been proposed to model the transient thermal coupling in multifinger SiGe HBTs, based on some considerations on the temperature distribution in the structure

• The model has been validated with the aid of 3D thermal TCAD simulations and found to be in good agreement

• On-wafer pulsed measurements have been conducted as well
Acknowledgments

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Thank you for your attention !!!
Temperature decay along $x$

\[ T \propto T_{\text{max}} \cdot \sqrt{\frac{a}{x^n + a}} \]
Finger 3 heating alone or with all other fingers

The thermal coupling from heat sources in proximity leads to an increase of the R and C

Comparison of the thermal evolution

Fitting realized just with a 3 poles recursive network, no coupling

Kr and Kc are kept the same

The **thermal coupling** from heat sources in proximity leads to an increase of the R and C
Model parameters

- 3 poles recursive Cauer network
- $R_{th}$ and $C_{th}$ for each finger
- $K_c$ and $K_r$ multiplying factors of the recursive network
- $C_{coupl}$ and $Exp_{Coupl}$ for the function describing the coupling coefficients versus distance
- $C_{coupl}$ for the delay in the coupling
- $Alfa$ for the temperature dependent thermal conductivity

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