

## Modelling and Simulation of Heterojunction Bipolar Transistors for THz Applications

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# Modeling and characterization of HBT in THz range

### Outline

- Introduction
  - THz spectrum, Si vs GaAs, THz application, SiGe roadmap
- State of the art SiGe HBT THz technology and modelling
- Electro-thermal investigations for modelling
- Can we trust the measurements beyond 100GHz ?
- Conclusion





# The THz range

#### Where can we use silicon?



# THz: Si vs GaAs (III-V)

### Impact of SiGe HBT BiCMOS on Radar Sensors



# Si-THz Near-Field Imaging Sensor at 0.5 THz

### **Ex Vivo Breast Tumor Identification**



Illustration of the conceptual sensor operation principle



Picture of the packaged imaging module with a 50 cent euro coin for size comparison.



Optical microscopic image of a 5  $\mu$ m thick deparaffinized breast tissue a). Associated THz near-field image in direct contact b). Image size is 142 x128 pixel at 22  $\mu$ m x 25  $\mu$ m)

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Source: U. R. Pfeiffer et. al., Microwave Magazine, Sept.-2019

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# Si-THz technology

### SiGe HBT Technology Evolution



# Si-THz technology

### State-of-the-art BiCMOS

Self-aligned architectures have been widely adopted for modern highspeed Si/SiGe:C HBTs:  $f_T$ >200GHz,  $f_{max}$ >300GHz

Substrate

Salicide
Contacts
Cu BEOL



Source: P. Chevalier, DOT7 WS, 2015

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# Si-THz technology

### State-of-the-art SiGe HBT with fT/fmax of 505 GHz/720 GHz



#### $j_c = 30 \text{ mA}/\mu m^2 = 30.000 \text{ A}/\text{mm}^2 \text{!!!}$

# SiGe-THz HBT compact modelling



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# Self-Heating and thermal coupling (1/4)

### Pulsed measurement system



Experimental set-up of the PMS, where DC and RF pulses are applied through the DC and RF ports of the bias tees at the base and the collector of the DUT.

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# Self-Heating and thermal coupling (2/4)

#### Pulsed measurement system: results



Output characteristics for V\_{BE} = 0.95 V measured with various pulse widths from 80 ns up to 50  $\mu s$ 



 $f_{\rm T}$  versus  $V_{BE}$  measured with 150 ns, 300 ns and 1  $\mu s$  pulse widths at constant  $V_{CE}$  = [0.5, 1.5] V

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# Self-Heating and thermal coupling (3/4)

### Investigation of Back-End-Of-line contribution





3D images of the standard test-structure M1 (a) and test-structure M6 with metal stacks above the emitter (b).



Cauer-type recursive network used to model the thermal impedance. The dissipated power Pd flows in the lower part (FEOL) and in the BEOL part

1200 Zth VM1 Zth VM3 1000 Zth VM6 mag(Z<sub>th</sub>) (K/W) 800 Zth VM8 600 400 200 1.0E+06 1.0E+04 1.0E+05 1.0E+07 1.0E+08 1.0E+09

Frequency (Hz)

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Extracted Zth from low frequency S-parameters measurements for the VM test structures

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# Self-Heating and thermal coupling (4/4)

DT

Intrinsic Si substrate

ST

FEOL

#### V<sub>BE</sub>=0.80V 120 Focus on thermal coupling: Measurement vs theory V<sub>BF</sub>=0.85V 100 V<sub>BE</sub>=0.90V Measurement: 80 V<sub>BE</sub>=0.95\ I<sub>c</sub> [mA] Ŧ 60 40 E1 20 Ts. T4 T1 T2 Тa 0.0 0.5 1.0 1.5 V<sub>CF</sub> [V] Measured (symbols) and simulated (lines) output Schematic diagram and layout of the test structures characteristics of a multi-emitter transistor. Theory: WF = 0.2 µm 420 Nith ST+DT $L_F = 5 \mu m$ **M8** Fin-1 Fin-3 **Thermal Coupling** 390 BEOL Factors in Multi-emitter With STI L<sub>jj</sub> (K) 360 structure, M No trench A. Gupta et al, M1-M5 IIT Madras, UB, ALL AND REPORT AND ALL O , A TCAD A THE DOLLAR A DR 330 to be published model (5)

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300

n

10

20

RTH,m = 18.5 k K/W

30

Pdiss (mW)

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40

50

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## Can we trust the measurements beyond 100GHz ?

### HICUM modelling vs measurement in THz range

 Comparison of the de-embedded measurement with HICUM model : (Device : STM's B55, Real dimensions 0.09 x 4.8 μm<sup>2</sup>)



Can we trust the measurement in the THz range?

- Measurement can be subject to many uncertainties
- Since HICUM not verified through measurements for high frequency, it cannot be considered as reference

 $\Rightarrow$  TCAD simulation can be used as a reference to settle the problem

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# **TCAD** simulation

### TCAD calibration and comparison to measurement

#### TCAD structure (information comes only from thesis and published work), Sentaurus



- Models:
  - Hydrodynamic model
  - Effective Intrinsic density
  - Band Gap Narrowing
  - Mobility models (like doping dependence and high field saturation)
  - SRH and Auger models are also included to account recombination
  - Parameters are calibrated from Monte Carlo simulation [F. M. Bufler, Full-band Monte Carlo simulation of electrons and holes in strained Si and SiGe. Herbert Utz Verlag, 1998]





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Tuan Van Vu , PhD thesis

# **TCAD** simulation

### TCAD calibration and comparison to measurement

#### DC characteristics

#### **CV** characteristics

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f_T(I_C)
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Measured vs. TCAD simulated Gummel characteristics

# TCAD simulation vs measurement in THz range

### TCAD comparison to measurement

Transmission coefficient



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Very good matching on magnitude and phase S21

# TCAD simulation vs measurement in THz range

### TCAD comparison to measurement

#### Assessment freq (GHz) 500 450 400 350 300 250 200 150 100 50 0 Mag (S12) Mag (S11) Phase Phase Mag (S21) Phase Mag (S22) Phase (S11) (S12) (S21) (S22)

- No global upper validity range
- The validity is dependent on:
  - the S-parameter itself
  - the geometry
  - the applied bias
- Issues with reflection coefficient?

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### **Measurement Set-up and test-structures**

### Measurement Set-up

- Four measurement benches are used for covering 1-500 GHz
- Agilent's E8361A VNA up-to 110 GHz using extenders (N5260-60003) above 67 GHz
- 140-220 GHz, 220-330 GHz & 325-500 GHz bands with a four-port Rohde & Schwarz ZVA24 VNA coupled with extenders (ZC220-ZC330-ZC500)



### **Test-structures layout**

Topview



Floor Plan

DUTs are well spaced to avoid neighboring effects

- Measurement Probe positioning errors (Thru to Line)
- Contact issue
  - □ AI pads
  - Multiple contacts on same pad

### Coupling with other test-structures

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#### EM simulation vs measurements

Photo of probes for different frequency bands and equivalent picture for EM simulation





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### EM simulation vs measurements

### Signature of probes and substrate to probe coupling







140-220 GHz

220-325 GHz





Electric field (E-field) distribution (top and side views) in the transistor-open at 220 GHz using two probe models

Due to gap between G-S-G in probes

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### EM simulation vs measurements

### Impact of neighbours



DUT : Line

TRL Calibrated measurement and EM simulation



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# TCAD simulation vs measurement in THz range

### Conclusion on the range of validity



Improvement ! Shift in reference plane cancels distributive effects Mag(S11) & other parameters are not improving equally, still investigation is in progress

# Modeling and characterization of HBT in THz range

### Conclusion

- SiGe HBT technology enters the THz range
- HICUM electrical compact model able to fit most of electrical characteristics; Improvements possible for

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- Collector Substrate modelling
- NQS modelling
- Thermal impedance modelling
  - Pulsed measurements
  - BEOL contribution
  - Thermal coupling
- Can we trust the measurements beyond 100GHz ?
  - Measurement has been performed up to 500 GHz
  - TCAD has been calibrated and used for verification
  - Identification of problems in Sxx parameters above 300 GHz
  - Revisiting OS de-embedding -> limits of lumped element approach
- Outlooks
  - Nothing will stop THz on Si





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