TCAD versus High Frequency Measurements of SiGe HBTs

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TCAD simulation vs measurement in THz range

Outline

- Motivation
  - Is the measurement accurate?
  - A view to test-structures

- TCAD calibration and comparison to measurement at high frequency

- Discussion on the range of validity

- Discussion of measurement issues

- Conclusion
HICUM modelling vs measurement in THz range

Outline: Is the measurement/model accurate?

- Comparison of the de-embedded measurement with HICUM model:
  (Device: STM's B55, Real dimensions 0.09 x 4.8 \( \mu \text{m}^2 \))

Can we trust the measurement above 250 GHz?

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

→ TCAD simulation can be used as a reference to settle the problem
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)

Measurement Bench
- probe station set-up for 140-220 GHz measurement
**Measurement Set-up and test-structures**

**Test-structures**

**Calibration procedure : on wafer TRL up to 500 GHz**

**Reference plane for TRL**

- Line : 110-500 GHz (183μm), Thru : 64μm
- Load is used for impedance correction

**Validity of TRL with our test structures:**

- symmetry of reflect and lines?
- Crosstalk ?

**De-embedding short – open**

- Validity of de-embedding of lumped elements up to 500 GHz ?
Measurement Set-up and test-structures

- **De-embedding**

- To cancel the effect of pad capacitance and access line
- OPEN-SHORT de-embedding from 1 -110 GHz
- SHORT-OPEN de-embedding from 140-500 GHz
TCAD simulation

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

- Hydrodynamic model
- Effective Intrinsic density
- Band gap Narrowing (BNG)
- 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]

Tuan Van Vu, PhD thesis
**TCAD simulation**

TCAD calibration and comparison to measurement

- **DC characteristics**

- Measured vs. TCAD simulated Gummel characteristics

- Two different dimensions chosen to check 3D effects

![Graph showing DC characteristics of a transistor with TCAD and measured data.](image-url)
TCAD simulation

TCAD calibration and comparison to measurement

- CV characteristics

![Graphs showing CV characteristics](image)
A little inaccuracies is normal in simulation as observed from capacitance.

For $f > 450$ GHz errors may due to Cross-talk!
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TCAD comparison to measurement

$f_T$ and $f_{\text{max}}$ vs freq

Frequency dependent $f_T$ and $f_{\text{max}}$ at $V_{\text{CB}}=0$ V for 90 nm x 4.8 µm device
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TCAD comparison to measurement

- Transmission coefficient

- Very good matching on magnitude and phase \( S_{21} \)
Good matching on magnitude of $S_{12}$ up to 325 GHz
⇒ phase of $S_{12}$ is difficult to measure
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TCAD comparison to measurement

- Reflection coefficient S11 and S22

- Mag (S11) shows some anomalous behavior above 250 GHz (geometry dependent)

- Trend of Mag S(22) is correctly given up to 350 GHz
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TCAD comparison to measurement

- Reflection coefficient $S_{11}$ and $S_{22}$

TCAD simulation confirms the anomalous deflection or trend on $S_{11}$ and $S_{22}$ beyond 350GHz
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TCAD comparison to measurement

- Assessment
  - Mag (S11) up to 250 GHz
  - Phase (S11) up to 300 GHz
  - Mag (S12) up to 500 GHz, for some bias points
  - Phase (S12) up to 500 GHz, but difficult to measure
  - Mag (S21) up to 500 GHz
  - Phase (S21) up to 500 GHz
  - Mag (S22) up to 350 GHz
  - Phase (S22) up to 325 GHz

- No global upper validity range
- The validity is dependent on the S-parameter itself, the geometry and the applied bias

- Issues with reflection coefficient?
Measurement issues

Test-structures layout

- Topview

DUTs are well spaced to avoid neighboring effects

- Measurement Probe positioning errors (Thru to Line)
- Contact issue
  - Al pads
  - Multiple contacts on same pad
- Change of coupling
Measurement issues

EM simulation vs measurements

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

![Image of probes for different frequency bands](image-url)

1-110GHz  
140-220GHz  
220-325 GHz  
325-500 GHz
Measurement issues

EM simulation vs measurements

- Signature of probes and substrate to probe coupling

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

140-220 GHz

220-325 GHz

Large discontinuities

Due to gap between G-S-G in probes
Measurement issues

EM simulation vs measurements

- Impact of neighbours

DUT: Line

- TRL Calibrated measurement and EM simulation

![EM simulation vs measurements graph](image-url)
TCAD simulation vs measurement in THz range

Conclusion on the range of validity

Change reference plane for TRL

Calibrated data have the same trend than HICUM simulation

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

- Measurement has been performed up to 500 GHz
  - On wafer TRL + SO de-embedding

- TCAD has been calibrated and used for verification
  - Validation of Sij measurement and H21 and Mason gain
  - Identification of problems in Sxx parameters above 300 GHz

- Revisiting OS de-embedding and comparison with HICUM has clarified the problem
  - SO de-embedding is no more valid for frequencies above 300GHz

- Outlooks
  - Work ongoing for improvement
    - New test-structure design
    - Probe tip improvement
Thanks for your attention

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