Modeling and Parameter Extraction of SiGe HBTs at Cryogenic Temperatures using Open-Source Tools DMT and VerilogAE

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OUTLINE

• Introduction, device and measurement set-up

• Transfer current of SiGe HBTs at cryogenic temperature

• Parameter extraction tools: DMT and VerilogAE

• Conclusions
Introduction, device and measurement set-up
Motivation

• Silicon-germanium (SiGe) heterojunction bipolar transistor (HBT) technology has achieved $f_T > 500$ GHz for industry prototyping processes

• BiCMOS technology has enabled commercial and emerging mm- and sub-mm-wave system-on-chip applications

• many applications can benefit from operating electronic circuits and devices at cryogenic temperatures (CTs):
  • space exploration
  • material physics and chemistry
  • satellites (e.g. for providing world-wide access to the Internet)
  • quantum computing

• SiGe HBTs have been demonstrated to operate at CTs with superior performance compared to room temperature => high speed can be traded in for lower noise and energy efficiency

  =>$\text{attractive technology for cryogenic applications}$

• Circuit design at cryogenic temperatures requires accurate compact model
Status of SiGe HBT modeling for low temperatures

• Process design kits (PDKs) for cryogenic circuit design still not available
  - need to extend ALL device models to cover low temperature operation

• Challenges for semiconductor foundries:
  • - significant (additional) measurement effort, lack of cryo equipment
  • - need to extend compact models for all devices (actives and passives)
  • - reliance on standard models for transistors

• HBT mainstream [standard] models used by foundries: [HICUM, MEX-TRAM], SGP, VBIC
  • - VA uses the same EC/models for large and small signal
  • - All compact models: main current and charge formulations based on drift-diffusion (DD) transport

=>present HBT compact models miss physics of low temperatures, especially tunneling current
Status of SiGe HBT modeling for low temperatures

• Attempts of modeling SiGe HBTs at low temperatures so far:
  • Standard SGP with an extension: fit DC down to 78 K (old SiGe tech.) [1]
  • MEXTRAM with an extension: fit DC down to 43 K, and AC down to 93 K (old SiGe tech.) [2]
  • small-signal EC: fit measurement at CT only for single $T$ and single operating point (advanced SiGe tech.) [3]
  • HICUM/L0 (advanced SiGe tech.): fit of existing parameters to cryo data at 12 K [4]
  • HICUM/L2 (advanced SiGe tech.): extension by empirical formulations and parameters fit DC and AC data from 4.3 to 298 K [5]

=>focus here: large-signal compact HBT modeling for “cryogenic” PDK base on HICUM/L2 v3.0.0

<table>
<thead>
<tr>
<th>Ref.</th>
<th>BiCMOS Tech.</th>
<th>$f_T$ (GHz)</th>
<th>DC</th>
<th>AC</th>
<th>$T$ scaling (K)</th>
<th>bias scaling</th>
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<tbody>
<tr>
<td>[1]</td>
<td>0.25 $\mu$m</td>
<td>50</td>
<td>✓</td>
<td></td>
<td>78 to 300</td>
<td>✓</td>
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<tr>
<td>[2]</td>
<td>0.25 $\mu$m</td>
<td>50</td>
<td>✓</td>
<td>✓</td>
<td>43 to 393(DC)</td>
<td>✓</td>
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<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>93 to 383(AC)</td>
<td></td>
</tr>
<tr>
<td>[3]</td>
<td>0.13 $\mu$m</td>
<td>170</td>
<td>✓</td>
<td>✓</td>
<td>15, 40, 77, 120, 200, 300*</td>
<td></td>
</tr>
<tr>
<td>[4]</td>
<td>0.13 $\mu$m</td>
<td>260</td>
<td>✓</td>
<td>✓</td>
<td>12</td>
<td>✓</td>
</tr>
<tr>
<td>[5]</td>
<td>0.13 $\mu$m</td>
<td>300</td>
<td>✓</td>
<td>✓</td>
<td>4.3 to 298</td>
<td>✓</td>
</tr>
</tbody>
</table>

*The model parameters were optimized for each temperature, respectively.
Large-signal equivalent circuit of HICUM/L2

(physics-based geometry-scalable industry standard model [6])

=> each element to be investigated over a wide $T$ range
Investigated devices

- IHP SG13G2 as well as two variants => tunneling characterization
- IHP D7 prototyping technology => modeling
  - with $(f_T, f_{\text{max}}) > (300, 500)$ GHz at room temperature
  - CBEBC configuration
    - $b_{E,\text{drawn}} = 0.13\,\text{um}$, $l_{E,\text{drawn}} = 10.16\,\text{um}$
- measurement results from 10 K to 473 K for HBT key characteristics
  - Forward, reverse gummel, output characteristics;
  - $I_{\text{BE}}, I_{\text{BC}}$
  - Cold S, Hot S parameter;
- all key characteristics shown for $V_{BC} = 0\,\text{V}$
Investigated devices

SiGeC HBT technology

production technology
$f_T = 200 \text{ GHz}, f_{\text{max}} = 275 \text{ GHz} [7]$

prototyping technology
$f_T = 500 \text{ GHz}, f_{\text{max}} = 700 \text{ GHz} [8]$

- doping concentrations
  - emitter, base, and buried layer highly doped $\Rightarrow$ no freeze-out
  - internal collector: highly doped in high-speed HBTs $\Rightarrow$ no freeze-out
  - internal collector: low/moderate in high-voltage HBTs, older technology $\Rightarrow$ partial freeze-out
- base width: 25 nm ...12 nm $\Rightarrow$ CE tunneling in advanced HBTs at low $T$
Measurement setup

• Electrical measurement equipment the same as at RT

• Differences compared to RT probe station:
  • vacuum chamber: <10^{-5} mbar, avoid air condensation, cryogenic probe station
  • vacuum pump: series connected diaphragm pump and turbo pump
  • cryogen, such as liquid helium (4 K) or liquid nitrogen (77 K)
  • dewar: container for cryogen
  • temperature controller: heat up the chuck
  • specialized DC and microwave probes
Measurement setup

Transfer current at cryogenic temperature
**Existing compact model vs. measurements**

- Low-temperature reduces kinetic carrier energy => lower diffusivity
- $T$ decreases -> bandgap increases -> larger BE barrier ($V_{DE}$) prevents diffusion of electrons from E to C
  
  => much lower drift-diffusion current as observed in measurements

- GICCR (DD) vs. Meas
  - well agreement from 473 to 73 K
  - model underestimates meas. below 73 K

- Previous investigation (in base) for $T < 73$K:
  - low and medium current densities: tunneling [9]

- *No suitable physics-based tunneling current expression available for compact-models*
  - only qualitative discussions of experimental results and/or device simulations
Characterization of tunneling current

- Transfer characteristic (with different $V_{BC}$ from -0.5 to 0.5 V) of three processes:
  - At 298 K (left figure), no obvious $V_{BC}$ dependence of $J_C$ at low and medium current densities;
  - At 4 K (medium figure), clear $V_{BC}$ dependence of $J_C$ at low and medium current densities due to tunneling current;
  - Ratio of $J_C$ (right figure) with different $V_{BC}$ shows the same trend:
    - At 298 K, ratio equals to 1
    - At CTs, ratio increases with reduced T
- Same process node (0.13um), but different tunneling current due to base doping concentration $\Rightarrow$ different conduction barrier widths

$J_C$ becomes significant at low and medium current densities at CTs
Potential barrier in base

• Left figure: Band diagram from TCAD simulation on similar profile at 30 K and different bias conditions
  • With increased $V_{BE}$, the conduction barrier in base becomes lower and narrower, which increases the tunneling probability
• Right figure: a schematic potential profile
  • Parabolic profile is used for analytical derivation of tunneling transmission factor
Compact model equation

• Transfer tunneling current is generally given by

\[ J_{T_{tu}} = \frac{2q}{h^3} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{0}^{\infty} T_{tu} f_{nE}(1 - f_{nC}) v_x dp_x dp_y dp_z, \]

with \( f_{nE}(f_{nC}) \) as Fermi-function in the emitter (collector), and \( T_{tu} \) as tunneling transmission probability. Under several assumption

\[ J_{T_{tu}} = c_{T_{tu},s} \int T_{tu} dW_x \text{ for } W_{b} \geq \Delta W_{E}. \]

compact model equation

\[ J_{T_{tu}} = J_{T_{tu}S} \sqrt{v_b} \exp(-a_{T_{tu}} \sqrt{v_b}) \exp \left( \left( \frac{v_{th}(\Delta V_{E})a_{T_{tu}}}{\sqrt{v_b}} \right) - 1 \right), \]

Three model parameters required: \( J_{T_{tu}S} \), \( a_{T_{tu}} \) and \( \Delta V_{E} \), and \( v_b \) is given by

\[ v_b = \frac{W_{b}}{q V_{DEi}^{\text{intrinsic}}} = 1 - \frac{V_{BE, \text{intrinsic}}}{V_{DEi}} = \left( \frac{C_{JEi}}{C_{JEi0}} \right)^{-\frac{1}{z_{Ei}}}. \]
Comparison between compact model and measurements

- Lines:
  - Blue short dashed lines: only tunneling equation implemented;
  - Red long dashed lines: only GICCR equation implemented, only low current densities related parameters are considered here, such as $q_0$ and $h_{jei}$;
  - Black solid lines: both tunneling and GICCR equations implemented.
- Left figure: only analytical equations are compared with the measurements.
- Right figure: equations are implemented in HICUM, and compact model simulation results are compared with measurements. High current effect and emitter resistance are considered.
Comparison between simulation and measurements

- With consideration of tunneling current, HICUM shows good agreement with measured values over a wide temperature range from 10 K to 473 K.
- Agreement shows strong physical background of HICUM.
Extraction tools: DMT and VerilogAE
DMT Introduction

• Modeling engineers rely on proprietary and difficult to extend tools, often use self-maintained scripts
  • Best practices, employed in the software industry for decades, often ignored (CI, automated testing, build systems, documentation)
  • Proprietary tools intrinsically difficult to extend and not freely available

• The issues inflicted by this practice include [12]:
  • Analysis/visualization/generation of data becomes difficult to reproduce;
  • Engineers work far from their maximum work-efficiency, as they are hindered instead of empowered, by their software infrastructure;
  • Knowledge built-up over decades may be lost when engineers leave a company or institution.
Features of DMT

• Device Modeling Toolkit (DMT) helps to solve these issues. DMT provides a **Python library** that offers [12]:
  • Classes and methods relevant to commonly used device engineering tasks
  • Abstract base classes for implementing interfaces to simulators; concrete implementations for open-source simulators Ngspice (Vogt, 2022), Xyce (Keiter et al., 2014) or Hdev (Müller et al., 2022) available
  • Bulk measurement data processing and reading routines
  • Handling of compact models and modelcards

• Git-project: https://gitlab.com/dmt-development/dmt-core

• Employs best practices principles used in the software industry:
  • Continuous integration (CI), including automated testing
  • Extensive documentation in code and also on separate website: https://dmt-development.gitlab.io/dmt-core/installation/install_dmt.html

• Interfaces to proprietary simulators and par. extraction GUI **not open-source at this time**, available for partners upon request
OpenVAF and VerilogAE

- VerilogAE provides a Python interface for Verilog A source files [13]:
  - Evaluate model equations
  - Analyze structure of model equations
  - Generate derivatives of model equations
  - Modelcard generation

- VerilogAE uses OpenVAF as back-end for Verilog-A compilation:
  - Directly generates executable machine code
  - Ultra fast compilation without the need for another compiler (gcc)
  - Implements the language standard in a clear and unified way
  - Has great ux (error messages)
  - GPL license, commercial partners can request commercial license, software integration services into circuit simulators and support from SemiMod
  - Very likely the most advanced Verilog-A compiler available today

- All CMC models can be compiled, currently being implemented it into Ngspice (release planed for end of 2022)

- Git project: https://man.sr.ht/~ DSPom/openvaf_doc/verologae/
GUI of DMT

Here, you can export model card, plots, data etc. in the format that you want.

Equations for the Y variable in the plot

Model Parameters

Extraction Parameters

To extract the model parameters step by step, each pop-up menu presents the different groups of parameters.

The boundaries to define the regions of variables, like current to be optimized.

Optimizer Options
Conclusions

• Existing foundry PDK models unsuitable for cryogenic operation

• Standard HBT models need to be extended:
  • Capturing low-temperature physics
  • Mathematical conditioning of new formulations
  • Additional model parameters require parameter extraction (and extended methods)

• Physical-based compact formulation of tunneling current has been derived
  • Model verification on (preferably) a variety of HBT process technologies needs to be done
  • Requires (regular) cryogenic measurements at foundries!

  ⇒ clear direction for model development, but lot of work still ahead
  first version of cryogenic HICUM/L2 has been delivered to foundries for
  cryogenic design applications

• DMT and VerilogAE have been used for parameter extraction.
  • Very efficient tools for parameter extraction
  • Extraction steps for various technologies have been implemented and applied:
    • SiGe HBTs, III-V HBTs, FD SOI FETs and passives
    • HEMTs and others FETs will be developed upon request

  • Already applied to commercial processes technologies from Globalfoundries, Infineon
Acknowledgments

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References


Thanks for your attention!

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