Outline

MOTIVATION    MODELLING    CHARACTERISATION    DATA MANAGEMENT    CONCLUSION
Motivation
Motivation
Variability study

1. Modelling
   - TCAD
   - VENDES

2. Characterisation
   - Post-processing tools
     - FoMpy
     - FSM

3. Data Management
   - Repository
     - MLFoM
1. Modelling
TCAD
VENDES

An in-house-built 3D finite-element based quantum-corrected semiconductor device simulation toolbox

N. Seoane et al, 2019, Materials, DOI:10.3390/ma12152391
VENDES
Finite Element (FE) mesh

- **Accurate description** of simulation domains
- Easy to apply **realistic deformations** to model variability sources
Variability models

Metal grain granularity (MGG)

- Grain size (GS)

Voronoi diagrams to reproduce the metal grains present in the gate

Nanosheet FET (NSFET) TiN metal gate with GS=3nm

Variability models

- Root mean square height (RMS)
- Correlation length (CL)

Variability models

- Root mean square height (RMS)
- Correlation length (CL)

G. Espiñeira et al, 2019, *EDL*, DOI: 10.1109/LED.2019.2900494
Variability models

Random discrete dopants (RDD)

- Number of dopants

N. Seoane et al, 2019, Materials, DOI:10.3390/ma12152391
2. Characterisation
Post-processing

• To study variability, it is necessary to process the simulator output data.

• Tools developed:
  • **FoMpy**: Figure of Merit python extraction tool
  • **FSM**: Fluctuation Sensitivity Map
FoMpy

FoMpy capabilities

- FoM extraction from I-V curves
- Statistical analysis
- Plot results
- Manage post-processed data

https://gitlab.citius.usc.es/modev/mlfompy
https://pypi.org/project/mlfompy/
Figure of merit (FoM) extraction
Figure of merit (FoM) extraction

Off-current ($I_{OFF}$)
Figure of merit (FoM) extraction

Threshold voltage ($V_T$)
Figure of merit (FoM) extraction

On-current ($I_{ON}$)
FoM extraction: $V_T$

**Linear extrapolation (LE)**

**Constant current (CC)**

G. Espiñeira et al, 2018, EUROSOI-ULIS, DOI: 10.1109/ULIS.2018.8354752
FoM extraction: $V_T$

**Second derivative (SD)**

- $V_T = 0.272$

**Third derivative (TD)**

- $V_T = 0.239$

G. Espiñeira et al, 2018, *EUROSOI-ULIS*, DOI: 10.1109/ULIS.2018.8354752
FoM extraction: \( V_T \)

For the same I-V curve

Large variation in \( V_T \) value depending on the extraction method

Being aware of this: avoids errors on data treatment and misinterpretations

<table>
<thead>
<tr>
<th>Extraction method</th>
<th>( V_T ) [mV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SD</td>
<td>272</td>
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<tr>
<td>TD</td>
<td>239</td>
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<tr>
<td>LE</td>
<td>251</td>
</tr>
<tr>
<td>CC</td>
<td>246</td>
</tr>
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</table>

10.7nm gate length FinFET  
\( V_D = 0.05V \)
Statistical variability: $\sigma V_T$

Si FinFET
10.7nm gate length
$V_D = 0.05V$
RDD variability

G. Espiñeira et al., DOI: 10.1016/j.sse.2019.03.055
## Statistical variability

<table>
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<tr>
<th>Extraction method</th>
<th>MGG GS=5nm</th>
<th>LER CL=20nm RMS=0.8nm</th>
<th>GER CL=20nm RMS=0.8nm</th>
<th>RDD</th>
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</thead>
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<tr>
<td>SD</td>
<td>32.8</td>
<td>16.0</td>
<td>3.3</td>
<td>6.7</td>
</tr>
<tr>
<td>TD</td>
<td>30.4</td>
<td>19.4</td>
<td>4.5</td>
<td>8.1</td>
</tr>
<tr>
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<td>34.5</td>
<td>13.7</td>
<td>3.2</td>
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12 nm gate length NWFET $V_D=0.7V$
### Statistical variability

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12 nm gate length NWFET $V_D=0.7V$
Fluctuation Sensitivity Map (FSM)

FSM capabilities

- Establish the most sensitive regions of the device to variability
- Variability prediction

FSM
Example: **MGG** variability, **gate contact** is the region of interest
• **Set of simulations:**
  - **Variability profiles** (contain the **WF values** in each point of the gate)
  - The **resulting FOMs** after the devices affected by variability have been simulated (e.g. $V_T$)
• For every point of the gate we calculate the FSM via a linear fit
$V_T$ FSM

FinFET $V_D=0.7V$
$V_T$ FSM

FinFET $V_D=0.7V$
$V_T$ FSM

FinFET $V_D = 0.7V$
$V_T$ FSM

Bottom Gate

FinFET $V_D=0.7V$

Middle Gate

Top Gate

Bottom Gate
$V_T$ FSM

Bottom Gate

Top Gate

Bottom Gate

$V_D=0.7V$
FSM prediction

12 nm gate length NSFET $V_D=0.7V$
MGG with $GS=7$ nm
3. Data Management
FAIR data principles

Findable

Accessible

Reusable

Interoperable

https://www.go-fair.org/fair-principles/
Readable
- To humans
- To computer

Understandable data
- Information of variables in dataset

Reproducible process
- Device dimensions and architecture
- Materials used and their description
- Doping values
- Simulation methodology
- Variability parameters
- Software, libraries and versions used
- Extraction method chosen

Accountability
REUSABILITY

FoM extraction

Future work
MLFoM

Statistical studies
Conclusion
Conclusion

• The *scaling* of semiconductor devices leads to **larger influence of variability** on device performance.

• TCAD based tools, that include the effect of **quantum confinement**, are required to assess the impact of variability sources when critical dimensions are below 20 nm.

• **Large ensembles** of different device configurations need to be modelled to obtain **statistical significance**.

• An **efficient post-processing** of simulation data requires automated tools to extract and analyze the IV characteristic **figures-of-merit**

• In this workshop, we have presented tools to model and characterize advanced semiconductor device variability, managing the generated data following the **FAIR principles**.
Thank you for your attention

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