Simulation-Based Transistor-SRAM Co-Design in the Presence of Statistical Variability and Reliability

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*ARM, Cambridge*

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Outline

- Motivation and Background
- Statistical TCAD based PDK
  - Device Design
  - Statistical Variability and Reliability
  - Statistical Compact Modelling
- Device and SRAM Co-Design
- Conclusions
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Transistor Wars

Rival architectures face off in a bid to keep Moore’s Law alive
By Khaled Ahmed, Klaus Schuegraf / November 2011

Predictable TCAD is the only way to provide reliable information of new technologies when there is no mature Silicon data available.
Early access of reliable PDK is essential for design team to meet tight requirement on time-to-market

*M.E.Mason, VLSI Symposium on Technology 2012
Predictive TCAD-Based PDK Development and Design-Technology Co-Optimization

- Nominal Device TCAD Design
- Statistical Devices Simulation
- Corner Device TCAD Simulation
- Nominal Device Compact Modelling
- Statistical Device Compact Modelling
- Corner Device Compact Modelling
- Nominal Device Specification
- Statistical Compact Model Library engine
- Corner Device Specification
- Statistical Circuit Simulation Engine
- Circuit Design Optimization Engine
The GSS Tool Suite that enable the Flow

**GARAND**
- 3D Statistical Variability Simulator
  - Drift diffusion, Monte Carlo (NEGF) modules.
  - Multiple variability sources
  - Random discrete dopants
  - Line edge roughness
  - Gate stack granularity
  - Trapped discrete charges
  - Others - custom

**MYSTIC**
- Statistical Compact Model Extractor
  - Nom and Stat Models
  - Multiple stat parameters
  - Supports PCA and NPM
  - High accuracy
  - Supports BSIM, PSP and HiSIM

**RANDOM SPICE**
- Statistical Circuit Simulator
  - Frontend for advanced statistical simulation
  - Supports ngspice, Eldo and Spectre.
  - Supports PCA and NPM.
  - Unprecedented SRAM analysis accuracy.
  - Performance/power/yield analysis (PPY)
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14nm DG FinFET specification

- Double gate FinFETs targeted at 14nm technology node.
- Devices targeted for high performance SRAM application.
- Process variation aware design.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Min (nm)</th>
<th>Max (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fin Width</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Fin Height</td>
<td>22</td>
<td>28</td>
</tr>
<tr>
<td>Gate Length</td>
<td>18</td>
<td>22</td>
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<table>
<thead>
<tr>
<th>Conditions</th>
<th>NMOS</th>
<th>PMOS</th>
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<tbody>
<tr>
<td>$T=85^\circ\text{C}$</td>
<td>$V_{DD} = 0.9\text{V}$</td>
<td></td>
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<tr>
<td>$I_{ON} (\text{mA}/\mu\text{m})$</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>$I_{OFF} (\text{nA}/\mu\text{m})$</td>
<td>10</td>
<td>10</td>
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<tr>
<td>DIBL (mV/V)</td>
<td>56</td>
<td>65</td>
</tr>
<tr>
<td>SS (mV/Dec)</td>
<td>86</td>
<td>88</td>
</tr>
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</table>
The role of predictive MC simulations

- Only EMC simulations can predict performance.
- Quantum corrections are essential.
- DD simulations can be calibrated to EMC.

Quantum effects are very important.
Process induced variability

- Captured by experiment design.
- Dependence on L, H_F, W_F, T_OX.
Process variability induces complex parameter correlations

- Correlation between DIBL and SS: \( \rho = 0.99 \)
- Correlation between \( V_{th} \) and DIBL: \( \rho = -0.99 \)
- Correlation between \( I_{off} \) and \( I_{on} \): \( \rho = 0.45 \)
- Correlation between SS and \( I_{on} \): \( \rho = 0.38 \)
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Statistical Variability Simulations

RDD

GER+FER

MGG
The $3\sigma$ of the line edge roughness for both GER and FER is 2nm, and the correlation length is 30nm.
Correlation between subthreshold figures of merit, such as $I_{OFF}$ and DIBL, can be a good indicator to show whether MGG is an active variability source.
Correlation between process and statistical variability

![3D graph showing the relationship between Hfin, Wfin, Lg, and sigmaVth(mV).]

![2D graph showing the relationship between Gate Length, Fin Width, and sigmaV_T(mV).]

![2D graph showing the relationship between Gate Length, Fin Width, and Avt(mV/µm).]
Statistical aspects of Reliability

Fresh

With degradation

Trapping Density (cm\(^{-2}\))
- 0
- 1E11
- 5E11
- 1E12

Normal Quantile

\(V_T (V)\)
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Statistical Compact Modelling Procedure

1. Process Variation Aware Device TCAD Design
2. Process Variation Aware Statistical Device Simulation
3. Extended Uniform Device Compact Modelling
4. Extended Statistical Device Compact Modelling
5. Unified Statistical Compact Model Libraries

Statistical Model

- Process Corner Extended Uniform Model
  - Nominal Uniform Model
    - Parameter Group I
    - Parameter Group II
Extended Uniform Model – Group 1 Parameter

![Graphs showing the relationship between various parameters and the extended uniform model for Group 1 parameter.](image)
Extended Uniform Model – Error Distribution
Extended Uniform Model – Figures of Merit

Complemented with parametric regression, the extended uniform model can accurately cover transistors at all geometry corners.
Strong correlation between statistical compact model parameter and device figure of merit demonstrates that extraction is physics based.
### Group 2 Parameter Generation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PHIG</th>
<th>ETA0</th>
<th>UA</th>
<th>U0</th>
<th>CDSC</th>
<th>VSAT</th>
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<td>-0.04</td>
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<td>0.86</td>
<td>0.36</td>
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<td>0.24</td>
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<td>0.36</td>
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<td>0.26</td>
<td>-0.65</td>
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</table>
Statistical Compact Modeling – Group 2 parameter
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Fin 1-1-1 High Density Cell
Fin 2-3-3 Performance Cell
Cell design trade off

- Metal Gate Work-Function Engineering

Graphs showing cell area, noise margin, read time, write time, and cell WNM as functions of cell configuration.

Metal Gate Work-Function Engineering
Impact of CD variation

**Graph 1:**
- **X-axis:** Read time (PS)
- **Y-axis:** SNM (V)
- Data points show a linear relationship with a 1:2:1 ratio.

**Graph 2:**
- **X-axis:** Write time (PS)
- **Y-axis:** Read time (PS)
- Data points form a scatter plot with a 1:2:1 ratio.

**Graph 3:**
- **X-axis:** Write time (PS)
- **Y-axis:** WNM (V)
- Data points show a curved relationship with a 1:2:1 ratio.

**Graph 4:**
- **X-axis:** WNM (V)
- **Y-axis:** SNM (V)
- Data points form a linear relationship with a 1:2:1 ratio.
Impact of Statistical Variation

- 2:3:3
  - $\mu_{SNM} = 0.142V$
  - $\sigma_{SNM} = 6.5mV$

- 1:2:1
  - $\mu_{SNM} = 0.215V$
  - $\sigma_{SNM} = 8mV$

- 1:1:1
  - $\mu_{SNM} = 0.151V$
  - $\sigma_{SNM} = 11mV$

SNM (V) vs. Frequency

SNM (V) vs. WNM (V)

SNM (V) vs. Write Time (PS)

SNM (V) vs. Read Time (PS)
Interplay between CD and statistical variation

- Slow corner has the best SNM performance.
- CD variation can introduce 10% degradation on standard deviation of SNM.
Under N/PBTI stress condition, SNM can be degraded by more than 25%.

However, write operation can be improved under stress condition.
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Conclusions

- Predictable TCAD is the only way to provide reliable information of new technologies when there is no mature data available.

- Early technology assessment can be enabled by predictable TCAD-based PDK.

- The device and SRAM co-design is demonstrated at the early technology development stage.