Variability-Aware Compact Model Strategy for 20-nm Bulk MOSFET

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Outline

- Introduction
- 20-nm bulk MOSFET
- Simulations of Process variation and Statistical variability sources
- Compact Modelling Strategy
- Application
- Summary
Introduction

• Variability is an unavoidable challenge for advanced MOSFET technology and circuit design. Global process variation (PV) and local statistical variability (SV) both involve.

• While novel technologies such as FinFET and FDSOI are being introduced, bulk planar technology is still adopted as major technology in 20-nm generation. It undergoes serious variability impact.

• Statistical Compact Modelling is a key effort for variability-aware technology circuit co-optimization to achieve high yield, and low power designs.
Variability Decomposition

• In general, the variability can be decomposed into global process variation and local random variability.
• PV: systematic, spatially correlated, long-range.
• SV: random, no (weak) correlation, short-range.

(Takeuchi, Nishida, Hiramoto, SISPAD 2009)

(D. Frank, IBM)
Simulation of 20-nm bulk MOSFETs

Process simulation
- Process follows realistic gate stack, shallow trench isolation (STI)
- \( L_G = 23.5 \text{nm}, W = 33 \text{nm} \).

Device simulation
- Accurate meshing (gate interface, STI corner)
- GSS Garand calibrated DD module
- Coupled density gradient quantum corrections.
Large Devices

- Large devices are simulated in respect of CDs.
- L/W effects are decoupled.
- It affiliates the compact models of short-channel effects and width effect.
Variability simulation
Process Variation

- 5 X 5 corner uniform simulation of CD variations
- Short-channel effect (Vt roll off)
- Width effect (STI corner enhanced field)

<table>
<thead>
<tr>
<th>L (nm)</th>
<th>17</th>
<th>20.25</th>
<th>23.5</th>
<th>26.75</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>W (nm)</td>
<td>24</td>
<td>28.5</td>
<td>33</td>
<td>37.5</td>
<td>42</td>
</tr>
</tbody>
</table>
Variability simulation
Statistical Variability

- RDD assignment is based on local channel doping and follows rejection technique; cloud in cell.

(GSS Garand)
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• LER is modelled by Fourier synthesis based on Gaussian autocorrelation; 2nm LER
Variability simulation
Statistical Variability

- RDD assignment is based on local channel doping and follows rejection technique; cloud in cell.
- LER is modelled by Fourier synthesis based on Gaussian autocorrelation; 2nm LER
- MGG in gate-first models two metal grains with work-functions of 0.2eV difference and 0.4/0.6 occurrence; 5nm average grain size
Statistical simulation strategy

- RDD, LER, MGG

Select from 5x5 matrix

\[ V_d = 0.9V \]

\[ \langle I_{on} \rangle = 23.4 \mu A \]

\[ \sigma V_T = 45.4 \text{mV} \]
Statistical simulation strategy

- RDD, LER, MGG
- Current: Fast/typical/slow corners

\[ V_d = 0.9 \text{V} \]

\[ \langle I_{on} \rangle = 40 \mu \text{A} \]

\[ \langle I_{on} \rangle = 15 \mu \text{A} \]
Statistical simulation strategy

- RDD, LER, MGG
- Current: Fast/typical/slow corners
- $V_T$-variation: Large/typical/small corners

$\sigma V_T = 66.9 \text{mV}$

$\sigma V_T = 38.3 \text{mV}$

$V_d = 0.9 \text{V}$
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Compact Model Extraction Strategy

• **First**, comprehensive nominal model.
• **Second**, one group of PV parameters are used to extract PV.
• **Third**, one orthogonal group of SV parameters are used to extract SV.
• **Fourth**, parameters are built as functions of PV space.
Nominal model extraction

- Sub-Vth (SS, Vth, Ioff);
- Low field mobility, Velocity saturation;
- Output resistance
- Vbb dependence, Vd dependence, Lg dependence
PV-SV Extraction

• Process variation extraction: average error ~ 3%
• Statistical variability extraction: capturing 1) variability magnitudes 2) correlations of figures of merit
Step 1: For each circuit, \((L, W) \sim \text{Distribution}\) (here Gaussian distribution with sigmas of 1.5nm and correlation of 0.5);

Step 2: Determine process variations by applying \(P = f(L, W)\) to group I parameters;

Step 3: For each transistor, apply SV (group II parameters orthogonal to PV parameters).
Statistical Models

CD process variations

• CD process variation is globally randomized.
Statistical Models

- CD process variation is globally randomized.
- Corresponding to each CD, local statistical variability is applied.

Statistical variability ensemble
For each (W,L) input
CD process variations

- CD process variation is globally randomized.
- Corresponding to each CD, local statistical variability is applied. SV could be different for distinct (L,W).
• With PV, the statistical variability magnitude is enhanced.
• With PV, the distributions of figures of merit are changed.
• Distribution of DIBL is largely changed due to a larger variation of L.
Summary

• We have simulated a matrix of PV and SV in 20-nm bulk planar MOSFETs following design of experiments.

• A variability aware compact modelling strategy is carried out to extract both PV and SV.

• This method can handle accurately the PV, SV and together total variability.

• With interactions of PV and SV, statistical variability of transistor figures of merit is largely changed in fluctuation magnitudes and distributions.
Acknowledgement

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Thank you for your attention!