A Complete Reliability Solution: Reliability Modeling, Applications, and Integration in Analog Design Environment

Tianlei Guo, Jushan Xie

Cadence Design Systems, Inc.
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Project Vision

Design for Reliability

Failure is NOT an Option

• Make reliability analysis relevant by providing
  – Predictive aging models
  – Aging analysis accelerated by temperature, process variation, ...
  – Support mission profiles
Simulating Device Aging
Terminology for Device Reliability Analysis

- **Age**
  - Device age is a parameter that represents the device degradation physical phenomena

- **Age (or lifetime or degradation) model**
  - Predicts the degradation in device characteristics due to a physical phenomena, such as HCI, NBTI, PBTI, TDDB, ...

- **Aged (or degraded) model**
  - is a device SPICE model that represents the effects of all kind of degradations at particular future time value

- **Fresh Simulation**
  - Is a simulation without degradation or a simulation at time = 0

- **Stress Simulation**
  - Is a simulation that represents the stress condition

- **Aging (or EOL) simulation**
  - is a simulation with worst case device degradation due to electrical stress, a simulation at the end of life
HCl (Hot Carrier Injection)

IMPACT OF HOT CARRIERS

- Interface state generation
- Single-carrier process (long devices)
- Mixed mode
- Multiple-carrier process (scaled devices)

STM experiments:

Ben Kaczer, 2016 IEDM tutorial
BTI (Bias Temperature Instability)

NBTI: NMOS BTI
PBTI: PMOS BTI strong
TDDB (Time-Dependent Dielectric Breakdown)

PHASES OF GATE DIELECTRIC BREAKDOWN

- Hard Breakdown (HBD)
- Soft Breakdown (SBD)
- Stress Induced Leakage Current (SILC)
- Oxide wear-out

Electrical stress = Additional gate oxide leakage paths (TDDB) + FET intrinsic parameters change ("BTI")
Cadence Aging Reliability Support
Aging Analysis in Spectre

**INPUT**
- Circuit Netlist & Spice model & Reliability model

**SIMULATION**
- RelXpert or Spectre

**OUTPUT**
- Device/Age Information
- Fresh circuit simulation
- Lifetime/Degradation calculation
- Age Waveform Generation
- Aged model generation
- Aged circuit simulation

Unified Reliability Interface (URI)

Schematic

ADE waveform

Aging Reliability Analysis
HCI and NBTI/PBTI Analysis Flow

- Fresh
  - Fresh Simulation
- Stress
  - Device Degradation, Lifetime
  - Degraded model/netlist Generation
  - Aging Simulation
  - Waveform Compare
  - Circuit degradation Check
- Aging/EOL
- Circuit Netlist + Reliability Model
- Stressing

Stressing

Aging
Reliability Models supported

- Reliability effects supported:
  - Built-in HCI, NBTI and PBTI
  - other mechanisms possible via URI (eg. TDDB, GOI)

- SPICE Models supported for degradation:
  - BSIM3, BSIM3V3, BSIM4, BSIMSOI, MOS9, MOS11, PSP 102, PSP 103, HVMOS, HISIM2 and HISIM_HV.
  - BSIMCMG, BSIMIMG, UTROI, UTROI2
  - BJT: VBIC, HiCUM and MEXTRAM
  - Resistor: native and R3
  - Diode
  - Verilog-A

- Reliability models:
  - ageMOS: Cadence proprietary reliability model for HCI, NBTI and PBTI (with recovery) and degraded model generation (for legacy nodes).
  - ageMOS2: Cadence proprietary reliability model for advance nodes.
  - URI: API to allow customer implement own reliability models.
  - TMI-aging, TMI self-heating models, TMI TDDB
Virtuoso Unified Reliability Interface (URI)

Using Custom Reliability Models

- The Virtuoso Unified Reliability Interface (URI) allows you to add your own (custom/proprietary) reliability equations/models and supports user-defined degradation models.
TMI Simulation flow

- TMI Aging model offered three simulation flows with .option tmiAge=1
  - Aging only simulation flow. (tmishe=0)
    - Aging stress w/o self-heating effect (calculate degradation rates under TempE)
    - Measurement simulation w/o self-heating effect.
  - Self-Heating only simulation flow. (tmishe=1)
    - w/o aging stress.
    - Measurement simulation w/i self-heating effect.
  - Aging simulation with self-heating effect. (tmishe=2)
    - Aging stress w/i self-heating effect (calculate degradation rates under TempE+dtemperature).
    - Measurement simulation either w/i or w/o self-heating effect.

<table>
<thead>
<tr>
<th>tmiShe</th>
<th>Self-heating</th>
<th>aging</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>-</td>
<td>Yes</td>
</tr>
<tr>
<td>1</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>Yes</td>
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Spectre/TMI interface in ADE
# Reliability models support matrix

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<thead>
<tr>
<th></th>
<th>RelXpert</th>
<th>Spectre Native</th>
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<tbody>
<tr>
<td>ageMOS</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>ageMOS2</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Extraction</td>
<td></td>
<td>X (verification)</td>
</tr>
<tr>
<td>TMI</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>URI</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Self-heating</td>
<td>X</td>
<td>X</td>
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<tr>
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<td>X</td>
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**TDDB*: prototype
New Aging Model
Model HCI Degradation Saturation Effect

S. Guo, R. Wang, Z. Yu, P. Hao, P. Ren, Y. Wang, R. Huang, Peking University, MOS-AK December 2016
Model limitation in FinFET BTI effect (log-log nonlinear)
Model result demonstration – **New BTI models**

New model equations for FinFET: DC verification

- Curve slope changed against time (in log-log, or log-lin scale)
- Gate bias dependency changed
Model result demonstration – New BTI models

History effect: sequential simulation step
BTI model with recovery effect - New Model
BTI model prediction with recovery effect

A periodic square waveform is applied on an inverter during a few milliseconds.

Then prediction for 3 years.
# Comparison of AgeMOS and AgeMOS2

<table>
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<tr>
<th><strong>AgeMOS</strong></th>
<th><strong>AgeMOS2</strong></th>
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<tbody>
<tr>
<td>Developed around 1995</td>
<td>Developed around 2015</td>
</tr>
<tr>
<td>Based on Lucky-Electron model</td>
<td>Based on trapping/de-trapping model</td>
</tr>
<tr>
<td>Degradation log-log linear</td>
<td>Degradation log-log nonlinear</td>
</tr>
<tr>
<td>Many enhancements</td>
<td>Degradation saturation/history effect</td>
</tr>
<tr>
<td>Using skew parameters</td>
<td>Using degradation directly</td>
</tr>
<tr>
<td>– Vth, U0, Ua, Ub, Nfactor, Vsat, …</td>
<td>– Vth and Ids degradation</td>
</tr>
<tr>
<td>Simple recovery model</td>
<td>Recovery with step-wise model</td>
</tr>
<tr>
<td>– linear extrapolation</td>
<td>– More accurate</td>
</tr>
<tr>
<td>– Frequency dependency</td>
<td></td>
</tr>
<tr>
<td><strong>Current CMC Approach</strong></td>
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AgeMos2 Model Extraction (Standalone tool)

- Grouped reliability characteristics, such as degradation vs. time curves with varying Vds for a fixed temperature.

- Loading the data, and treating it for extraction preparation, such as sorting, regrouping, data checking, etc.

- Fitting error report compared to the input data, simulation results in text files, graphically, etc.

- Specified reliability model parameter extraction

- Output EDA readable reliability modelcard

Data complete

- Yes

- No
Reliability Monte Carlo
Reliability Variation Components

Process Variation (PV) \rightarrow Variation \rightarrow Aging variation (AV) \rightarrow Correlation
Simulation Diagram for Flow I (1+N flow) (Aged model + Process Variation))

- Can perform Aging MC with current foundry aging + MC model
- Not expensive
Simulation Diagram for Flow II (N+N flow) (Age Variation + Process Variation)

MC Fresh
- PV spice model
- AV reliability model

MC RUNs: N+N

PV transistor-level simulation
AV aging calculations
Aged spice model generations
PV transistor-level simulation

MC Stress
Fresh variation

MC Aging
Degradation variation

$V_{TH}$ Comparison between Flow Zero, I and II

- Variation distribution (Y-axis)
- Variation of aged $V_{TH}$ of flow I (only PV) is smaller than flow II (PV + AV)
Process Variation and Aging Variation Correlation

- Aged $V_{TH}$ and $I_{DS}$ variation become smaller after considering correlation between PV/AV

Spectre syntax for correlation analysis

```plaintext
16 simulator lang=spectre
17 option1 options temp=25 tnom=25
18 parameters vin = -0.8
19 parameters ving = -0.8
20 parameters vinb = 0
21 //Define the process parameters
22 parameters dvshiftmc=-0.0375065
23 parameters hfimc=3.3e-08
24 parameters xlmc=1.4e-08
25 parameters nbn=0.18
26 //Define the statistics
27 statistics {
28   process {
29     vary dvshiftmc dist=gauss std=12 percent=yes
30     vary hfimc dist=gauss std=5 percent=yes
31     vary xlmc dist=gauss std=8 percent=yes
32     vary nbn dist=gauss std=4 percent=yes
33     correlate param = [ dvshiftmc nbn ] cc = 0.8
34     correlate param = [ hvfmc nbn ] cc = 0.6
35     correlate param = [ xlmc nbn ] cc = 0.6
36   }
37 }
```
Scatter Points for Operation Outputs

➢ The scatter points between aged $V_{TH}$ and aged $I_{DS}$, $G_M$, $G_{DS}$, $R_{OUT}$, $I_{GS}$, and $V_{DSAT}$

➢ The correlation between PV/AV makes the outputs correlation more complicated
13-Stage Ring Oscillator Waveform Variation

Flow II shows the fresh and aged RO waveform variation. The voltage degradation variation includes the PV-aware age calculations.