Physics-Based Modeling for Total Ionizing Dose Effects

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2016-06-28
Outline

• Background
  • Total Ionizing Dose Effects in CMOS

• Physics-based TCAD Simulation
  • Governing Equations
  • Solver Implementation
  • Results

• Physics-based Compact Modeling
  • Motivation
  • Core Equations
  • Results
Physical Mechanism of TID: Consensus

- Ionizing radiation $\rightarrow$ e/h pairs
- e/h pairs recombine unless separated by E-field
- $e^-$ swept out quickly
- $h^+$ hopping slowly
- $E'$ centers capture holes (trapped charge)
Trapped Charge Build-up in Oxide
TID-Induced Parasitic Channel
Physics and Governing Equations

Ionization:

\[ G_{rad} = Y(E) \cdot g_0 \cdot \dot{D} \]

\[ Y(E) = \left( \frac{E}{E + 1.35 \times 10^6 \text{V/cm}} \right)^{0.9} \quad \text{for X ray} \]

\[ Y(E) = \left( \frac{E}{E + 0.55 \times 10^6 \text{V/cm}} \right)^{0.7} \quad \text{for } \gamma \text{ ray} \]

Electrostatics: ....

Transport of mobile species: ....

Reactions: ....

## Physics and Governing Equations

### Electrostatics

\[ \nabla \varepsilon \nabla \psi = -\frac{1}{e} (p + T_p - n) \]

### Transport of mobile species

<table>
<thead>
<tr>
<th>Species</th>
<th>Equation</th>
</tr>
</thead>
</table>
| Electron | \[
\frac{dn}{dt} = \nabla \cdot (\mu_n n E + D_n \nabla n) + G_n - R_n \]
| Hole | \[
\frac{dp}{dt} = -\nabla \cdot (\mu_p p E - D_p \nabla p) + G_p - R_p \]
| \(H^+\) | \[
\frac{dH^+}{dt} = -\nabla \cdot (\mu_{H^+} H^+ E - D_{H^+} \nabla H^+) + G_{H^+} - R_{H^+} \]

Reactions:

....
### Physics and Governing Equations

**Reactions:**

<table>
<thead>
<tr>
<th>Reaction Type</th>
<th>Reaction Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole capture at $D_A$</td>
<td>$D_A + p \rightarrow D_A^+$</td>
</tr>
<tr>
<td>Electron capture at $D_A$</td>
<td>$D_A^+ + n \rightarrow D_A$</td>
</tr>
<tr>
<td>Hole capture/emission at $D_B$</td>
<td>$D_BH + p \rightleftharpoons D_BH^+$</td>
</tr>
<tr>
<td>H+ release from $D_B$</td>
<td>$D_BH^+ \rightarrow D_B + H^+$</td>
</tr>
<tr>
<td>Electron capture from $D_B$</td>
<td>$D_BH^+ + n \rightarrow D_BH$</td>
</tr>
<tr>
<td>Interface trap production</td>
<td>$H^+ + SiH \rightarrow N_{it} + H_2$</td>
</tr>
</tbody>
</table>
Numerical Implementation

- 3D TID solver in Genius
  - TID effect slowly disturb the potential in silicon region
    - Only solve TID equations on silicon oxide, while
    - keeps potential constant at silicon/metal regions
  - Do global potential update every ~3K Rad
  - This makes the TID solver stable and fast
TID Simulation Flow

OP (worst-base bias) → TID (100krads) → Steady state & IV Sweep

TID (200krads) → Steady state & IV Sweep

TID (300krads) → Steady state & IV Sweep

TID (400krads) → Steady state & IV Sweep

TID (500krads) → Steady state & IV Sweep
Parasitic Channel due to TID

100krad/(Si)

Transistor Channel

Drain

Source

Parasitic channel

neck

concave

convex

300krad/(Si)

500krad/(Si)

700krad/(Si)

0.13um CMOS nMOSFET
Parasitic Channel due to TID

- 0.13um, another layout
- 65nm, nMOSFET
Simulated IV Curves due to TID

![IV Curves](image-url)
IV Curves of Sidewall Parasitic Tr

Separate parasitic from intrinsic MOSFET
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TID in CMOS: Experiment Data

F. Faccio, IEEE TNS v52 p2413 (2005)
M. Li, IEEE TNS v58 p2876 (2011)

Z.L. Liu RADECS 2011 PA2
Motivation: Why Substrate Bias?
TID-Induced Parasitic Channel

- Intrinsic MOSFET
- Corner Parasitic MOSFET
- Sidewall Parasitic MOSFET
TID in CMOS: Mechanism

- Corner parasitic MOSFET dominates
- Sidewall parasitic MOSFET dominates
Sub-threshold IV of Parasitic Transistor

sub-threshold IV

\[ I_{ds} = \mu \frac{W}{L} V_T^2 C_{dep} \exp \left( \frac{V_{gs} - V_{th}}{\kappa V_T} \right) \exp \left( \frac{V_{bs}}{\eta V_T} \right) \left( 1 - e^{-\frac{V_{ds}}{V_T}} \right) \]

Vg dependence  Vb dependence

threshold voltage and fixed charge

\[ V_{th} = V_{fb} - \frac{Q_D}{C_{ox}} + 2\phi_b \left( 1 + \frac{C_{dep}}{C_{ox}} \right) \]

\[ Q_D = 1.2 \times 10^{11} \text{ cm}^{-2} \times q_0 \times \left( \frac{D_D}{100 \text{ krad}} \right)^{0.65} \]
Model Synthesis: IV

smoothing function: sub-threshold to above threshold

\[ Q_{\text{inv}} = \frac{2C_{\text{ox}} \kappa V_T \cdot \ln \left[ 1 + \exp \left( \frac{V_{gs} - V_{th}}{2\kappa V_T} \right) \right]}{1 + 2\kappa \frac{C_{\text{ox}}}{C_{\text{dep}}} \exp \left( -\frac{V_{gs} - V_{th} - 2V_{\text{off}}}{2\kappa V_T} \right) \exp \left( \frac{-V_{bs}}{\eta \times V_T} \right)} \]

Main IV equation:

\[ I_{ds} = \mu V_T Q_{\text{inv}} \cdot \left[ 1 - \exp \left( -\frac{V_{ds}}{V_T} \right) \right] \cdot \left( \frac{Z}{L} \right)_{\text{eff}} \cdot f_W \]

W and L dependence

\[ \left( \frac{Z}{L} \right)_{\text{eff}} = Z_{\text{eff}} \cdot \frac{(L_{\text{min}} + L_{\text{ref}})}{(L + L_{\text{ref}}) \cdot L_{\text{min}}} \]

\[ f_W = (A_W \times W^{B_W} + C_W) \]
Simulation Results

Compact Model vs TCAD

dose dependence

Vb dependence
Summary

• Physics-Based Modeling of TID Effects
  • TCAD level
    • First 3D solver for TID effects
    • Not and Nit in oxide
    • Parasitic channel in MOSFET due to TID
    • Separate contribution from parasitic channels

• Compact model level
  • Guided by TCAD simulation of parasitic IV
  • Models the Vbs dependence of leakage current
  • Implemented as subcircuit macro