Physics-Based Modeling for Total Ionizing Dose Effects

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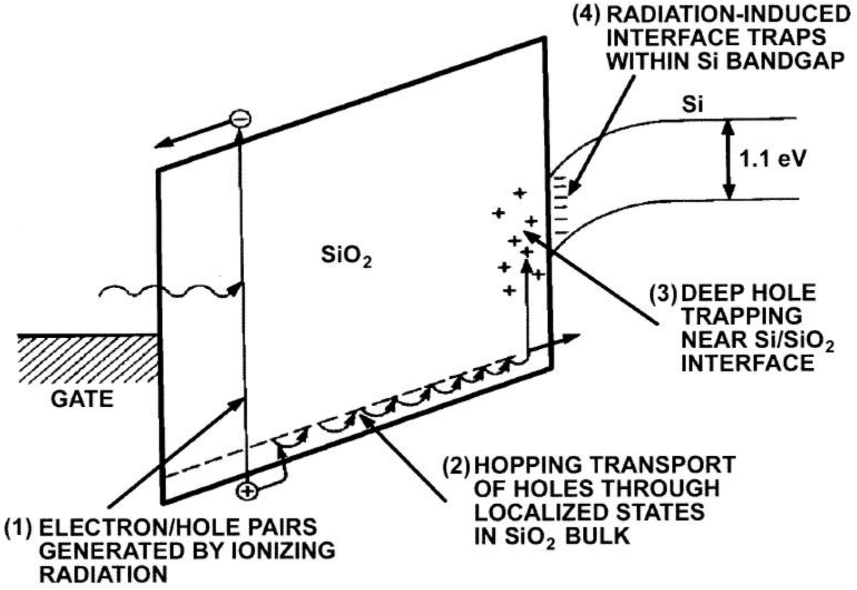
Outline

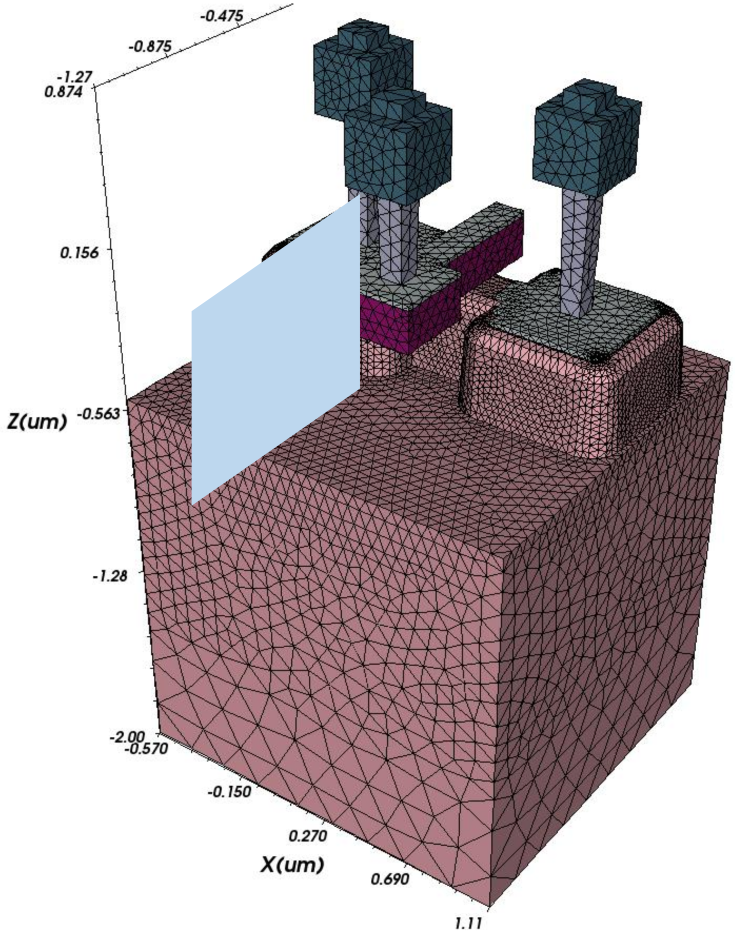
- Backgroud
    - Total Ionizing Dose Effects in CMOS
- Physics-based TCAD Simulation
    - Governing Equations
    - Solver Implementation
    - Results
- Physics-based Compact Modeling
    - Motivation
    - Core Equations
    - Results

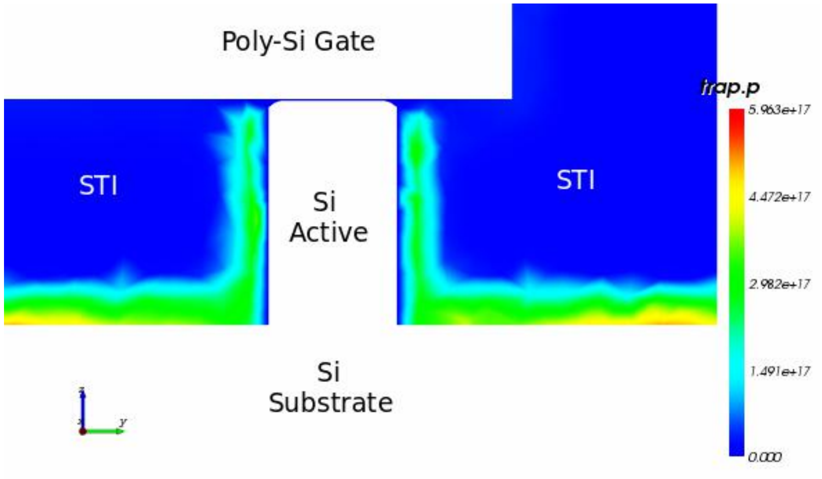
Physical Mechanism of TID: Consensus

- Ionizing radiation → 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)

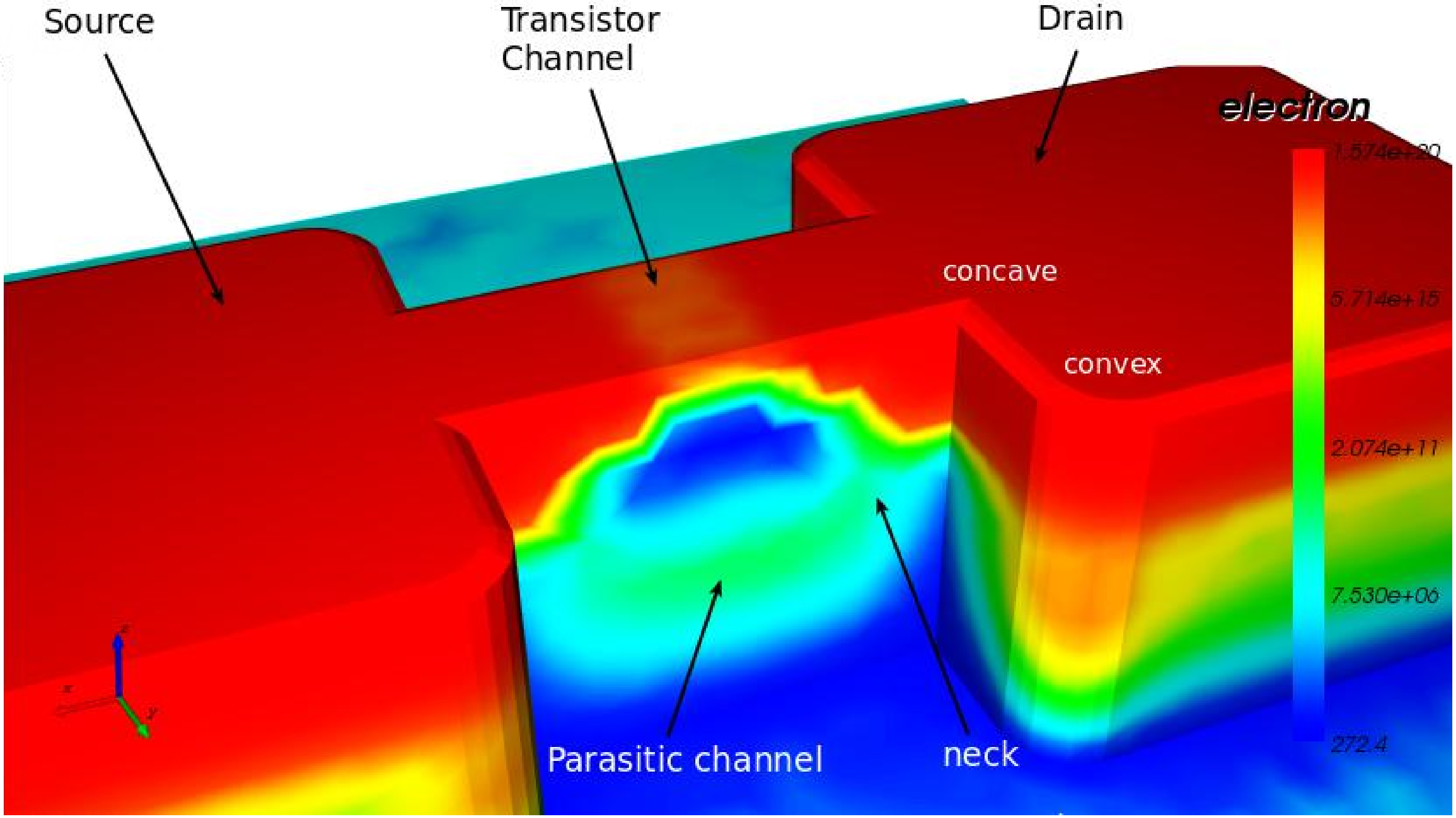


Trapped Charge Build-up in Oxide





TID-Induced Parasitic Channel



Physics and Governing Equations

Ionization:

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

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

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

Electrostatics: ....

Transport of mobile species: ....

Reactions: ....

I. S. Esqueda, Modeling of total ionizing dose effects in advanced complementary metal-oxide-semiconductor technologies. PhD thesis, Arizona State University, 2011.

Physics and Governing Equations

Electrostatics

$$\nabla \epsilon \nabla \psi = -\frac{1}{e}(p + T_p - n)$$

Transport of mobile species

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:

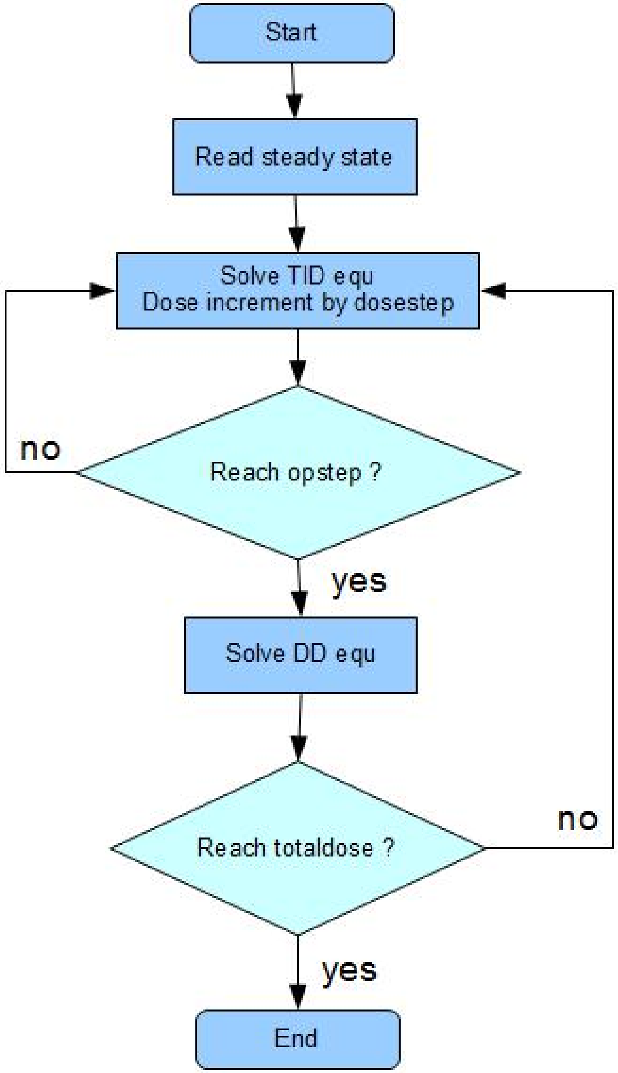
hole capture at D_A	$D_A + p \rightarrow D_A^+$
electron capture at D_A	$D_A^+ + n \rightarrow D_A$

hole capture/emission at D_B	$D_B H + p \rightleftharpoons D_B H^+$
H+ release from D_B	$D_B H^+ \rightarrow D_B + H^+$
electron capture from D_B	$D_B H^+ + n \rightarrow D_B H$

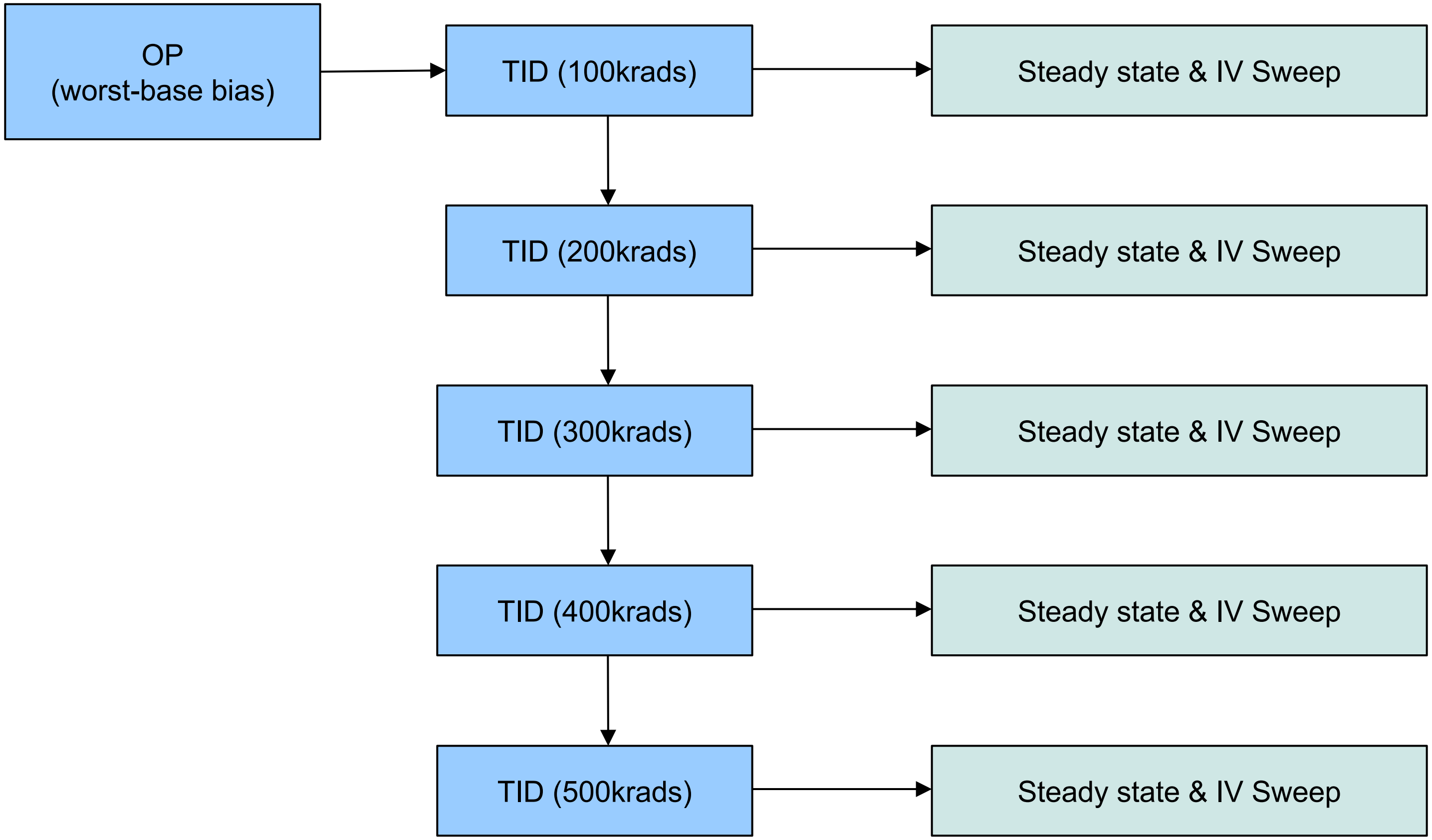
Interface trap production	$H^+ + SiH \rightarrow N_{it} + H_2$

Numerical Implimentation

- 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)

TID (200krads)

TID (300krads)

TID (400krads)

TID (500krads)

Steady state & IV Sweep

Steady state & IV Sweep

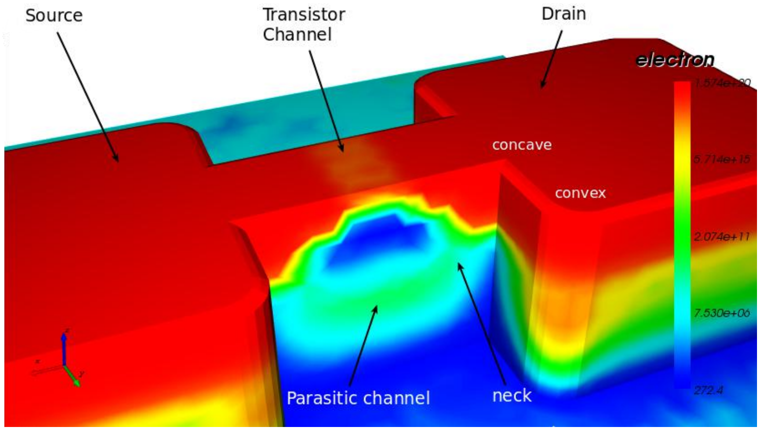
Steady state & IV Sweep

Steady state & IV Sweep

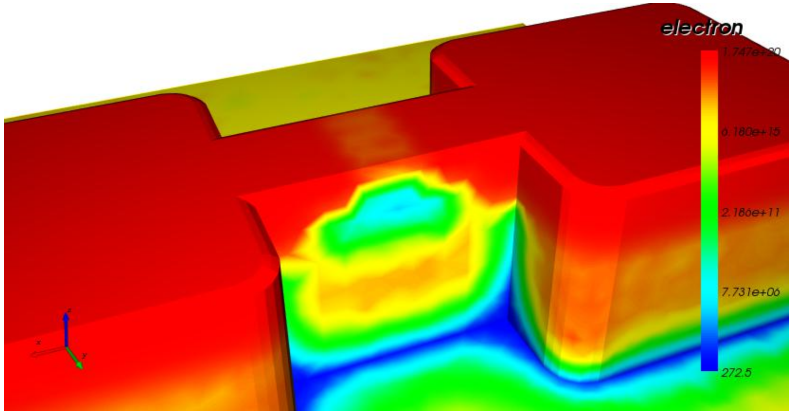
Steady state & IV Sweep

Parasitic Channel due to TID

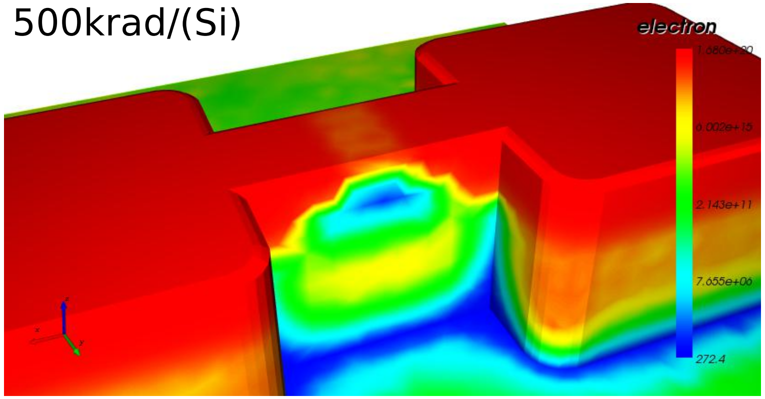
100krad/(Si)



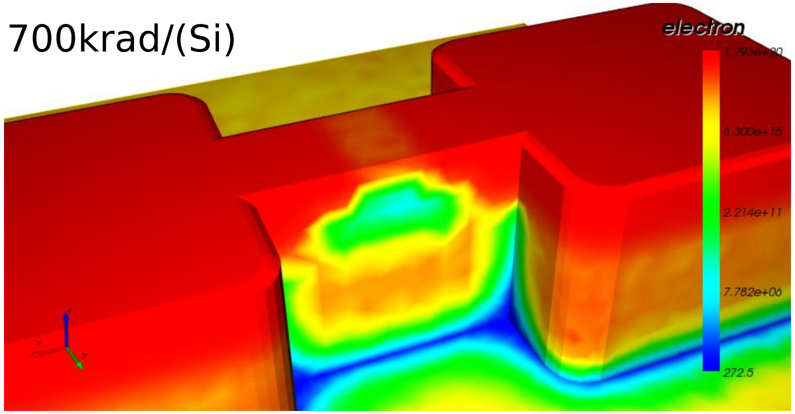
300krad/(Si)



500krad/(Si)

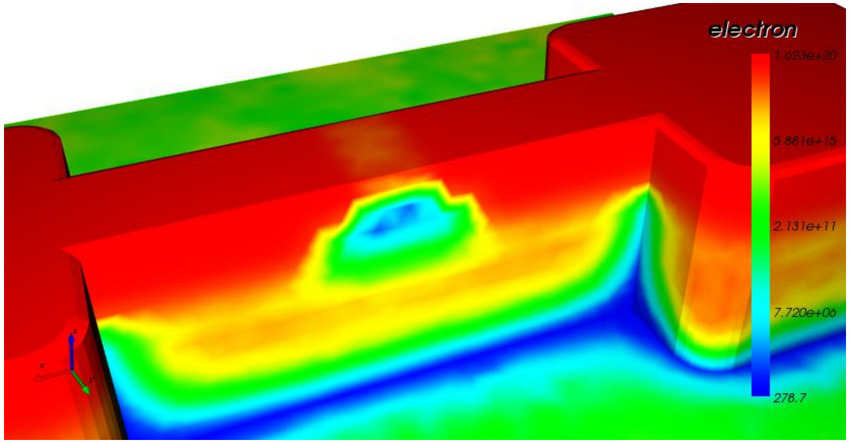


700krad/(Si)

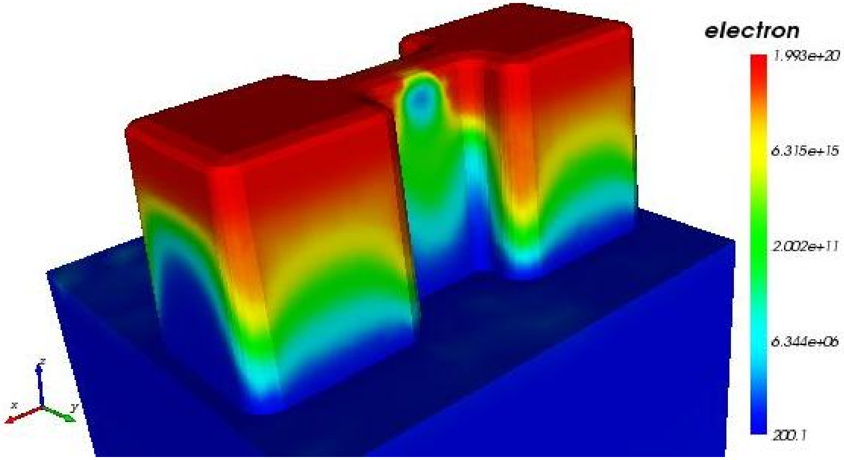


0.13um CMOS nMOSFET

Parasitic Channel due to TID

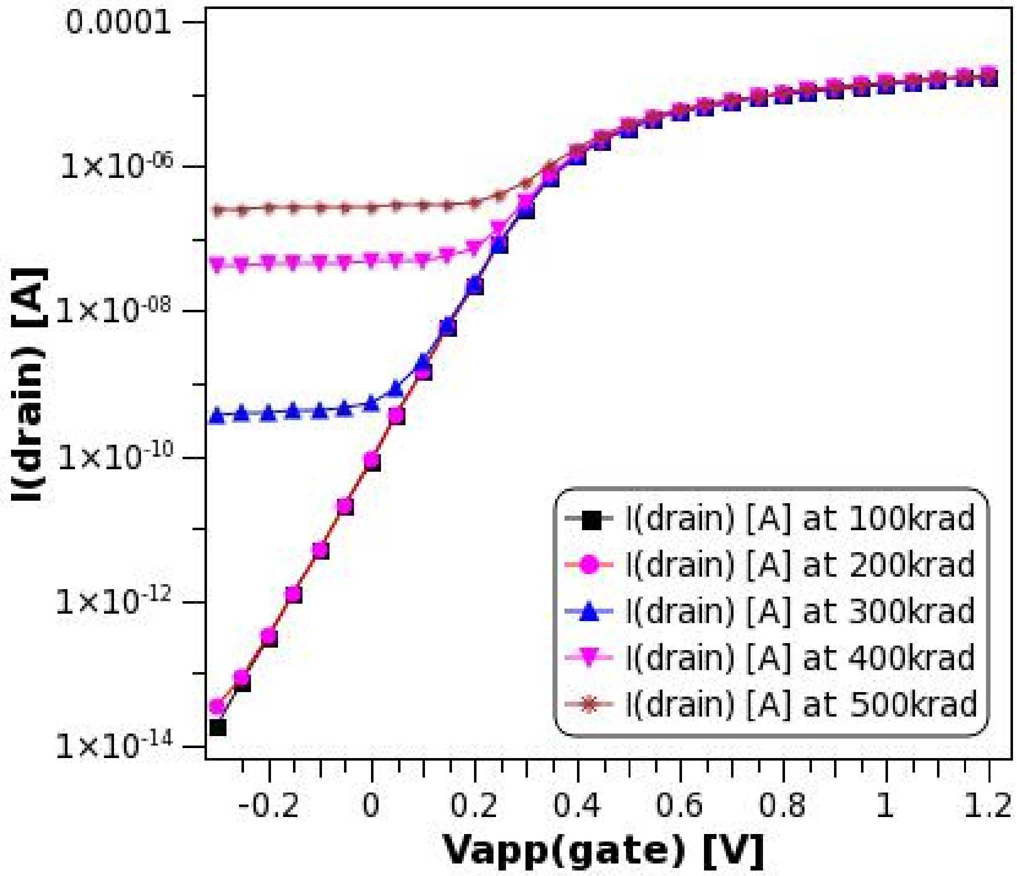


- 0.13um, another layout



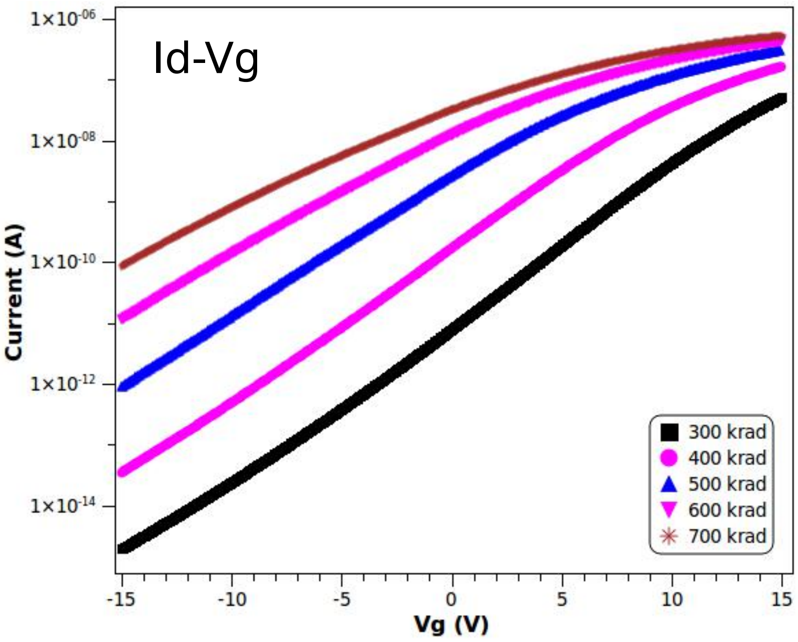
- 65nm, nMOSFET

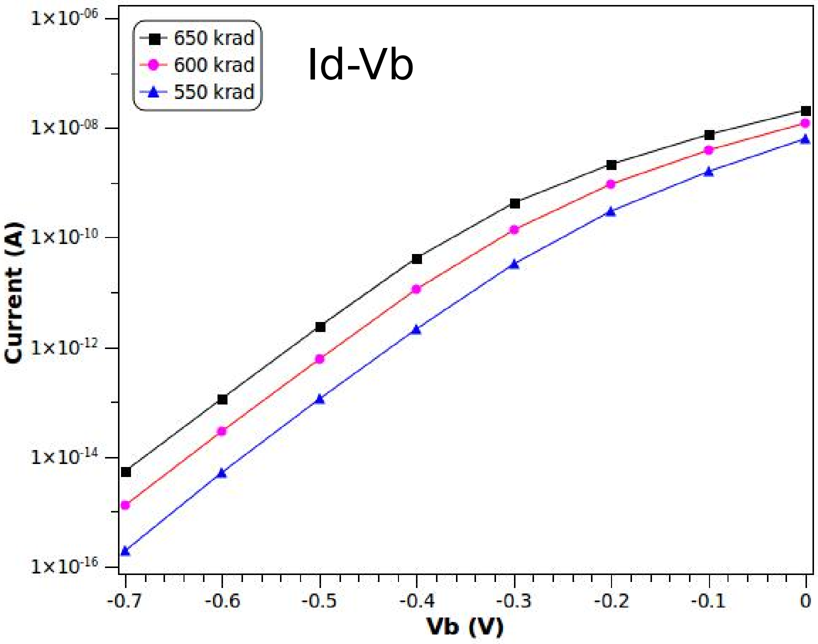
Simulated IV Curves due to TID



IV Curves of Sidewall Parasitic Tr

Separate parasitic from intrinsic MOSFET





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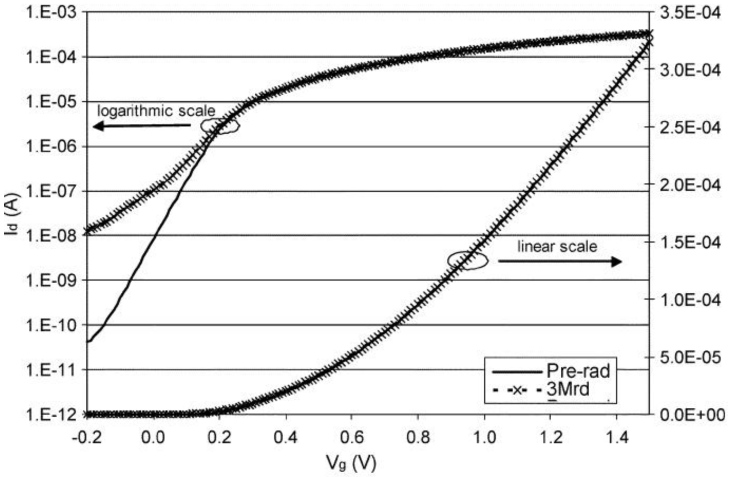
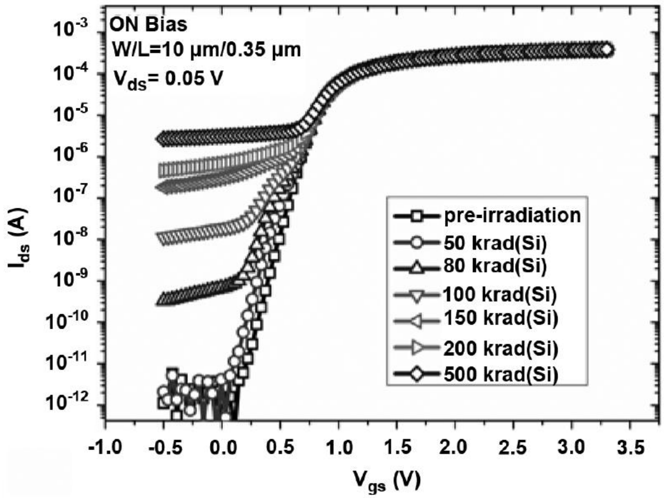
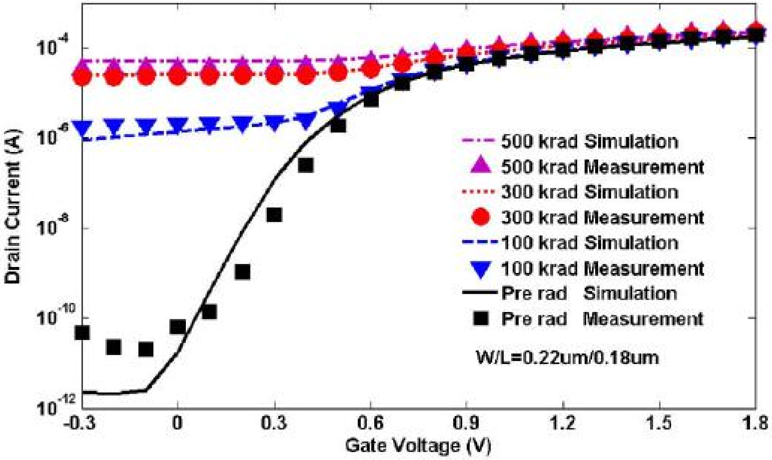
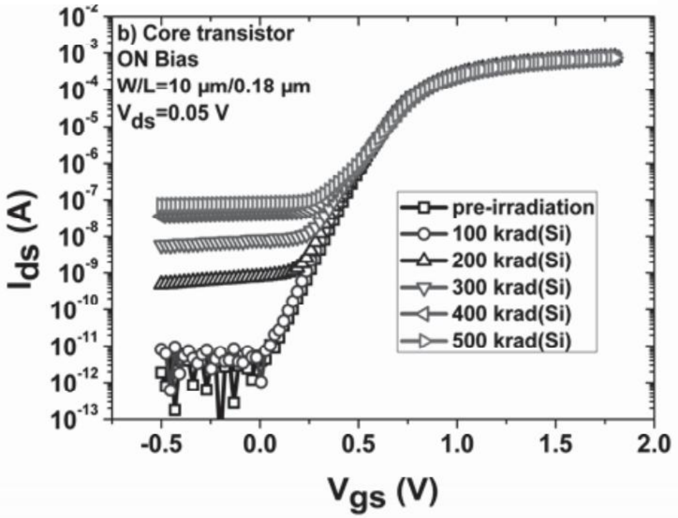
TID in CMOS: Experiment Data





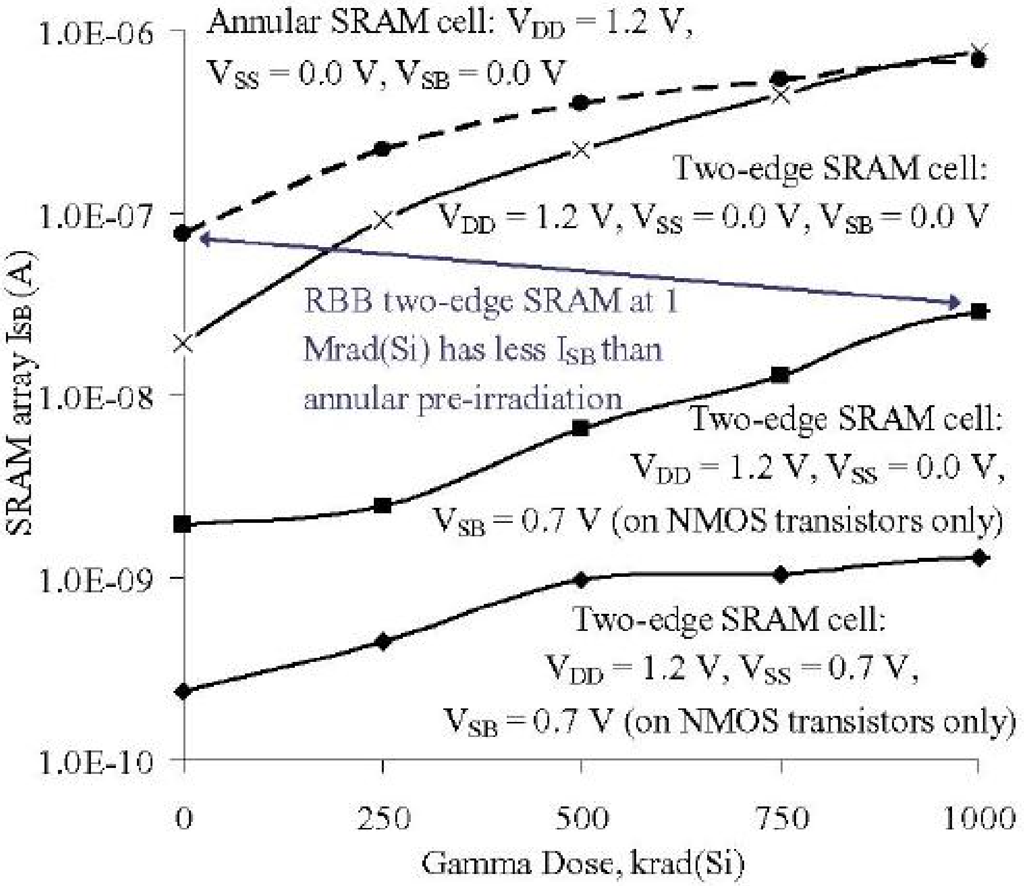




F. Faccio, IEEE TNS v52 p2413 (2005)
M. Li, IEEE TNS v58 p2876 (2011)

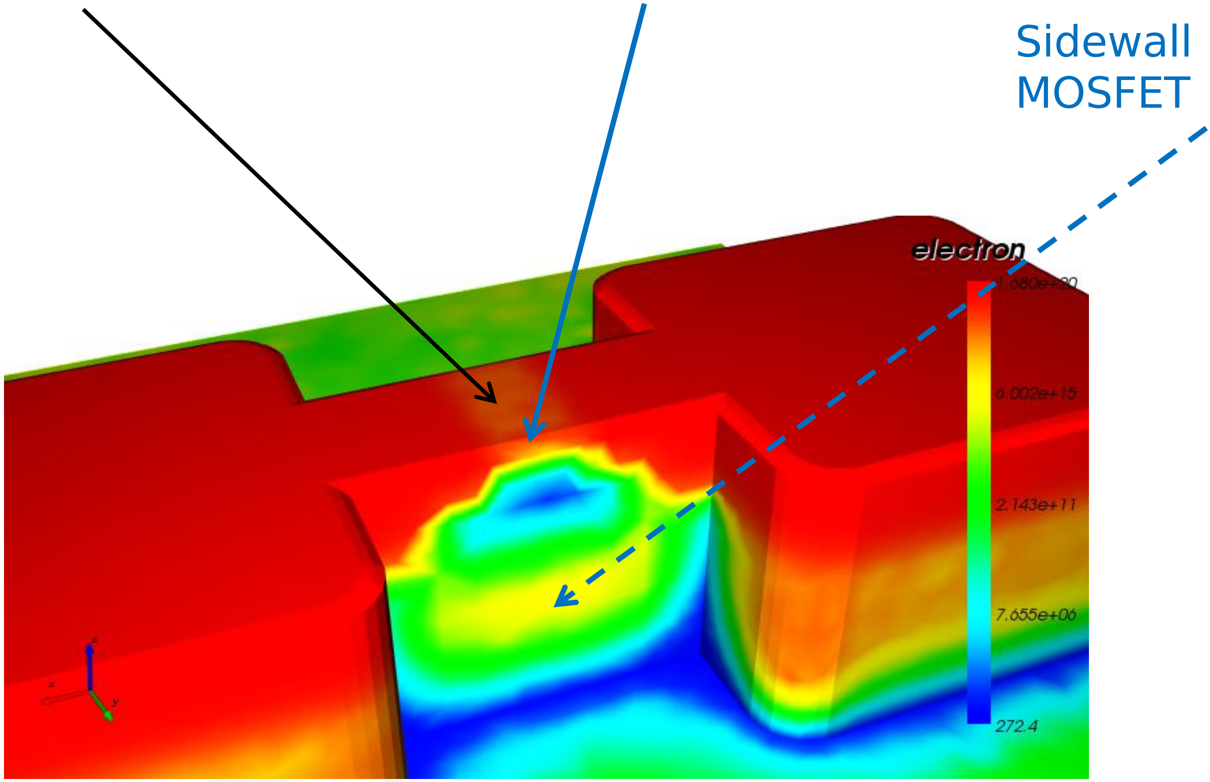
Z.L. Liu IEEE TNS v58 p1324 (2012)
Z.L. Liu RADECS 2011 PA2

Motivation: Why Substrate Bias?



L.T. Clark IEEE TNS v54 p2028 (2007)

TID-Induced Parasitic Channel

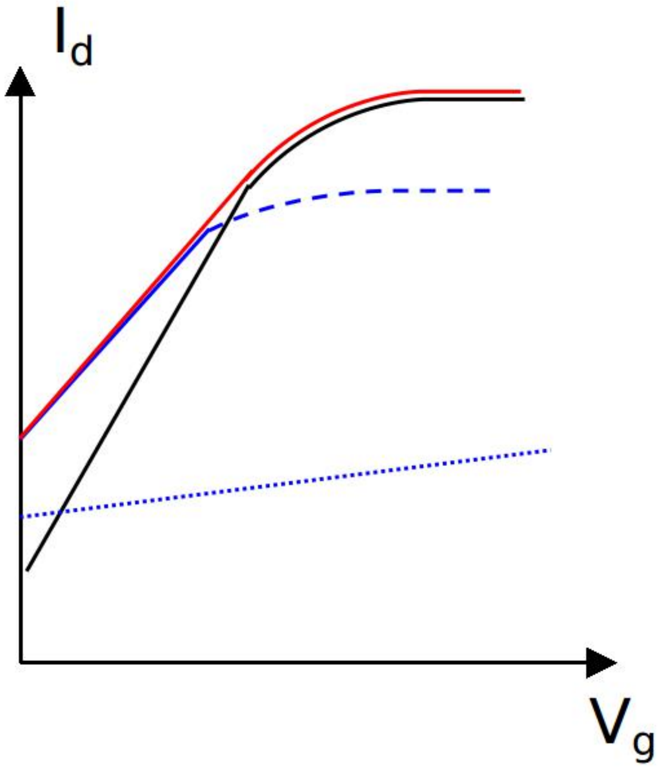


Intrinsic MOSFET

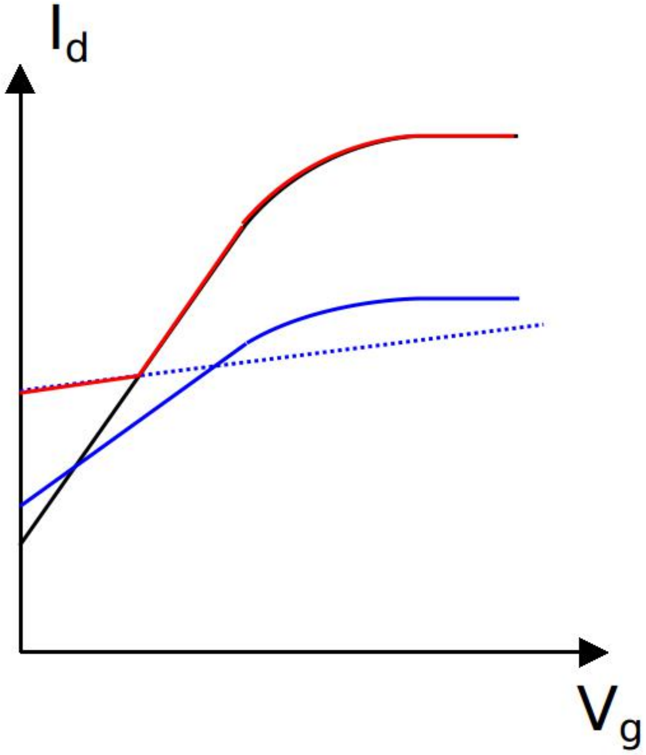
Corner Parasitic MOSFET

Sidewall Parasitic MOSFET

TID in CMOS: Mechanism



corner parasitic
MOSFET dominates



sidewall parasitic
MOSFET dominates

Sub-threshold IV of Parasitic Transistor

sub-threshold IV

$$I_{\mathrm{ds}} = \mu \frac{W}{L} V_T^2 C_{\mathrm{dep}} \underbrace{\boxed{\exp \frac{V_{\mathrm{gs}} - V_{\mathrm{th}}}{\kappa V_T}}}_{\text{Vg dependence}} \underbrace{\boxed{\exp \frac{V_{\mathrm{bs}}}{\eta V_T}}}_{\text{Vb dependence}} \left(1 - \mathrm{e}^{-\frac{V_{\mathrm{ds}}}{V_T}}\right)$$

threshold voltage and fixed charge

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

$$Q_D = 1.2 \times 10^{11}\,\mathrm{cm}^{-2} \times q_0 \times \left(\frac{D_D}{100\,\mathrm{krad}}\right)^{0.65}$$

Model Synthesis: IV

smoothing function: sub-threshold to above threshold

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

Main IV equation:

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

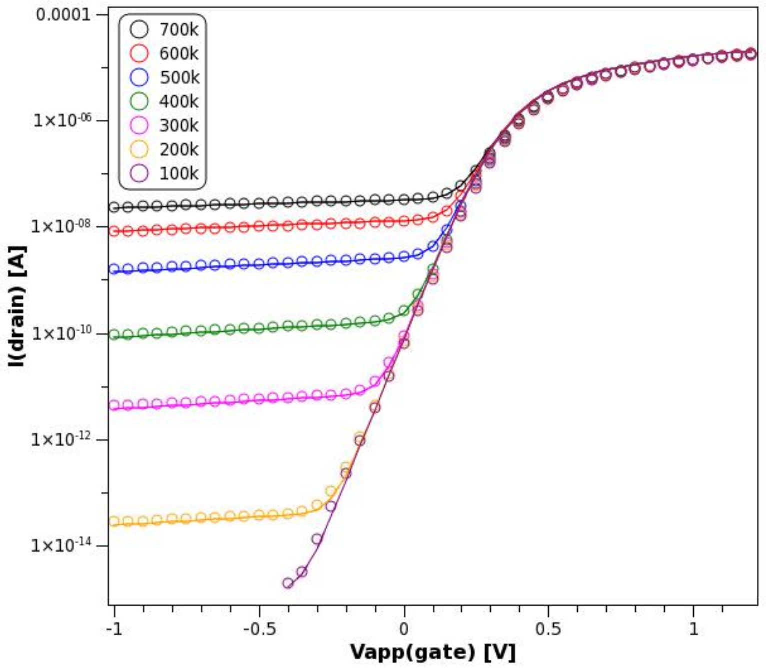
W and L dependence

$$\left(\frac{Z}{L}\right)_{\mathrm{eff}} = Z_{\mathrm{eff}} \cdot \frac{(L_{\mathrm{min}}+L_{\mathrm{ref}})}{(L+L_{\mathrm{ref}})\cdot L_{\mathrm{min}}}$$

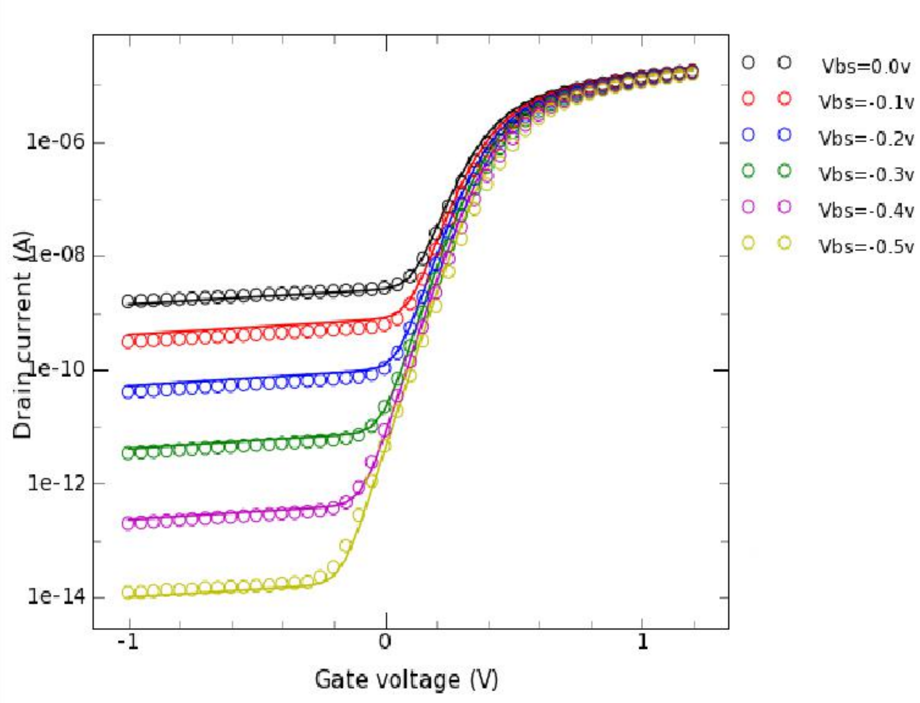
$$f_W = \left(A_W \times W^{B_W} + C_W\right)$$

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