Modeling Total Ionizing Dose Effects in Deep Submicron Bulk CMOS Technologies

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Motivation

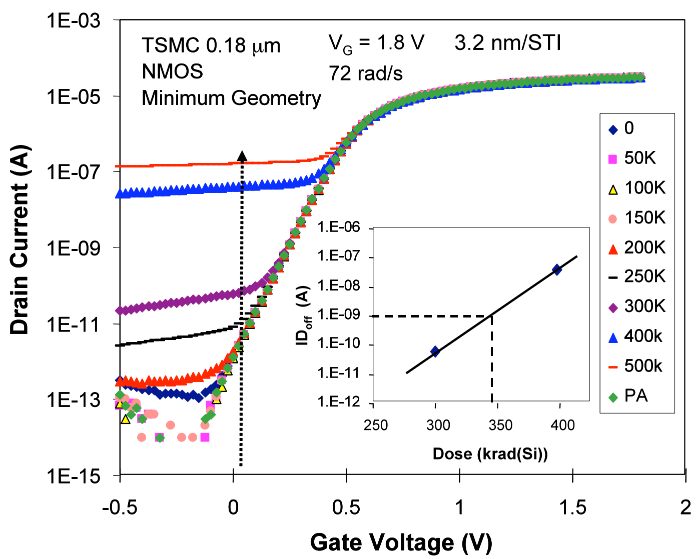
- **Characterize ionizing radiation damage effects in advanced bulk CMOS device technologies**
- **Develop multi-scale analytical modeling approaches for radiation damage that are:**
  - **scalable with technology and design parameters**
  - **capable of both short-term and long-term predictions of device performance**
  - **compatible with standard circuit simulators and compact models**

Previous Research - 2005

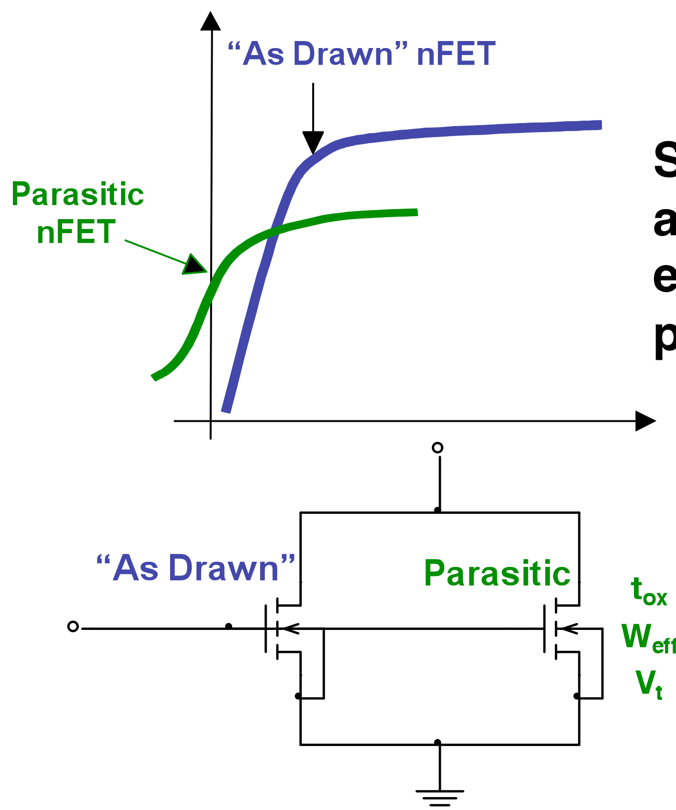
- "Device-level Radiation Effects Modeling"

  Overview of numerical (TCAD) simulation approaches for modeling drain-source leakage in bulk CMOS devices

<u>0.18 μm data</u>



After Lacoe NSREC SC 2003

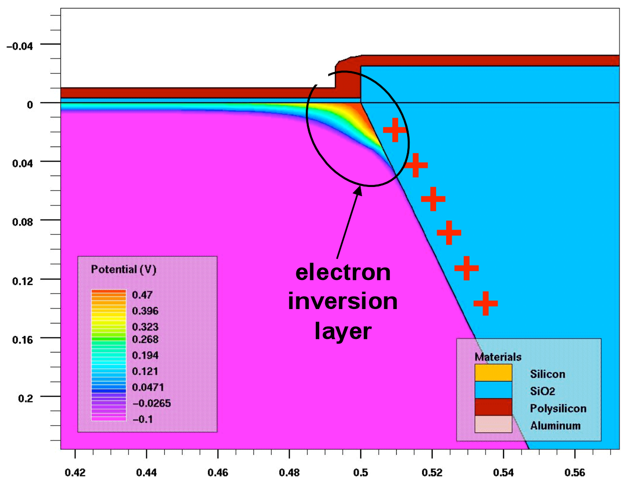


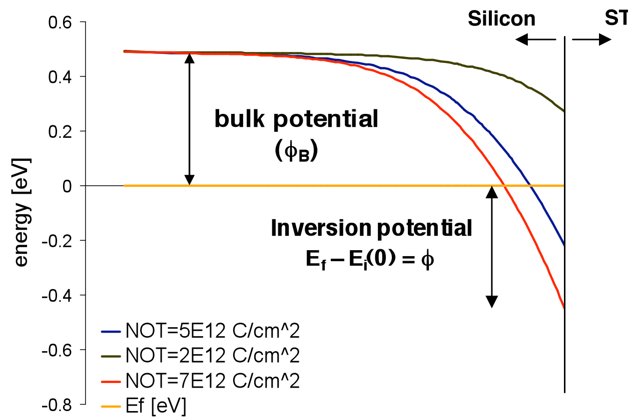
Simple modeling approach required extraction of key parasitic parameters

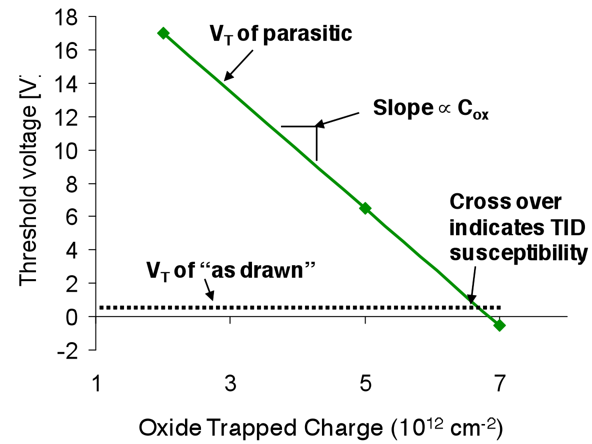
threshold voltage
effective width
oxide thickness

Previous Research - 2005

2D modeling approach for parameter extraction



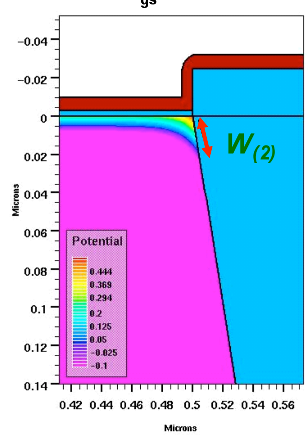




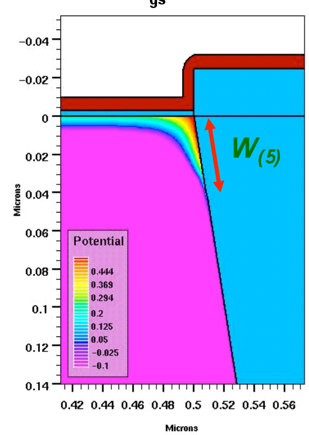
Sheet charge added to STI creates inversion layer along sidewall

Analysis of surface potential shift along sidewall enable estimates of V_t, t_{ox}, and W_{eff}

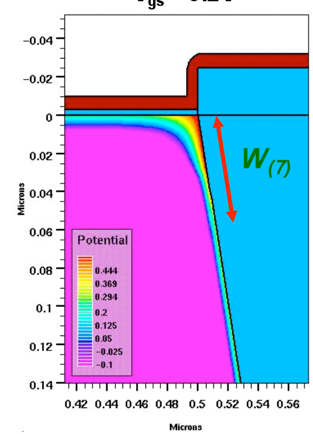
$N_{ot} = 2x10^{12}$ cm^2
$V_{gs} = 0.2V$



$N_{ot} = 5x10^{12}$ cm^2
$V_{gs} = 0.2V$

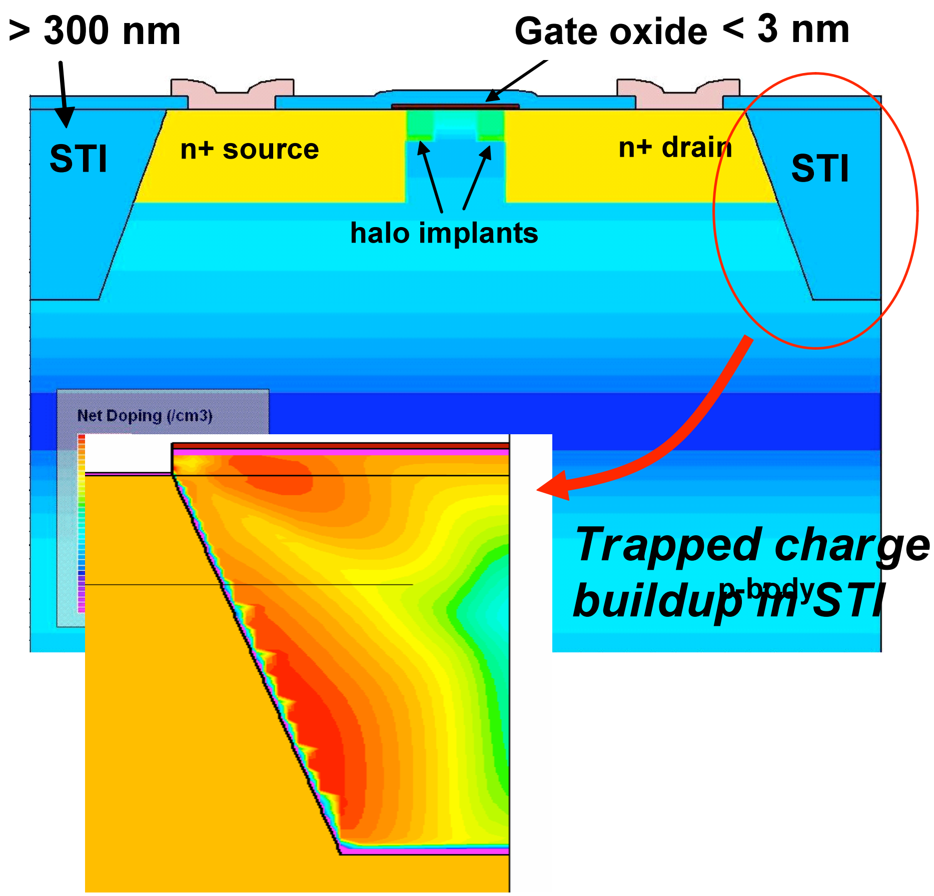


$N_{ot} = 7x10^{12}$ cm^2
$V_{gs} = 0.2V$



Previous Research - 2005

Volumetric modeling of defect buildup in isolation oxide



Adapt Radiation Effects Module (REM) in Silvaco ATLAS to model volumetric distributions of charge buildup

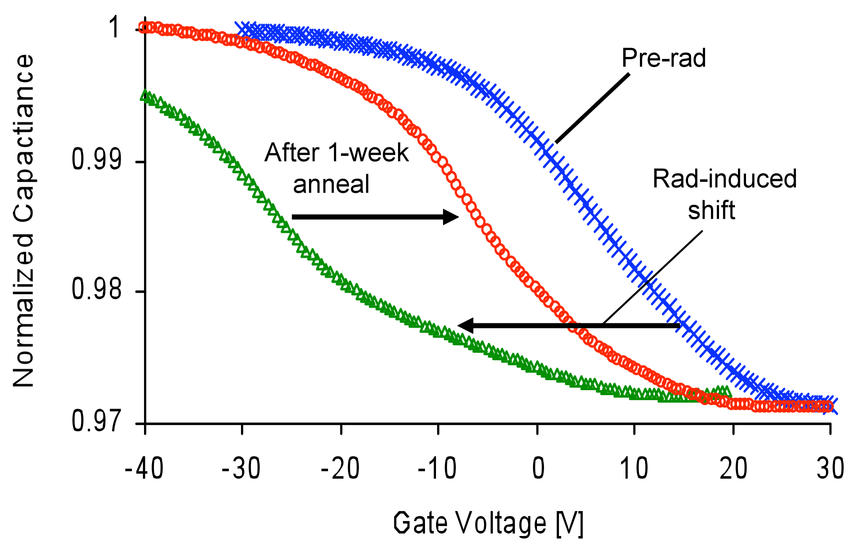
Results used to evaluate 2D modeling approach

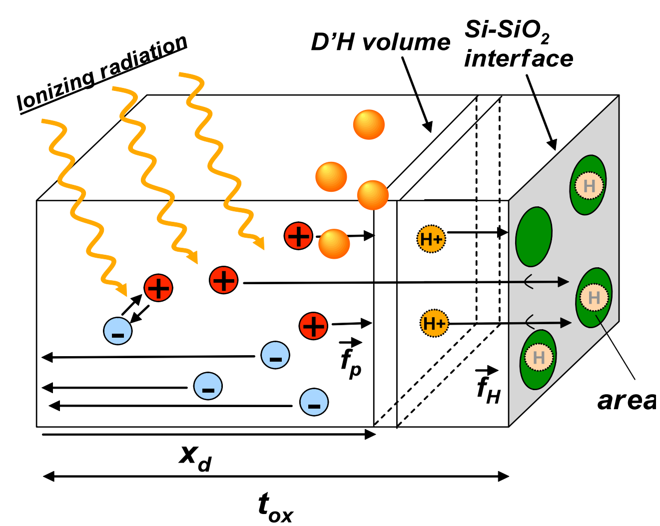
<u>Conclusion:</u> more accurate models required to capture effects

Previous Research - 2006

- "Total Ionizing Dose Effects in Bulk Technologies and Devices"

  Characterize, parameterize TID effects. Formalize closed form analytical expressions for TID effects in devices (130nm CMOS).





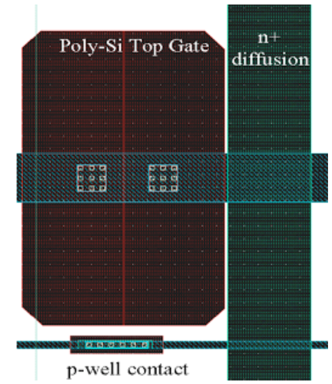
$$\Delta N_{ot} \approx D k_g f_y (\vec{\varepsilon}) f_{ot} (\vec{\varepsilon}) t_{ox}$$

$$\Delta N_{it} \approx D k_g f_y (\vec{\varepsilon}) f_{DH} f_{it} t_{ox}$$

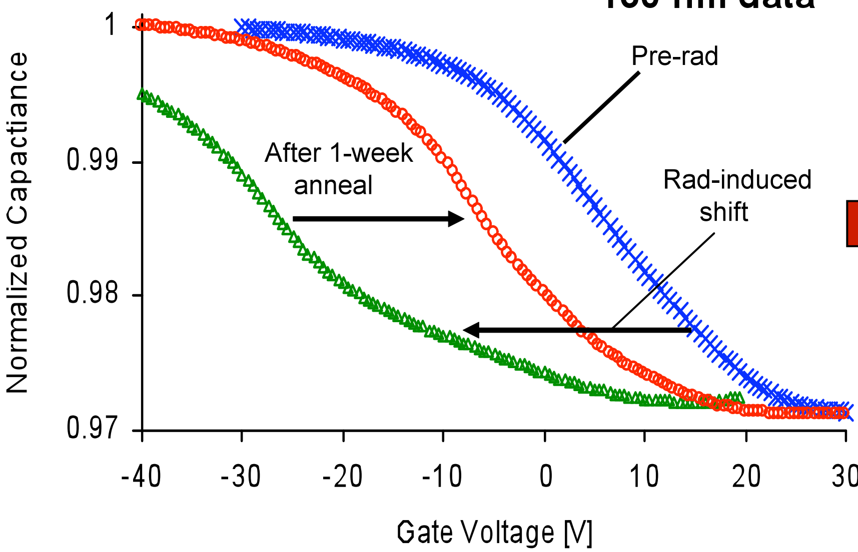
Previous Research - 2006

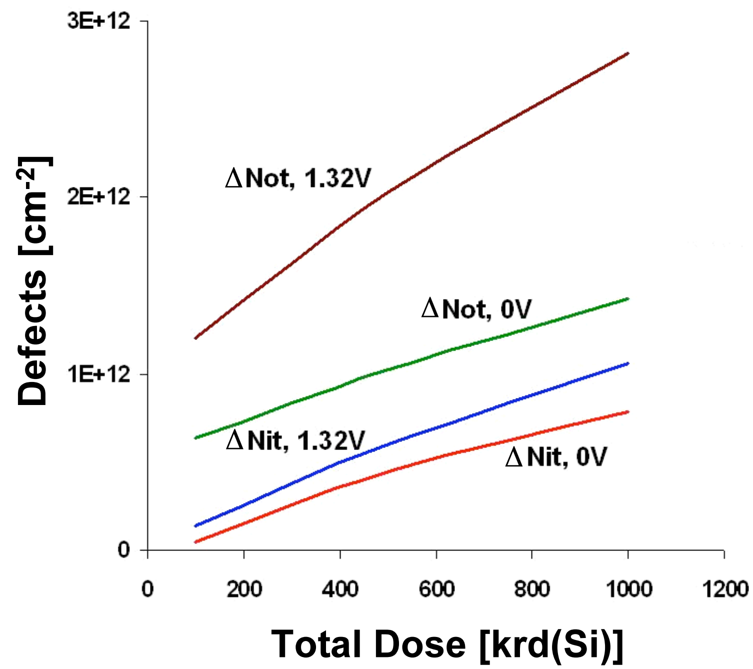
Experimental Characterization

Radiation testing on specialized structures e.g., FOXCAPs, FOXFETs) enabled measurements of defect buildup in 130 nm bulk CMOS



130 nm data

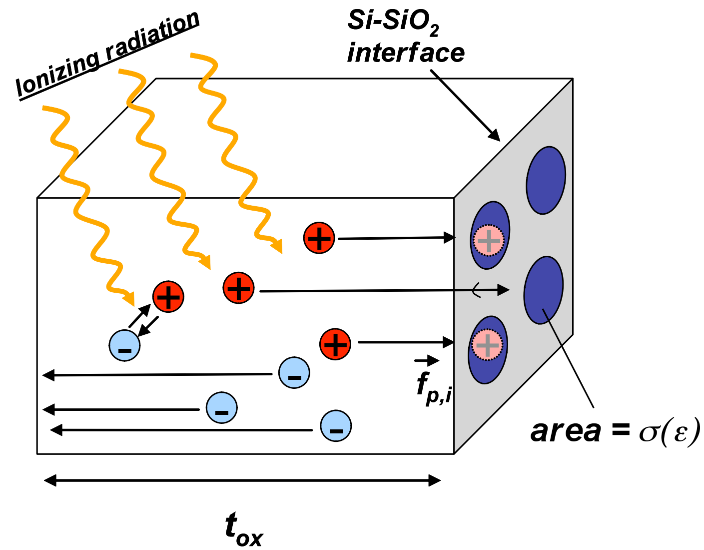




Previous Research - 2006

Analytical Model Development

Models for defect buildup (N_{ot} and N_{it}) enable extraction of technology specific of TID parameters (e.g. f_{ot})



<u>Core model eqs. for N_{ot}</u>

$$\frac{\partial f_p}{\partial x} = \dot{D} k_g f_y - \frac{\partial p}{\partial t} \approx \dot{D} k_g f_y$$

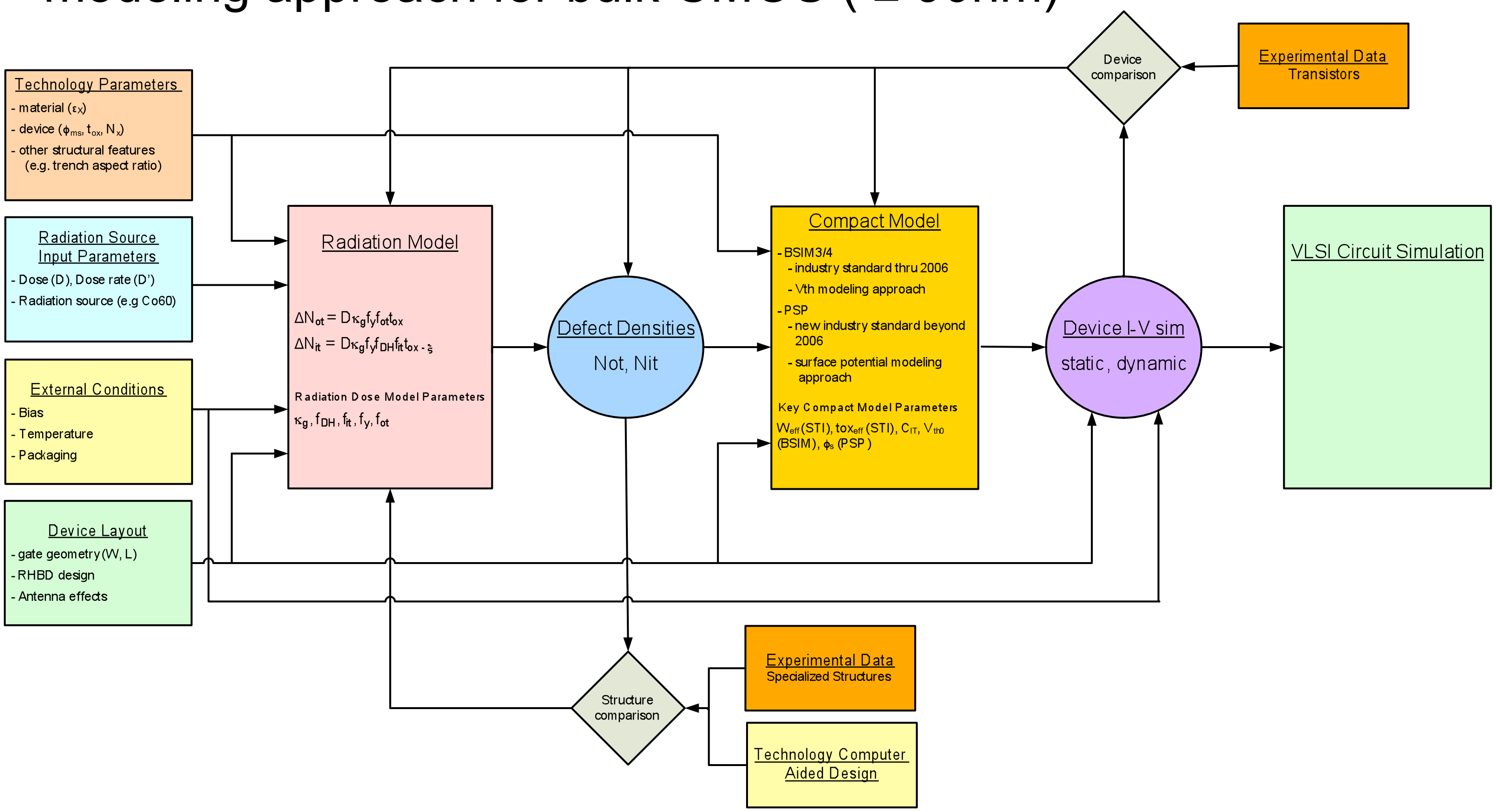
$$\frac{\partial N_{ot}}{\partial t} = \left(N_T - N_{ot}(t)\right)\sigma f_p - \frac{N_{ot}(t)}{\tau} \approx N_T \sigma f_{p,i}$$

$$\Delta N_{ot} = \underbrace{N_T \sigma}_{f_{ot}} \underbrace{\dot{D} \Delta t}_{D} k_g f_y t_{ox}$$

Similar models used to analytically model interface trap buildup

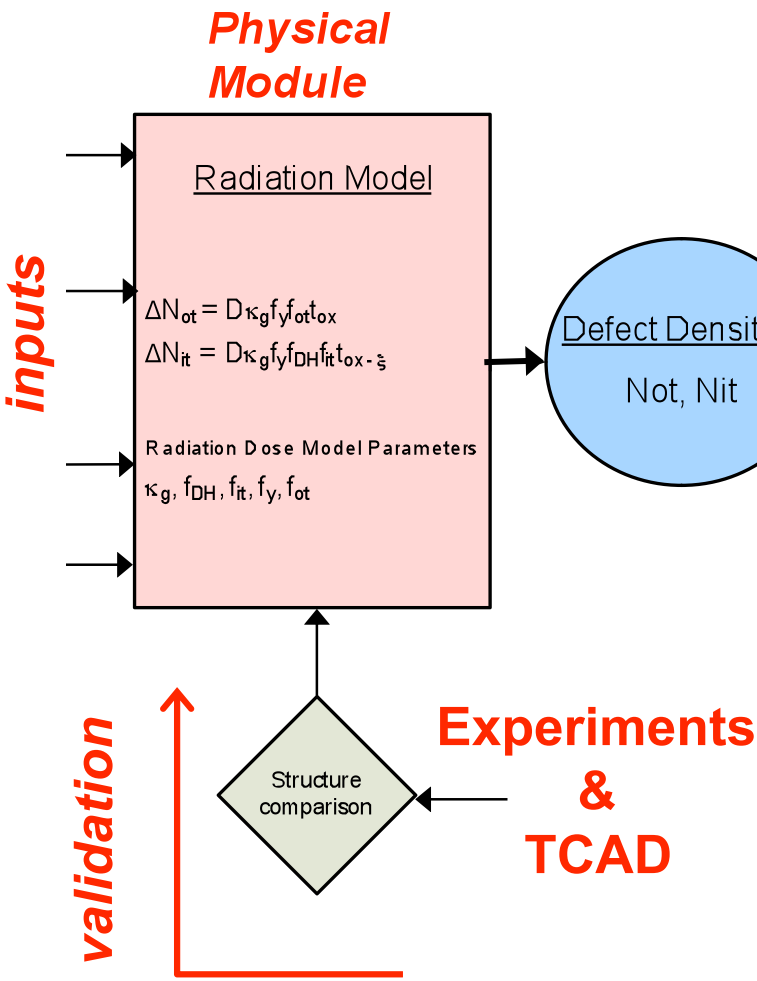
Previous Research - 2007

- "Modeling Total Ionizing Dose Effects in Deep Submicron Bulk and SOI CMOS technologies"
  - Description and initial validation of radiation-enabled compact modeling approach for bulk CMOS (≥ 90nm)



Previous Research - 2007

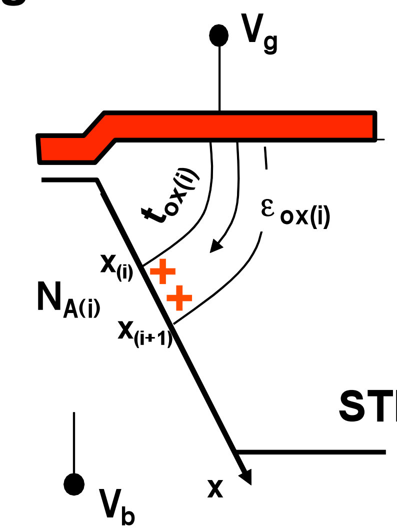
Radiation-enabled compact modeling (physical module)



Simple model extended to capture multiple parasitics along STI sidewall

Model captures:

$N_{A(i)}$, $\phi_{MS(i)}$, $t_{ox(i)}$, $\varepsilon_{ox(i)}$, and V_{gb}



Requires iterative e-field calculation

$$\vec{\varepsilon}_{ox}(i) \approx \frac{V_{gb} - \phi_{ms}(i) - \psi_s(i)}{t_{ox}(i)} + \frac{qN_{ot}(x_i)}{\epsilon_{ox}}$$

Previous Research - 2007

Radiation-enabled compact modeling (surface potential)

Nit, Not
from phys. mod.

$$\psi_s(x,y) = V_G - V_{FB}(x,\psi_s(x,y)) + Q_s(x,\psi_s(x,y))$$

$$V_{FB}(x,\psi_s(x,y)) = V_{FB0}(x) - \frac{qN_{ot}(x)}{C_{ox}(x)} + \frac{qN_{it}^{charged}(x,\psi_s(x,y))}{C_{ox}(x)}$$

$$Q_s(x,\psi_s(x,y)) = \gamma(x)\sqrt{\psi_s(x,y) + \phi_t \frac{n_i^2}{(N_A(x))^2} e^{\left(\frac{\psi_s(x,y)-V(y)}{\phi_t}\right)}}$$

$\psi_s(x,y)$

Surface potential information used for I-V calculations of device response

Previous Research - 2008

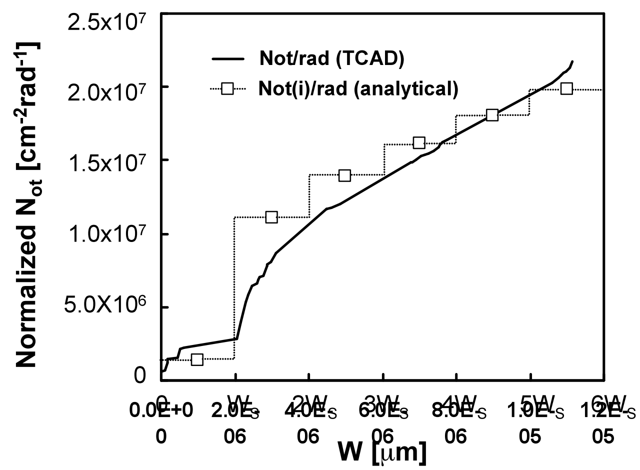
- "Surface potential-based analytical modeling of TID effects in CMOS devices"
  - Closed form analytical models fit to degraded I-V characteristics in nFETs

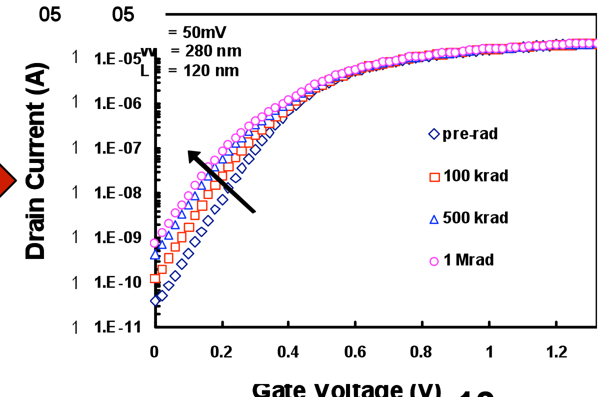
$$t_{ox}(i)$$

$$\varepsilon_{ox}(i) \approx \frac{V_{gb}}{t_{ox}(i)}$$

$$f_y(i) \approx \frac{\varepsilon_{ox}(i)}{\varepsilon_{ox}(i) + \varepsilon_0}$$

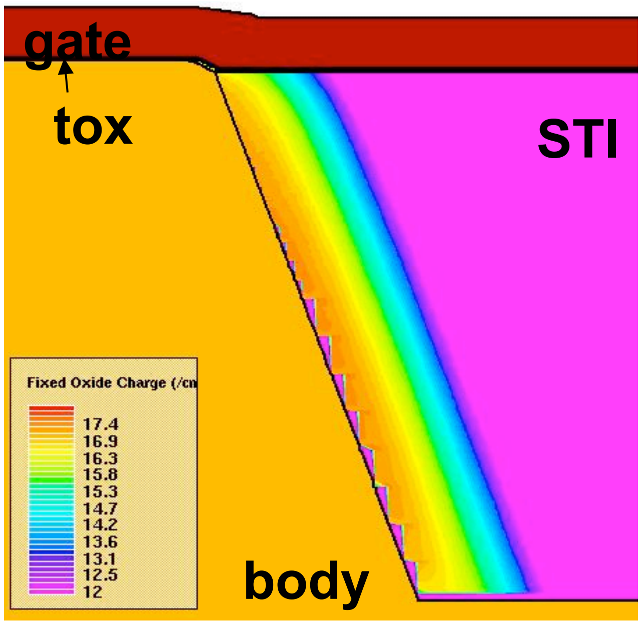
$$\Delta N_{ot}(i) \approx N_T \sigma D g_o f_y(i) t_{ox}(i)$$



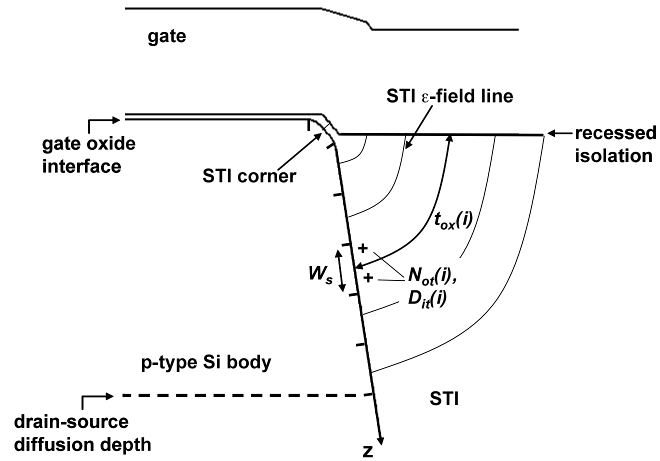


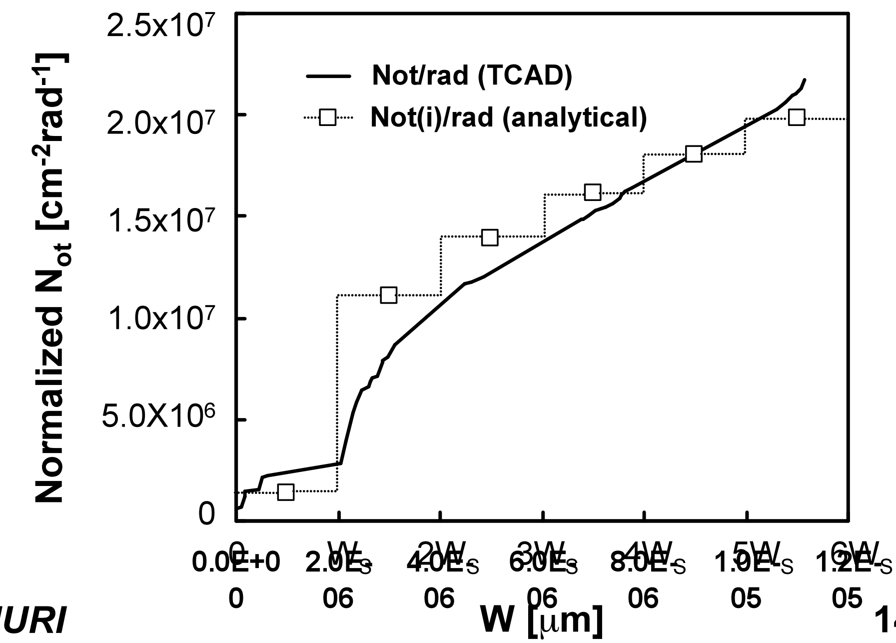
Previous Research - 2008

Analytical model for Not buildup calibrated to TCAD



2-D device simulations with REM calculate N_{ot} buildup (precursors set near sidewall)





Previous Research - 2008

Compact modeling with surface potential equations

Equations for surface potential :

$$(V_g - \varphi_{ms} + \phi_{nt} - \psi_s)^2 = \gamma^2 \cdot \varphi_t H(u)$$

$$\phi_{nt} = \frac{q}{C_{ox}}[N_{ot} - D_{it}(\psi_s - \phi_b)]$$

(After C. McAndrew, TED, 2002)

$$H(u,\varphi_n) = e^{-u} + u - 1 + e^{-\beta(2\varphi_b + \varphi_n)}(e^u - u - 1)$$

Drift/diffusion currents:

$$I_{drift} = \left[V_g - \varphi_{ms} + \varphi_{nt}\right](\psi_{sd} - \psi_{ss}) - \frac{1}{2}(\psi_{sd}^2 - \psi_{ss}^2) - \frac{2\gamma}{3}\left[(\psi_{sd} - \phi_t)^{3/2} - (\psi_{ss} - \phi_t)^{3/2}\right]$$

$$I_{diff} = \varphi_t\left[(\psi_{sd} - \psi_{ss}) - \gamma\left(\sqrt{\psi_{sd} - \varphi_t} - \sqrt{\psi_{ss} - \varphi_t}\right)\right]$$

Model Parameters

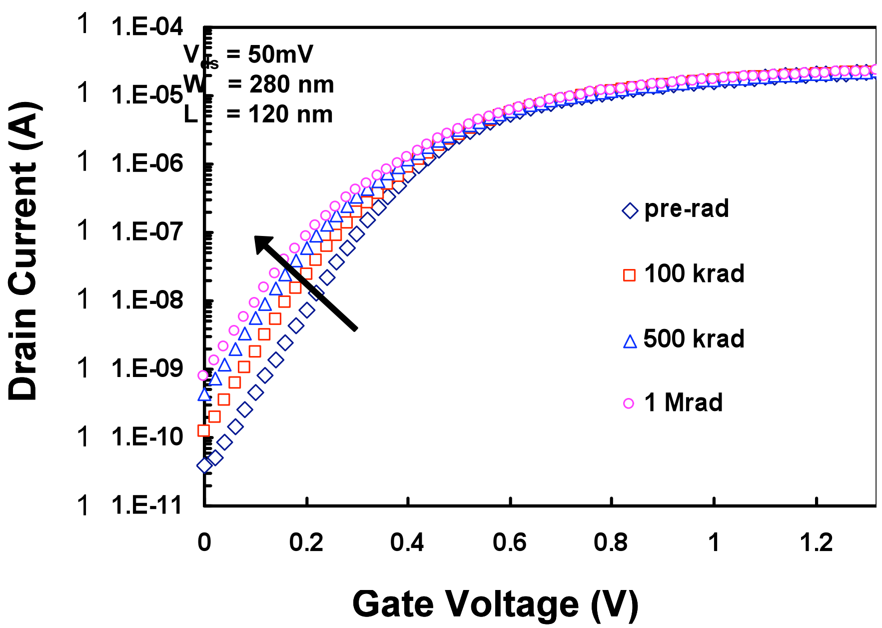
- V_g - *gate voltage*
- ψ_s - surface potential
- H - normalized field
- γ - bulk parameter
- ϕ_{ms} - workfunction difference

Equations solved iteratively with MATLAB

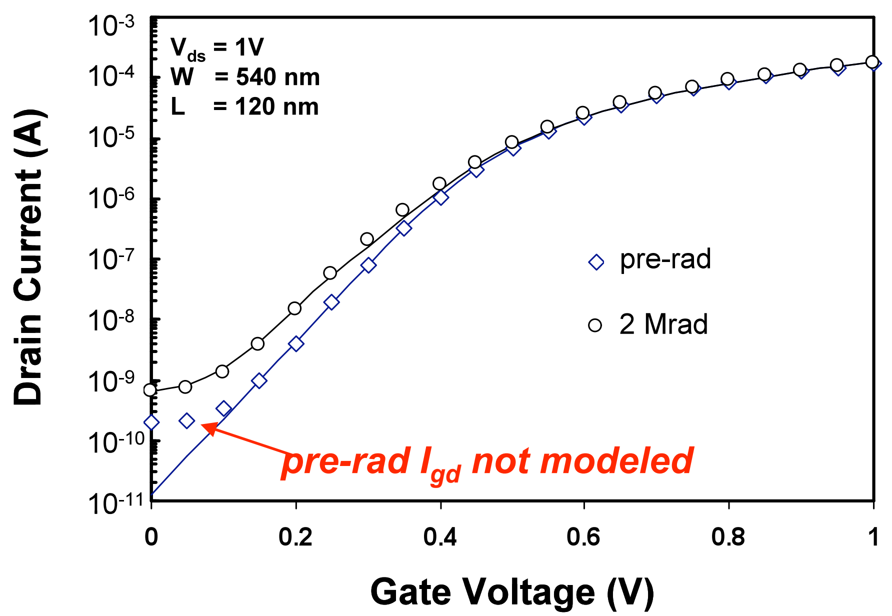
Previous Research - 2008

Comparison of data and model

130 nm data



90 nm data

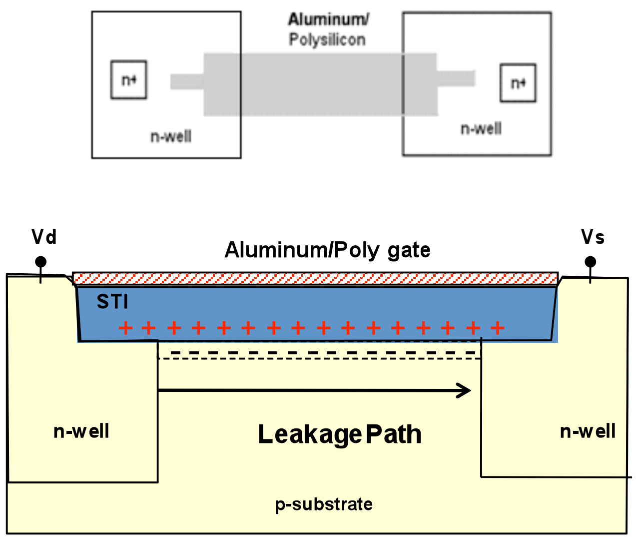


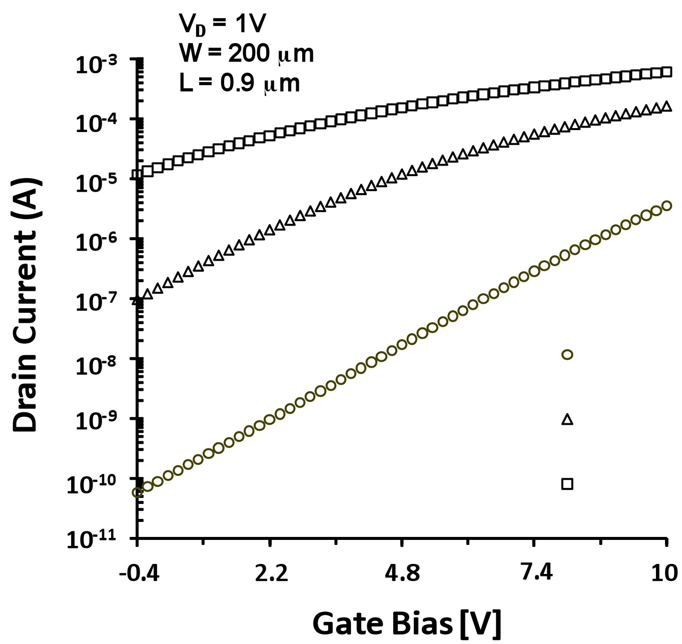
Comparison of measured pre- and post-irradiation data (symbols) with modeled radiation response characteristics (solid lines) for single stripe nFETs in 130 and 90 nm technologies

Previous Research - 2009

- "Modeling Total Ionizing Dose Effects in Deep Submicron CMOS Technologies "

  Revised analytical model for TID defect buildup compared to FOXFET I-V and TCAD simulations





Previous Research - 2009

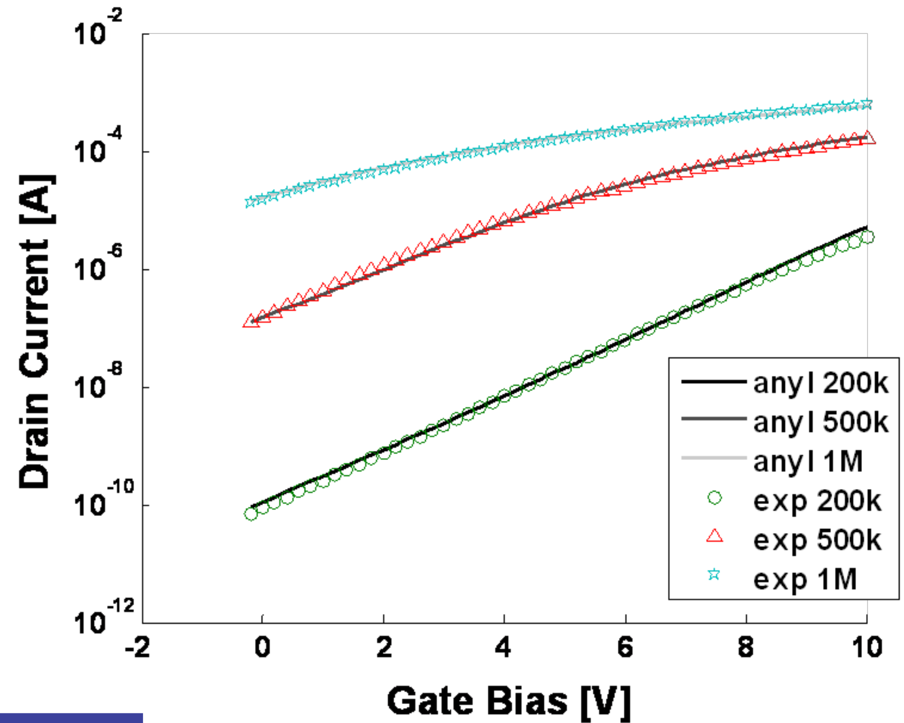
SP equations fit to FOXFET data

$$I_{Drift} = (V_{gb} - V_{fb})(\psi_{sd} - \psi_{ss}) - \frac{1}{2}(\psi_{sd}^2 - \psi_{ss}^2)$$
$$- 2\frac{\gamma}{3}\left[(\psi_{sd} - \varphi_t)^{3/2} - (\psi_{ss} - \varphi_t)^{3/2}\right]$$

$$I_{Diff} = \varphi_t\left(\psi_{sd} - \psi_{ss} + \gamma\left(\sqrt{\psi_{sd} - \varphi_t} - \sqrt{\psi_{ss} - \varphi_t}\right)\right)$$

$$(V_{gb} - \varphi_{ms} + \varphi_{nt} - \psi_s)^2 = \gamma^2 \cdot \varphi_t H(u)$$

$$\varphi_{nt} = \frac{q}{C_{ox}}\left(N_{ot} - D_{it}\cdot(\psi_s - \varphi_b)\right)$$



Fit w/ analytical model

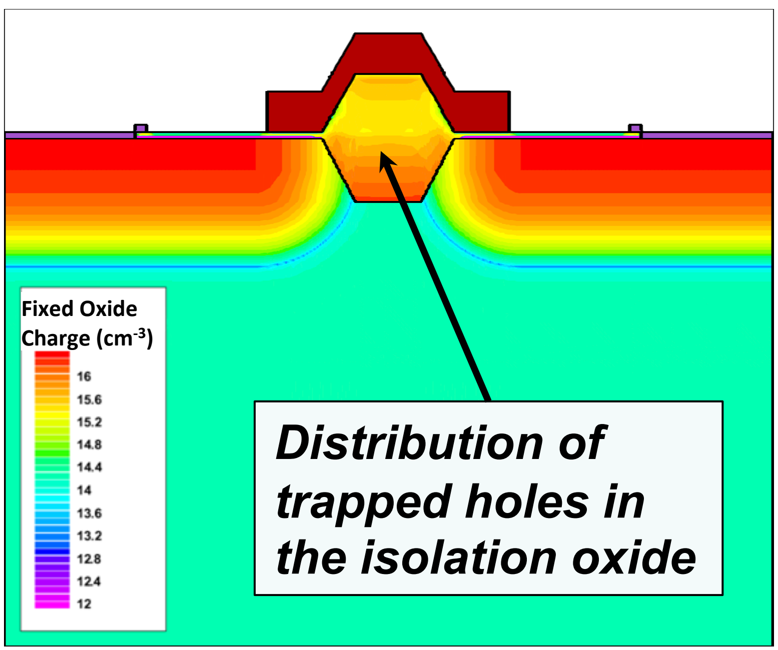
Dose [krad(Si)]	N_{ot} (cm^{-2})	D_{it}(cm^{-2}/V)
200	1.92×10^{12}	2.6×10^{11}
500	2.39×10^{12}	6.0×10^{11}
1000	2.75×10^{12}	8.0×10^{11}

Fit based on approximations for oxide thickness, body doping, workfunction, etc.

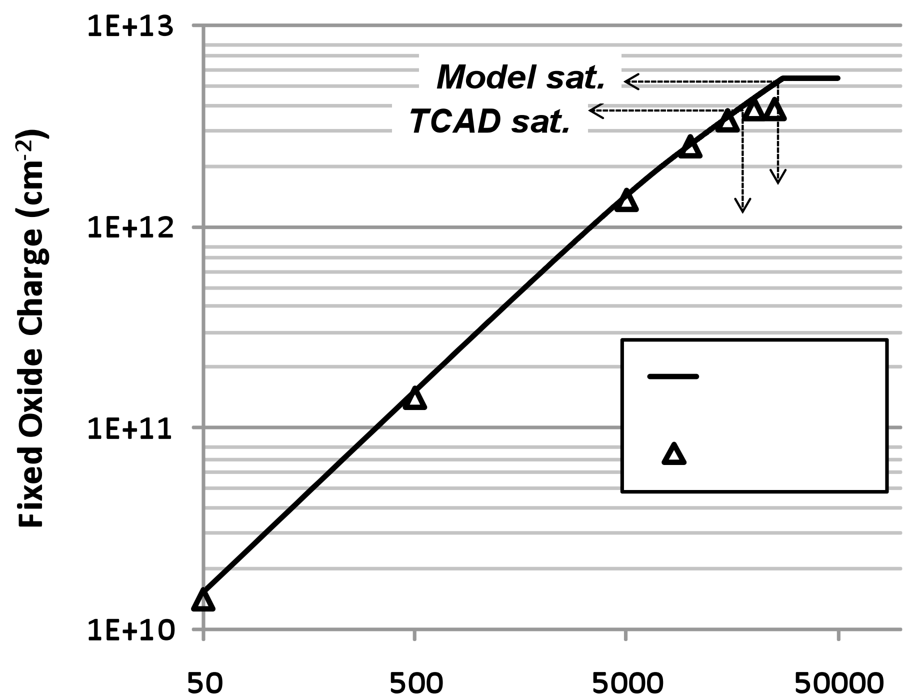
Previous Research - 2009

TCAD model validation

TCAD simulations with REM models trapped charge buildup at specified dose in FOXFET



(after Barnaby et al., TCAS I 2009)



Analytical model compares well to physically-based numerical simulations

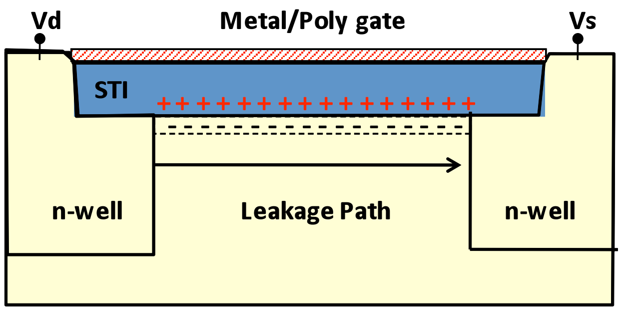
Recent Work (2010)

- **Refinement of PSP model for model of TID effects on bulk CMOS isolations oxides**

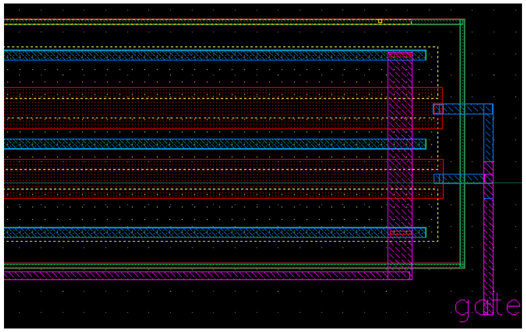
Bulk CMOS - Experimental Details

90 nm low-standby power (LSP) nwell-nwell poly-gate FOXFETS
L = 1.5 μm, W = 200 μm

FOXFET cross-section



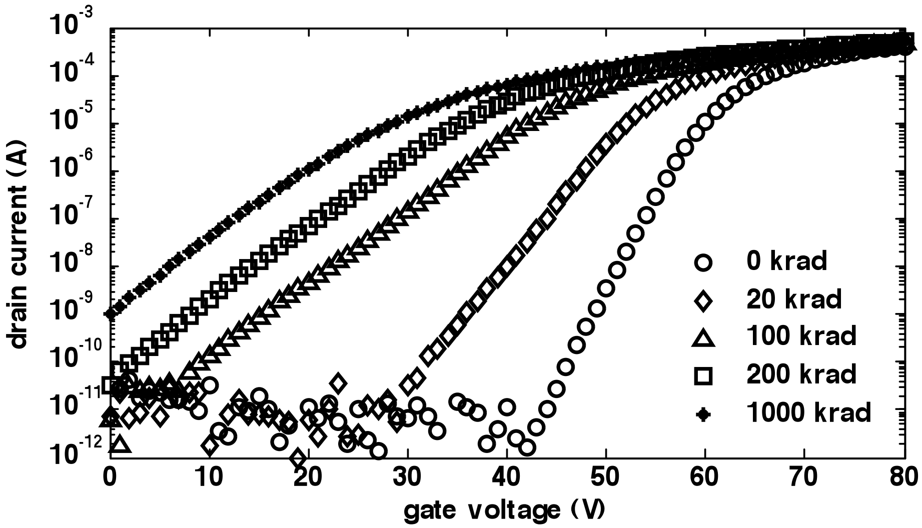
FOXFET layout



Fabrication support from ISI

Irradiation Tests

- ^{60}Co gamma chamber
- dose rate =1200 rad(SiO_2)/min
- worst-case biasing conditions (gate voltage V_g = V_{dd} other terminals grounded).



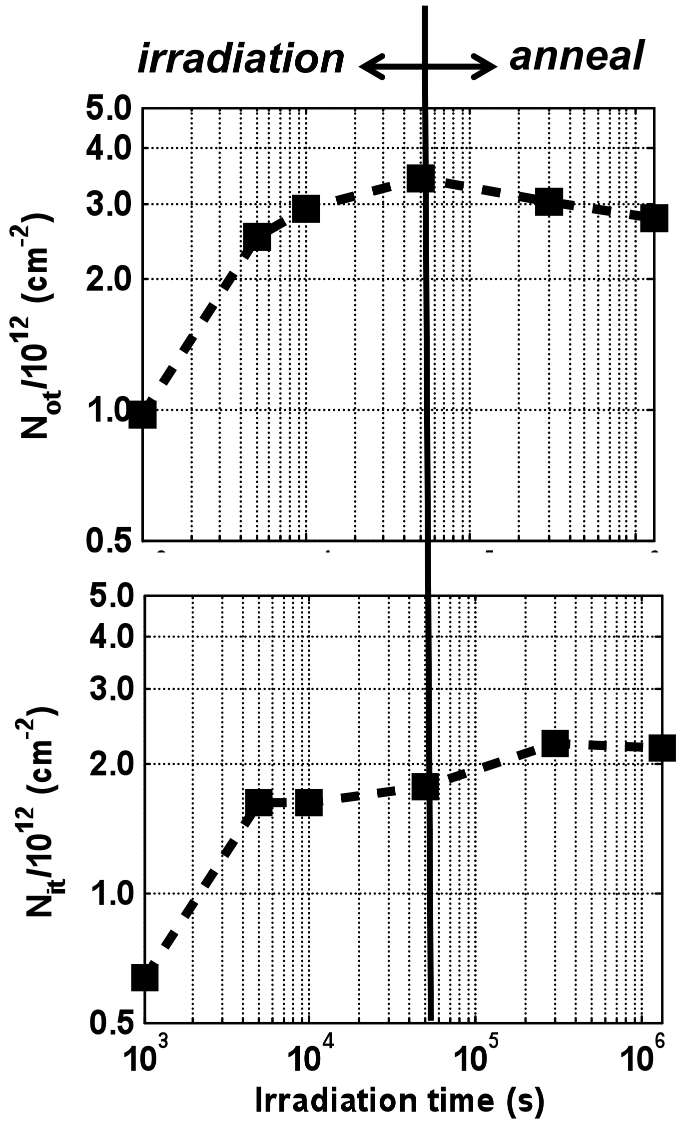
Bulk CMOS – Defect Extraction

McWhorter-Winokur technique used to extract defect buildup from experimental data

$$\Delta N_{ot} = -\frac{C_{ox}\Delta V_{mg}}{q}$$

$$\Delta N_{it} = \frac{C_{ox}\left(\Delta V_{inv} - \Delta V_{mg}\right)}{q}$$

after P. S. Winokur, et al., TNS 1984.



RE-PSP model for bulk CMOS

First order SP model

$$(V_g - \varphi_{ms} + \phi_{nt} - \psi_s)^2 = \gamma^2 \cdot \varphi_t H(u)$$

$$\phi_{nt} = \frac{q}{C_{ox}}[N_{ot} - D_{it}(\psi_s - \phi_b)]$$

Model not compatible w/ PSP's standard form equation

$$(V_g - V_{FB} - \xi\psi_s)^2 = \gamma^2 \phi_t H(\beta\psi_s)$$

Model refinements for PSP implementation

$$\left\{V_g - \left[\overbrace{\varphi_{ms} - \frac{q}{C_{ox}}\left(N_{ot} + D_{it}\phi_b\right)}^{V_{FB}}\right] - \xi\psi_s\right\}^2 = \gamma^2 \cdot \varphi_t H(u), \quad \xi = 1 + \frac{q}{C_{ox}} D_{it}$$

$$V_g^* = V_g / \xi$$

$$V_{FB}^* = V_{FB} / \xi$$

$$\gamma^* = \gamma / \xi$$

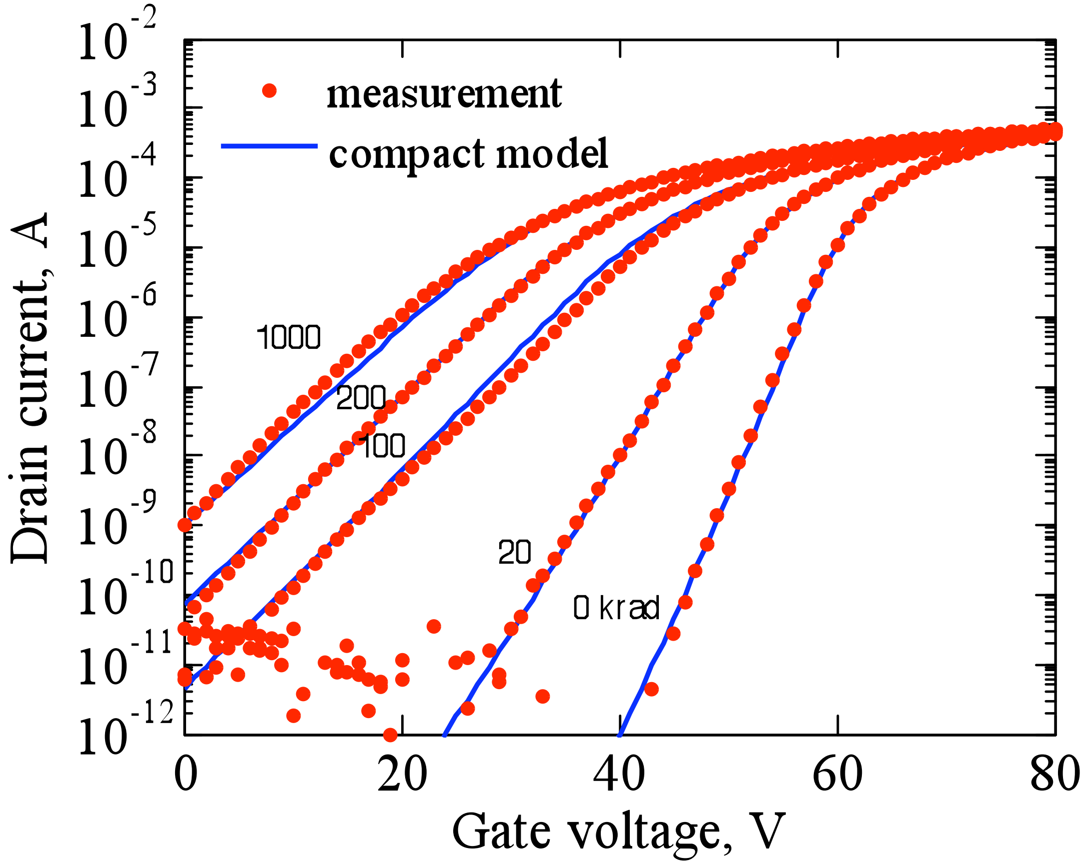
$$(V_g^* - V_{FB}^* - \psi_s)^2 = (\gamma^*)^2 \phi_t H(\beta\psi_s)$$

Revised formulation fully PSP compatible!

RE-PSP model for bulk CMOS

PSP model uses symmetric linearization

($I_{ds} = \frac{W}{L}\mu_{eff}C_{ox}\left(q_{im} + \alpha_m\phi_t\right)\Delta\psi$ ***) to fit data***



- **fits DC data over exposure range**
- **incorporation into PSP supports capture of secondary effects, e.g., small-geometry effects, mobility degradation**

Work to be presented at 2010 NSREC

Conclusions

- Multi-scale models of TID effects in deep sub-micron bulk CMOS require defect buildup and surface potential modeling approaches compatible with standard circuit simulators
- Well known basic mechanisms (e.g charge yield and trapping efficiency) can be applied to analytically model defect buildup in specific technologies as function of environmental inputs
- Defect calculations incorporated in industry standard compact models (e.g. PSP) enable prediction of device and circuit response

Journal Publications

- **I. S. Esqueda**, H. J. Barnaby, **M. L Mclain,** P. C. Adell, F. E. Mamouni, S. K. Dixit, R. D. Schrimpf, W. Xiong, "Modeling the Radiation Response of Fully-Depleted SOI n-Channel MOSFETs," *IEEE Trans. on Nuclear Science*, vol. 56, no. 4, pp. 2247 - 2250, 2009.
- H. J. Barnaby, **M. L. McLain**, **I. S. Esqueda**, **X. J. Chen**, "Modeling Ionizing Radiation Effects in Solid State Materials and CMOS Devices," *IEEE Trans. on Circuits and Systems – I: Regular Papers,* vol. 56, no. 8, pp. 1870 – 1883, 2009
- **M. McLain**, H. J. Barnaby, K. E. Holbert, R. D. Schrimpf, **H. Shah**, A. Amort, M. Baze, J. Wert, "Enhanced TID susceptibility in sub-100 nm Bulk CMOS I/O transistors and circuits," *IEEE Trans. on Nuclear Science*, vol. 54, pp. 2210 - 2217, 2007.
- P. C. Adell, H. J. Barnaby, R.D. Schrimpf, B. Vermeire, "Band-to-band tunneling (BBT) induced leakage current enhancement in irradiated fully depleted SOI devices," *IEEE Trans. on Nuclear Science*, vol. 54, pp. 2174 - 2180, 2007.
- H. J. Barnaby, **M. Mclain**, **I. S. Esqueda**, "Total-ionizing-dose effects on isolation oxides in modern CMOS technologies," *Nuclear Instruments and Methods in Physics Research B* 261 (2007) 1142–1145.
- H. Barnaby, "Total-ionizing-dose effects in modern CMOS technologies," *IEEE Trans. on Nuclear Science*, vol. 53, pp. 3103-3121, 2006 *(review article)*.
- **I. S. Esqueda**, H.J. Barnaby, M. L. Alles, "Two-dimensional methodology for modeling radiation-induced off-state leakage in CMOS technologies," *IEEE Trans. on Nuclear Science*, vol. 52, pp. 2259-2264, 2005.

Conference Presentations

- **M. L. McLain**, H. J. Barnaby, **I.S. Esqueda**, **J. Oder**, B. Vermeire, “Reliability of high performance standard two-edge and radiation hardened by design enclosed geometry transistors,” *2009 IEEE International Reliability Physics Symposium Proceedings*, April 26-30 2009, pp. 174 – 179.
- H. J. Barnaby, **M. L. Mclain**, **I. S. Esqueda,** and **X. J. Chen**, “Modeling Ionizing Radiation Effects in Solid State Materials and CMOS Devices*,” IEEE Custom Integrated Circuits Conference* (CICC), September 2008, pp. 273 – 280.
- **M. L. Mclain**, H. J. Barnaby, P. C. Adell, “Analytical model of the radiation response in FDSOI MOSFETs,” *2008 IEEE International Reliability Physics Symposium Proceedings*, April 2008, pp. 643 - 644.
- **I. S. Esqueda**, H. J. Barnaby, F. E. Mamouni, R. D. Schrimpf, “Modeling of Ionizing Radiation-Induced Degradation in Multiple Gate Field Effect Transistors,” *2009 RADECS*, Brugge, Belgium, September 2009.
- **I. S. Esqueda**, H. J. Barnaby, **M. L Mclain**, P. C. Adell, F. E. Mamouni, S. K. Dixit, R. D. Schrimpf, W. Xiong, “Modeling the Radiation Response of Fully-Depleted SOI n-Channel MOSFETs,” *IEEE Nuclear and Space Radiation Effects Conf.*, Quebec City, CA., July 2009.
- **M. L Mclain**, H. J. Barnaby, K. E. Holbert, “Modeling Ionizing Radiation Effects in Shallow Trench Isolation Field Oxide FETs, “*IEEE Nuclear and Space Radiation Effects Conf.,* Quebec City, CA., July 2009.
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