DEPARTMENT OF DEFENSE
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Physics for Simulation of Single-Event Transients

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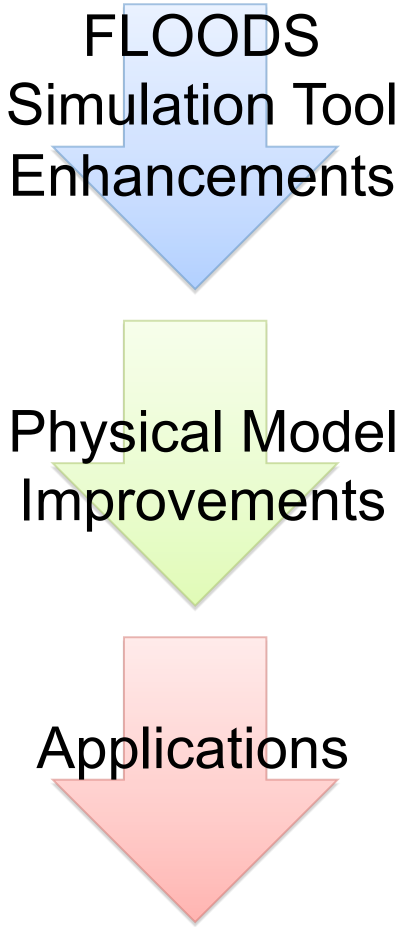
Outline



FLOODS Simulation Tool Enhancements

Physical Model Improvements

Applications

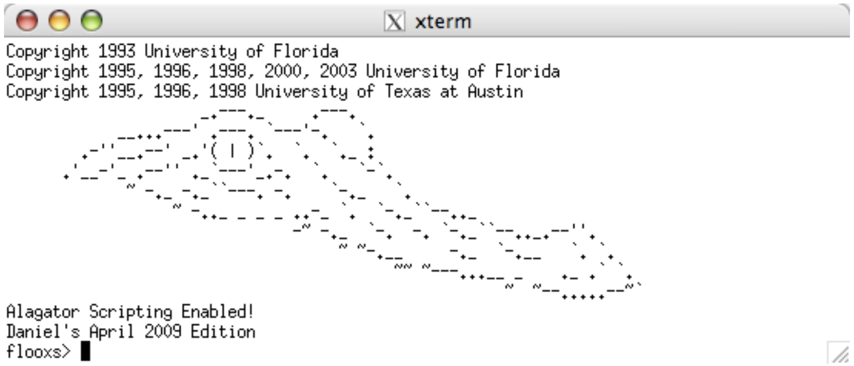
- Finite Element Discretization
- Adaptive Gridding
- Mobility Modeling
  - Proposed Mobility Model
  - Piezoresistance Model
- Strained-Si Simulations
  - N+/P Diode
  - MOSFET
- Summary

FLOOPS / FLOODS (FLOOXS)

- **Fl**orida **O**bject **O**riented **P**rocess/**D**evice **S**imulator

- Immediate prototyping and testing of new models

- Multi-dimensional (1-D, 2-D, 3-D)
- P = Process / D = Device 90% code shared
- Scripting capability for PDE’s - Alagator



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Alagator Scripting Enabled!
Daniel's April 2009 Edition
flooxs>
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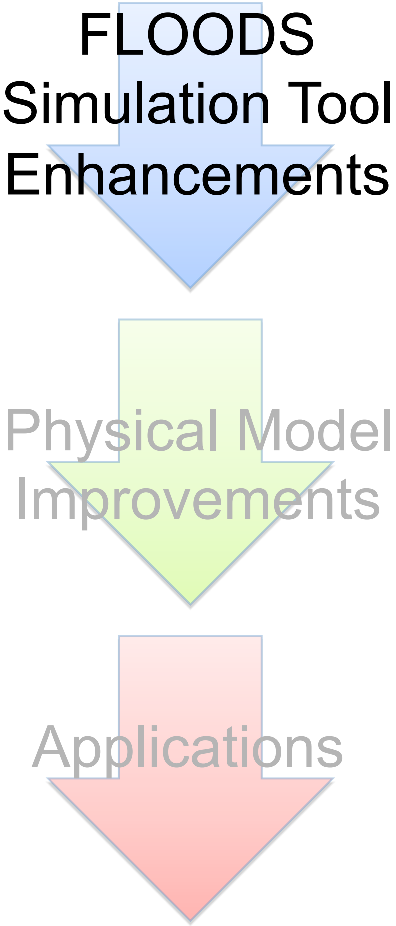
FLOODS Simulation Tool Enhancements



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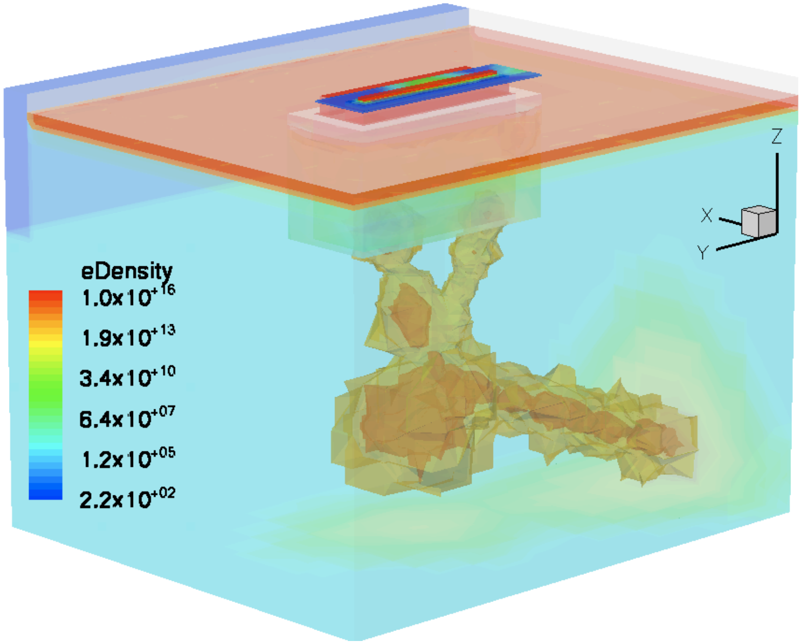
FEM Discretization Motivation

- Commonly-used Finite-Volume “Scharfetter-Gummel” method convergence problems
- Why? Particle strikes can generate carriers throughout the device -> rarely aligned with the grid



2006 Vanderbilt “Radiation Effects” MURI Review

Device Simulator Discretization

- The set of coupled, time-dependent partial differential equations (PDEs) that govern semiconductor device behavior can be written as

$$\nabla \cdot (\varepsilon \nabla \psi) = -q\left(p - n + N_D^+ - N_A^-\right)$$

1. Poisson Equation

$$\frac{dn}{dt} = \frac{1}{q} \nabla \cdot J_n - U_n$$

2. Electron Continuity Equation

$$\frac{dp}{dt} = -\frac{1}{q} \nabla \cdot J_p - U_p$$

3. Hole Continuity Equation

ε - dielectric permittivity

ψ - electrostatic potential

n, *p* - electron, hole densities

J_n, J_p – electron, hole current densities

U_p, U_n - net recombination rates

N_D^+, N_A^- - ionized donor and acceptor densities

Discretization Method Comparison

Drift-Diffusion Current Density

$$J_n = qn\mu_n \mathrm{E} + qD_n \boxed{\nabla n}$$

$$J_p = qp\mu_p \mathrm{E} - qD_p \boxed{\nabla p}$$

Boltzmann Relations

$$\phi_n \equiv \psi - \frac{kT}{q} \ln\left(n / n_i\right)$$

$$\phi_p \equiv \psi + \frac{kT}{q} \ln\left(p / n_i\right)$$

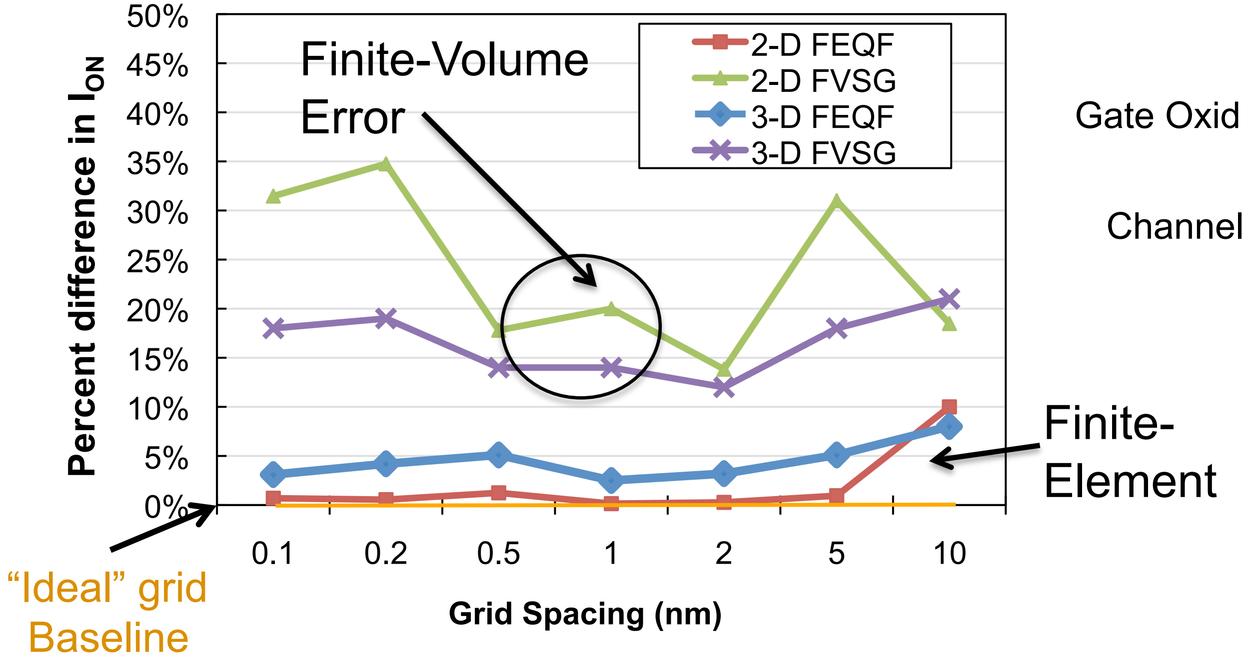
Quasi-Fermi Current Density

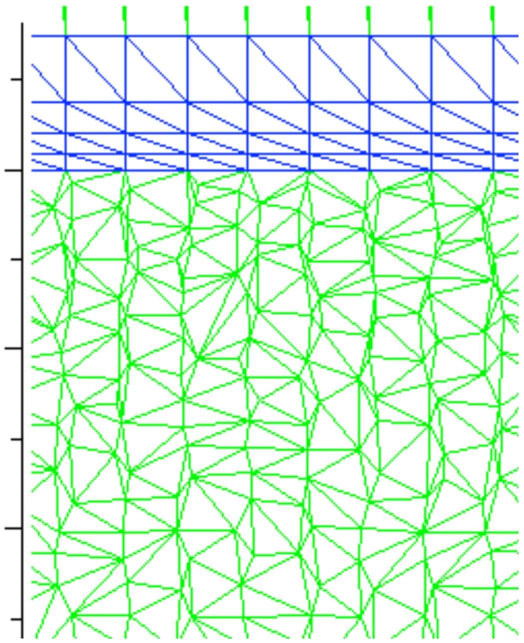
$$J_n = -q\mu_n n \boxed{\nabla \phi_n}$$

$$J_p = -q\mu_p p \boxed{\nabla \phi_p}$$

Method	Finite Volume Scharfetter-Gummel (FVSG)	Finite Element Quasi-Fermi (FEQF)
Solution Variables	n, p, ψ	ϕ_n, ϕ_p, ψ
Current Density $J_{n,p}$	Defined on Edges	Continuous

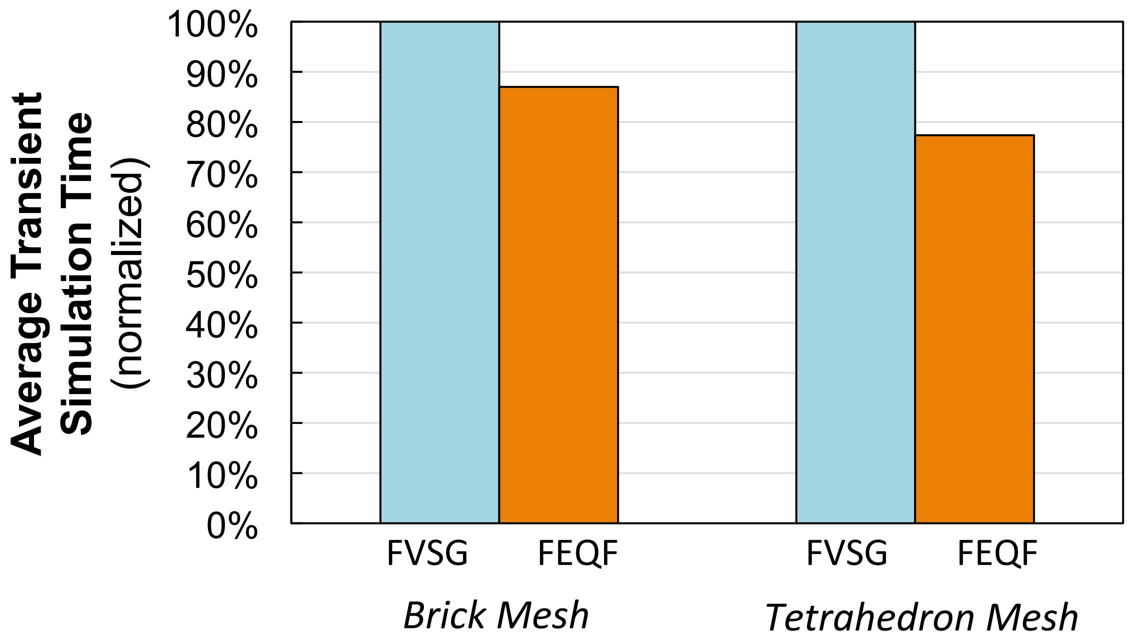
Discretization - Node Randomization





- Each mesh node randomly displaced by up to 40%
- The randomization of the grid created a large number of obtuse triangles (negative edge couplings)
- Results for both FEQF and FVSG methods were compared against equivalent structures with ideal meshes.

Quasi-Fermi Method – Transient Results

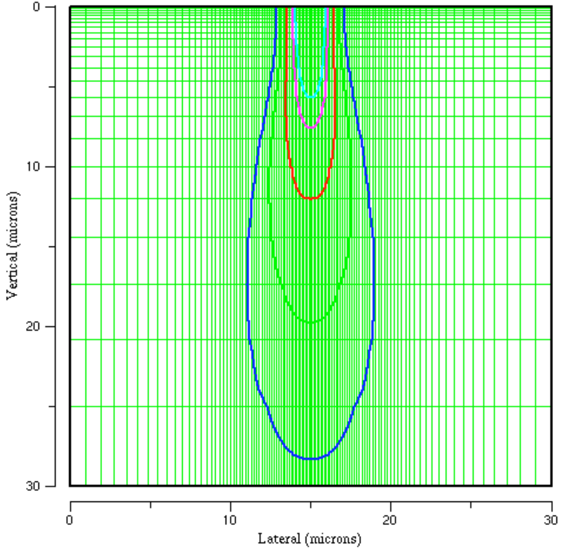


- FEQF -> fewer Newton steps to converge (simulation time savings)
- Transient convergence stability
  - Better handling of isotropic current flow.
  - Converges even if all charge is deposited at t=0

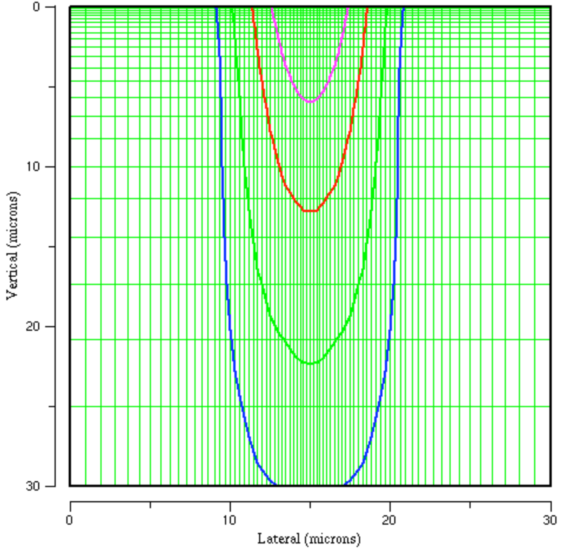
Adaptive Gridding - Concept

- Transient vs. DC simulations
  - Transient simulations require up to 100's of time steps
- Single Event simulations focus on transient behavior
- Adaptive gridding -> time benefit
  - Reduce number of nodes as transient progresses

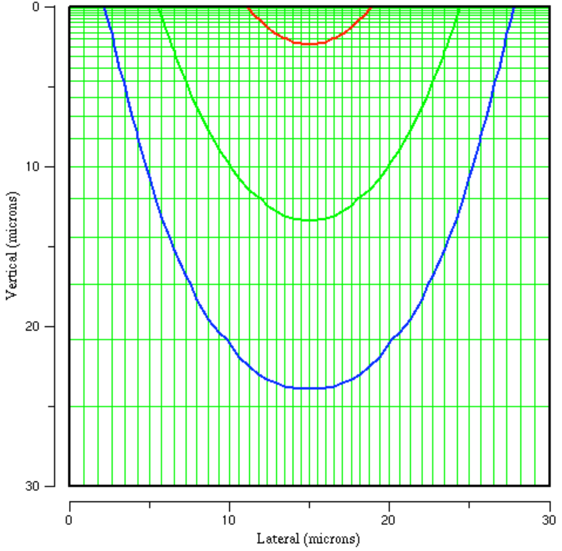
t = 0, nodes=3000



t > 0, nodes=2000

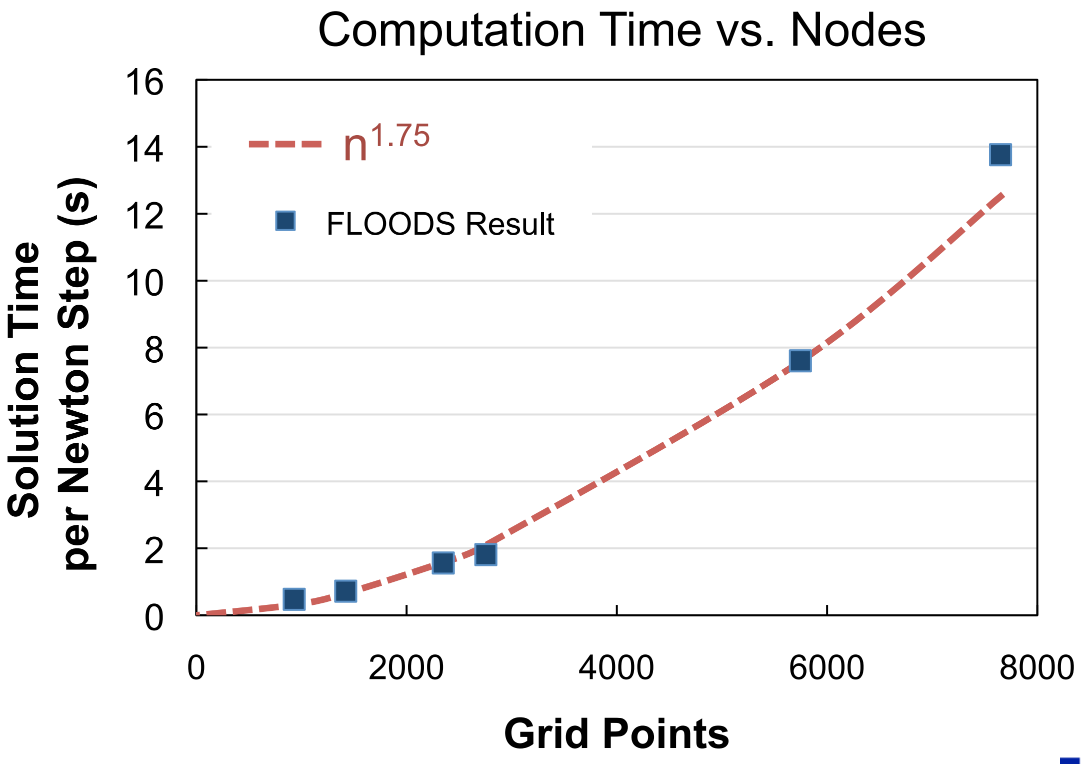


t >> 0, nodes=1000

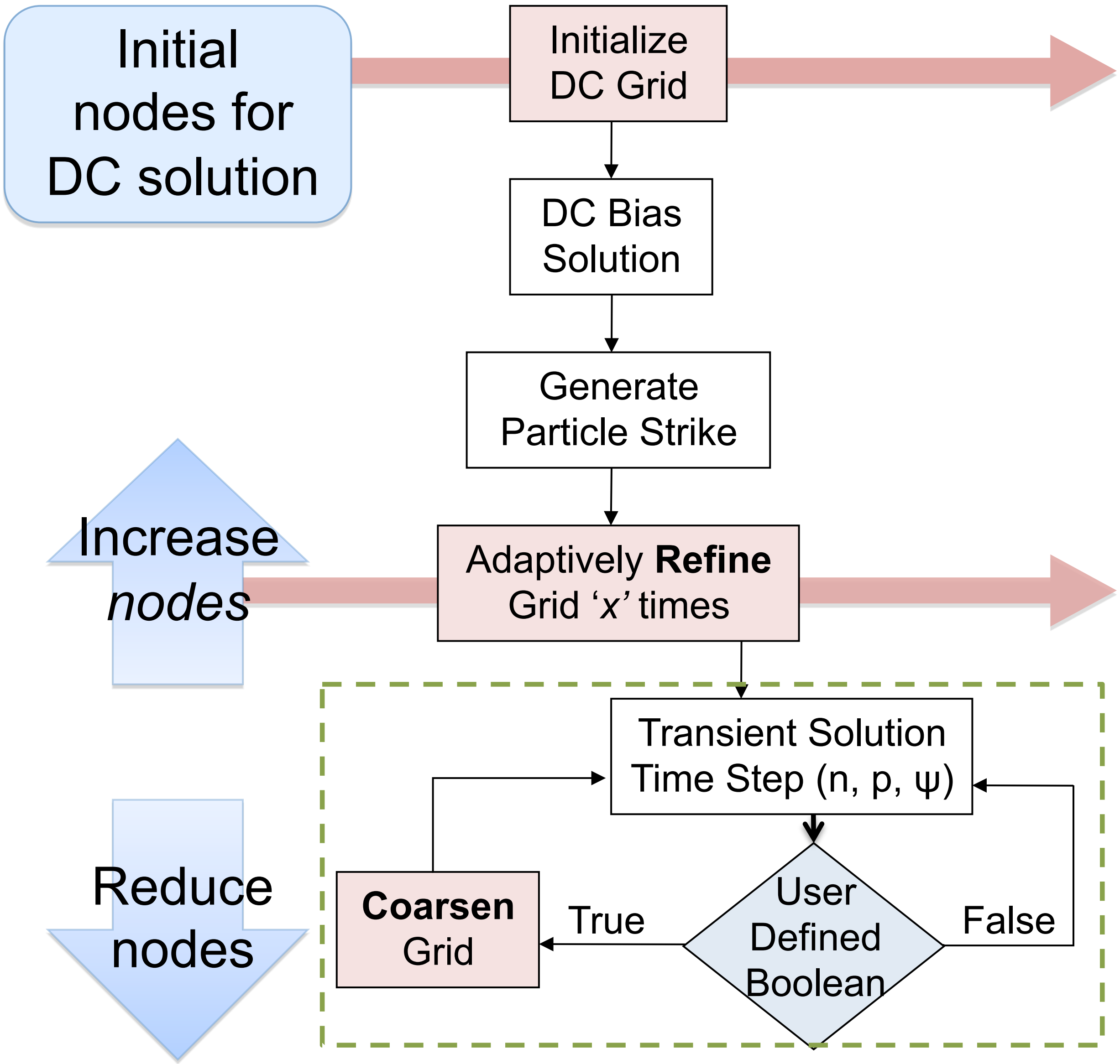


Adaptive Gridding – Motivation

- Need ways to reduce transient simulation time
- Solution time increases rapidly based on the number of grid points ‘nodes *n*’ -> simulation time ∝ $n^{1.75}$



Adaptive Gridding - Methodology



Initial nodes for DC solution

Initialize DC Grid

DC Bias Solution

Generate Particle Strike

Adaptively **Refine** Grid '*x*' times

Increase *nodes*

Transient Solution Time Step (n, p, ψ)

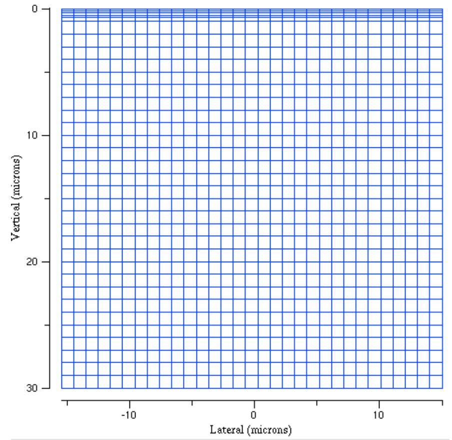
User Defined Boolean

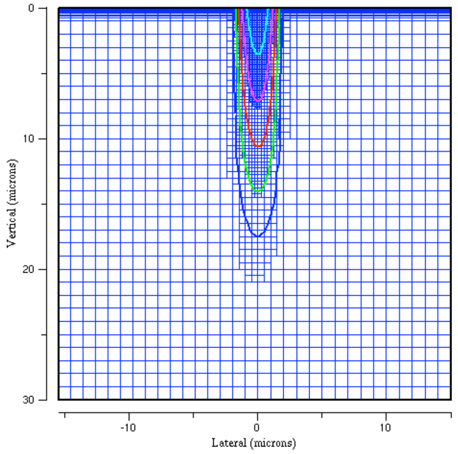
True

False

Coarsen Grid

Reduce nodes





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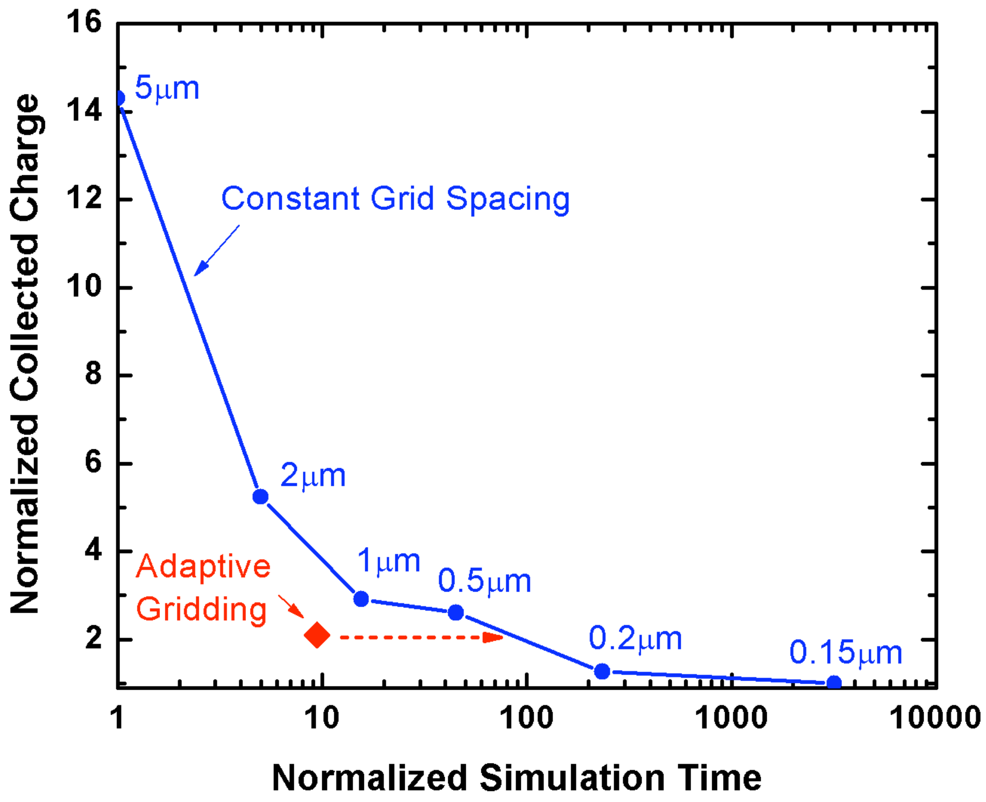
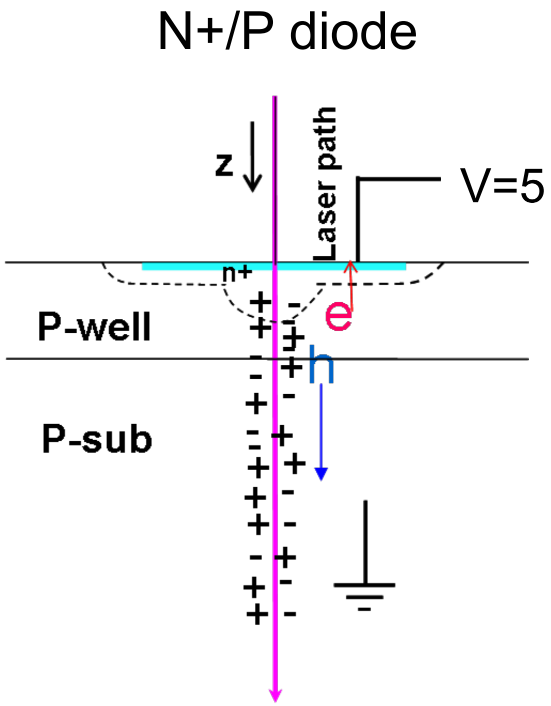
Adaptive Gridding – SET Results

- Preliminary 2-D results (N+/P diode transient):





- Time benefit / accuracy tradeoff

Physical Model Improvements

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Proposed Mobility Model (Silicon)

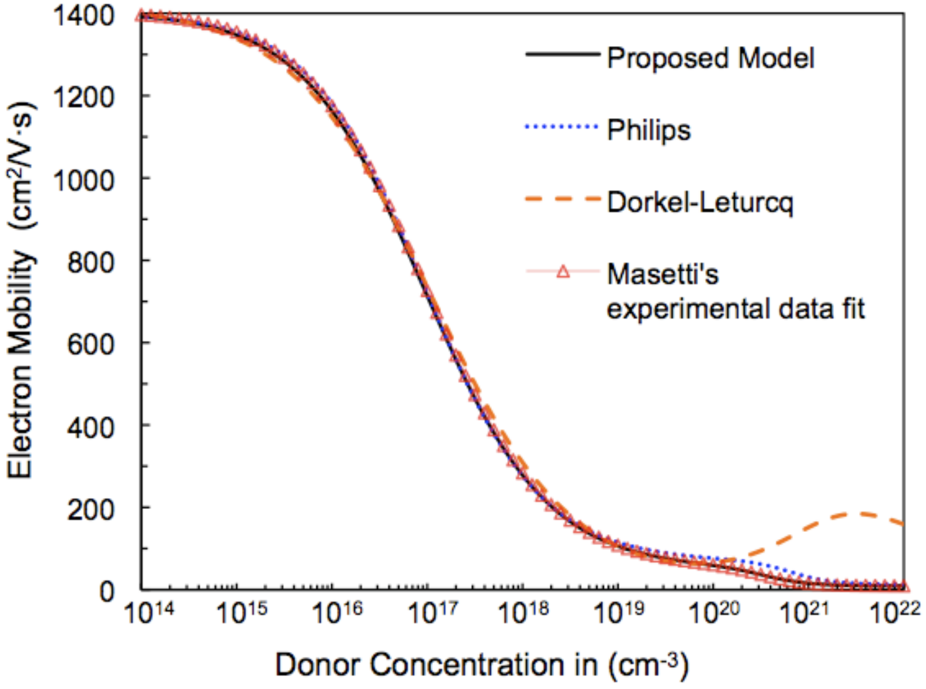
- Mobility model -> simulation results $J_n = -q \boxed{\mu_n} n \nabla \phi_n$
- Existing bulk models not accurate for single-event simulations (high-injection e-h pair conditions)

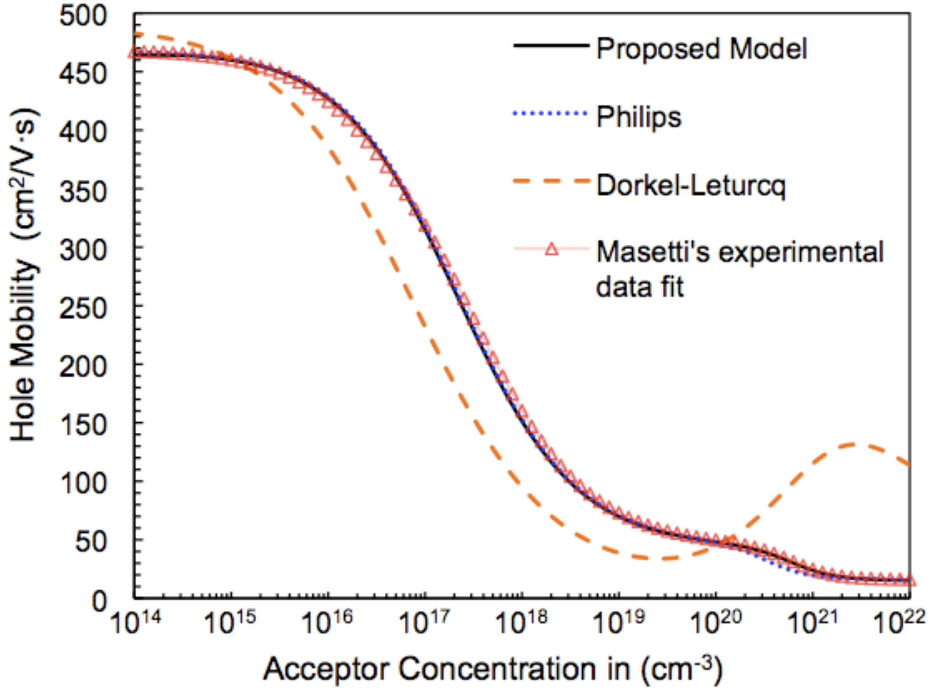
Qualitative Comparison of Commonly Used Bulk Silicon Mobility Models

Parameter Model	Majority Carrier Mobility	Minority Carrier Mobility	Carrier-Carrier Scattering	Temperature Dependence
Proposed	+	+	+	+
Philips	+	+	-	+
Dorkel-Leturcq	-	n/a	+	+
Masetti	+	n/a	n/a	n/a
Arora	-	n/a	n/a	+
Caughey-Thomas	-	n/a	n/a	n/a

+	Accurate model fitting to experimental data
-	Loose approximation to experimental data
n/a	Not available in model

Majority Carrier Mobility



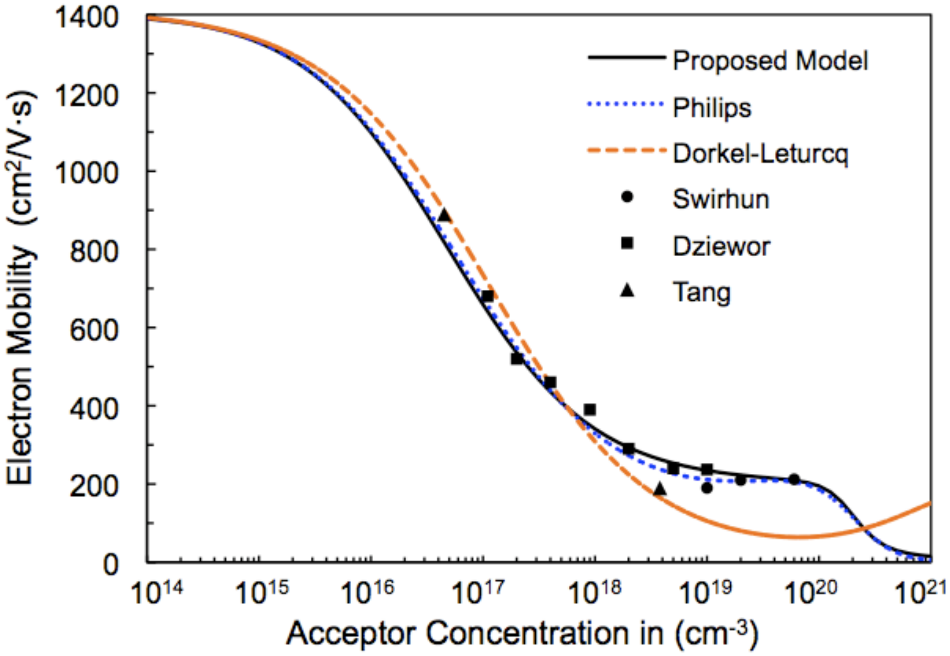


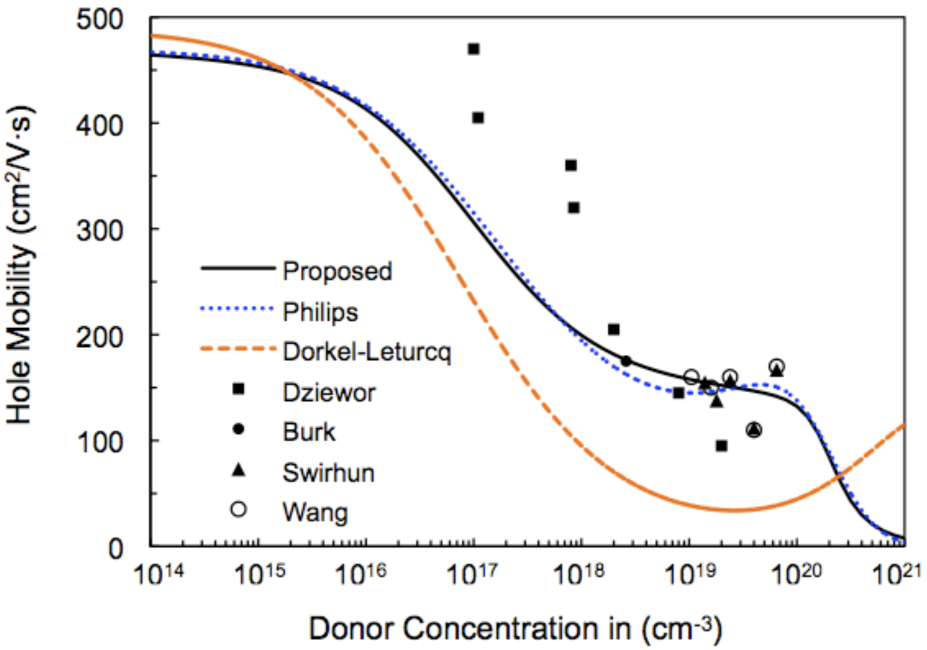
$$\mu_{i,maj} = \mu_0 T_n^{\gamma_0} + \frac{(\mu_{\max}-\mu_0)T_n^{\gamma_1}}{1+\left(\dfrac{N}{C_{ref,1}T_n^{\gamma_2}}\right)^{\alpha_1 T_n^{\gamma_3}}} - \frac{\mu_1}{1+\left(\dfrac{C_{ref,2}}{N}\right)^{\alpha_2}}$$

low concentration fitting

high concentration fitting

Minority Carrier Mobility



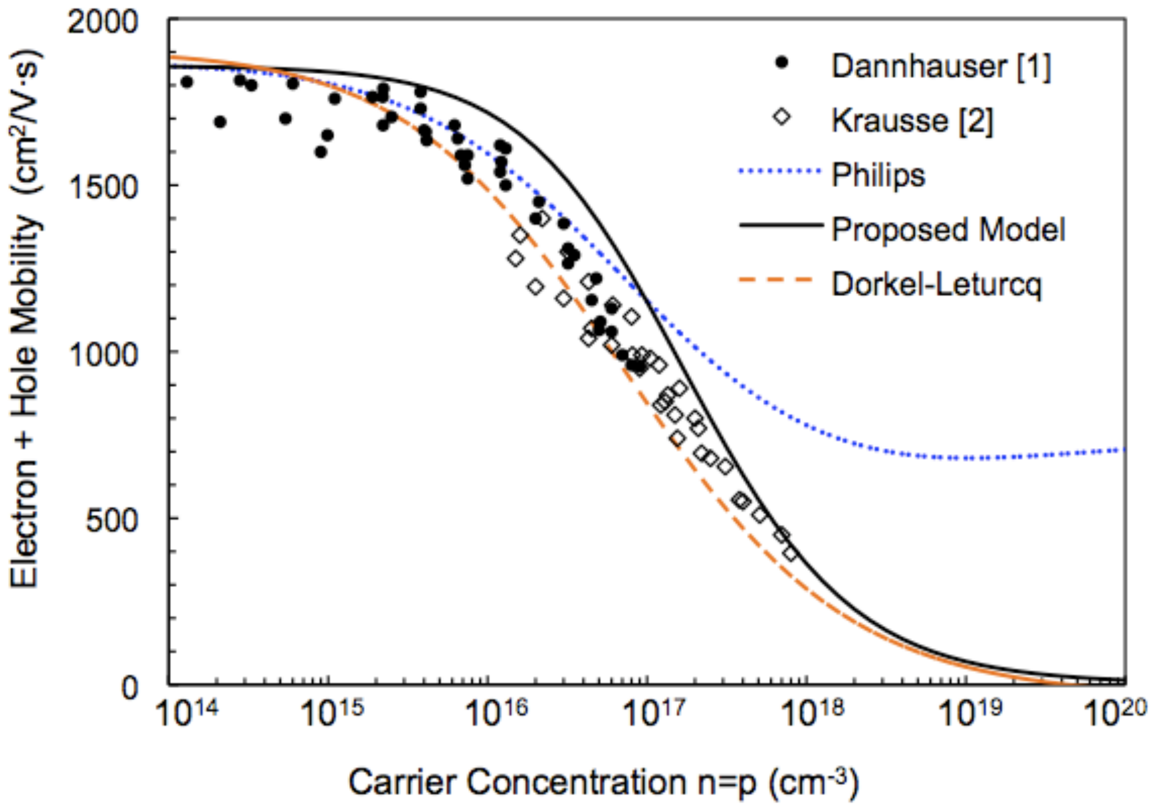


$$\mu_{i,\min} = \mu_0 T_n^{\gamma_0} + \frac{(\mu_2-\mu_0)T_n^{\gamma_4}}{1+\left(\frac{N}{C_{ref,3}T_n^{\gamma_2}}\right)^{\alpha_1 T_n^{\gamma_3}}} - \frac{\mu_3}{1+\left(\frac{C_{ref,4}}{N}\right)^{\alpha_2}} + \frac{\mu_4}{1+\left(C_{ref,5}/N\right)^{\alpha_4}}$$

low concentration fitting

mid-high concentration fitting

Carrier-Carrier Scattering

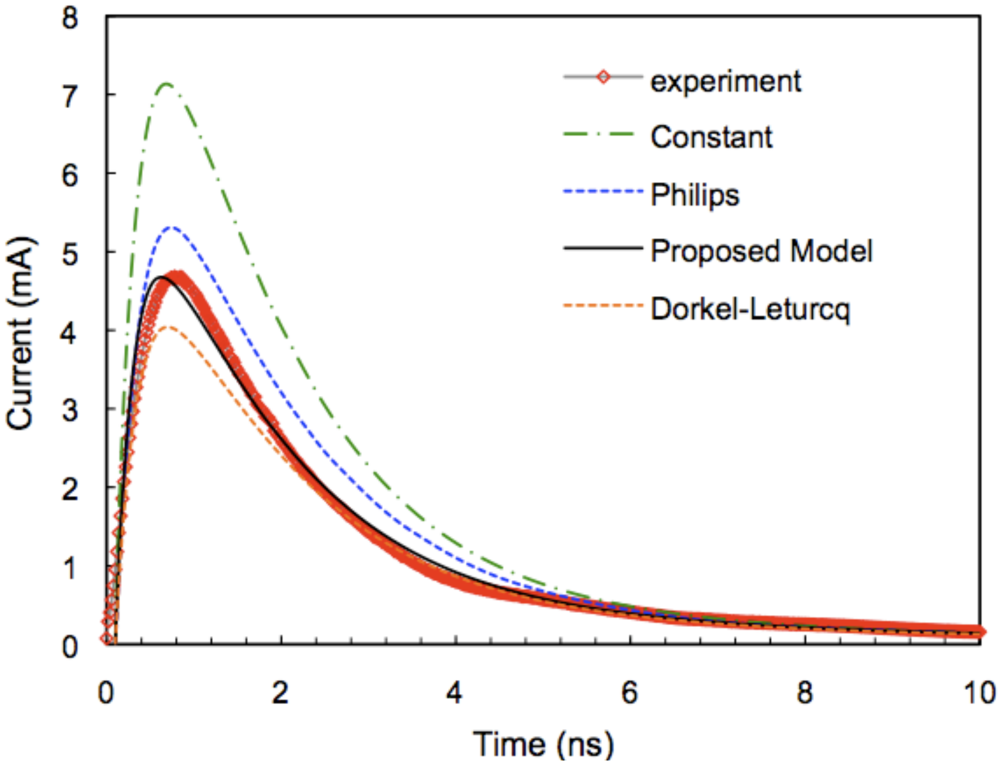


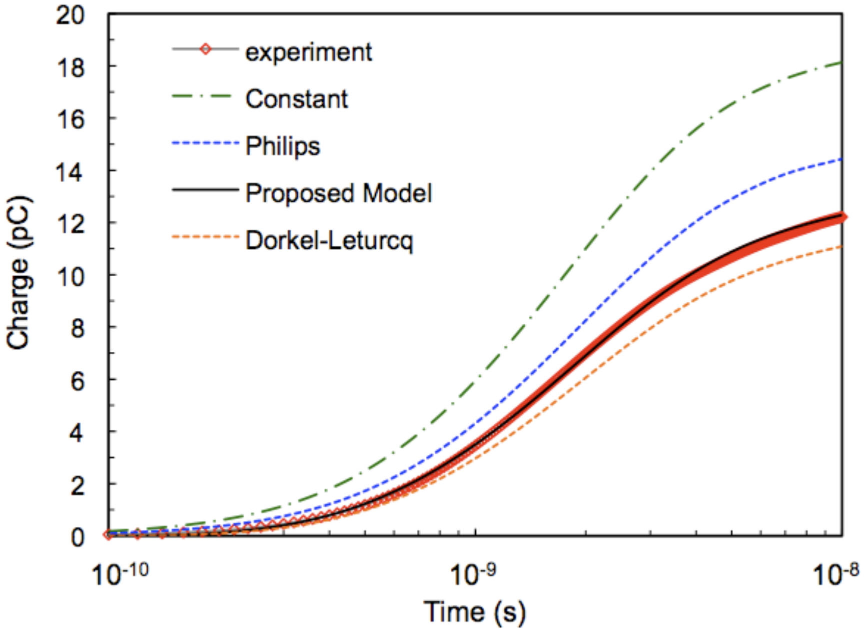
Conwell-Weisskopf carrier-carrier formulation proposed by Choo[5]:

$$\mu_{cc} = \frac{2\times10^{17}\,T^{3/2}}{\sqrt{np}}\left[\ln\left(1+8.28\times10^{8}\,T^{2}\,(pn)^{-1/3}\right)\right]^{-1}$$

Simulation vs. Experiement

- Reverse-biased N^+/P diode (TNS 2009 – H. Park)
- Single-photon absorption
  - -laser energy = 13.5 pJ, radius = 6 μm

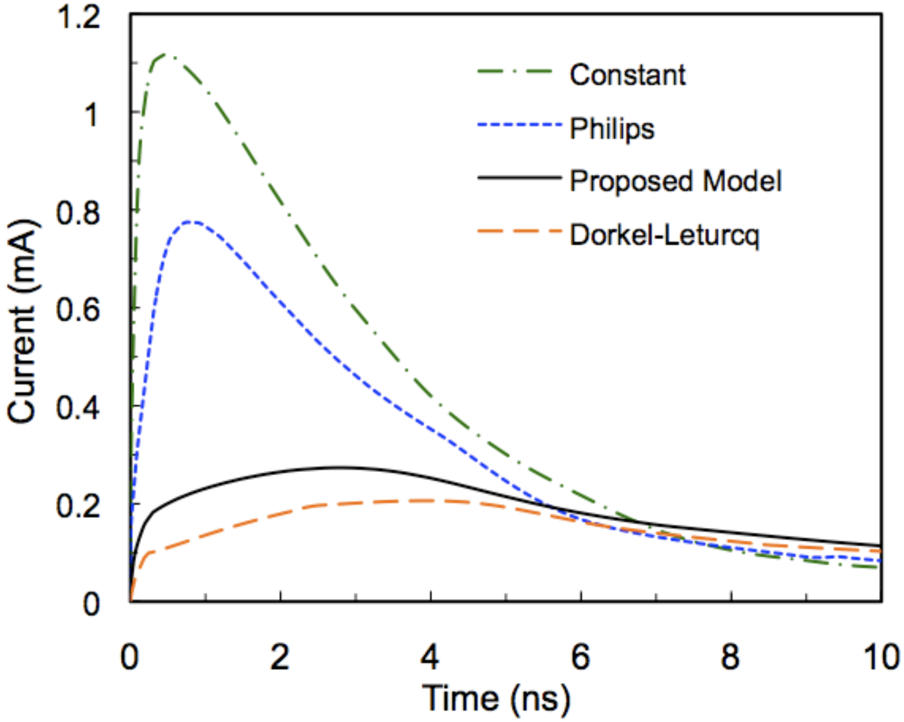


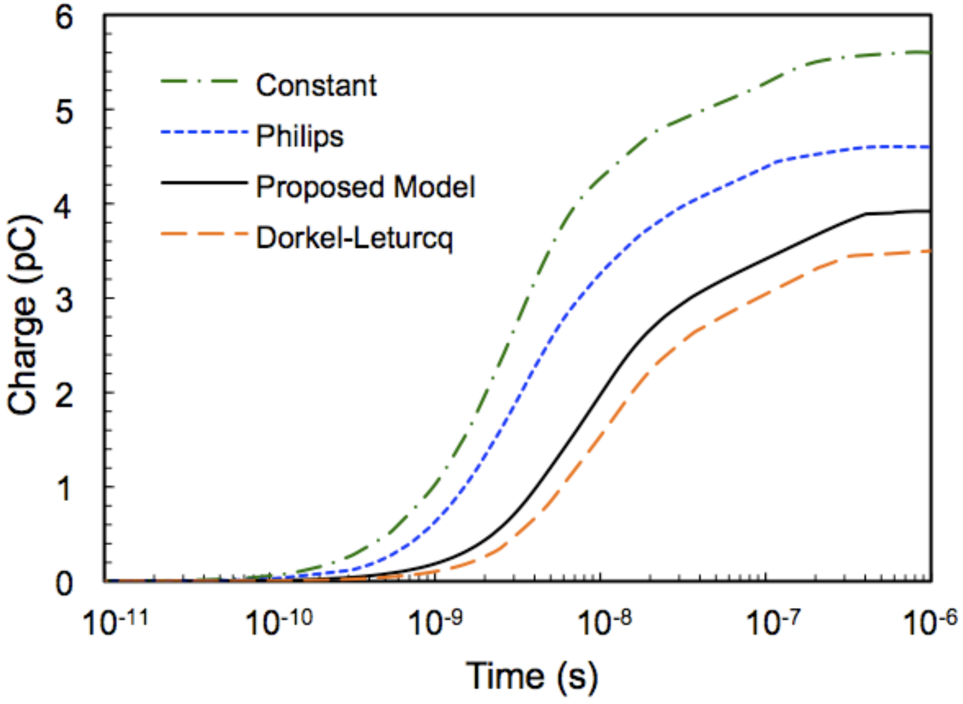


Note: Constant mobility μ_e=1417, μ_h=470.5 $cm^2/V\cdot s$

Simulation Results - Continued

- Reverse-biased Si N$^+$/EPI/P$^+$ diode
- Cylindrical Gaussian, LET = 20 MeV-cm^2/mg





Simulation Results – Computation time

- The proposed model performed well in terms of computational efficiency
- Example: 3-D n+/p diode structure composed of ~6000 volume elements

- Matrix assembly and linear solution time:
  - **9.66** seconds per Newton step for the proposed model
  - **9.73** seconds per Newton step for the Philips model.

Piezoresistance mobility model

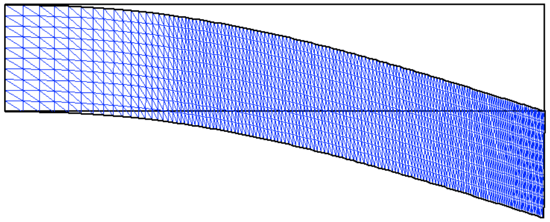
- Piezoresistivity is the change in electrical resistivity with mechanical stress

stress

$$J_X(\sigma) \cong \left(1 + \frac{-\Delta\mu_{xx}}{\mu_{xx}}\right) J_X(0) = \left(1 + \pi_{11}\sigma_{xx}\right) J_X(0)$$

current density

mobility change



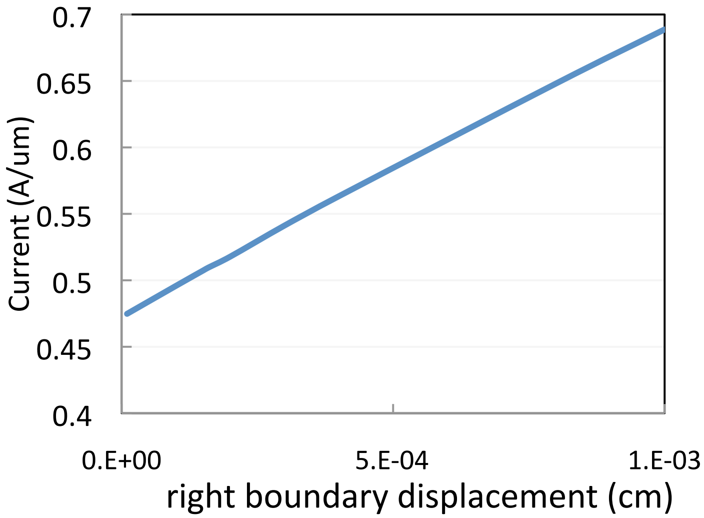
“Smith” coefficients [8]

Material	n-Si	p-Si
π_{11}	-102.2	6.6
π_{12}	53.4	-1.1
π_{44}	-13.6	138.1

10^{-5} MPa $^{-1}$

$$\left[\pi_{ij}\right] = \begin{bmatrix} \pi_{11} & \pi_{12} & 0 \\ \pi_{12} & \pi_{11} & 0 \\ 0 & 0 & \pi_{44} \end{bmatrix}$$

beam bending for n-type resistor



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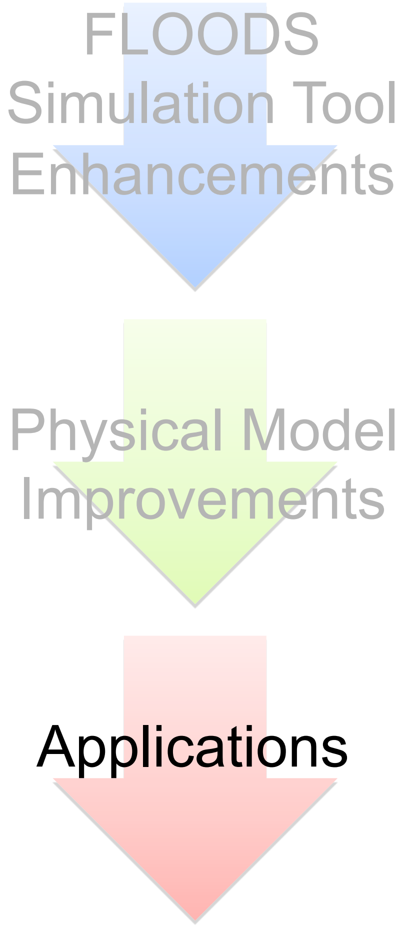

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  - **MOSFET**
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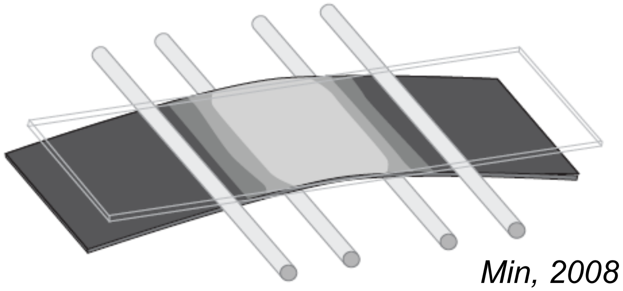
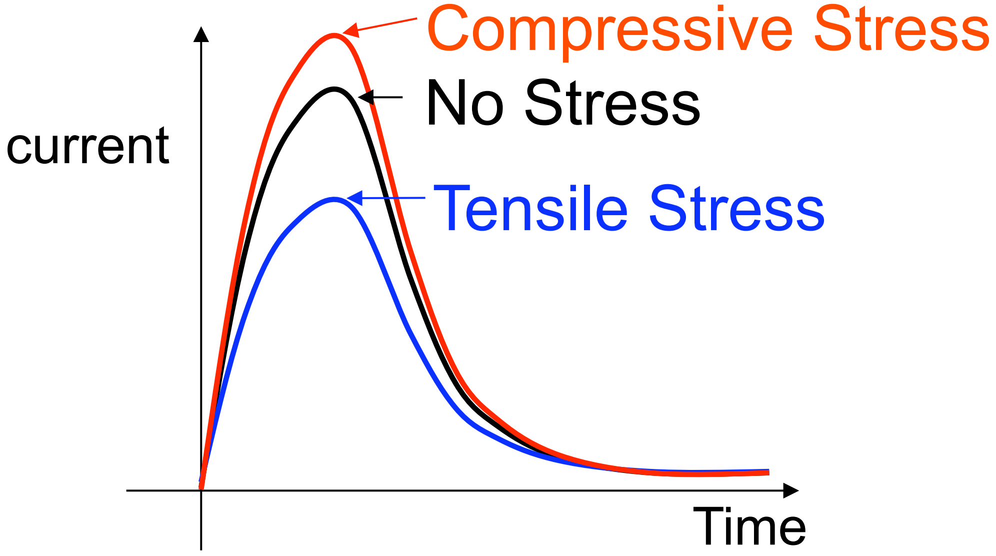
Current Transients under Uniaxial Stress

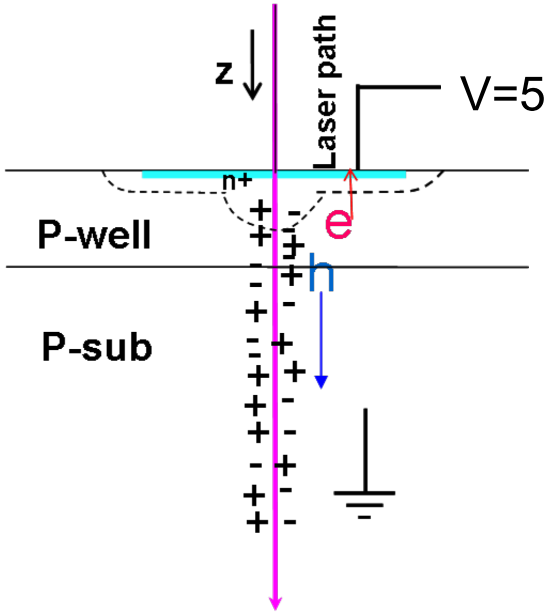
Uniaxial stress



Min, 2008



N+/P diode

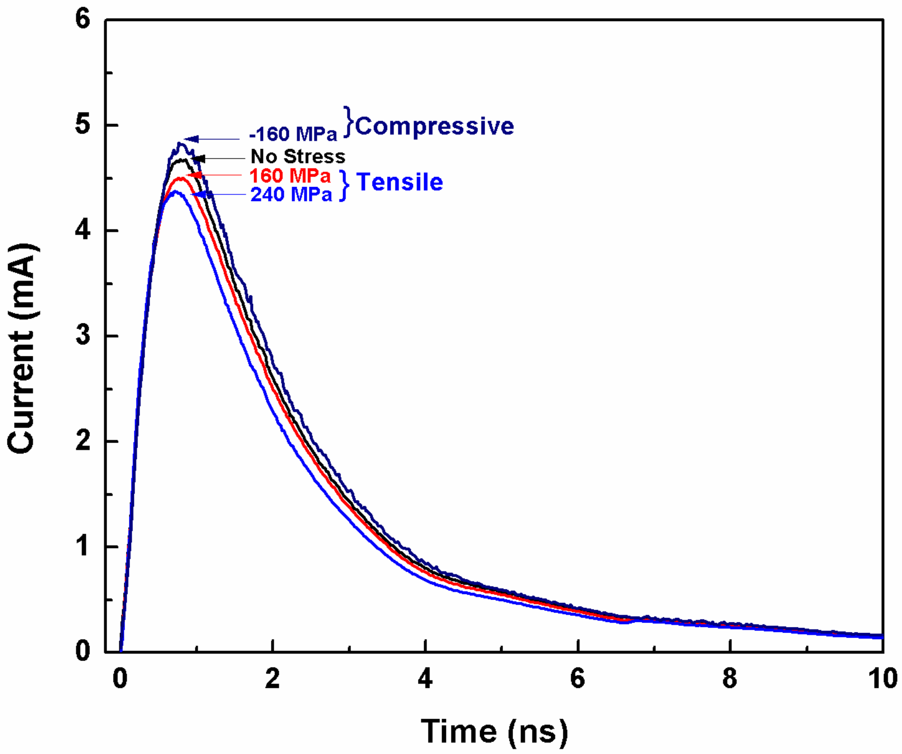


How does different type of stress change current transient in diodes?

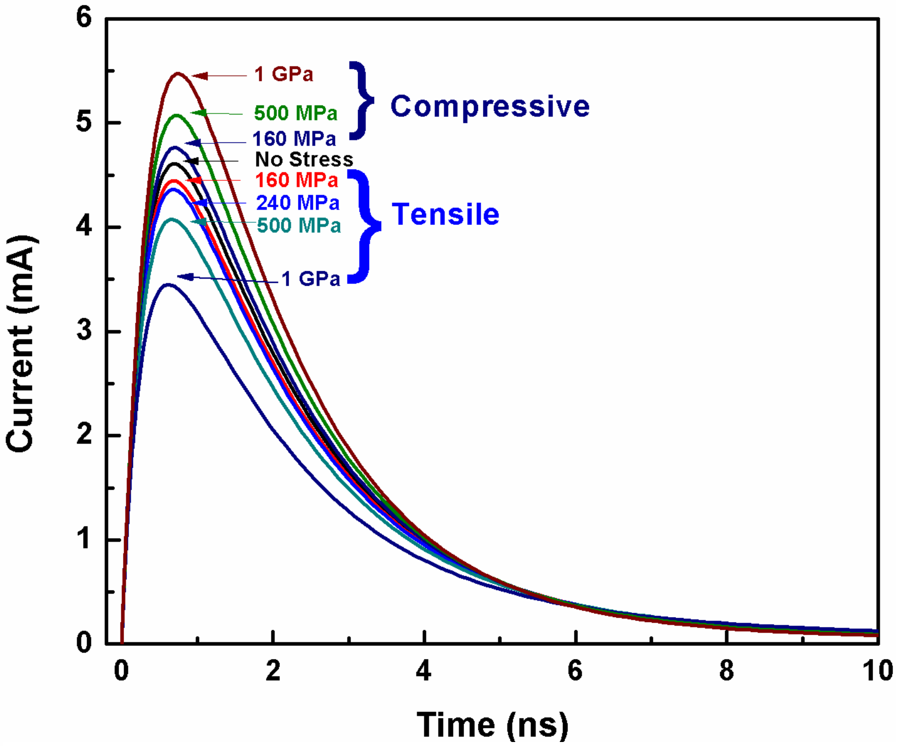
(I_{max} : peak current, Q: charge collection)

Experiment vs. 2-D Simulation results

Experiment (H. Park)



FLOODS 2-D Simulation

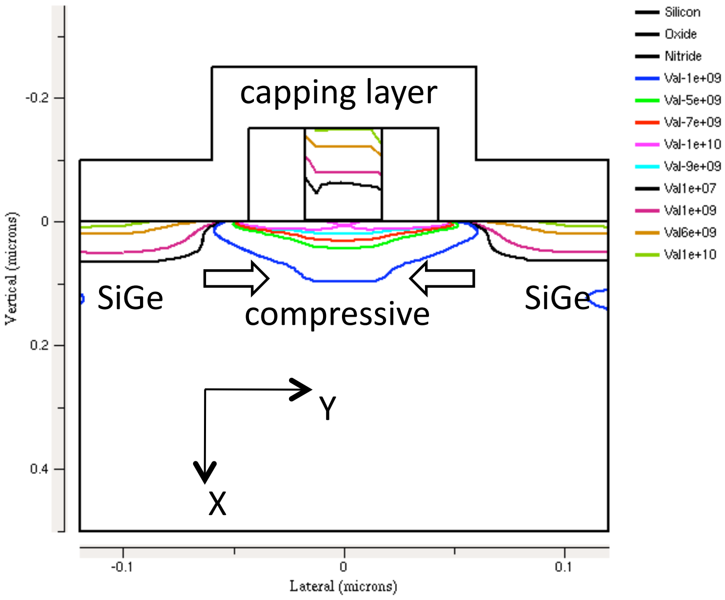


2D simulation results are in agreement with experimental ones.

Strained-Si MOSFET

Simulation Work:

- Match curves for current transients under uniaxial stress following experiment (MOSFET – H. Park)
- Compared I-V characteristics for MOSFET devices with and without process induced strain for the same technology node
- Verify FLOOXS output
- Predictive SEU simulations

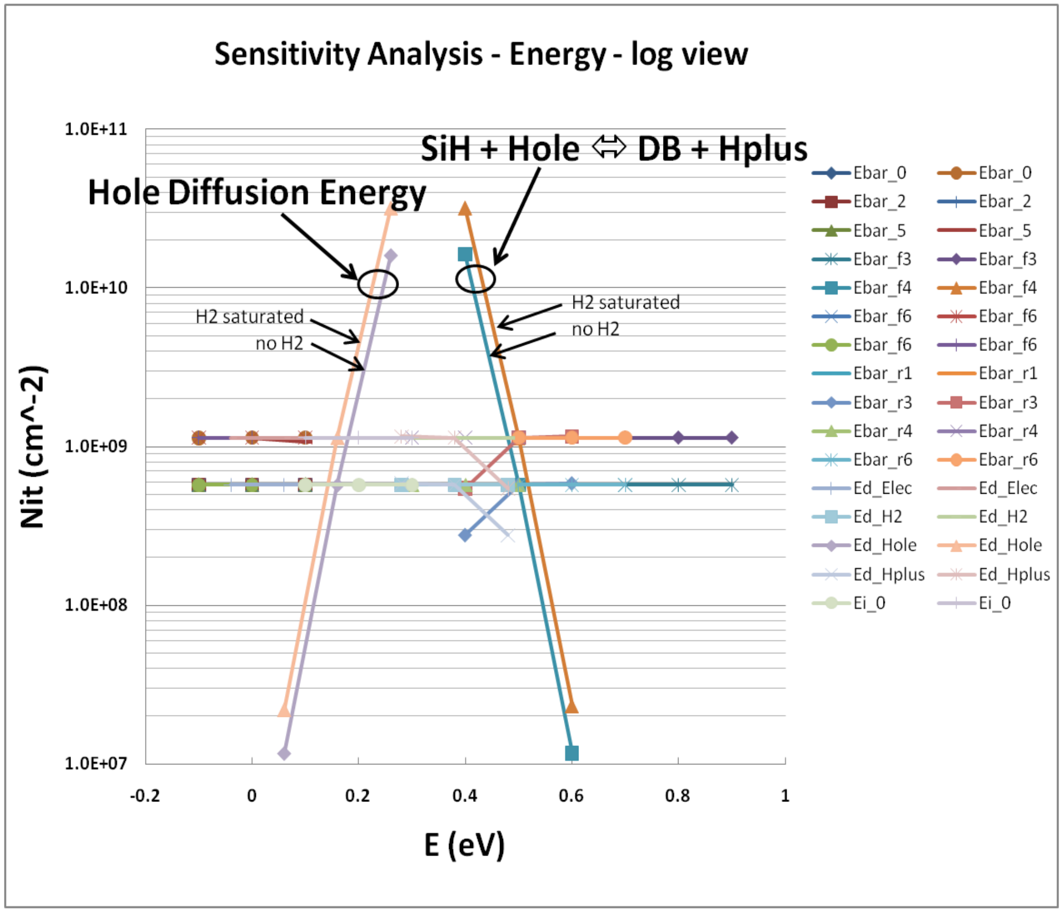


FLOOXS predicted stress profile [dyne/cm2] (Y component) ~1 GPa in channel region

Hydrogen

- Simulate in FLOODS
  - Hydrogen Soak Anneals
  - Co-60 Radiation Exposure
  - Diffusion + Field Transport
  - Hole / Hydrogen / Vacancy / N_{it} Interactions in Oxides
- Include and Verify Reactions from DFT Results (Tuttle)
  - $V_o + h^+ \Leftrightarrow V_o^+$
  - $H_2 + V_o^+ \Leftrightarrow V_oH + H^+$
  - $e^- + V_o^+ \Leftrightarrow V_o$
  - $V_oH + h^+ \Leftrightarrow V_o + H^+$
  - $Si\text{-}H + h^+ \Leftrightarrow DB + H^+$
  - $DB + h^+ \Leftrightarrow DB^+$
  - $DB^+ + H_2 \Leftrightarrow Si\text{-}H + H^+$
- Match N_{it} Measurement (Vanderbilt)
- Sensitivity Analysis

TNS, TBP - Vanderbilt + UF



Summary

- Simulation tool enhancements (time & convergence):
  - Finite Element Discretization (SISPAD 2009)
  - Adaptive Gridding (NSREC 2010)
- Physical model improvements (accuracy)
  - Proposed Mobility Model (TNS - under review)
  - Piezoresistance model
- Applications
  - Strained-Si Diode (TNS 2009)
  - Strained-Si MOSFET (in progress)
  - Hydrogen

THANKS!

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