Sentaurus TCAD Introduction

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TCAD Application Segments

CMOS

- Advanced CMOS (Si, SOI, etc.)
- Atomistic modeling
- Statistical modeling
- Reliability

Memory

- Flash
- DRAM
- ReRAM

Opto

- Image Sensors
- Solar Cells
- Photodetectors

Analog/RF

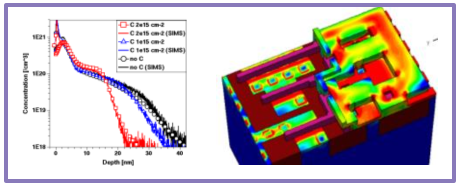
- High-speed devices
- Compound semiconductors

Power

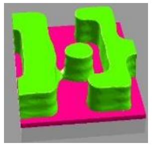
- Discrete devices
- Power ICs
- Silicon and wide bandgap
- ESD

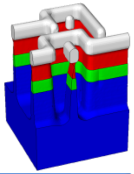
TCAD Product Portfolio

Sentaurus Process



Sentaurus Lithography





Sentaurus Topography

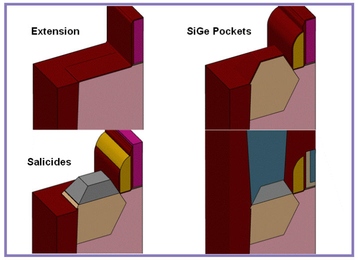
Process Simulation
- Sentaurus Process
- Sentaurus Lithography
- Sentaurus Topography

Structure Editing
- Sentaurus Structure Editor

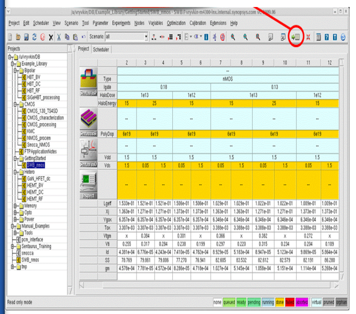
Device and Interconnect Simulation
- Sentaurus Device
- Raphael
- Sentaurus Interconnect

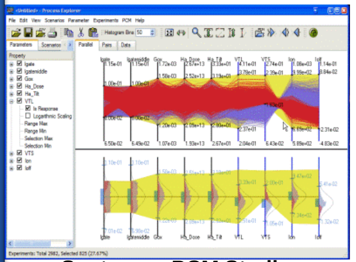
Framework
- Sentaurus Workbench
- Sentaurus PCM Studio

Sentaurus Structure Editor



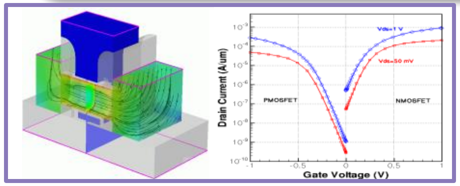
Sentaurus Workbench

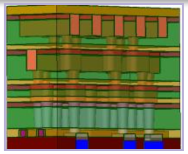




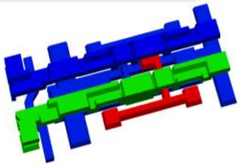
Sentaurus PCM Studio

Sentaurus Device





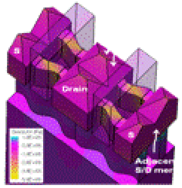
Sentaurus Interconnect

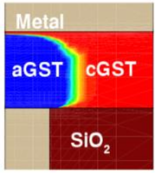


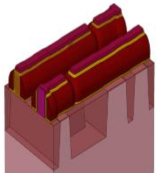
Raphael

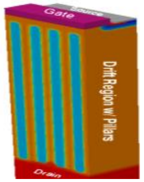
TCAD Development Focuses

- New Technology Support
  - More Moore
    - FinFET, FDSOI, III-V, etc.
  - More than Moore
    - Analog/RF, CIS, solar, power (Si, SiC, GaN), TSV, etc.

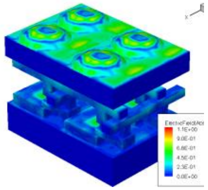


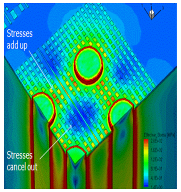




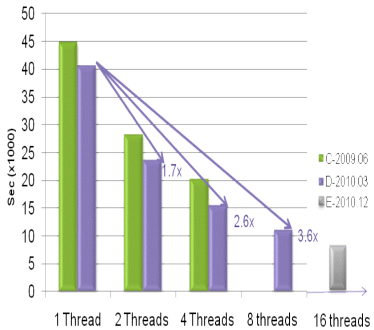


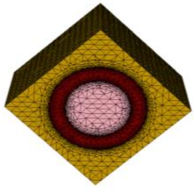
- 3D Support (FinFET, NVM, Power, SRAM, CIS)
  - Improved meshing and geometric operations
  - Stress modeling
  - BEOL reliability modeling
  - Topography simulation

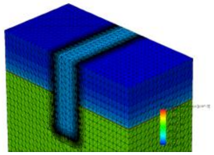




- Performance and Usability
  - Improved multi-CPU scaling
  - Process simulation speed-up
  - More intuitive user interface







TCAD Supported Platforms

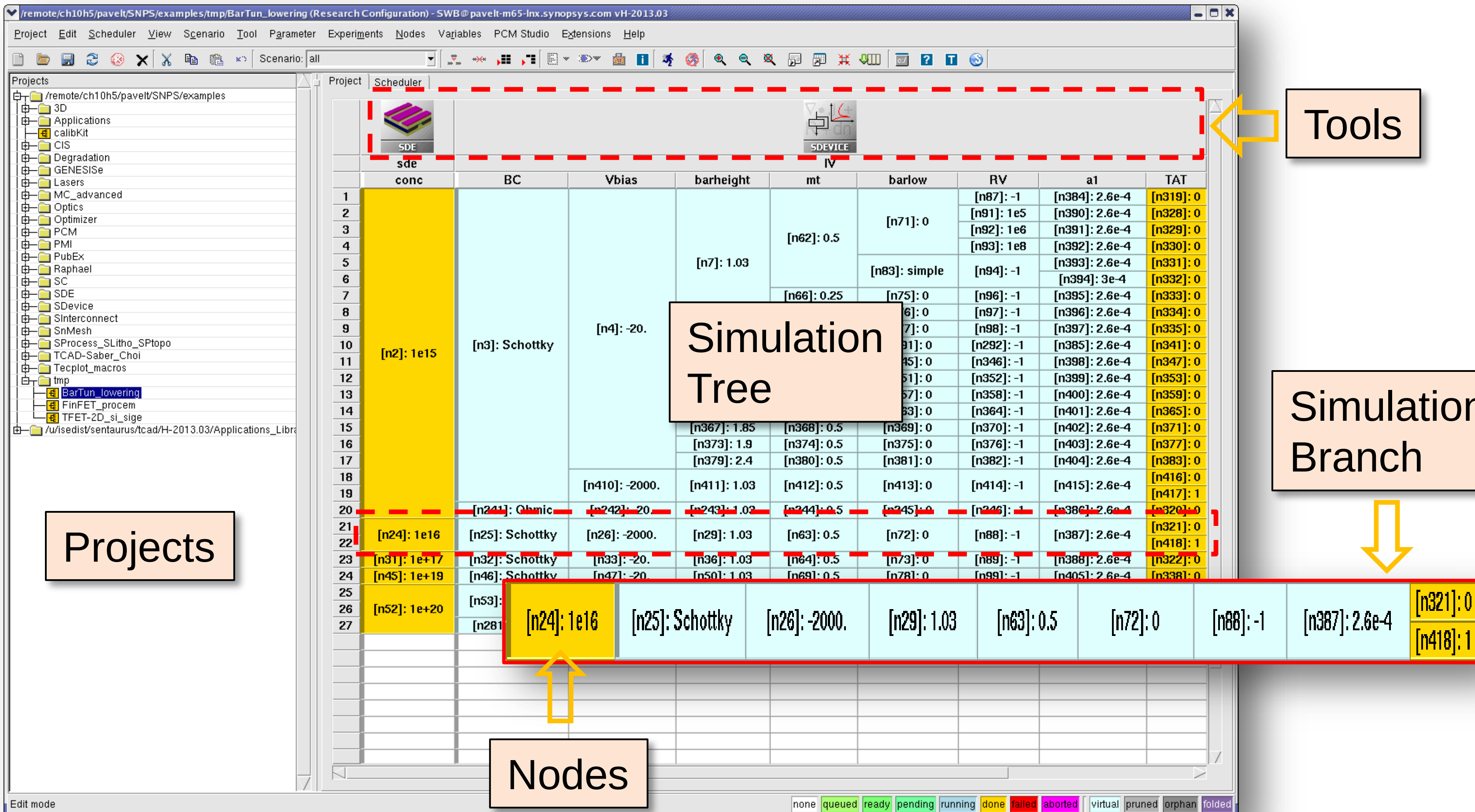
Platforms supported in I-2013.12 release:

- x86_64[1] Red Hat Enterprise Linux 5.7, 5.9, 6.2, 6.4
- x86_64[1] SUSE Linux Enterprise Server 10SP3, 10SP4[2], 11SP1[2], 11SP2[2]
- IBM RS6000 64-bit AIX[3] 6.1-TL6-SP5

1. The 64-bit (x86_64) Linux software is binary compatible with the Intel orAMDx86_64 processors running Red Hat Enterprise Linux.
2. Binary-compatible hardware platform or operating system. Note, however, that binary compatibility is not guaranteed.
3. Sentaurus Device Electromagnetic Wave Solver, Sentaurus Interconnect, Sentaurus Topography, and Sentaurus Topography 3D are not available on AIX.

Sentaurus Workbench – TCAD Simulation Platform

- Sentaurus Workbench GUI

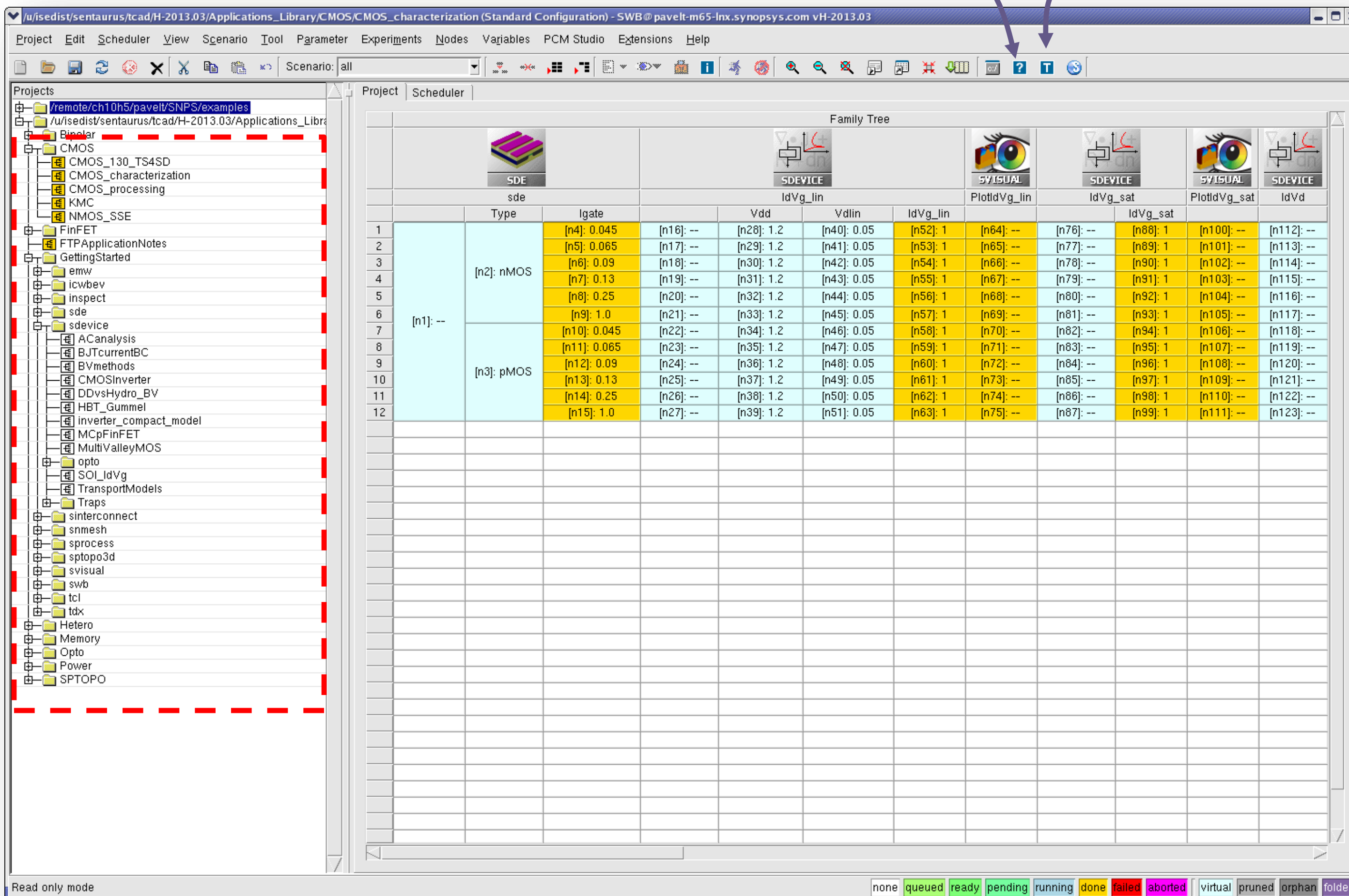


Sentaurus Workbench – Easy Material & Manual Access

Manuals

HTML-training

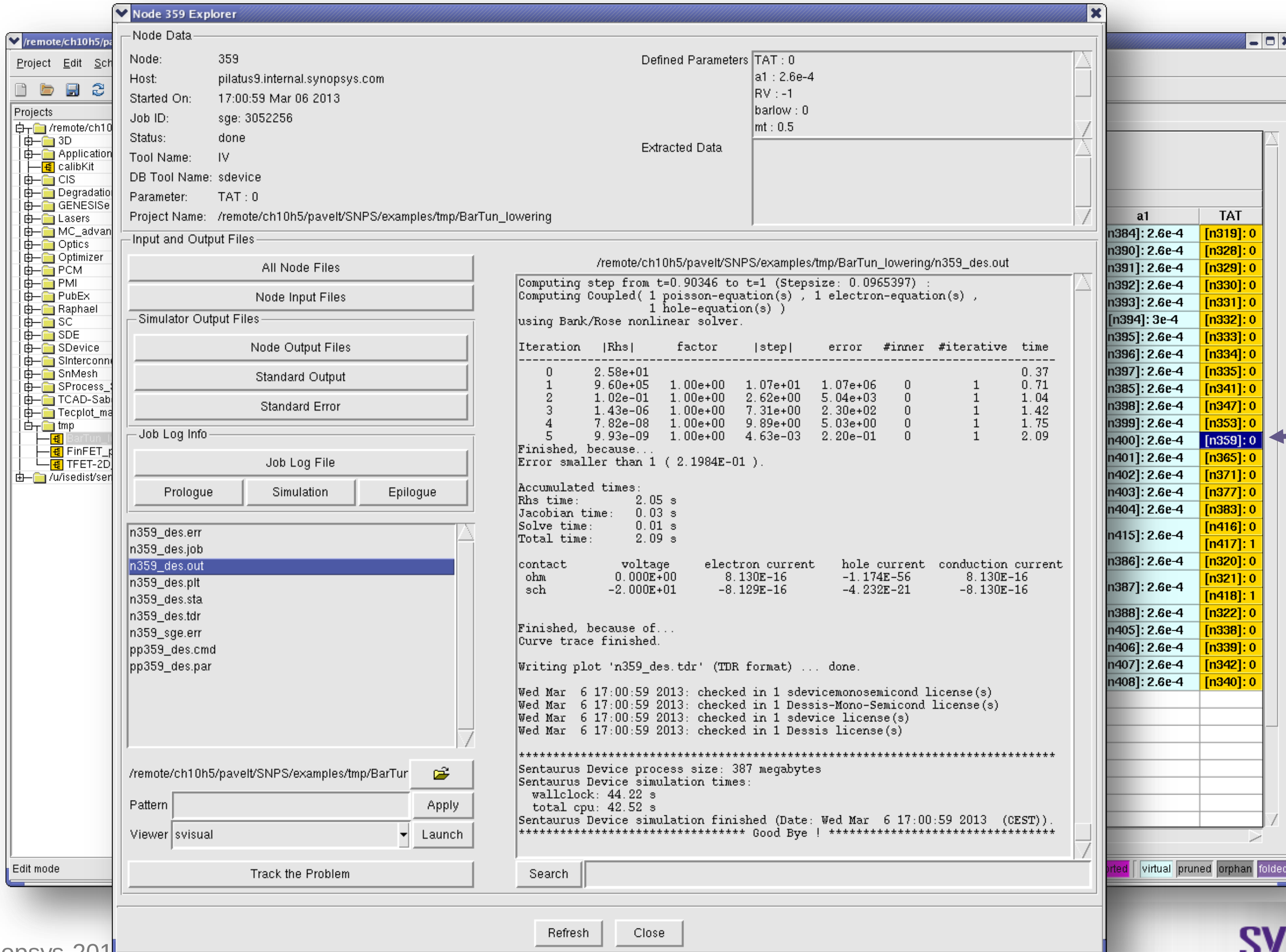
Public Application Example Library



SYNOPSYS® Accelerating Innovation

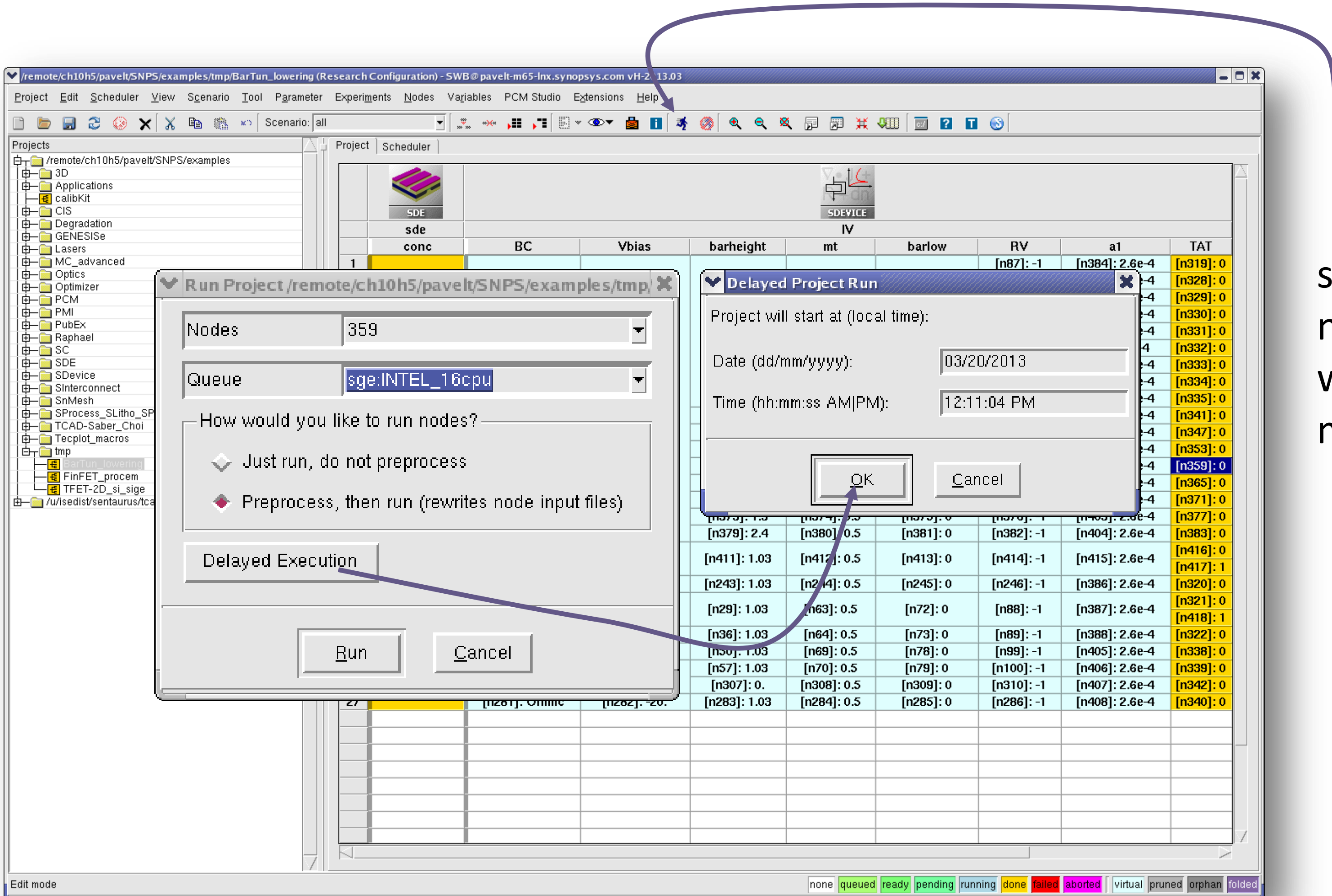
Sentaurus Workbench – Node Explorer

- Node Explorer (F7) provides quick access to all node data



mouse
double-click
on node

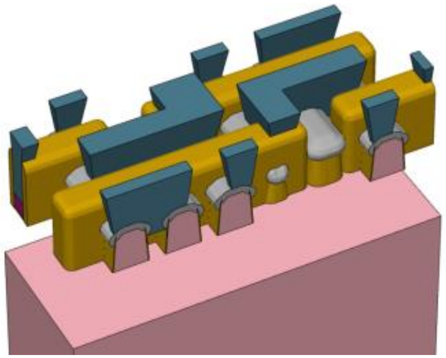
Sentaurus Workbench – Flexible Execution Controls



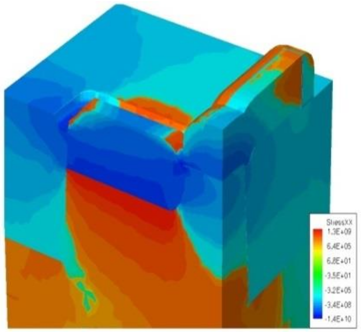
selected nodes run with one mouse click

Sentaurus Process Simulator

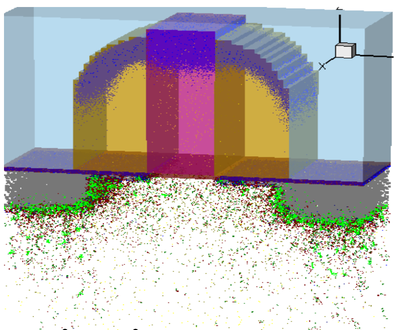
- General purpose multidimensional (2D/3D) process simulator
- Integrated 3D geometric modeling engine (depo/etch/pattern)
- Adaptive meshing (to geometry/species changes)
- API for user-defined models
- Advanced physical models:
  - Analytic and Monte Carlo implantation
  - Diffusion: laser/flash annealing, kinetic Monte Carlo
  - Mechanical stress
  - Oxidation/Silicidation



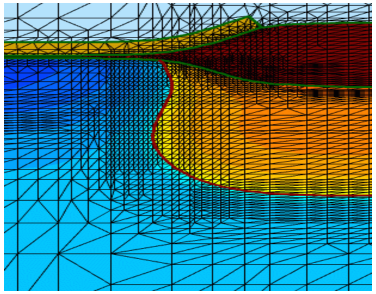
FinFET SRAM



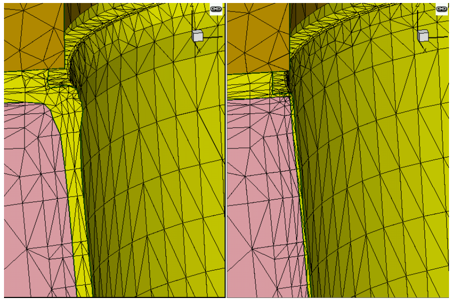
Mechanical Stress



Kinetic Monte Carlo



Adaptive Meshing

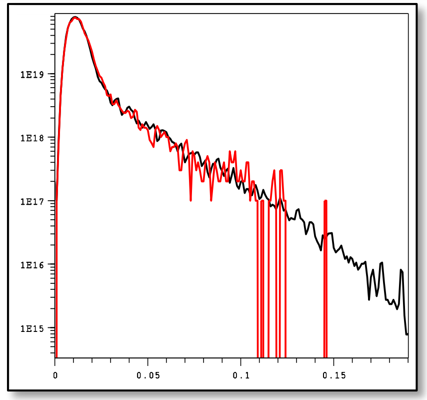


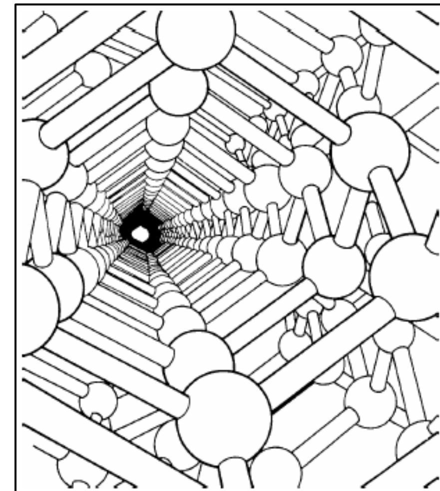
Oxidation

Implantation

```
implant Arsenic dose=1e14 energy=50 tilt=7 rotation=0 info=2
```

- MC Implantation
  - Sentaurus MC
  - (Crystal-TRIM)
- Analytic Implantation
  - Primary Distributions
    - Gaussian
    - Pearson (4 parameters)
    - Dual Pearson (9 parameters)
  - Screening
  - Damage Model
  - Amorphization
  - Molecular Implant
  - Calibrated Implantation Tables





- Arsenic: 0.5~400keV
- Antimony: 1.5~600keV
- BF2: 0.5~400keV
- Boron: 0.2~517keV(silicon)
- Germanium: 1~50keV
- Indium: 1~400keV
- Phosphorus: 0.3~400keV

- Tilt: 0~60
- Oxide: 0~100nm

Dopant Diffusion

- Flash/Laser Anneal
- Dopant Activation and Clustering
- Solid Phase Epitaxial Regrowth
- Epitaxy
- Clustering of Defects
- Pressure-dependent Defect Diffusion
- Segregation & Dose Loss
- Kinetic MC Diffusion

$\frac{\partial C_{A_s}}{\partial t} = -R_{AI} - R_{AV} + R_{AI,V} + R_{AV,I}$	Substitutional
$\frac{\partial C_{AI}}{\partial t} = -\nabla . J_{AI} + R_{AI} - R_{AI,V}$	Dopant Interstitial Pair
$\frac{\partial C_{AV}}{\partial t} = -\nabla . J_{AV} + R_{AV} - R_{AV,I}$	Dopant Vacancy Pair
$\frac{\partial C_{I}}{\partial t} = -\nabla . J_{I} - R_{AI} - R_{AV,I} - R_{IV} - R_{c}$	Interstitial
$\frac{\partial C_{V}}{\partial t} = -\nabla . J_{V} - R_{AV} - R_{AI,V} - R_{IV}$	Vacancy

- Diffusion Model Hierarchy
  - Constant (constant diffusion coefficient)
  - Fermi (point defects equation not solved, defects in equilibrium)
  - Charged Fermi (same as Fermi+total dopant flux is due to dopant-defect pairs)
  - Pair (dopant-defects pairs are in local equilibrium with dopant and defect concentrations)
  - Charged Pair (same as Pair+reaction rates are state charge dependent)
  - React (incl.defects, rates are not charge state dependent)
  - Charged React (same as React+mobile charged dopant-defects)

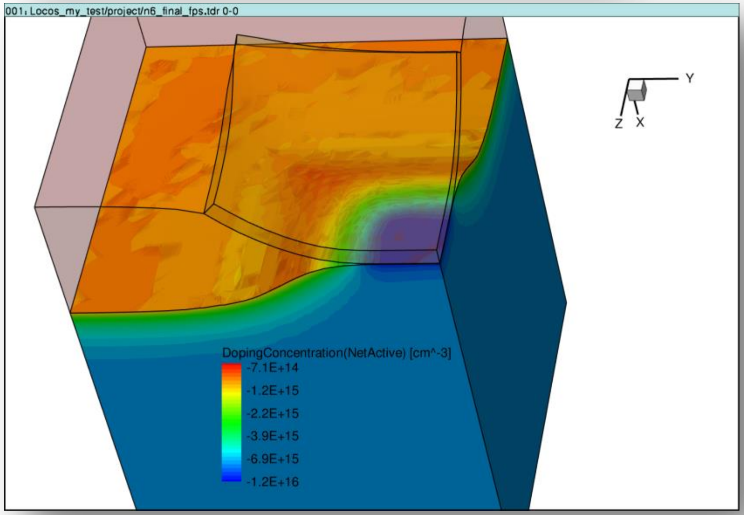
Oxidation/Silicidation

- Oxidation Model Hierarhy
  - Deal/Grove Model
  - Massoud Model
  - Mixed Flows (Hirabayashi approach)
- Stress-Dependent Oxidation (SDO)
- Orientation-Dependent Oxidation
- Doping-Dependent Oxidation
- Trap-Dependent Oxidation
- In Situ Steam-Generated Oxidation (ISSG)
- Silicidation
- Oxynitridation ($N_2 0$)
- Moving Boundaries and Adaptive Mesh
- 3D Oxidation

$$\frac{dx}{dt} = \frac{B}{A+2x}$$

$$\frac{dx}{dt} = \frac{B}{A+2x} + C\exp\left(-\frac{x}{L}\right)$$

$$\frac{dx}{dt} = \frac{dx_{H2O}}{dt} + \frac{dx_{O2}}{dt} = \frac{B_{H2O}}{A_{H2O}+2x} + \frac{B_{O2}}{A_{O2}+2x}$$

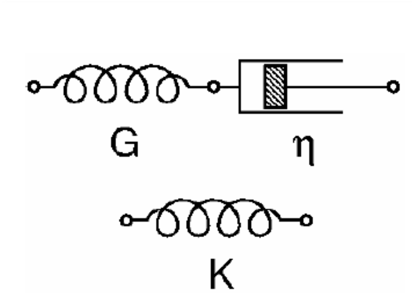


Mechanical Stress Modeling

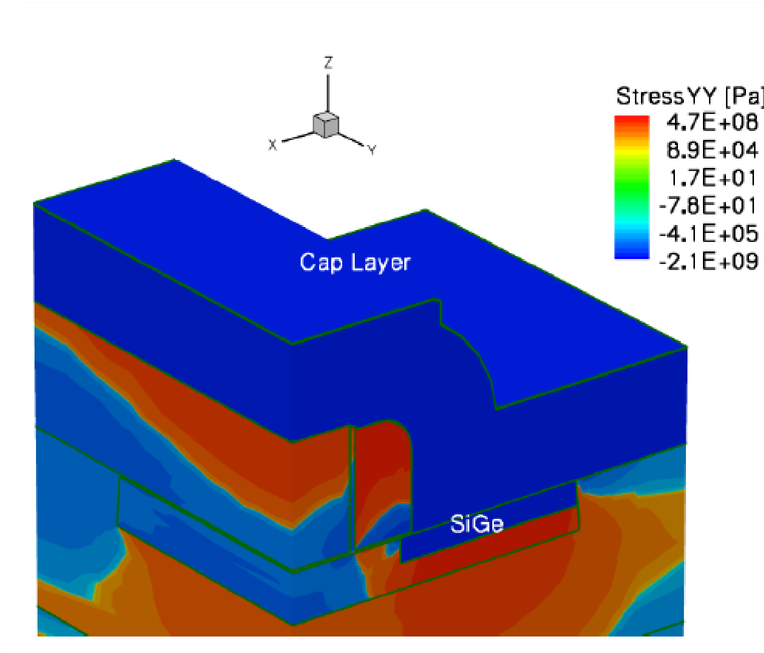
- Stress Model
  - Viscoplasticity
  - Plasticity
  - Viscoelasticity

$$\frac{\dot{\sigma}'_{jk}}{G} + \frac{\sigma'_{jk}}{\eta} = 2d'_{jk}$$

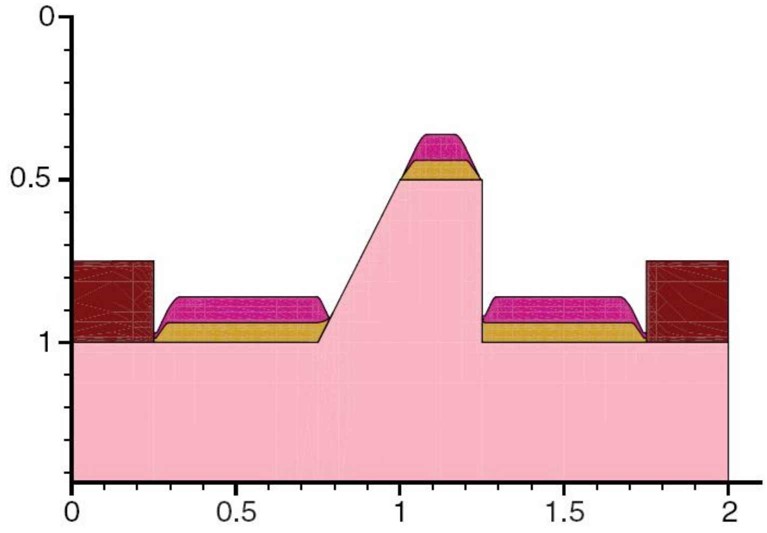
$$\sigma_{kk} = 3K\varepsilon_{kk}$$



- Stress Causing Mechanisms
  - Stress Induced by Growth of Material
  - Stress Induced by Densification
  - Stress Induced by Thermal Mismatch
  - Lattice Mismatch Stress
  - Intrinsic Stress



Etching/Deposition

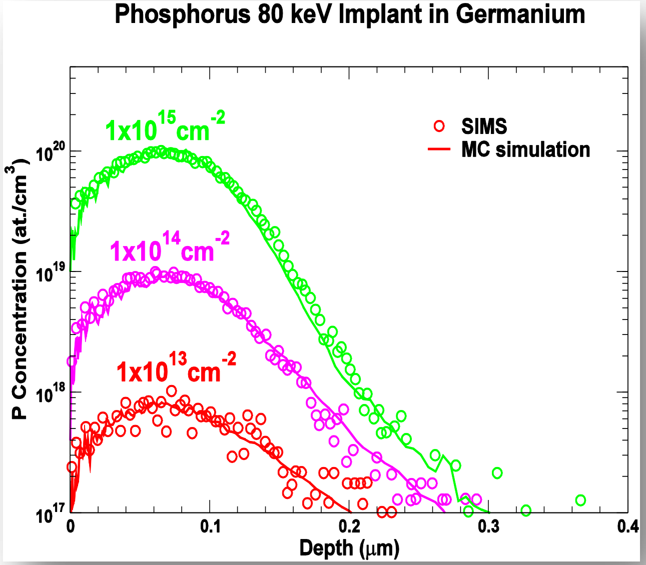


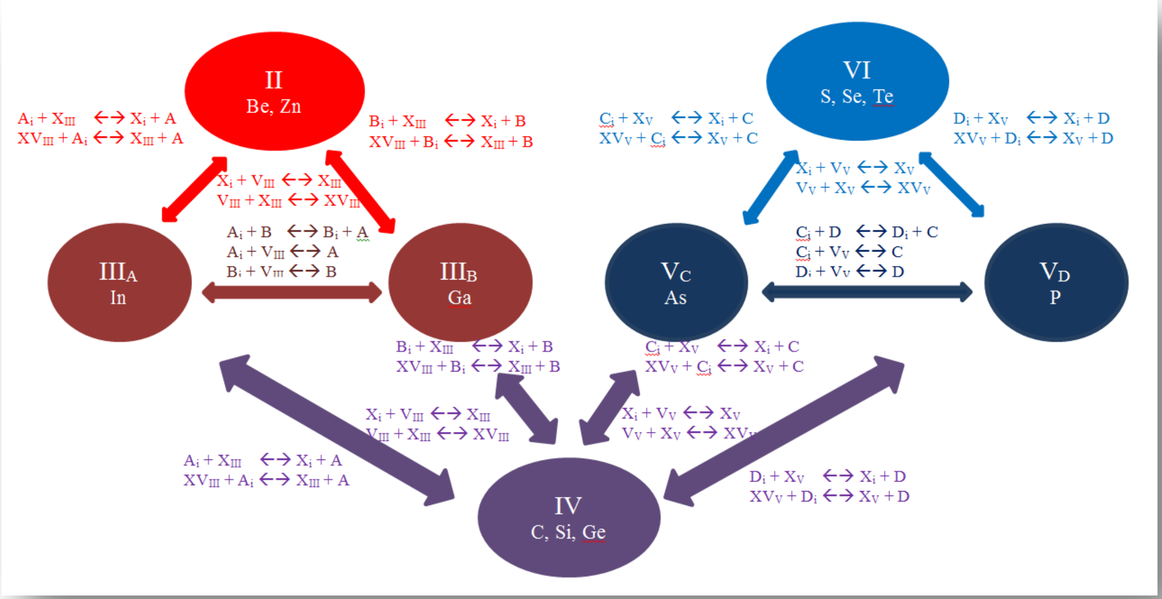
- Etch Models
  - Isotropic
  - Anisotropic & Directional
  - Polygonal
  - CMP
  - Fourier
  - Crystallographic
  - Trapezoidal
- Depo Models
  - Isotropic
  - Fill & Polygon
  - Fourier
  - Selective Deposition
- Algorithms
  - Analytic
  - Level-set

- 3D Geometry Generation
  - MGOALS3D (level-set)
  - Integrated SDE
  - S-Topo 3D
  - Meshing with Sentaurus Mesh

Non-Si Materials Process Simulation

- MC Implantation
  - SiGe and Ge
  - 4H-, 6H-SiC
  - III-V, including III-N
- Diffusion & Activation
  - First prototype available in H-2013.03 release for 4H-SiC and III-V (InGaAs/InP)





Sentaurus Process Kinetic MC

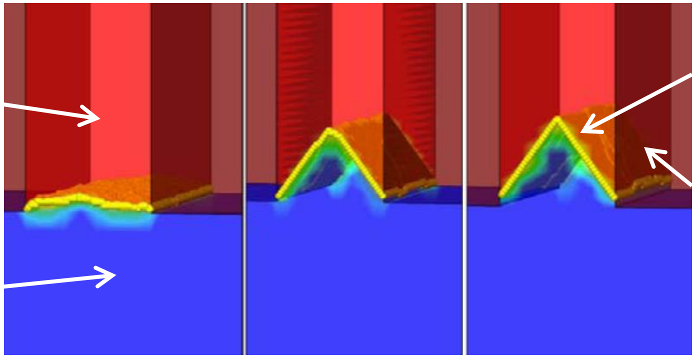
- Command to switch

```
SetAtomistic
```

- Considers only defects and impurities, and ignores the lattice for diffusion simulation
- Supported options: *diffuse, deposit, etch, implant, init, line, photo, profile, region, select, strip*
- LKMC: Fully Atomistic Modeling of SPER (Solid Phase Epitaxial Regrowth)
  - SPER velocity depends on the substrate orientation with approximate ratios of 20:10:1 for orientations (100), (110), and (111)

amorphous Si

crystalline Si



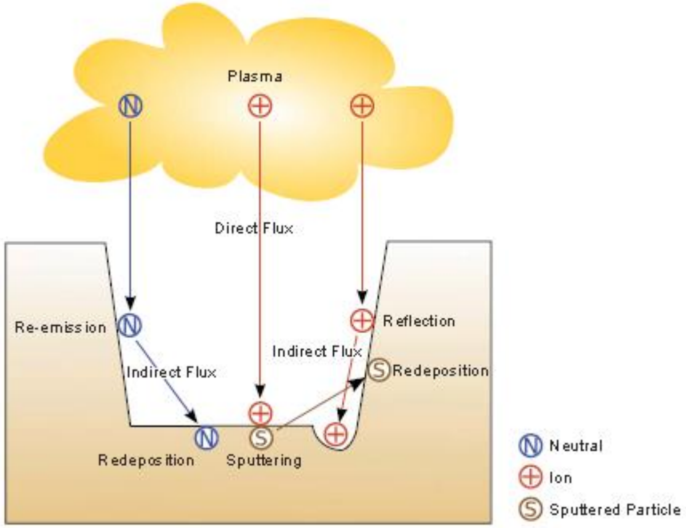
(111) planes

Oxide

Sentaurus Topography 3D

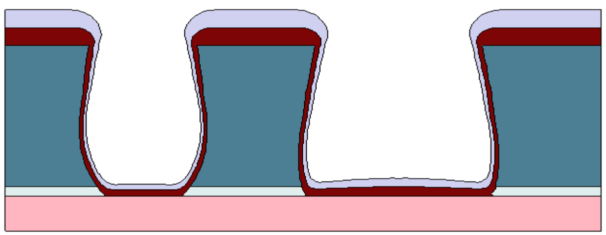
General overview

- Sentaurus Topography 3D is a three-dimensional simulator for evaluating and optimizing critical topography-processing steps such as etching and deposition
- Simulates deposition and etching processes by using the level-set method to evaluate the surface evolution during the process
- Models categories:
  - Built-in models
  - User-defined models within Rate Formula Module (RFM)
  - User-defined models within a Physical Model Interface (PMI)
- Support of different reaction species, different fluxes, re-deposition, …

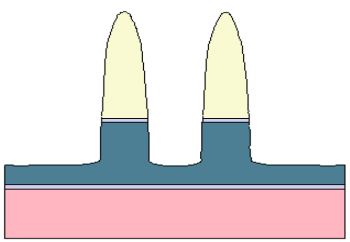


Sentaurus Topography Simulator

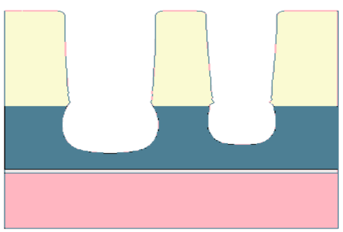
- Multidimensional (2D/3D)
- Robust level-set numerical models
- Deposition models (LPCVD, PECVD, HDP-CVD, APCVD, SOG, reflow)
- Etching models (wet, HDP, RIE, ion milling, CMP)
- Interface to Sentaurus Process & Sentaurus Lithography



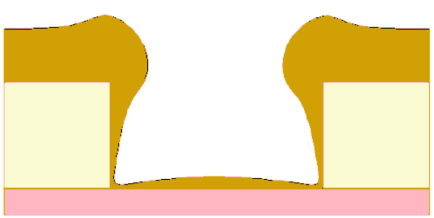
Physical vapor deposition



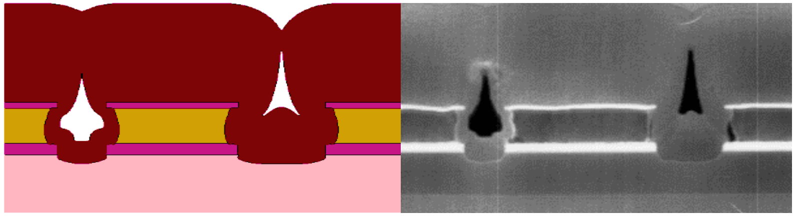
Ion milling



RIE



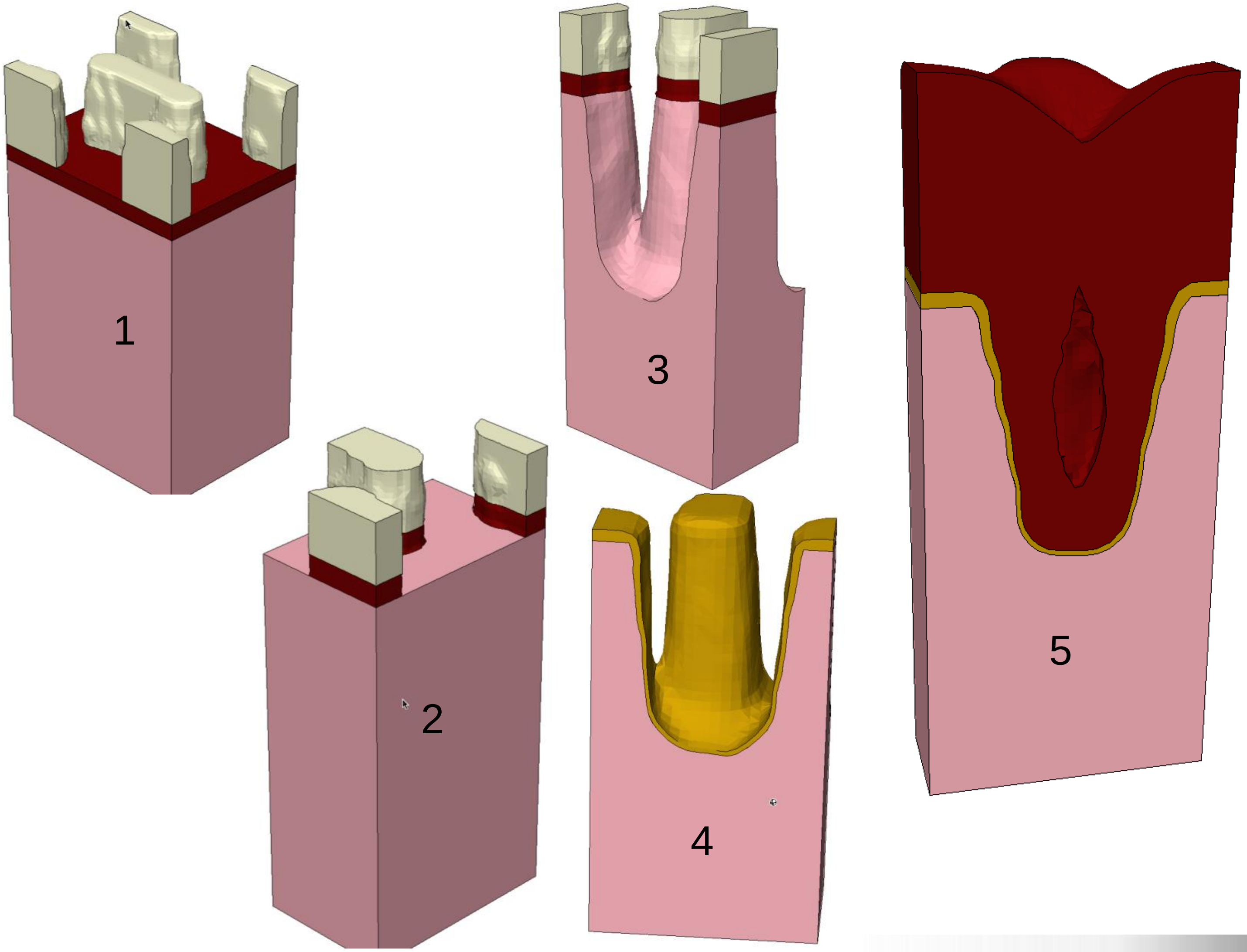
O3 / TEOS APCVD



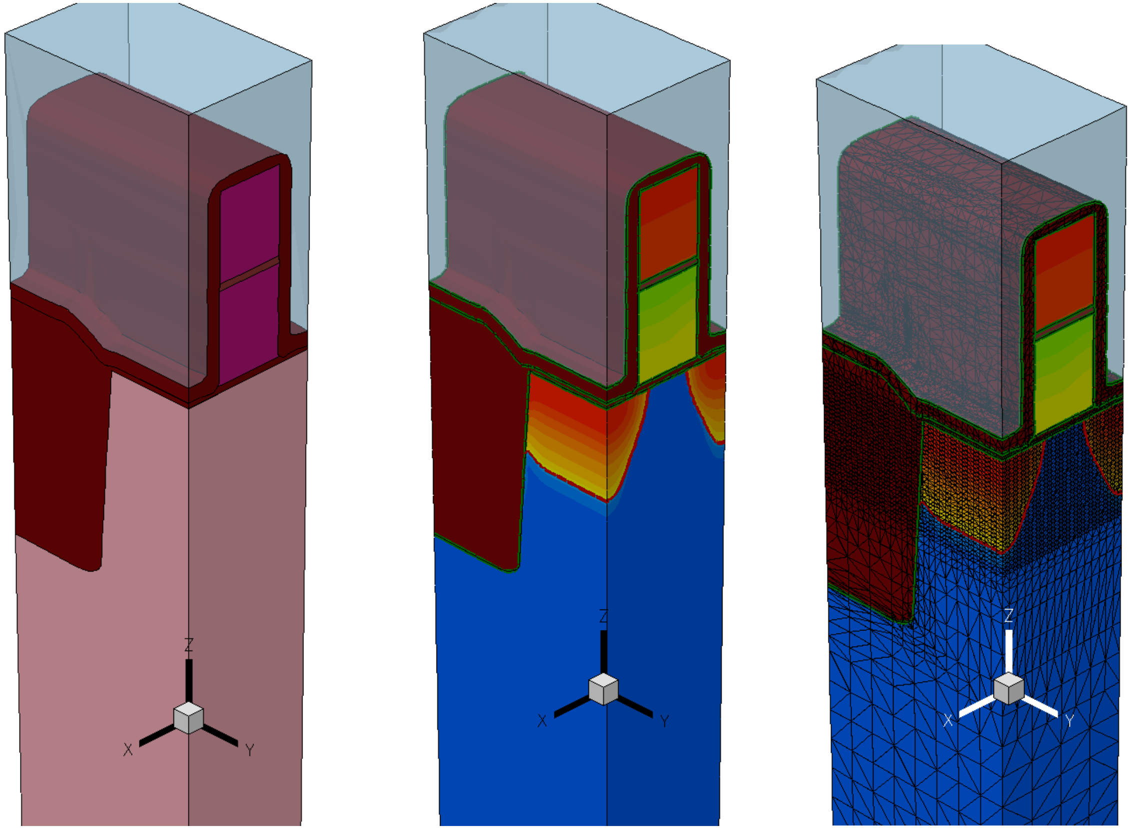
Tench filling with void formation

Etching and Deposition Example

DRAM Flow, using built-in models



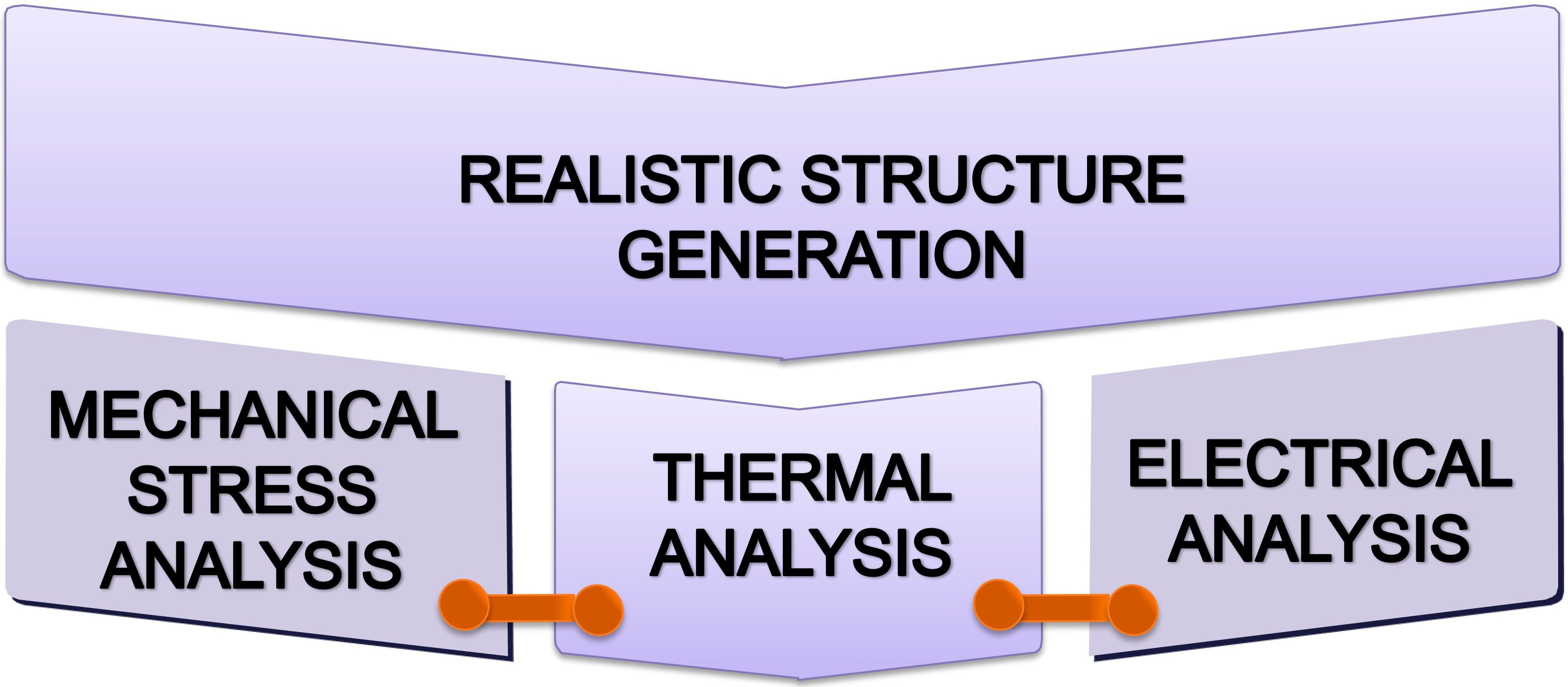
Coupling Topography to Process



Geometry
Sentaurus Topography

Doping and meshing
Sentaurus Process

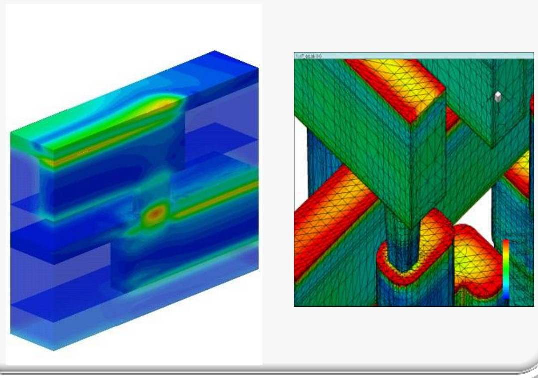
Sentaurus Interconnect



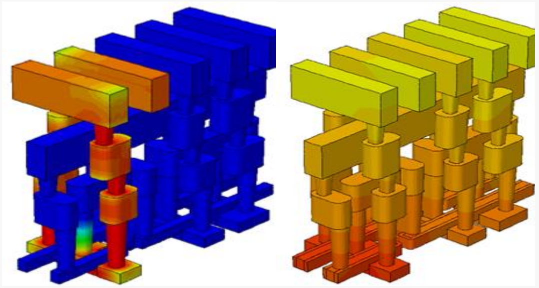
Sentaurus Interconnect Tool Overview

- Focus on BEOL device structures

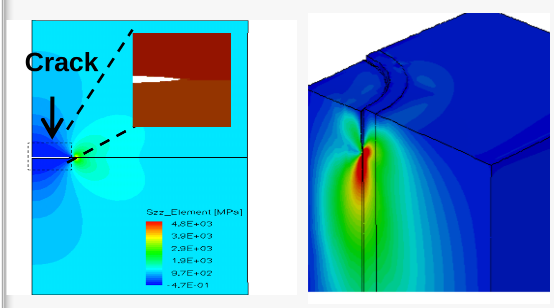
Mechanical Stress



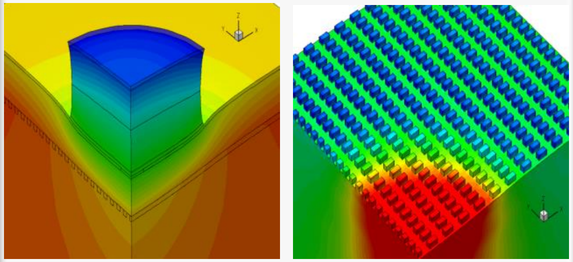
Electro-Thermal



Fracture Mechanics



TSV Proximity

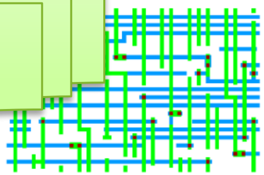


Sentaurus Interconnect Simulation Flow

Process Info

Deposition material=Oxide
Etch mask=Metal_2

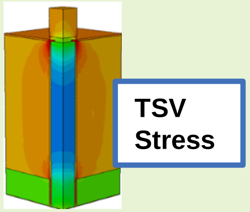
Layout Info
GDSII

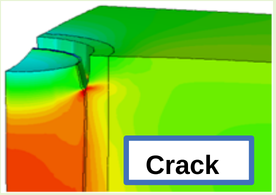


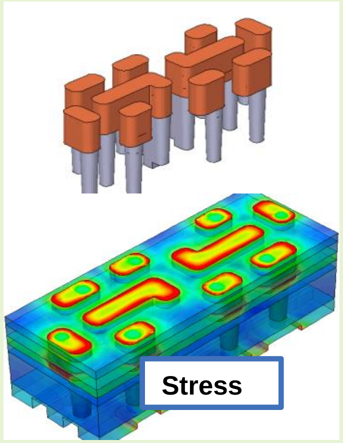
ICWB-EV Plus

Material Property Database

Sentaurus Interconnect

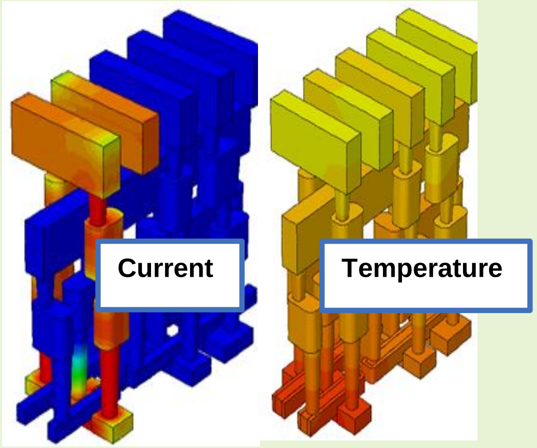




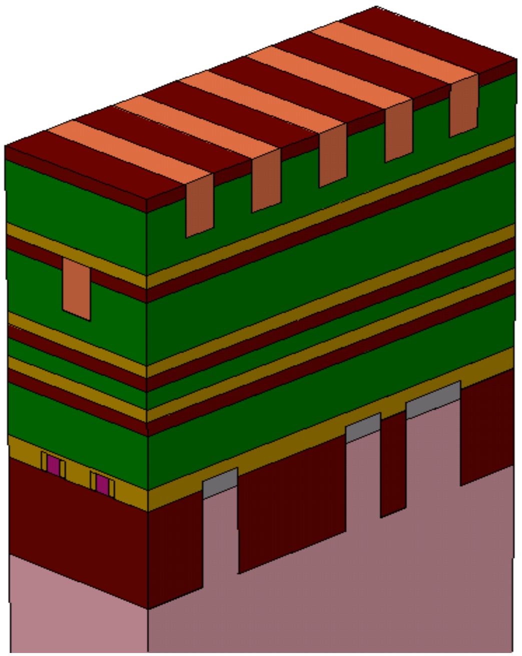


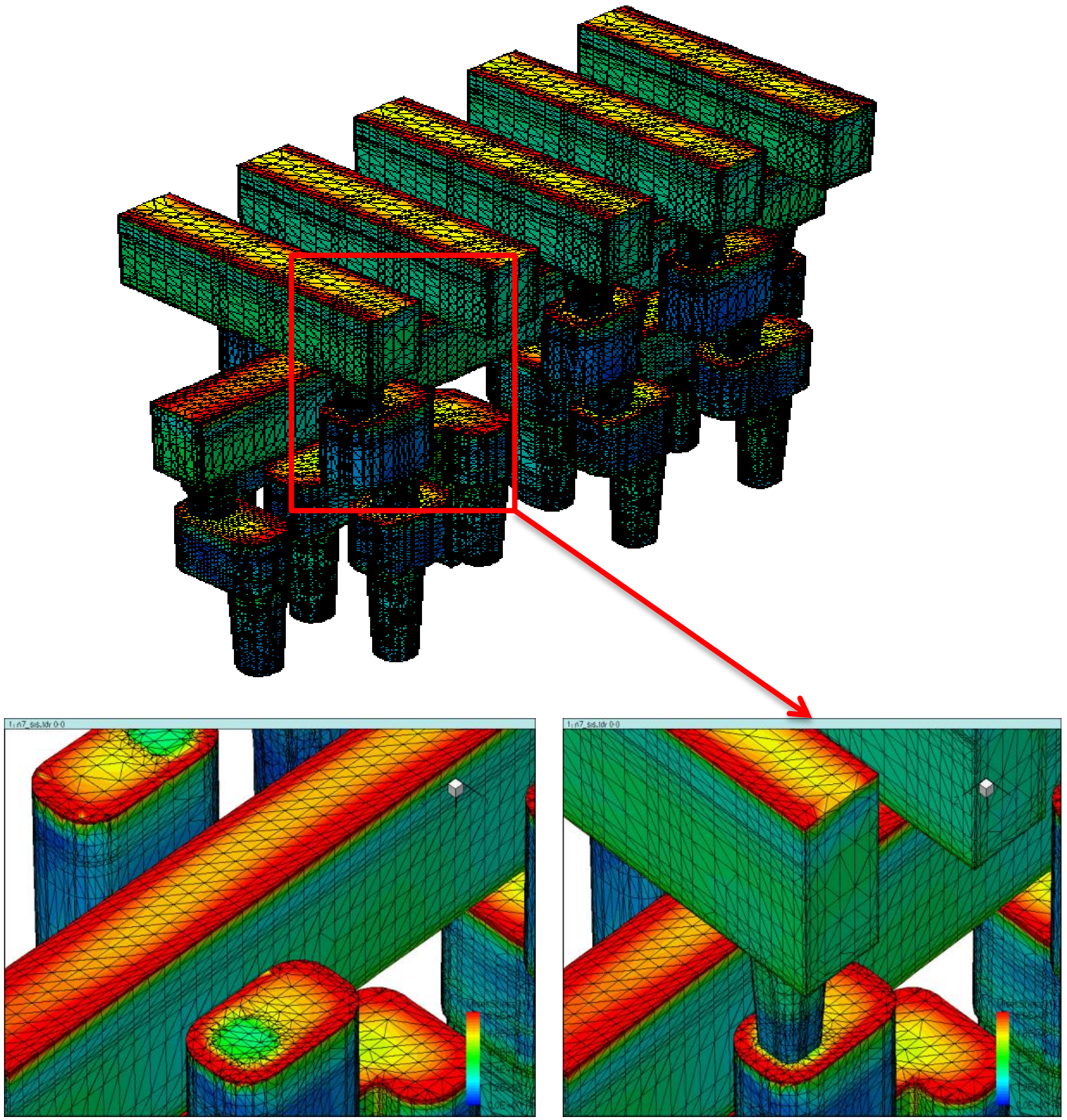
Realistic 3D Structures with :

- **Mechanical Stress Fields**
- **Electrostatic Potential**
- **Current Density**
- **Thermal hot-spots**
- **Mobility Variations**
- **Crack Propagation**

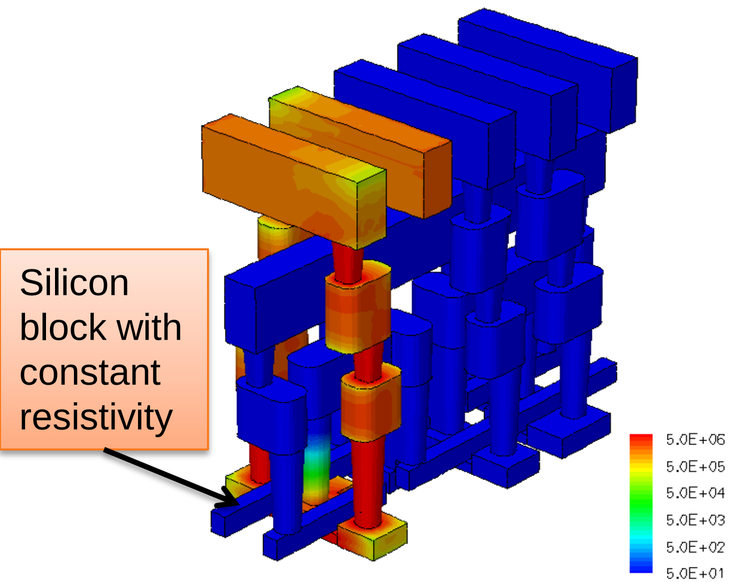


BEOL Structure Meshing

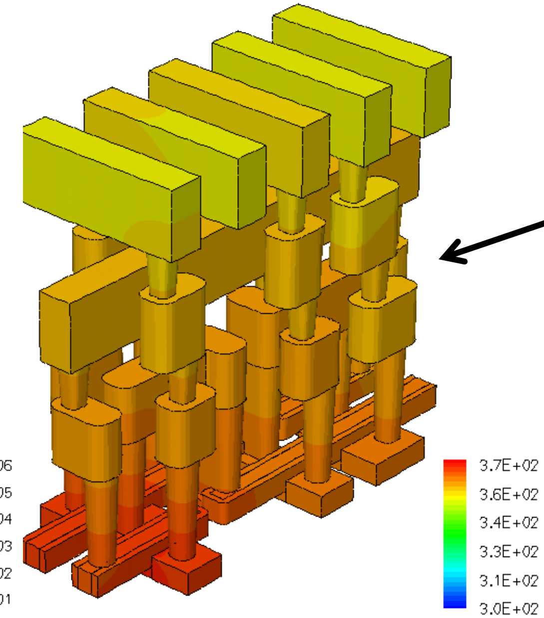




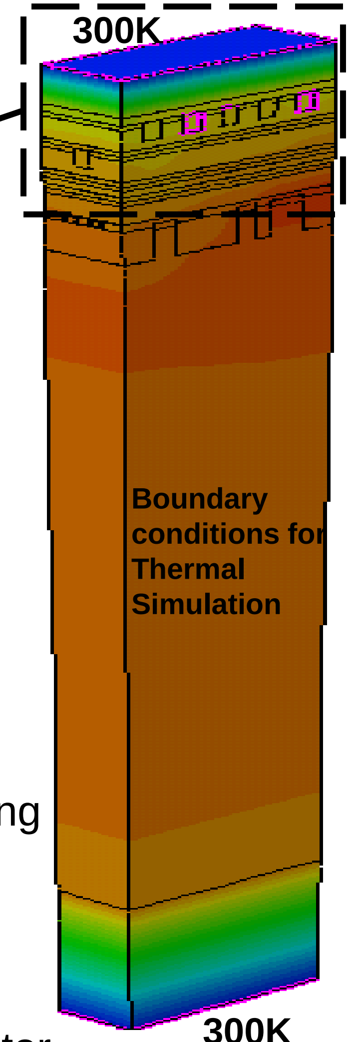
Self Heating and Temperature Gradients



Current Flow



Self Heating and Temperature Gradient

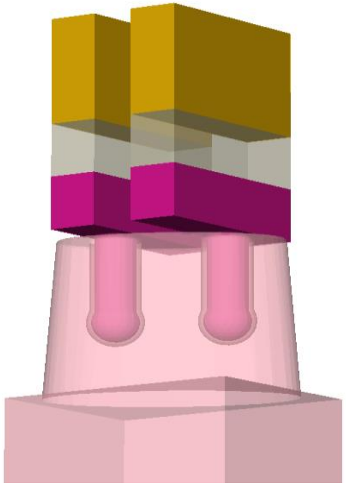


- Performing electrical and thermal simulation alongside stress simulation, using the same input file and structure setup helps evaluate reliability and performance trade-offs efficiently

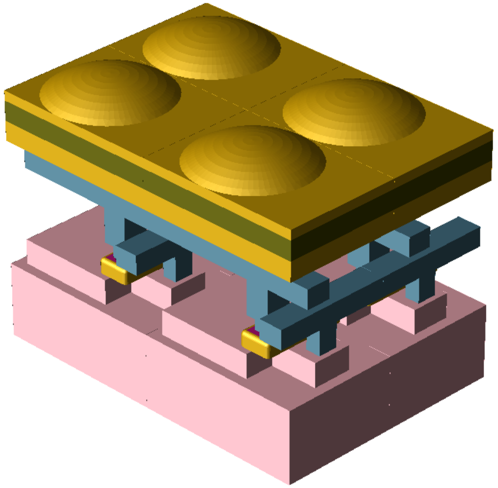
- Self-heating simulation allows 3D-IC engineers to estimate impact on transistor performance and validate chip-level models for thermal-aware placement

Sentaurus Structure Editor

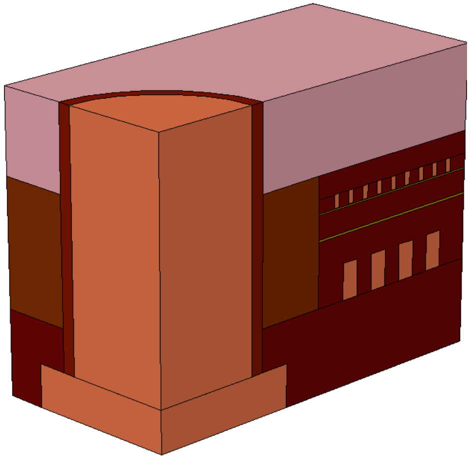
- Geometrical operations
- Easy to use GUI
- Scripting language
- Advanced geometrical modeling with analytic doping definitions
- Direct interface to meshing engines



S-RCAD DRAM



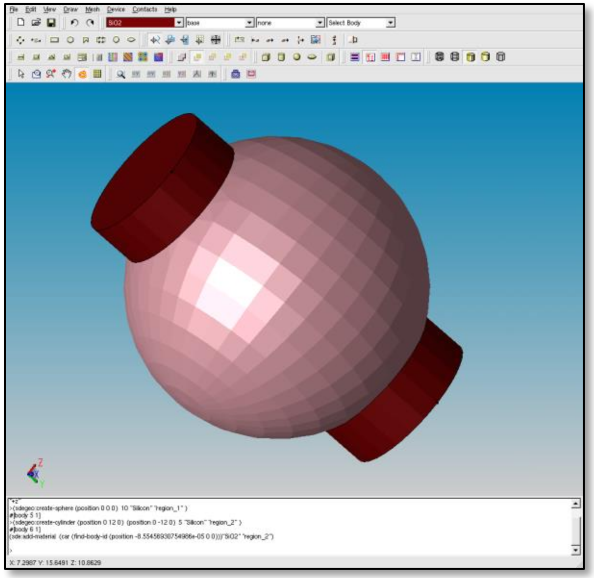
CIS pixels with microlenses

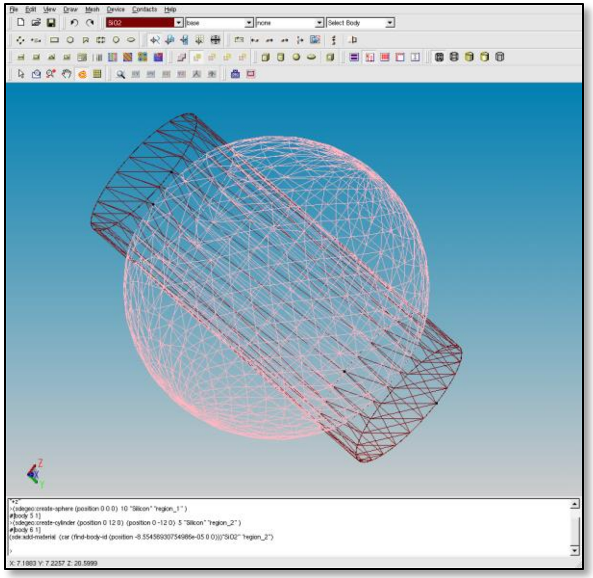


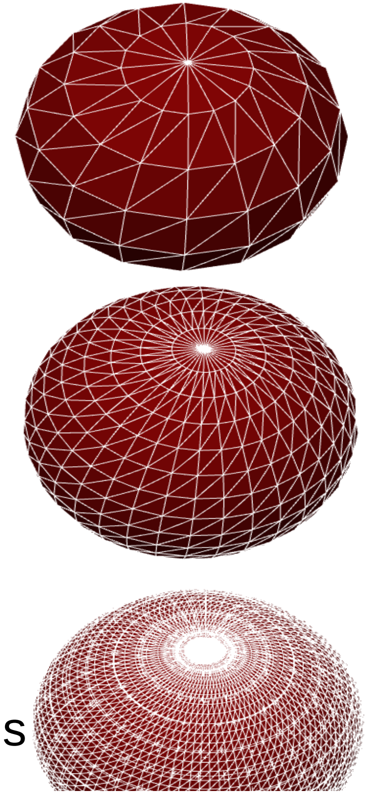
TSV Structure

ACIS Geometry Kernel

- Based on boundary representation.
- An ACIS boundary representation is a hierarchical decomposition of the topology of the model into lower-level topological objects.
- A typical body contains faces, edges, vertices, and may also includes lumps, shells, loops, and wires.







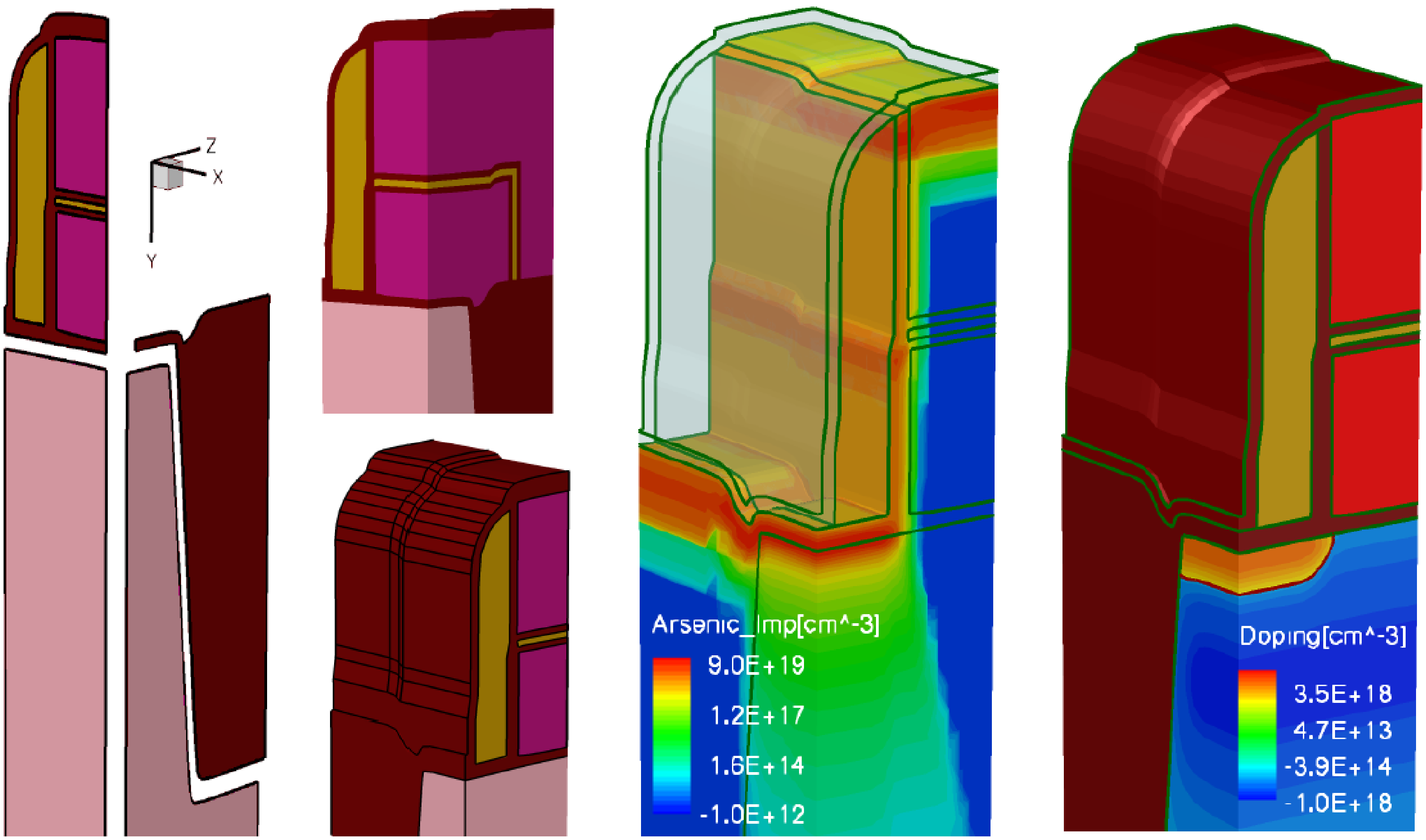
Tessellation controls

Scheme Language

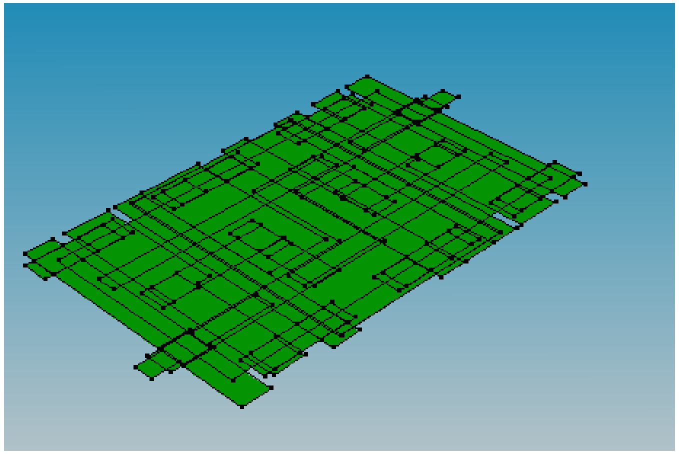
- Strings
- Lists
- Arithmetic Expressions
- Boolean Operations
- Loops
- Logical Operations
- Procedures
- System Calls

- (sde:clear)
  - It is helpful to reset SDE
- (define “var_name” “Value”)
- (define VAR 0)
  - a constant
- (define VAR (+ 1 4))
  - an operation
- (define VAR (list 1 2 3 ‘a ‘b “f g”))
  - a list

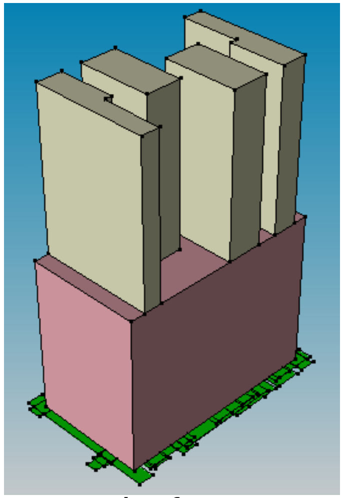
2D -> 3D Structure Construction



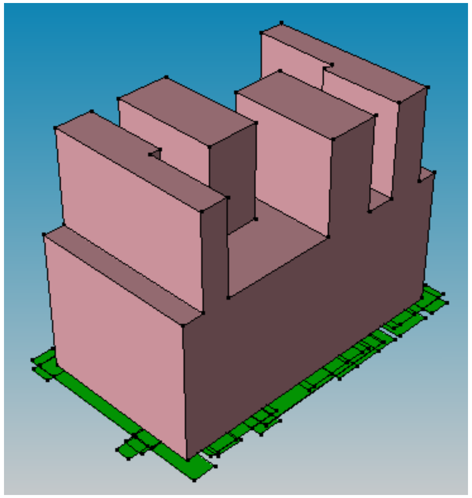
Layout Based Device Design



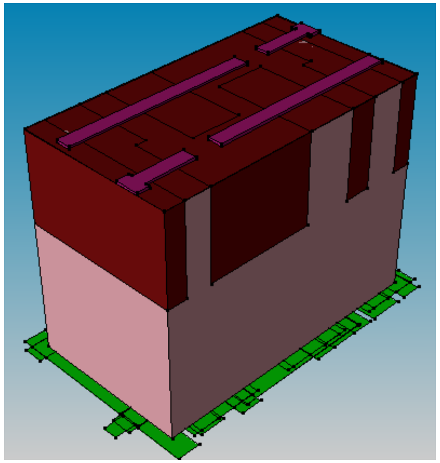
Loaded Layout



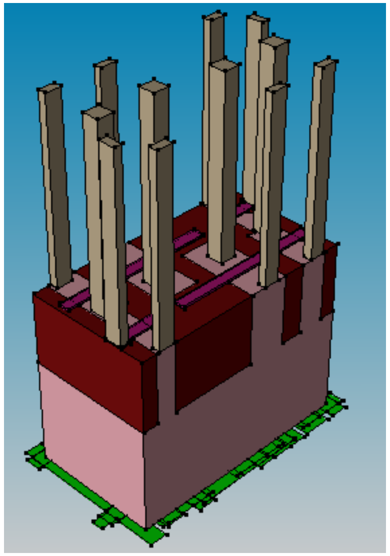
Resist for STI



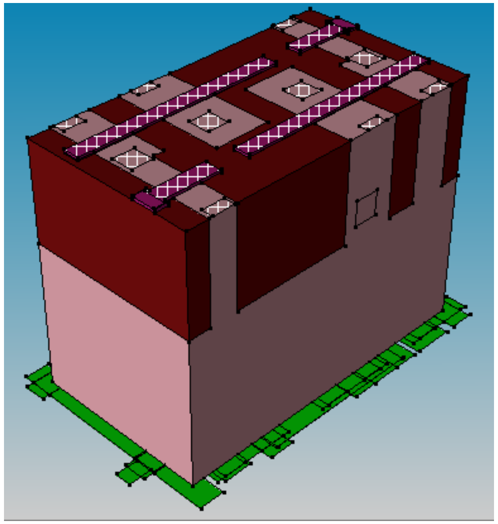
Silicon etching



STI formation (oxide filling) and
Polysilicon / gate oxide generation



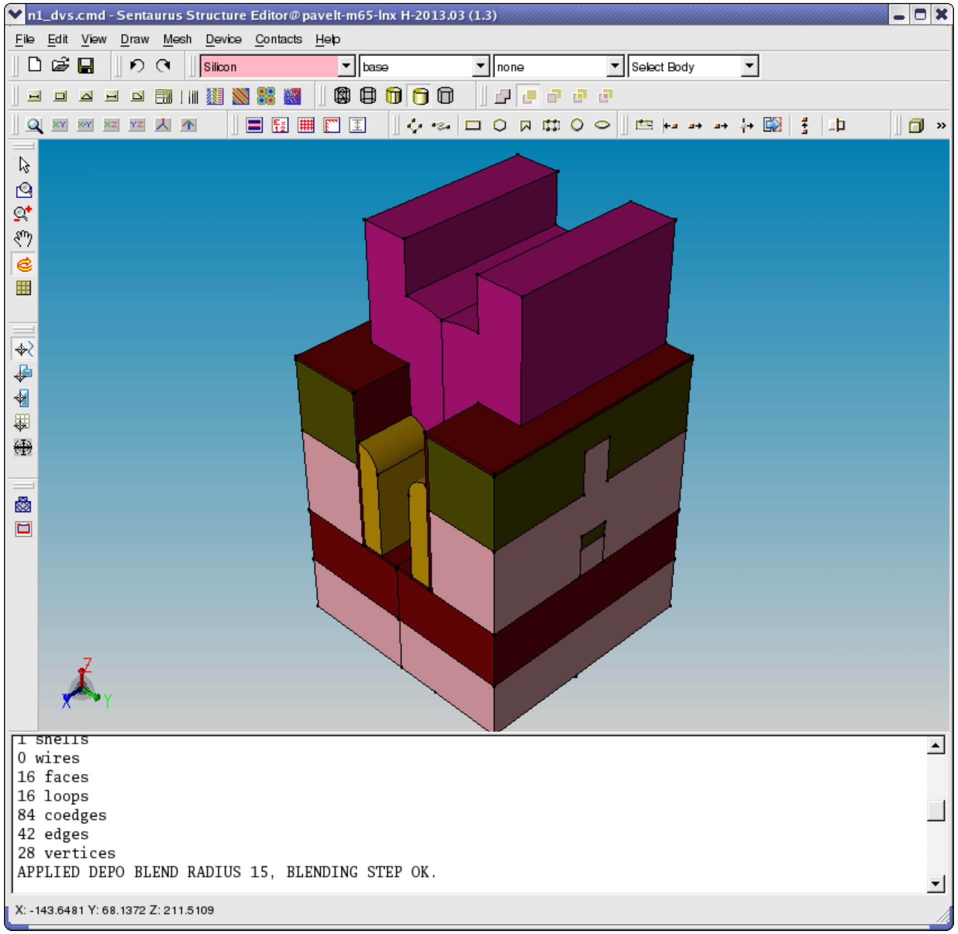
Metal generation for contacts



Final boundary structure

Process Emulation Mode

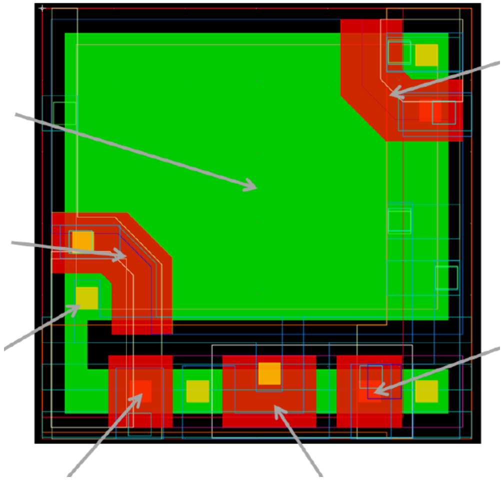
- Translates processing steps into geometric operations
- Works only in 3D
- Commands not accessible from GUI
- Support for:
    - Iso- & Aniso- Depo/Etch
    - Placement of analytical profiles w.r.t mask
    - GDS2 file loading
    - Masks definition and Patterning



Process Emulation - 3D CIS Structure

- A Sentaurus Structure Editor (SDE) script was done to generate “boundary” and “doping” files for Sentaurus Mesh (S-Mesh)
- GDS2 file is loaded into SDE and layers are built out of GDS2 layers

```
(define GDSFILE "TCAD_PIXEL_v3.gds")
(define CELLNAME "TCAD_PIXEL_v3")
(define LAYERNAMES (list 'PWELL 'POLY 'ACT 'NO_PW 'NPLUS
'CONT 'PW_LVT 'MET1 'VIA1 'MET2 'VIA2 'MET3 'VIA3 'MET4
'ULENS 'PD1 'PD2 'SN1 'SN2 'SN3 ))
(define LAYERNUMBERS (list '1:0 '8:0 '9:0 '17:82 '32:0 '34:0
'35:0 '40:0 '41:0 '42:0 '43:0 '44:0 '49:0 '50:0 '89:0 '92:82
'93:0 '94:0 '94:43 '94:95 ))

(sdeicwb:gds2mac "gds.file" GDSFILE "cell" CELLNAME
"layer.names" LAYERNAMES "layer.numbers" LAYERNUMBERS
"sim3d" (list 0 -6000 6000 0) "scale" 1.0e-3 "domain.name"
"SIM3D" "mac.file" "TCAD_PIXEL")
```



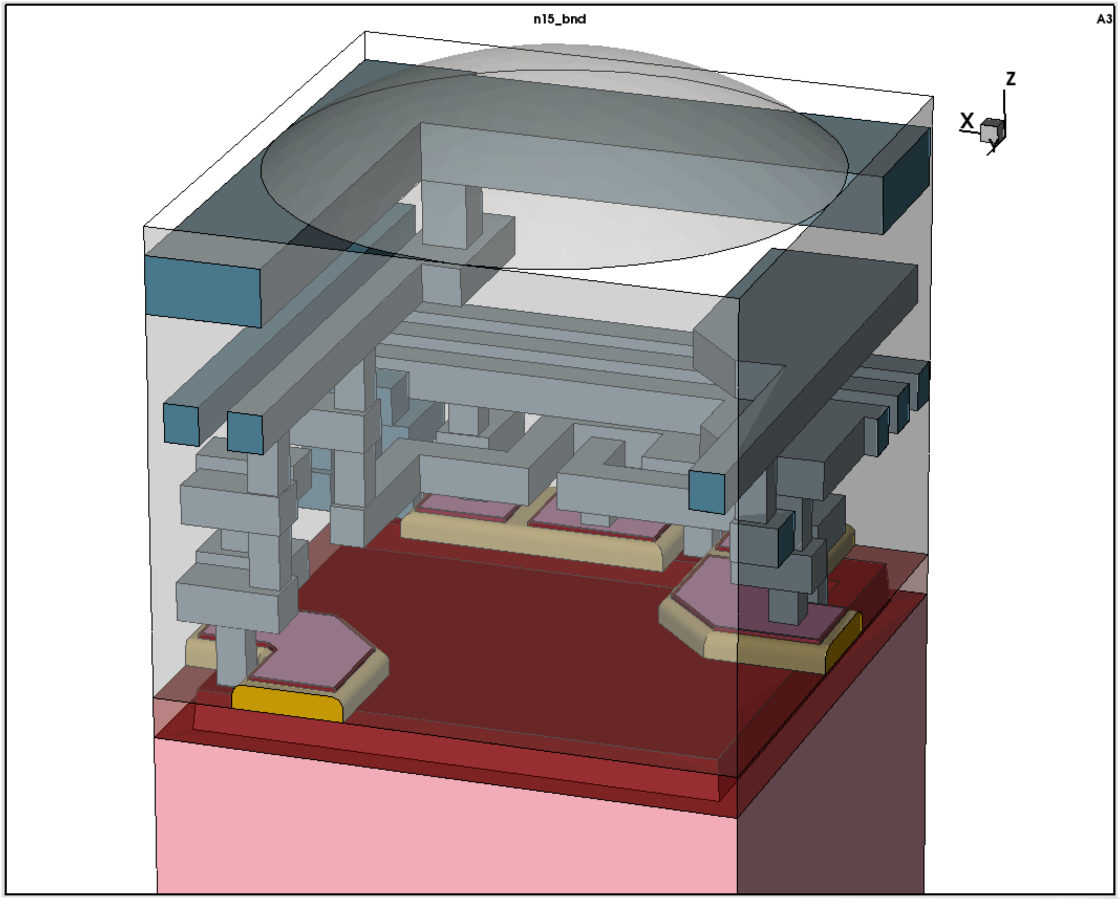
Process Emulation - 3D CIS Structure

- Geometry is built step by step using deposition/etch/patterning features of SDE
- Scripting language (scheme) allows full customization, using variables, lists, strings and built-in ACIS functions.

```
(define TSUB 7.0)

(sdepe:add-substrate "material" "Silicon" "thickness" TSUB "region" "substrat")

(sdepe:pattern "mask" "ACT" "polarity" "light" "material" "Resist" "thickness" 1  "type"
"aniso" "algorithm" "sweep" )

(sdepe:etch-material "material" "Silicon" "depth" 0.420  "taper-angle" 5)

(entity:delete (find-material-id "Resist"))

(sdepe:fill-device "material" "Oxide" "height" (+ TSUB 0.008))


(sdepe:pattern "mask" "POLY" "polarity" "light" "material" "PolySilicon" "thickness" 0.3
"type" "aniso" "algorithm" "sweep" )
```

Process Emulation - 3D CIS Structure

- SDE is based on ACIS (product from Spatial, Dassault-System) and allows complex solid modeling
- Micro-lens is part of a sphere inserted on top of the CIS

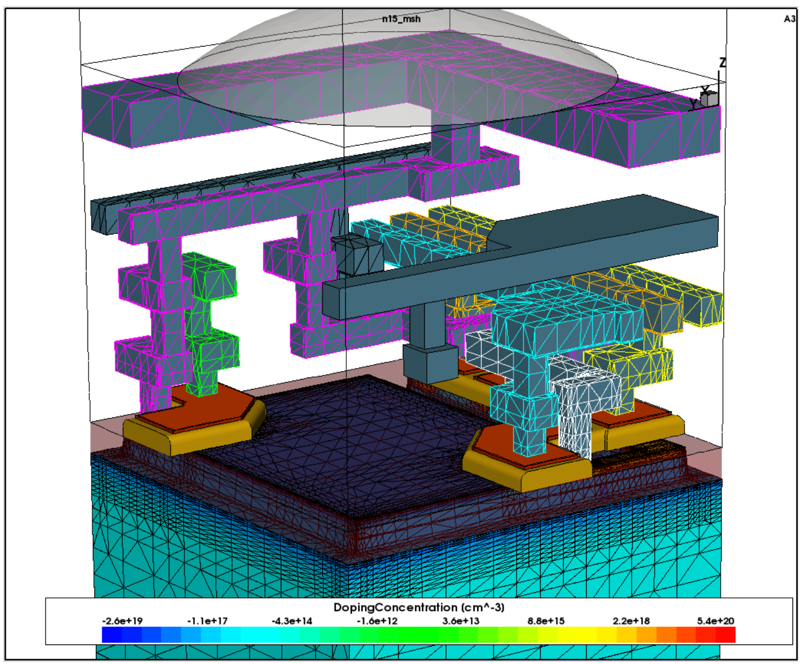


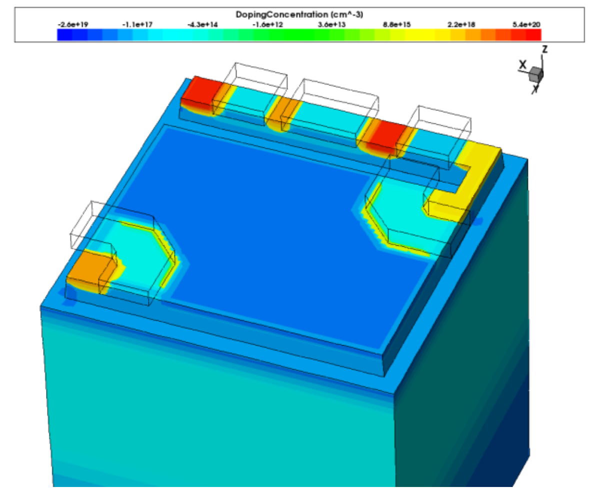
SYNOPSYS® Accelerating Innovation

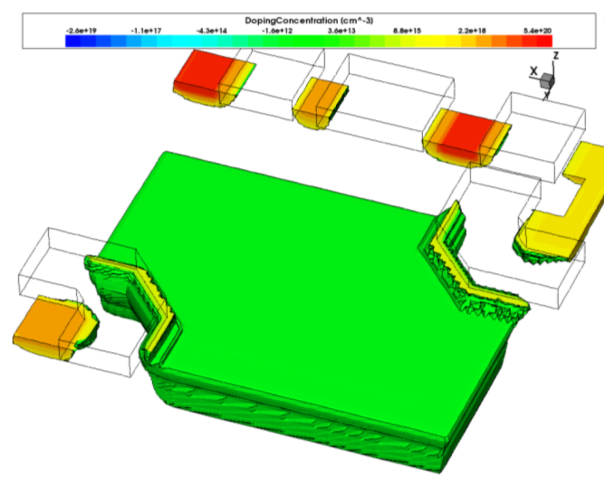
Process Emulation - 3D CIS Structure + doping

- Doping from analytical or SIMS profiles
- Doping from 1D/2D or 3D process simulation
- Meshing with Sentaurus Mesh

COL	
MEM	
RST_MN	
RST_PH	
SEL	
SUB	
TRA	
VREF_P	

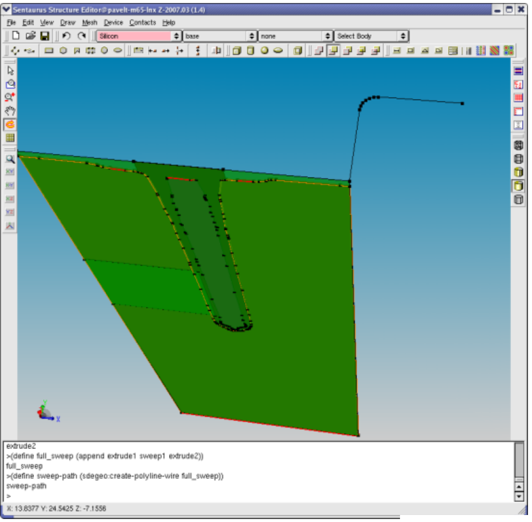


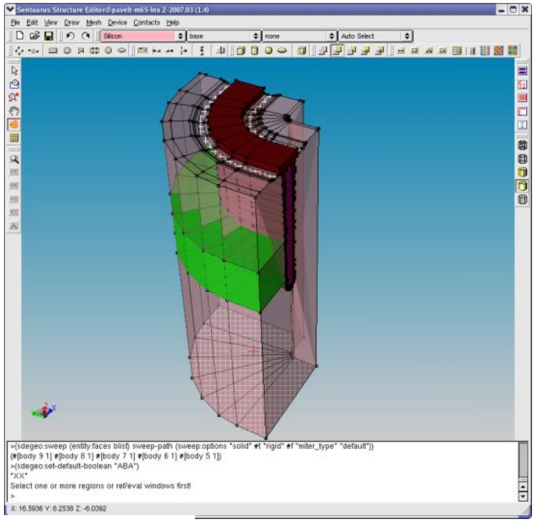




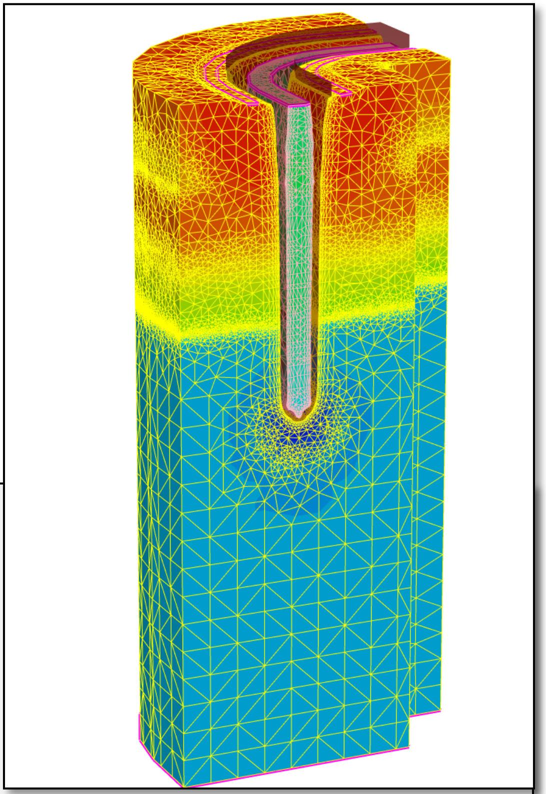
Advanced Tool Operations

2D geometry sweep with SDE / 2D doping sweep with SnMesh





Resulting 3D mesh/profile:



2D submesh:

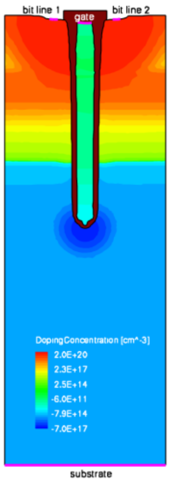
Definitions {

SubMesh “trench2D" {

Geofile = "trench2D.tdr"

}

}



Placements {

SubMesh “trench2D" {

Reference = " trench2D "

EvaluateWindow {

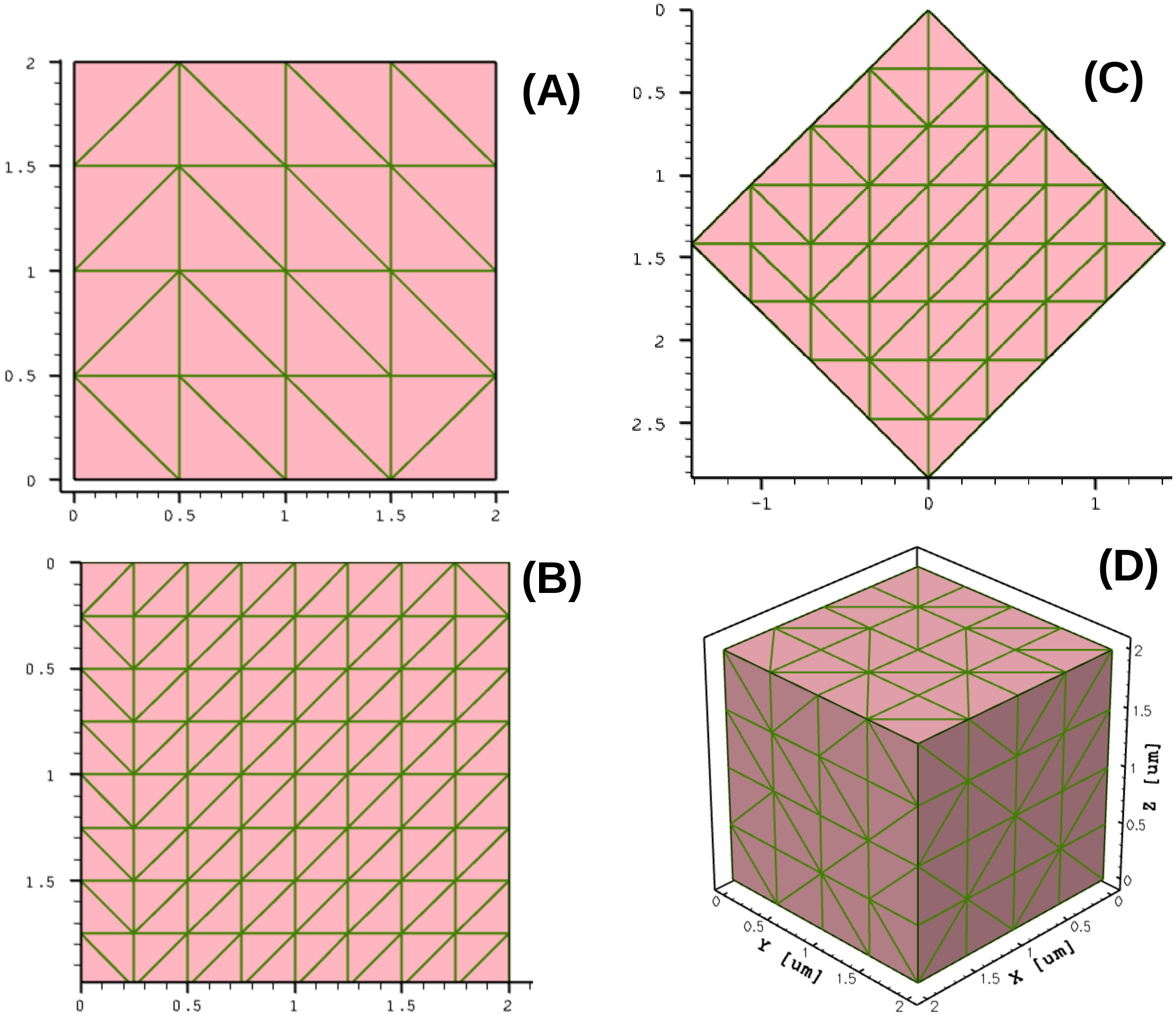
Element = SweepElement {

Base = Polygon [(0 20 3.3288) (8.2 20 3.3288)

(8.2 20 -20) (0 20 -20)]

Path = [(8.2 20 3.3288) (8.2 22 3.3288) (8.21 22.1 3.3288) …] }}}}

SnMesh - Quadtree/Octree Spatial Decomposition



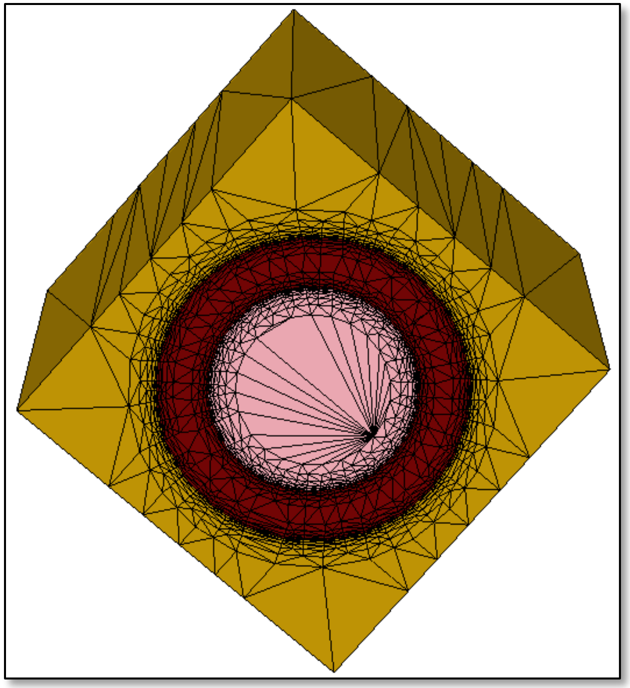
(A) Quadtree algorithm
- mesh step proportional to device size

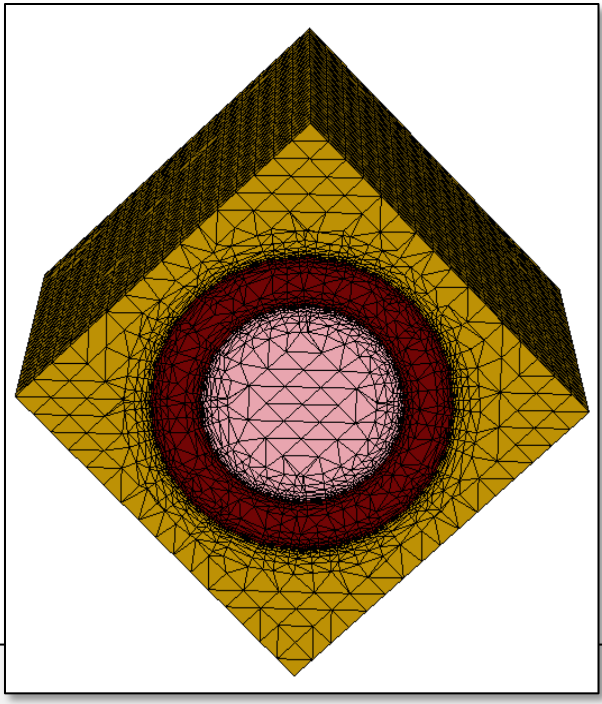
(B) Quadtree algorithm
- mesh step not proportional to device size

(C) Quadtree algorithm
- non axis-aligned boundary

(D) Octree algorithm - mesh step proportional to device size

Unified (octree/quadtree + normal offsetting) Meshing Algorithm

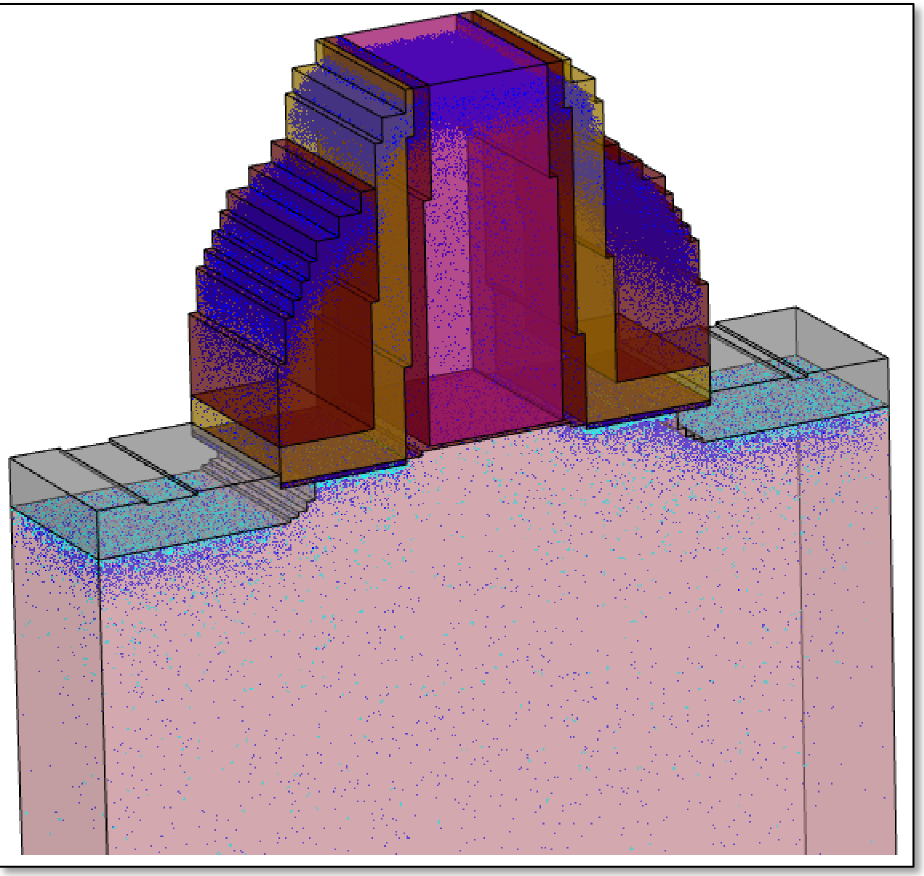




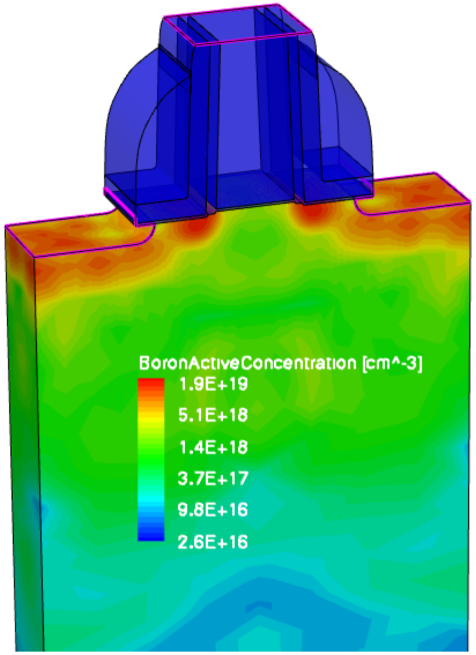
```
Offsetting {
  noffset material "Silicon" "Oxide" {
          hlocal=0.002
     }
     noffset material "Oxide" "Silicon" {
          hlocal=0.002
     }
}
```

```
Definitions {
     Refinement "R5" {
          MaxElementSize = ( 0.026 0.026 0.026 )
     }
}
Placements {
     Refinement "GDJ_RP" {
          Reference = "R5"
          RefineWindow = Cuboid [(-0.2 -0.2 0) (0.20 0.2 0.5)]
     }
}
```

Doping Deatomization

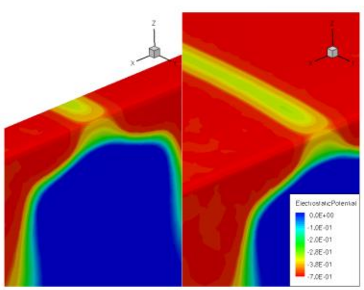


```
Particle "BoronParticles" {
  ParticleFile = "kmc_final.tdr"
  Species = "BoronActiveConcentration"
  ScreeningFactor = 3.5e6
  AutoScreeningFactor
  Normalization
}
```

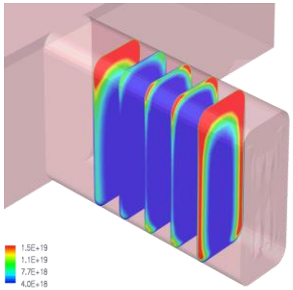


Sentaurus Device Simulator

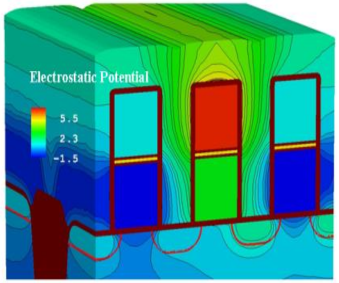
- General purpose multidimensional (2D/3D) device simulator
- Silicon, SiGe, Ge, SiC, III-V compounds (including III-N materials)
- Drift-diffusion, Hydrodynamic, Thermodynamic, and Monte Carlo transport
- Wide range of advanced physical models
  - Stress-dependent mobility enhancement
  - Quantization and random doping effects
  - Circuit mixed-mode, small-signal AC, Harmonic Balance
  - Variability Analysis



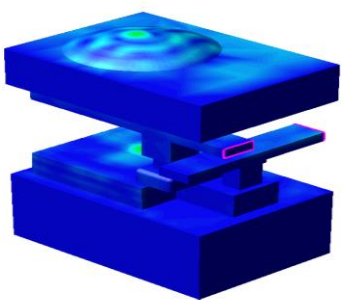
STI Narrow Width Effect



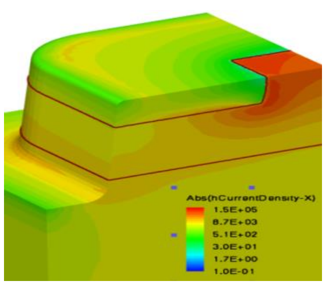
FinFET



NAND Flash

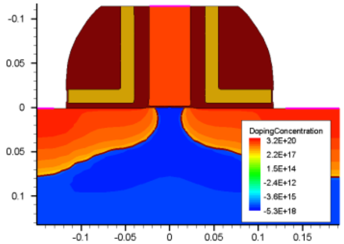


CMOS Image Sensor

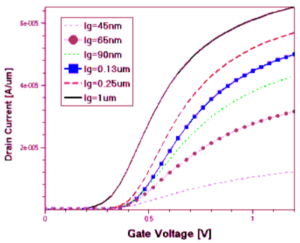


UMOS

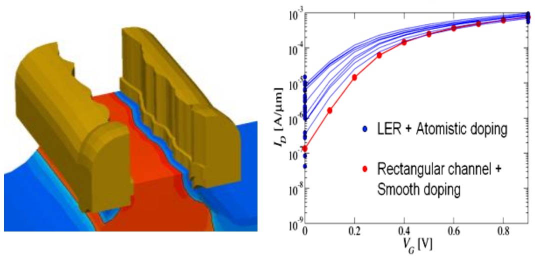
Sentaurus Device for CMOS



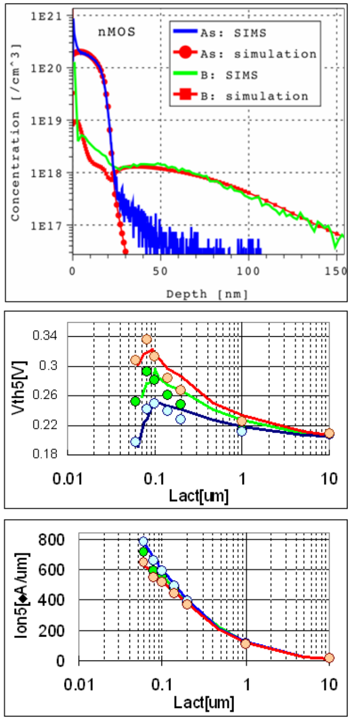
50nm NMOS



IdVg



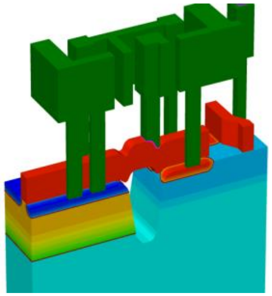
Line Edge Roughness Variability



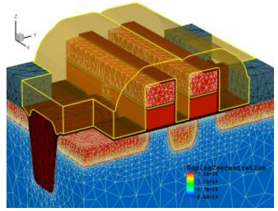
Calibration to SIMS, Roll-off and Ion

- Carrier quantization in the channel
- Hydrodynamic transport
- Noise analysis
- High-k dielectrics
- Mechanical stress and strain effects
- Stochastic geometry and doping variability
- Remote Coulomb scattering
- Advanced surface mobility modeling
- Non-local band-to-band and impact ionization
- Gate leakage
- Energy dependent energy relaxation time
- Degradation kinetics
- IFM based variability analysis

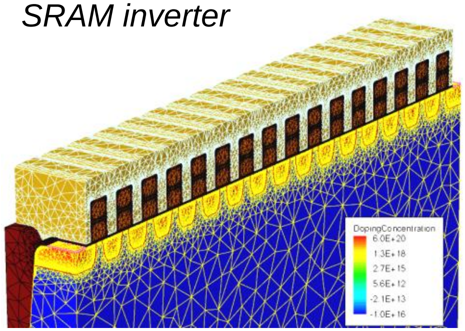
Sentaurus Device for Memory



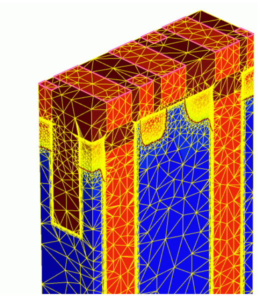
SRAM inverter



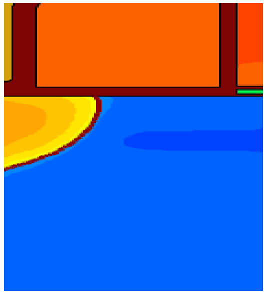
NOR Flash



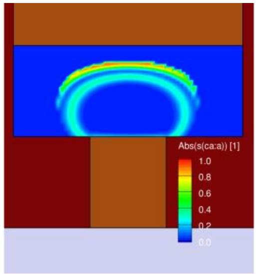
NAND Flash



DRAM Cell



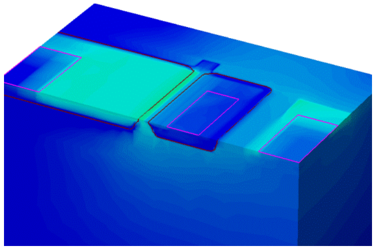
SONOS/NROM



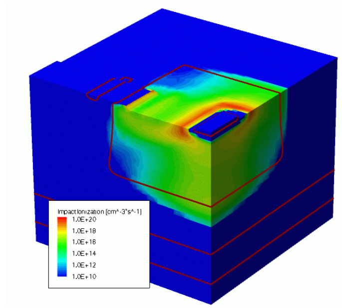
PRAM

- Carrier quantization in the channel
- Spherical Harmonic Expansion
- Non-local tunneling
- Hot Carrier Injection
- 3D capacitive effects
- Multi State Configuration including the state dependent physical models and parameters
- Cycling analysis
- Mixed-mode simulations
- Advanced surface mobility modeling
- Non-local band-to-band, TAT, and impact ionization
- Interface trap degradation

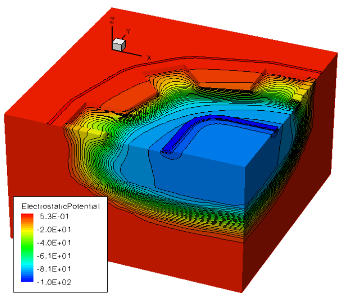
Sentaurus Device for Power



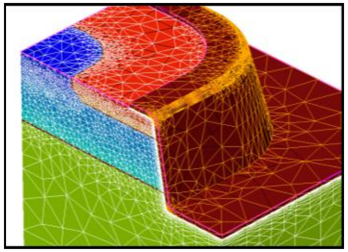
ESD Protection



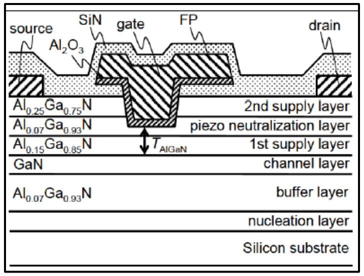
IGBT



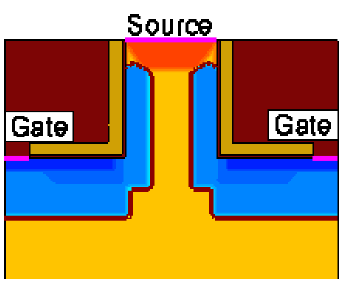
P-LDMOS



UMOS



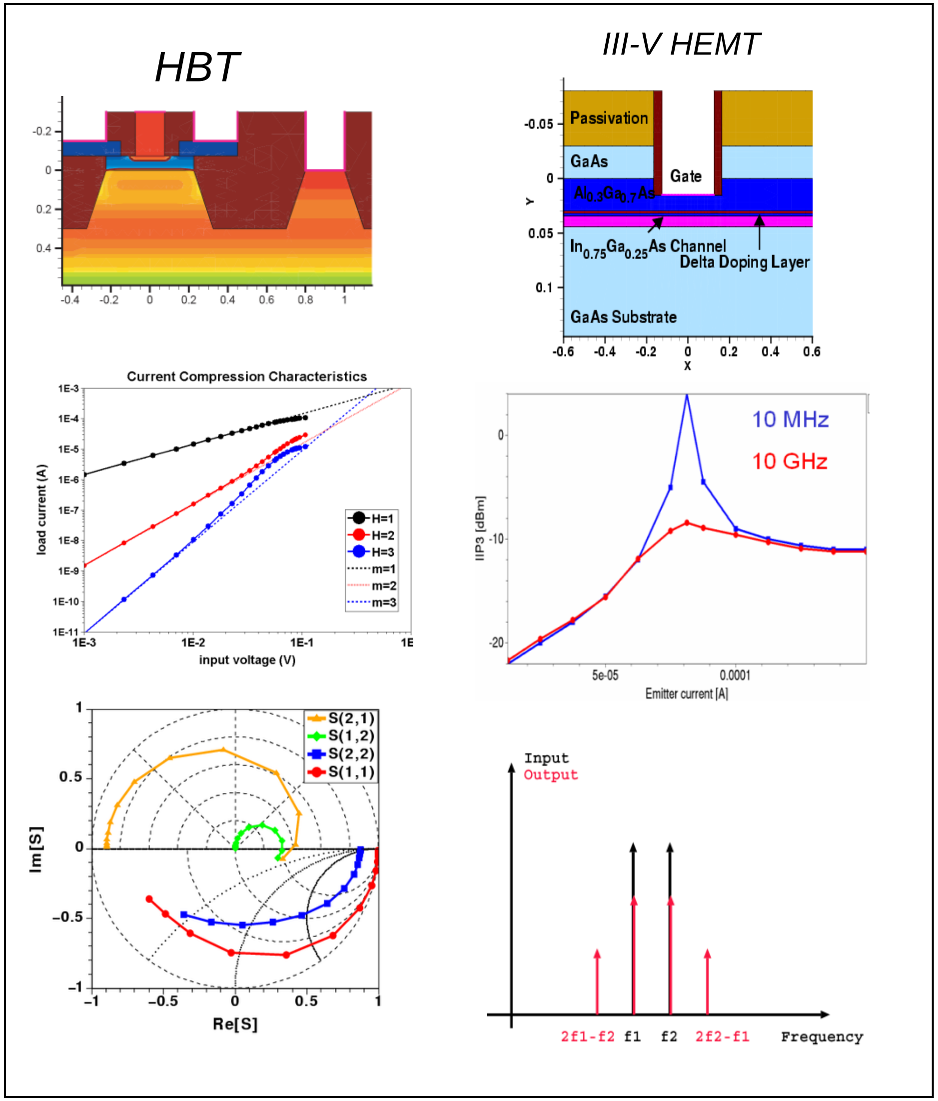
III-N HFET



SiC VJFET

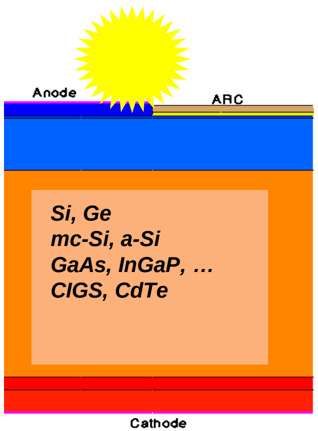
- Thermodynamic carrier transport
- 3D geometry effects
- Mixed-mode simulations including the circuit protective elements, represented by compact models
- Heat dependent kinetic model parameters
- Non-local gate tunneling
- Trapping dynamic
- Composition dependent model parameters
- Heterointerface carrier transport
- Carrier thermionic emission
- Carrier quantization in the channel
- Piezo and spontaneous polarization
- Doping Incomplete Ionization
- Material anisotropy

Sentaurus Device for RF

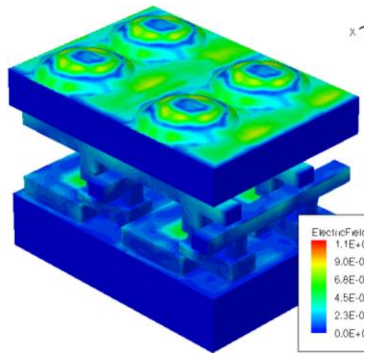


- Hydrodynamic transport
- Small-signal AC analysis
- Harmonic balance analysis
- Carrier quantization
- Bulk and interface traps
- Mechanical stress and strain effects
- Energy dependent energy relaxation time
- Anisotropy effects
- Composition dependent model parameters
- Non-local barrier tunneling
- Stress dependent models
- Polarization fields

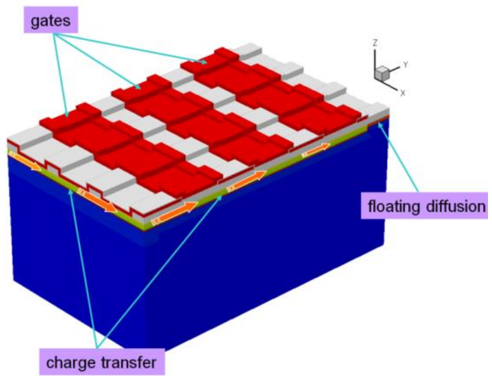
Sentaurus Device for Optics



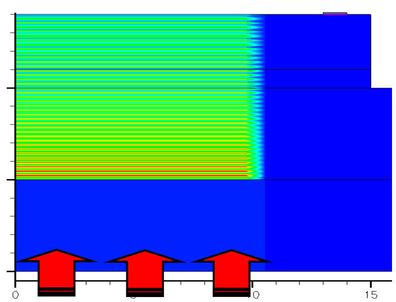
Solar Cells



CMOS Image Sensors



CCD

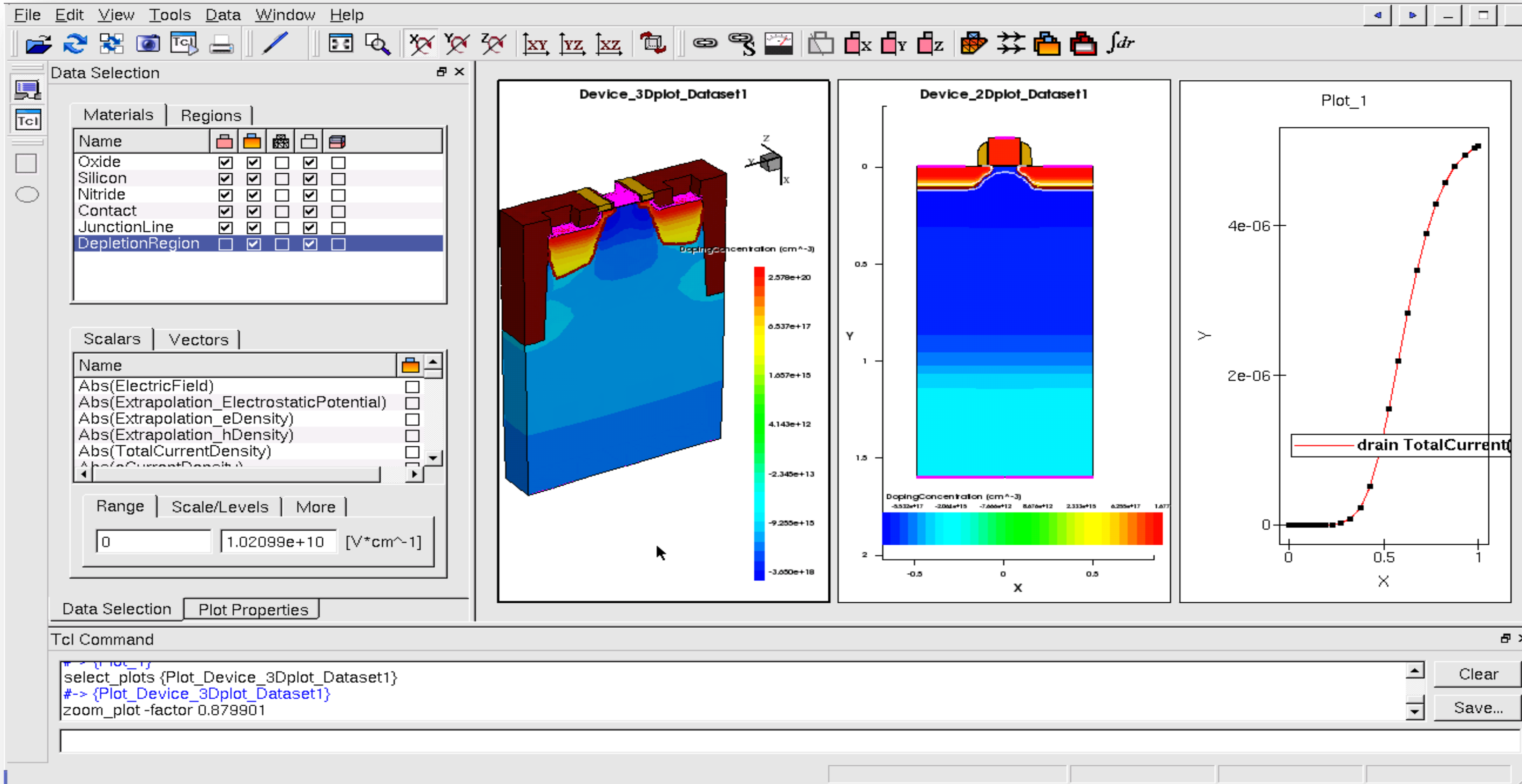


Photodetectors

- Drift-diffusion carrier transport
- Advanced optical solvers:
  - Transfer Matrix Method
  - Beam Propagation Method
  - Raytracing
  - FDTD Maxwell solver
- 3D geometry effects
- Mixed-mode simulations including the circuit periphery elements
- Carrier trapping
- Composition dependent model parameters
- Heterointerface carrier transport
- Advanced models for photon and free carrier absorption
- Organic semiconductors

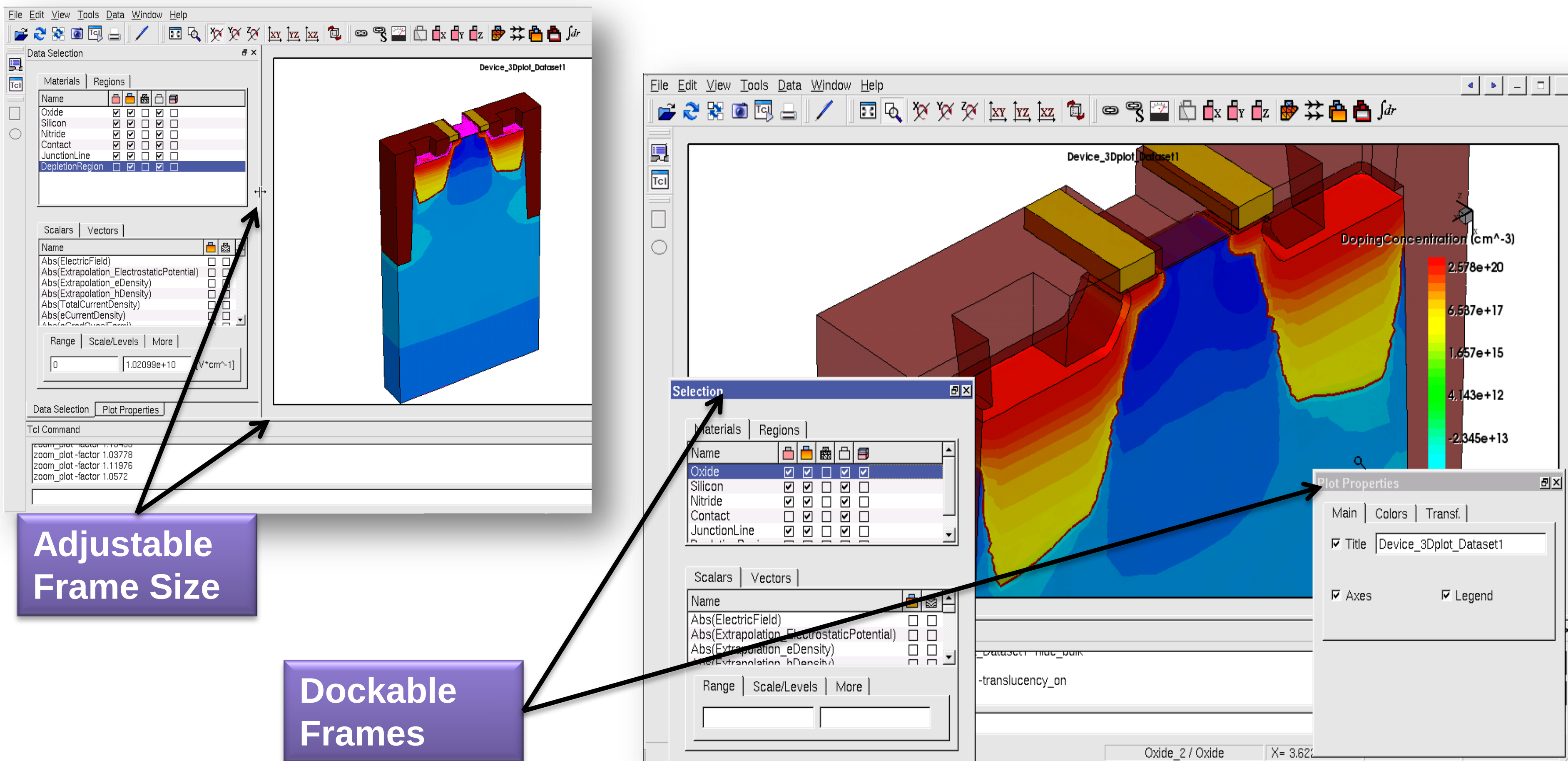
Sentaurus Visual - New TCAD Visualization Platform

- Visualization product for 1D, 2D and 3D plots and structures generated by all TCAD tools

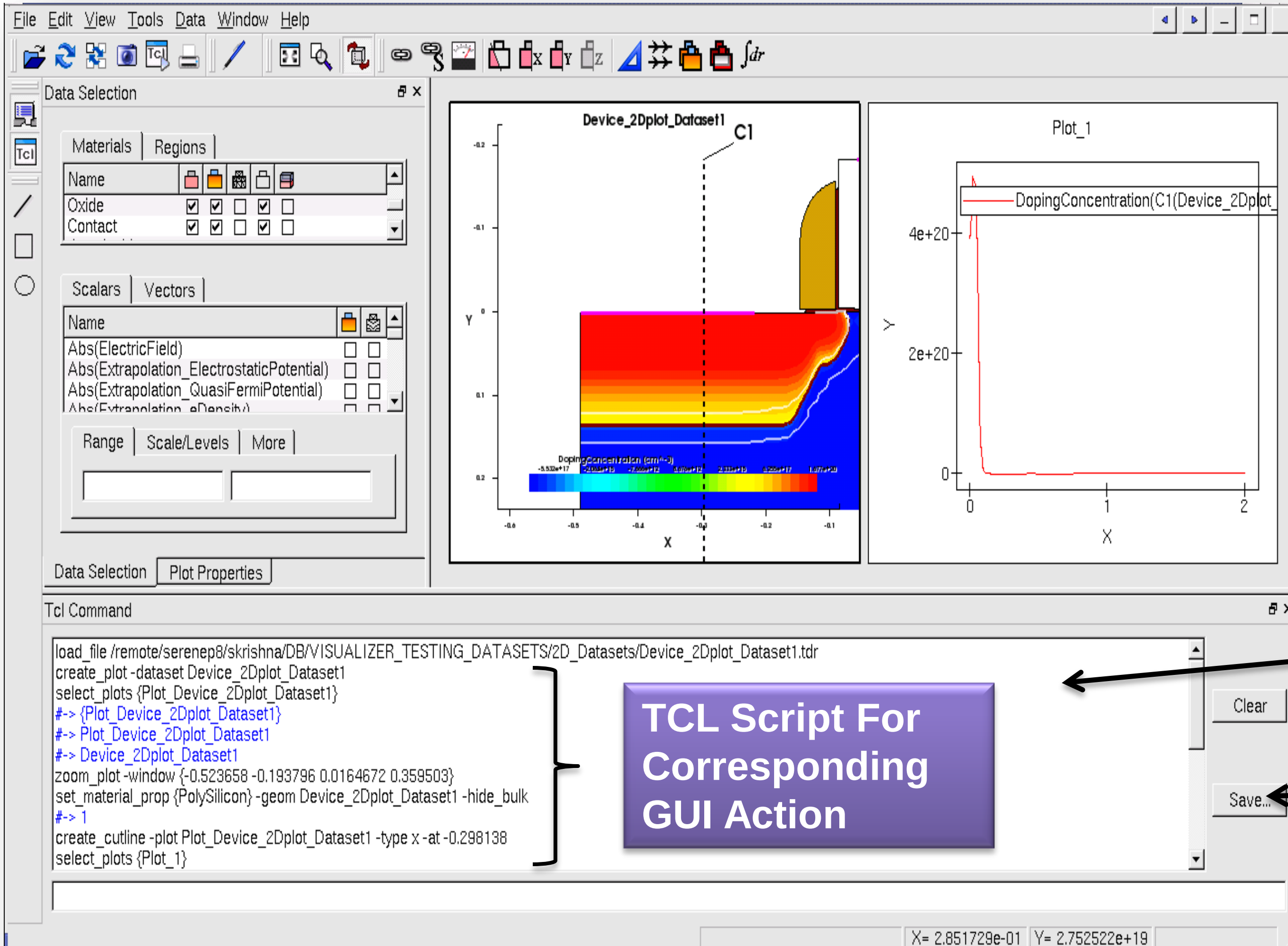


Sentaurus Visual - Enhanced GUI

- Better utilization of GUI real estate



Sentaurus Visual - Tcl Scripting Interface



- Powerful TCL Interface
- Consistent with Scripting Capabilities in other Sentaurus TCAD tools

Active TCL Command Window

Saving TCL Script to File

Sentaurus TCAD

Radiation Analysis

Radiation Environment

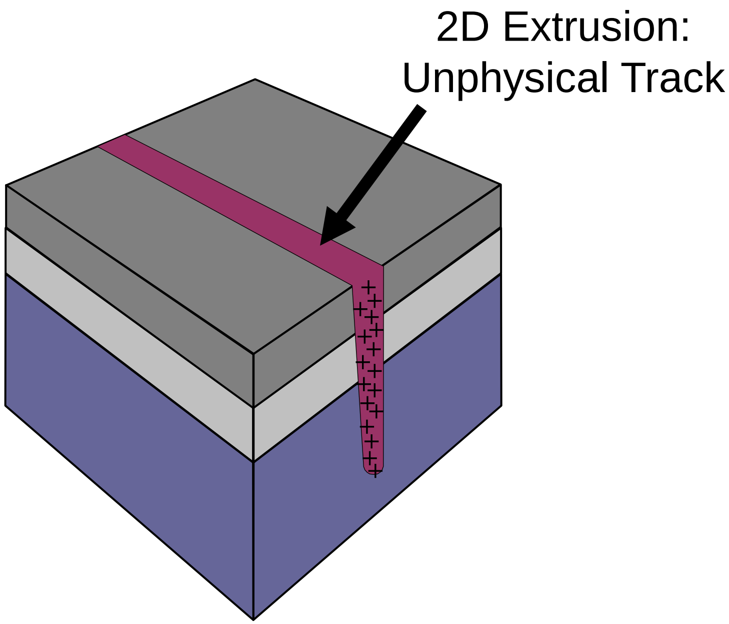
- Single Event
  - Due to single ionizing particle (alpha particle, heavy ion or neutron) , generation of electron-hole pairs in semiconductors
  - Leading to Soft-Error as Single Event Upset (SEU)
  - Leading to Hard-Error as Single Event Gate Rupture (SEGR), Latch-Up (SELU) or Breakdown (SEB)

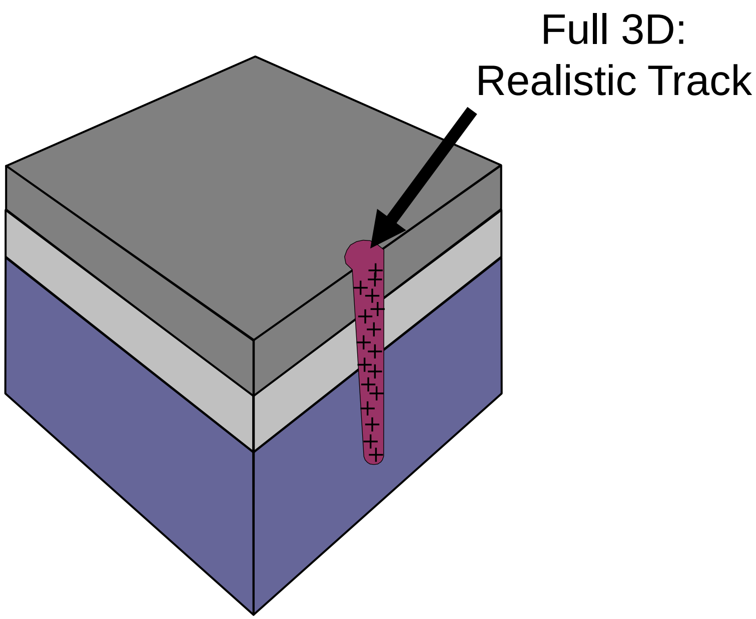
- Total Dose
  - Due to long radiation exposure (nuclear power, aerospace), resulting in trapped carriers in insulators
  - Leading to performance degradation (increased leakage current, threshold voltage shift)

Sentaurus Device Models: Particle Interaction

- Alpha Particles
  - Analytical description of the carriers generation depending on the incident particle energy
  - 3D cylindrical distribution
- Heavy Ion
  - Analytical description of the carriers generation depending on the incident ion
  - Spatially defined charge description through LET
  - 3D cylindrical distribution

2D vs 3D Description of Charge Track





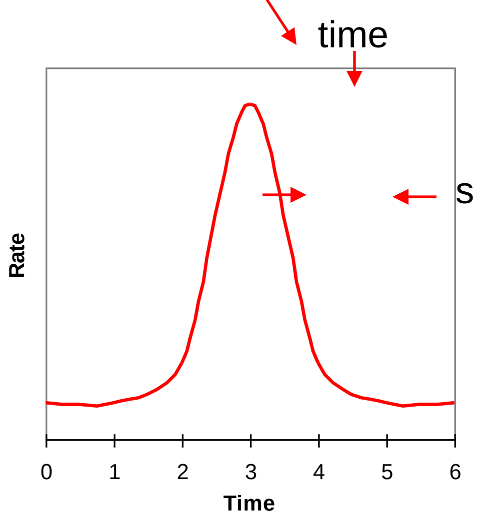
Sentaurus Device Heavy Ion Model

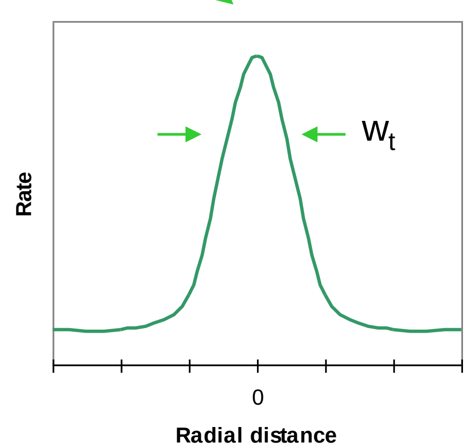
Electron-hole generation rate: $G(l,w,t) = T(t) \times R(w,l) \times G_{LET}(l)$

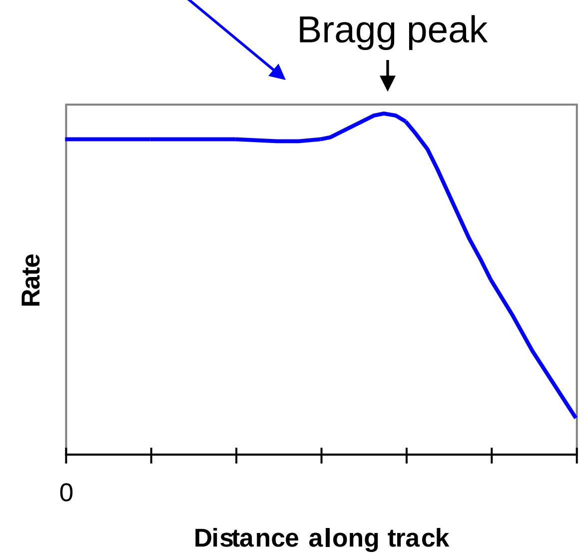
$$T(t) = \frac{2 \cdot \exp\left(-\left(\frac{t - time}{s_{hi}}\right)^2\right)}{s_{hi}\sqrt{\pi}\left(1 - erf\left(\frac{time}{s_{hi}}\right)\right)}$$

$$R(w,l) = \begin{cases} e^{-\left(\frac{w}{w_t(l)}\right)} \\ e^{-\left(\frac{w}{w_t(l)}\right)} \end{cases}$$

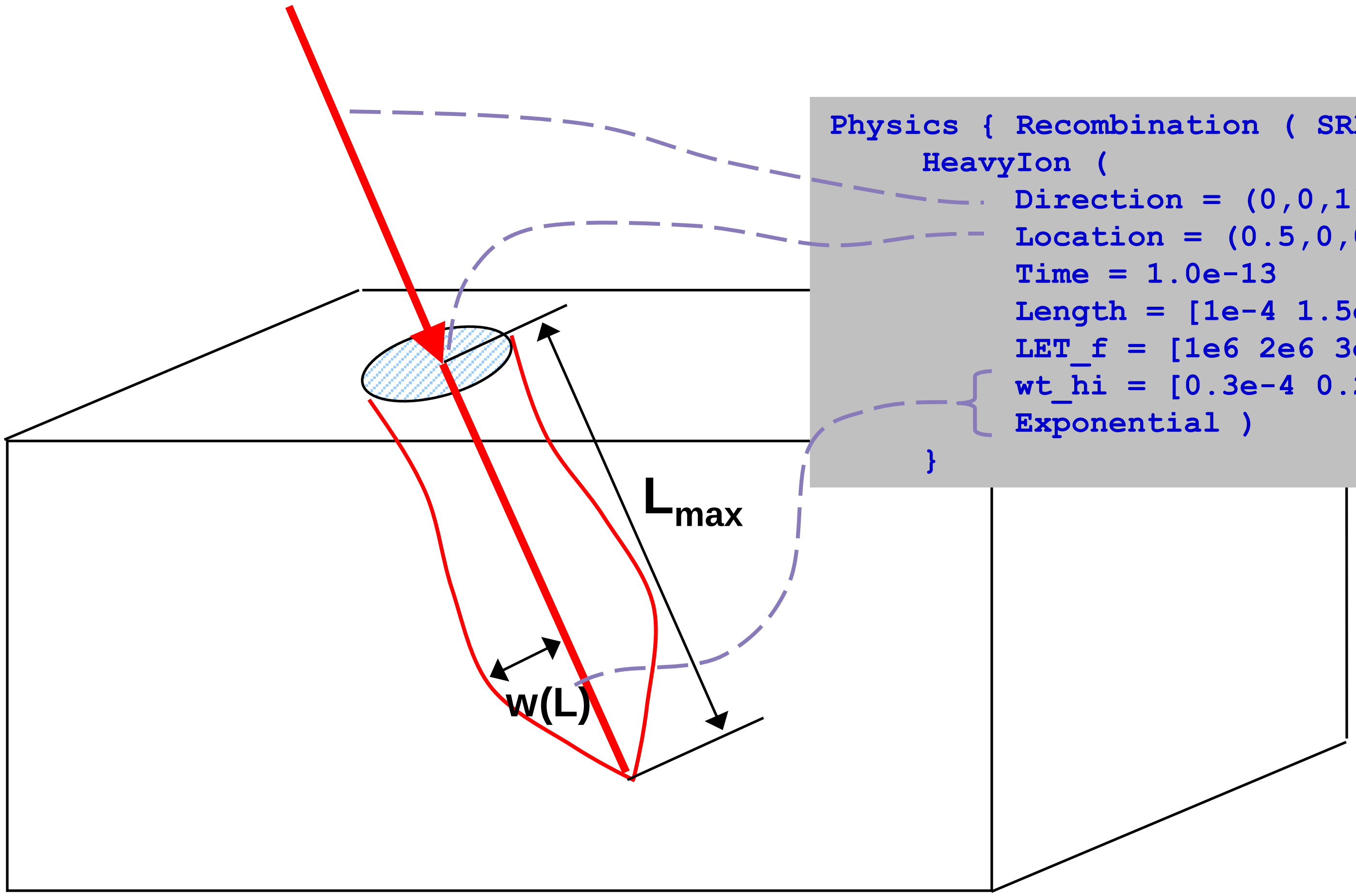
$$G_{LET}(l) = a_1 + a_2 \times l + a_3 e^{a_4 \times l} + k'\left[c_1 \times (c_2 + c_3 \times l)^{c_4} + LET\_f(l)\right]$$







Simulation of Charge Track



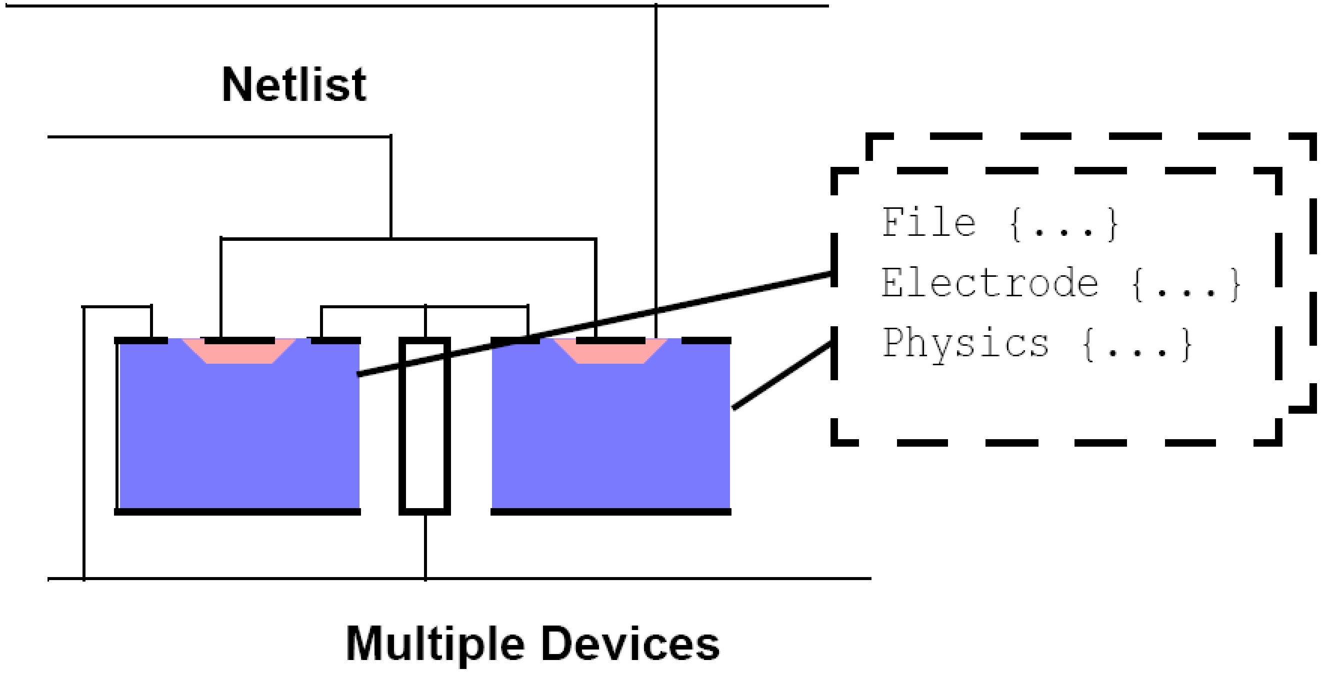

```
Physics { Recombination ( SRH(DopingDep) )
     HeavyIon (
          Direction = (0,0,1)
          Location = (0.5,0,0.7)
          Time = 1.0e-13
          Length = [1e-4 1.5e-4 1.6e-4 1.7e-4]
          LET_f = [1e6 2e6 3e6 4e6]
          wt_hi = [0.3e-4 0.2e-4 0.25e-4 0.1e-4]
          Exponential )
     }
```

Models for Total Dose Radiation

- Electric-Field Dependent Yield Function
- Self-Consistent Trapping Kinetics in Oxide:
  - Standard V-model based on carrier concentration
  - Proprietary J-model based on carrier current
- Spatial Distribution of Traps
  - Region or interface-wise
  - User defined profile
- Arbitrary Energy Spectra of Traps
- Electric-Field Dependent Cross Section
- Thermal Ionization of Traps

Mixed-Mode Simulation

- Sentaurus Device is a device and circuit simulator
- Allows numerical devices to be embedded in SPICE netlist



Mixed-Mode Compact Models

- Standard SPICE Models
  - BJT
  - Berkeley SPICE 3 Version 3F5 models
  - BSIM1, BSIM2, BSIM3, BSIM4
  - B3SOI
  - MESFET
- User-Defined
  - Compact model interface (CMI) available for user-defined models.
  - Implemented in C++ and linked to executable at run-time

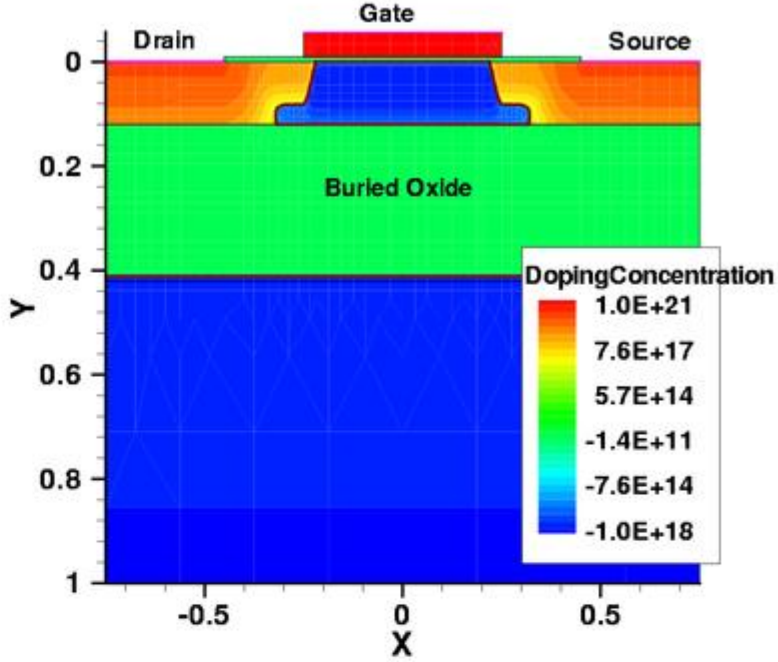
Sentaurus Advantages for Rad-Hard

- 1D / 2D / True 3D
- DC, AC, Transient
- Most Advanced Transport Models in Semiconductors and Insulators
- Mixed-Mode: Numerical and SPICE Models
- Robust Numerical Algorithms
- Parallel Solvers
- Dynamic Memory Allocation
- Physical Model Interface

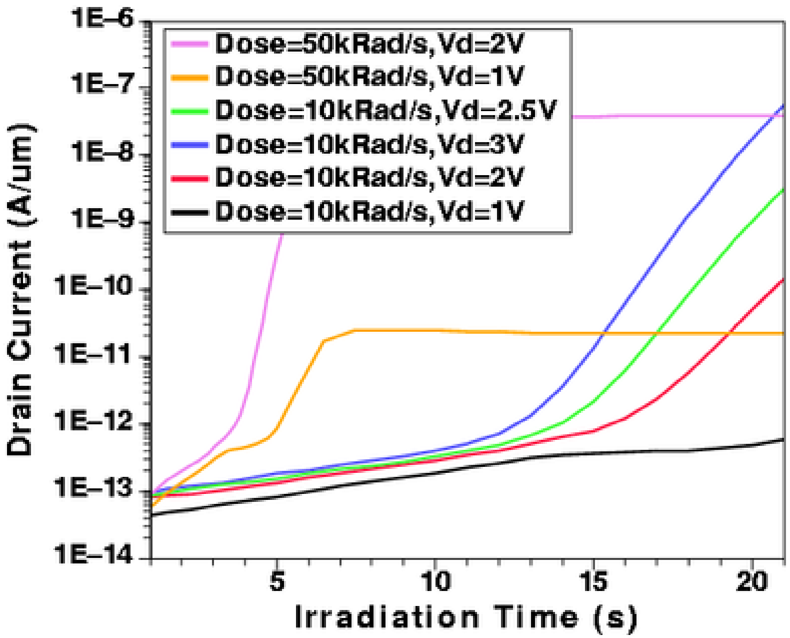
2D Application Examples

Total Dose Effect: SOI nMOSFET

SOI nMOS transistor structure



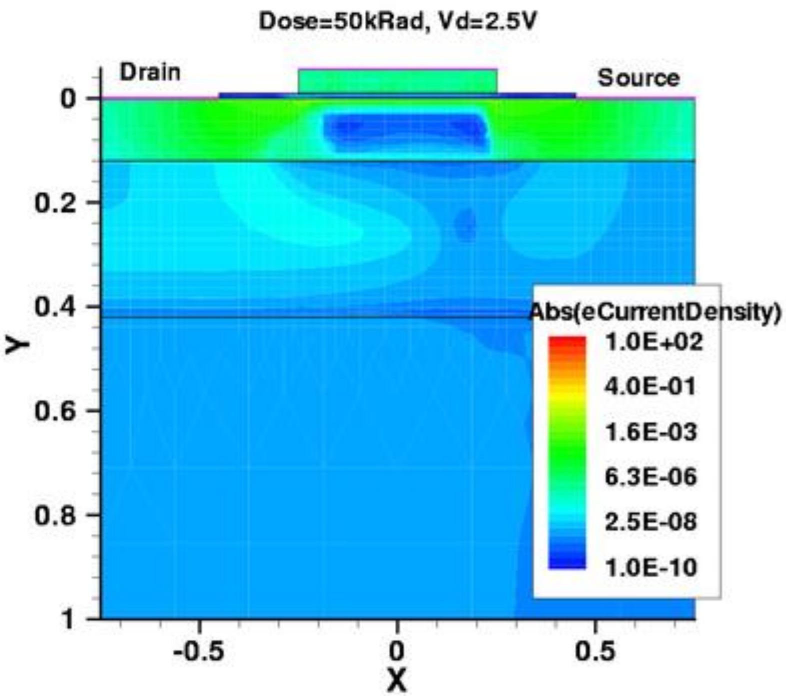
Drain current vs. irradiation time

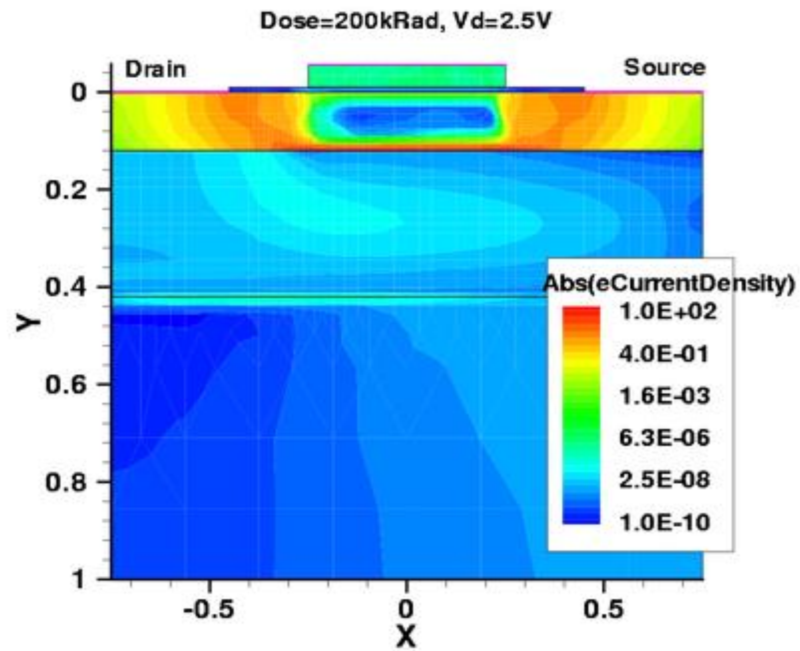


The leakage current increases with the dose and drain bias showing electric field dependence

Total Dose Effect: SOI nMOSFET

Electron Current Density in SOI Device after Irradiation

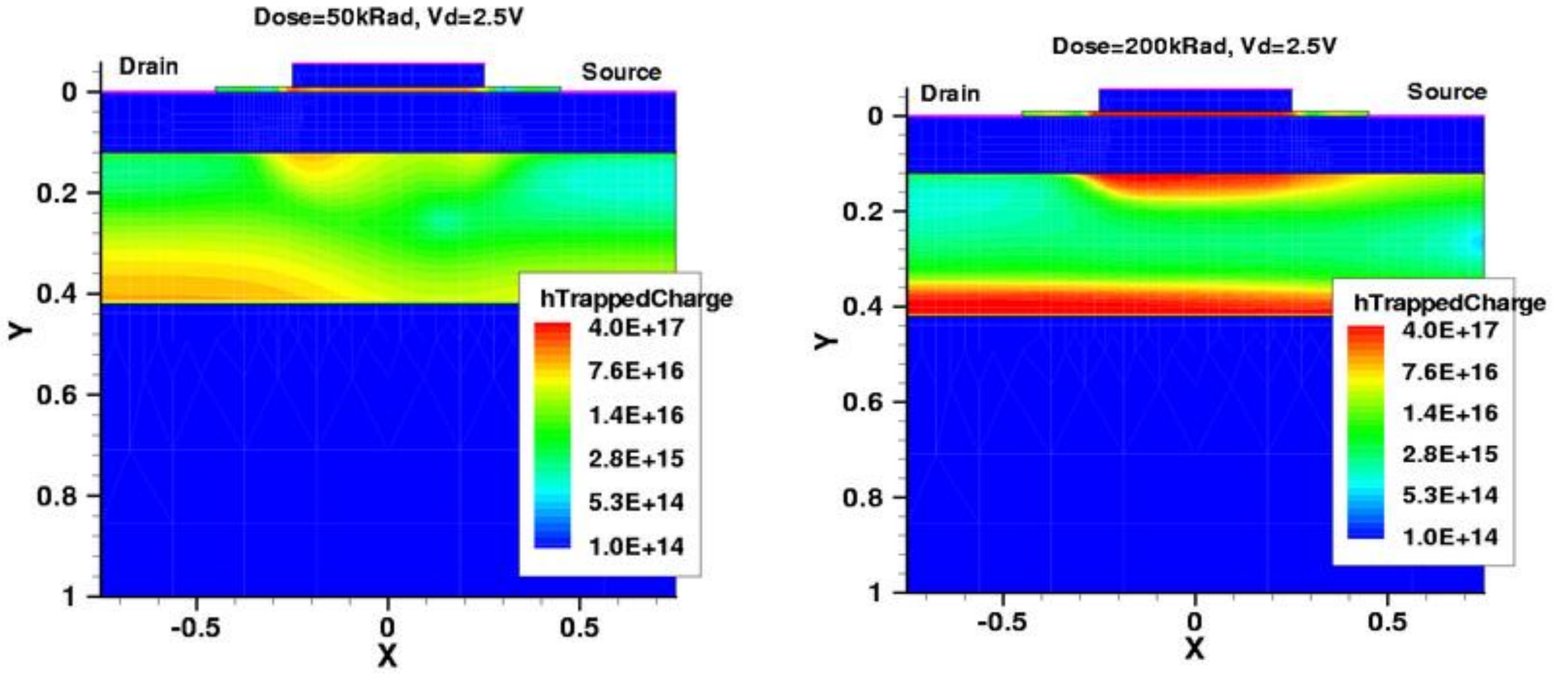




Expected back-channel in irradiated SOI nMOS devices is observed

Total Dose Effect: SOI nMOSFET

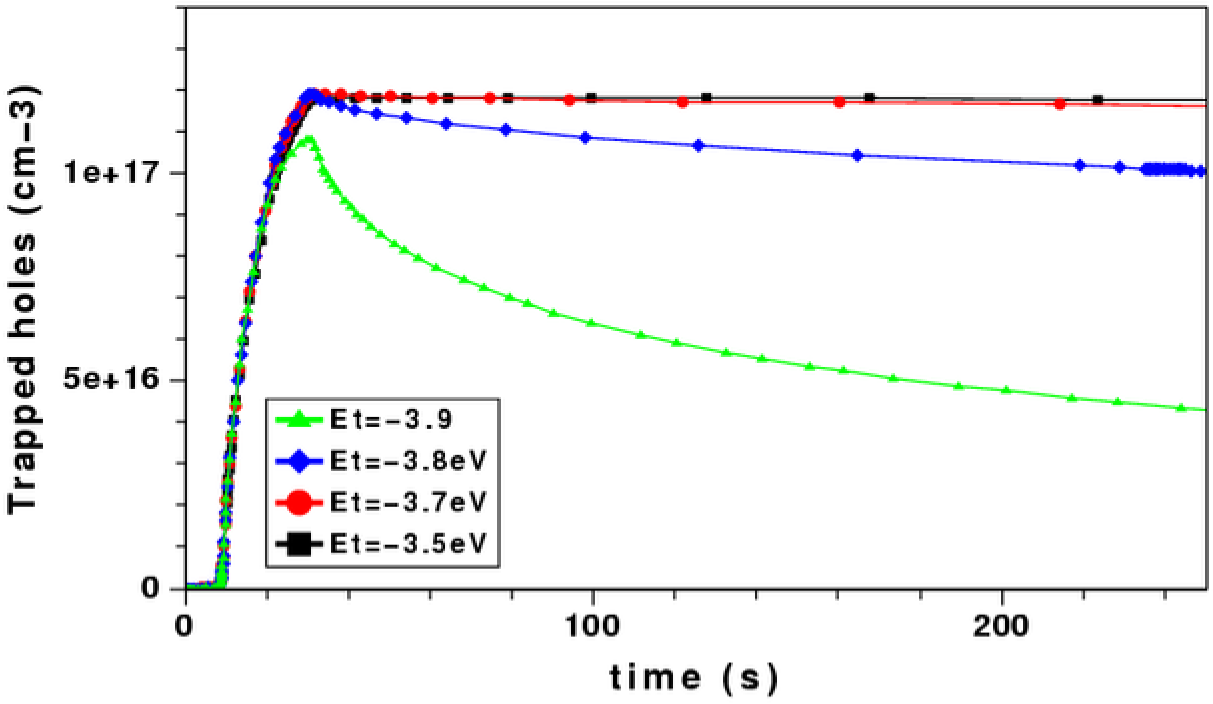
Trapped Hole Distribution in Irradiated Device



Because of self-consistent and field-dependent trapping kinetics, trapped hole distribution strongly depends on electric field

Total Dose Effect: SOI nMOSFET

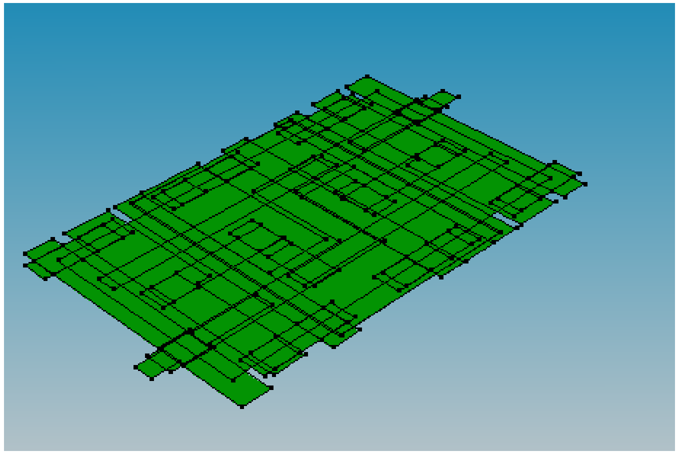
Transient Evolution of Trapped Hole Density after Irradiation



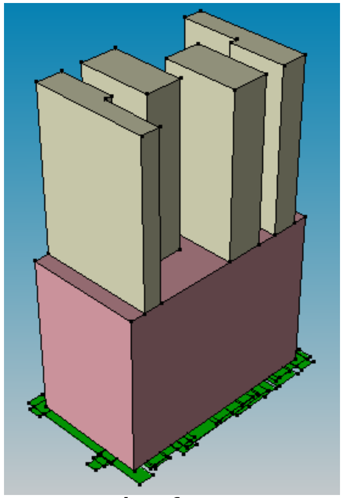
Sentaurus Device enables the modeling of de-trapping, depending on the energetic distribution of traps

3D Application Examples

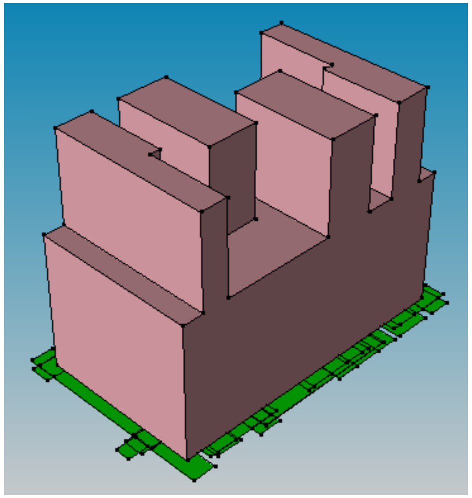
Structure Generation



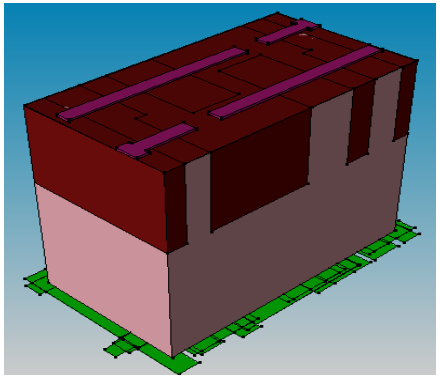
Loaded Layout



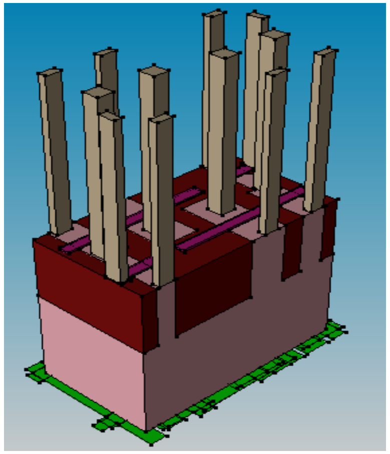
Resist for STI



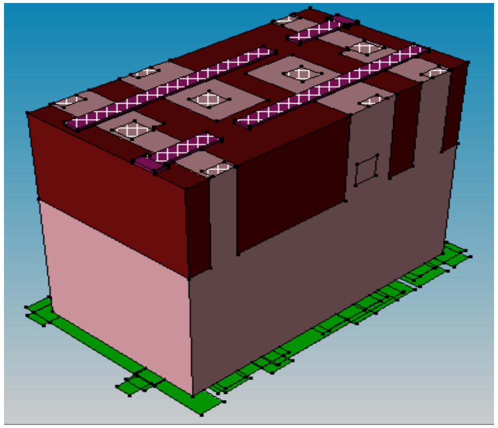
Silicon etching



STI formation (oxide filling) and
Polysilicon / gate oxide generation



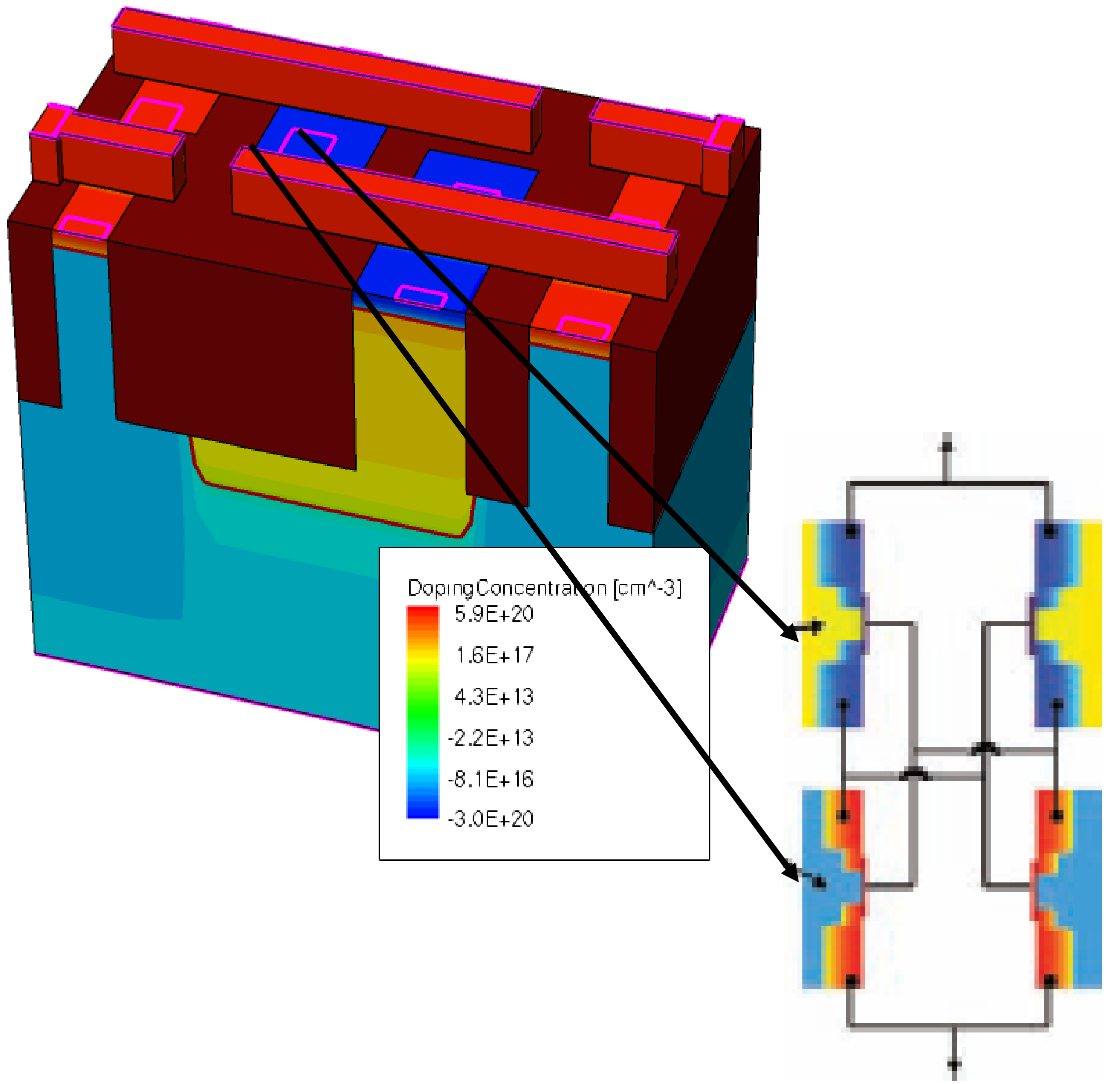
Metal generation for contacts



Final boundary structure

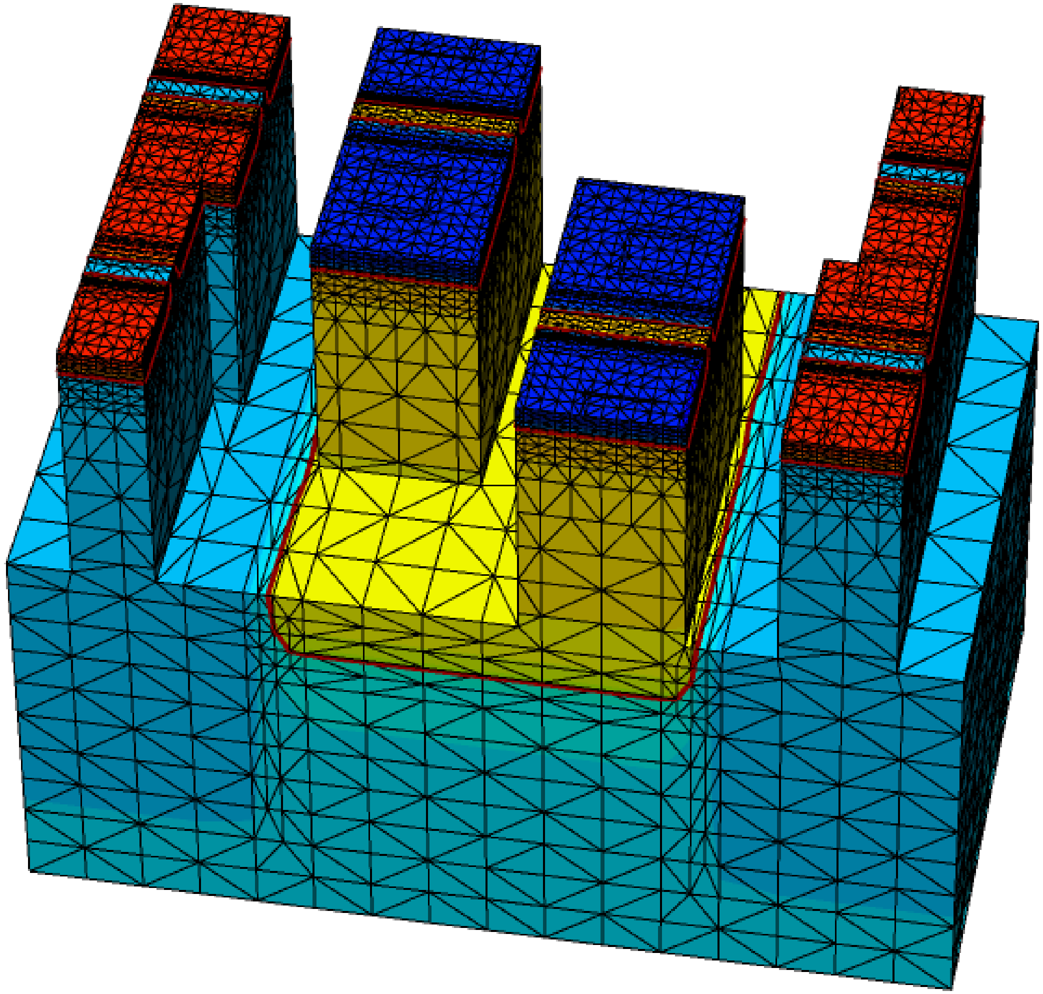
Doping Definition

- Constant doping profile in Polysilicon and Pwell
- Analytical doping profile (Gaussian) in the Source/Drain of NMOS and PMOS Transistors
- Analytical doping profile (Gaussian) in the channel of NMOS and PMOS Transistors
- Analytical doping profile (Gaussian) in the access drain (bit line) and access gate (word line).



Meshing

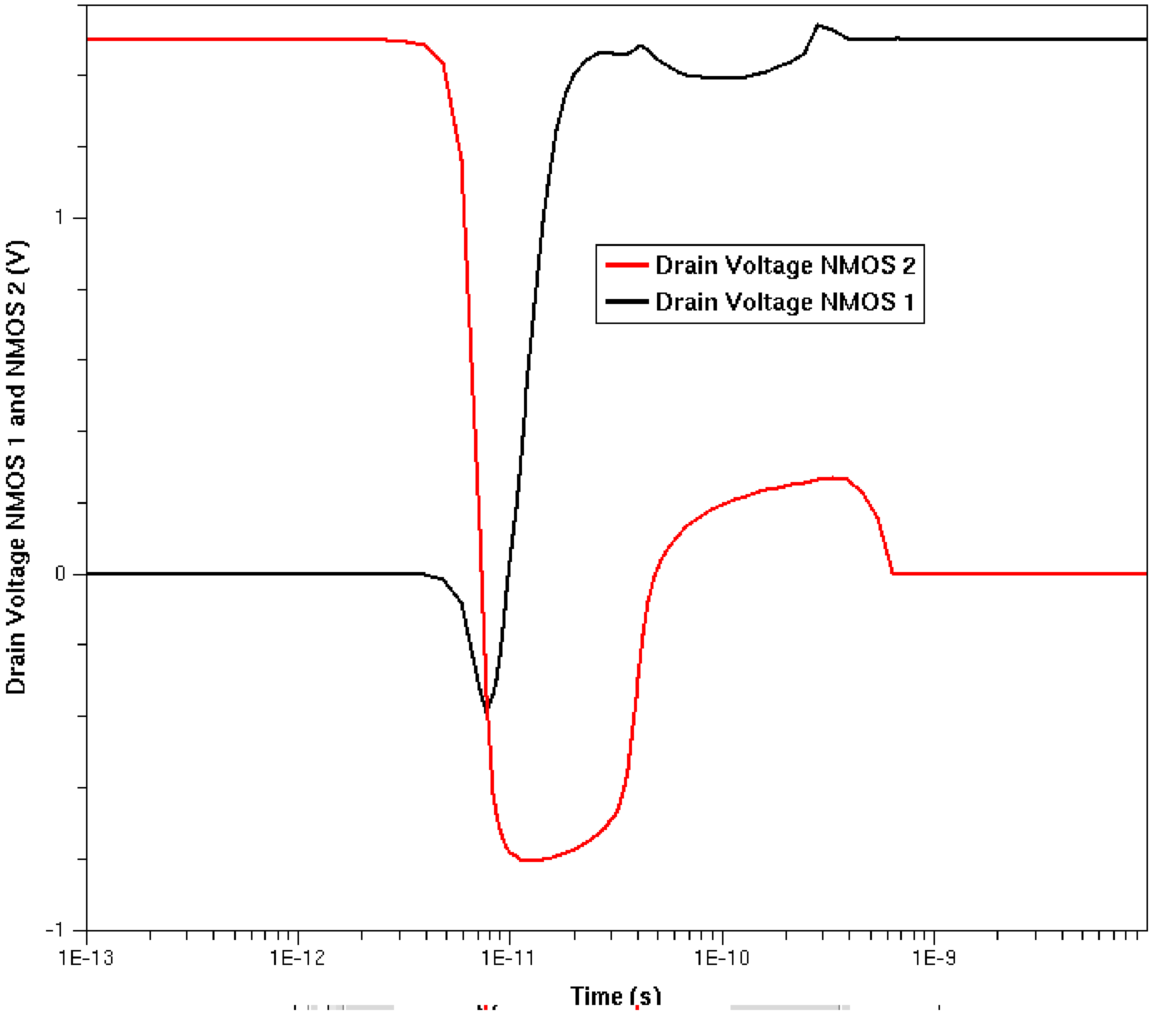
- Meshing strategy:
  - Refinement on doping (junctions refinement)
  - Refinement at Silicon / Gate Oxide interface
- Refinement in the channel of NMOS and PMOS Transistors.
  - Relaxed mesh inside the substrate



- Mesh statistics:
  - Mesh nodes number: 31825
  - Meshing time: 114 s

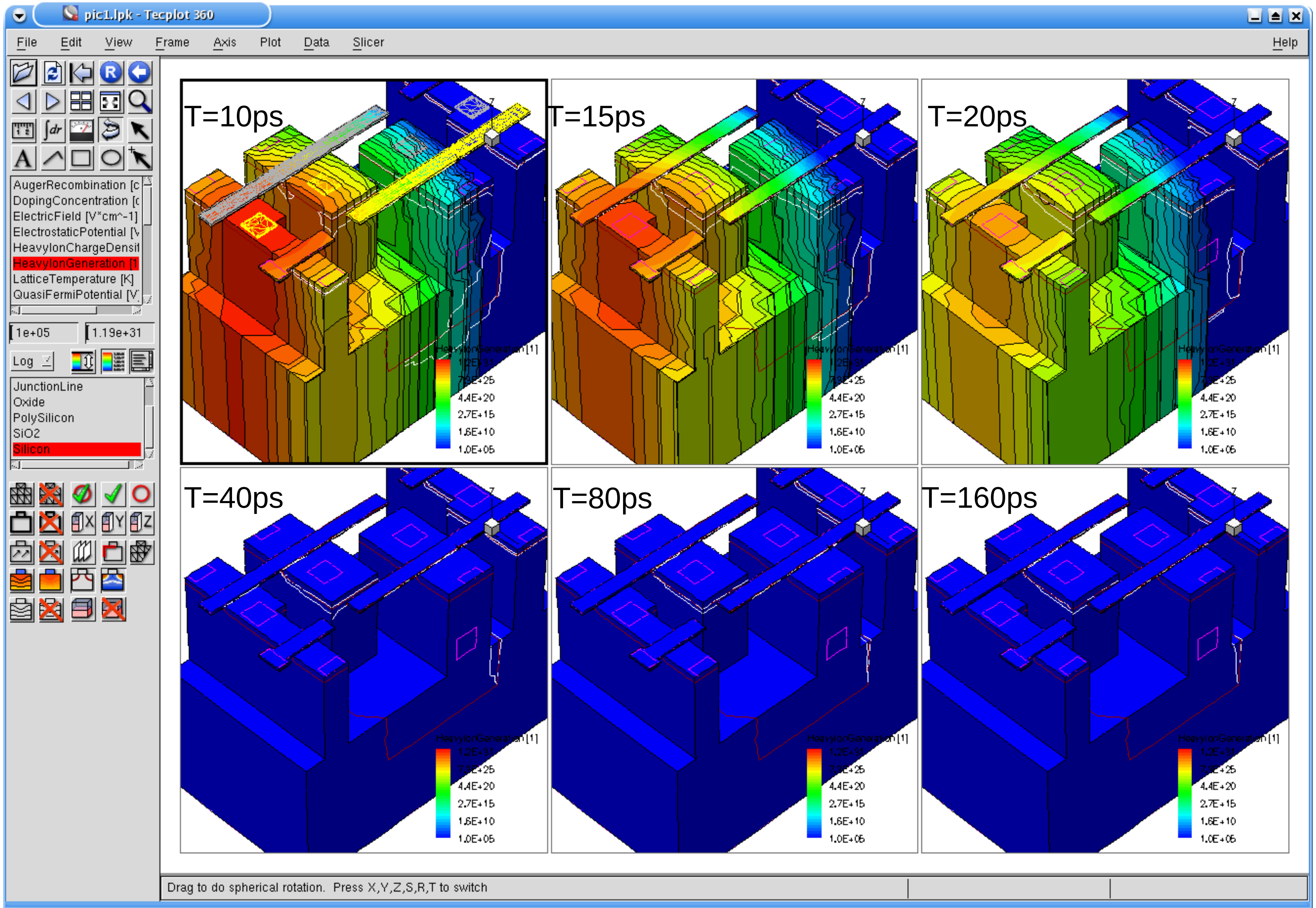
Bit Flipping

- At t=1e-13s Vds(nmos2)=1.5V and Vds(nmos1)=0V.
- The peak of the Gaussian Distribution of Heavy ion is at 1e-11s.
- At t=1e-8s, Vds(nmos1)=1.5V and Vds(nmos2)=0V.
- The SRAM cell switched states



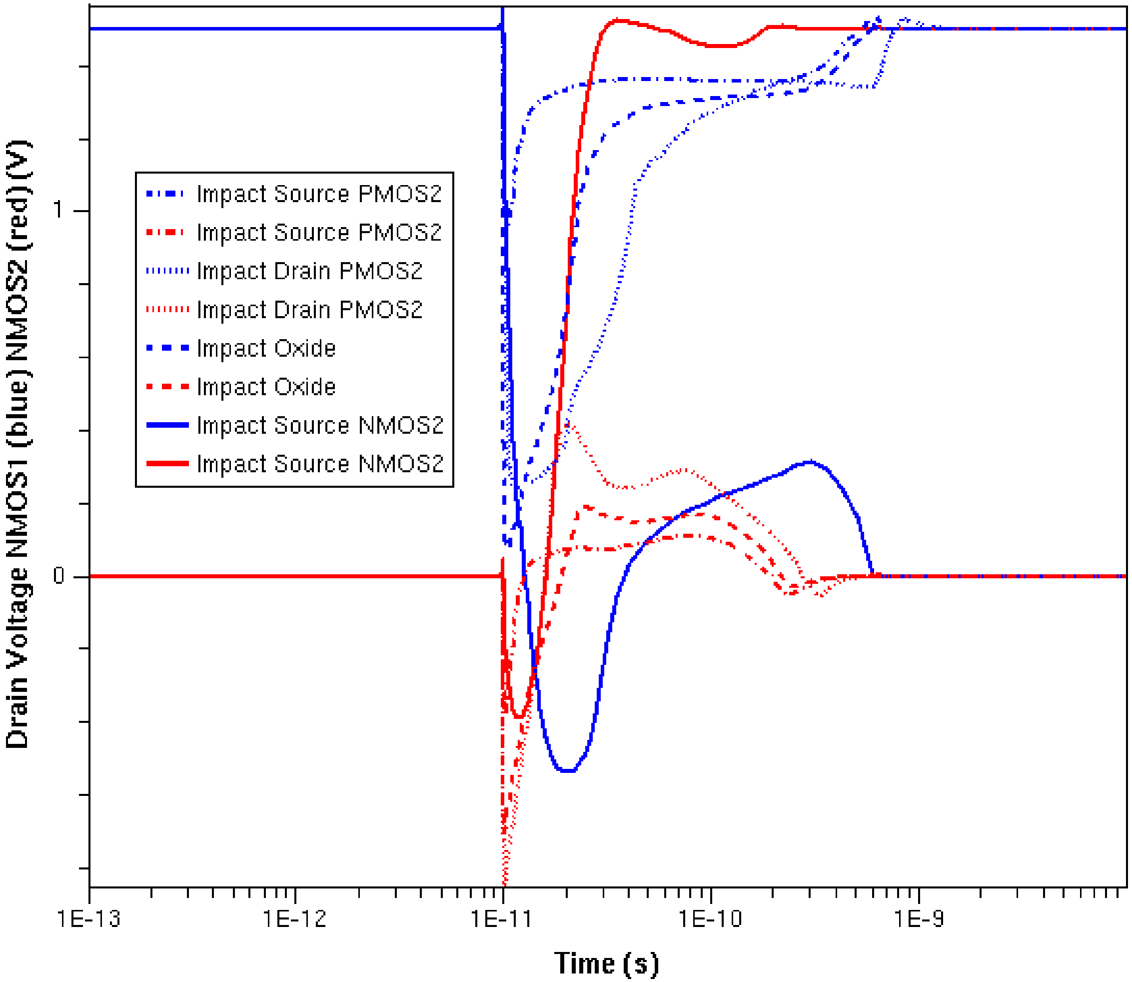
Node voltages versus time for NMOS drains as a result of a single event strike. The SRAM cell switched states

Generation Rate from Particle Strike



Dependence on Impact Points

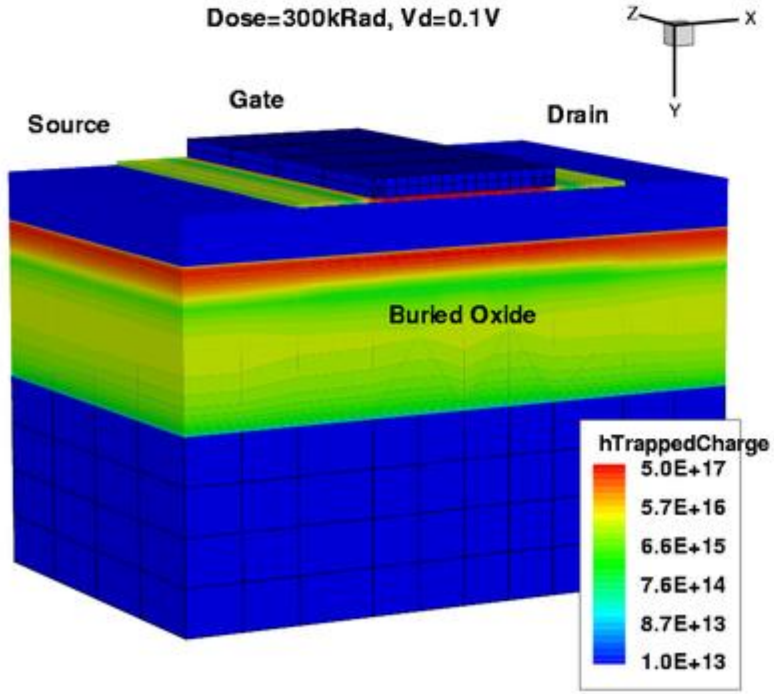
- The heavy ion direction is set to (0, 0, -1).
- Four different heavy ions impact points are simulated:
  - Source NMOS2
  - Source PMOS2
  - Drain PMOS2
  - Oxide
- **The SRAM cell does not switches states anymore for impact points in Source & Drain PMOS2 and in the oxide.**

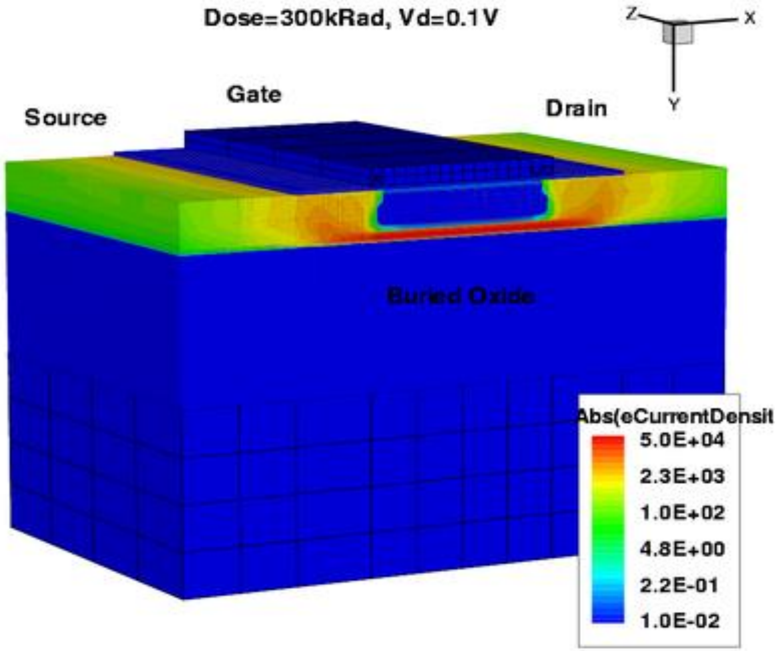


Node voltages versus time for NMOS drains as a result of a single event strike. Depending on the impact point ,the SRAM cell switched states

Total Dose Effect: 3D SOI nMOSFET

Trapped Hole and Electron Current Distributions in 3D SOI nMOS after 300kRad Irradiation

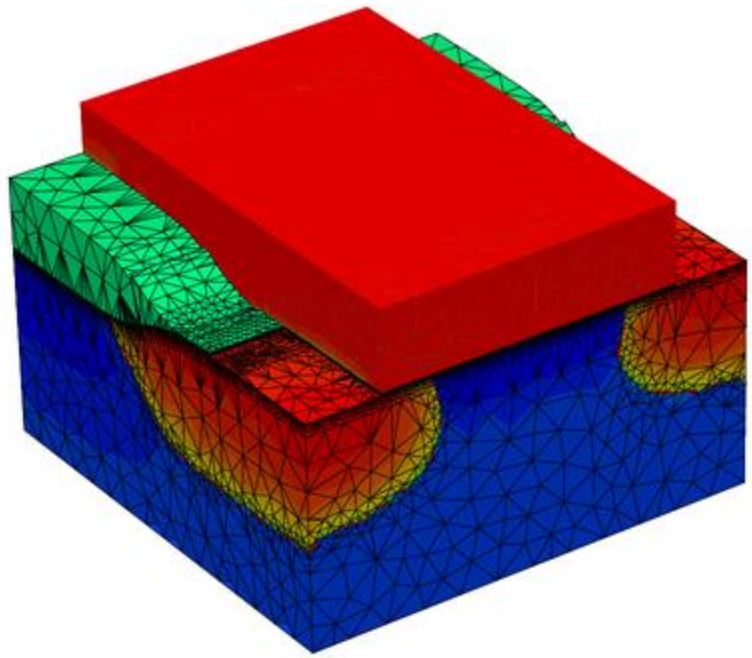




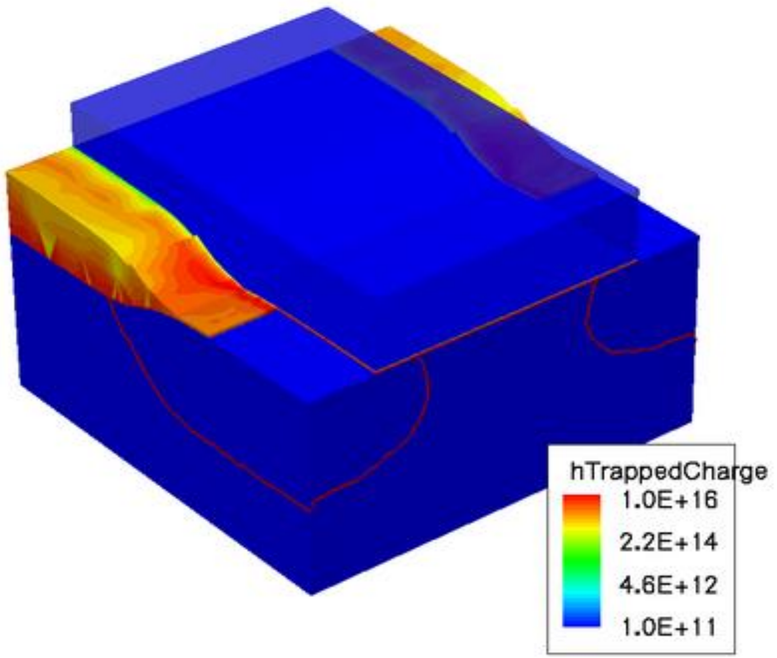
Expected trapped hole profile in the buried oxide and induced back-channel are observed in 3D

Total Dose Effect: 3D nMOS w/ LOCOS

Noffset meshing of 3D MOS with LOCOS



Trapped hole density after 10kRad irradiation

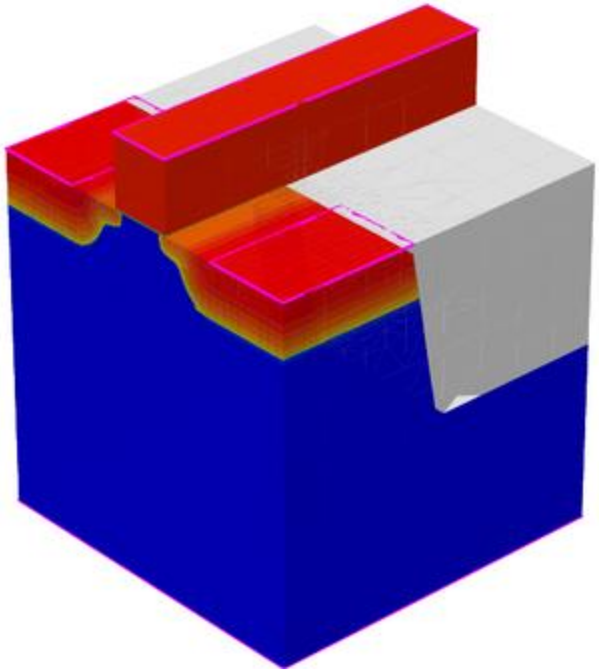


Noffset3D, normal offsetting mesh, creates fine grid along the interfaces where traps are located

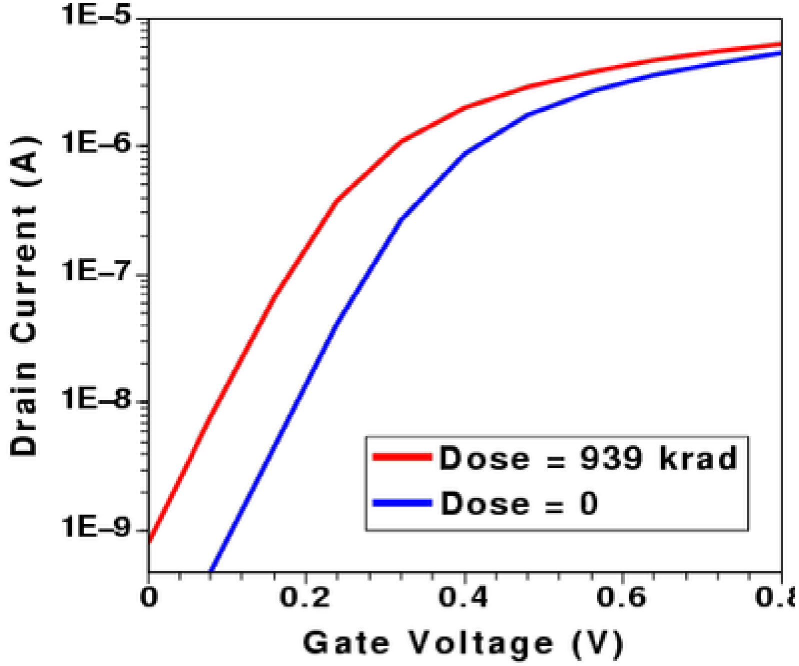
Total Dose Effect: 3D Trench MOSFET

Threshold Voltage Shift

Geometry and Doping



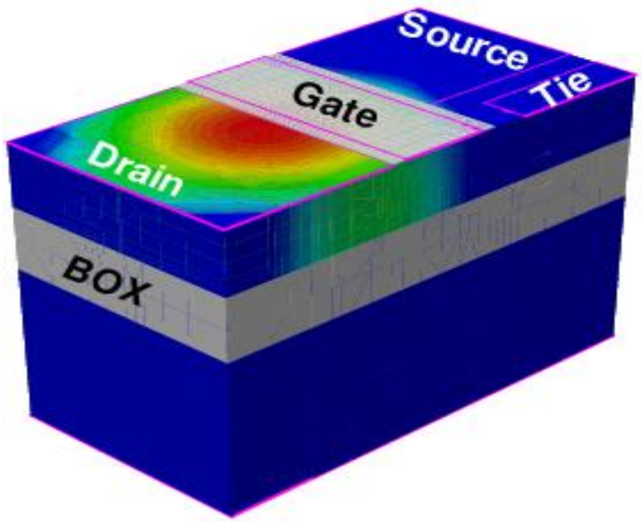
Drain Current vs. Gate Voltage



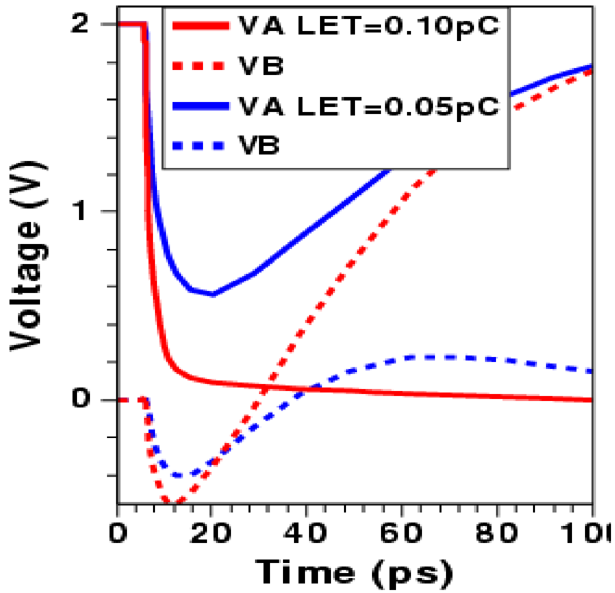
CMOS SOI

SEU: SOI SRAM Cell Upset

3D charge deposition profile



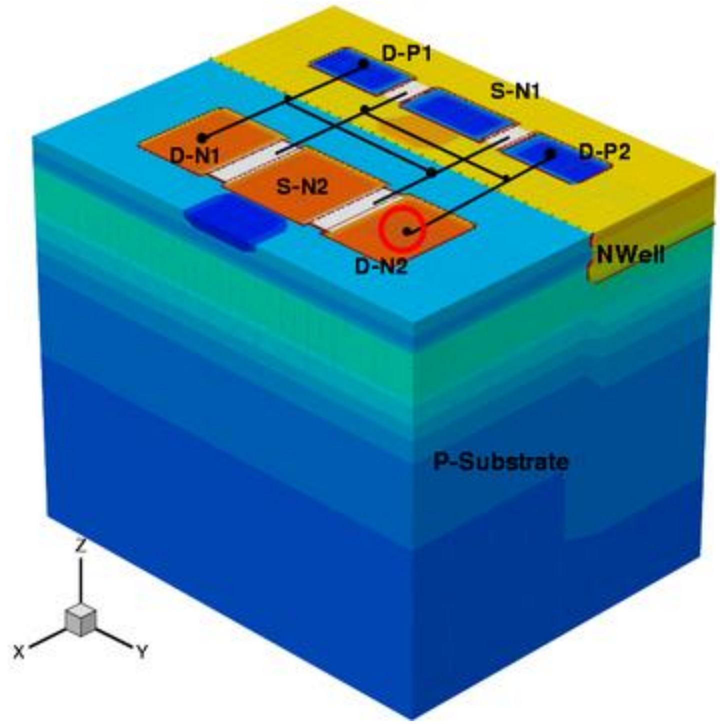
Voltage response for different ion energies



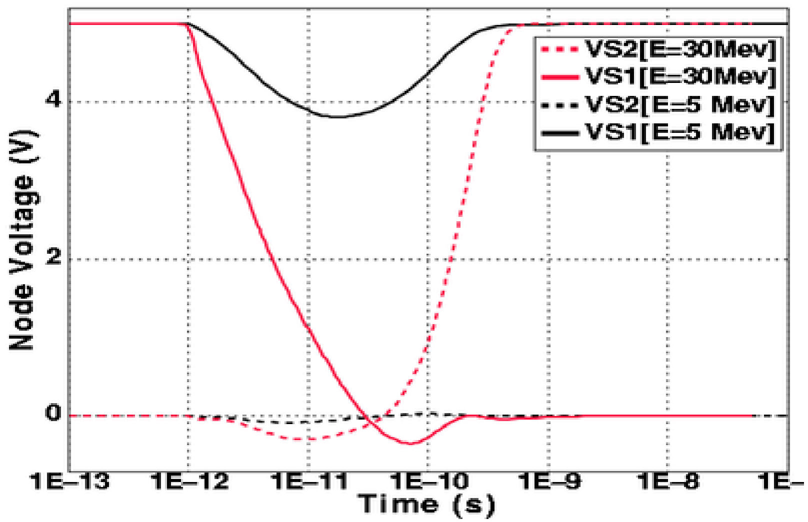
SEU can be accurately modeled using a mixed-mode approach including part of the system as SPICE elements

SEU: 3D SRAM Cell Upset

3D SRAM structure



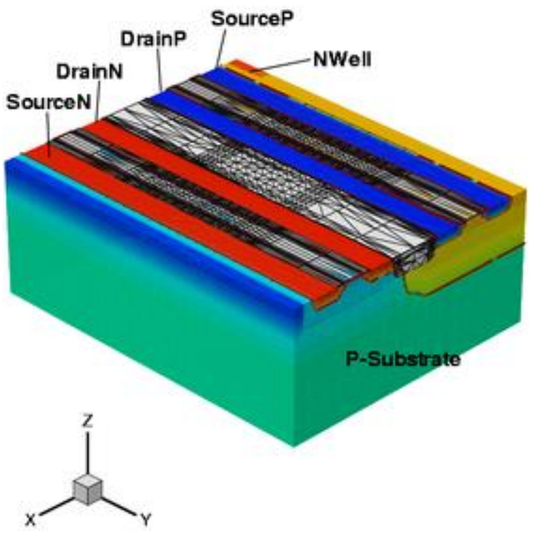
Node voltage response for 2 heavy ion energies



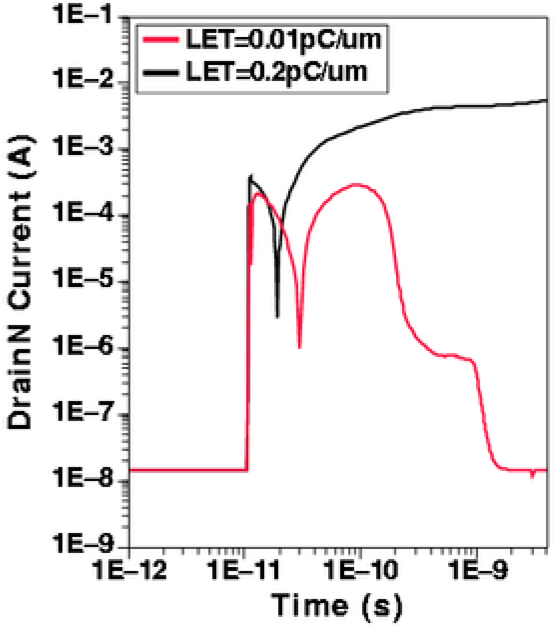
As expected, the three dimensional SRAM flips depending on the incident particle energy, the ion strikes into the drain of the off-nMOS

SEU: CMOS Inverter Latch-up

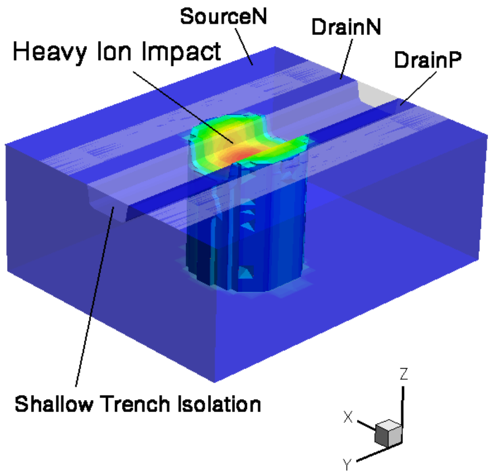
CMOS inverter structure



Current response for 2 LETs



Ion impact on CMOS structure



Because of parasitic bipolar effects in CMOS structure, the device latches up when incident particle energy is high enough

Thank You

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