Simulation of Photodetectors in Synopsys TCAD

SIMDET 2025

Synopsys TCAD Team

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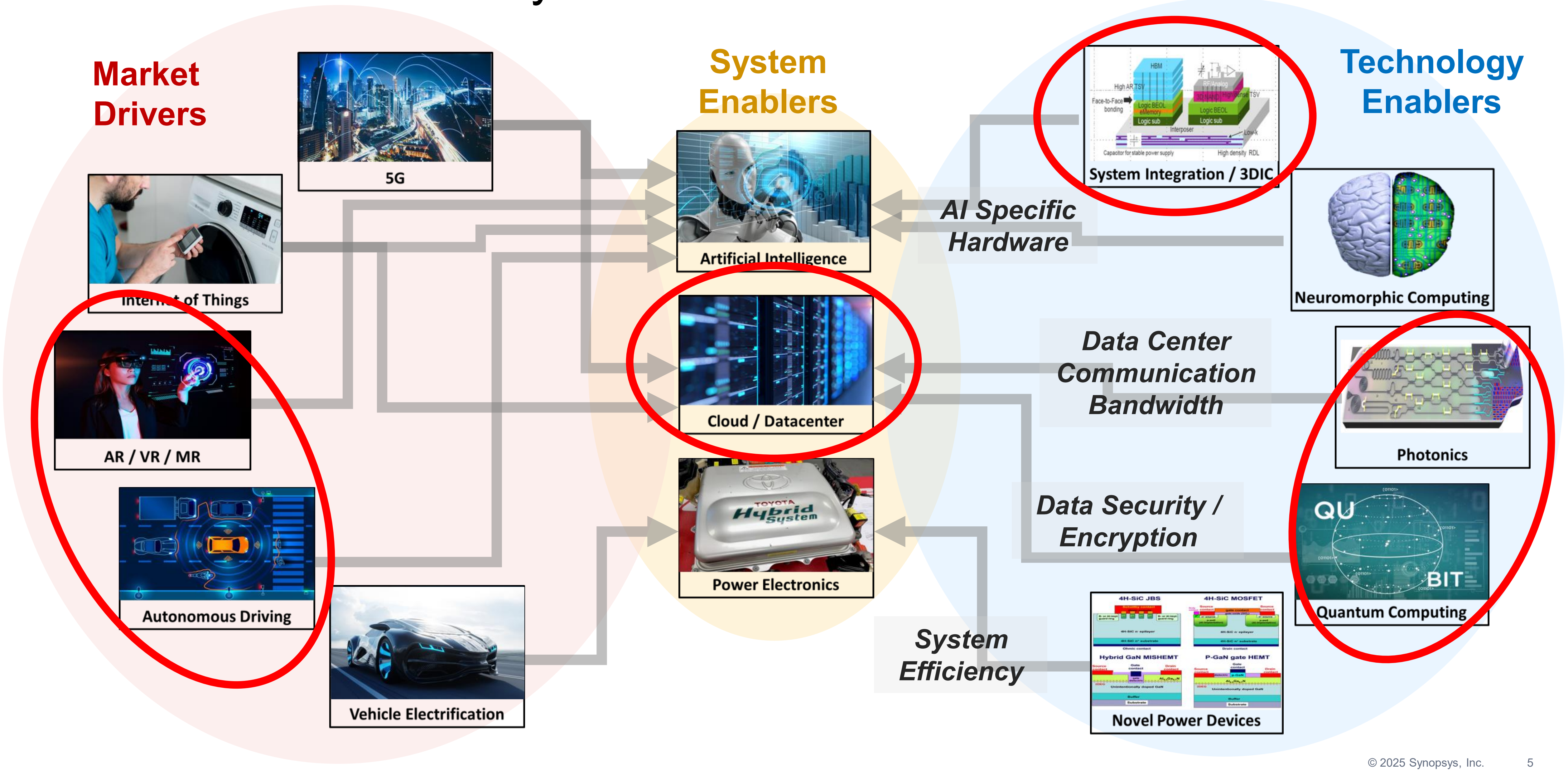
Outline

- Semiconductor Industry Trends
- Photodetector Simulation
- Particle / Radiation Detection

Semiconductor Industry Trends

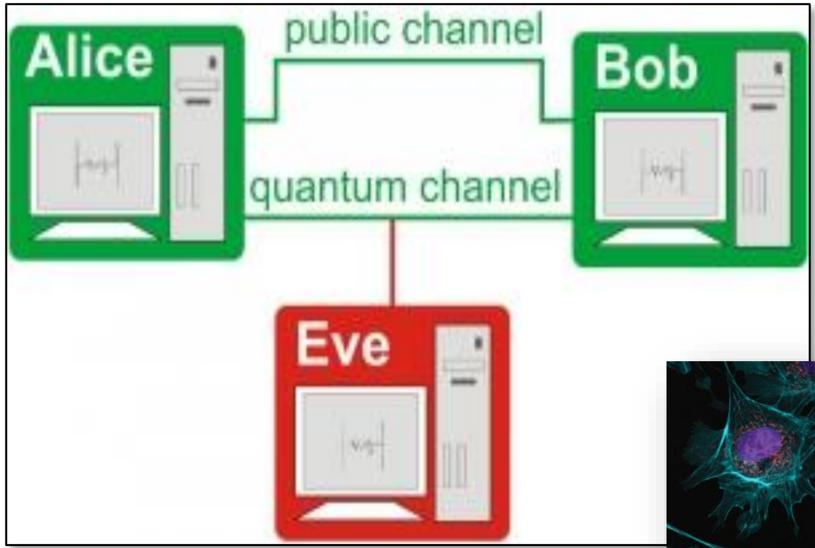
Transformational Applications Continue to Motivate and Drive Semiconductor Industry Growth



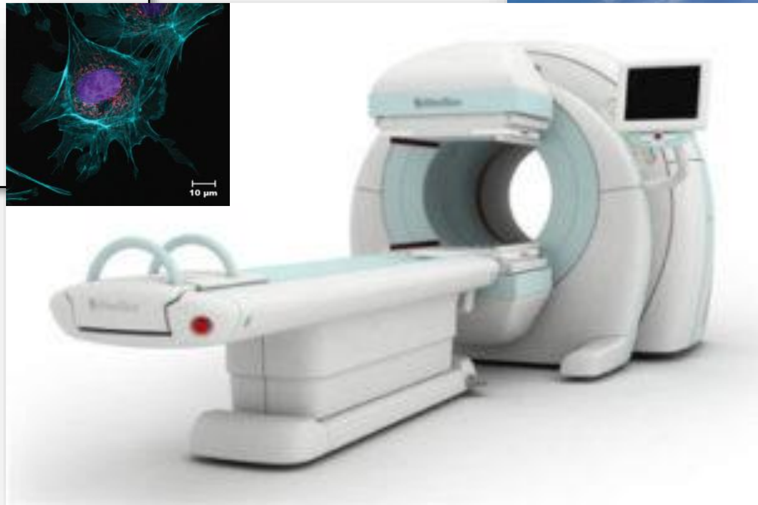
Optical Sensors and Detectors Are Pervasive in Consumer Applications …

… And Are System Enablers in Industrial and Scientific Applications

Quantum Communication / Optical Quantum Computing

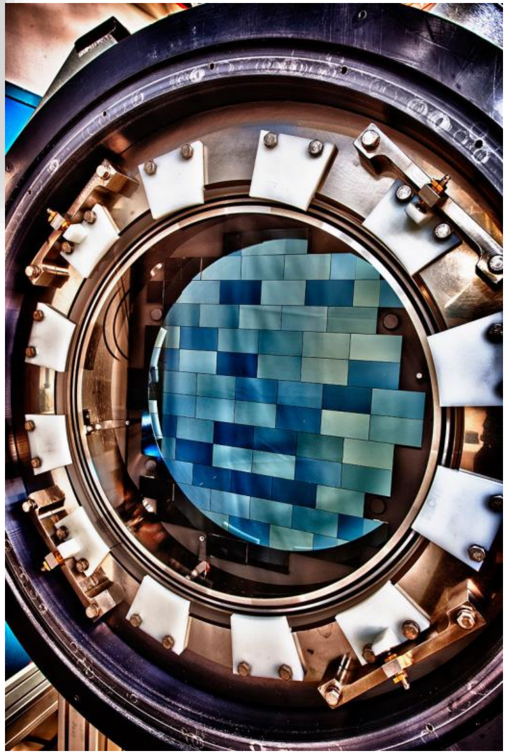


Remote Sensing / Ranging



Medical Imaging

Particle Physics

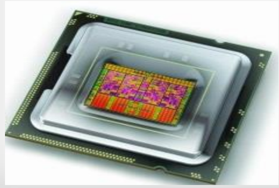


Photodetector Simulation

- **Optical Solvers in Sentaurus**
- CMOS Image Sensors
- Single Photon-Avalanche Diodes

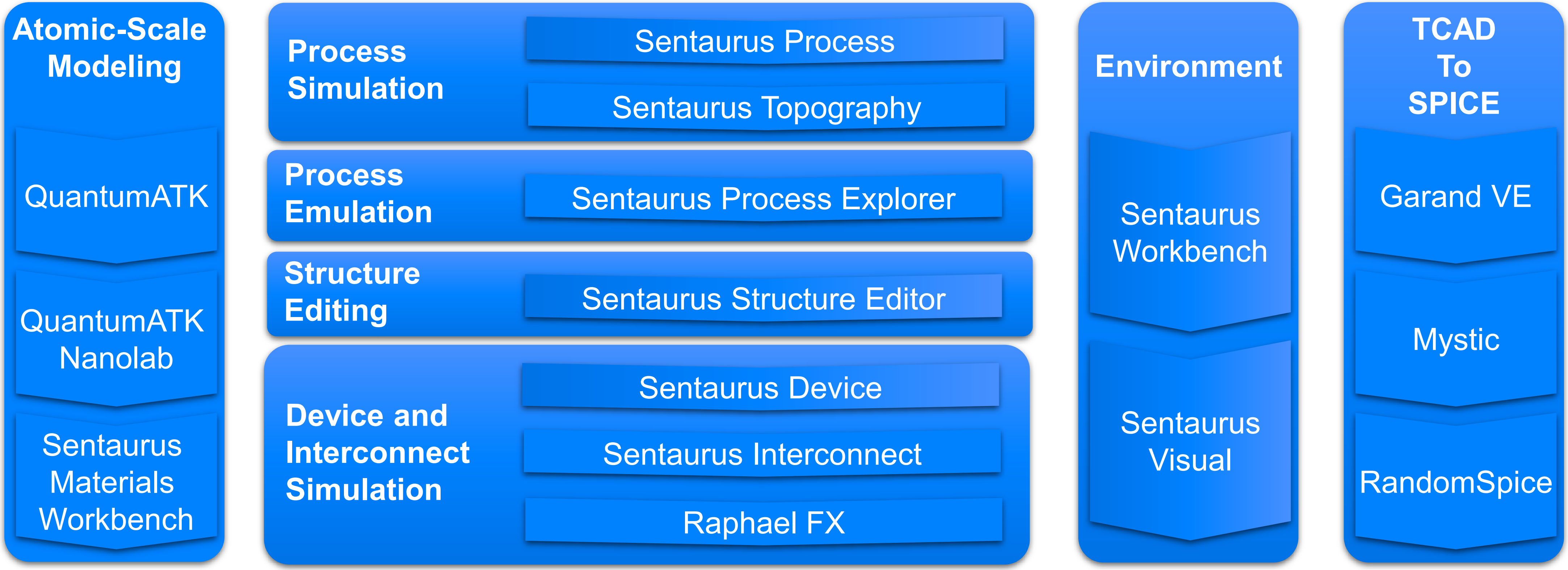
Sentaurus Covers All Major Semiconductor Segments

Solutions For Advanced Logic, Memory, Power, Analog/RF, Opto-Electronics



Logic	Memory	Power	Analog/RF	Opto
Planar CMOS	NAND / NOR Flash	Si IGBT	SiGe HBT	CIS
FinFET	DRAM	SJ-LDMOS	GaAs HEMT	CCD
Nanowire FET	3D NAND	BCD	GaAs HBT	Photodetectors
Tunnel FET	PRAM	SiC	GaN HEMT	Silicon Solar Cells
Research Devices	STT-RAM	GaN	SiC MESFET	III-V Solar Cells

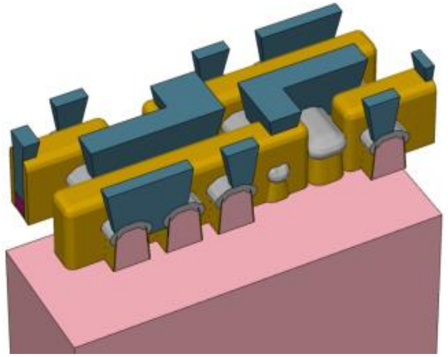
Synopsys TCAD Product Family is the Industry Leader



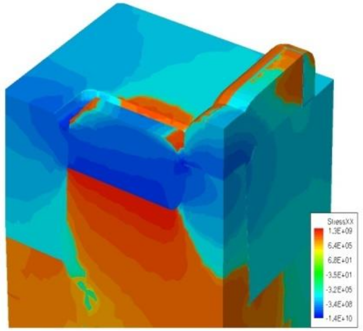
- Production-proven 3D simulation technology
- Integrated simulation flows: atomic-scale, TCAD, SPICE model extraction
- Most accurate results through atomic-scale modeling and calibrated TCAD models

Sentaurus Process Simulator

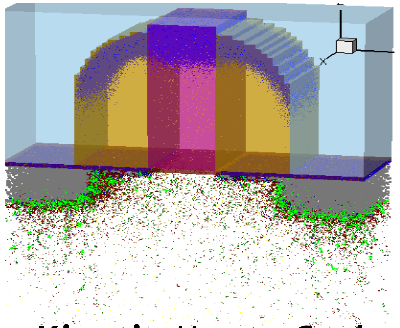
- General purpose multidimensional (2D/3D) process simulator
- Integrated 3D geometric modeling engine
- API for user-defined models
- Advanced physical models:
  - Analytic and Monte Carlo implantation
  - Diffusion: laser/flash annealing, kinetic Monte Carlo
  - Mechanical stress
  - Oxidation
  - Geometric and level-set deposition and etching



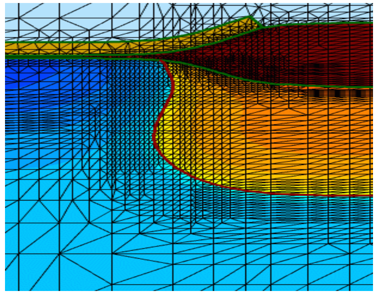
FinFET SRAM



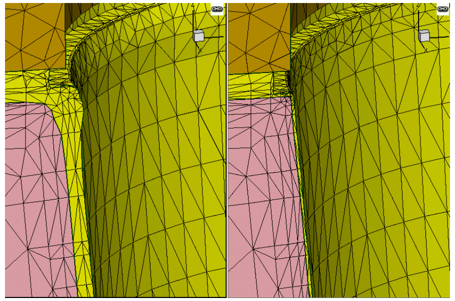
Mechanical Stress



Kinetic Monte Carlo



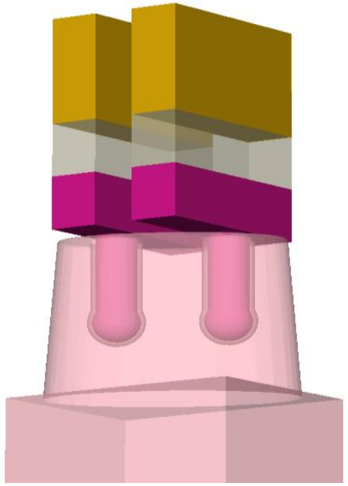
Adaptive Meshing



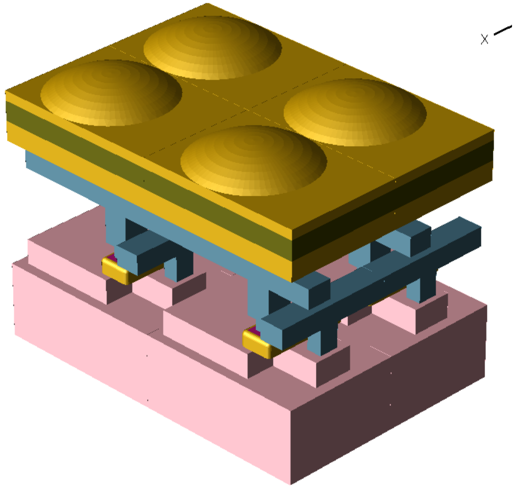
Oxidation

Sentaurus Structure Editor

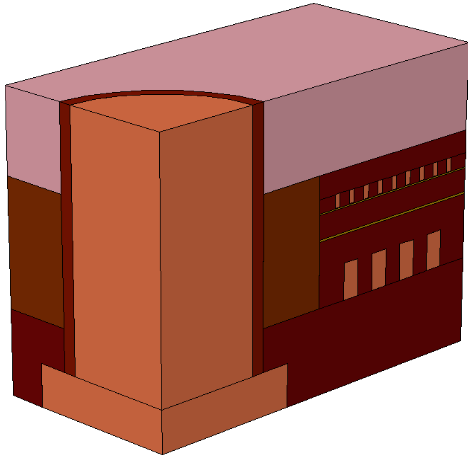
- Geometrical operations
- Easy to use GUI
- Scripting language
- Advanced geometrical modeling with analytic doping definitions
- Direct interface to meshing engines



S-RCAD DRAM



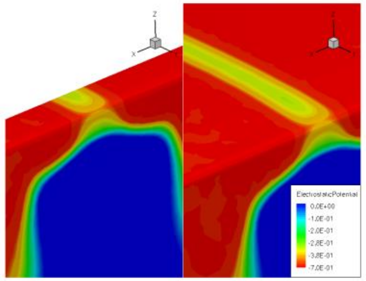
CIS pixels with microlenses

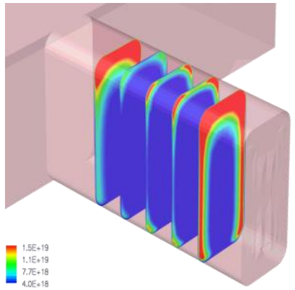


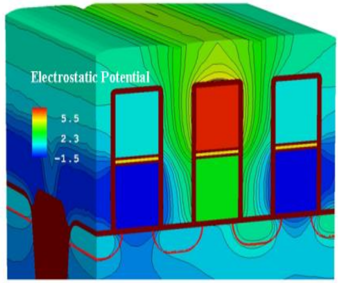
TSV Structure

Sentaurus Device Simulator

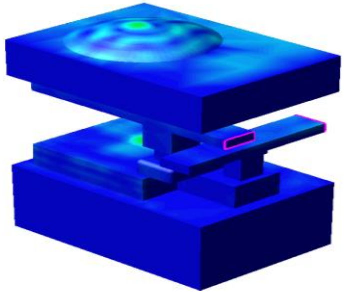
- General purpose multidimensional (2D/3D) device simulator
- Full 3D meshing engines
- Silicon and compound semiconductors
- Drift-diffusion, hydrodynamic and Monte Carlo transport
- Wide range of advanced physical models
  - Strained silicon mobility enhancement
  - Quantization and random doping effects
  - Non-volatile memory operation
  - Raytracing and Maxwell FDTD solver

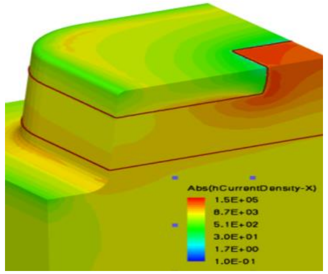

STI Narrow Width Effect


FinFET



NAND Flash


CMOS Image Sensor


UMOS

Sentaurus Device Simulator

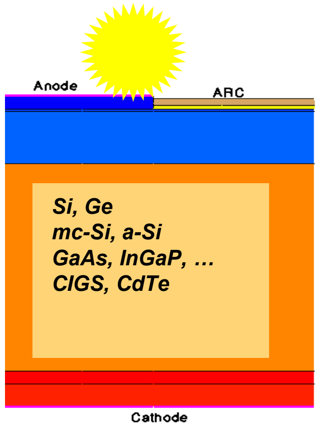
Transport models is available in **S-Device**:

- Drift-Diffusion (isothermal charge transport)
- Thermodynamic (non-isothermal charge and heat transports)
- Hydrodynamic (non-isothermal charge, carrier energy, and heat transport)
- Monte-Carlo carrier transport based on Boltzmann transport equation
- Carrier quantization with
    - Modified local density approximation
    - Density gradient
    - Schroedinger

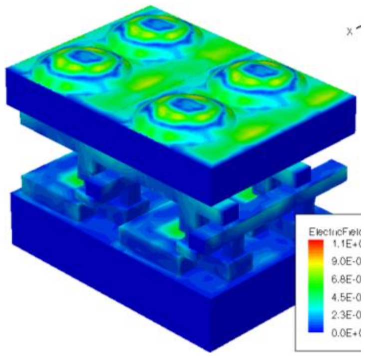
S-Device applies the following methods:

- Steady-State analysis
- Transient analysis
- Small-signal AC analysis
- Noise analysis
- Optical AC analysis
- Mixed-mode: numerical and compact SPICE models

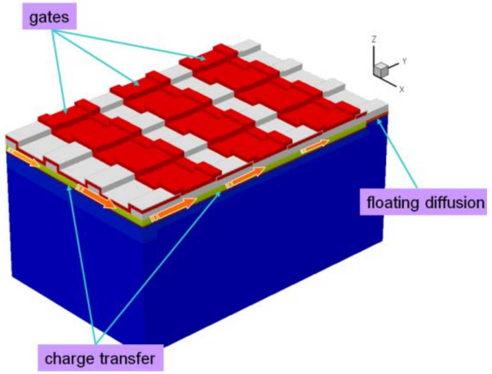
Sentaurus Device for Optics



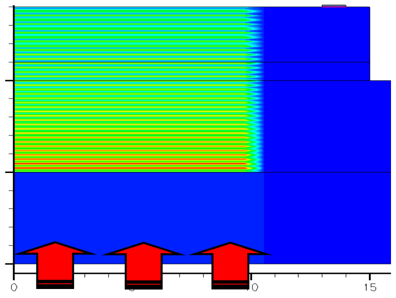
Solar Cells



CMOS Image Sensors



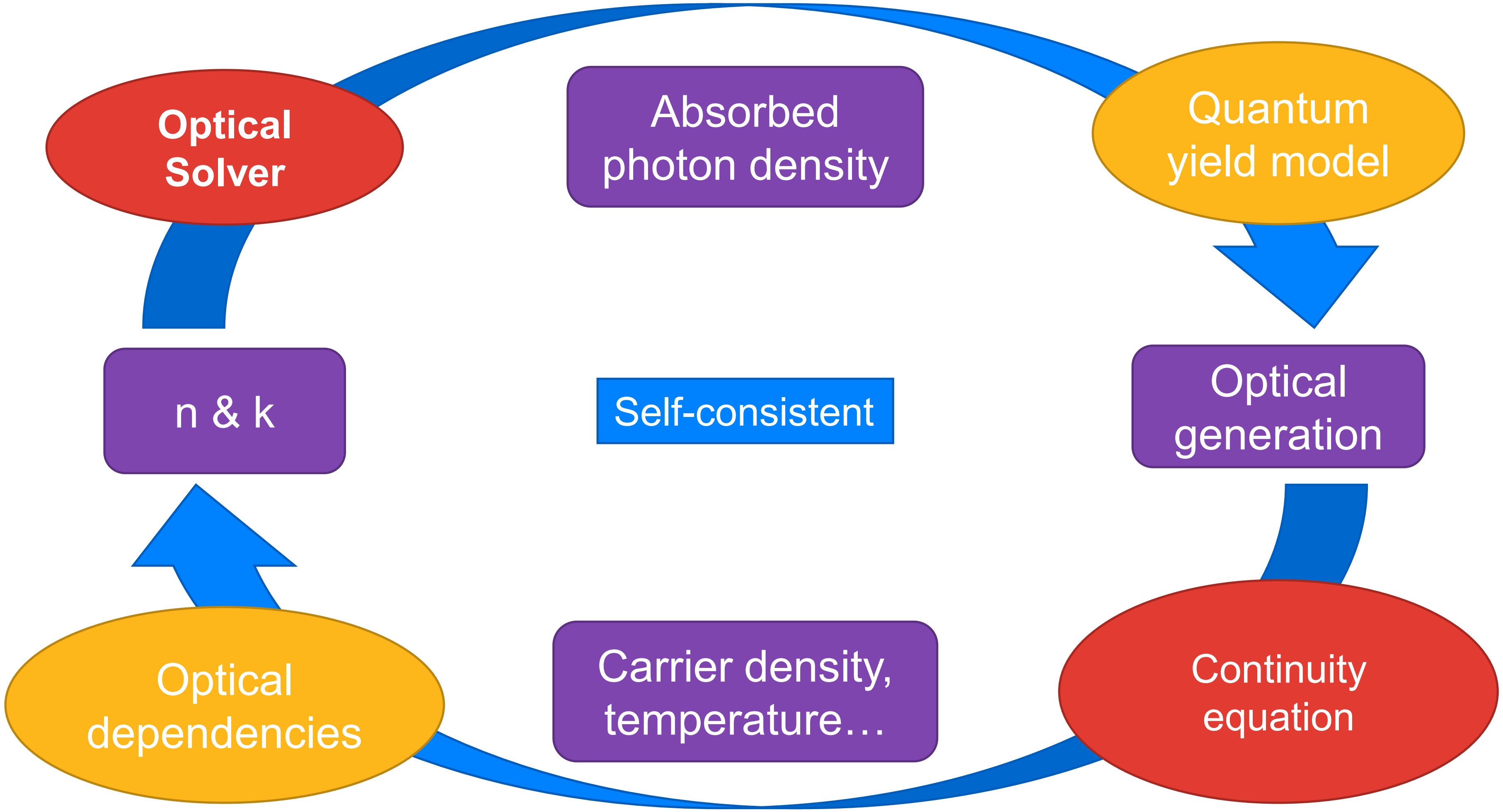
CCD



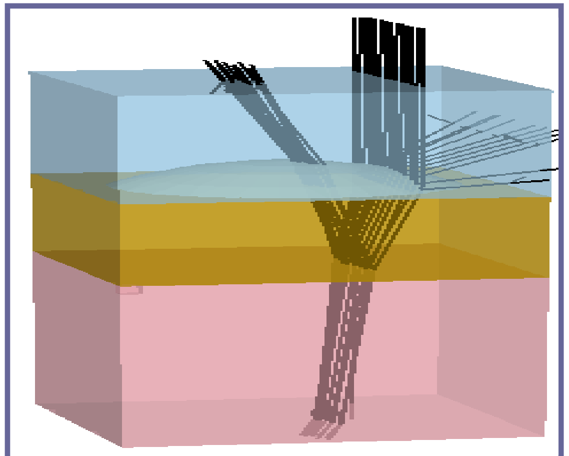
Photodetectors

- 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

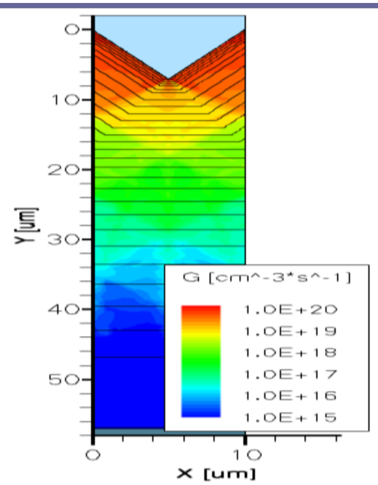
General Optoelectronics Simulation Flow



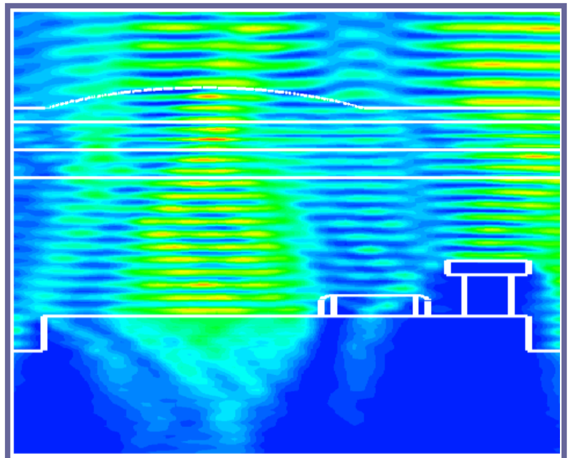
Optical Models in Sentaurus Device



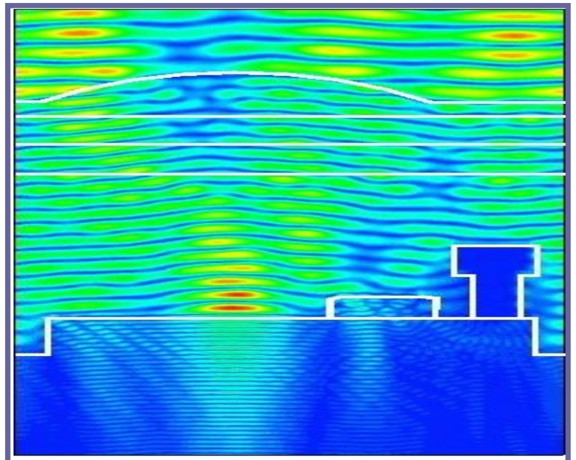
Ray Tracing (RT)



Transfer Matrix Method (TMM)



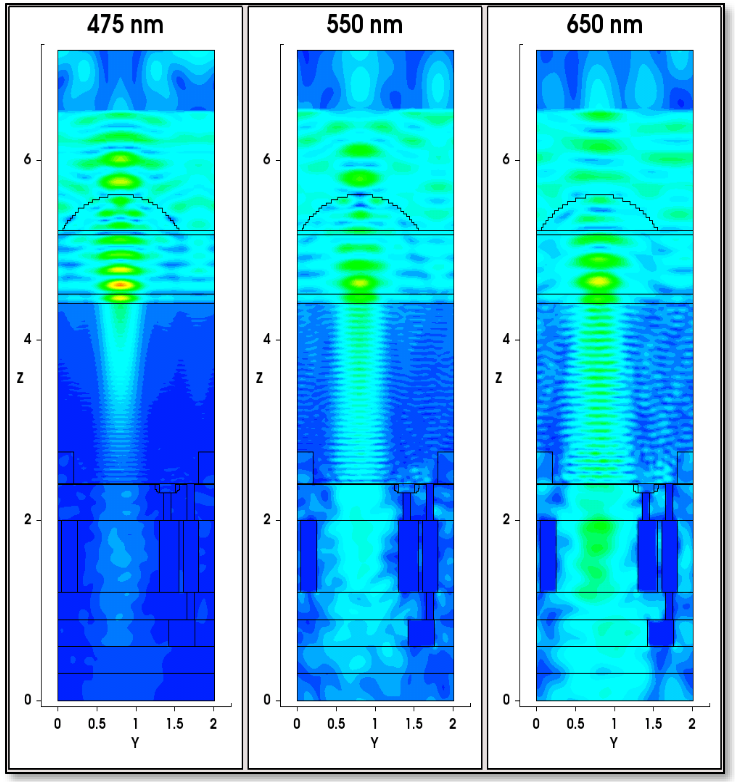
Beam Propagation Meth. (BPM)



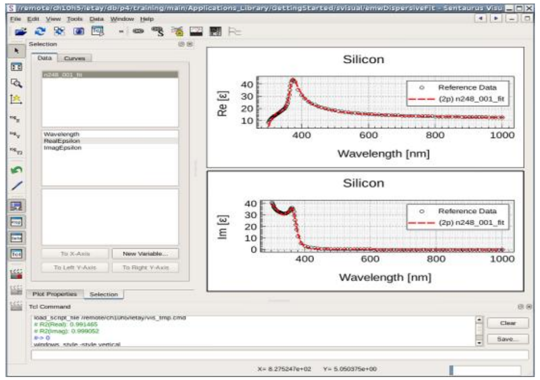
Electromagnetic Solver (EMW)

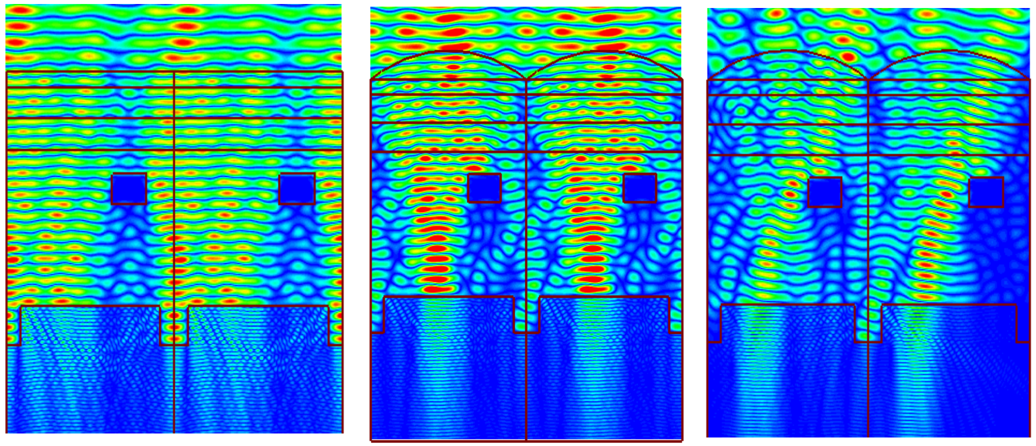
Sentaurus Device EMW: Highly Accurate Optical Solver

- Simulates the propagation of electromagnetic waves via full-wave, time-domain solution (FDTD) of Maxwell's equations



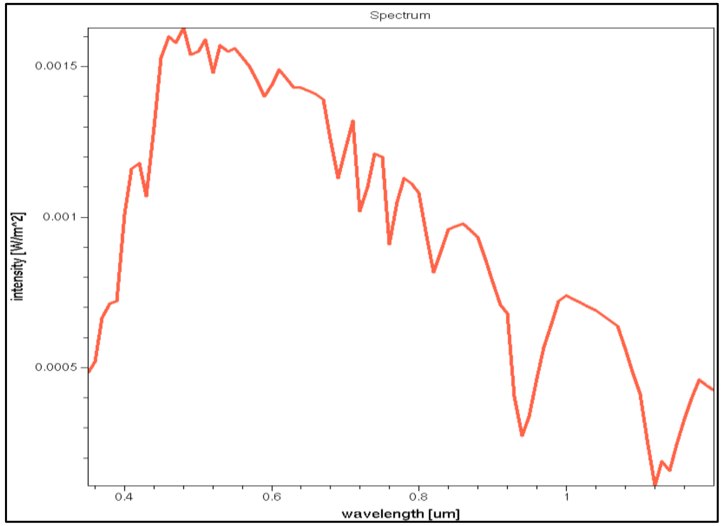
- Simulates refraction, reflection, diffraction / interference and absorption
- Automatic Reflection, Transmission, Absorption (RTA) extraction
- Supports all major boundary conditions
  - Perfect Electric Conductor (PEC), Perfect Magnetic Conductor (PMC)
  - Periodic, periodic oblique
  - Absorbing: Mur, Higdon, Convolutional Perfectly Matched Layer (CPML)
- Multiple excitation sources: plane wave, Gaussian beam, CODE V
- Dispersive media models



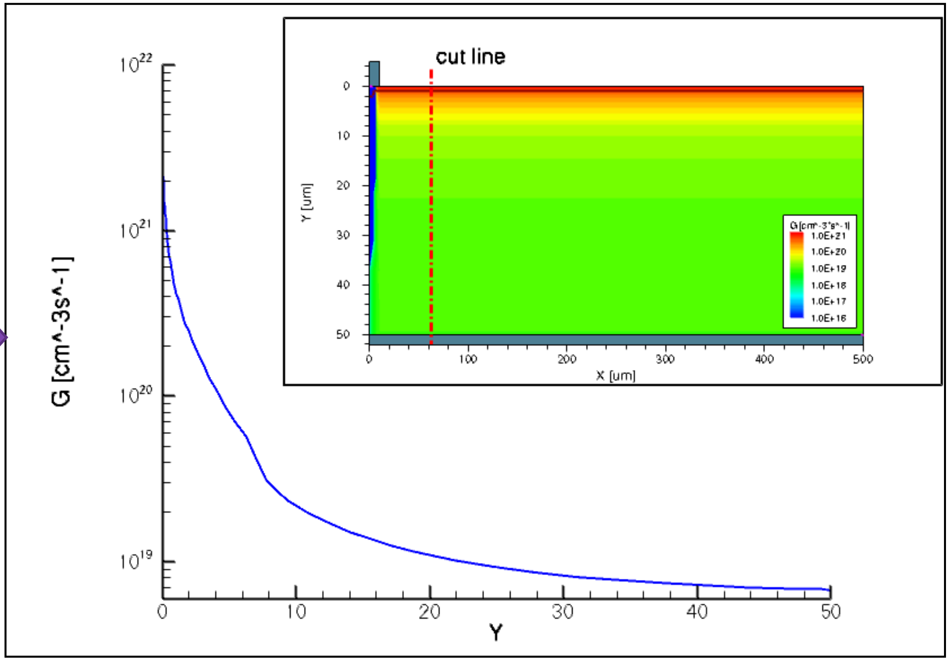


Optical Generation is Calculated as a Function of Depth and λ

- Light absorption in semiconductor regions leads to optical generation
- The structure may contain reflectors or other structures used to increase collection efficiency



Surface Reflection and Transmission at given λ



Device Simulation Applied to Optoelectronic Devices

- System of semiconductor device equations:

Poisson:	$\nabla \cdot \varepsilon \nabla \emptyset = -q(p - n + N_D - N_A) - \rho_{trap}$
Continuity:	$\nabla \cdot \mathbf{J}_\mathrm{n} - \mathrm{q}\frac{\partial \mathrm{n}}{\partial \mathrm{t}} = \mathrm{q}(\mathrm{R} - \mathrm{G}) \qquad -\nabla \cdot \mathbf{J}_\mathrm{p} - \mathrm{q}\frac{\partial \mathrm{p}}{\partial \mathrm{t}} = \mathrm{q}(\mathrm{R} - \mathrm{G})$

- In majority of cases, drift-diffusion is sufficient for treating current transport in optoelectronic devices:

$$\mathbf{J}_\mathrm{n} = -nq\mu_n \nabla \Phi_\mathrm{n} \qquad \mathbf{J}_\mathrm{p} = -pq\mu_p \nabla \Phi_\mathrm{p}$$

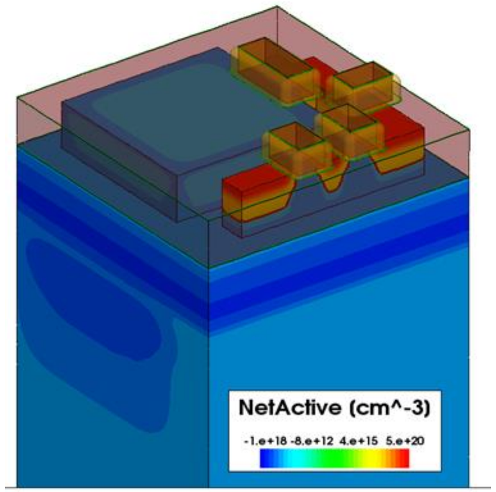
- Solution modes:
  - Quasi-static (I-V curves, EQE vs λ, etc)
  - Transient (light pulses, current/voltage pulses)
  - Small-Signal AC (responsivity, …)

Photodetector Simulation

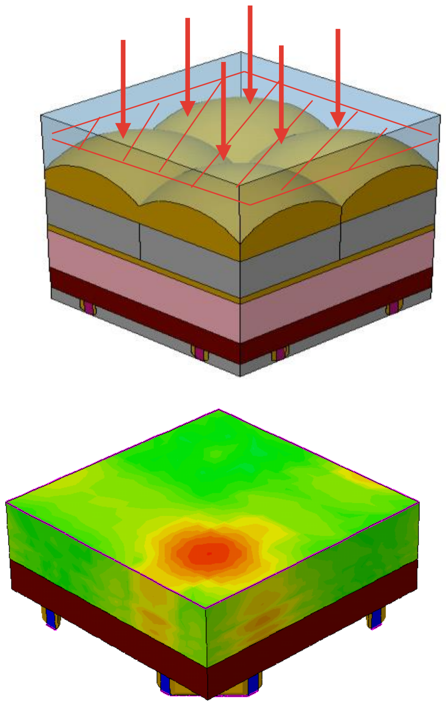
- Optical Solvers in Sentaurus
- **CMOS Image Sensors**
- Single-Photon Avalanche Photodetectors

Sentaurus Offers a Fully Integrated TCAD Solution for CIS

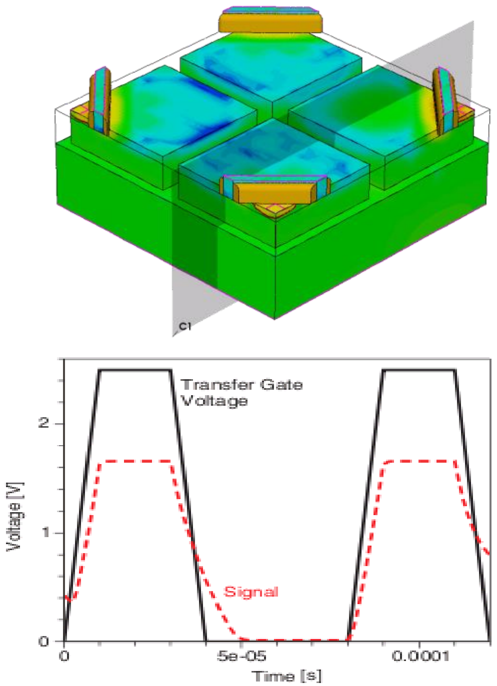
Process / Structure Simulation



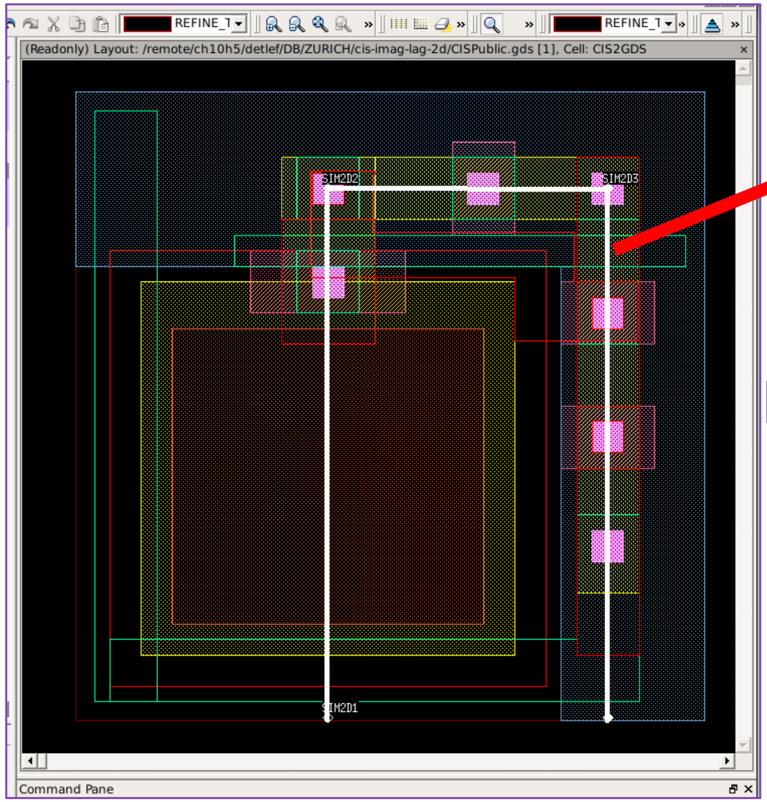
Optical Simulation

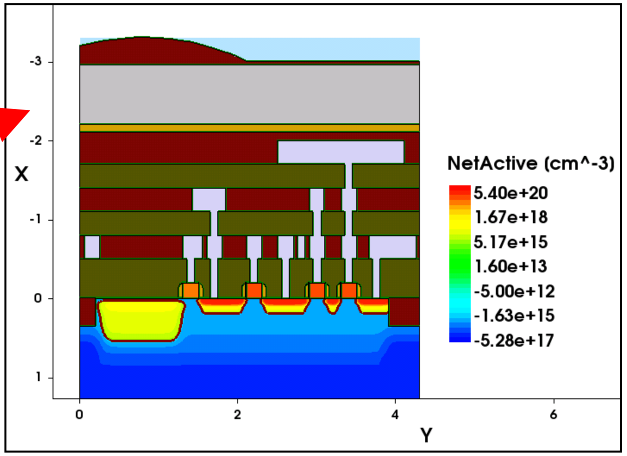


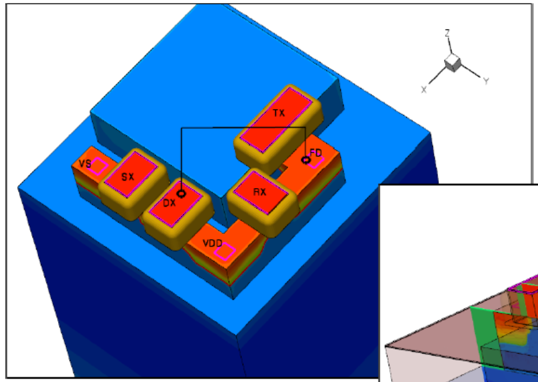
Electrical Simulation

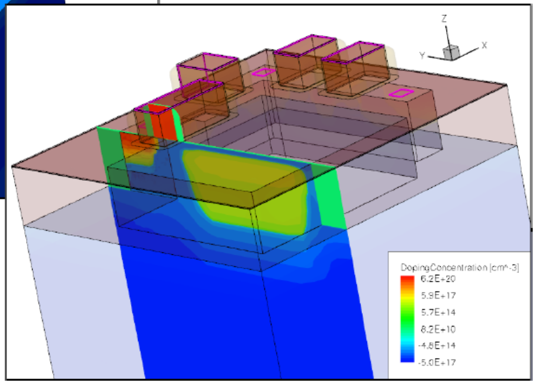


Sentaurus Provides a Capability to Generate CIS Structures from Mask Information

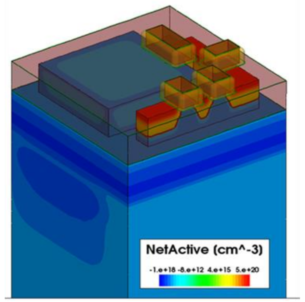




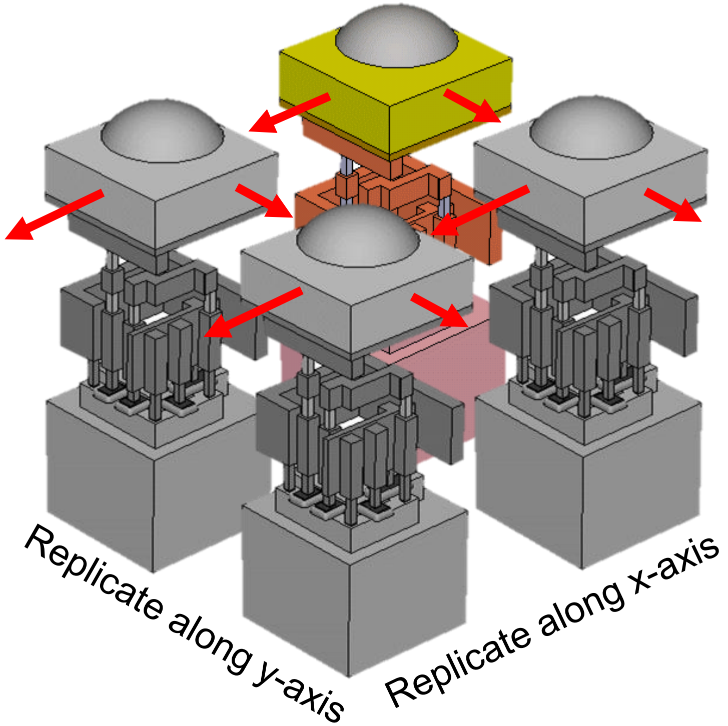


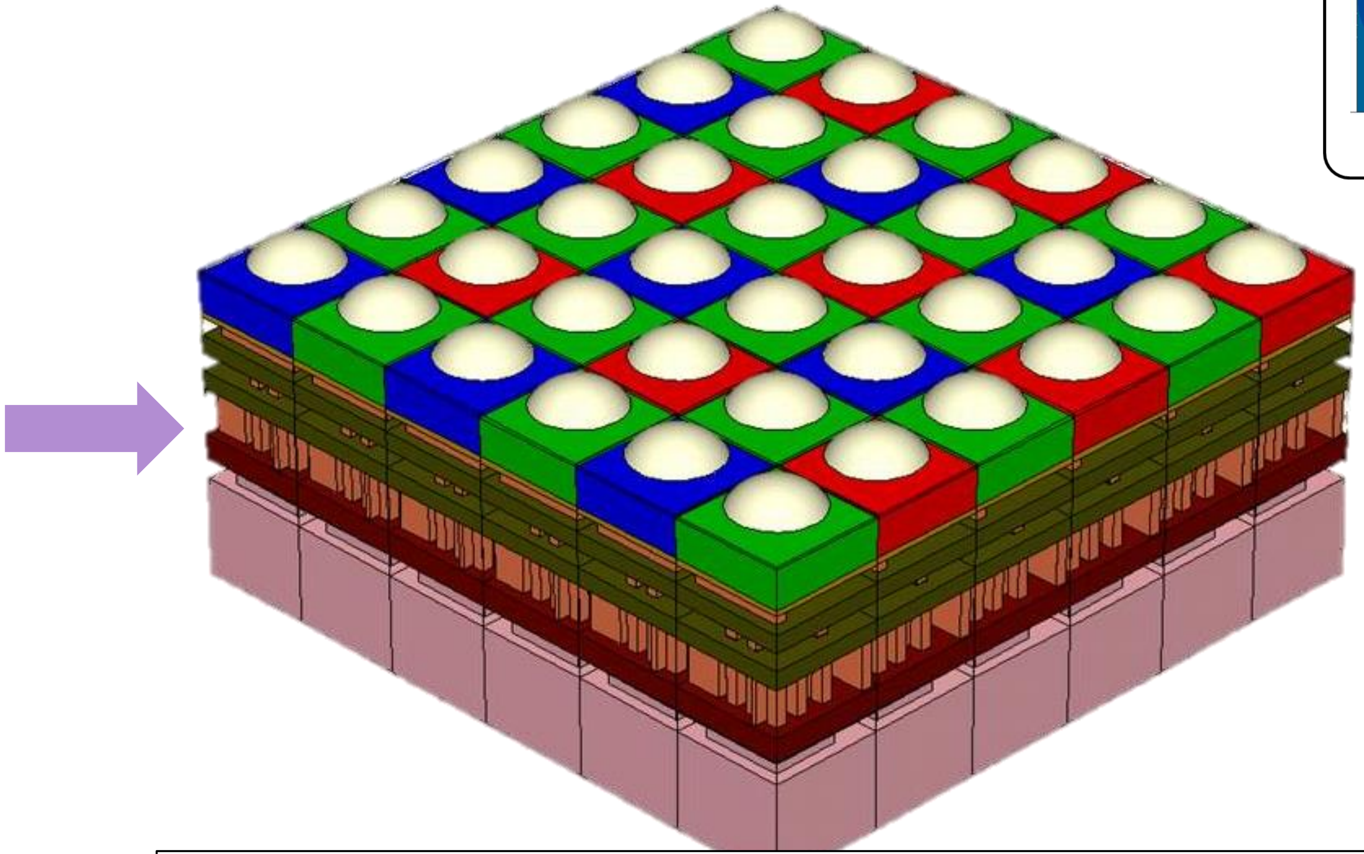


Process / Structure Simulation

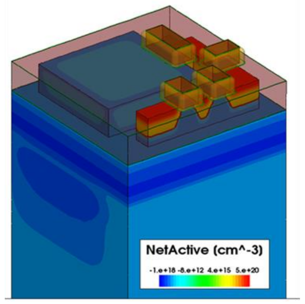


Sentaurus Offers Flexible Ways to Replicate CIS Structures to Construct Pixel Arrays





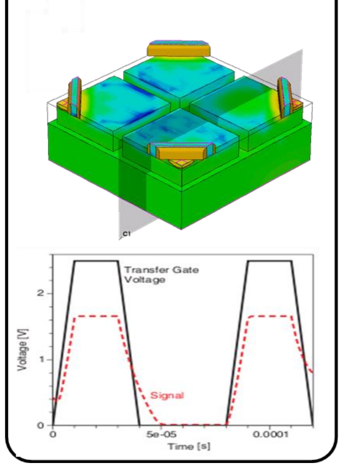
CIS pixel array with Bayer color filter pattern applied



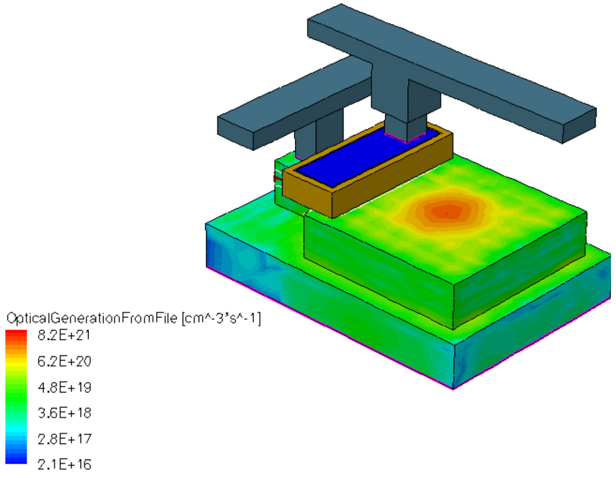
Device Simulation Enables Analysis and Mitigation of Crosstalk

- Electrical simulation is performed on target pixel (11) and adjacent pixel (12) to investigate optical cross talk
- Change to potential in pixel 12 after reset indicates crosstalk

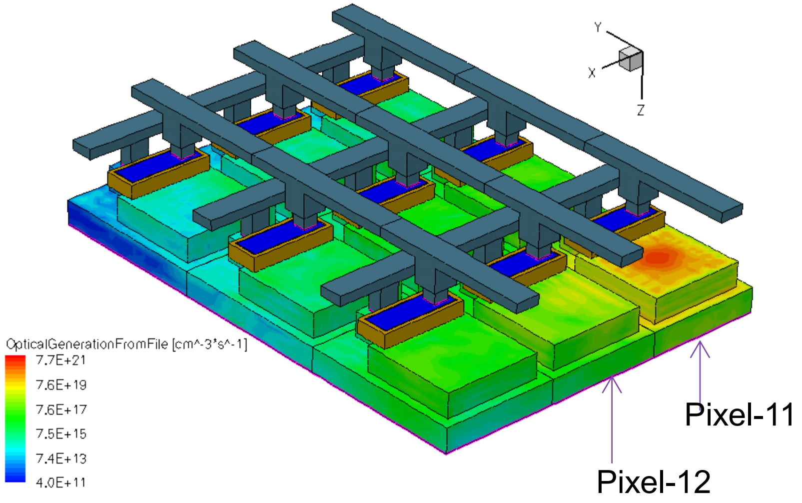
Electrical Simulation

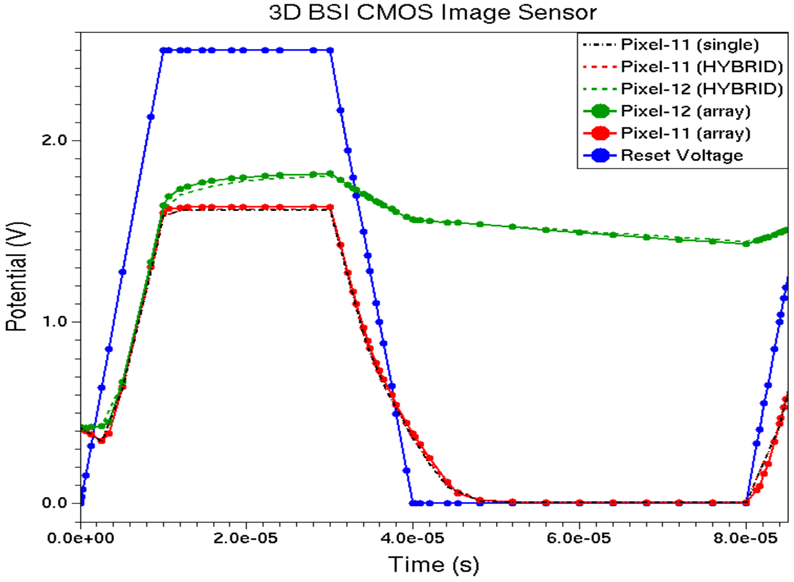


Single Pixel



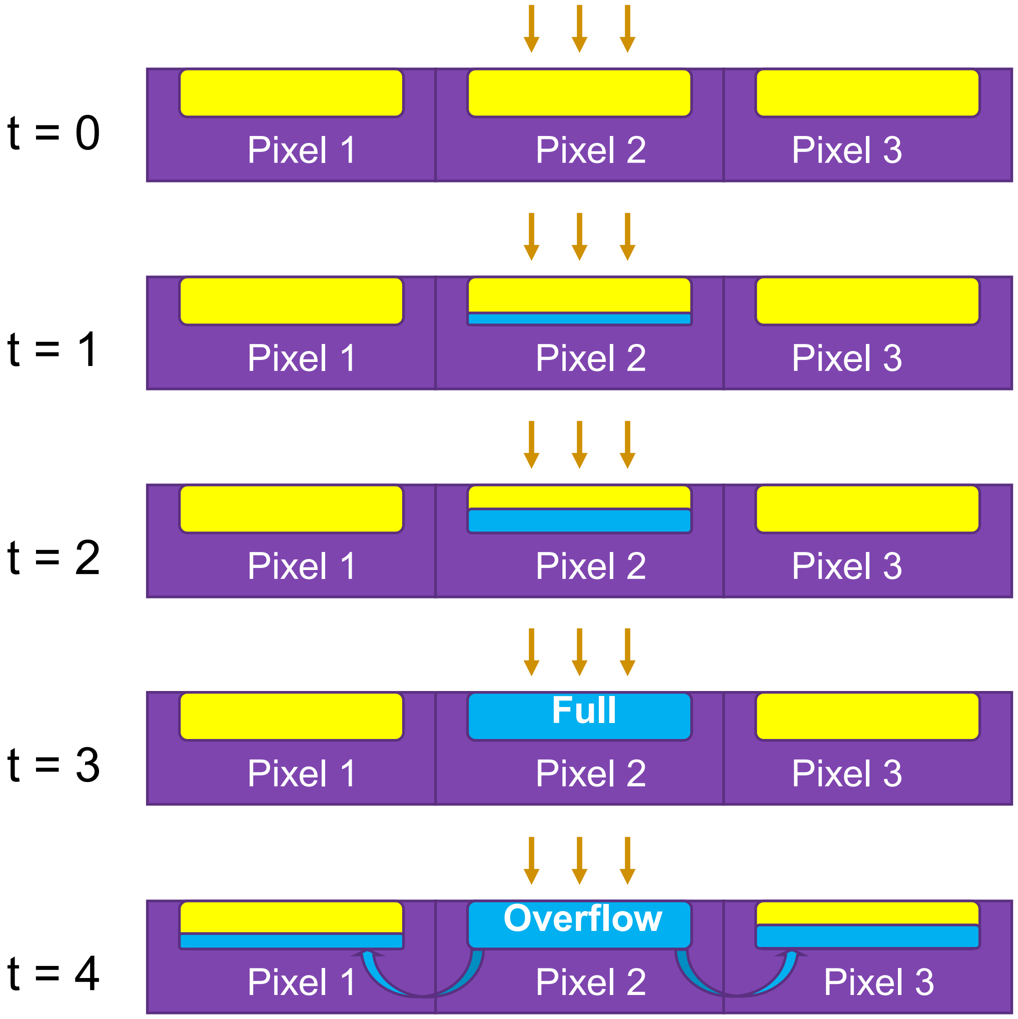
Pixel Array

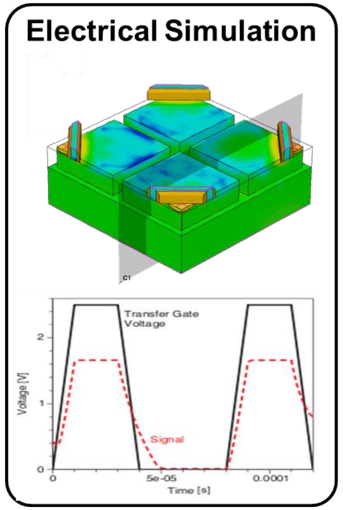




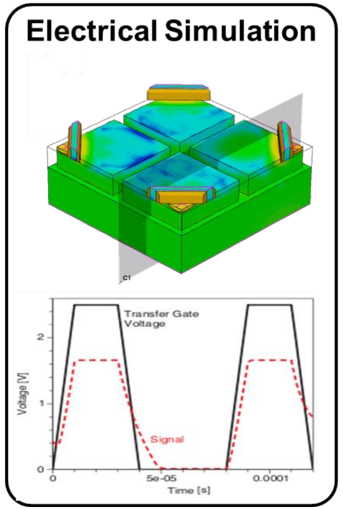
Analysis of Blooming Effect

- Light source overloads capacity of pixel; number of generated electrons exceeds capacity of the doping well
- “Spillover” of electrons from illuminated pixel into the neighboring pixels
- Typically a problem with CCDs
- CMOS image sensors can also be affected depending on layout of pixels





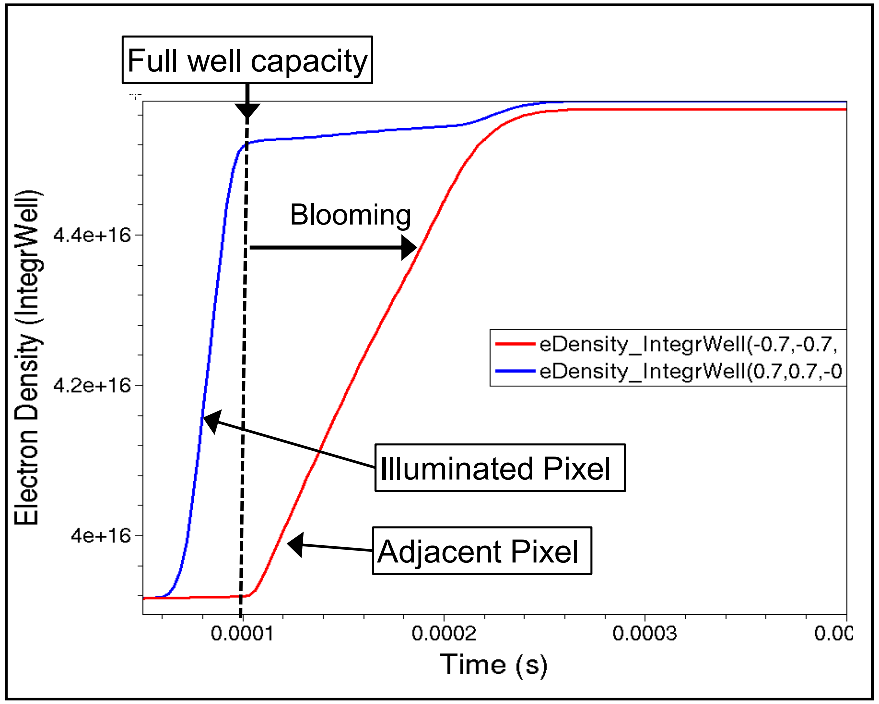
Electrical Simulation Computes the Time Need to Reach Full Well Capacity to Prevent Blooming



- In this example, at 0.105 μs the well reaches full capacity
  - Before this time, only optical crosstalk contributes electrons to adjacent pixels
  - After this time, the electron concentration in adjacent pixels is from “spillover”

Sentaurus Device syntax for capturing integrated electron density over specified region of the CMOS image sensor structure

```
CurrentPlot {
   Potential ( (0.7, 0.7, -0.7))
   eDensity (
    Integrate(DopingWell (0.7 0.7 -0.7))
    Average(DopingWell (0.7 0.7 -0.7))
   )
   OpticalGeneration ( (0.7, 0.7, -0.7)
    Integrate(DopingWell (0.7 0.7 -0.7))
    Average(DopingWell (0.7 0.7 -0.7)))
   )
}
```

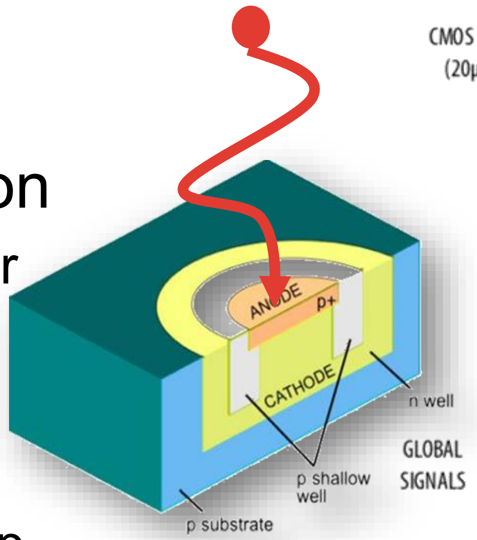


Photodetector Simulation

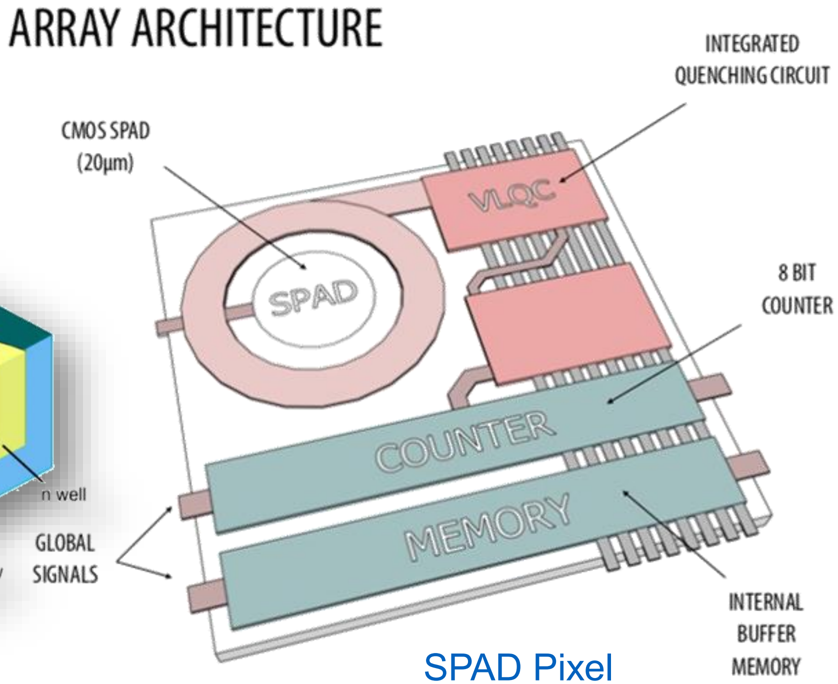
- Optical Solvers in Sentaurus
- CMOS Image Sensors
- **Single-Photon Avalanche Photodetectors**

Single Photon Avalanche Diodes

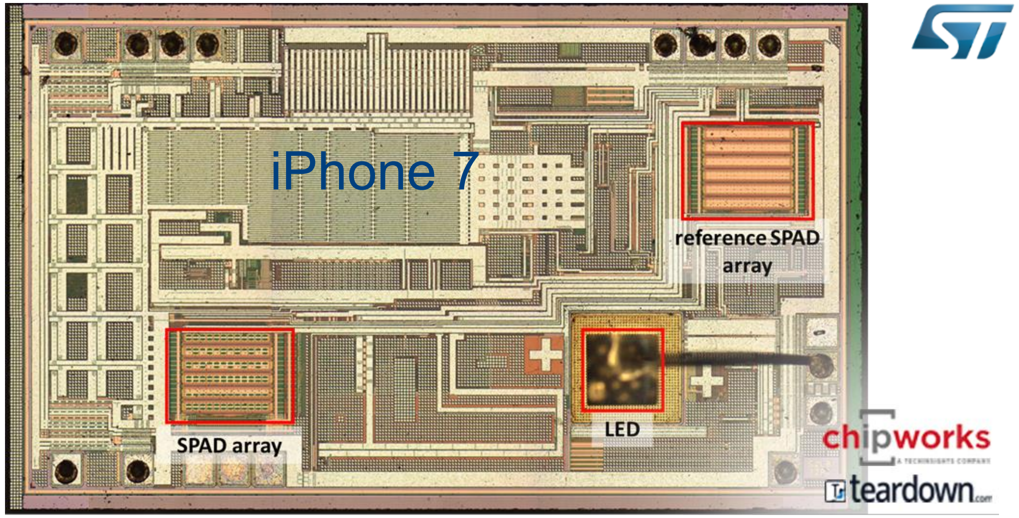
- Device capable of detecting a single photon
  - pn junction biased such that photoexcited carrier rapidly triggers avalanche breakdown
  - Operates as photon counter or Time Of Flight
  - Timing accuracy ~ 30 ps – 100 ps
  - Variation due to stochastic transport and build up
  - More sensitive than Avalanche Photo Diodes (APDs)
- Standard CMOS fabrication
  - Sensor integrated with circuitry and logic
  - Combined to form SPAD arrays
- Silicon and III-V architectures
  - Sensitive to different wavelengths



SPAD



SPAD Pixel



How Do SPADs Operate?

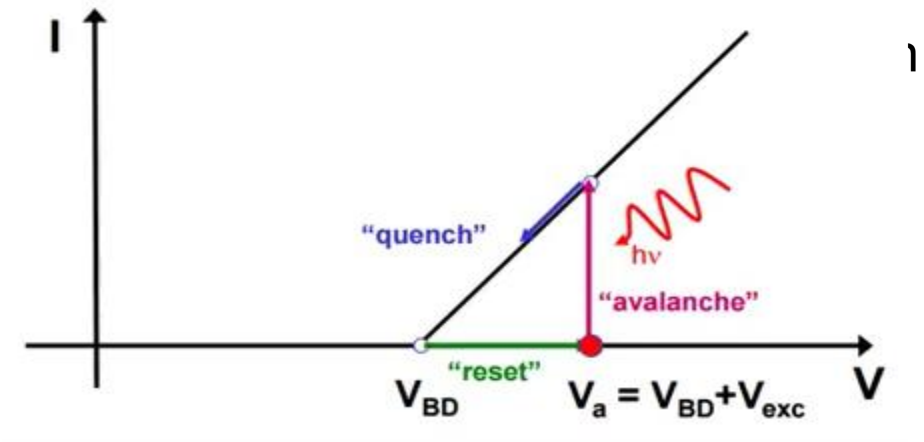
1. Bias device at a voltage higher than the breakdown voltage, ie, $V_a > V_{BD}$

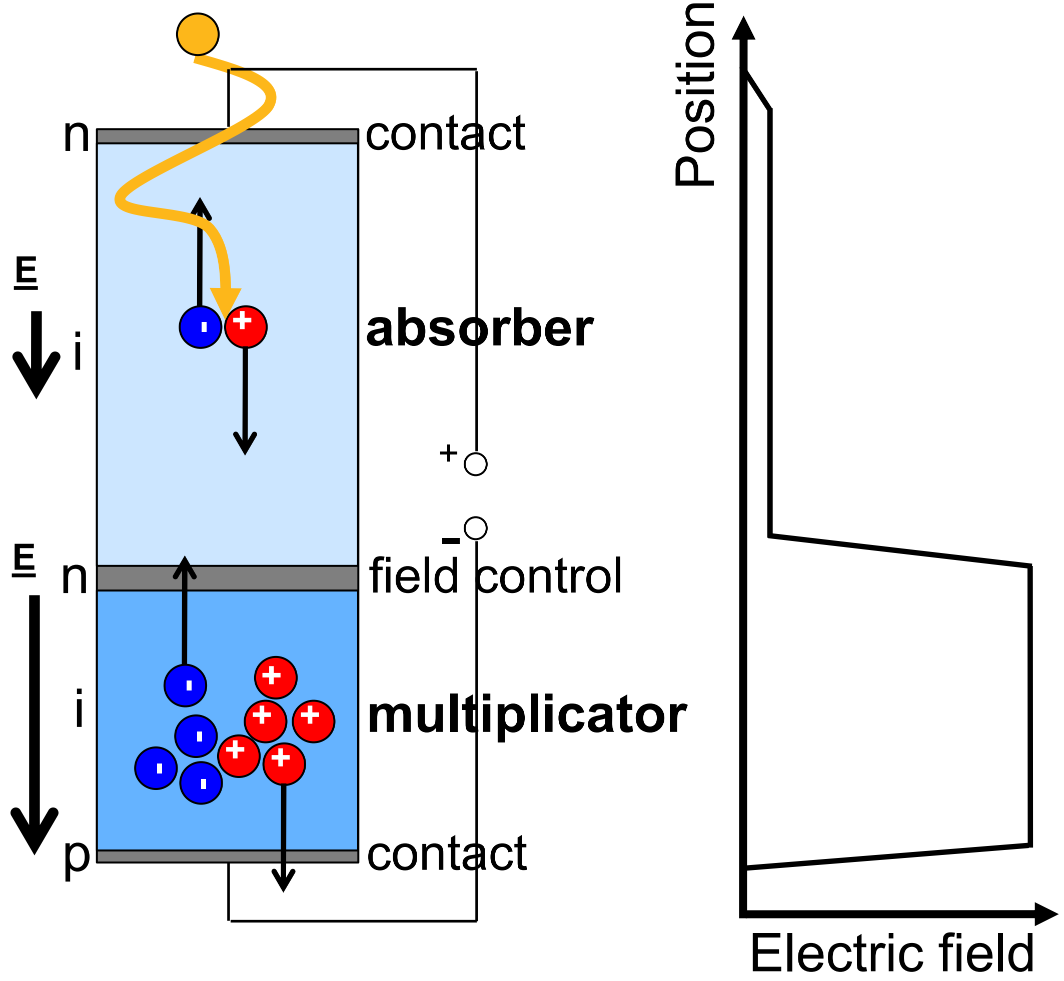
2. Single photon creates a detectable current (avalanche)

3. Device voltage is reduced below V_{BD} to lower avalanche current (quenching)

4. Device voltage is restored back to V_a (reset)

5. D





Synopsys TCAD SPAD Modelling Approaches

- Quasi-stationary Drift Diffusion
  - solve McIntyres differential equation for breakdown probability P_e
  - gives P_e, Dark Count Rate (DCR) and Photon Detection Efficiency (PDE)
  - no carrier dynamics, no minority carrier effects
- Transient Drift Diffusion
  - tweaked with PMI (no SRH generation, quantized avalanche [Webster *et al*, 2013])
  - reflects carrier dynamics
  - sweep through absorption locations
- Full-band Monte Carlo (Garand MC)
  - full physics: dead space, accurate P_e, stochastic distributions
  - computationally more expensive. 2nd DD step required for DCR calculation

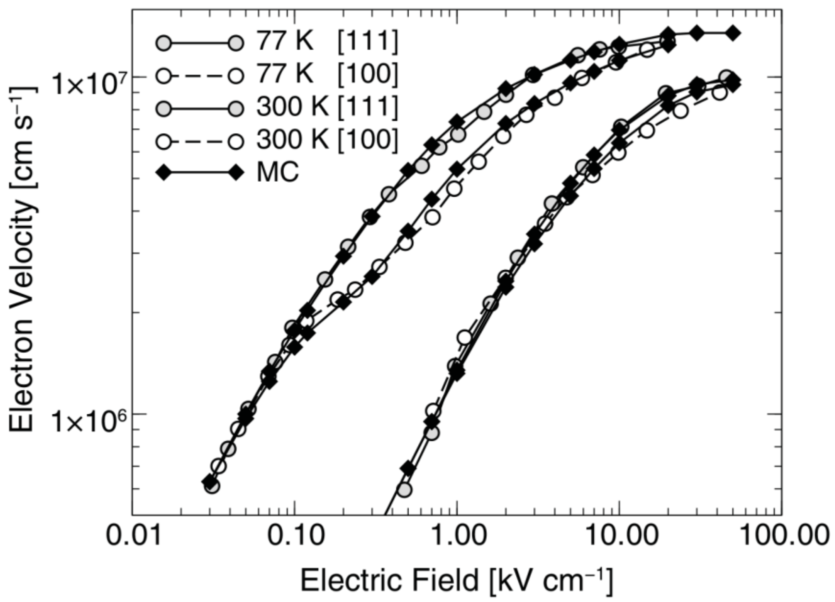
Garand MC – Physical Models

Band Structure

- Efficient analytic or accurate full band models

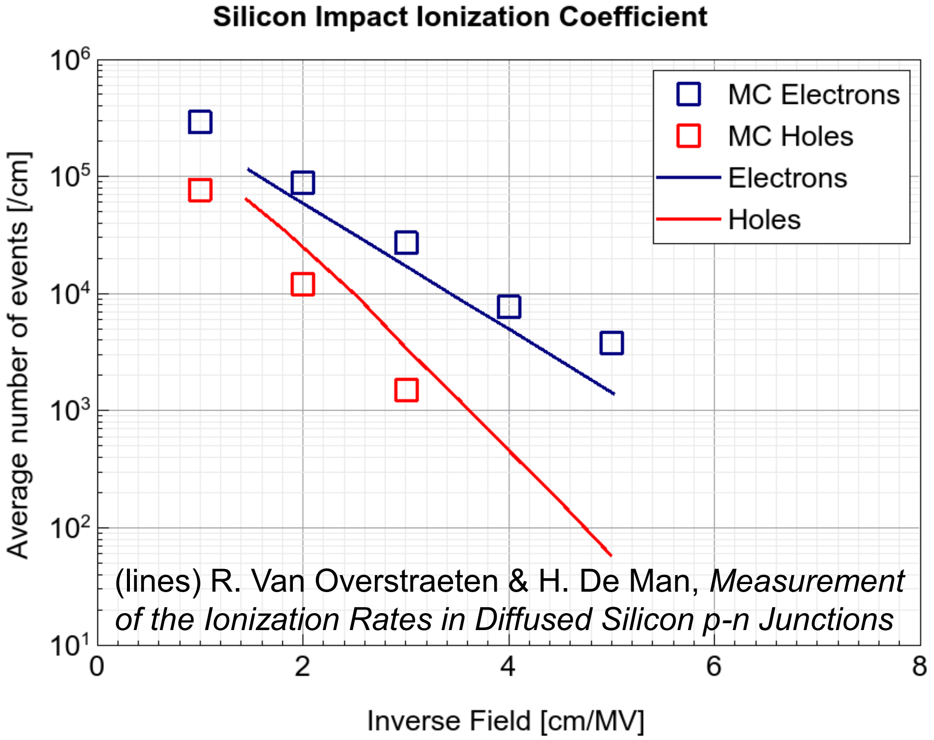
Phonon Scattering

- Well calibrated bulk Silicon transport

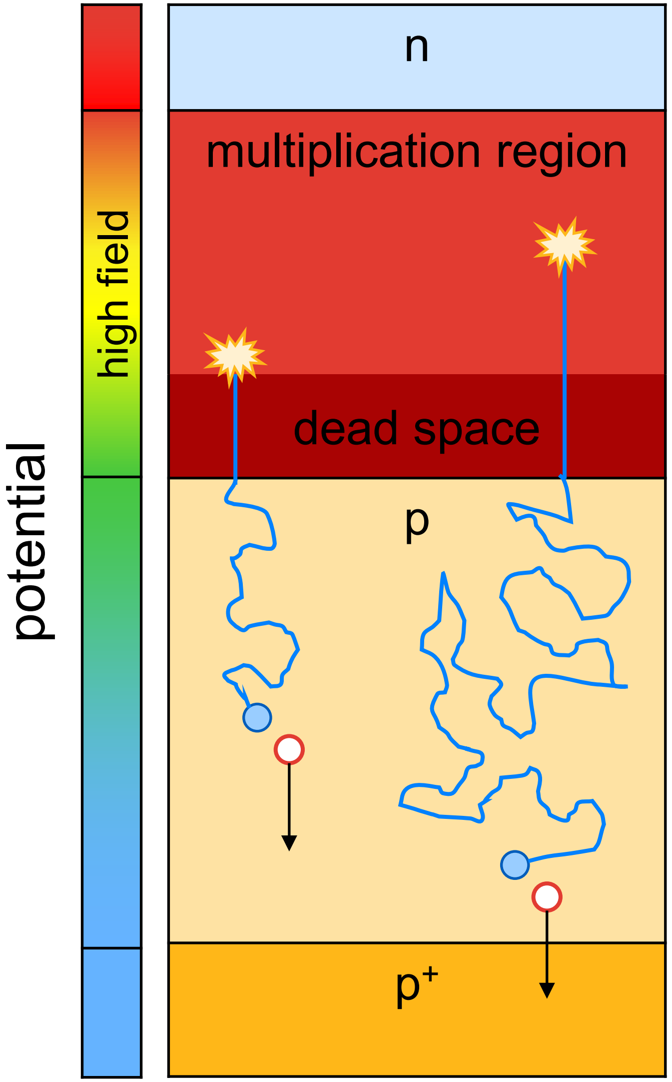


Impact Ionization

- Empirical rate calibrated for electrons & holes
- Development of enhanced model underway



Detection Time Distribution – Jitter

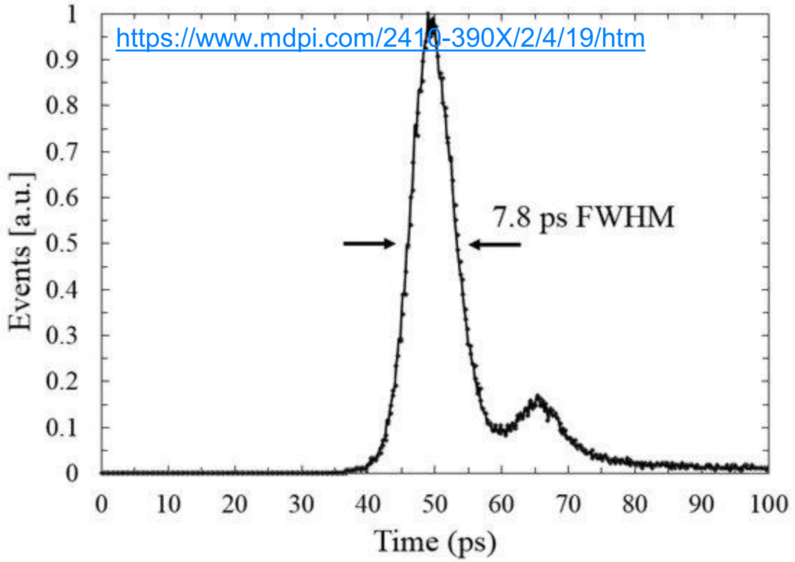


Impact Ionization => random pair creation (Monte Carlo transport)

also resolves dead space, within which carriers have insufficient energy for impact ionization

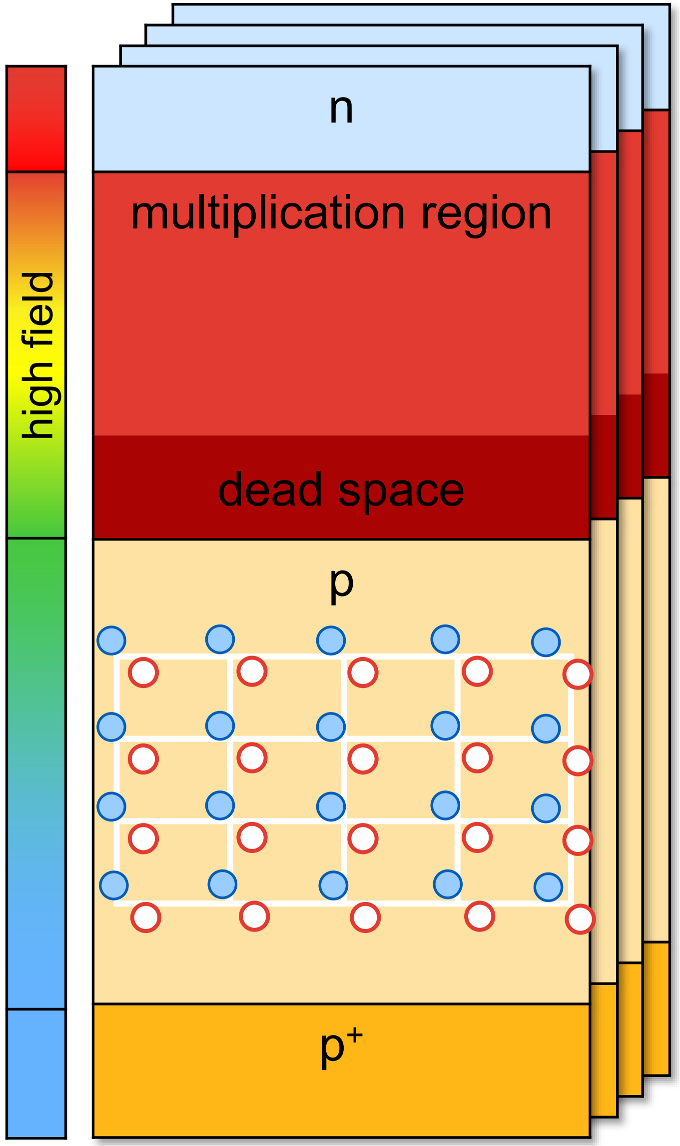
Photon absorption => random pair creation (S-Device optics)

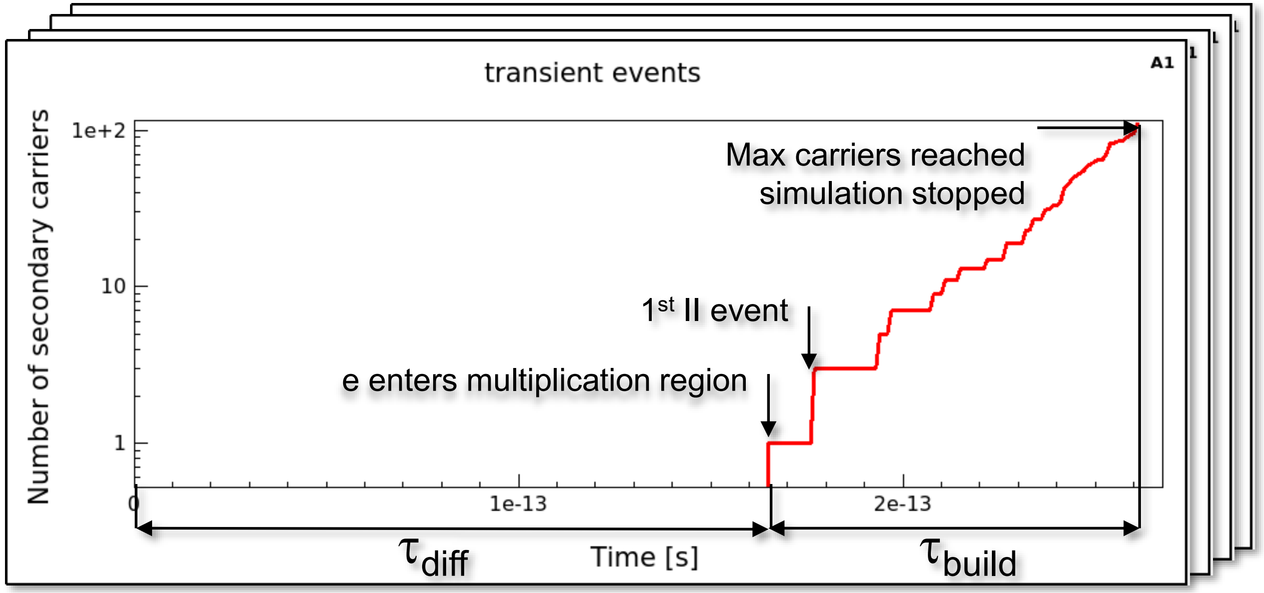
Phonon scattering => random walk (Monte Carlo transport)



- Random processes result in jitter
- Important design parameter
- Limits system resolution
  - photon arrival time
  - LiDAR object resolution

Garand MC – Execution Model

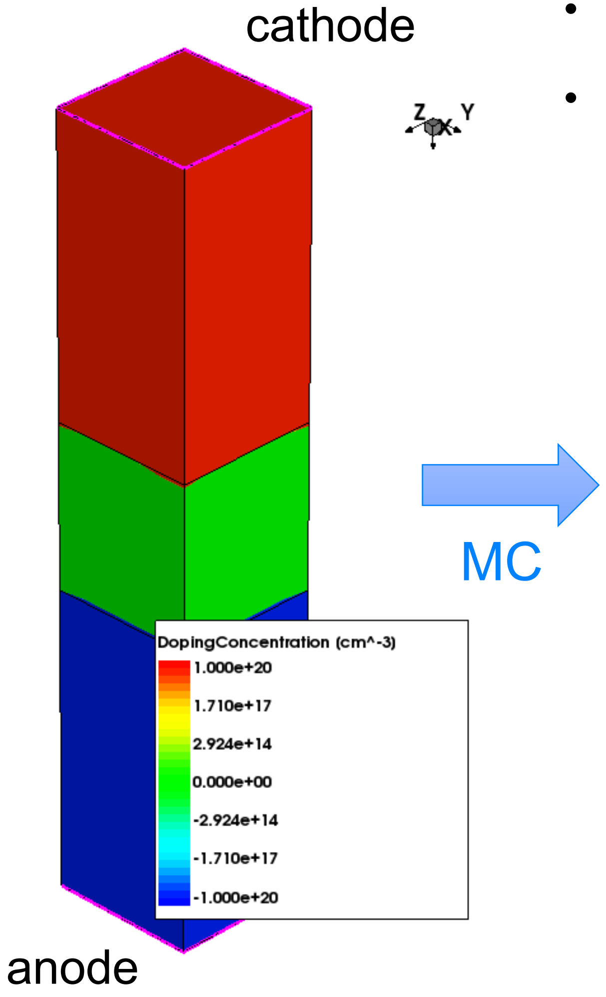


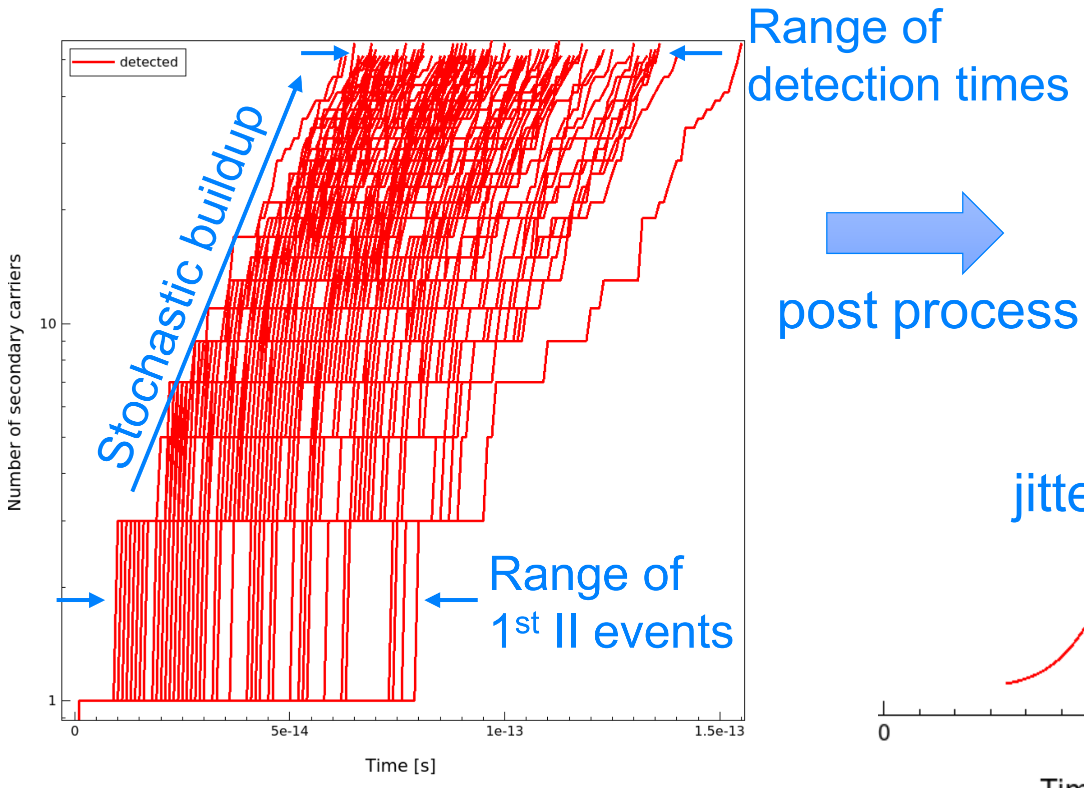


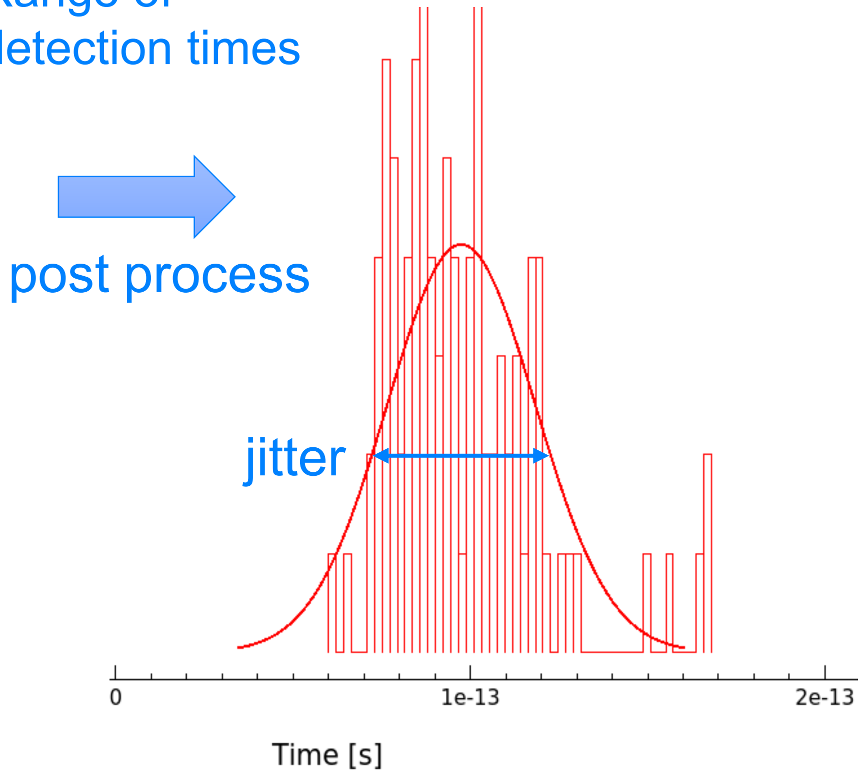
- Garand MC simulates carrier diffusion and impact ionization
- History of each photo excited carrier is output for processing
- Multiple histories may be simulated in a single MC instance
- Multiple instances may be run and all output aggregated
  - easily scalable, limited by resource & licences only
- More samples => more accuracy

Example– Carrier Histories and Jitter

- Simple structure from Sentaurus Structure Editor using analytic doping profiles
- Photoexcite electrons and holes either side of intrinsic region
- Extract jitter and breakdown probability (avalanche / no avalanche)

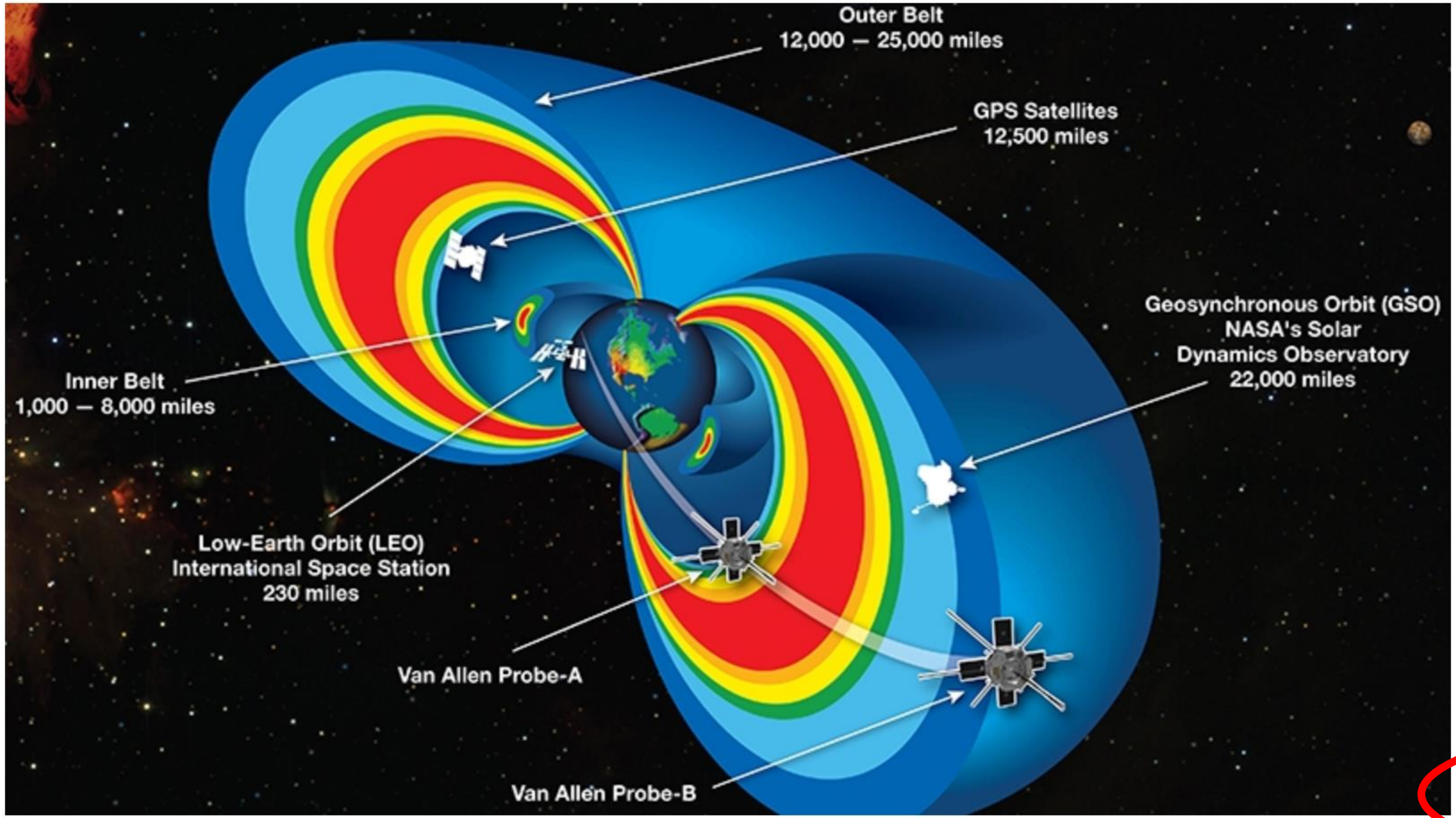


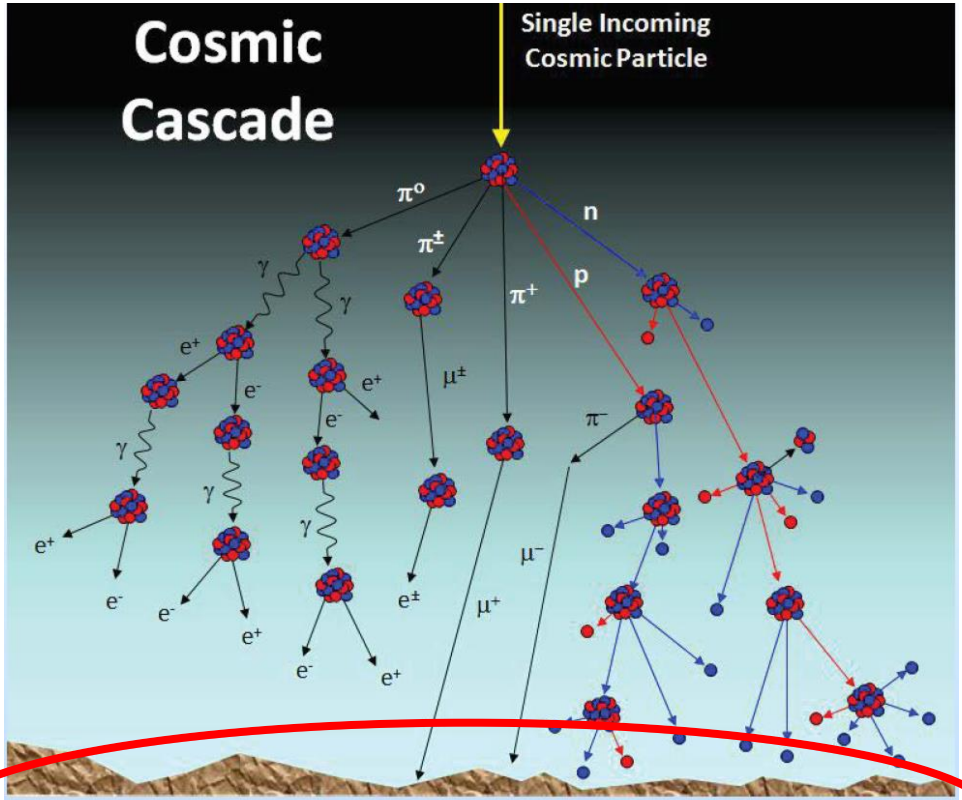




Particle Detection / Radiation Analysis

The Problem: Radiation Environment Around the Earth Is Critically Damaging to Electronics; Requires Radiation Hardening





R. C. Baumann, *IEEE NSREC Short Course*, 2013.

Even on the Earth's surface, radiation impacts reliability of electronic systems

Radiation Effects Are Broadly Classified into Two Areas

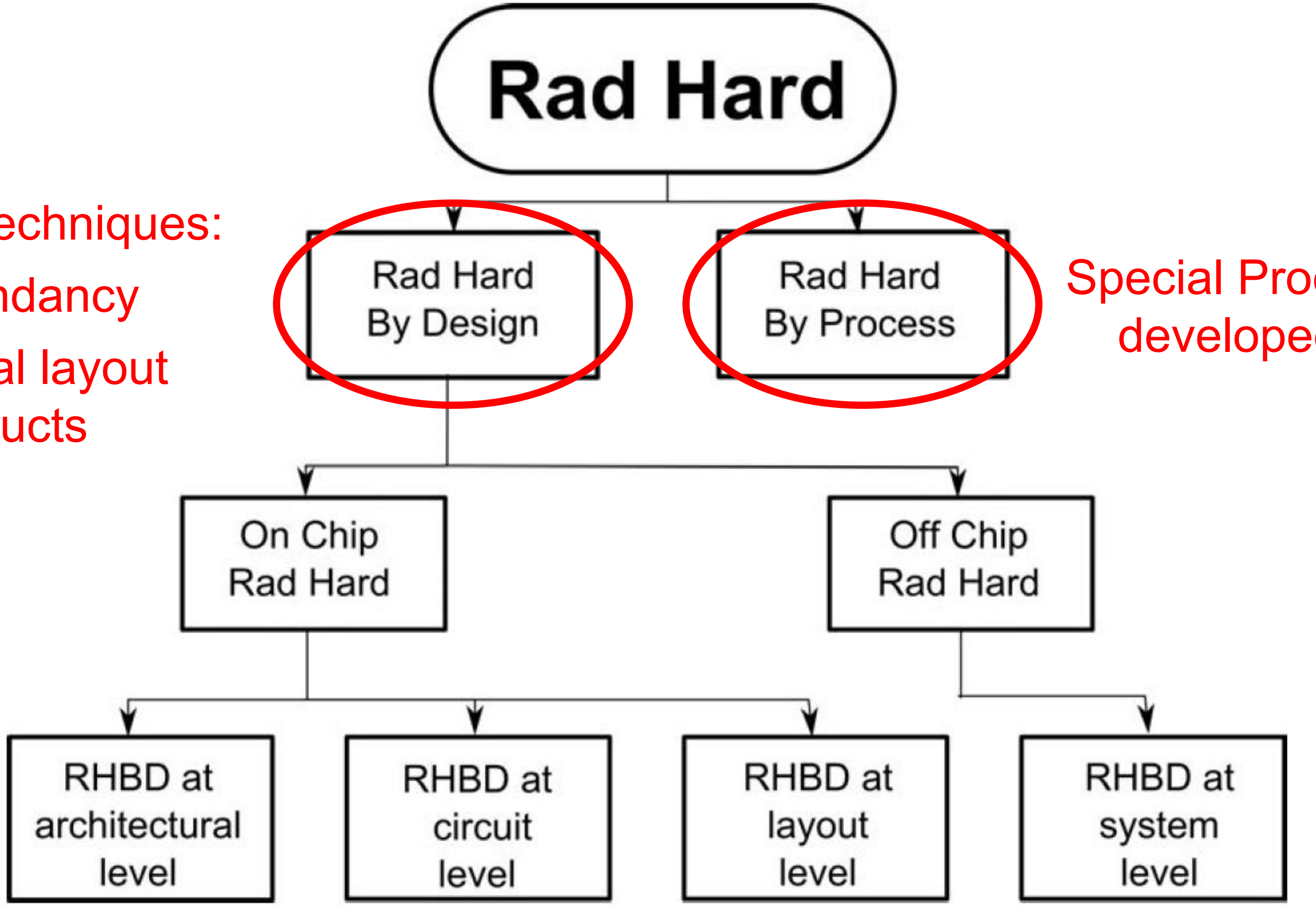
Cumulative effects
- Displacement damage
- Total ionizing dose (TID)

Single event effects (SEE)
- Non-destructive effects
  - Single event transient (SET)
  - Single event upset (SEU)
  - Single even function interrupt
- Destructive effects
  - Single event latchup
  - Single event snapback
  - Single event burnout
  - Single event gate rupture

There are Two Main Techniques for Radiation Hardening

Design Techniques:

- Redundancy
- Special layout constructs



Special Process Techniques developed by foundries

RHBD = Rad-Hard By Design

Heavy Ion Model

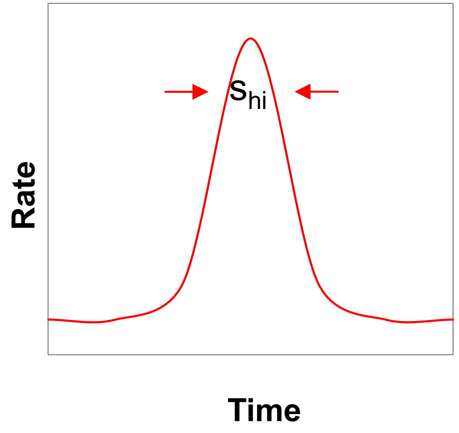
- Analytical generation model dependent on ion LET
- Customizable model through API: Physical Model Interface (PMI)

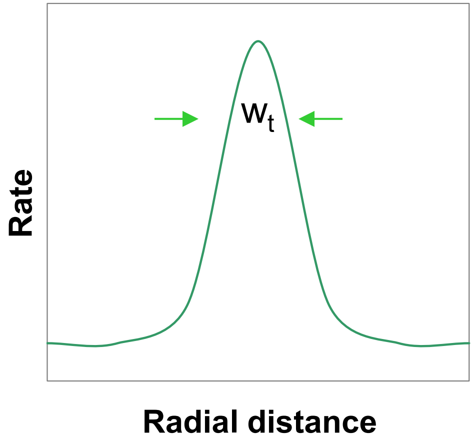
Electron-hole generation rate: $G(l,w,t) = T(t) \times R(w,l) \times G_{LET}(l)$

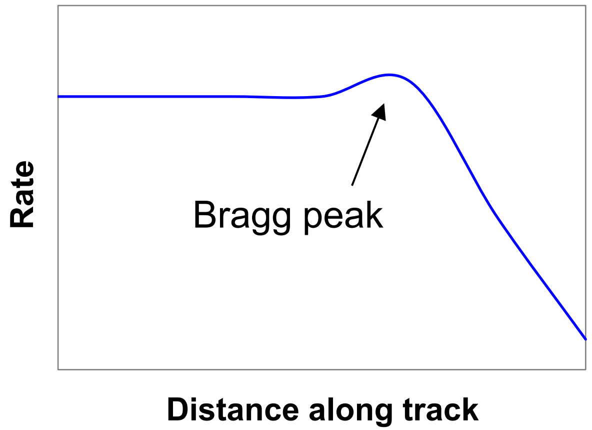
$$T(t) = \frac{2 \cdot \exp\left(-\left(\frac{t - time}{s_{hi}}\right)^2\right)}{s_{hi}\sqrt{\pi}\left(1 - erf\left(\frac{time}{s_{hi}}\right)\right)}$$

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

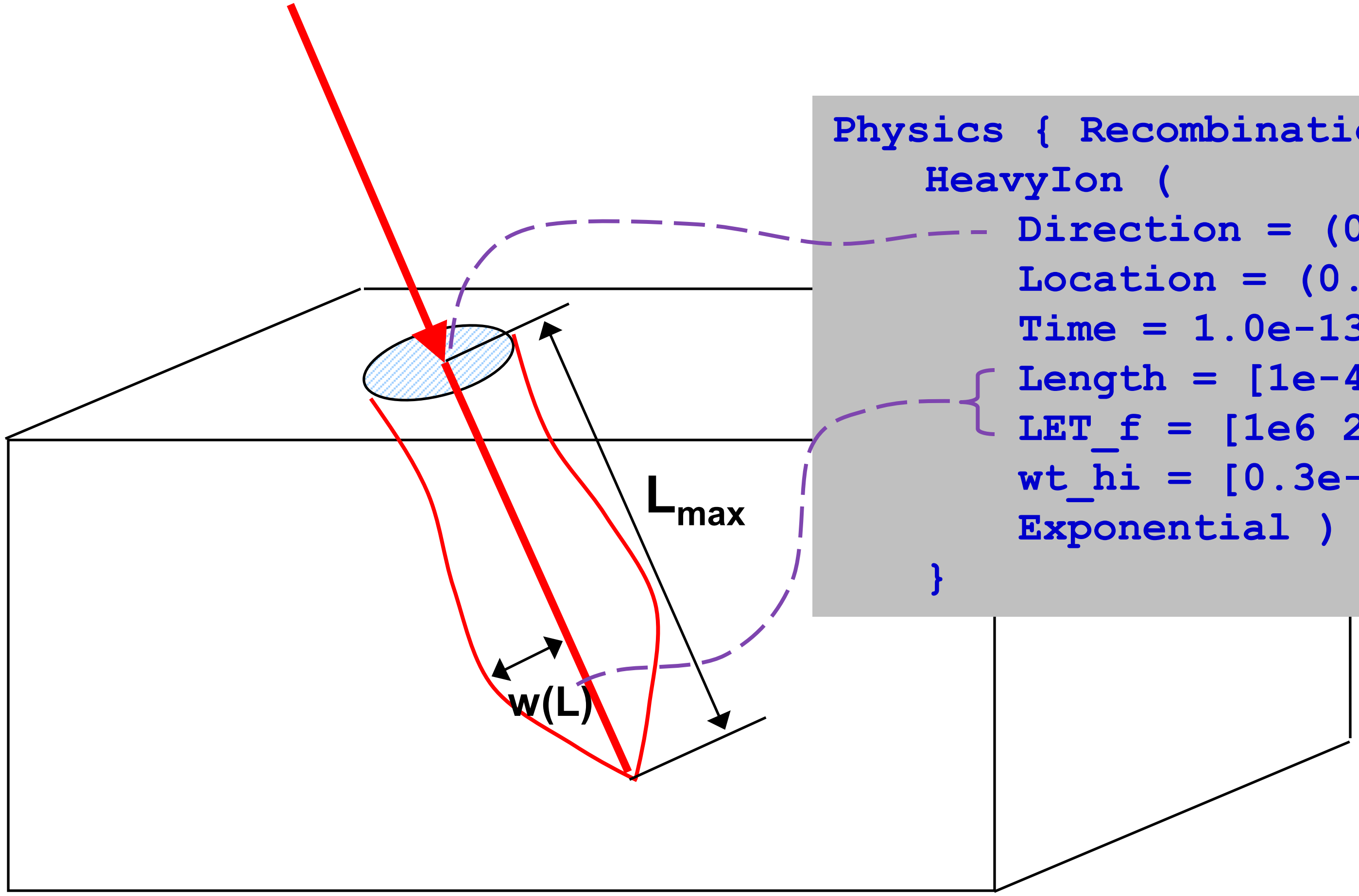
$$G_{LET}(l) = a_1 + a_2 \times l + a_3 e^{a_4 \times l} + k'\left[c_1 \times (c_2 + c_3 \times l)^{c_4} + LET\_f(l)\right]$$







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 )
    }
```

TID Simulation Approach

- The received radiation dose is transferred into a space charge, captured by traps located in dielectric

- Carrier generation by gamma radiation with electric field dependent yield function:

```
Physics {
   Radiation (
     DoseRate = @DoseRate@
     DoseTime = (50,500)
     DoseTSigma = 2
     )
}
```

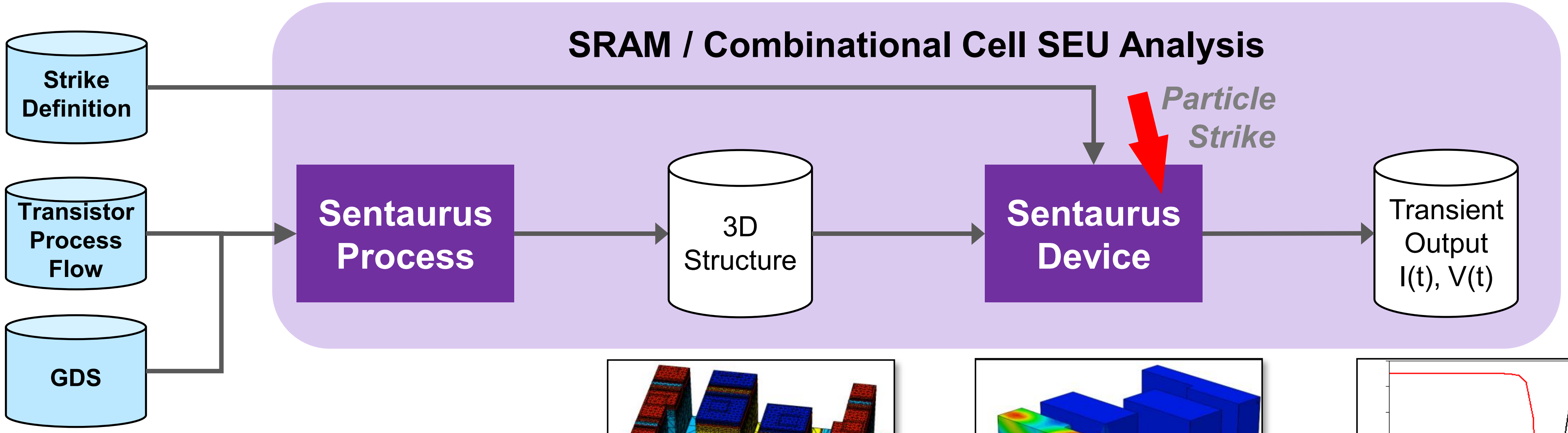
$$G_r = g_0 D \cdot Y(F)$$

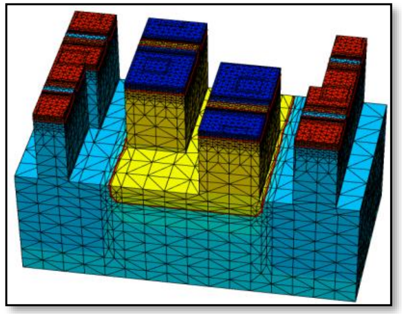
$$Y(F) = \left(\frac{F + E_0}{F + E_1}\right)^m$$

- Oxides are defined as `OxideAsSemiconductor` where transport and local trap capture and emission equations are solved

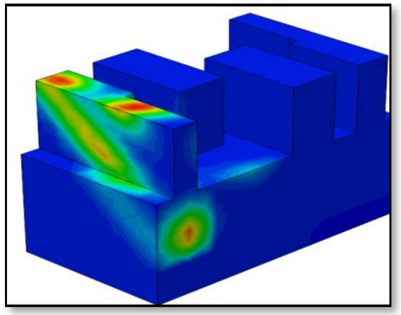
```
Physics(Material="OxideAsSemiconductor"){
    Traps (
    (Donor Conc=@Conc@ Level EnergyMid=@EMid@ FromMidBandGap
        eXsection = 1e-11 hXsection = @xSec@ )
    )
}
```

SRAM / Combinational Cell Single Event Upset (SEU) Simulation Flow

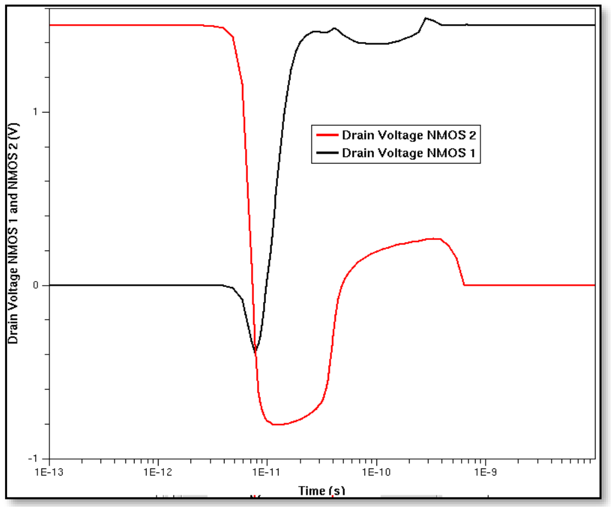




Process structure meshed for device simulation

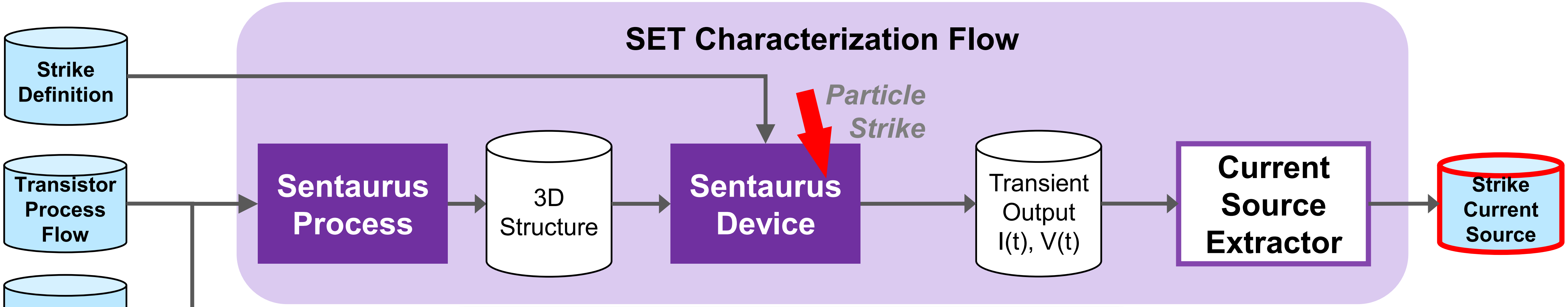


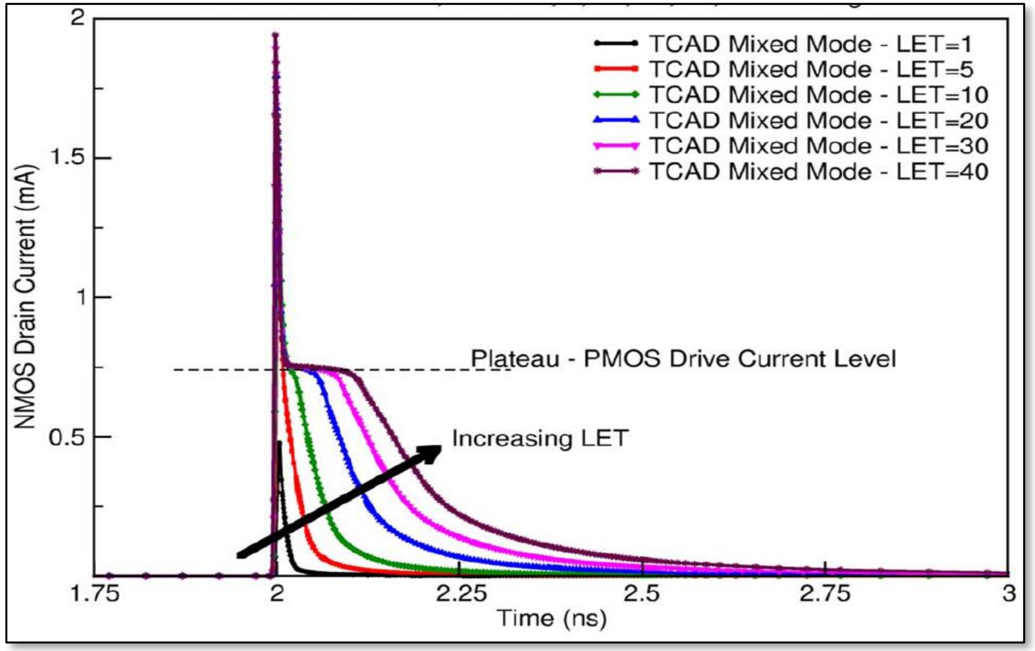
Charge collection in structure is input for transient device simulation

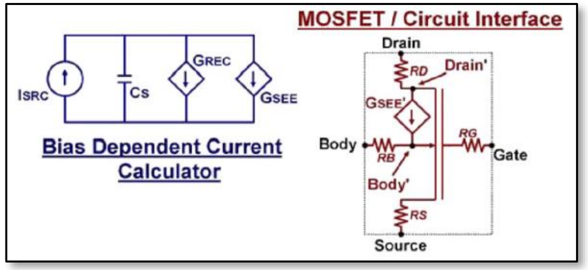


Transient output indicates if bit is upset for specific strike definition

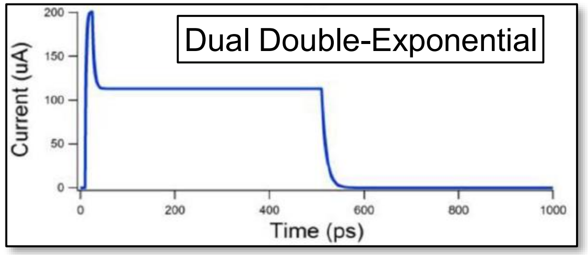
Single Event Transient (SET) Characterization Flow







Kaupilla et al, IEEE Nucl. Sci., 56, (6), Dec 2009



Black et al, IEEE Nucl. Sci., 62, (4), Aug 2015

Synopsys TCAD has Extensive Capabilities to Support the Design of Semiconductor Detectors

- CMOS Image Sensors (CIS), with focus on 3D process optimization and co-design with amplifier circuits
- Single Photon Avalanche Photodiodes (SPAD)

Thank you for your attention

www.synopsys.com/TCAD

Contact us at: tcad_team@synopsys.com

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