Simulation of Photodetectors and Radiation Effects in Synopsys TCAD

SIMDET 2021

Synopsys TCAD Team
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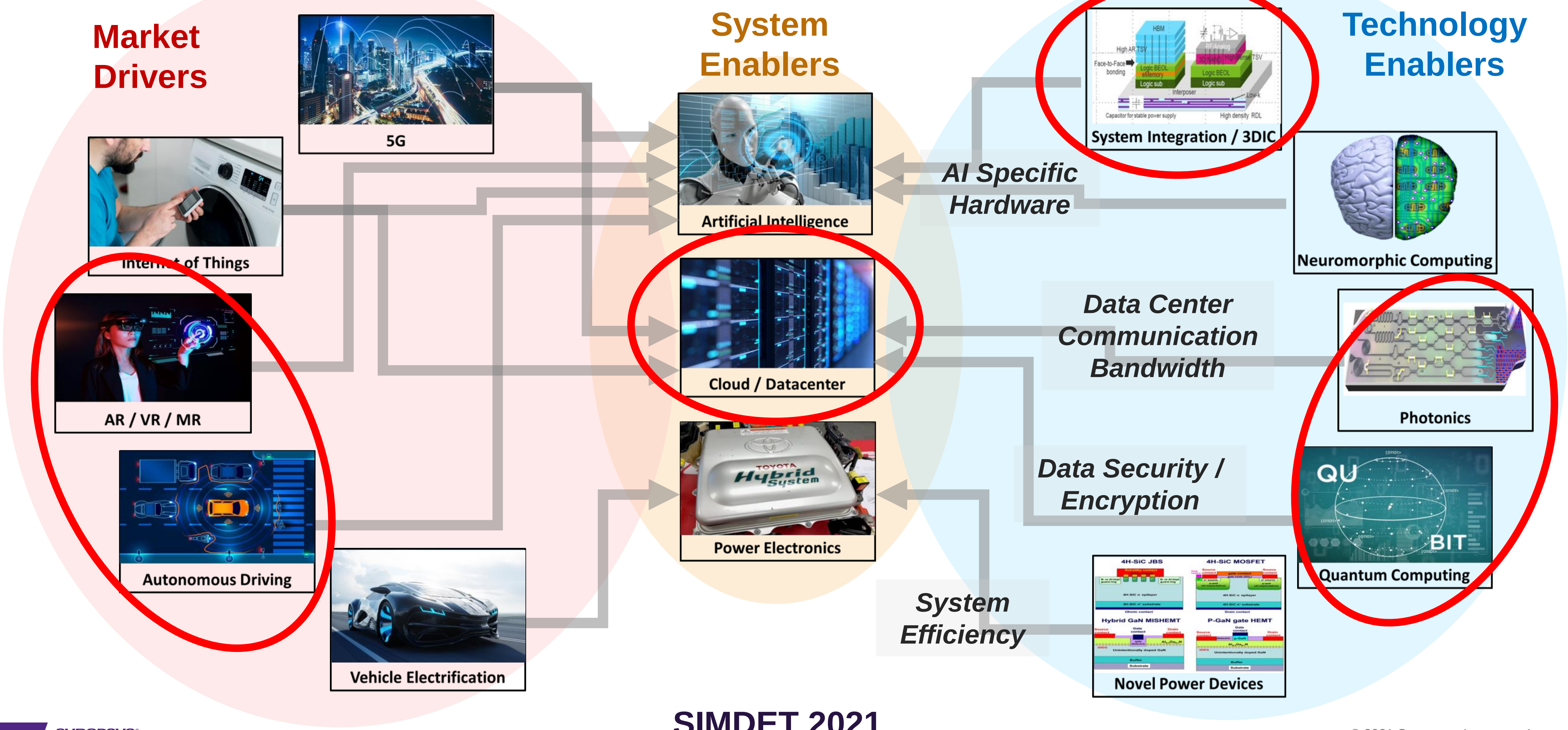
29 November 2021

Outline

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

Semiconductor Industry Trends

Transformational Applications Continue to Motivate and Drive Semiconductor Industry Growth



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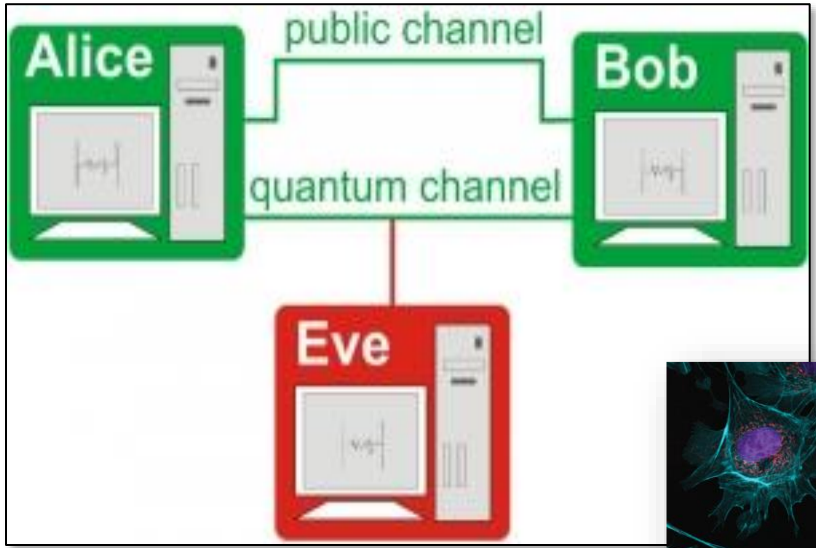
Optical Sensors and Detectors Are Pervasive in Consumer Applications …

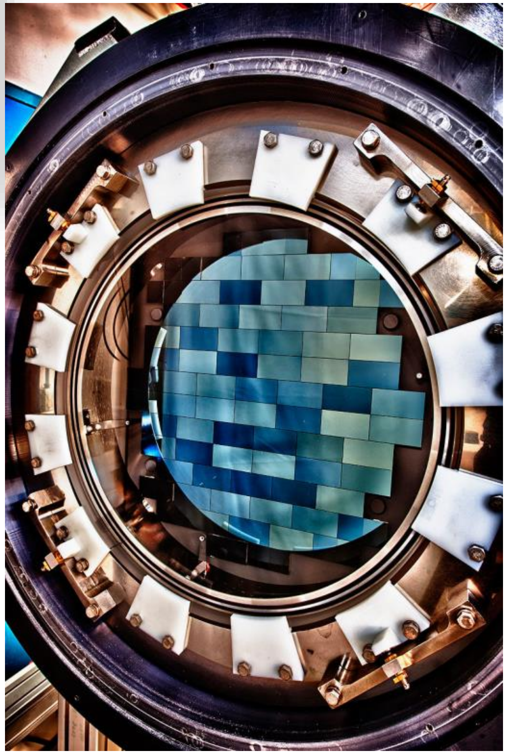
… And Are System Enablers in Industrial and Scientific Applications

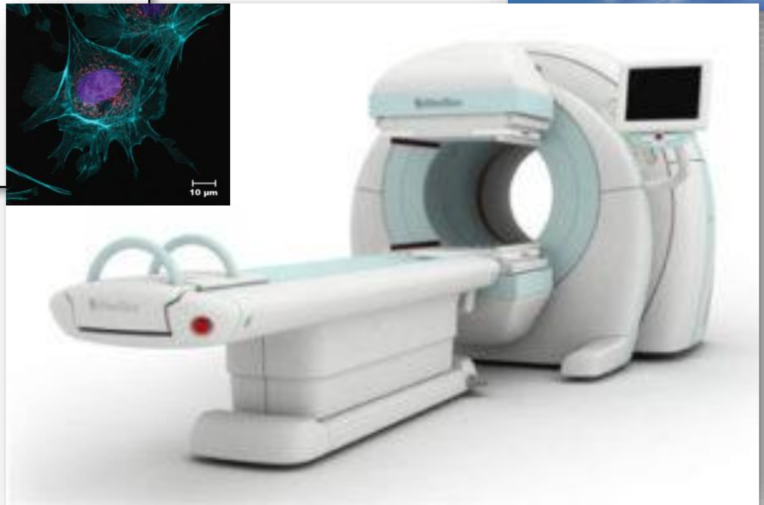
Quantum Communication / Optical Quantum Computing



Remote Sensing / Ranging

Particle Physics





Medical Imaging

Photodetector Simulation

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

Synopsys TCAD Product Family is the Industry Leader

Atomic-Scale Modeling
- QuantumATK
- QuantumATK Nanolab
- Sentaurus Materials Workbench

Process Simulation
- Sentaurus Process
- Sentaurus Topography

Process Emulation
- Sentaurus Process Explorer

Structure Editing
- Sentaurus Structure Editor

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

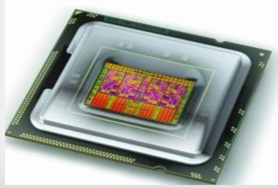
Environment
- Sentaurus Workbench
- Sentaurus Visual

TCAD To SPICE
- Garand VE
- Mystic
- RandomSpice

- 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

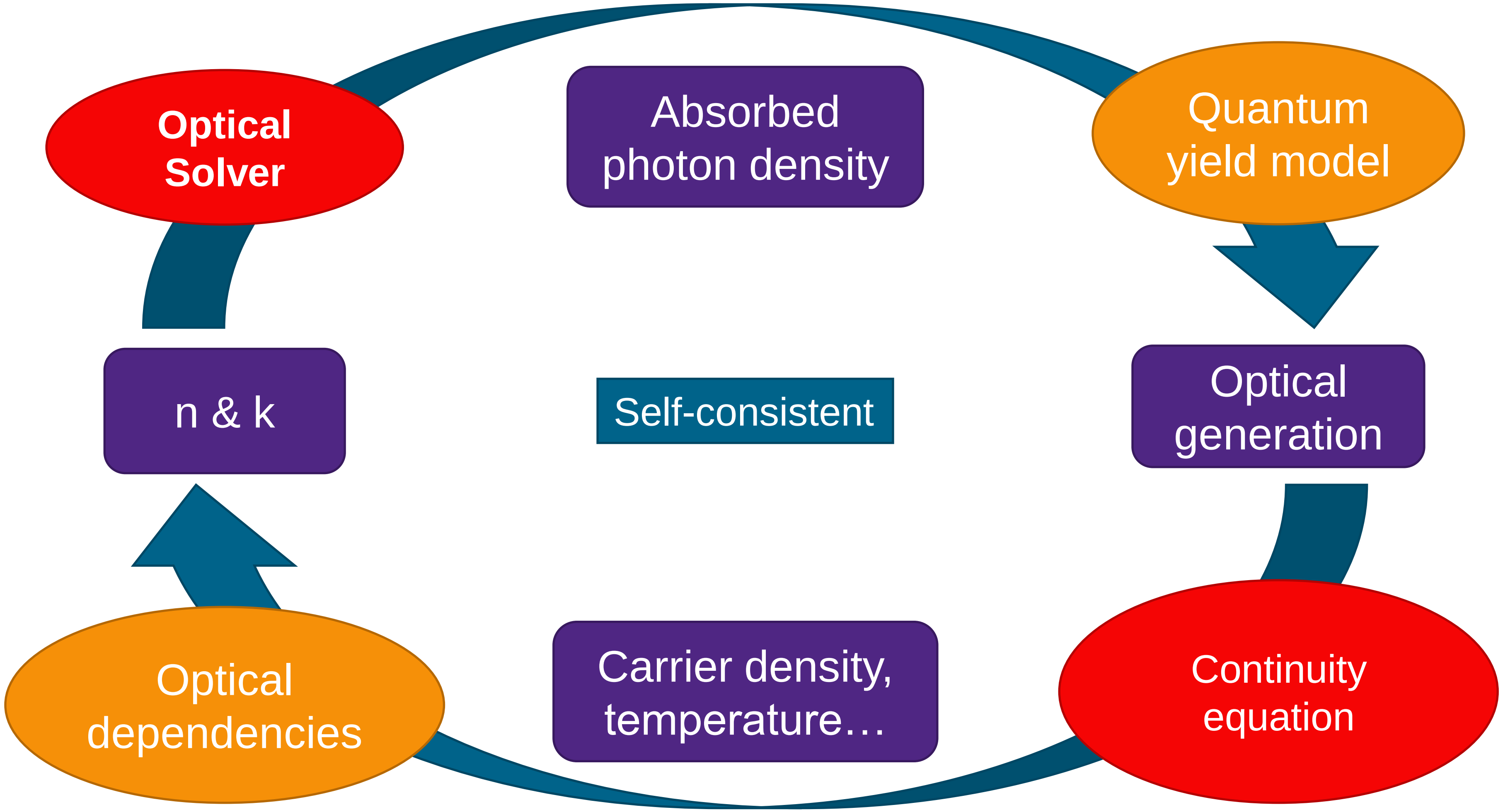
Sentaurus Covers All Major Semiconductor Segments

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

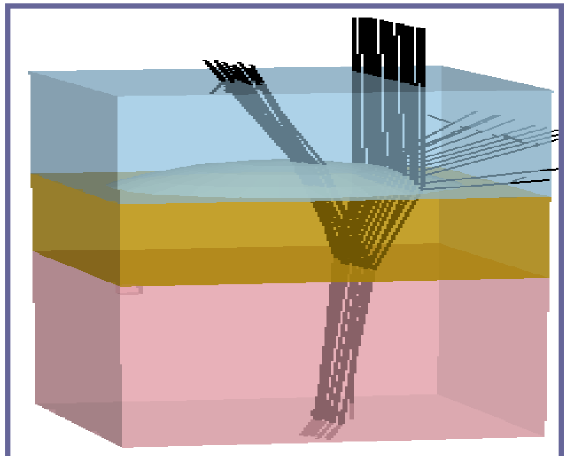


Logic	Memory	Power	Analog/RF	Opto
Planar CMOS	NAND / NOR Flash	Si IGBT	SiGe HBT	CIS
FinFET	DRAM	SJ-LDMOS	GaAs HEMT	CCD
Nanowire FET	3D NAND	BCD	GaAs HBT	Photodetectors
Tunnel FET	PRAM	SiC	GaN HEMT	Silicon Solar Cells
Research Devices	STT-RAM	GaN	SiC MESFET	III-V Solar Cells

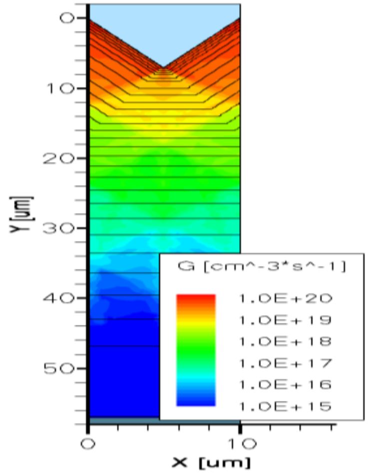
General Optoelectronics Simulation Flow



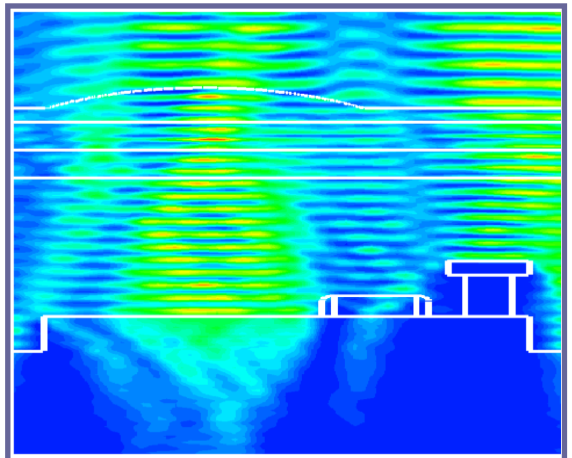
Optical Models in Sentaurus Device



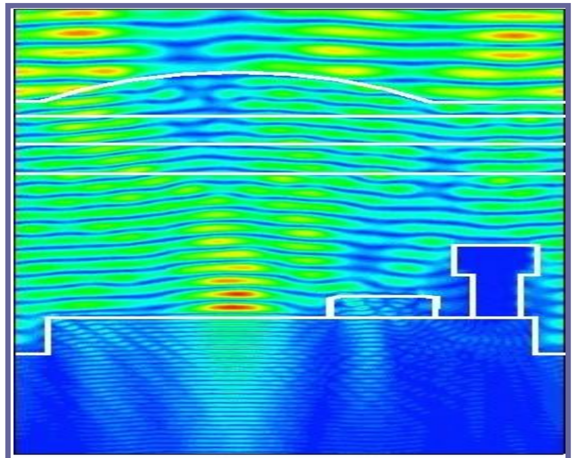
Ray Tracing (RT)



Transfer Matrix Method (TMM)



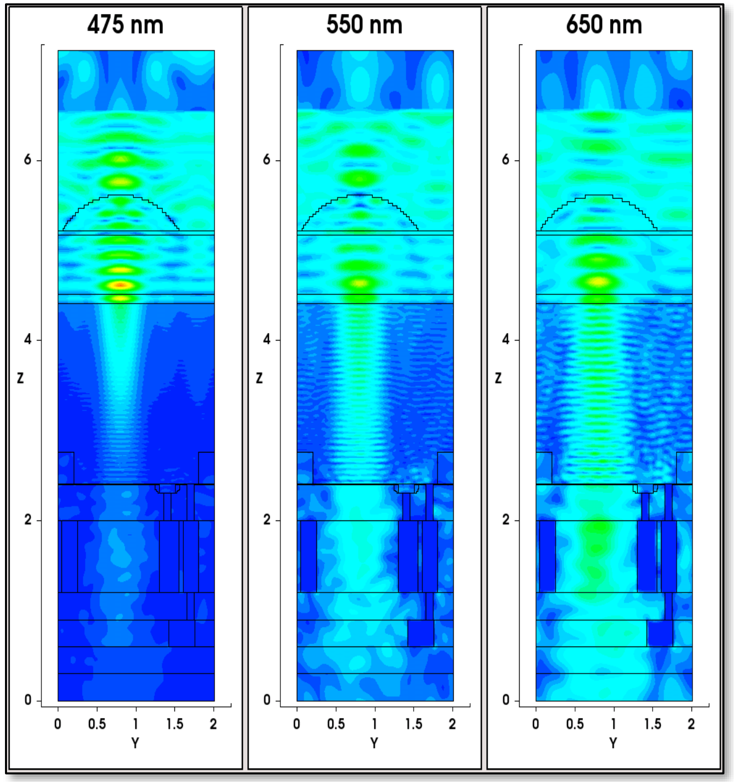
Beam Propagation Meth. (BPM)

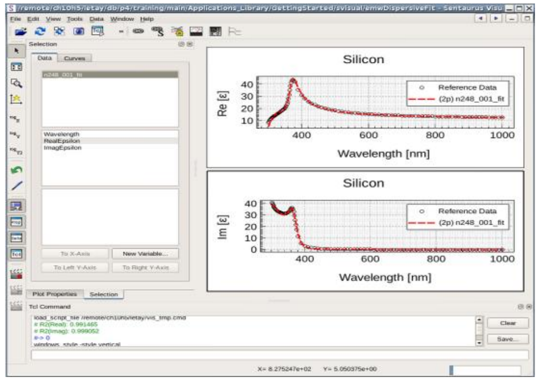


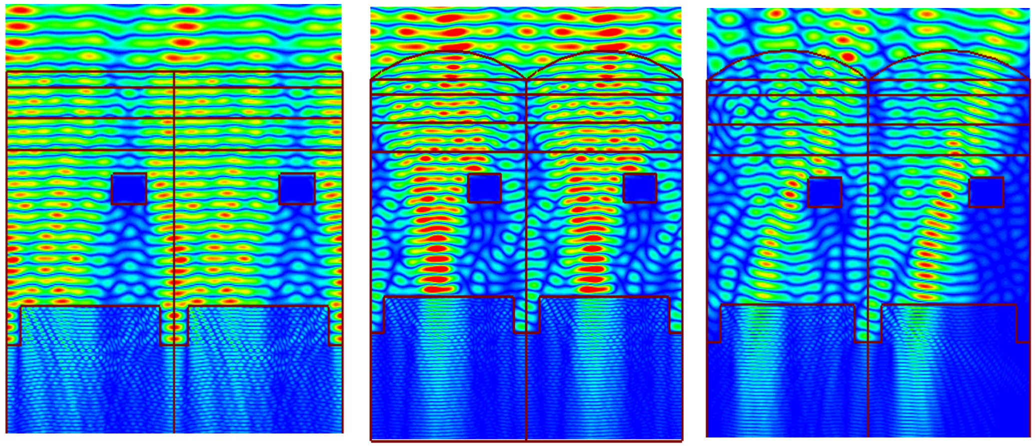
Electromagnetic Solver (EMW)

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







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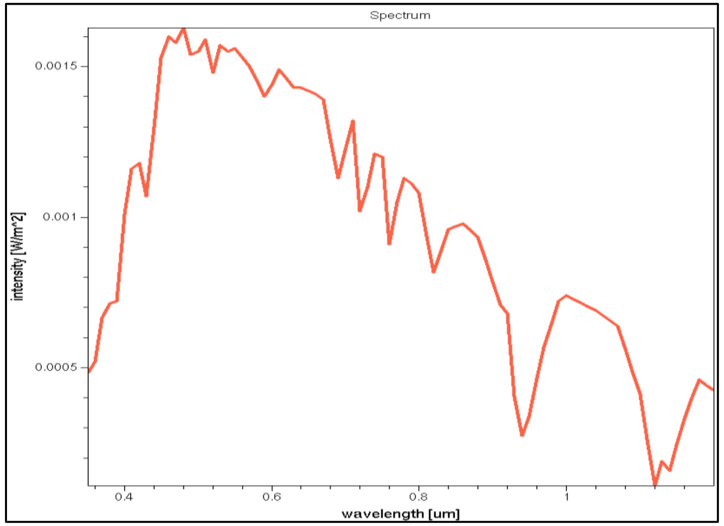
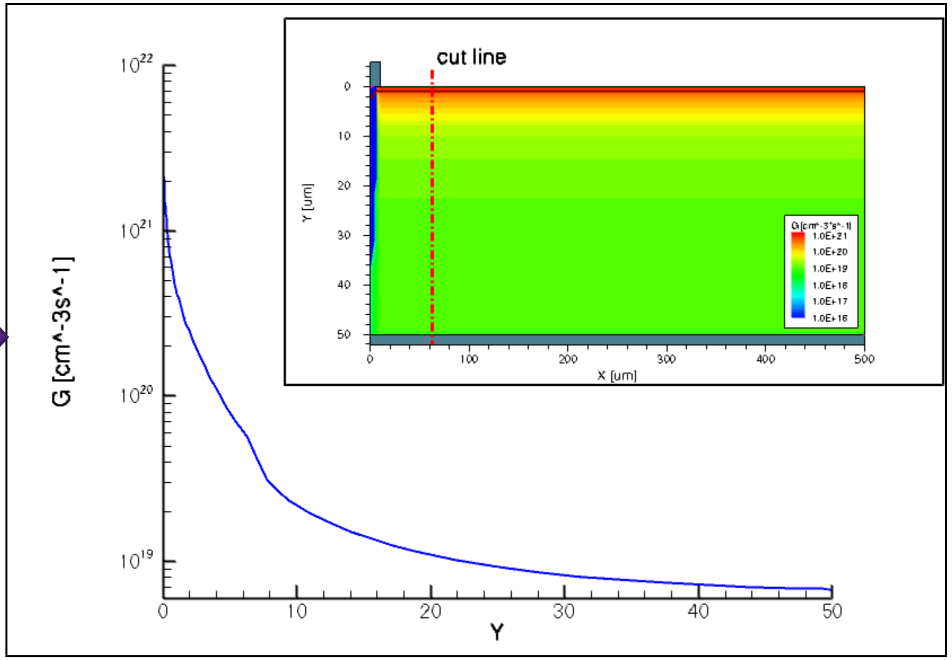
Optical Generation is Calculated as a Function of Depth and λ

- 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:	$\nabla \cdot \mathbf{J}_n - q\frac{\partial n}{\partial t} = q(R - G) \quad -\nabla \cdot \mathbf{J}_p - q\frac{\partial p}{\partial t} = q(R - G)$

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

$$\mathbf{J}_n = -nq\mu_n \nabla \Phi_n \qquad \mathbf{J}_p = -pq\mu_p \nabla \Phi_p$$

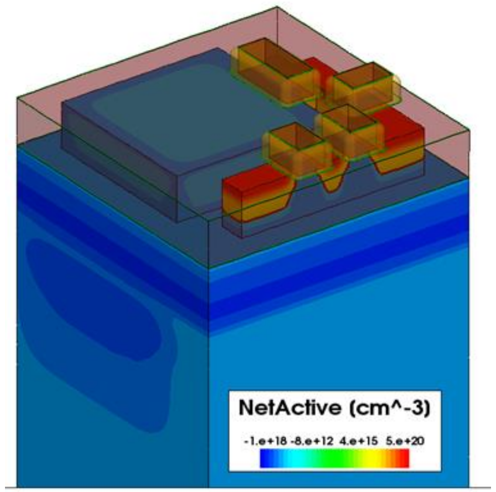
- Solution modes:
  - Quasi-static (I-V curves, EQE vs λ, etc)
  - Transient (light pulses, current/voltage pulses)
  - Small-Signal AC (responsivity, …)

Photodetector Simulation

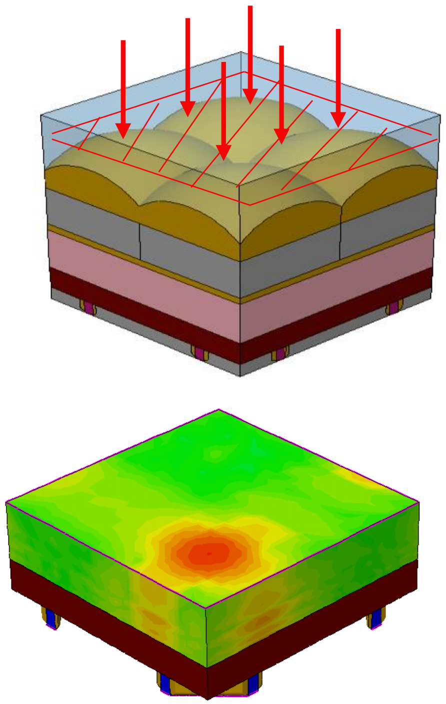
- Optical Solvers in Sentaurus
- **CMOS Image Sensors**
- Single-Photon Avalanche Photodetectors
- Superconducting Nanowire Single-Photon Detectors

Sentaurus Offers a Fully Integrated TCAD Solution for CIS

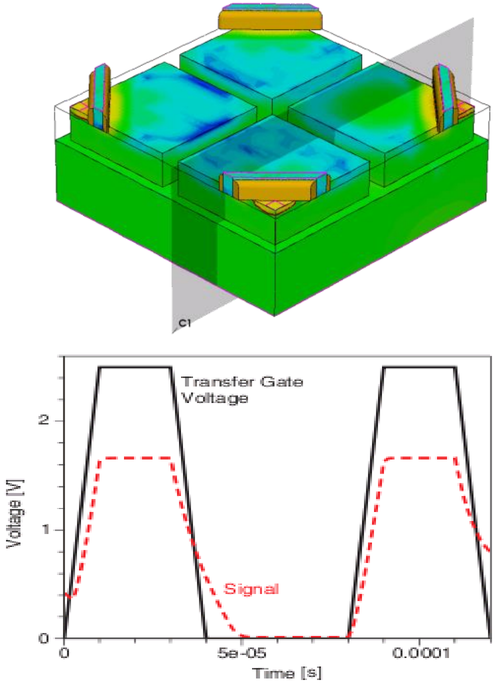
Process / Structure Simulation



Optical Simulation

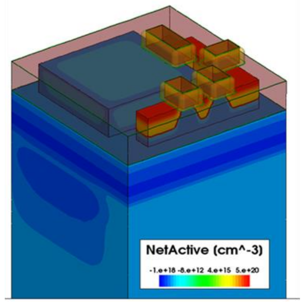


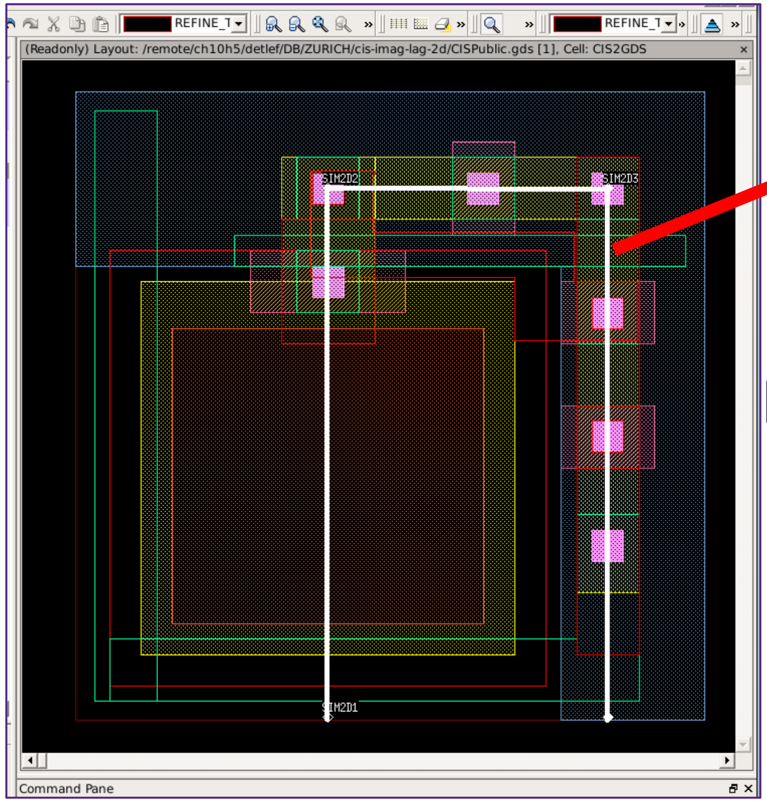
Electrical Simulation

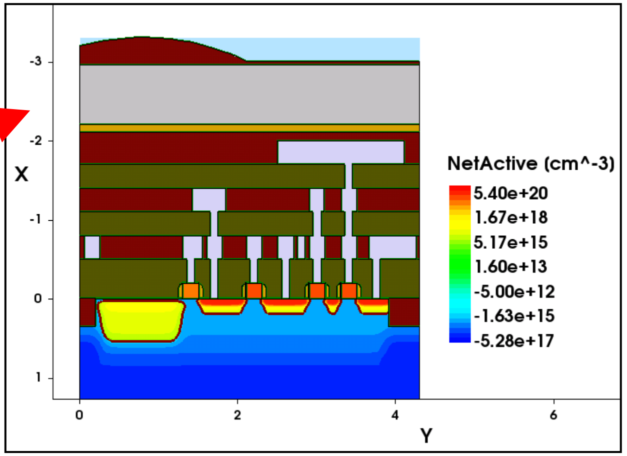


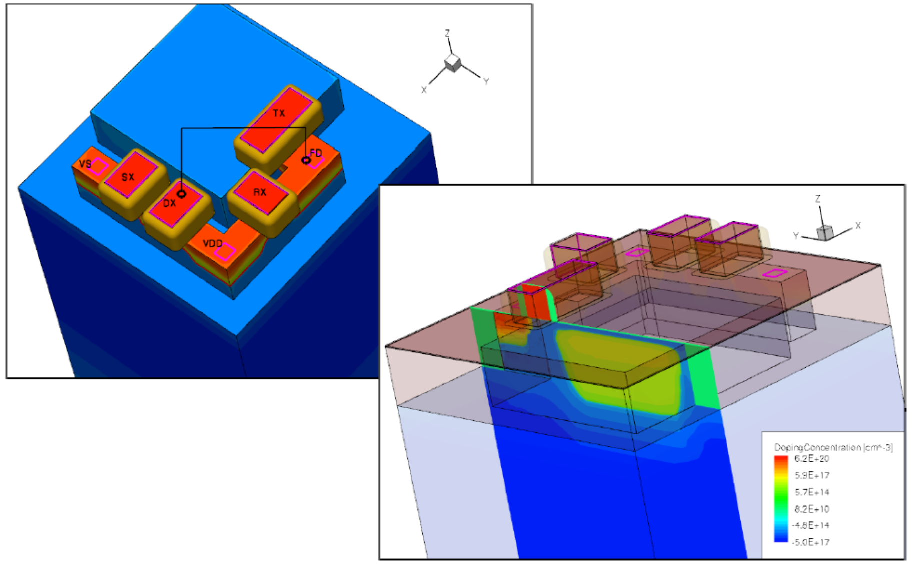
Sentaurus Provides a Capability to Generate CIS Structures from Mask Information

Process / Structure Simulation

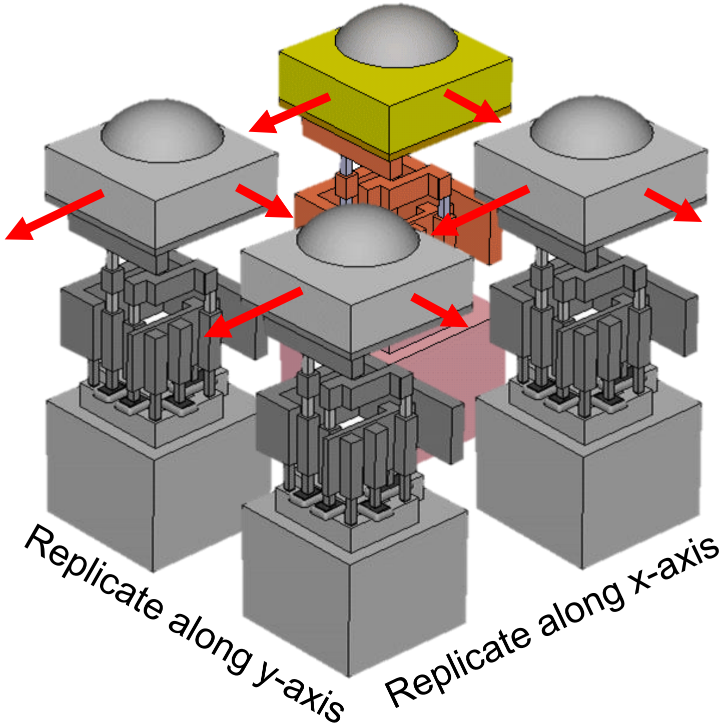


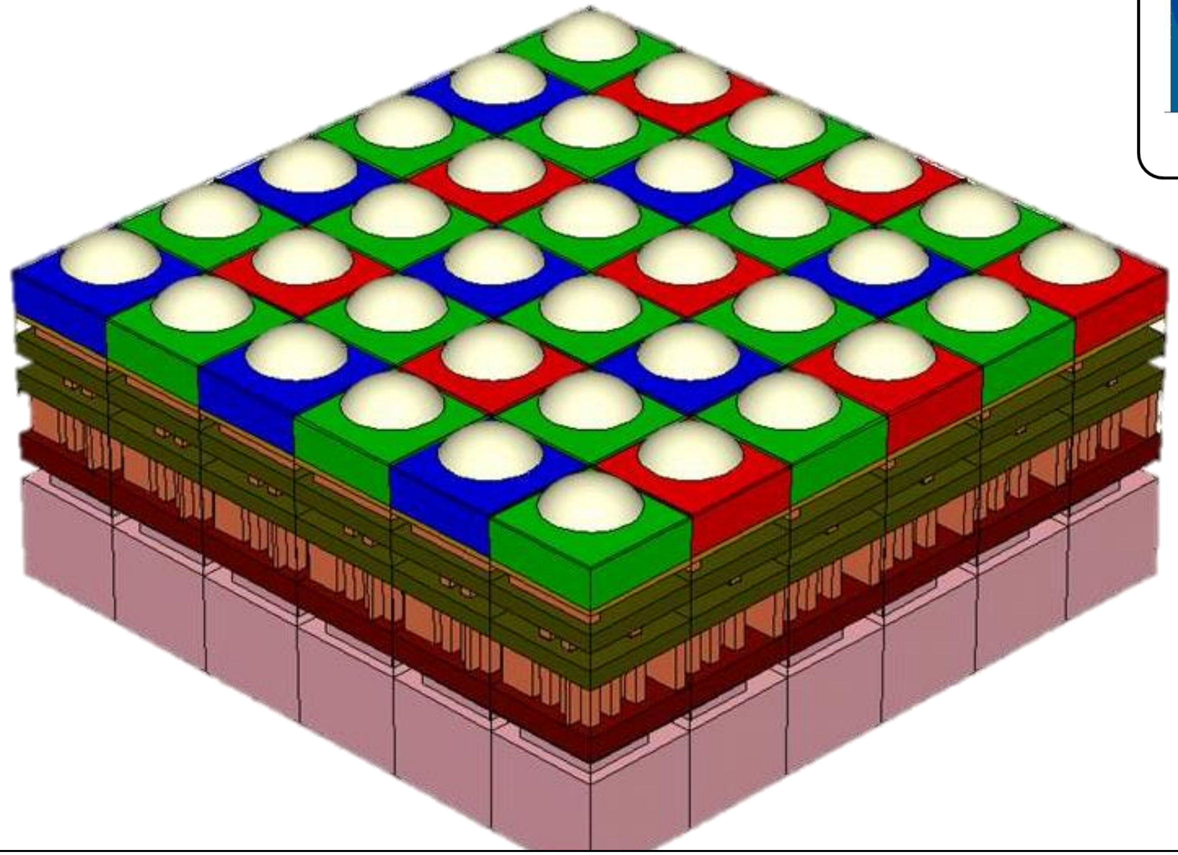




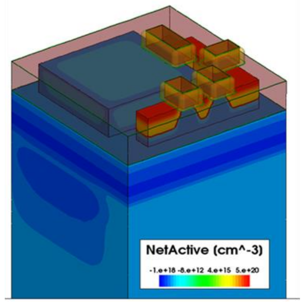


Sentaurus Offers Flexible Ways to Replicate CIS Structures to Construct Pixel Arrays



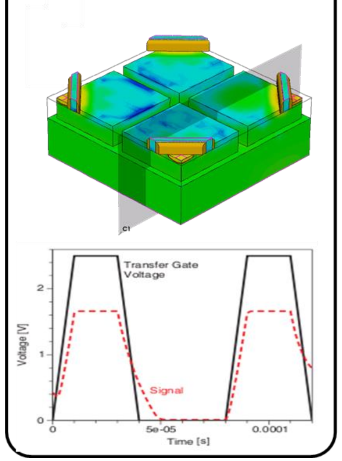


CIS pixel array with Bayer color filter pattern applied



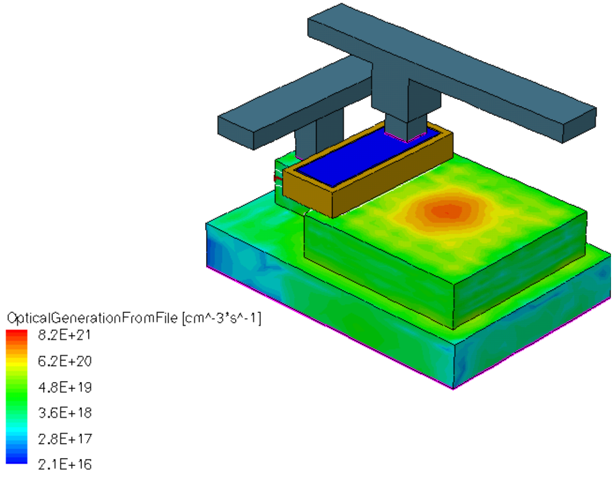
Device Simulation Enables Analysis and Mitigation of Crosstalk

Electrical Simulation

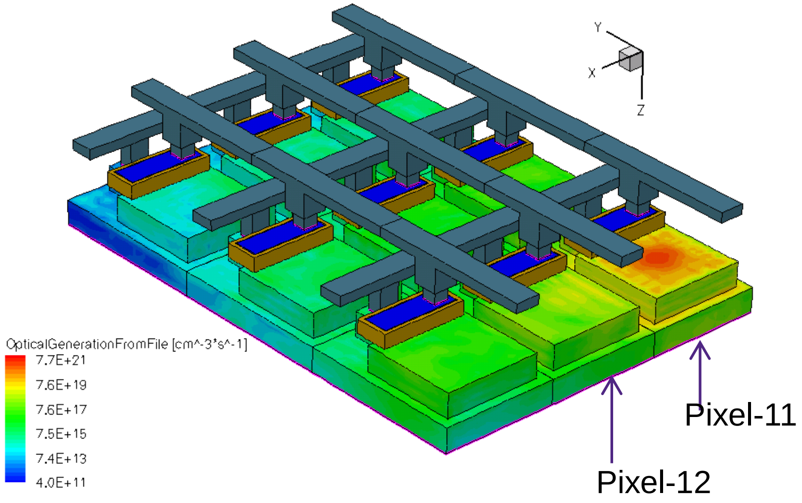


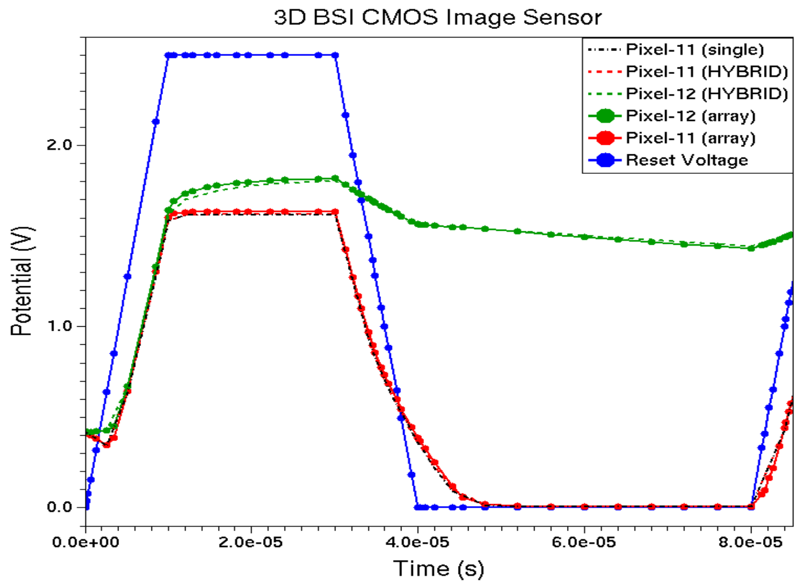
- Electrical simulation is performed on target pixel (11) and adjacent pixel (12) to investigate optical cross talk
- Change to potential in pixel 12 after reset indicates crosstalk

Single Pixel



Pixel Array





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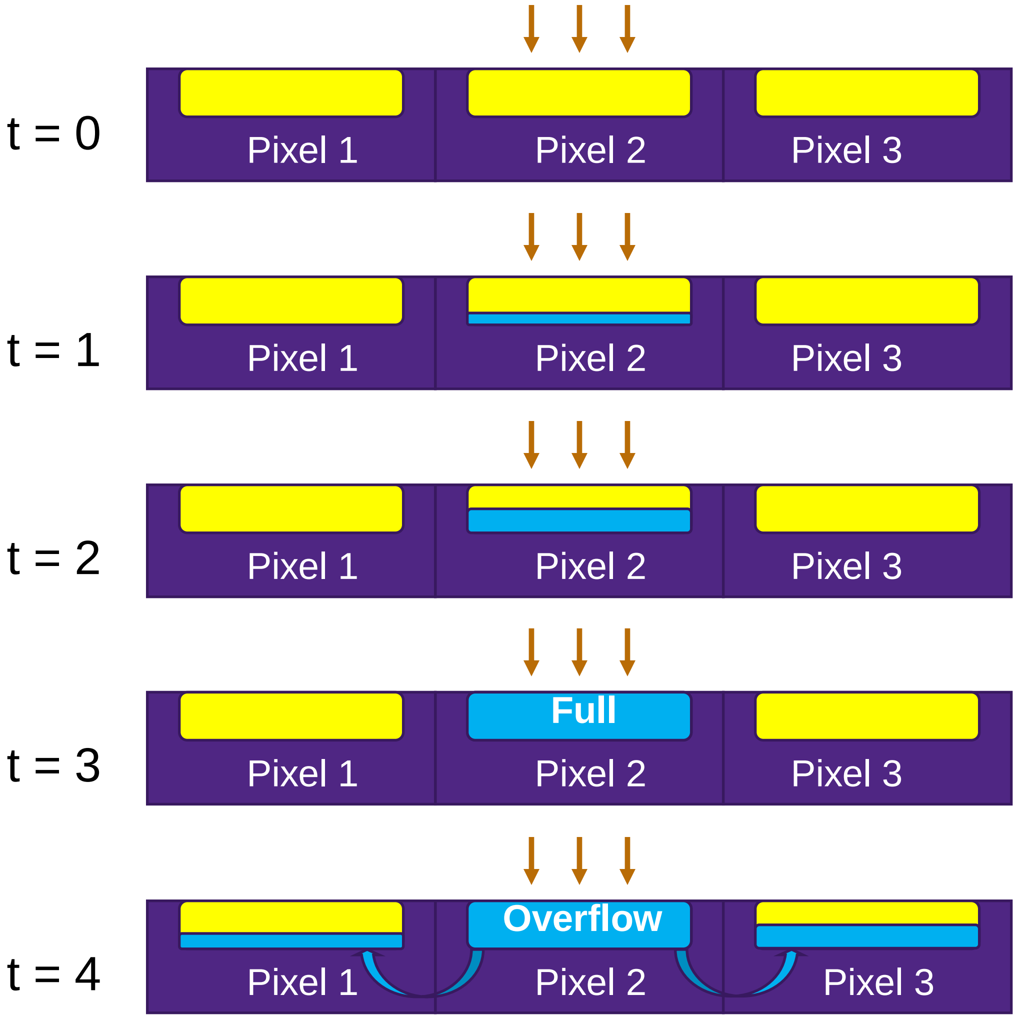
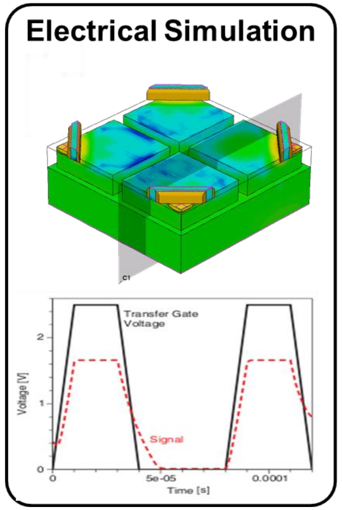
Analysis of Blooming Effect

- 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





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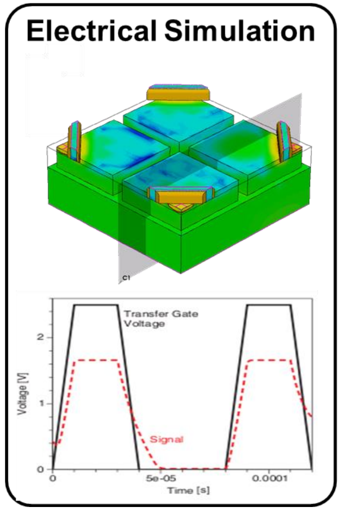
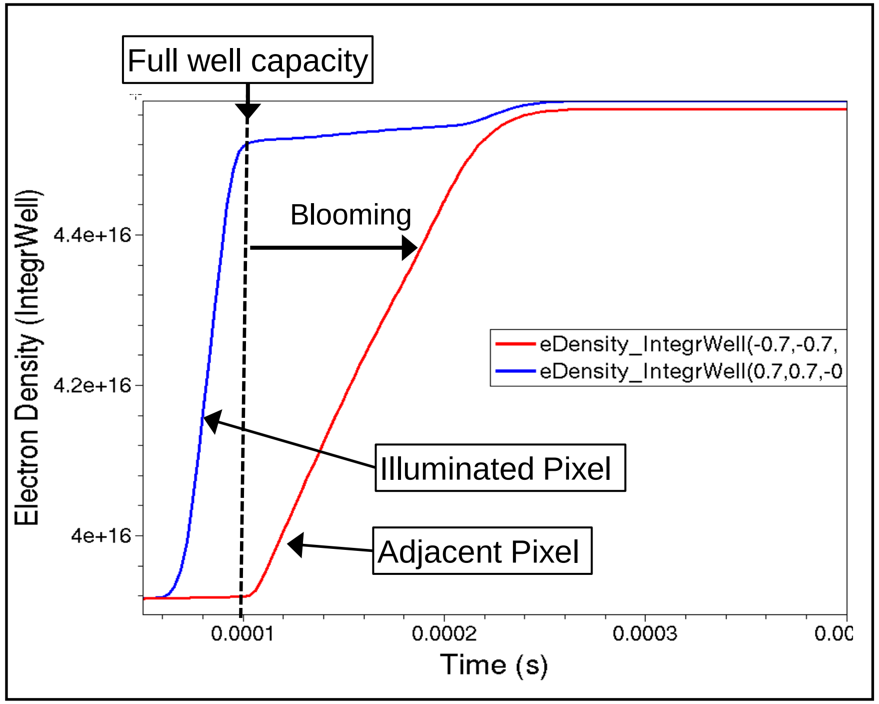
Electrical Simulation Computes the Time Need to Reach Full Well Capacity to Prevent Blooming



- 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)))
   )
}
```

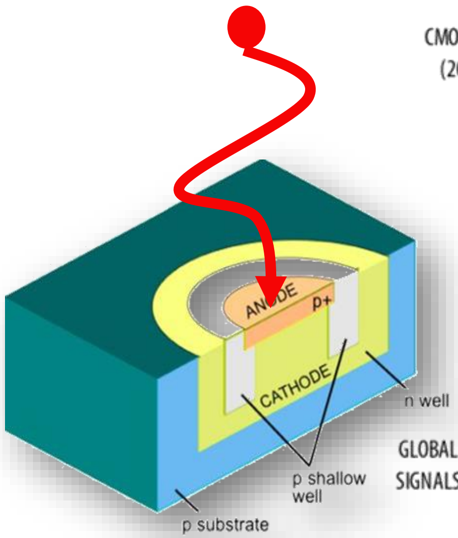


Photodetector Simulation

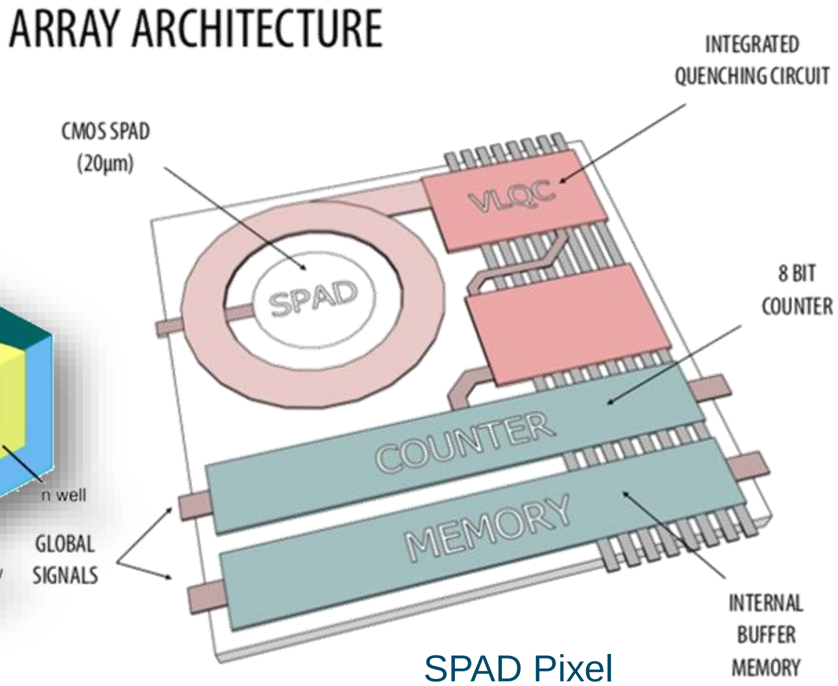
- Optical Solvers in Sentaurus
- CMOS Image Sensors
- **Single-Photon Avalanche Photodetectors**
- Superconducting Nanowire Single-Photon Detectors

Single Photon Avalanche Diodes

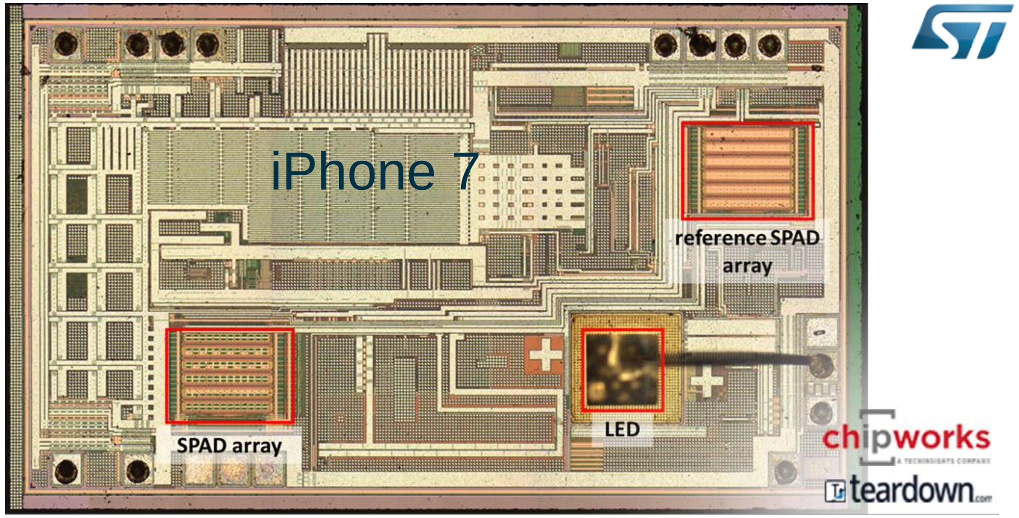
- Device capable of detecting a single photon
  - pn junction biased such that photoexcited carrier rapidly triggers avalanche breakdown
  - Operates as photon counter or Time Of Flight
  - Timing accuracy ~ 30 ps – 100 ps
  - Variation due to stochastic transport and build up
  - More sensitive than 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

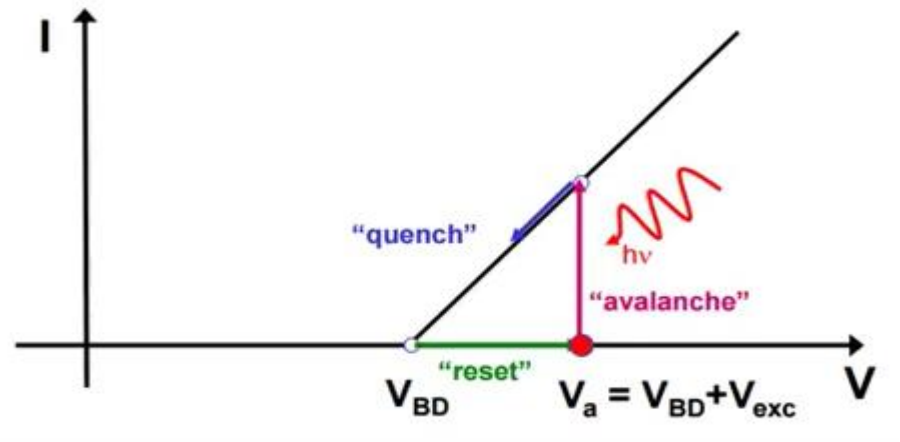


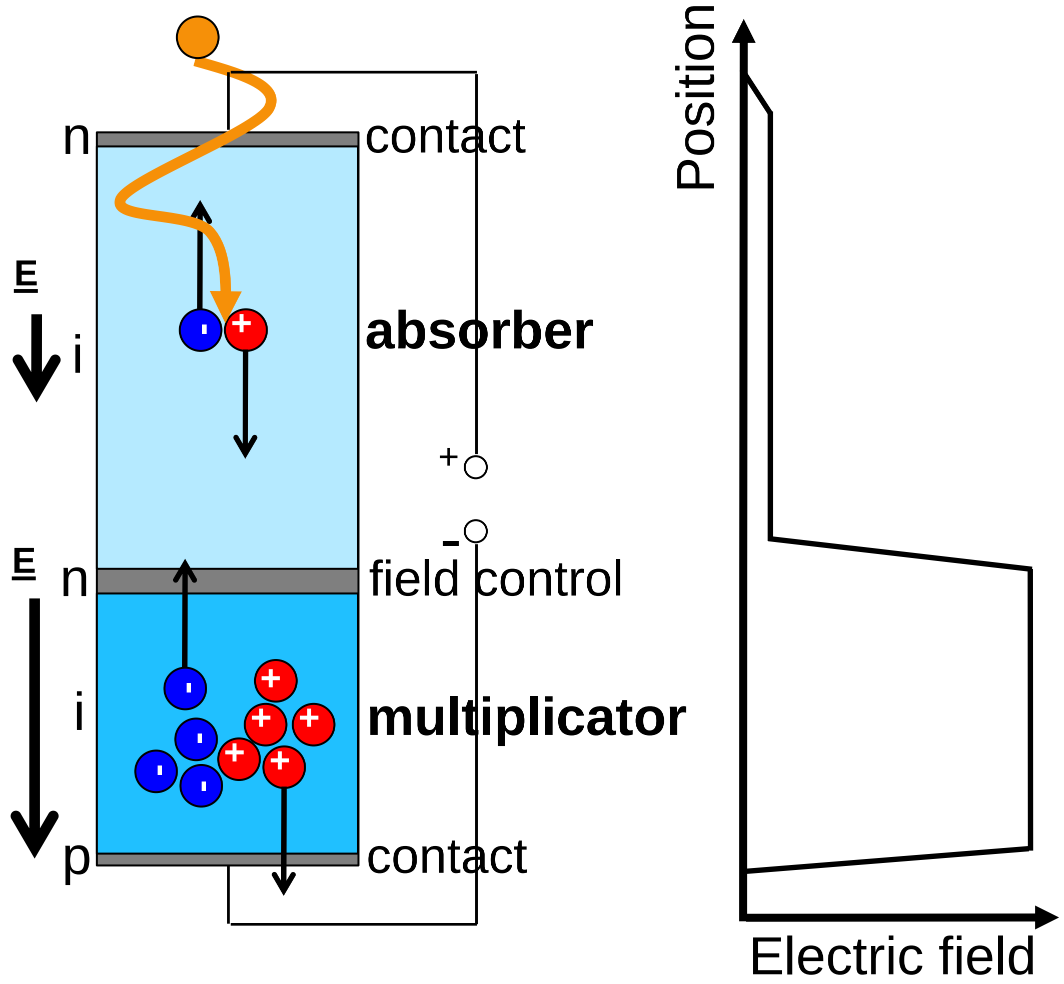
SPAD Pixel



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. Device is ready to detect another photon





Synopsys TCAD SPAD Modelling Approaches

O-2018.06, P-2019.03, Q-2019.12

- 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

R-2020.09

- Full-band Monte Carlo (Garand MC)
  - full physics: dead space, accurate P_e, stochastic distributions
  - computationally more expensive. 2^{nd} DD step required for DCR calculation

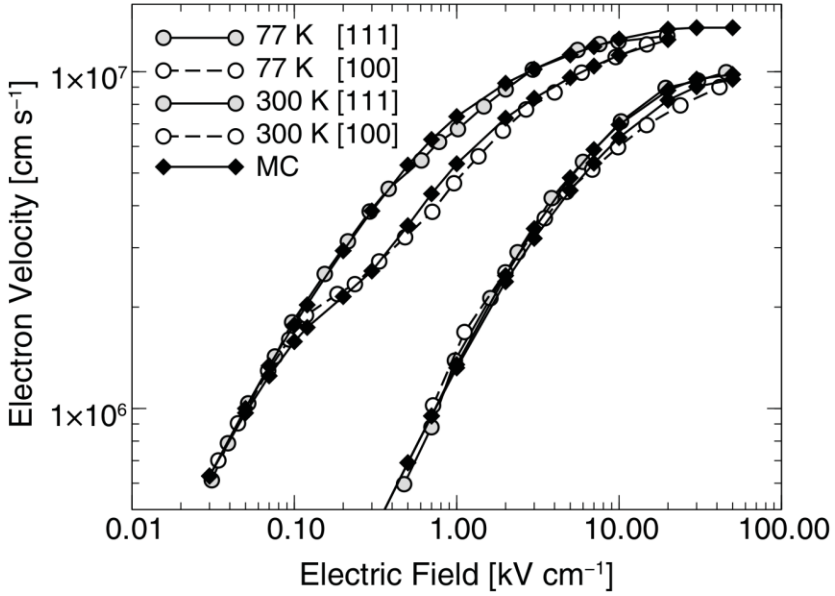
Garand MC – Physical Models

Band Structure

- Efficient analytic or accurate full band models

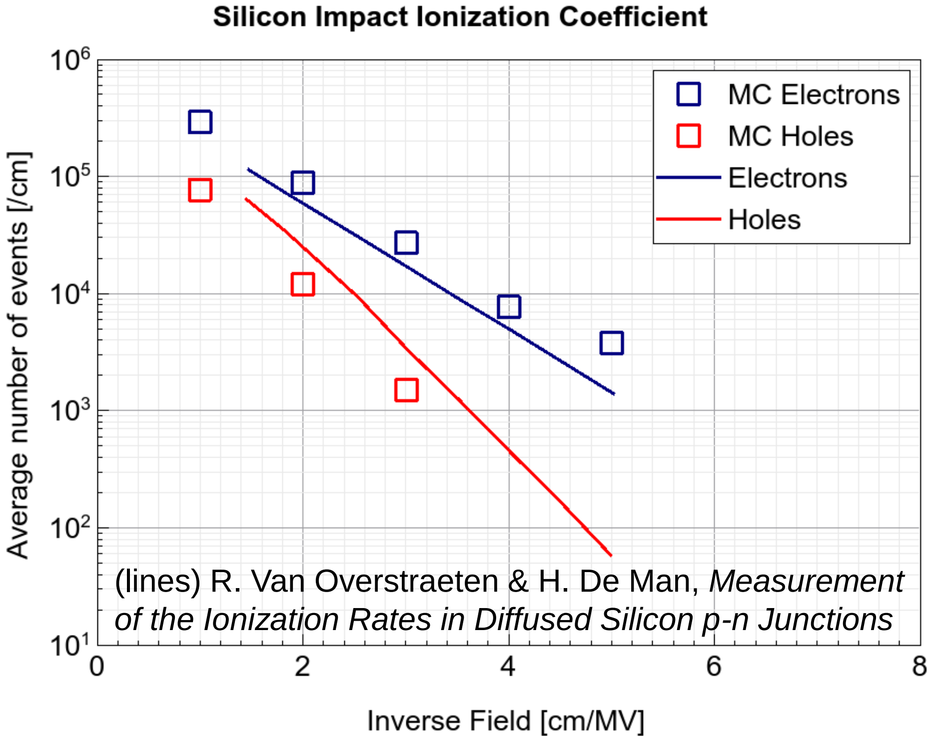
Phonon Scattering

- Well calibrated bulk Silicon transport

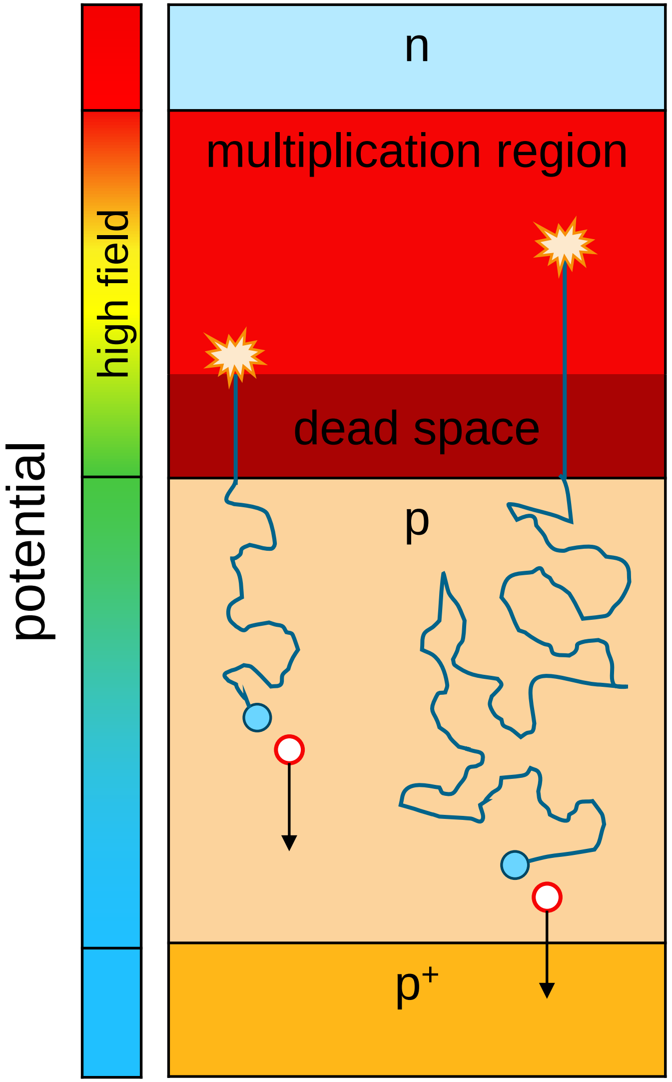


Impact Ionization

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



Detection Time Distribution – Jitter

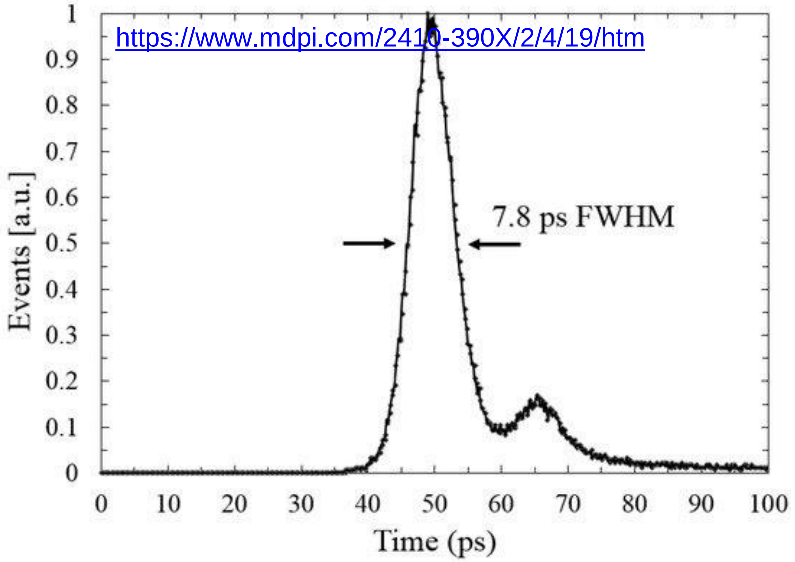


Impact Ionization => random pair creation (Monte Carlo transport)

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

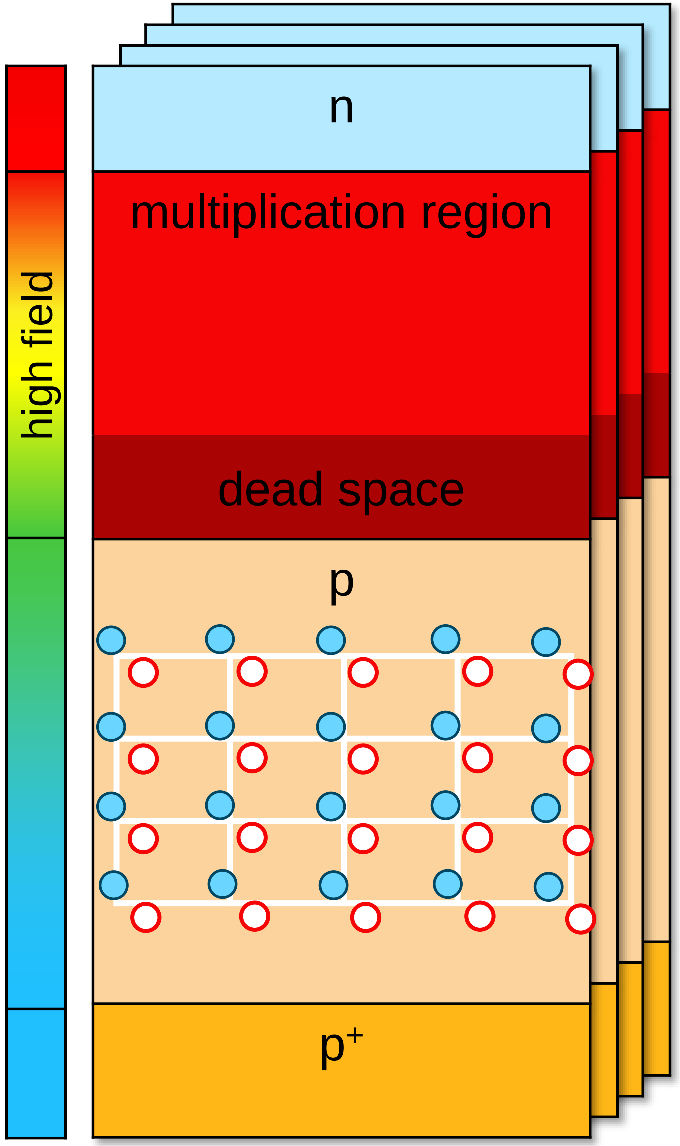
Photon absorption => random pair creation (S-Device optics)

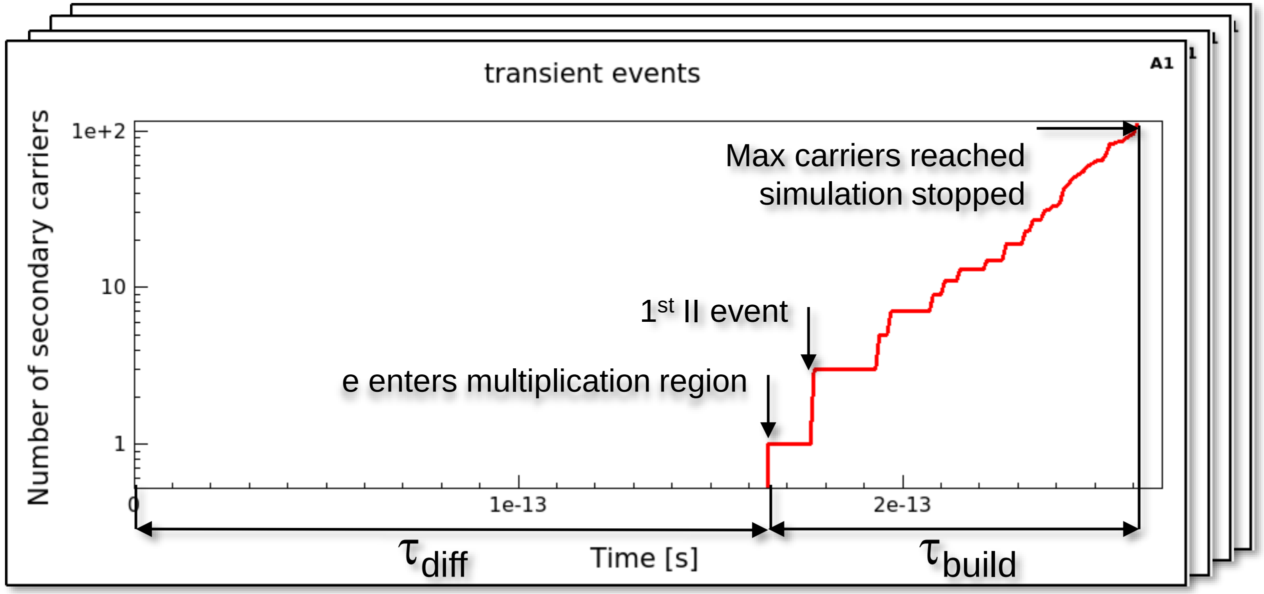
Phonon scattering => random walk (Monte Carlo transport)



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

Garand MC – Execution Model

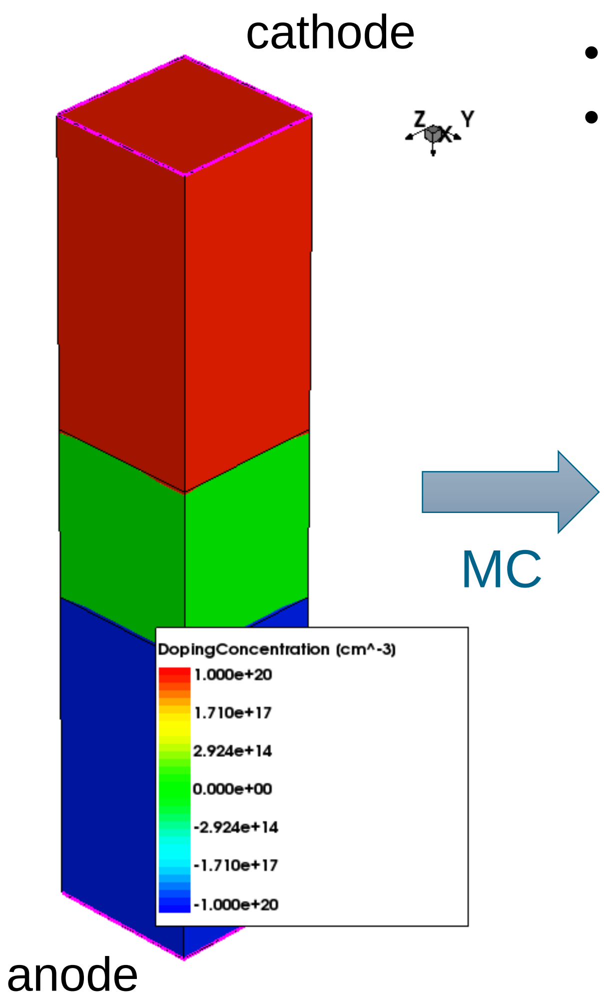


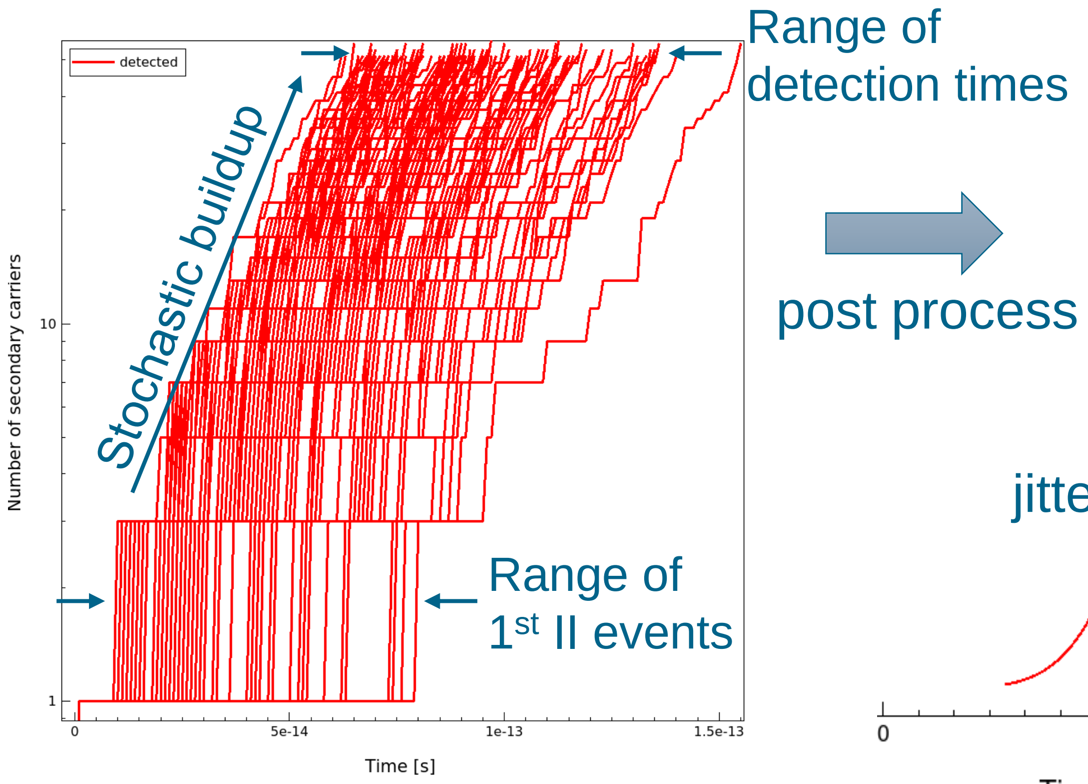


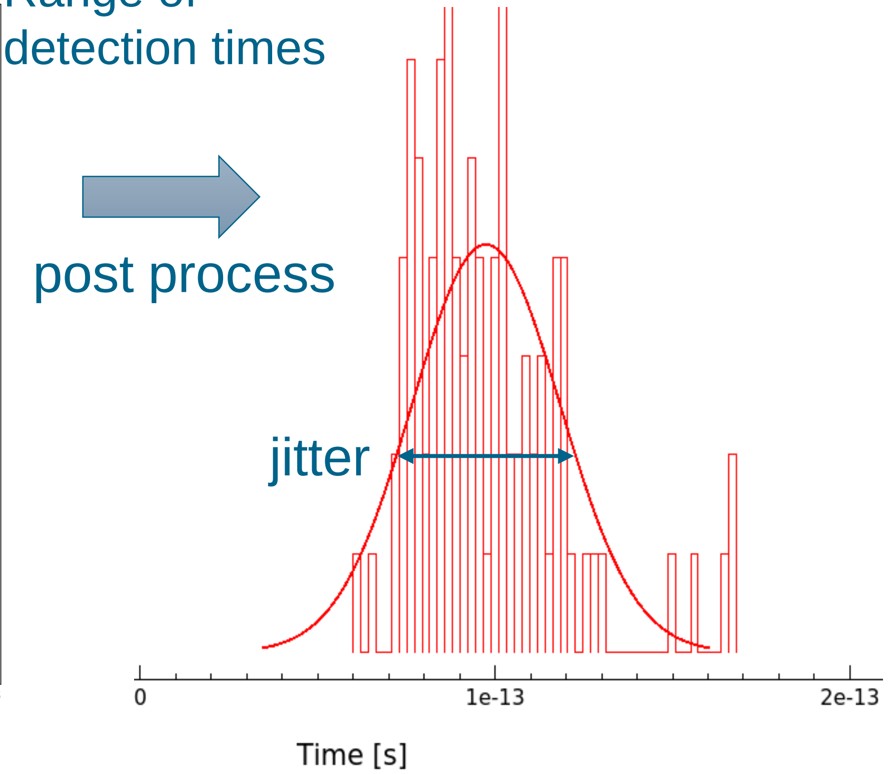
- Garand MC simulates carrier diffusion and impact ionization
- History of each photo excited carrier is output for processing
- Multiple histories may be simulated in a single MC instance
- Multiple instances may be run and all output aggregated
  – easily scalable, limited by resource & licences only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







Photodetector Simulation

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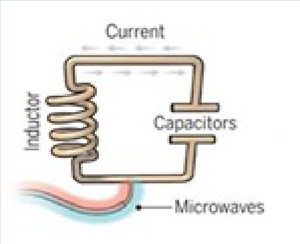
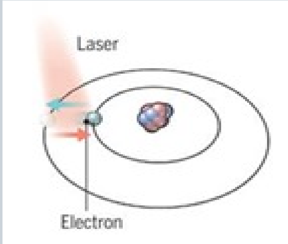
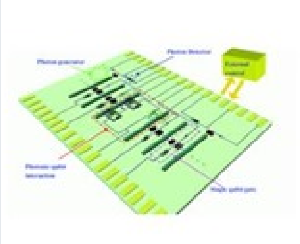
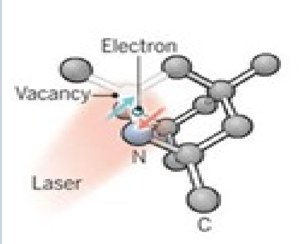
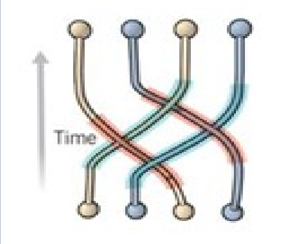
- Single-Photon Avalanche Diodes
- **Superconducting Nanowire Single-Photon Detectors**

Quantum Computing Promises to Revolutionize Key Industries: Drug Development, Finance, Cybersecurity …

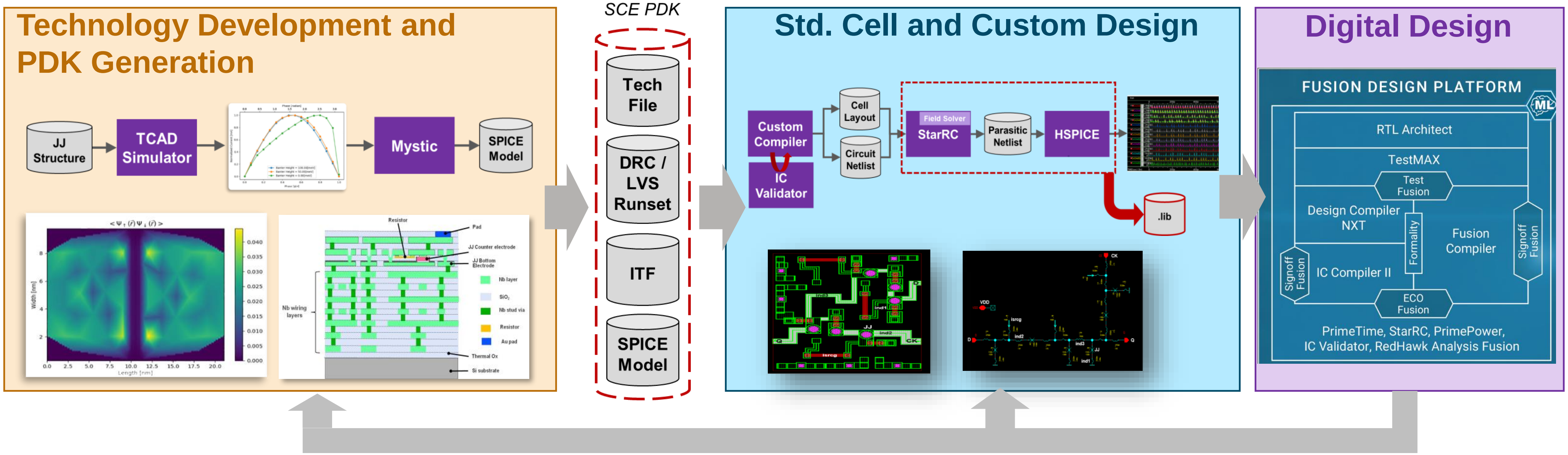
Several qubit types are in R&D for physical realization of quantum computers

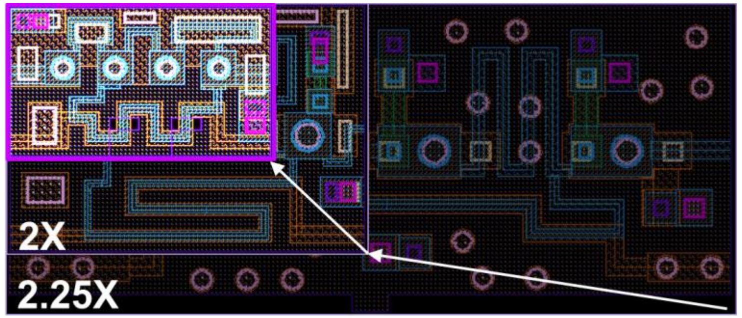
	Supercond. qubits	Trapped Ion qubits	Spin qubits	Photonic qubits	Diamond Vacancy qubits	Topological qubits
						
Technology Platform	Superconducting	**Ca** or **Sr** ions trapped in semiconductor chips	Semiconductor quantum dots (Si CMOS)	Semiconductor (Photonic ICs)	Semiconductor (Diamond)	Superconducting or Semiconductor (Compound)

Near term Synopsys focus is to support development of superconducting qubit quantum hardware

1. Natural extension from SuperTools development
2. Superconducting qubits are engineered systems ("artificial atoms"), amenable to design

SCE EDA Flow Developed Under IARPA SuperTools Supports the Design of Large Scale SCE Circuits





Source: S. Tolpygo, et al., MIT LL, EUCAS 2017

DTCO flow supports scaling of SCE technologies to achieve higher functionality

+

Provides foundation for new solutions to address Quantum Computing superconducting designs

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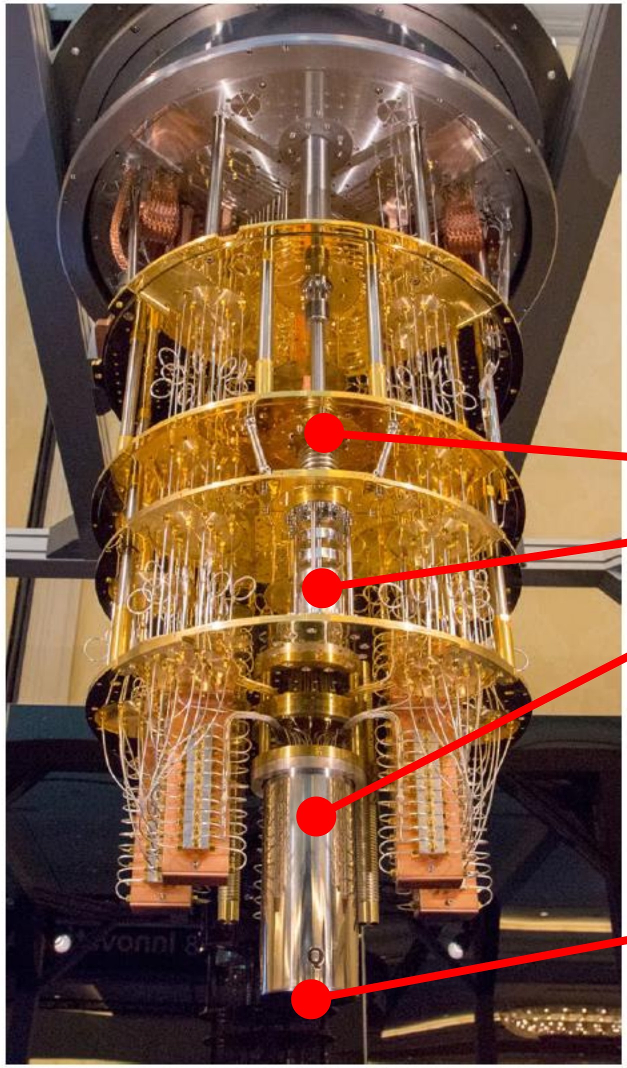
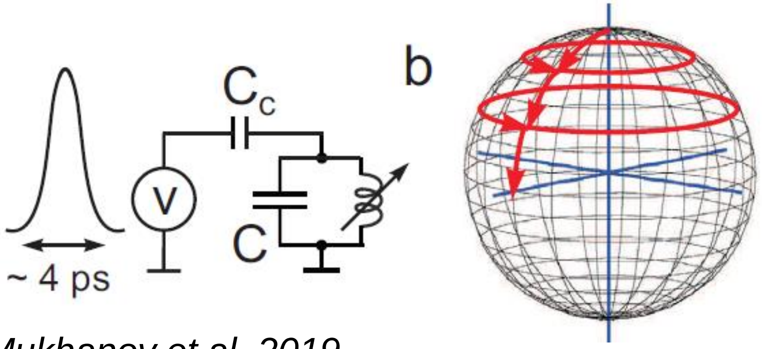
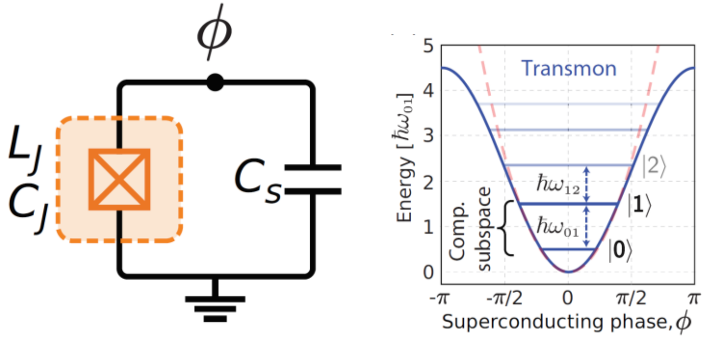
Synopsys Focus: Extend SuperTools Flow to Support Optimization of Superconducting-Based Quantum Hardware



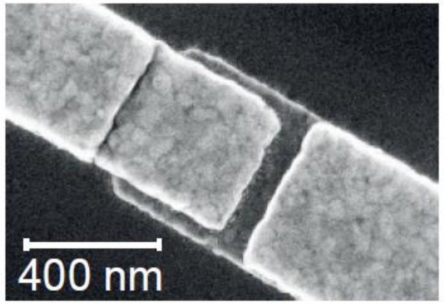


Mukhanov et al, 2019

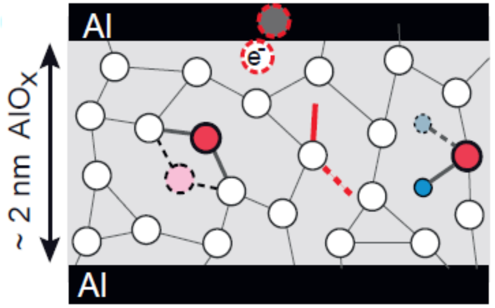


Krantz et al, 2019

Design of superconducting and cryo-CMOS qubit control and read out interface circuits

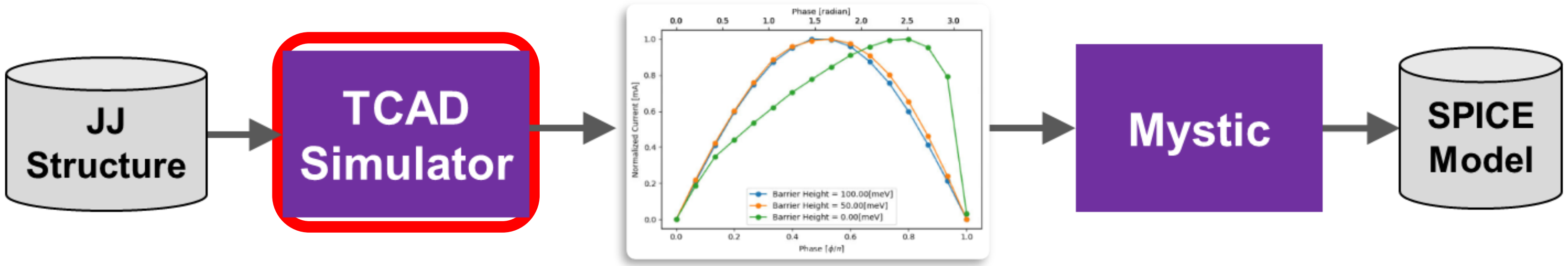


Design, noise modeling and manufacturing optimization of superconducting qubits



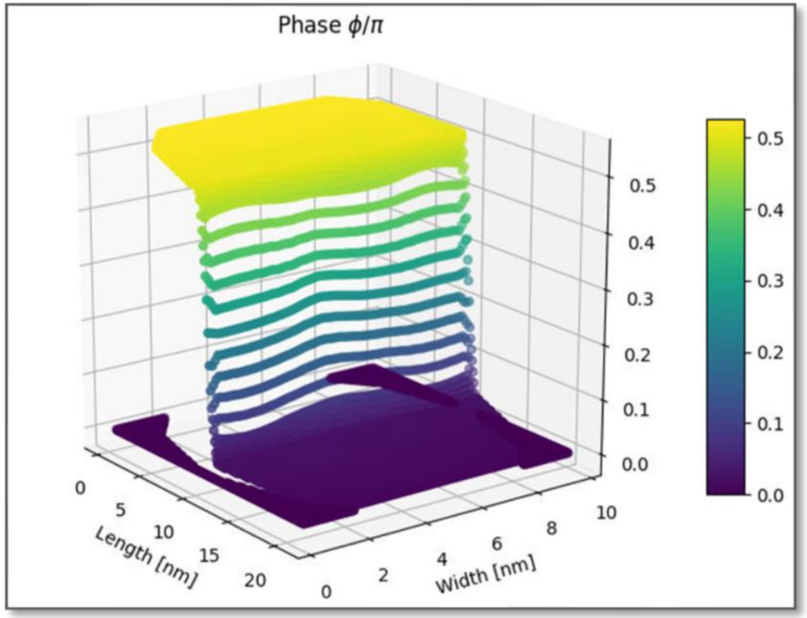
Müller et al, 2019

TCAD SCE Simulator Is Used to Model Josephson Junctions for Single Flux Quantum Circuits and Superconducting Qubits



TCAD Data: I-V, Transient

- Fully quantum mechanical simulator
- Inputs: device structure and material properties
- Outputs:
  - Current vs. phase relations
  - Current vs voltage characteristics
  - Cooper pair density profile, proximity effect
  - Temperature dependence

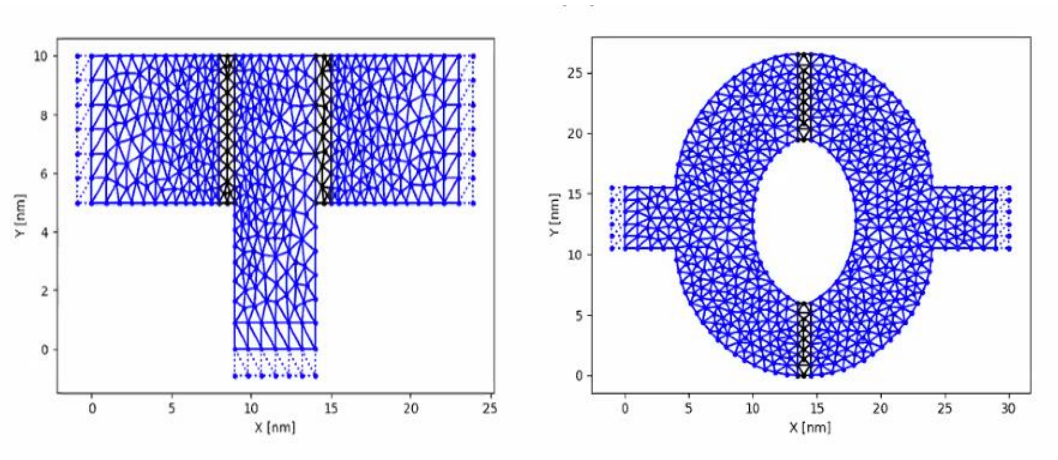


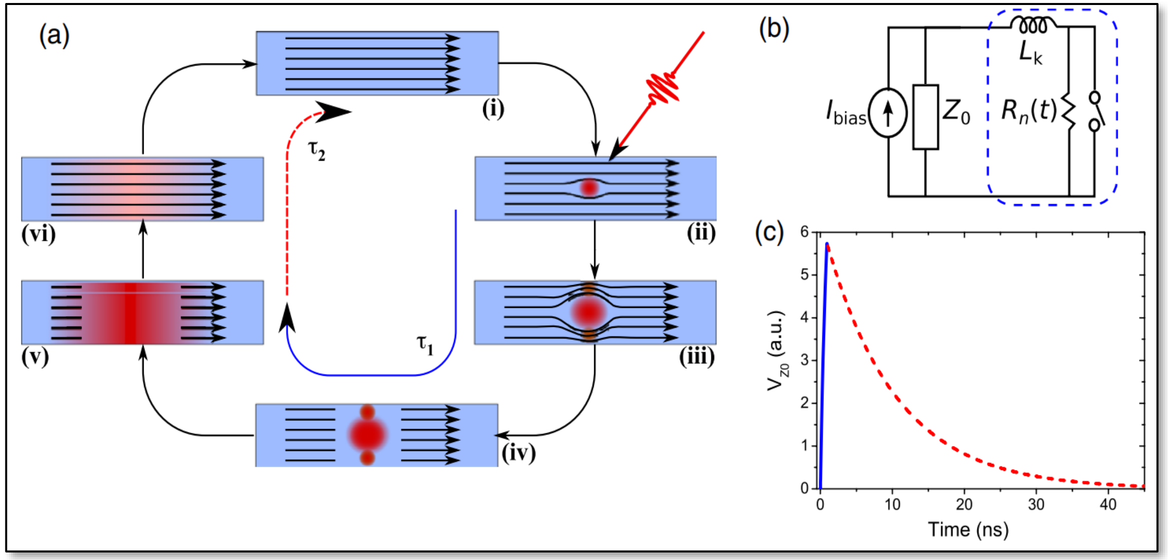
Spatial distribution of superconducting phase across JJ for $\phi_L = \frac{\pi}{2}, \ \phi_R = 0$

Beyond Simulation of JJs, TCAD SCE Simulator is Being Extended to Simulate Superconducting Nanowire Single Photon Detectors

- Employs FEM to solve quantum transport problem based on Bogoliubov-deGennes (BdG) Hamiltonian
- Arbitrary 1D / 2D / 3D structures
- Parallelized for efficient computation

- SNSPDs are critical devices for Quantum Communication and Optical Quantum Computers
- Performance optimization motivates design modeling and fabrication improvements

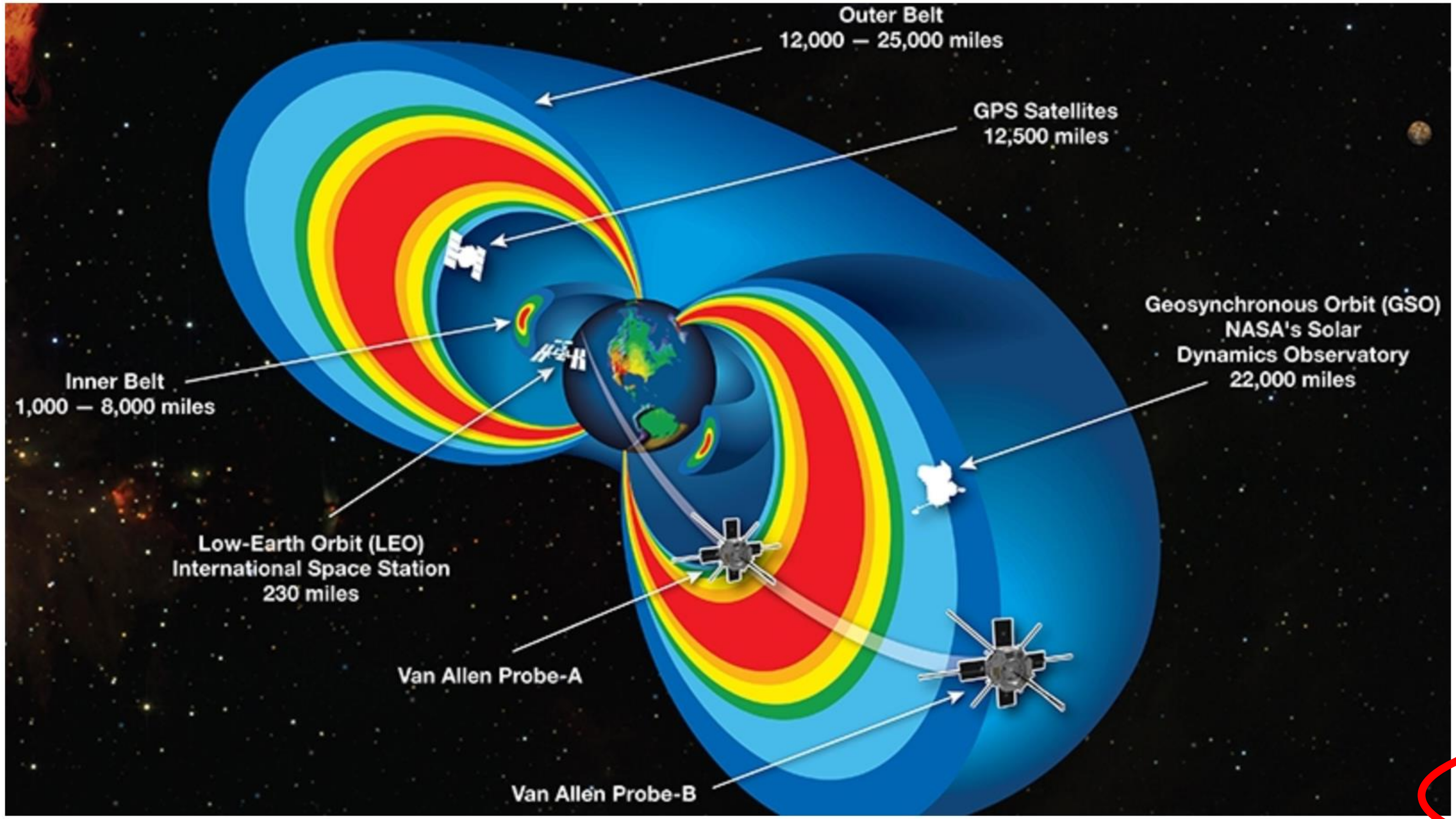


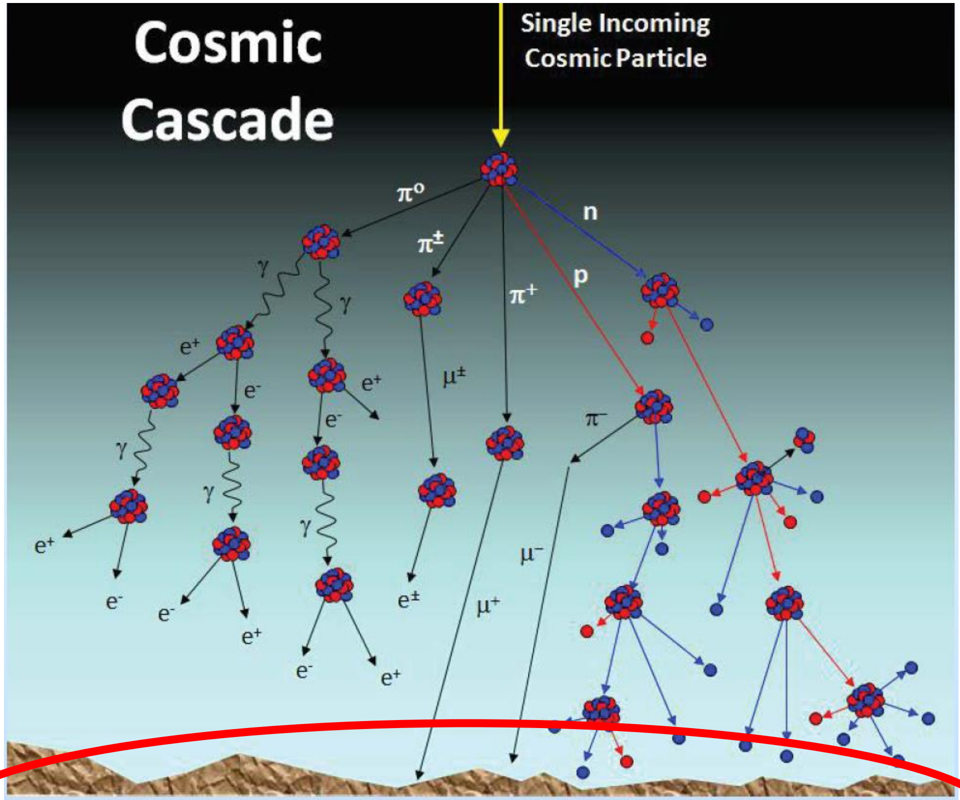


Natarajan et al, Supercond. Sci. Technol. **25** (2012) 063031

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

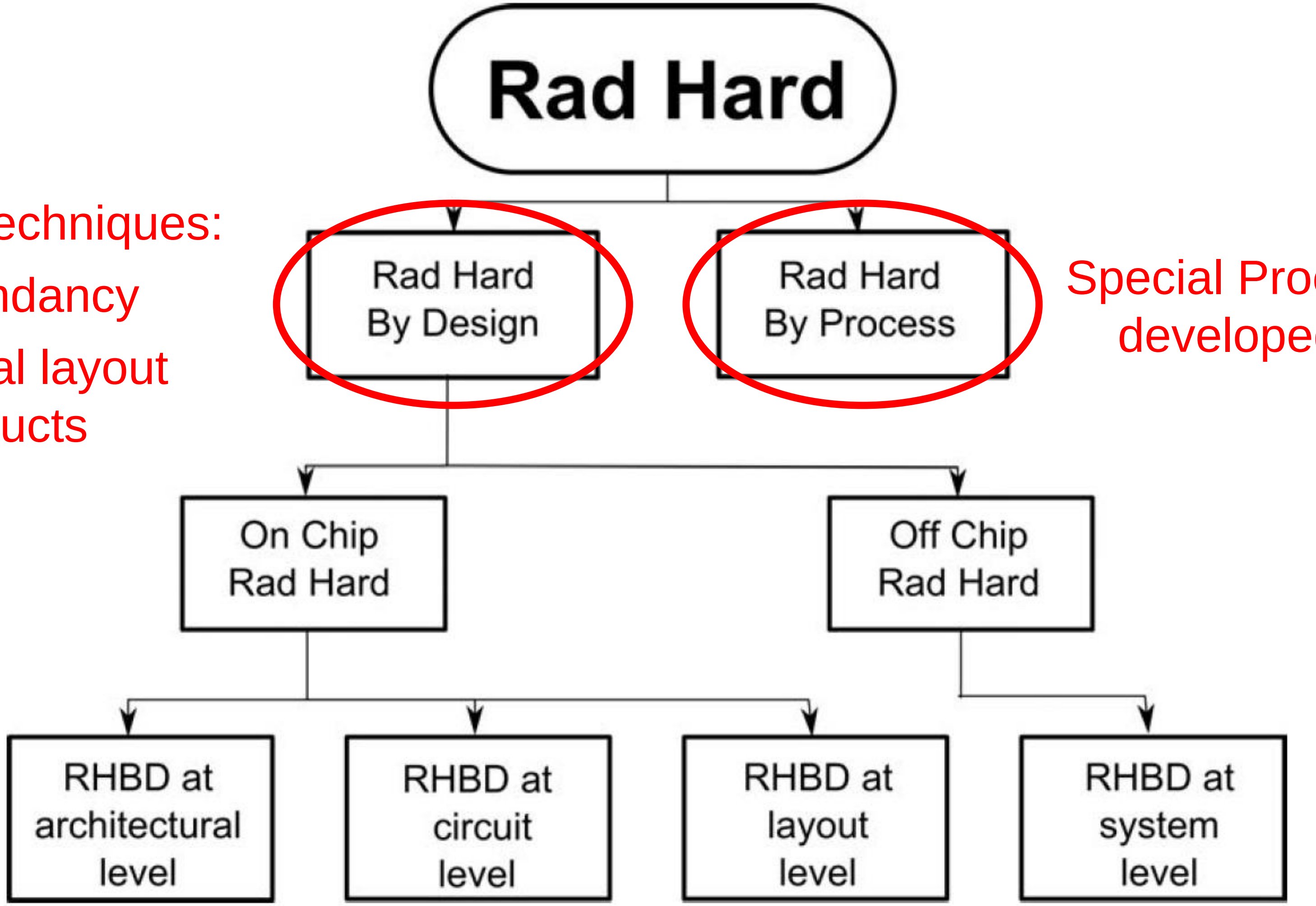
Cumulative effects
- Displacement damage
- Total ionizing dose (TID)

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

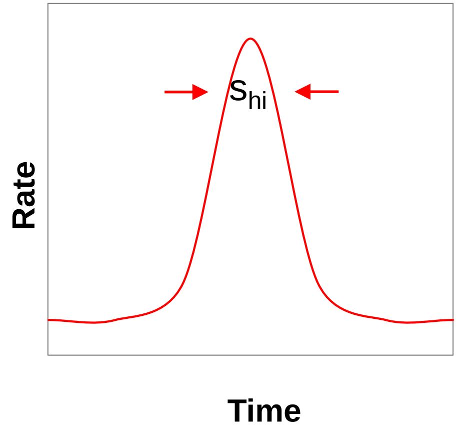
- Analytical generation model dependent on ion LET
- Customizable model through API: Physical Model Interface (PMI)

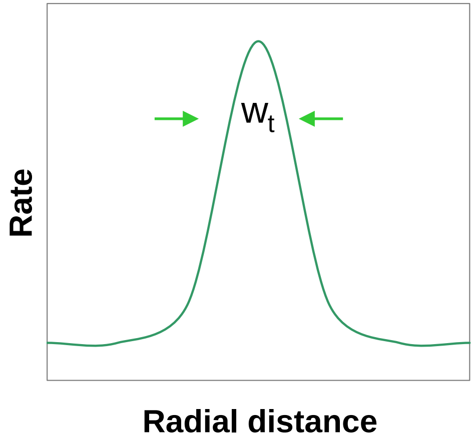
Electron-hole generation rate: $G(l,w,t) = T(t) \times R(w,l) \times G_{LET}(l)$

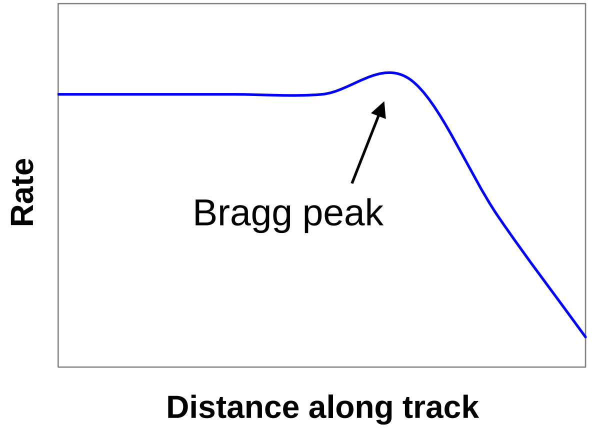
$$T(t) = \frac{2 \cdot \exp\left(-\left(\frac{t - time}{s_{hi}}\right)^2\right)}{s_{hi}\sqrt{\pi}\left(1 - erf\left(\frac{time}{s_{hi}}\right)\right)}$$

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

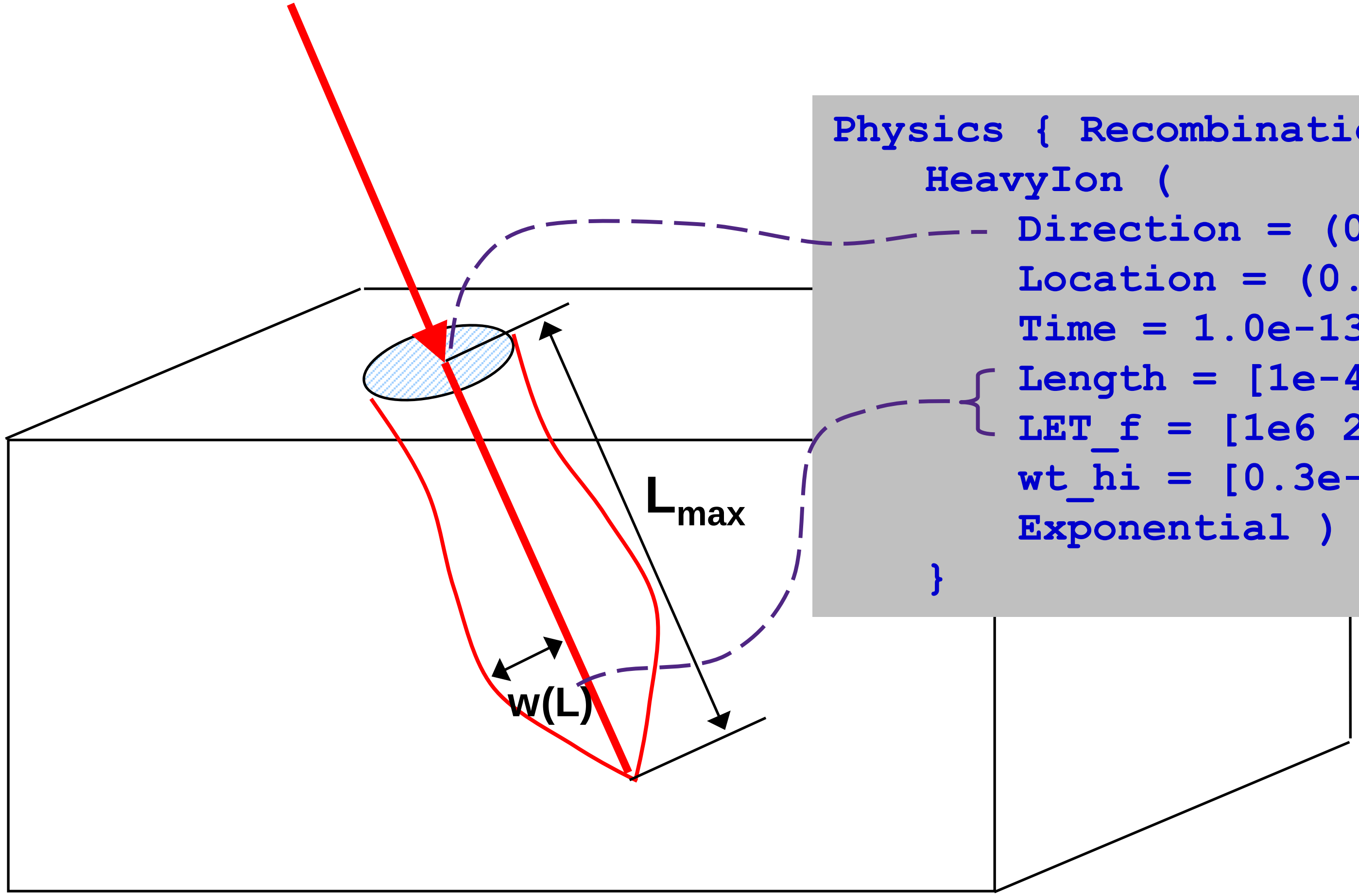
$$G_{LET}(l) = a_1 + a_2 \times l + a_3 e^{a_4 \times l} + k'\left[c_1 \times (c_2 + c_3 \times l)^{c_4} + LET\_f(l)\right]$$







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
     )
}
```

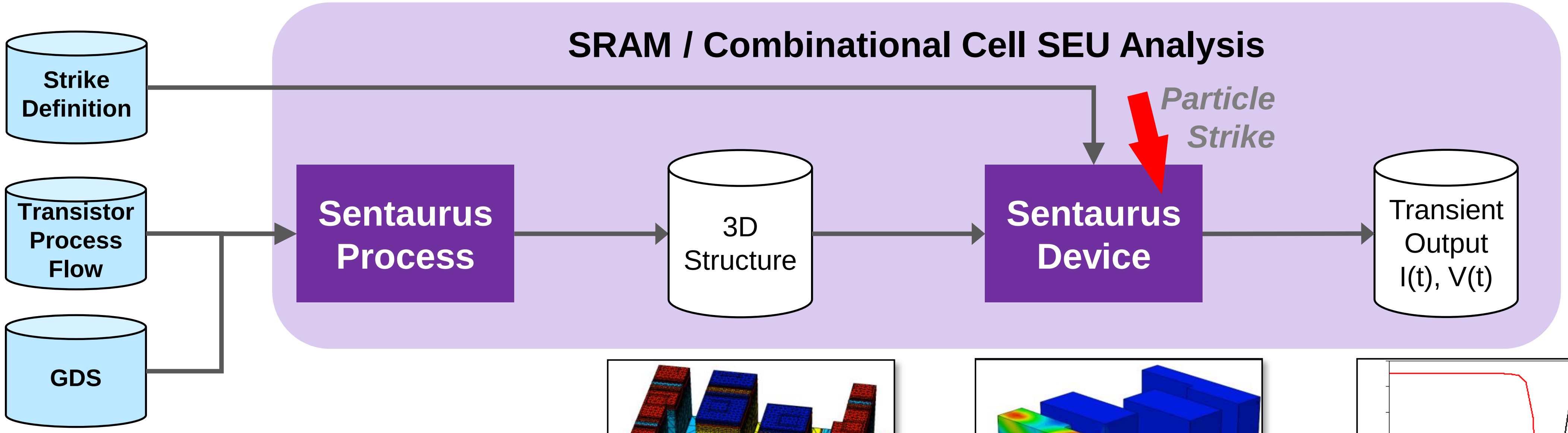
$$G_r = g_0 D \cdot Y(F)$$

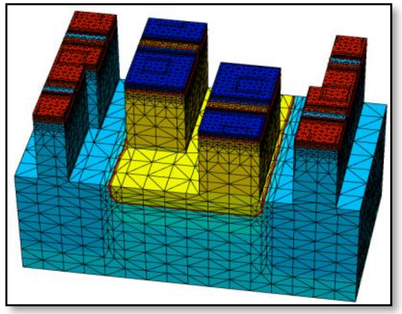
$$Y(F) = \left(\frac{F + E_0}{F + E_1}\right)^m$$

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

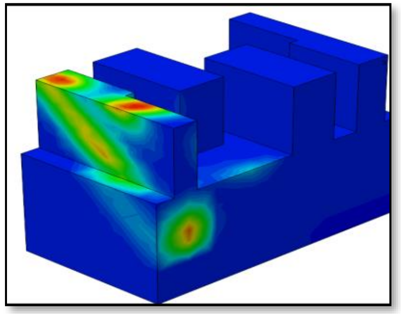
```
Physics(Material="OxideAsSemiconductor"){
    Traps (
    (Donor Conc=@Conc@ Level EnergyMid=@EMid@ FromMidBandGap
        eXsection = 1e-11 hXsection = @xSec@ )
    )
}
```

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

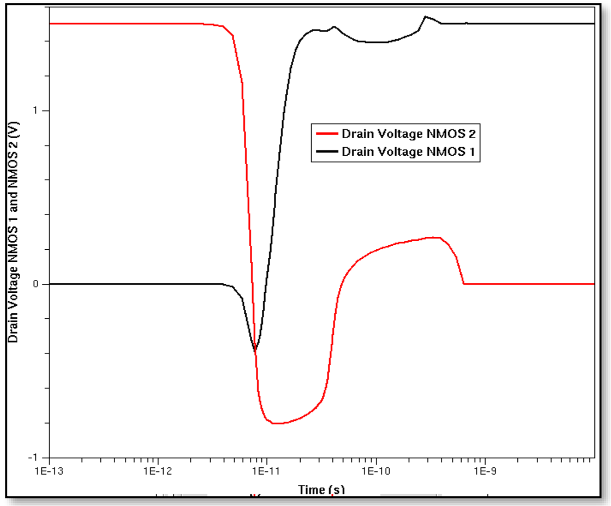




Process structure meshed for device simulation

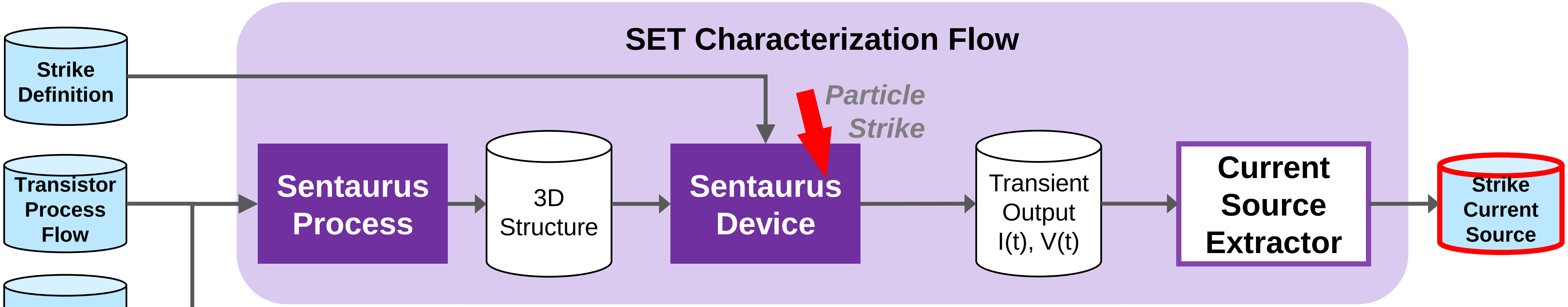


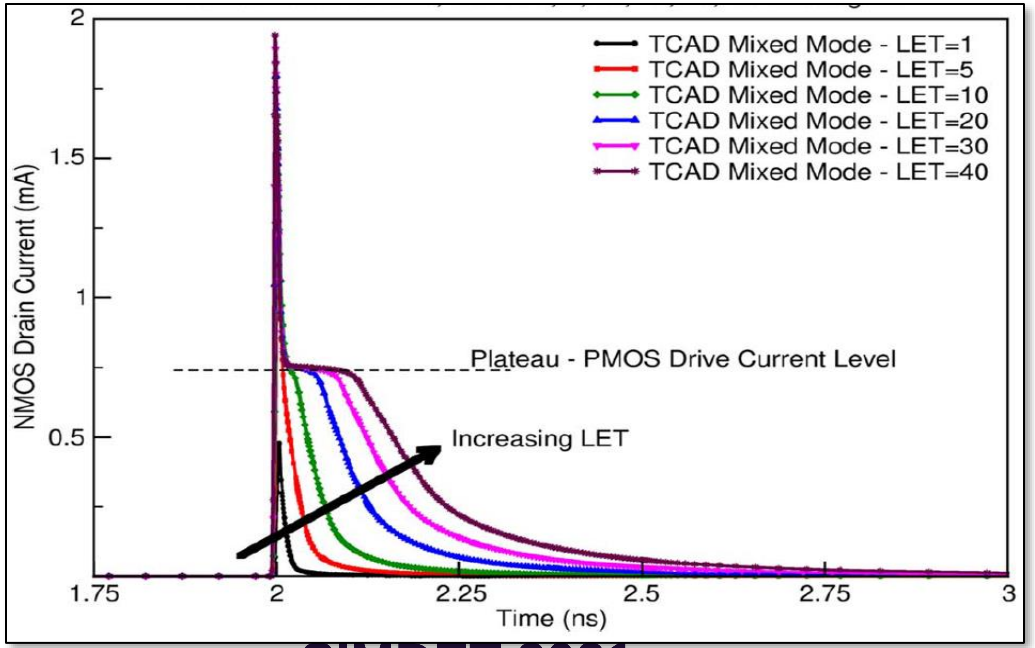
Charge collection in structure is input for transient device simulation

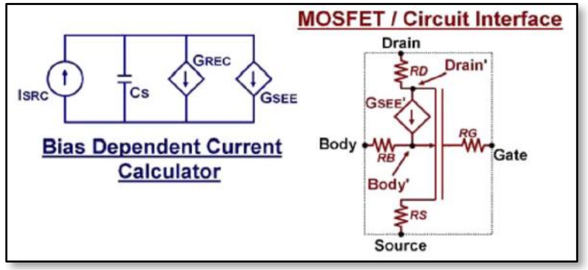


Transient output indicates if bit is upset for specific strike definition

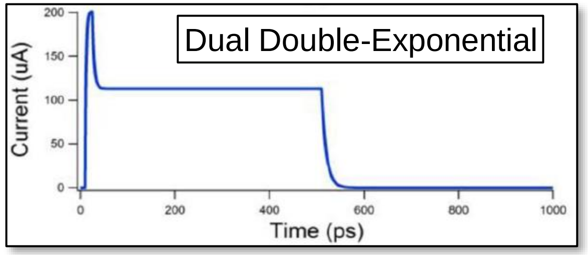
Single Event Transient (SET) Characterization Flow







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



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

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Synopsys TCAD Has Extensive Capabilities to Support the Design of Semiconductor and Superconductor Detectors

- CMOS Image Sensors (CIS), with focus on 3D process optimization and co-design with amplifier circuits
- Single Photon Avalanche Photodiodes (SPAD)
- Development of TCAD simulator for superconducting electronics with application to Superconducting Nanowire Photo Detectors (SNSPD)
- TCAD-to-SPICE flows for radiation effects

Thank you for your attention

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