Uses of Silvaco in HEP Experiments

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Topics

- Importance & need of ‘Simulations’
- Introduction to SILVACO & its framework
- SILVACO in HEP Experiments:
  - Pad diodes
  - Strip Detectors
  - Pixel Detectors
  - LGAD Detectors
  - APD Detectors
  - CMOS Detectors
  - 3D Detectors

  & many more……..

What is a ‘Simulation’?

A ‘simulation’ is an ‘imitation of reality’ !!

- How does it work?

Simulations are calibrated with past measurement data. Various system design parameters are then tweaked to achieve desired requirements. Finally the design is fabricated in the industry for cross checking of the results.

- Where is it essential?

A non-linear system. A multi-variable with interacting components system.

- Areas of discipline.

Engineering, business, mathematics, statistics, anthropology, sociology, psychology, medicine, physics,… and many more.

Hence, ‘Simulation’ is a critical technology !!

Why is a ‘Simulation’ performed?

1. Why not do measurements? – They are more realistic!

   We can! BUT….
   Experiments can be very very costly!!
   Require human, material resources.
   Affected by environmental conditions.

2. Is ‘simulation’ really helpful?

   Definitely!
   Provides a closer look into the physics taking place @ microscopic level!
   Builds better understanding.
   Unaffected by environmental conditions, activity time, resource availability.
   From initial to final step, the events can be tracked. → Insightful evaluation
   Can play with lot of parameters.

Introduction to 'SILVACO'

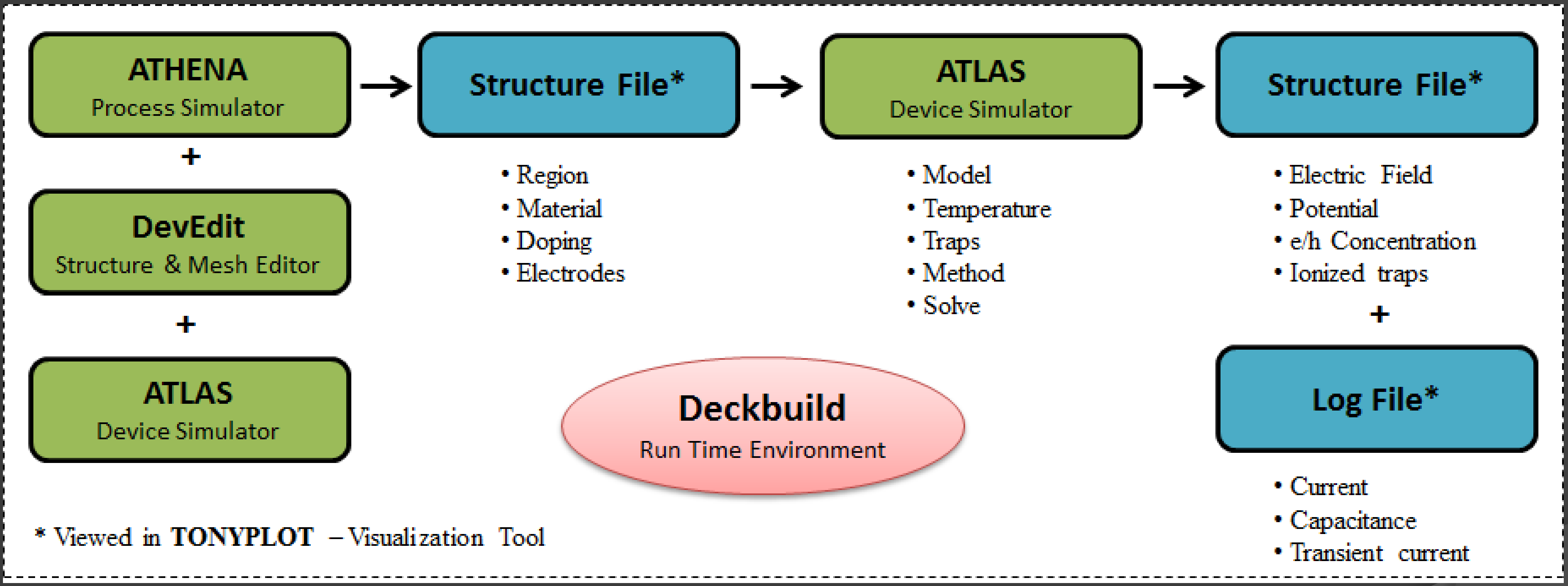
SILVACO is a provider of 'TCAD (Technology Computer Aided Design) process & device simulator software and EDA (Electronic Design Automation) software'.

- Was founded in 1984 by Dr. Ivan Pesic.
- And since then, plenty publications in peer review journals!
- Headquarters in Silicon Valley, California with development offices in USA, UK.

- EDA Products: SmartSpice, Gateway, Spayn, Clever, Expert, Quest, Spider, Harmony, Guardian, AccuCell, AcuuCore, etc.

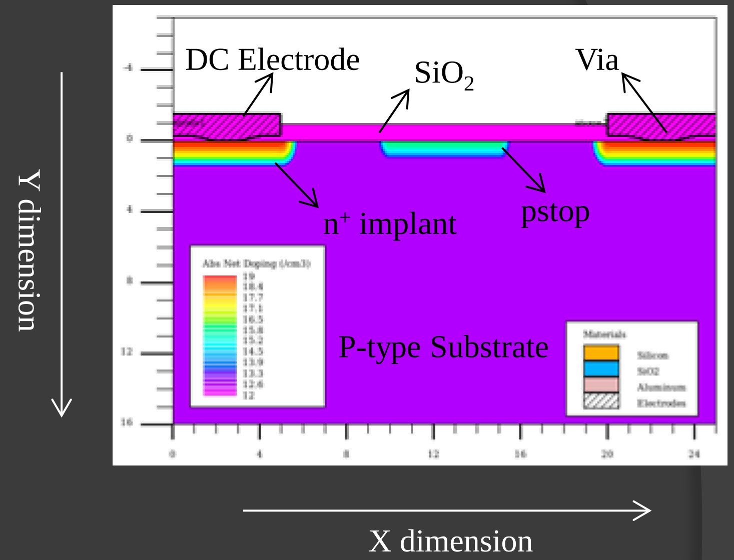
- TCAD Products: Victory Process, Victory Cell, Athena, Victory Device, Atlas, Victory Stress, Interactive Tools, Virtual Wager Fab (VWF), etc.

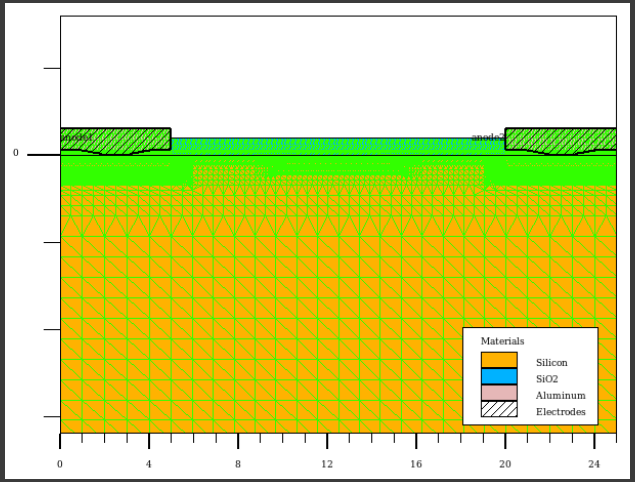
SILVACO Simulation Framework



(1) Structure Specification

1) Physical dimensions of structure – length, breadth, thickness
2) Doping profile – p-type/n-type, concentration, depth
3) Contacts – DC/AC electrodes
4) Oxides – coupling, passivation
5) Isolation structures – pstop, pspray
6) MESHING





- Grid of points defined on the structure = Mesh points
- Poisson, Current density, Continuity Eq. solved @ each point
- Large # mesh points -> Slow, Good convergence
- Small # mesh points -> Faster, Bad convergence
- Compromise b/w simulation time & convergence
- Fine mesh near high field gradient regions & coarse elsewhere

(2) Models & Numerical Method Selection

3 Equations for 3 unknowns (φ, n, p):

Poisson Equation

$$\nabla^2 \varphi = -\frac{\rho}{\varepsilon}$$

$$\rho = p - n + N_D^+ - N_A^-$$

Current Density Equation

$$J_n = q\left(n\mu_n E + D_n \frac{\partial n}{\partial x}\right)$$

$$J_p = q\left(p\mu_p E - D_p \frac{\partial p}{\partial x}\right)$$

Continuity Equation

$$\frac{\partial n}{\partial t} = \frac{1}{q}\nabla . J_n - r_n + g_n$$

$$\frac{\partial p}{\partial t} = -\frac{1}{q}\nabla . J_p - r_p + g_p$$

These equations use one of these specified models.

These equations are solved using one of the methods.

Physical Models:

a) Mobility – Concentration dependent, parallel field dependent
b) Impact ionization – Selberherr, Van Overstraten
c) Generation & Recombination – Shockley Read Hall
d) Oxide physics – Fowler-Nordheim, Interface charge accumulation
e) Tunnelling – Band-to-band, Trap-assisted

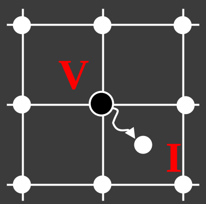
Numerical Methods:

a) Gummel
b) Newton
c) Block

(3) Radiation Damage: Bulk & Surface Traps

Bulk Damage

Particle with $E_K >$ E_d , incident on Si lattice



Vacancy
+
Interstitial

↓

Point defects + Cluster defects = Bulk traps

Surface Damage

Generation of eh pairs in SiO_2

↓

'e's move to Si-SiO_2 interface & recombine, 'h's can't because of low mobility.

↓ Trapping in $SiO_2 = N_{ox}$

↓ Trapping at Si-SiO_2 interface

Radiation Damage Model developed by DU: 2 Bulk + 1 N_{ox} + 2 Interface Trap Model

* R. Dalal et al., PoS (Vertex2014).

Bulk Traps

Trap	Energy Level	Density (cm^{-3})	σ_e (cm^{-2})	σ_h (cm^{-2})
Acceptor	E_C - 0.51 eV	4 X Φ	2.0×10^{-14}	3.8×10^{-14}
Donor	E_V + 0.48 eV	3 X Φ	2.0×10^{-15}	2.0×10^{-15}

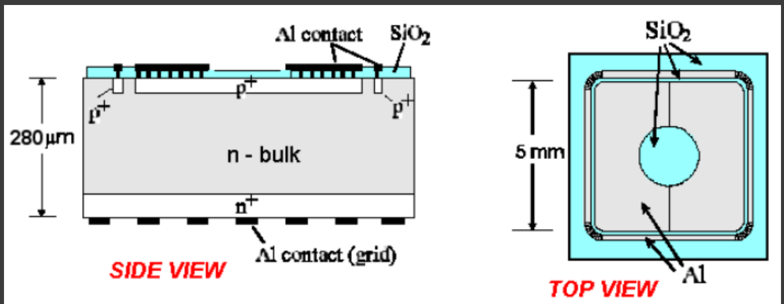
Interface Traps

N_{it}	Energy Level	Density (cm^{-2})	σ_e (cm^{-2})	σ_h (cm^{-2})
Acceptor	E_C - 0.60 eV	0.6 X N_{ox}	0.1×10^{-14}	0.1×10^{-14}
Acceptor	E_C - 0.39 eV	0.4 X N_{ox}	0.1×10^{-14}	0.1×10^{-14}

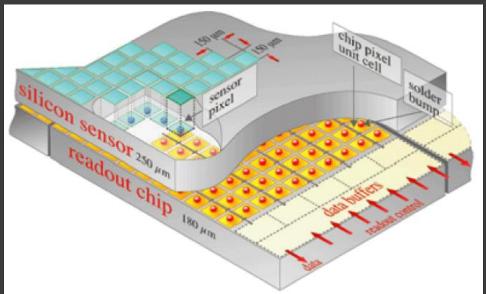
N_{ox} (Fixed Positive Oxide Charge Density)

Fluence, Φ ($n_{eq}.cm^{-2}$)	N_{ox} density(cm^{-2})
Non-Irradiated	$5.0 \times 10^{10} – 5.0 \times 10^{11}$
1.0×10^{14}	$1.0 \times 10^{11} – 8.0 \times 10^{11}$
5.0×10^{14}	$5.0 \times 10^{11} – 1.2 \times 10^{12}$
$> 1.0 \times 10^{15}$	$8.0 \times 10^{11} – 2.0 \times 10^{12}$

‘Silicon Detectors’ in HEP

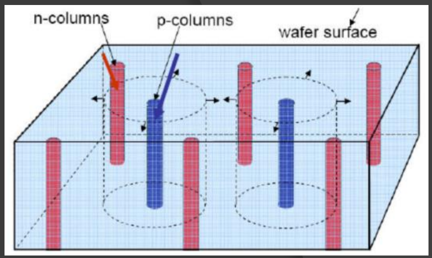


Pad Diode



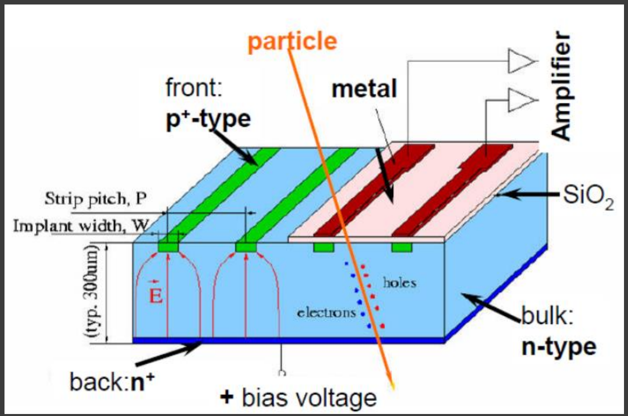
Pixel Detectors

For vertexing. Provides 2D information.



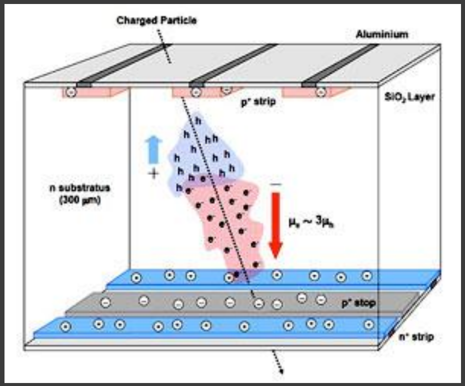
3D Columnar Detectors

Faster. Provides 2D information.



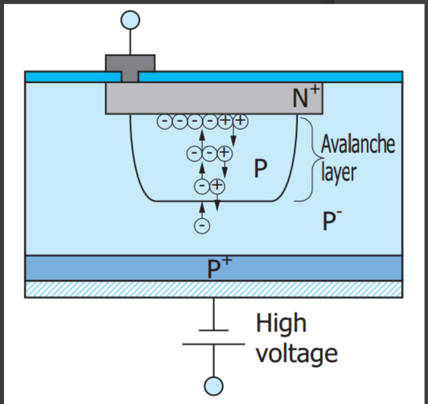
Single sided Strip Detectors

For tracking. Provides 1D information.



Double sided Strip Detectors

For tracking. Provides 2D information.

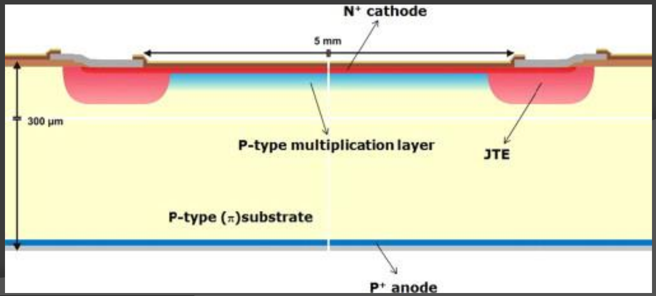


Avalanche Photodiode

Provides intrinsic gain by high E.field region in a deep multiplication well

Low Gain Avalanche Detectors

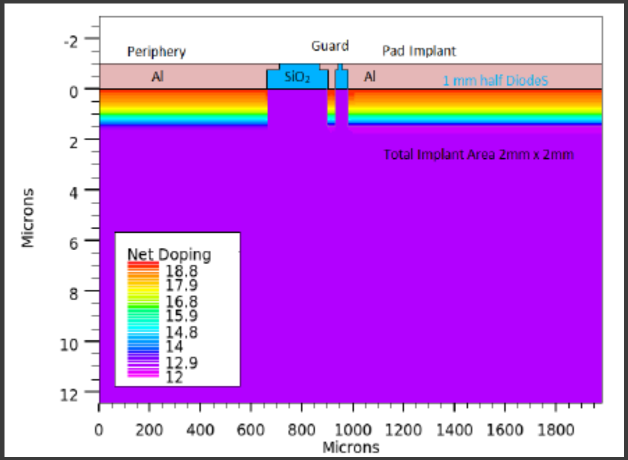
Provides intrinsic gain by local very high E.field region by controlled avalanche in small, but highly doped multiplication well



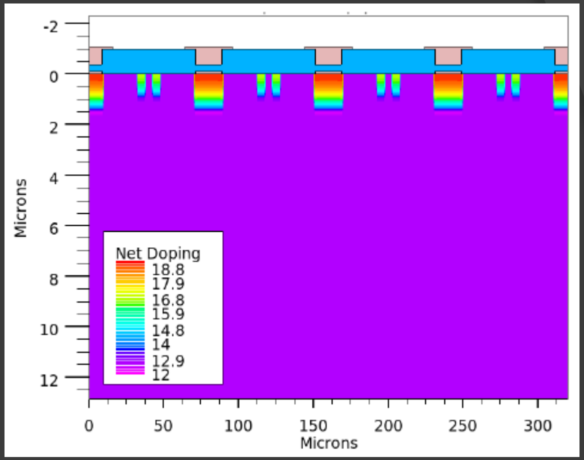
…. & many more!!

Structures in SILVACO

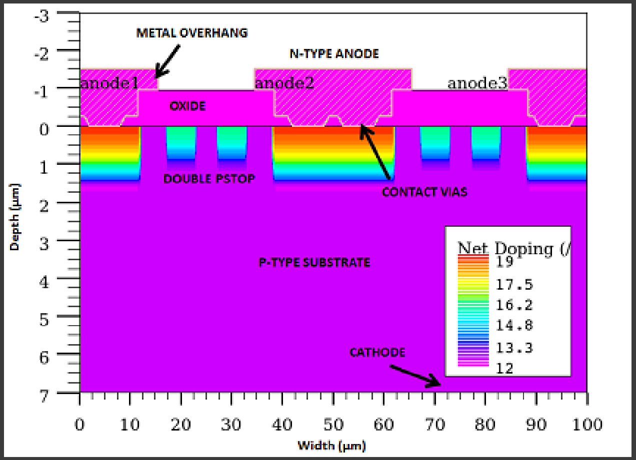
(1) Pad Diode



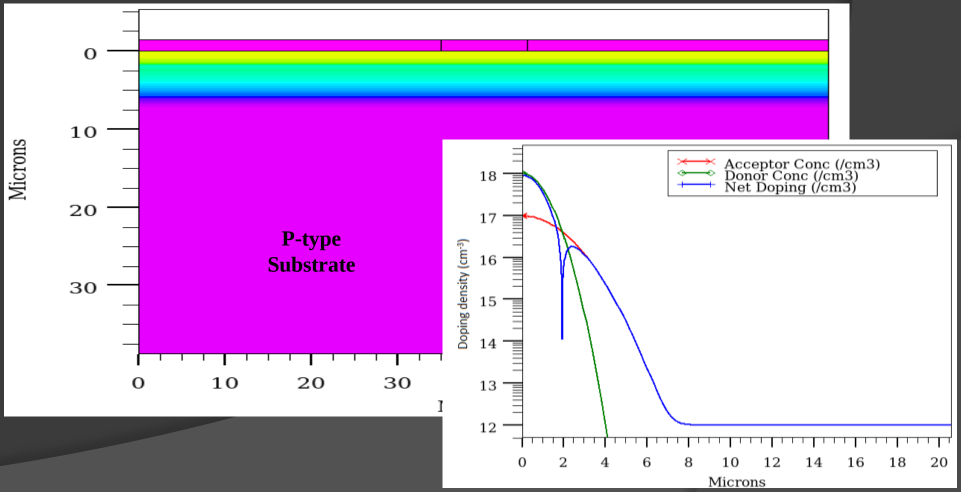
(2) Strip Detector



(3) Pixel Detector

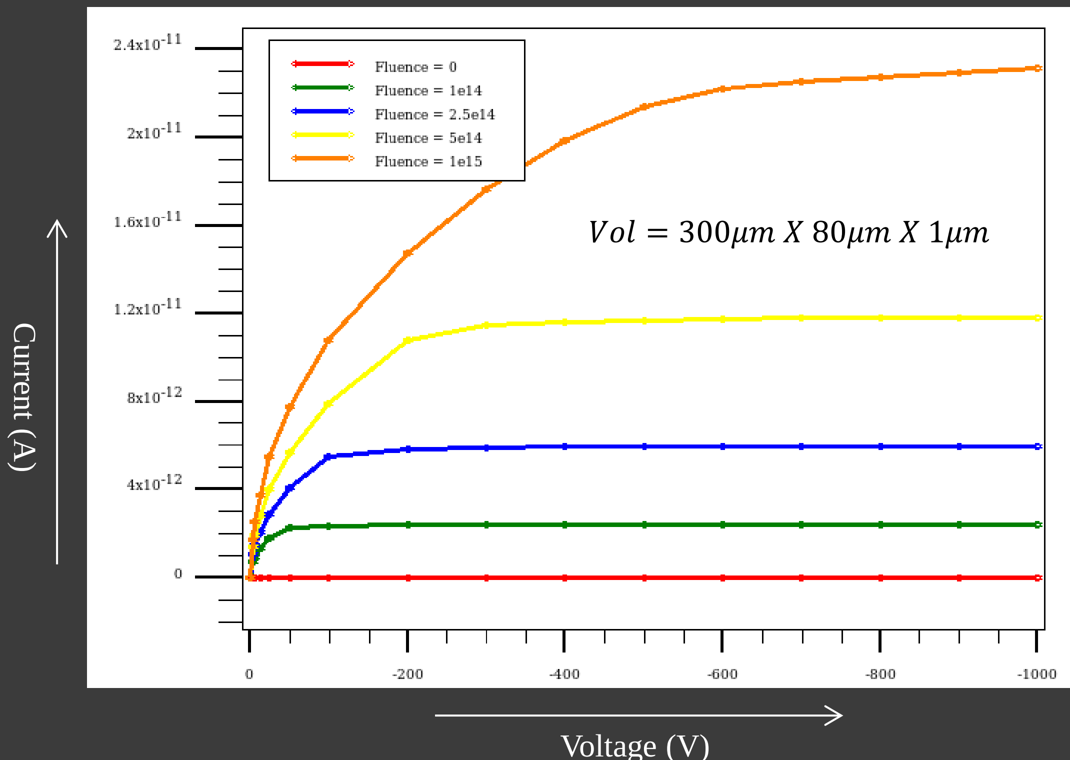


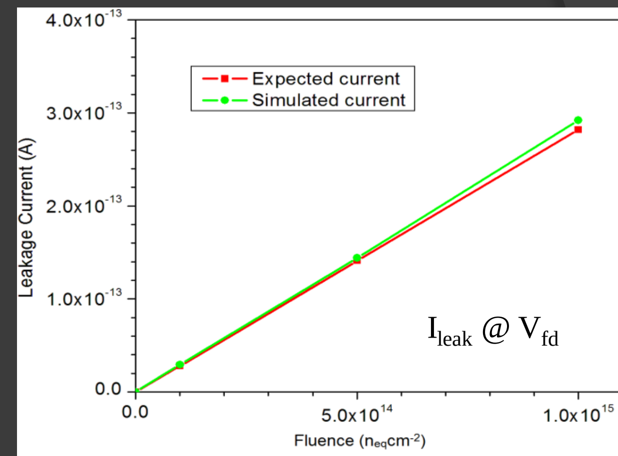
(4) Low Gain Avalanche Detector

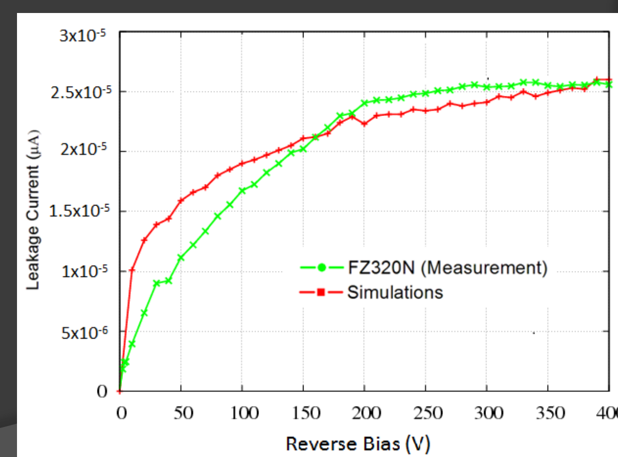


Pad Diode - IV

Detector is reverse dc biased. → Leakage current is measured (in dark).
Importance: Leakage Current value is a measure of NOISE at a particular voltage.
Critical at high fluence because SNR goes down.





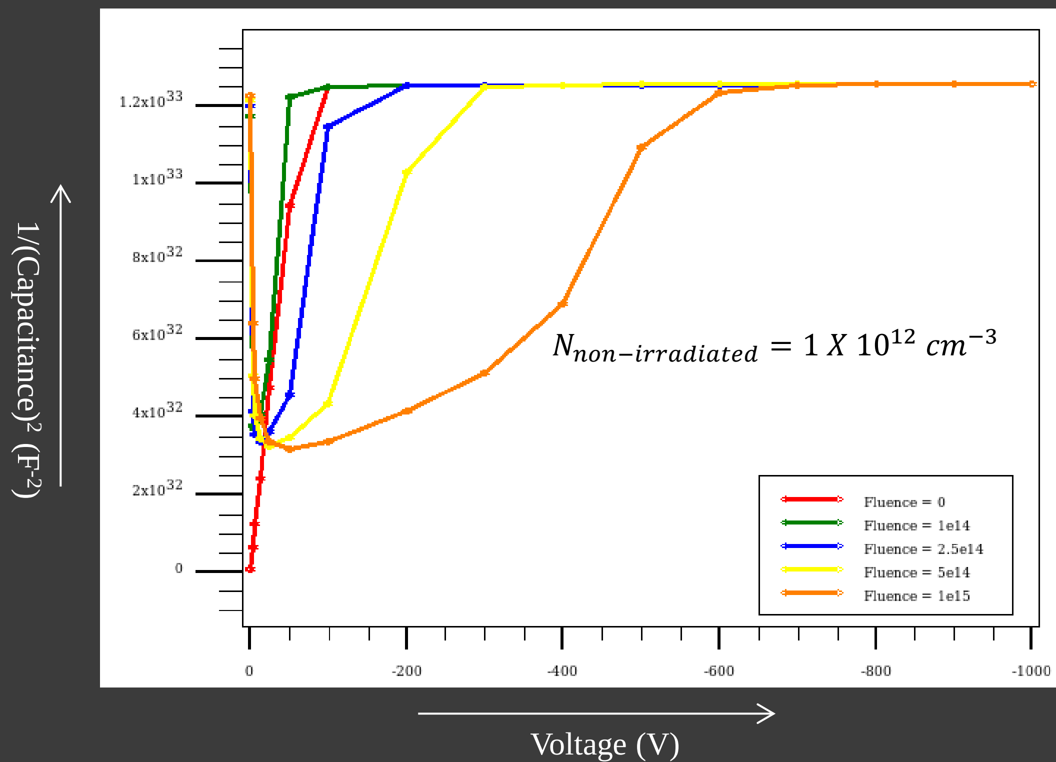


$$\Delta I = I_{irradiated} - I_{non-irradiated} = \alpha.\varphi.Vol$$
$$\alpha(253K) = 8.8 \; X \; 10^{-19} A/cm$$

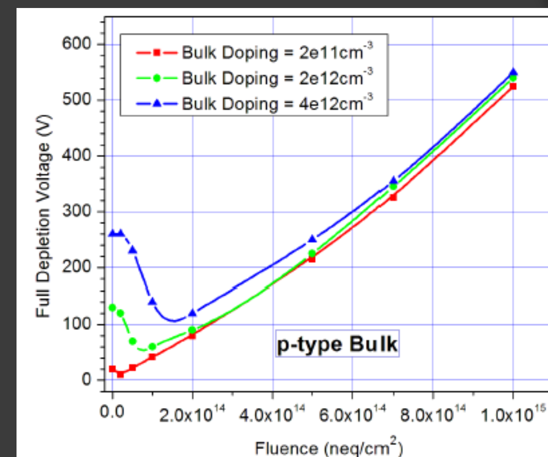
* CMS Detector Note. Simulation of Silicon Devices for the CMS Phase II Tracker Upgrade. CMS DN-2014/016.

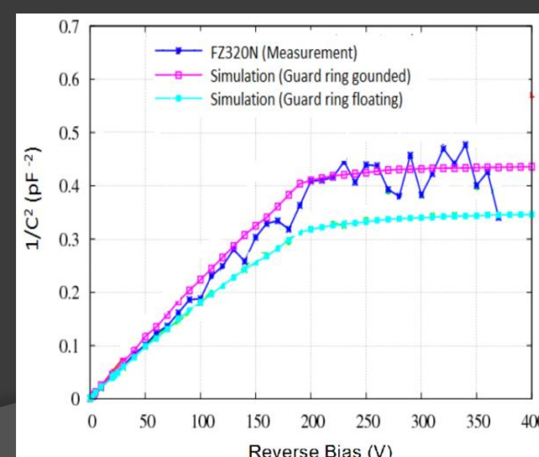
Pad Diode - $C^{-2}V$

Detector is reverse dc biased & a small amplitude ac signal is provided at a frequency of 1kHz.
→ Impedance is measured.
Importance: Detector operation voltage is chosen 1.5 times of the full depletion voltage.



$$V_{fd} = \frac{ed^2}{2\epsilon} N_{eff}$$





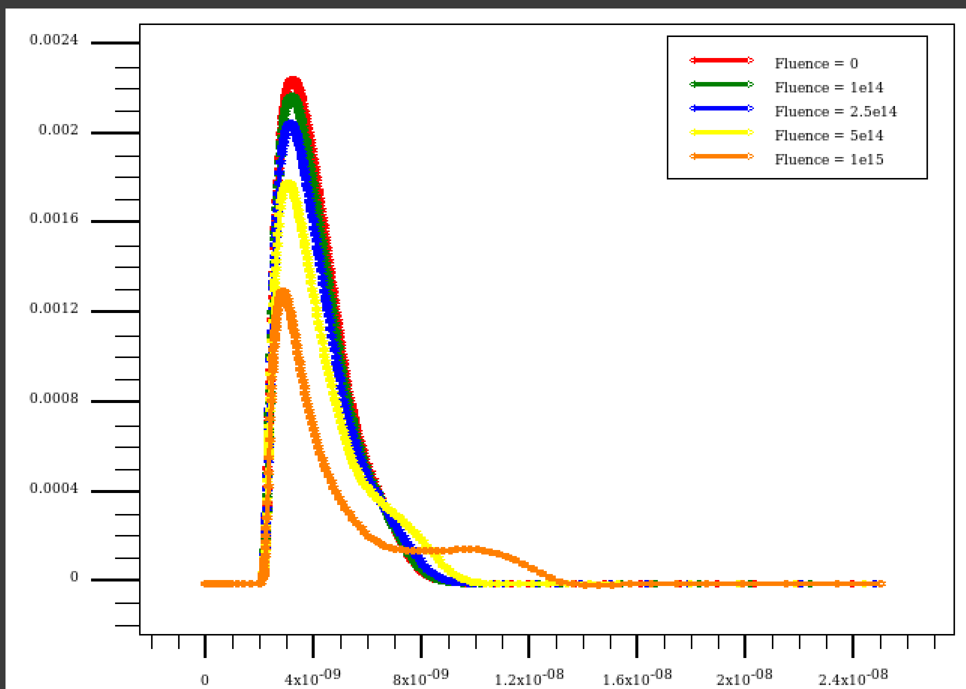
* CMS Detector Note. Simulation of Silicon Devices for the CMS Phase II Tracker Upgrade. CMS DN-2014/016.

Pad Diode - Transient Current Technique

Detector is reverse dc biased & an Infrared laser is shone from top or bottom. → Transient voltage is measured as a function of time.

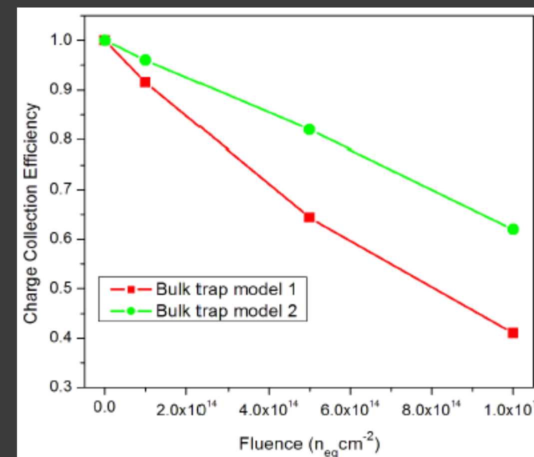
Importance: Detector charge collection profile with voltage & fluence.

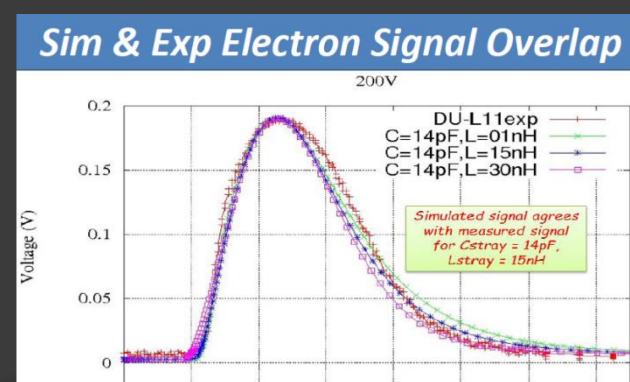
TCT voltage (V)



Transient Time (s)

CC = area under IR laser TCT curve





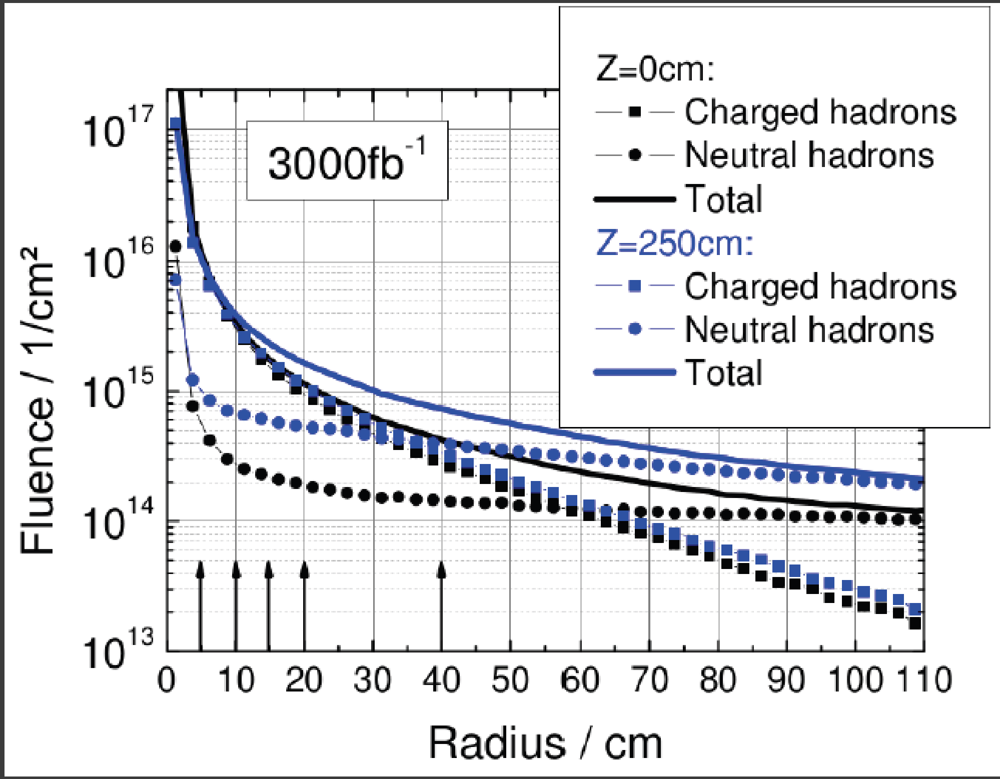
* R. Dalal et al., PoS (Vertex2014).. and Experimentation. Panjab University. March 2014.

* G. Jain. Workshop on Contemporary Trends in High-Energy Physics

LHC Environment

LHC to undergo upgrade in year 2022 → High Luminosity - LHC

* S. Muller, The Beam Condition Monitor and the Radiation Environment of the CMS Detector at the LHC, IEKP-KA/2011-1, CMS TS-2010/042 (2011).



The current tracker can not survive in HL-LHC ! ☹

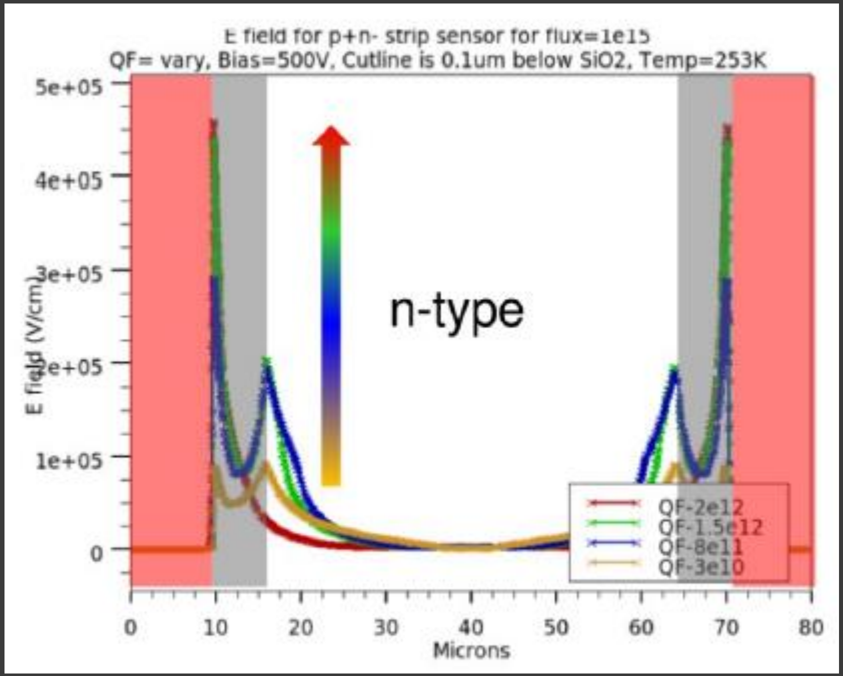
↓

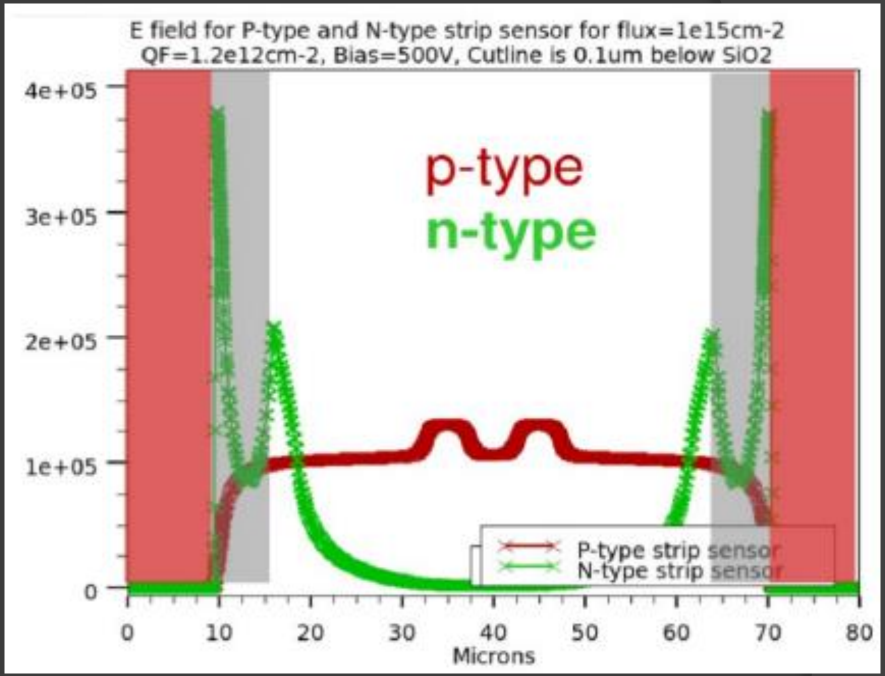
A 'NEW TRACKER' is required !!

New Tracker: Radiation hard material, granular → Material growth techniques, substrate, implant, configuration, thickness, geometry are crucial parameters

* H. Behnanian. 13th IPRD. 2014 JINST 9 C04033

P-type OR N-type substrate





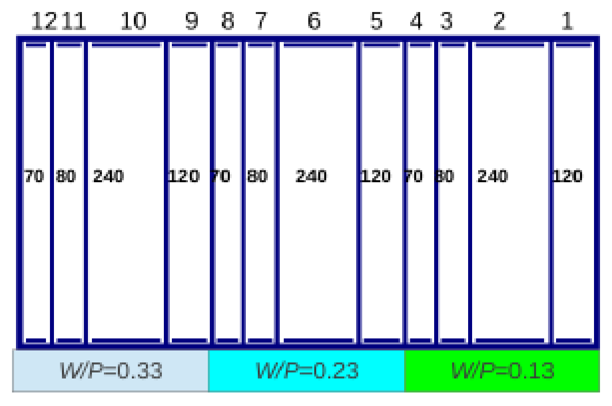
Increasing fluence → More radiation damage → Higher bulk & surface damage → Qf grows → E.Field @ implant edges shoots!

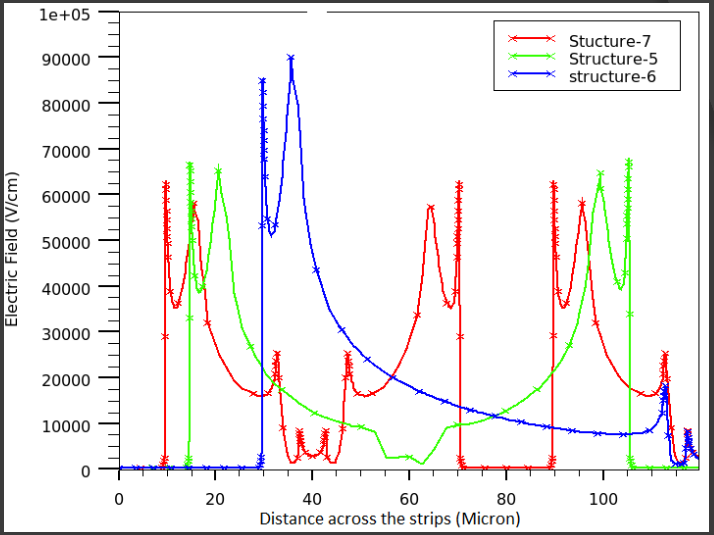
Reverse effect of Qf on E.Field for p-type substrates. Increase in Qf, decreases E.Field!

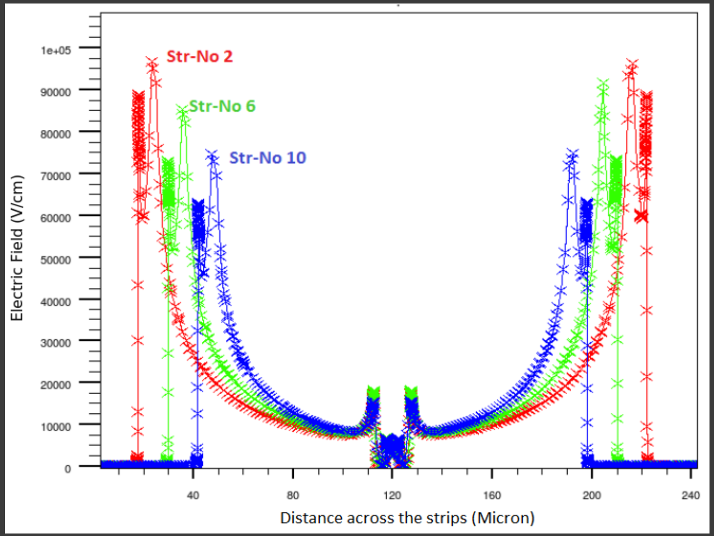
* R. Ranjeet et al., Simulations for Hadron Irradiated n+p- Si Strip Sensors Incorporating Bulk and Surface Damage, presented at 23rd RD50 Workshop, CERN, Switzerland (2013).

Width & Pitch

HPK Campaign







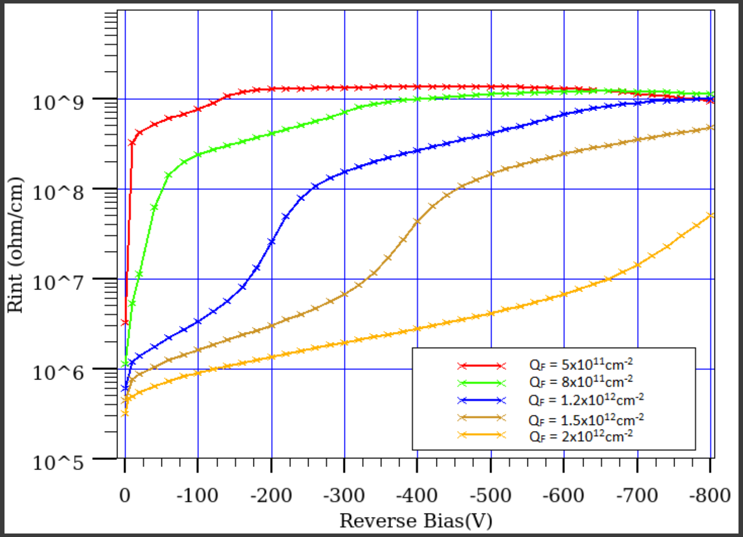
As the strip pitch increases, the electric field at the implant edge rises.

As the strip width increases, the electric field at the implant edge decreases.

* CMS Detector Note. Simulation of Silicon Devices for the CMS Phase II Tracker Upgrade. CMS DN-2014/016.

Inter-strip Resistance

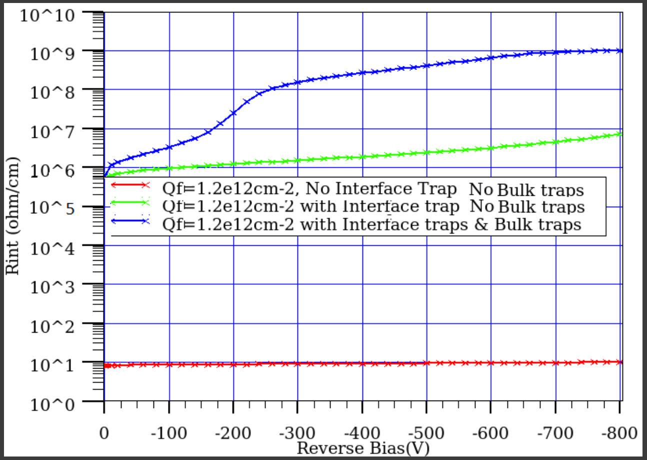
R_{int} is a surface property.
→ It was thought that it is affected by surface damage (Q_f) only.

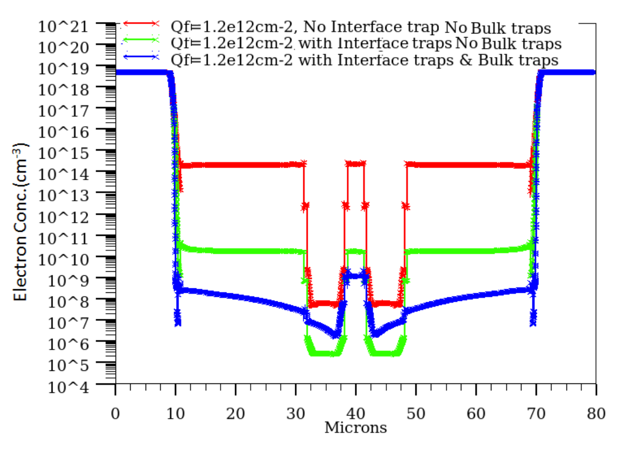


Increase in Q_f attracts more e^-s towards the n^+ side of the detector.
→ R_{int} decreases.

BUT, this was not seen experimentally!!

Both surface (Q_f + N_{it}) & bulk damage traps play a role in deciding R_{int}!





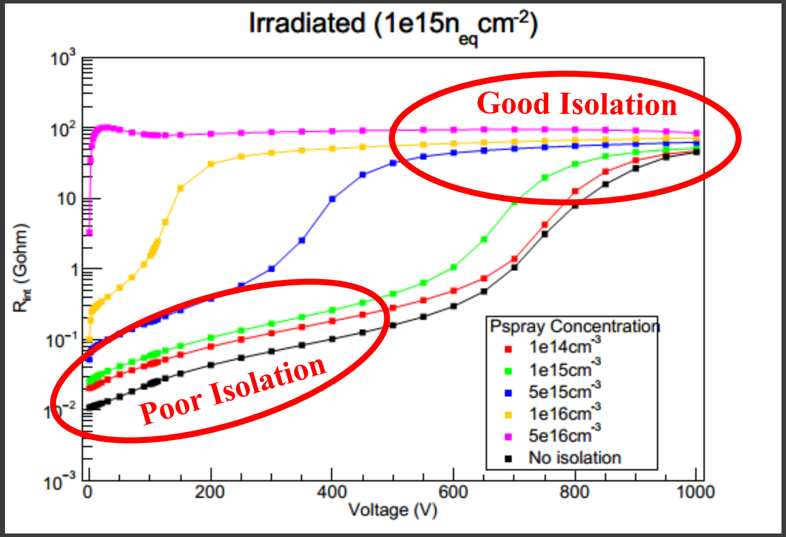
N_{it} = 2 acceptor type traps

Bulk traps = Acceptor & Donor traps, but near the n^+ implant, acceptor traps are more ionized

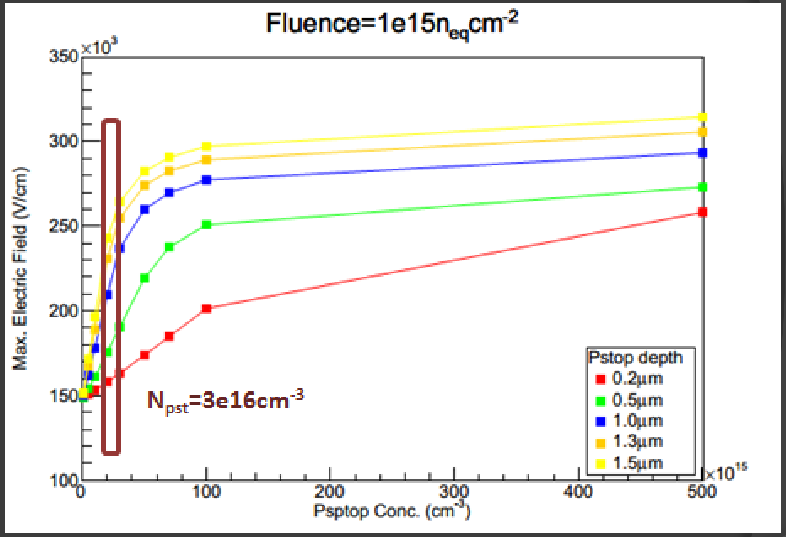
→ These two COMPENSATE the effect of accumulation of e^-s by Q_f (positive fixed oxide charge traps)

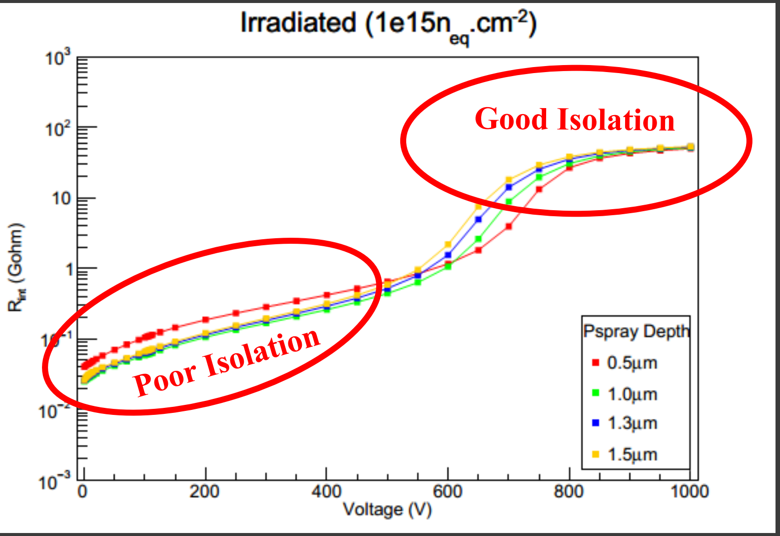
*R. Dalal., G. Jain, et al Simulation of Irradiated Si Detectors. POS (Vertex 2014).

Inter-pixel Resistance & Max. E.Field



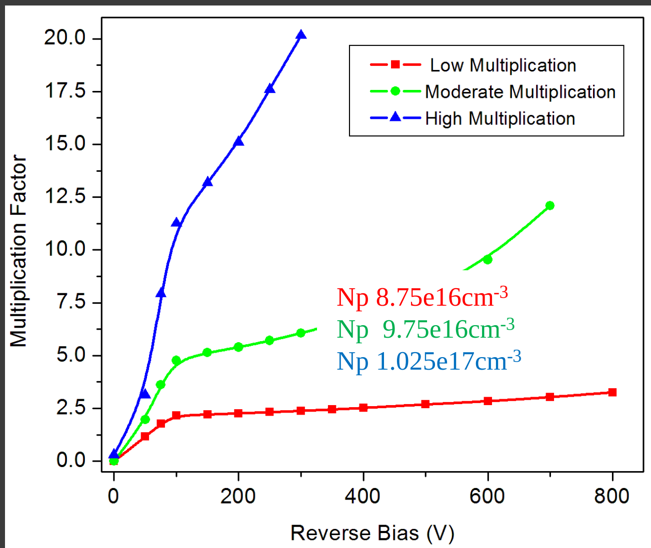
A higher concentration & a deeper pspray/pstop provides good isolation. But, this also leads to a rise in the electric field!



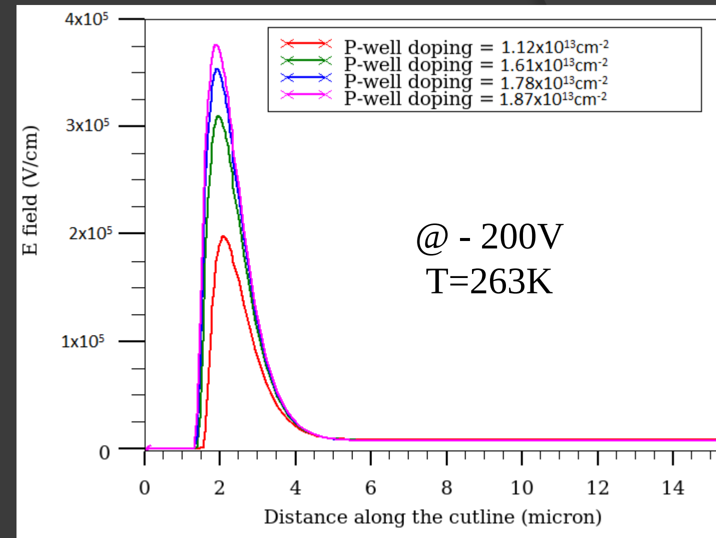


Therefore, an optimized concentration & depth of the isolation structure has to be chosen.

High Gain in LGADs



The reason for higher multiplication factor is that the localised electric field peaks up with increasing p-well concentration.

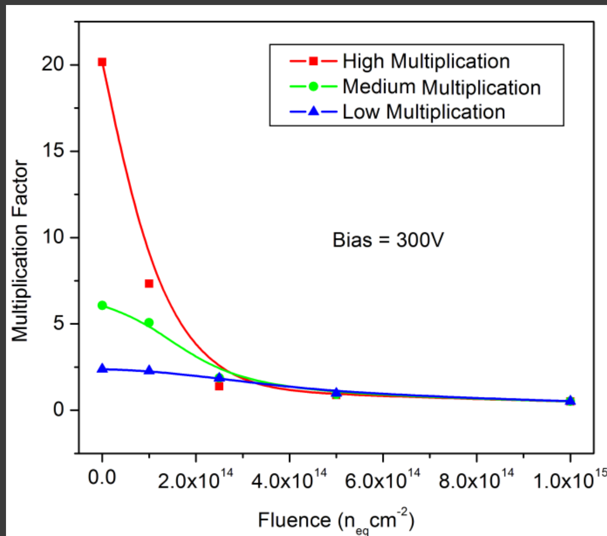


N_p (cm^{-3})	p-well dose in cm^{-2} (gain)				
	d_p=5.5µm	d_p=6 µm	d_p=6.5 µm	d_p=6.8 µm	d_p=7.1 µm
8.75 x10^{16}	1.26x10^{13} (1.0)	1.38 x10^{13} (1.0)	1.49 x10^{13} (1.1)	1.56 x10^{13} (1.4)	1.63x10^{13} (3.2)
9.75 x 10^{16}	1.40 x10^{13} (1.0)	1.53 x10^{13} (1.0)	1.66x10^{13} (1.2)	1.73x10^{13} (2.1)	1.81x10^{13} (19.5)
1.025 x 10^{17}	1.47 x10^{13} (1.0)	1.60 x10^{13} (1.0)	1.74 x10^{13} (1.3)	1.82x10^{13} (2.8)	1.90x10^{13} (-)

GAIN does not depend on dose only. It rather depends on the entire doping profile of both the n$^+$ implant & the p-well!

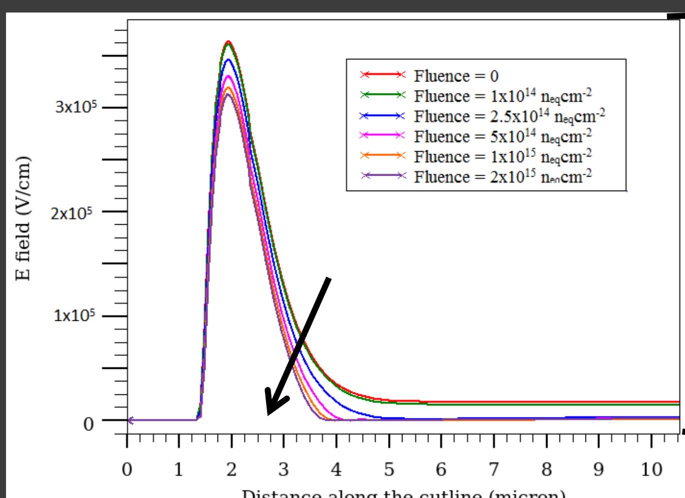
* R. Dalal, G. Jain, A. Bhardwaj, K. Ranjan. TCAD simulation of Low Gain Avalanche Detectors. NIM A. Manuscript accepted.

LGAD Gain with Fluence

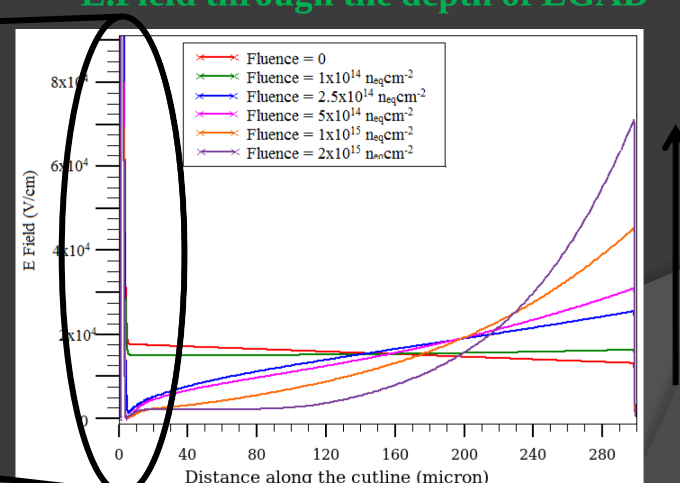


- Gain is same for all fluence ≥ 2.5 x 10^{14} $n_{eq}cm^{-2}$
- Almost no multiplication for fluence ≥ 5 x 10^{14} $n_{eq}cm^{-2}$
- Peak E.Field inside p-well is lowered with increasing fluence.
- Width of multiplication region is also reduced.
- E.field just below the p-well is strongly lowered with fluence.
- This leads to inefficient charge collection.
- Backside E.field peak grows with fluence.

E.Field @ frontside of LGAD



E.Field through the depth of LGAD



* R. Dalal, G. Jain, A. Bhardwaj, K. Ranjan, TCAD simulation of Low Gain Avalanche Detectors. NIM A. Manuscript accepted.


THANK YOU FOR YOUR ATTENTION
ANY QUESTIONS?
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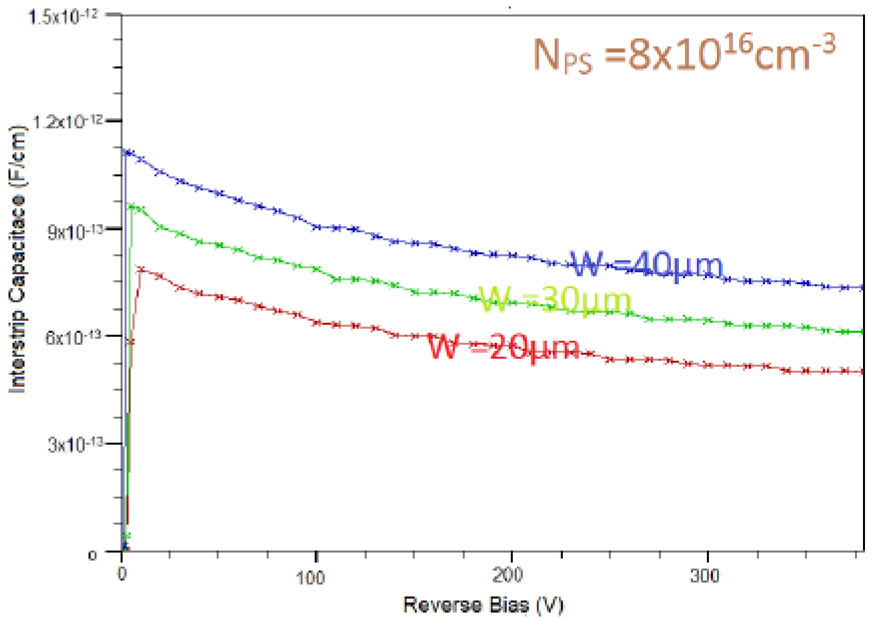
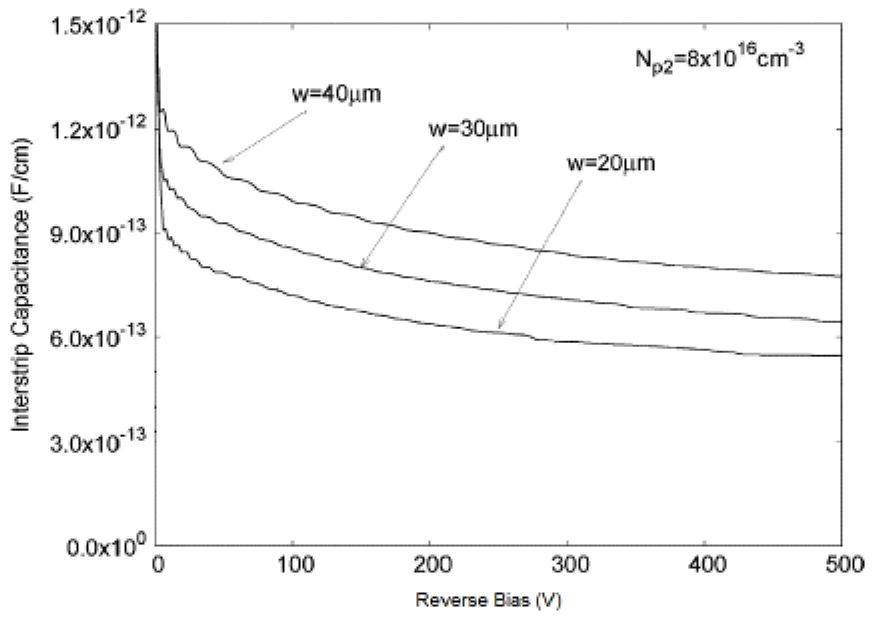
Interstrip Capacitance





* R. Dalal.. PhD Thesis. Delhi University, India.

* C. Piemonte. Device simulations of isolation techniques for silicon microstrip detectors made on p-type substrates. IEEE Trans. Nucl. Sci., NS-53 (3):1694, 2006