TCAD simulations of Low Gain Avalanche Detectors incorporating improved impact ionization modelling

Chakresh Jain
Kalpna Tiwari, Rahul Sharma, Namrata Agrawal, Ashutosh Bhardwaj, Kirti Ranjan

Department of Physics and Astrophysics
University of Delhi, India

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Remote Talk

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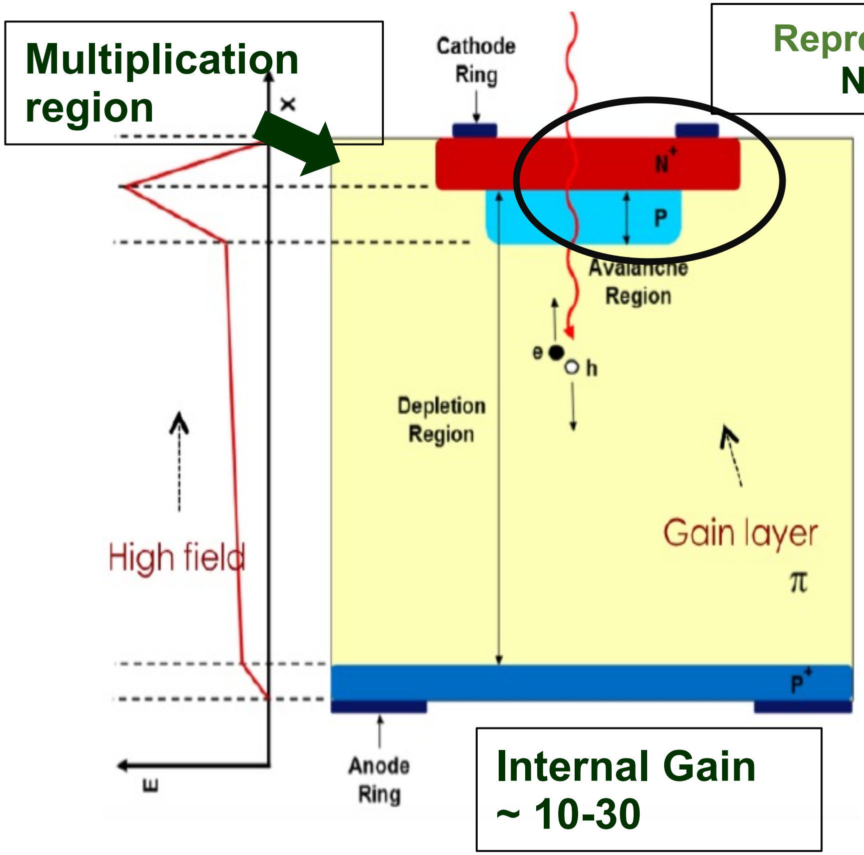
Low Gain Avalanche Detector

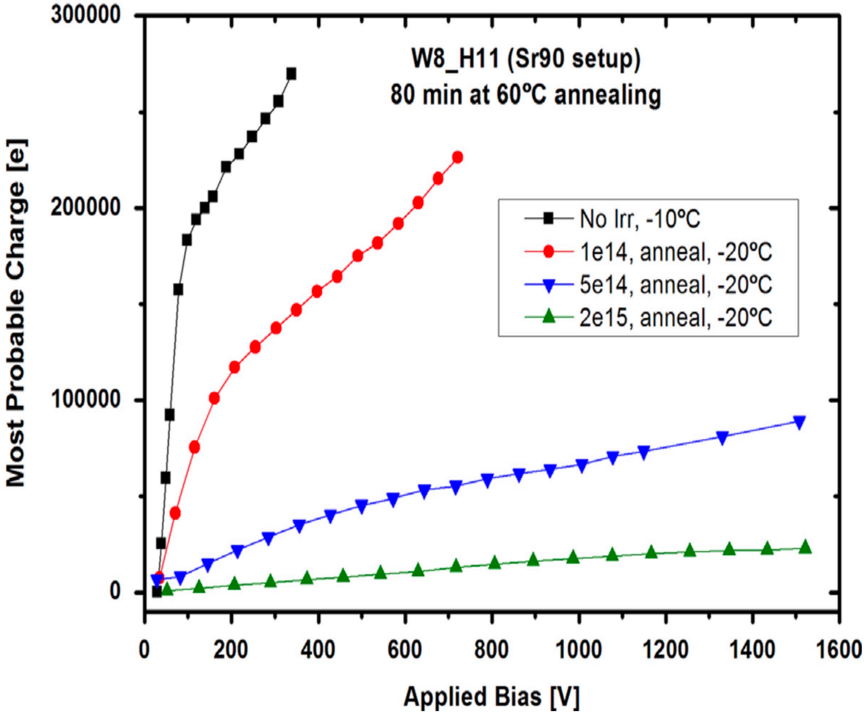
G. Pellegrini, et al. *Measurements of Low Gain Avalanche Detectors (LGAD) for high energy physics applications*, 9th International 'Hiroshima' Symposium (2013).



Multiplication region

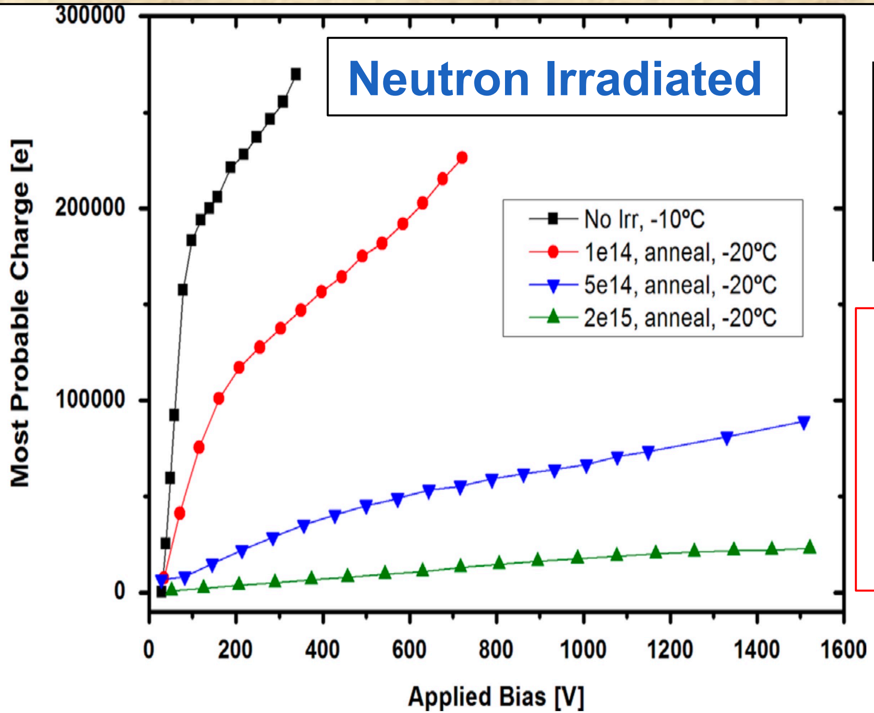
Internal Gain ~ 10-30

Representative response of a thick LGAD (300 µm):
Non-irradiated as well as Neutron Irradiated



- **Traditional n-on-p detector with the additional p-type layer**
- **Creation of a region of strong electric field on application of suitable bias**
- **Avalanche starts at a critical electric field (close to 3×10^5 V/cm)**
- **Local & controlled 'charge multiplication' → Internal Gain**
- **Potential for accurate timing measurements**

Motivation



- Charge multiplication behavior or Internal gain vanishes at,
  - About 2e15 n_{eq} cm^{-2} for neutrons

- ➢ Understanding the Radiation Damage Mechanism is crucial to reproduce and predict the performance of LGADs in intense radiation environment
  - Enhance the Radiation hardness !

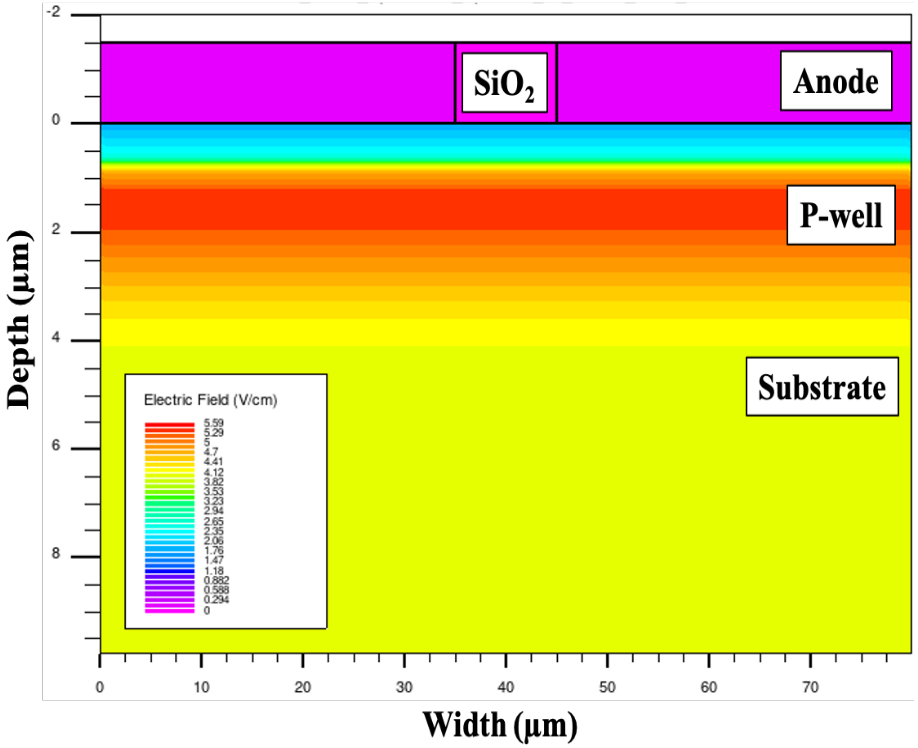
Neutron Radiation Damage Modelling for LGADs

- Previously, Delhi Group developed a Neutron Radiation Damage Model for Standard Silicon Sensors
  - ✓ Successfully reproduced macroscopic behavior → IV, CV, CCE, Trapping Prob.

- Present work: Application of conceived Neutron Model to LGADs incorporating,
  - ➢ Gain Layer Degradation: Acceptor Removal → Irradiated
  - ➢ Accurate modelling of Impact Ionization Mechanism → Irradiated, Non-Irradiated

*G. Pellegrini et al., Technology developments and first measurements of Low Gain Avalanche Detectors for high energy physics applications. NIM A 481 (2002) 297–305.

LGAD: Simulation Structure and parameters

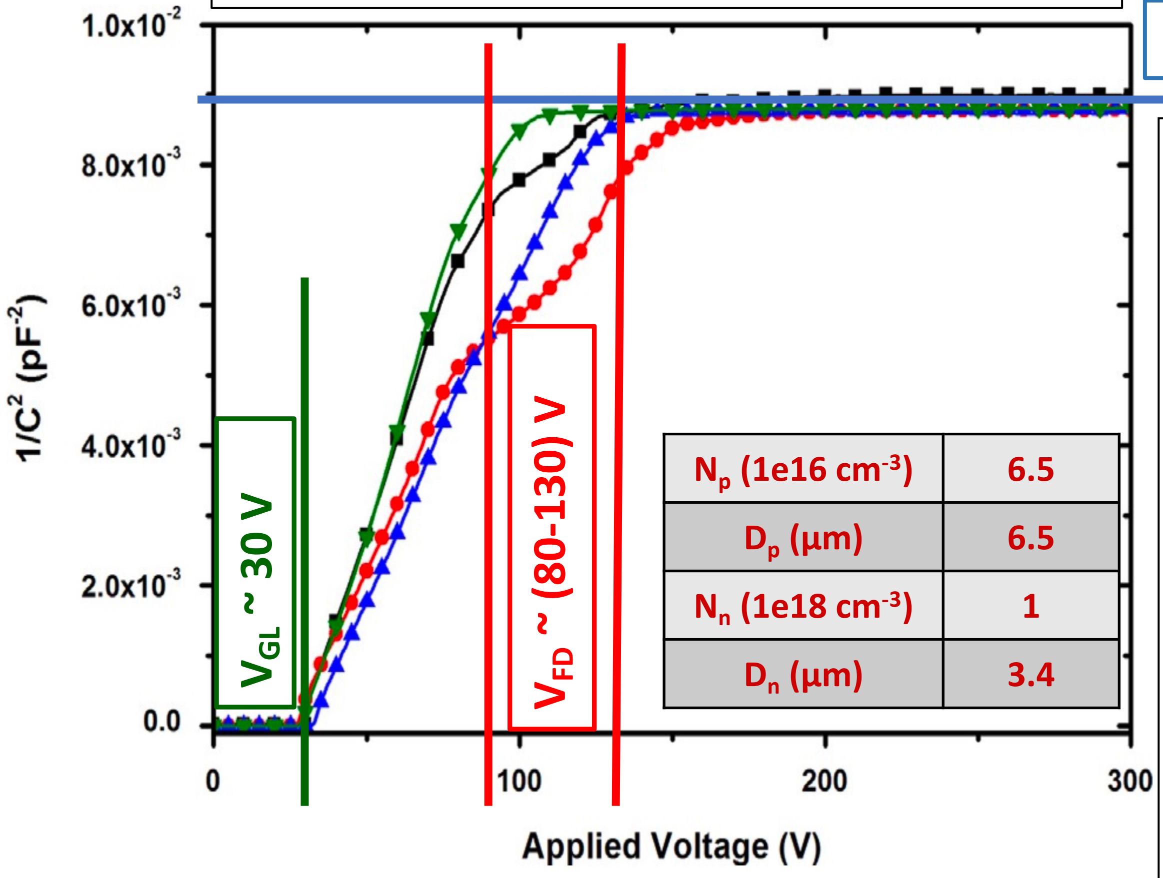


Design Parameter	Value
Physical Thickness, d (μm)	300 (Given)
Bulk Doping, N_b (cm^{-3})	Next Page !
p-well doping conc., N_p (1e16 cm^{-3})	
p-well doping depth, D_p (μm)	
Implant doping conc., N_n (1e16 cm^{-3})	
Implant doping depth, D_n (μm)	
Neutron Fluence (1MeV n_{eq} cm^{-2})	0, 1e14
Temperature	253K, 263 K

- **LGAD structure is simulated using SILVACO TCAD platform**
  - Performance of the device is analyzed : IV, CV and Charge Collection (CC) behavior

Motivation behind the Design parameters of LGAD

Measured $1/C^2$ vs Bias: Non-Irradiated



N_p (1e16 cm^{-3})	6.5
D_p (µm)	6.5
N_n (1e18 cm^{-3})	1
D_n (µm)	3.4

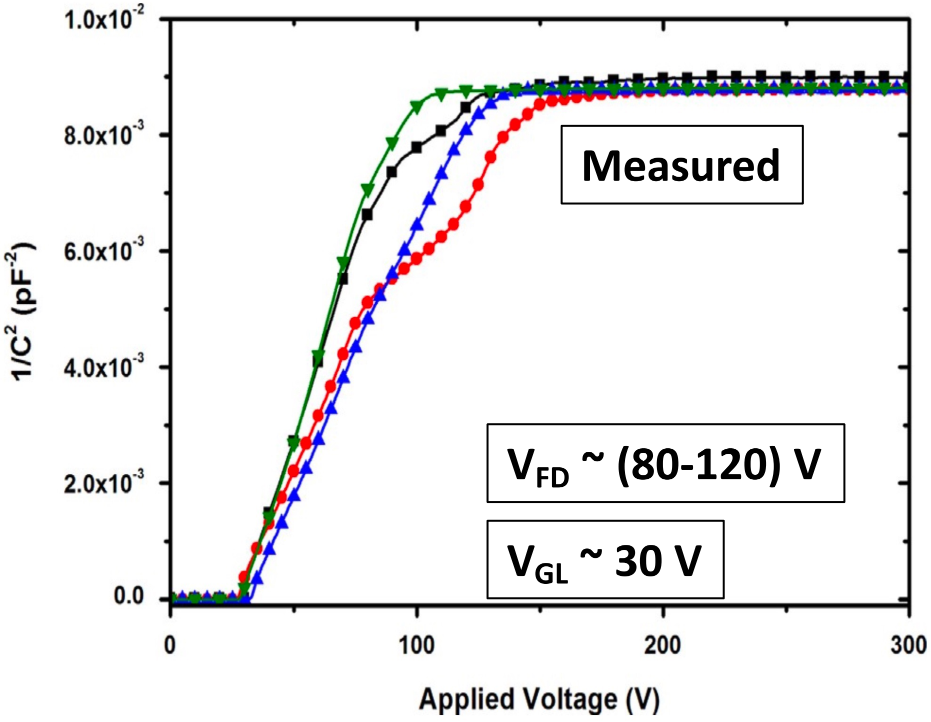
Saturation Value of $1/C^2$

- Saturation Value of $1/C^2$
  - ✓ Estimation of active thickness, t
- Linear portion of the plot between V_{FD} & V_{GL}
  - ✓ Estimation of Bulk Doping Density, N_b (1.5e12 cm^{-3})
- Gain Layer Voltage, V_{GL}
  - ✓ Estimation of gain layer doping profiles (N_p, D_p) and implant doping profile (N_n, D_n)

➢ In Addition, to assist the parameter estimation, a systematic sensitivity analysis is performed to assess the impact of different design parameters on V_{GL} and E_{peak} developed in the Gain Layer.

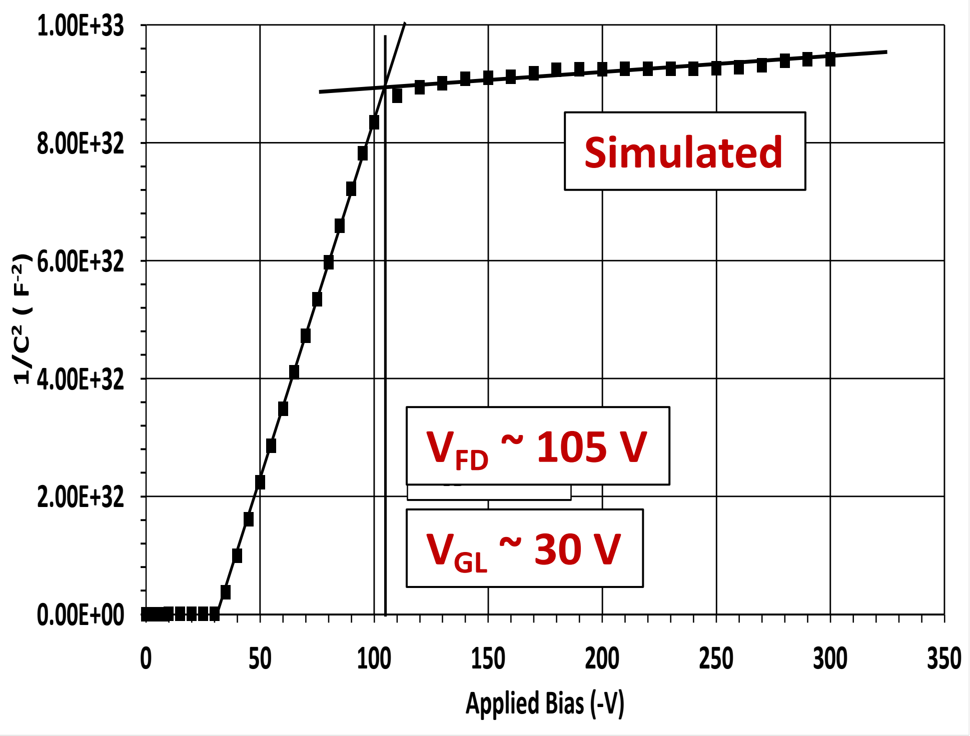
*G. Pellegrini et al., Technology developments and first measurements of Low Gain Avalanche Detectors for high energy physics applications. NIM A 481 (2002) 297–305.

CV Characteristics (Non-Irradiated LGAD): Measured vs Simulation (Silvaco)



V_{FD} ~ (80-120) V

V_{GL} ~ 30 V



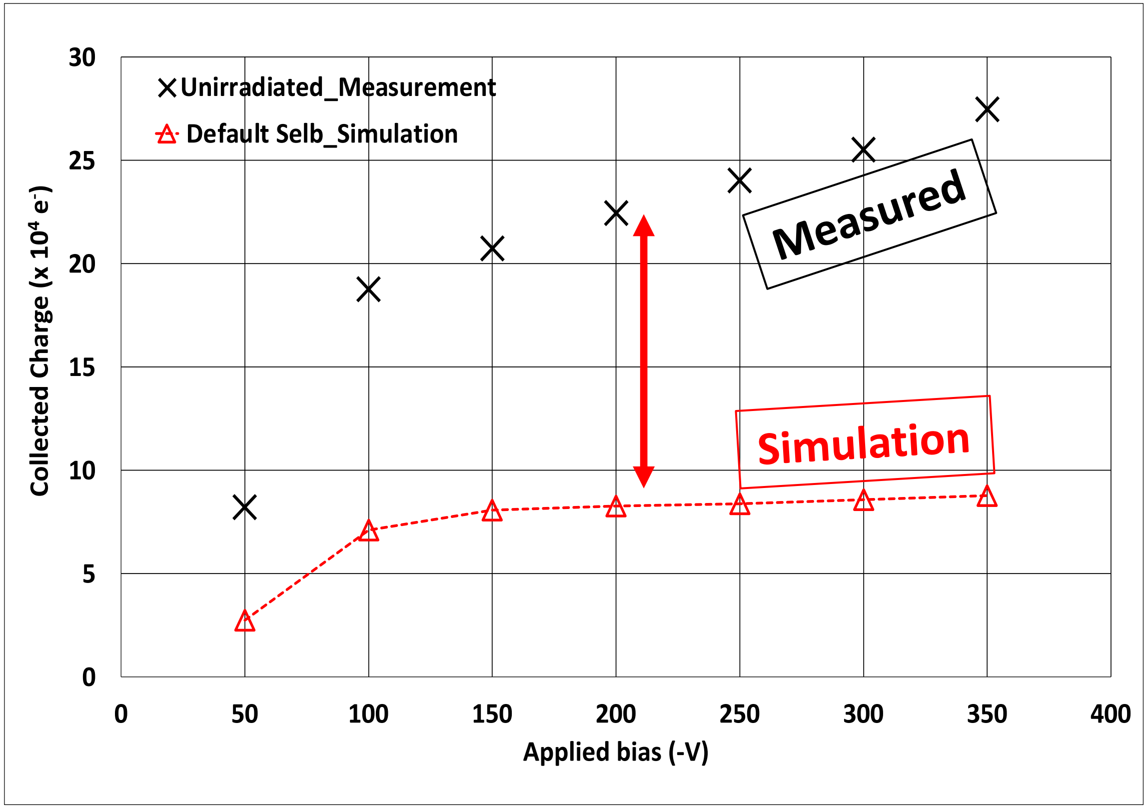
V_{FD} ~ 105 V

V_{GL} ~ 30 V

- The differences in the saturation value of 1/C^2 observed in experimental data and simulation results is due to the differences in dimensions of the actual device and simulated structure
  - Experimental Structure (Area ~ 5x5 mm^2); Simulated Structure (Area ~ 80x1 µm^2)
  - Physical thickness of simulated structure is kept the same as the experimental structure
- Simulation result is in a good agreement with the corresponding measurement result

*G. Pellegrini et al., Technology developments and first measurements of Low Gain Avalanche Detectors for high energy physics applications. NIM A 481 (2002) 297–305.

Charge Collection (Non-Irradiation): Measured vs Simulation



- For TCT simulations, IR Laser (Wavelength = 1060 nm) is used to create the signal charge
  - TCT simulations are performed using **Mixed-Mode**

- Absolute collected charge (CC) is shown as a function of applied bias voltage.
- Simulated CC remains lower than the measured values for all bias voltages up to 350V

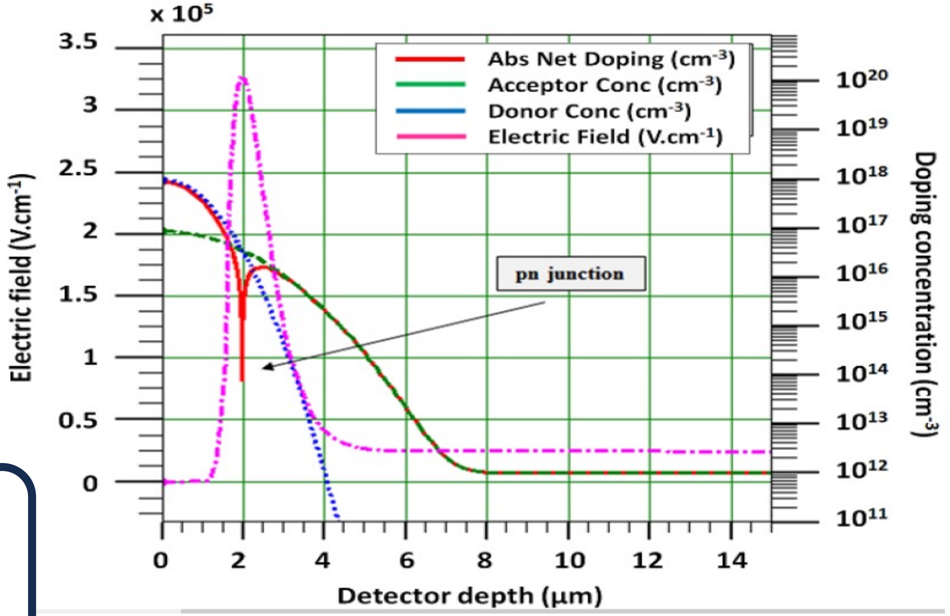
✓ Good agreement b/w measured & simulation results for non-irradiated CV: V_{GL}, V_{FD}

- Collected charge deviates drastically even for the non-irradiated case !!

*G. Pellegrini et al., Technology developments and first measurements of Low Gain Avalanche Detectors for high energy physics applications. NIM A 481 (2002) 297–305.

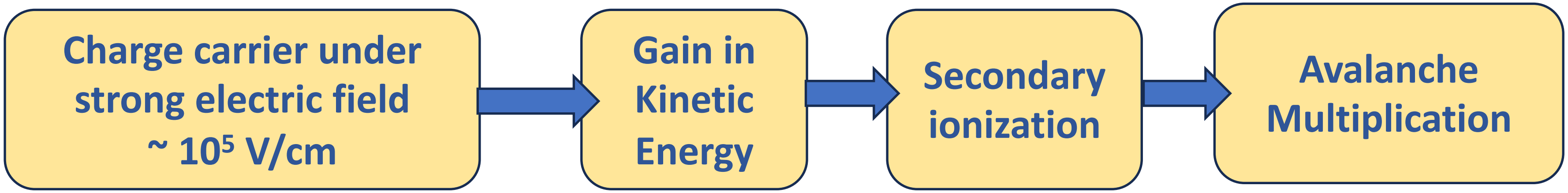
Investigation for low CC in simulations

- Collected Charge in LGADs is very sensitive towards the doping profiles and the resulting electric field profile developed in the gain layer
  - Requires accurate implementation of electric field distribution
  - Doping and electric field profiles in real devices is not well known !



❖ Difficulty in modeling precise electric field configurations in TCAD Simulations*

- Impact Ionization Process



Charge carrier under strong electric field ~ 10^5 V/cm → Gain in Kinetic Energy → Secondary ionization → Avalanche Multiplication

- Charge generation in LGADs is due to the internal multiplication of charge carriers drifting through the high field p-well region → Primary characteristics of LGADs

❖ Accurate Modeling of Impact ionization process is required for reliable TCAD results

*E. Curras, M. Moll, Study of Impact Ionization Coefficients in Silicon With Low Gain Avalanche Diodes, IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 70, NO. 6, JUNE 2023, DOI: 10.1109/TED.2023.3267058

Impact Ionization Modeling in Silvaco

- **Selberherr model** is used in simulations to implement the effects of impact ionization
  - Selberherr Model is based on Classical Chynoweth Law

Chynoweth Law

$$\alpha(n,p) = A_{(n,p)} \exp\left[-\frac{B_{(n,p)}}{E}\right]$$

Where, E = Local Electric Field

$\alpha(n,p)$ = Impact Ionization Coefficients

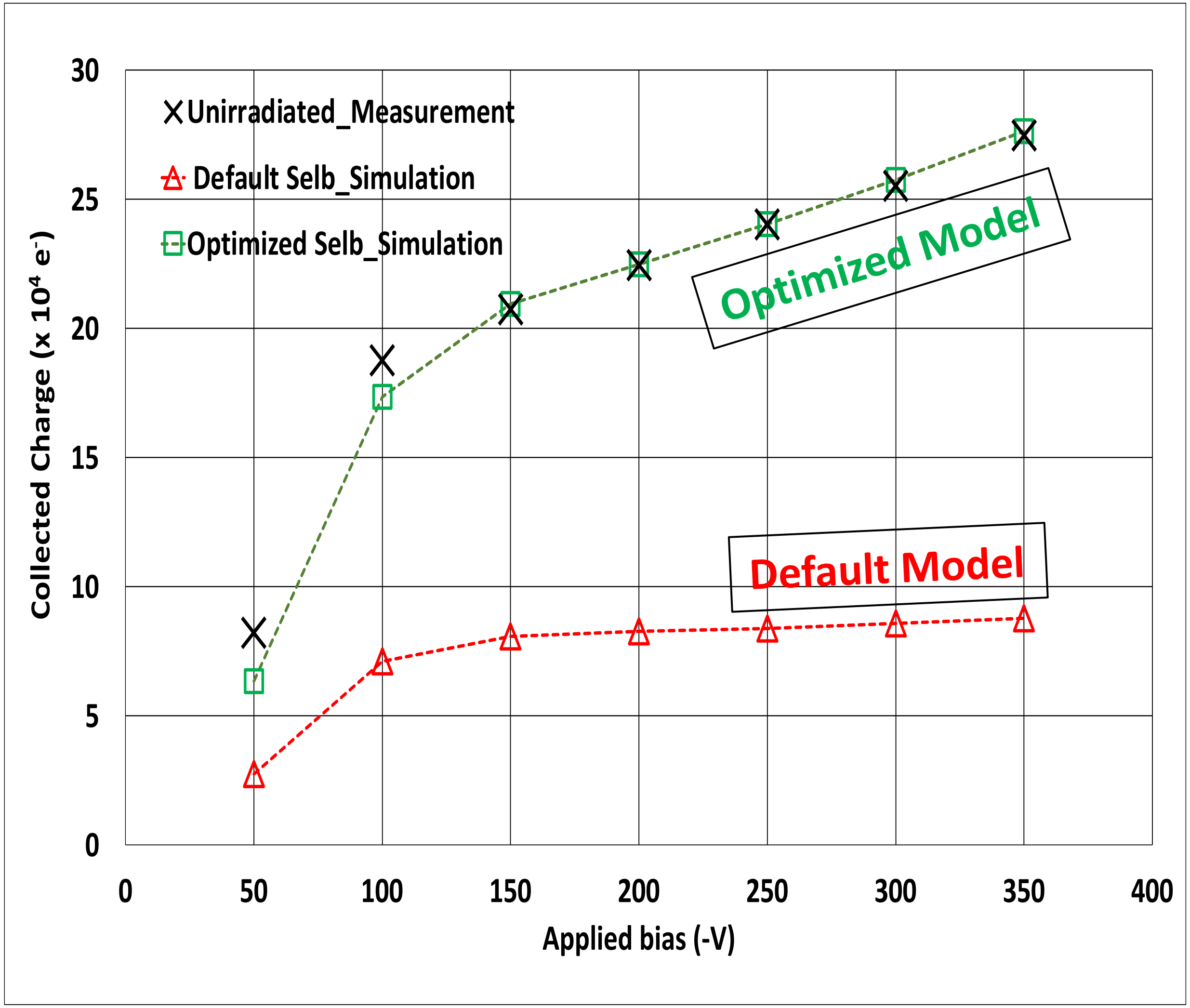
$A_{n,p}$, $B_{n,p}$ = model parameters controlling impact ionization

- ❖ High electric fields in p-well region make the simulation highly sensitive to impact ionization model parameters A (n, p) and B (n, p)
  - ❖ Careful tuning of the model parameters is of critical importance

✓ For parameter optimization, a sensitivity study is performed to assess the impact of each of these parameters on charge collection

$E < 4e5\ Vcm^{-1}$	Selberherr Default		Selberherr Optimized	
Parameter	Electrons	Holes	Electrons	Holes
A ($10^5\ cm^{-1}$)	**7.03**	15.8	**19.53**	15.8
B ($10^6\ Vcm^{-1}$)	1.231	2.036	1.231	2.036

CC (Non-Irradiation): Measured vs Simulation (After Impact Ionization Model Optimization)



- ✓ **Before Optimization:** **About 70% deviation is observed b/w measured results and simulations performed using default model parameters**

- ✓ **After Optimization:** **good agreement b/w measured & simulation results with improved impact-ionization modeling with optimized model parameters.**

➢ **Conclusion: Impact Ionization Model Parameters need to be optimized for LGADs**

*G. Pellegrini et al., Technology developments and first measurements of Low Gain Avalanche Detectors for high energy physics applications. NIM A 481 (2002) 297–305.

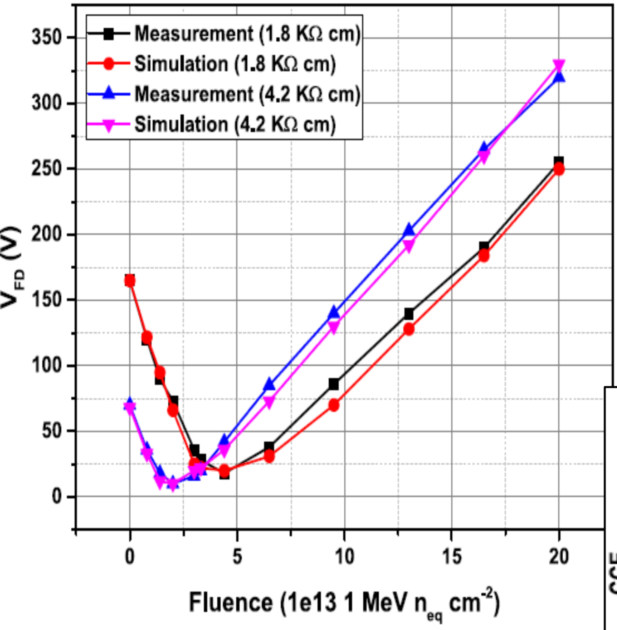
Charge Collection: Neutron Irradiated LGAD

Neutron damage model: On Conventional Sensors

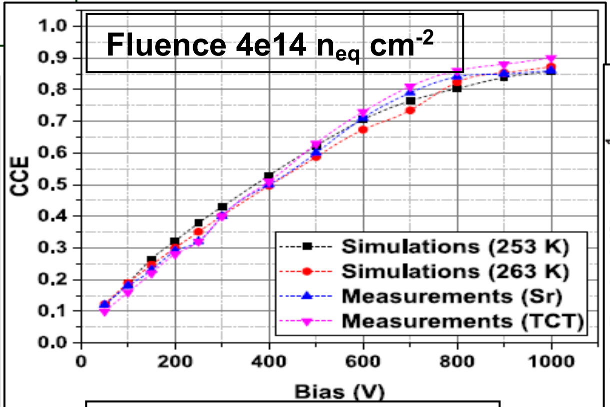
- To implement the effects of Neutron Irradiation in TCAD simulations for irradiated LGADs, the Neutron Radiation Damage Model* developed earlier by Delhi Group for conventional silicon sensors is incorporated.

Trap Type	Energy Level (eV)	G_{int} (cm^{-1})	σ_e (cm^2)	σ_h (cm^2)
Acceptor	$E_c - 0.51$	4	9×10^{-15}	3.8×10^{-14}
Donor	$E_v + 0.48$	1	1×10^{-14}	1×10^{-14}

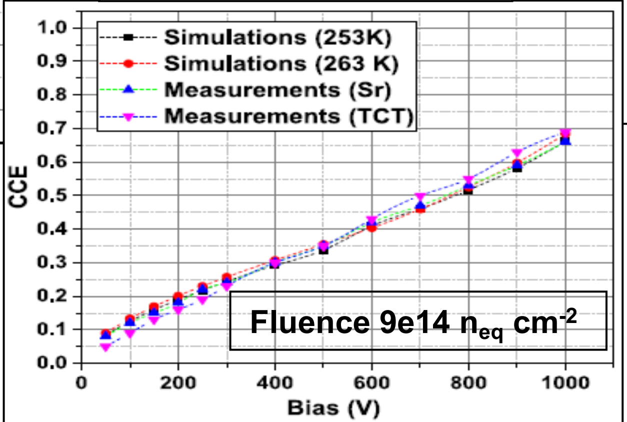
- **Salient Features of Neutron Radiation Damage Model**
  - Neutron Model includes two traps: an Acceptor and a Donor
  - Reproduces the behavior of traditional silicon detectors (both strip and diode structures)

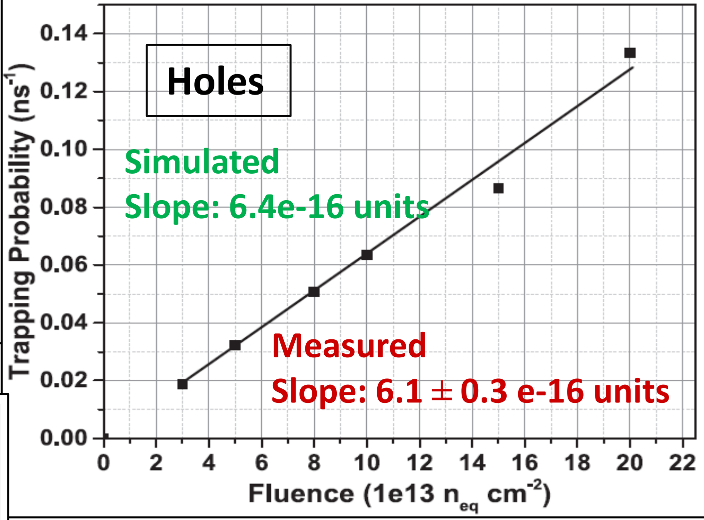


V_{FD} Vs neutron Fluence upto 4e14 n_{eq} cm^{-2}



CCE vs Neutron Fluence





Trapping Prob. vs Neutron Fluence upto 4e14 n_{eq} cm^{-2}

Modeling of neutron radiation-induced defects in silicon particle detectors, Chakresh Jain, Saumya Saumya, Geetika Jain, Ranjeet Dalal, Namrata Agrawal, Ashutosh Bhardwaj and Kirti Ranjan, Semicond. Sci. Technol. 35 (2020) 045021. DOI: 10.1088/1361- 6641/ab74ea.

Gain Layer Degradation in LGADs

- **Irradiated LGAD structures incorporate an additional effect—an Acceptor Removal Mechanism***
  - **High fluence exposure leads to removal of acceptor atoms**
  - **Prominent in the p-type gain layer of LGADs and hence called Gain Layer Degradation***
  - **Impacts:**
    1. **Reduces effective doping concentration in p-well**
    2. **Limits the achievable gain of LGADs at higher fluences**

- **Neutron Model is insufficient to inherently take care of the effect of acceptor removal in LGADs**
  - **In Simulations, the effect is implemented using Analytical Modeling of p-well Concentration**

Analytical Modeling of p-well Concentration*

$$N_A = N_{A,0}\,\exp(-c\,\Phi_{eq})$$

Where,

ϕ_{eq} = Incident Fluence

$N_{A,0}$ = Initial Acceptor Concentration

N_A = Acceptor Concentration at fluence ϕ_{eq}

c = Acceptor Removal Constant

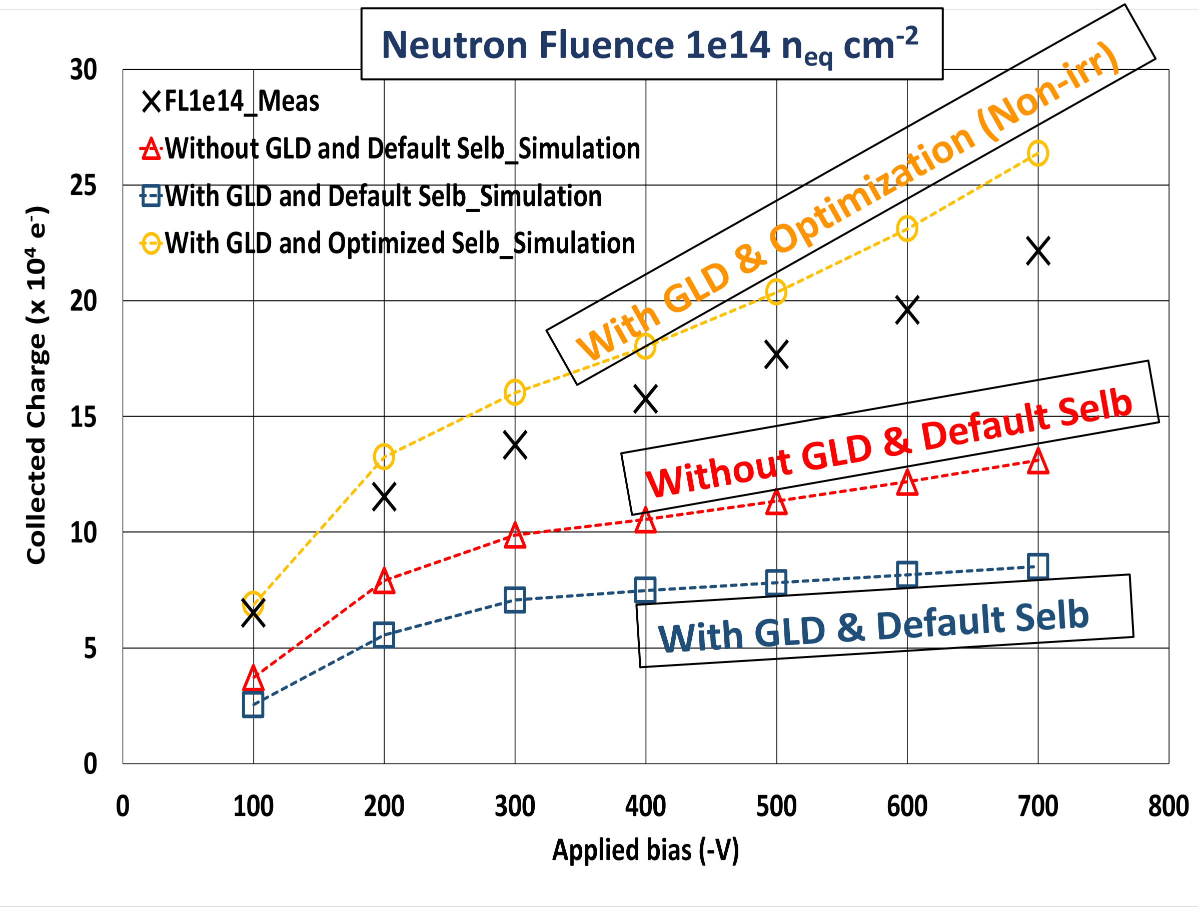
Measured c* ~ (7.4 – 10)x10^{-16} cm^2 (For Neutron Irradiation)

present simulations, c = 8x10^{-16} cm^2

*⁺G. Kramberger, et al., Radiation effects in low gain avalanche detectors after hadron irradiations, J. Instrum. 10 (2015) P07006

*E. Curras Rivera et al., Gain layer degradation study after neutron and proton irradiations in Low Gain Avalanche Diodes, arXiv:2306.11760v1 [physics.ins-det], 2023

Charge Collection (Neutron-Irradiation): Measured vs Simulation (1/2)



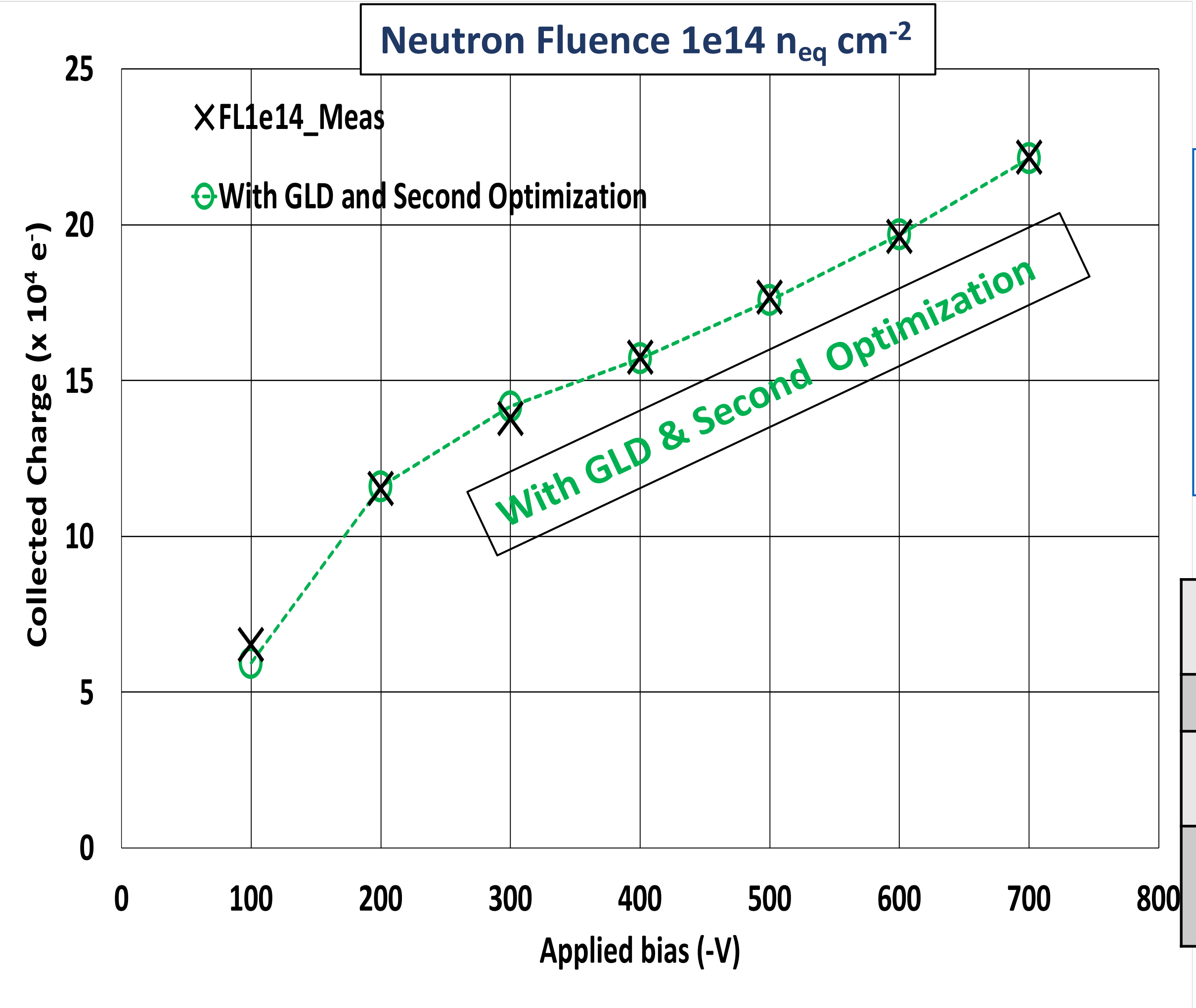
- ➢ Simulated Results obtained <u>without implementing GLD</u> and using <u>default impact ionization model parameters</u> underestimate the measurement results.
- ➢ The deviation further increases with incorporation of GLD due to Acceptor Removal Mechanism
- ✓ After Optimization: Simulation tend to slightly overestimate the measured result

Two Possible Approaches:

- ✓ A Different optimization of model parameters is used for irradiated case (Presently used)
- ➢ Use a slightly higher value of acceptor removal constant “*c*” (Future Work)

*G. Pellegrini et al., Technology developments and first measurements of Low Gain Avalanche Detectors for high energy physics applications. NIM A 481 (2002) 297–305.

Charge Collection (Neutron-Irradiation): Measured vs Simulation (2/2)



- ✓ **After Second Optimization: Good agreement b/w measured & simulation results with improved impact-ionization modeling with optimized model parameters.**

E < 4e5 Vcm^{-1}	Selberherr Default	Selberherr Optimized
Parameter	**Electrons**	**Electrons**
A (10^5 cm^{-1}) Non-Irradiated	7.03	19.53
A (10^5 cm^{-1}) ϕ=1e14	**7.03**	**17.53**

*G. Pellegrini et al., Technology developments and first measurements of Low Gain Avalanche Detectors for high energy physics applications. NIM A 481 (2002) 297–305.

Summary & Future Outlook

- Silicon detectors are installed nearest to the interaction point
  - Have to face the largest flux of charged and neutron hadrons
  - Crucial to understand the radiation damage mechanism of silicon detectors
- LGADs are a promising solution for future colliders
- Silvaco TCAD simulation platform has been used to study radiation damage
- Accurate implementation of electric field profile and impact ionization mechanism is required to reproduce the experimental data
  - Necessitates the careful tuning of model parameters to compensate for inaccuracy: Improved Impact Ionization Modelling
- Gain Layer Degradation is implemented analytically along with the Delhi's Neutron Radiation Damage model to account for the effects of Neutron irradiation on LGADs.
- Simulation Results with improved modelling are found to be in a good agreement with the measurements results

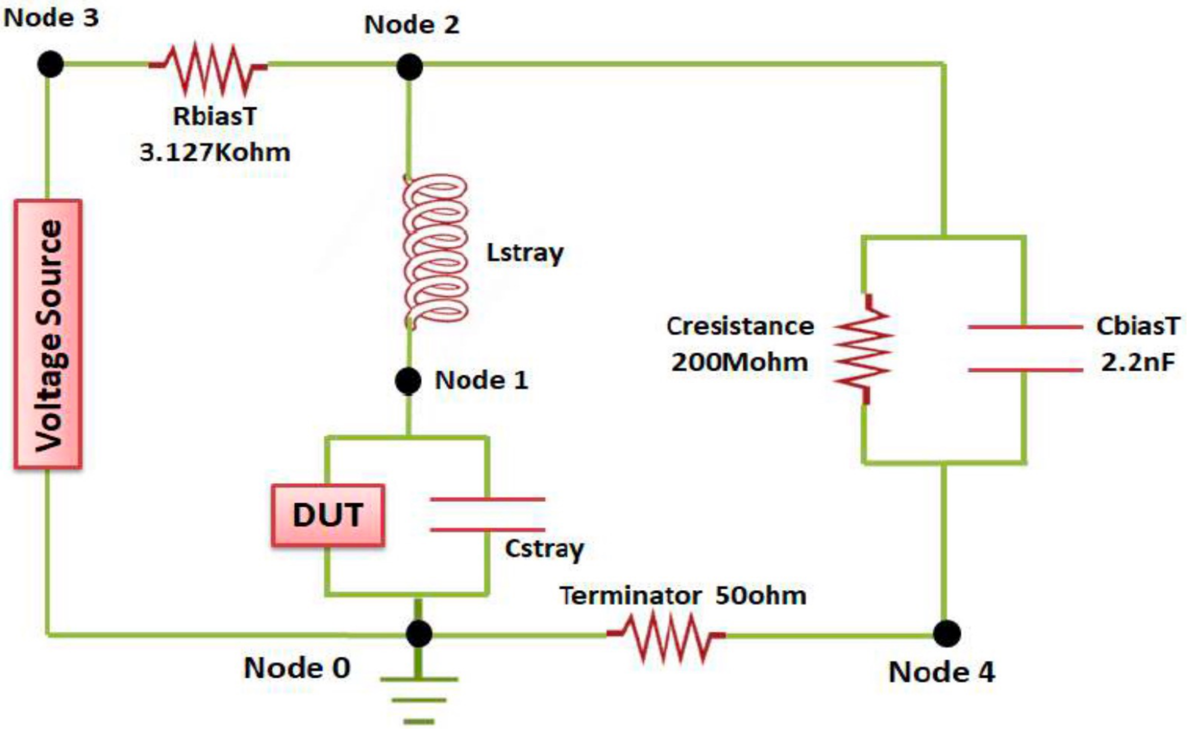
- Future Outlook
  - *The results will be further analysed by changing the acceptor removal constant value*
  - *Modelling Approach will be further applied to different fluence levels and different thicknesses*

Thanks for your Attention !

Back Up

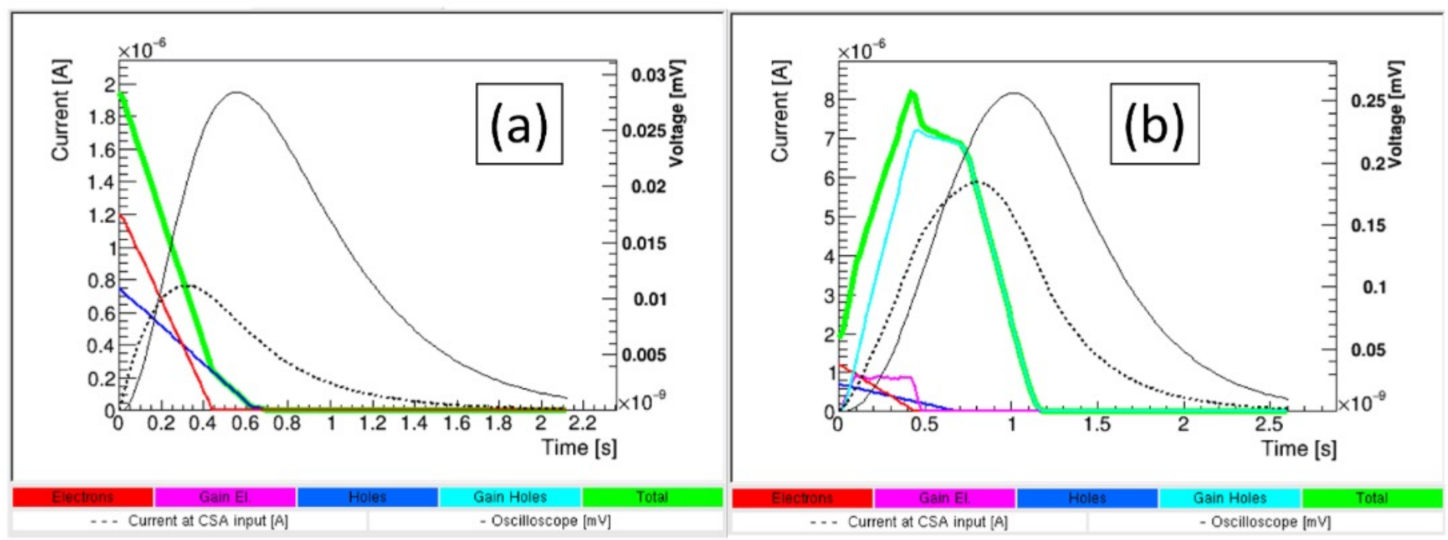
Mixed Circuit and Device Simulations: MixedMode

- **Mixed-Mode is a circuit simulator**
  - **Includes elements (resistors, inductors, capacitors etc.) that can be simulated using device simulation**
  - **Used to simulate circuits that contain semiconductor devices**
- **Transient Current Technique simulations are performed in the Mixed-Mode**
  - **Implemented the exact readout network of the measurement set-up in the simulations**
  - **Significantly influences the rise time and shape of the pulse**



Nodal representation of TCT circuit elements used for TCT simulations

Figure 3. Weightfield2 [21] simulations of current pulses generated by an MIP traversing a 50-μm thick (**a**) diode and (**b**) LGAD with a gain of 10. In addition, the signal as read-out by a 500 MHz scope is shown. Red curves are current induced by primary electrons, magenta by multiplied electrons, blue by primary holes and light blue by multiplied holes. Total currents are in green.



Both devices initially have a null rise time because the signal starts developing as soon as the carriers (electrons and holes) move into the bulk. However, for later times, the signal decreases in the diode, while it increases in the LGAD because of the contribution of the multiplied holes drifting to the back contact in the LGAD. In both cases, the full signal develops in about one nanosecond. To have signals completely developed in this time frame, the electric field in the substrate should be high enough for the holes to rapidly drift and be collected at the back contact. An electric field of about 3–4 V/μm is enough for the multiplied holes to drift all the way through the substrate thickness in less than one nanosecond for a 50 μm thick LGAD.

Sensors **2023**, *23*(4), 2132; https://doi.org/10.3390/s23042132

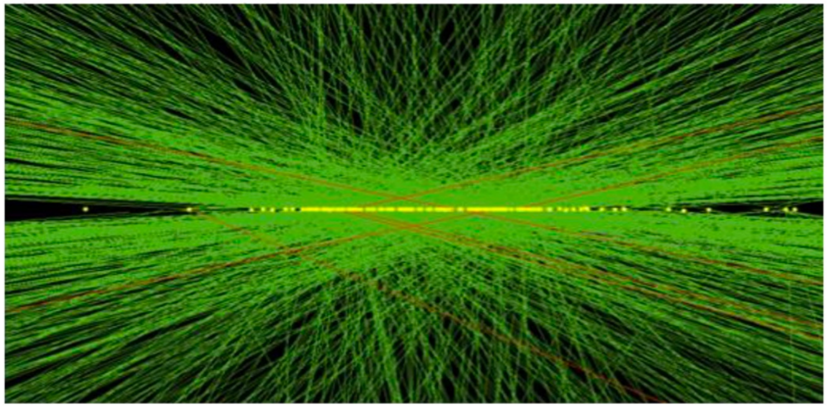
Introduction & Motivation : HL-LHC Upgrade (1/2)

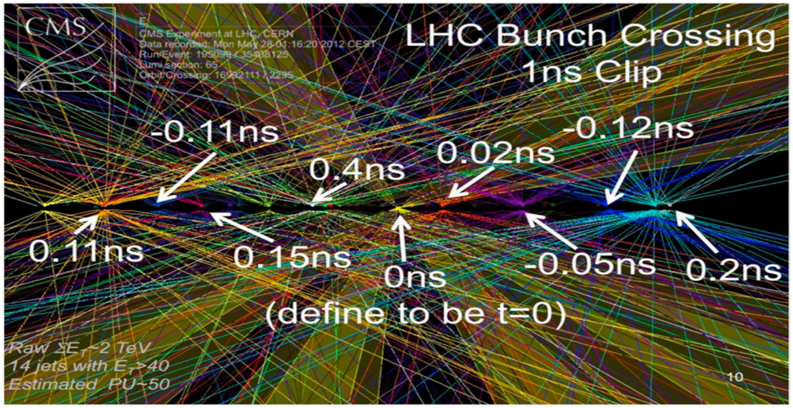
Design values	LHC –Runs 1,2,3	HL-LHC Phase
Peak Luminosity (L) in cm^{-2}s^{-1}	1.5 x 10^{34}	5 - 7.5 x10^{34}
Expected Integrated L	500 fb^{-1}	3000-4000 fb^{-1}
Average Pileup	50	140-200

- The HL-LHC and future hadron colliders, such as the FCC, present **significant challenges** for data processing.
  - Reconstruction of thousands of tracks, overlapping vertices, etc.

- Need to **resolve piled-up tracks** of charged particles emerging from **several vertices**.

- Separated not only in space but also in time by a **few tens of picoseconds**

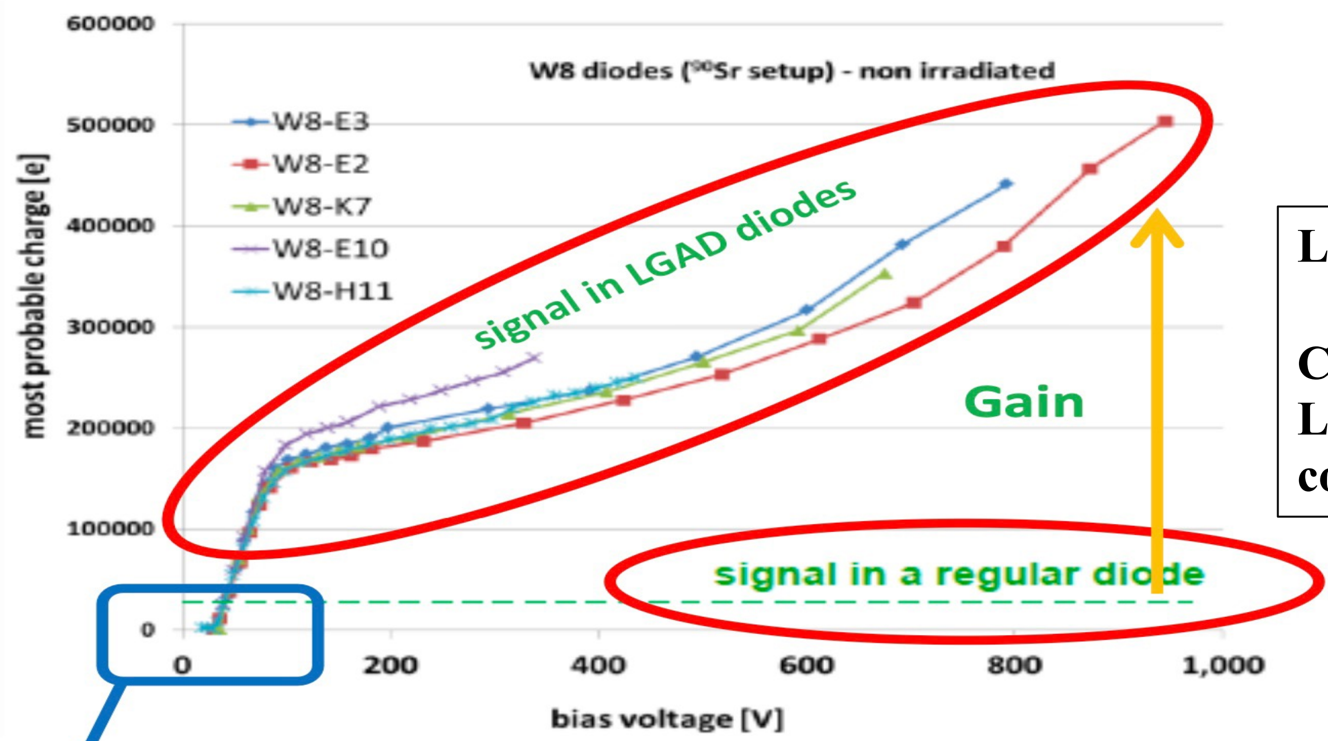




Pile-up: (https://doi.org/10.5170/CERN-2015-005, *Hartmut F-W Sadrozinski et al 2018 Rep. Prog. Phys. 81 026101

Some Experimental Results on LGAD - Nonirradiated

Non-Irradiated



LGAD Gain =

Charge collected by LGAD / Charge collected by PIN

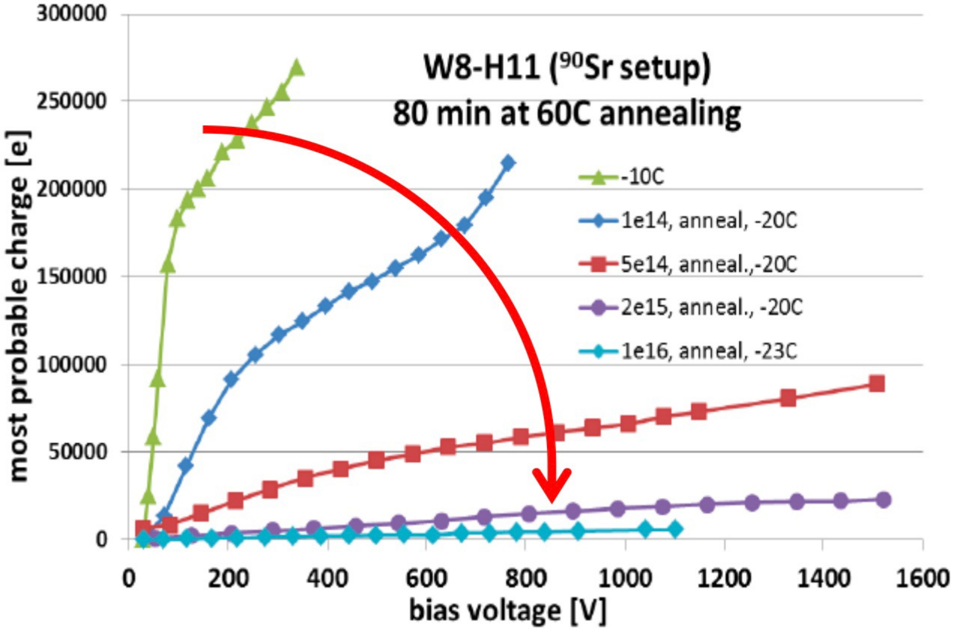
*G. Kramberger et al., 23rd RD50 workshop.

LGAD gain is: ~7 @ 500V, ~15 @ 900V! ☺

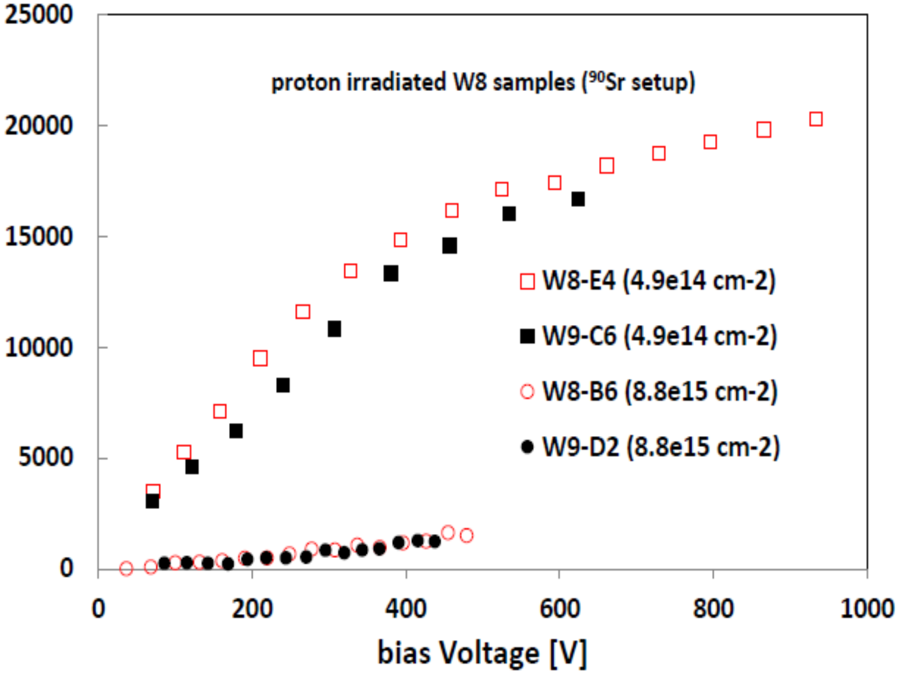
- Voltage Foot: LGAD Signal starts after a bias voltage
- Gain Layer voltage: Corresponds to the depletion of gain layer
- Can be used to calculate depletion depth of p-well

Challenge: Radiation Damage

Irradiated LGAD



Neutron Irradiated



Proton Irradiated

- As hadron fluence increases the collected charge (CC) decreases with high rate
- Charge multiplication behavior or Internal gain vanishes at,
  - About 2e15 n_{eq} cm^{-2} for neutrons
  - About 5e14 n_{eq} cm^{-2} for protons

Understanding the Radiation Damage Mechanism is crucial to enhance the Radiation hardness !

*G. Kramberger et al., 23rd RD50 workshop
*Hartmut F.-W. Sadrozinski, 23rd RD50 Workshop