29th

RD50 - Radiation hard semiconductor devices for very high luminosity colliders

LGAD design for harsh radiation environment using TCAD simulations

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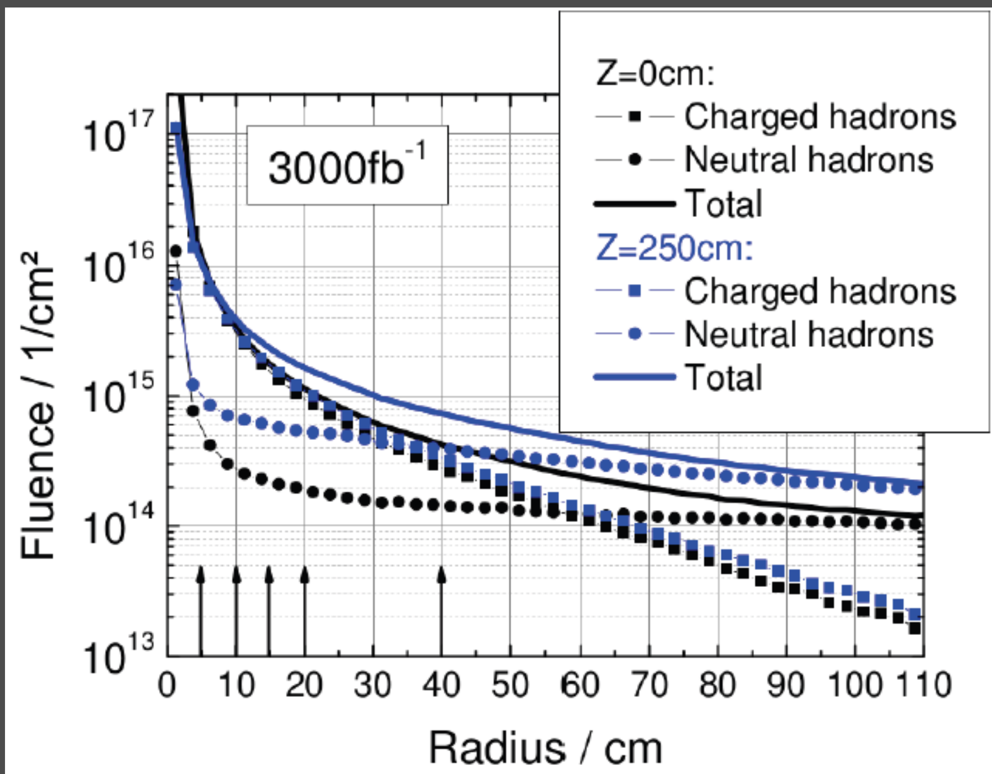
Plan of the presentation

- Principle of Low Gain Avalanche Detectors (LGADs)
- Motivation for the work
- Dependence of LGAD signal on –
  - → implant doping profiles
  - → detector thickness
  - → substrate/bulk resistivity
- Parameter optimization for radiation hard design for thin LGAD
- Summary

Introduction

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 cannot survive in HL-LHC ! ☹

With radiation, silicon detectors get damaged – both bulk & surface!
→ Electrical detection properties affected.
→ Increase in I_{leak} contributes to noise.
→ CCE decreases.

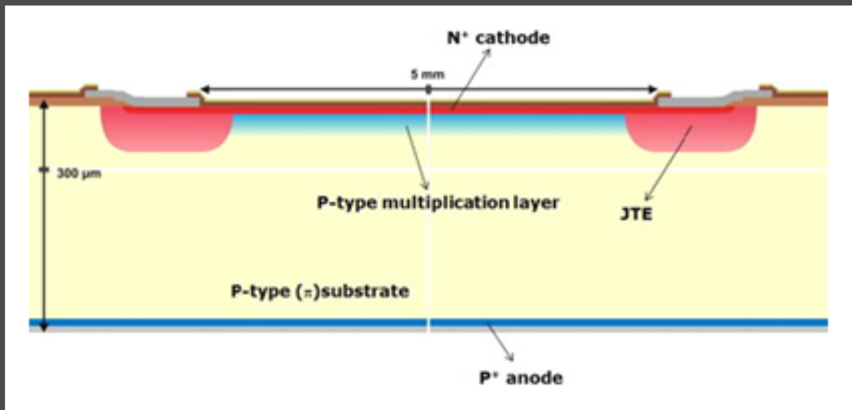
↓

A 'NEW TRACKER' is required !!

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

One possibility is to introduce an 'internal gain' in the detector → LGAD ☺

Low Gain Avalanche Detector

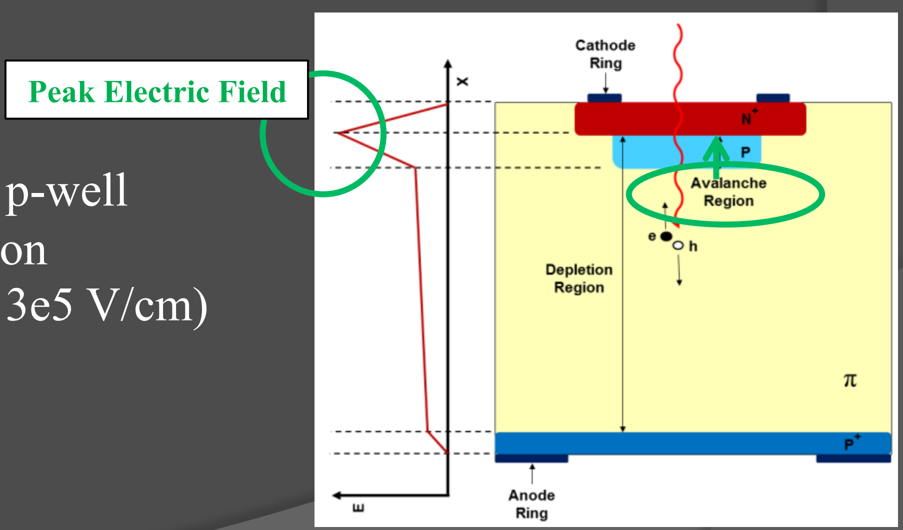


*Marta Baselga, 8th Trento workshop, 2013.

LGAD – traditional PIN detector, but with a deeper p-type multiplication layer (also called p-well) just below the n^+ implant.

Purpose of the p+ layer

- PN junction formed between n^+ implant & p-well
- A strong electric field builds in a local region
- Avalanche starts at critical electric field (> 3e5 V/cm)
- Local & controlled 'charge multiplication'
- Internal gain increases signal



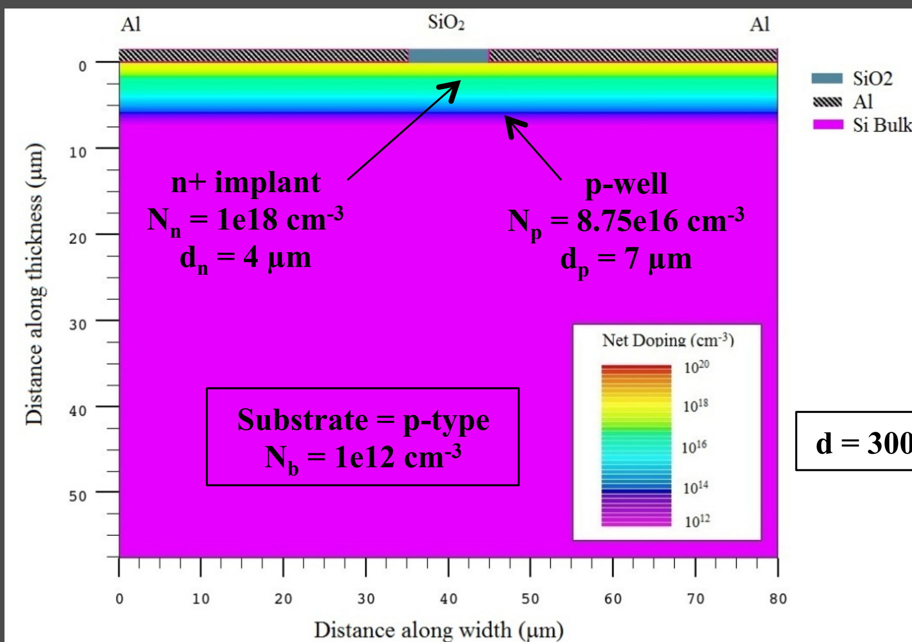
*Giulio Pellegrini, 23rd RD50 workshop.

LGAD Design in TCAD

Tune LGAD parameters for (sufficiently) high gain at high fluences!
→ Understand LGAD parameters responsible for gain.
→ Tune them for operation at high irradiation level.

2D LGAD Device Simulations in 'TCAD Silvaco' simulation framework

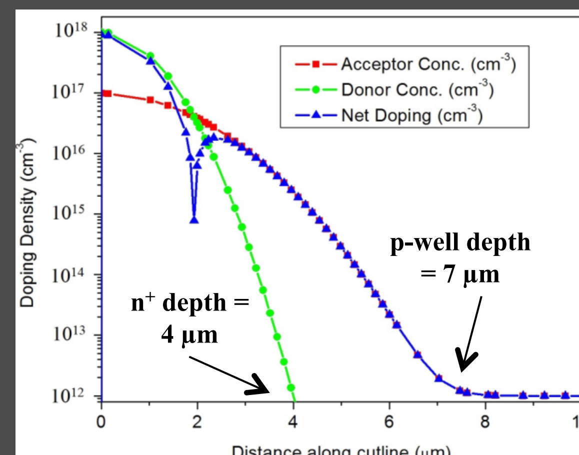
LGAD plane parallel structure



d = 300 µm

#Only a small cross-section is used for faster simulations. Area-factor is used within the simulation code to take care of scaling w.r.t to a real device.

Implant 1D doping profile



*R. Dalal, G. Jain et al., NIM A. Volume 836, 11 November 2016, Pages 113–121. **Slides 9-11.**

2 bulk traps Radiation Model

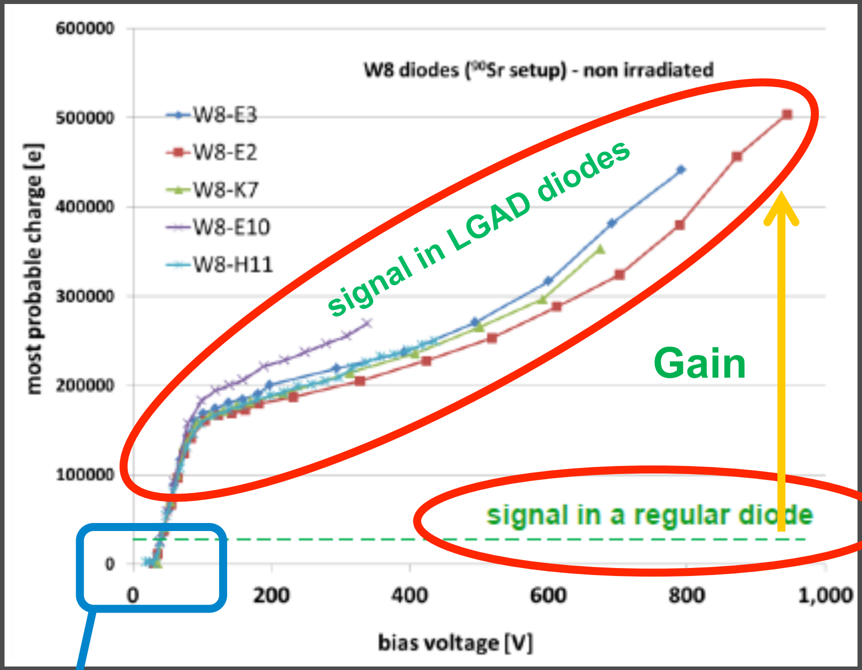
Trap	Energy Level	Density (cm^{-3})	σ_e (cm^{-2})	σ_h (cm^{-2})
Acceptor	E_C - 0.51 eV	4 X Φ	2.0 x 10^{-14}	3.8 x 10^{-14}
Donor	E_V + 0.48 eV	3 X Φ	2.0 x 10^{-15}	2.0 x 10^{-15}

*R. Dalal, G. Jain et al, PoS(Vertex2014)030 (2014).

Calibration with measurements

Some Experimental Results

Non-Irradiated



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

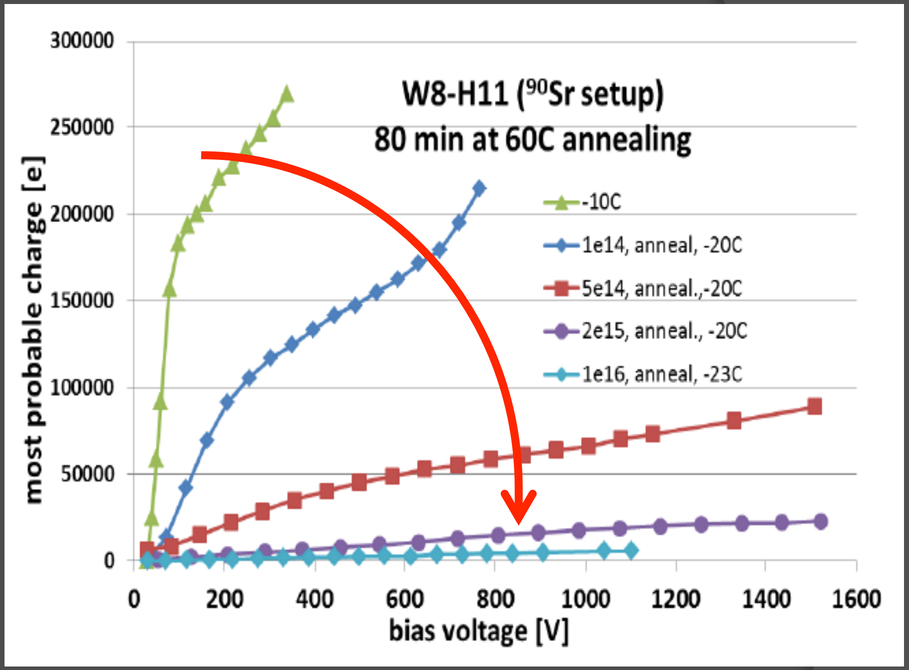
LGAD gain is: ~7 @ 500V, ~15 @ 900V! ☺

Voltage foot: LGAD signal starts after a bias voltage.

- Depletion voltage of p^+ multiplication layer

*Hartmut F.-W. Sadrozinski, 23rd RD50 workshop.

Irradiated



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

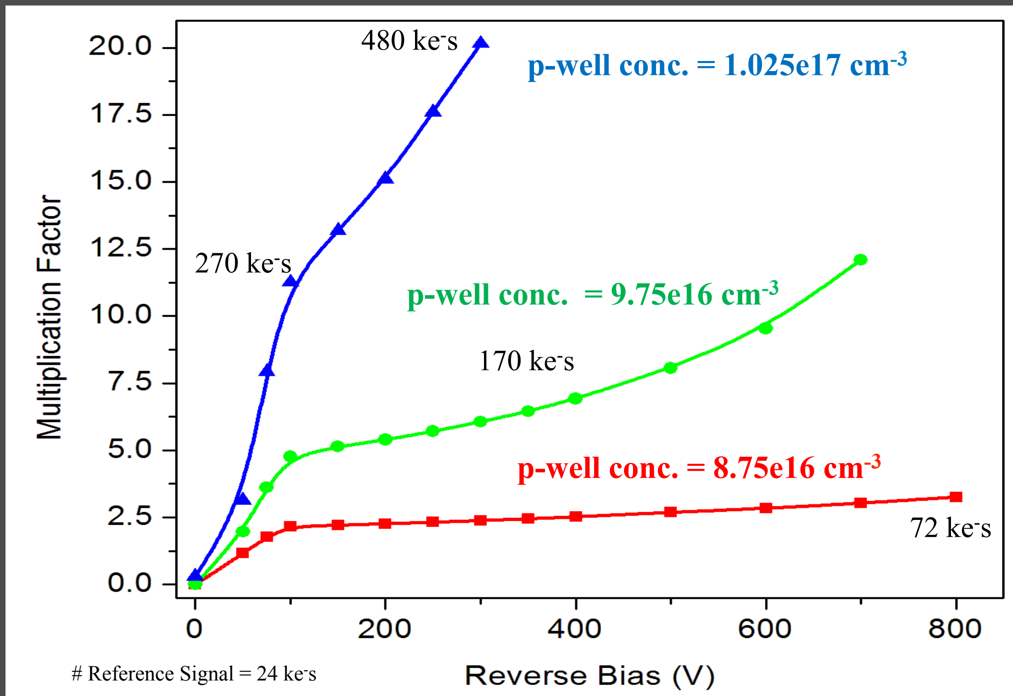
The gain falls off rapidly with irradiation !! ☹

Reason/Solution?!

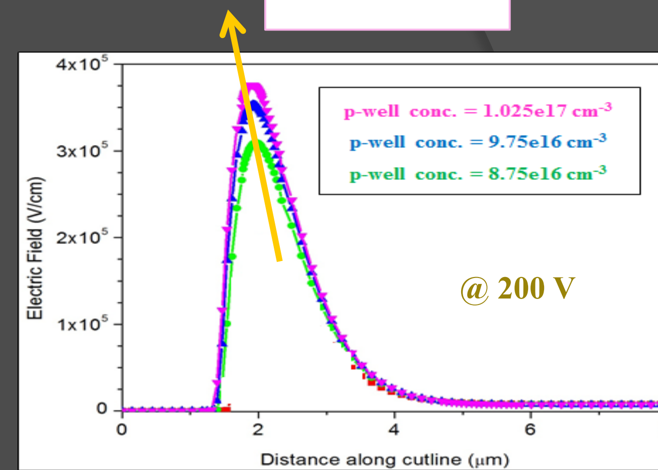
#LGAD Gain = Charge collected by LGAD / Charge collected by PIN

#Detector thickness = 300 μm

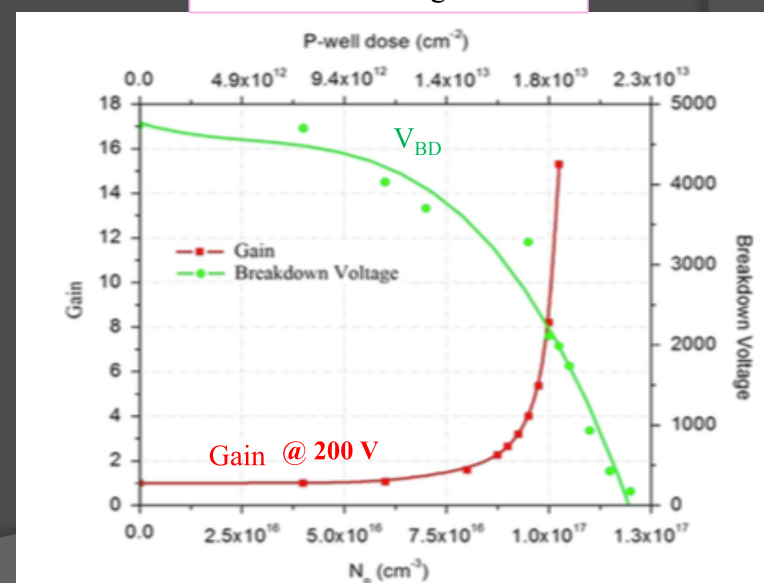
Simulated Result: Non-Irradiated



Peak E.field



Breakdown Voltage & Gain

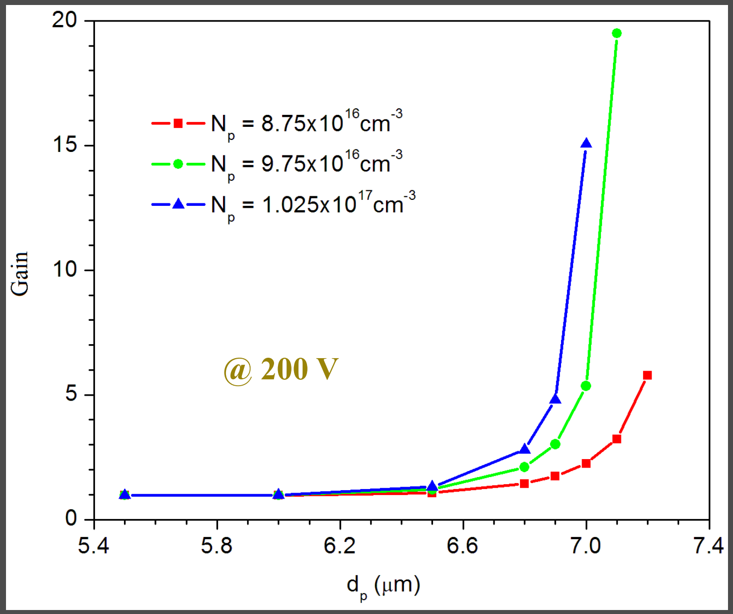


Increase in p-well conc. increases LGAD gain!

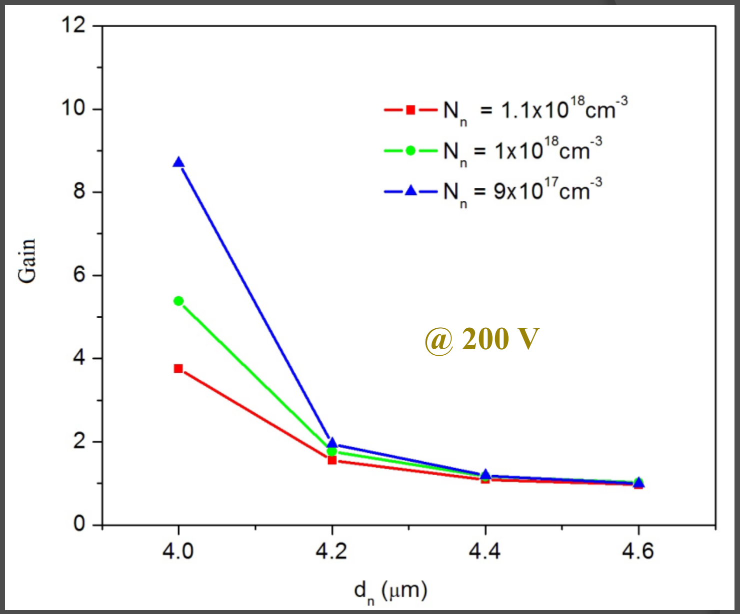
Because: increase in p-well conc. builds a stronger p-well-n$^+$ junction. Hence a higher peak electric field generates at the junction. This provides larger avalanche and thereby larger gain.

Effect of Doping Profiles

p-well layer



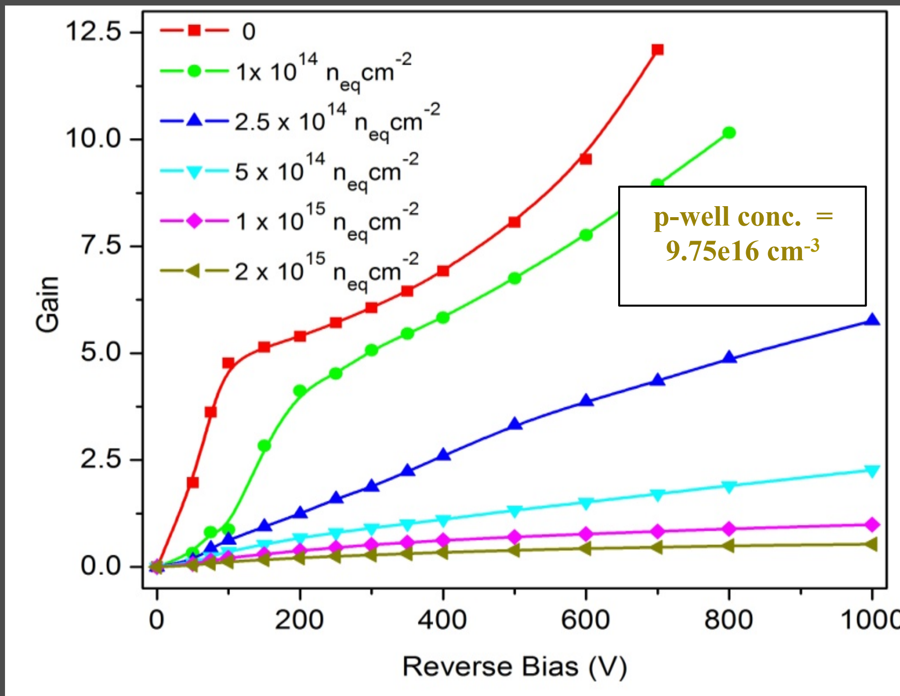
n+ implant



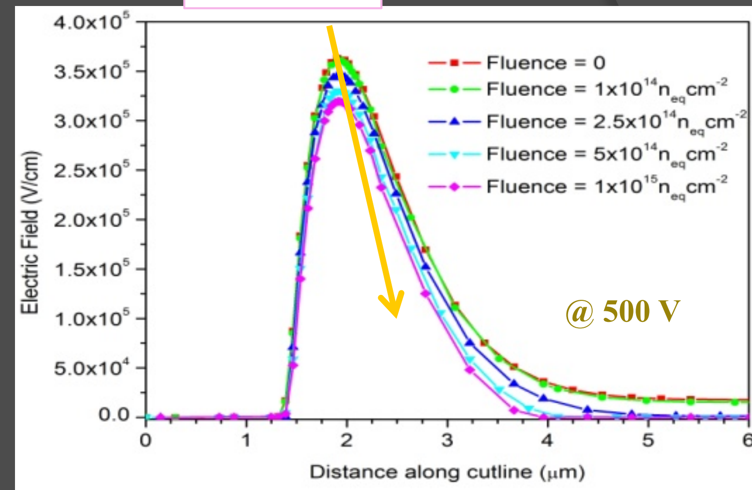
N_p (cm^{-3})	p-well dose in cm^{-2} (gain)				
	d_p=5.5μm	d_p=6 μm	d_p=6.5 μm	d_p=6.8 μm	d_p=7.1 μm
8.75 x10^{16}	1.26x10^{13} (1.0)	1.38 x10^{13} (1.0)	1.49 x10^{13} (1.1)	1.56 x10^{13} (1.4)	1.63x10^{13} (3.2)
9.75 x 10^{16}	1.40 x10^{13} (1.0)	1.53 x10^{13} (1.0)	1.66x10^{13} (1.2)	1.73x10^{13} (2.1)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

- Increase in the dp (for a given Np) results in higher acceptor density and hence leads to the higher electric field around the n+ /p-well junction, leading to the increase in gain.
- For a given dp, the gain increases with increase in Np beyond a minimum dp.
- Decrease in d_n & increase in N_n, pushes the p-well-n$^+$ junction deeper inside the Si bulk where the p-well concentration is lower. This results in lower LGAD gain!
- Also profiles with similar p-well dose, may provide different gain to the device.

Simulated Result: Irradiated

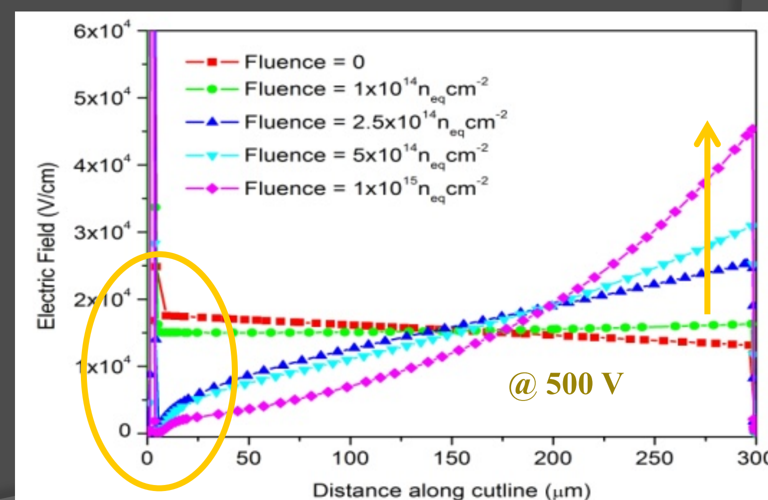


Peak E.field



LGAD gain decreases with increase in fluence!

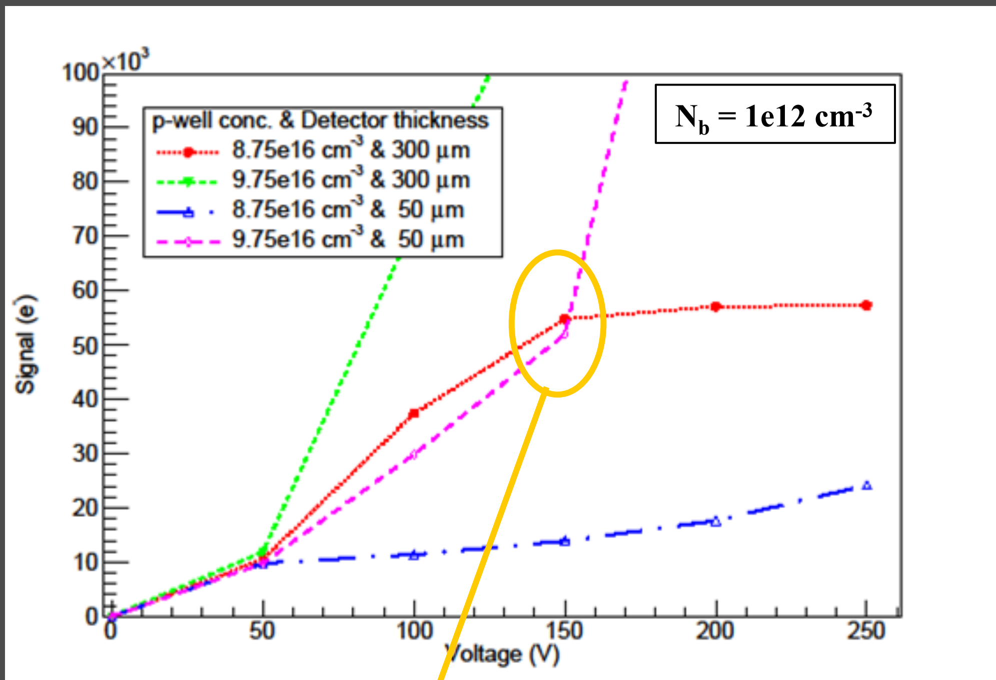
Bulk E.field



Because: 1. Peak e.field & its width decreases with fluence. E.field grows at backside of detector.
2. E.field just below the p-well region drops to very low value. Inefficient charge collection.

Effect of detector thickness

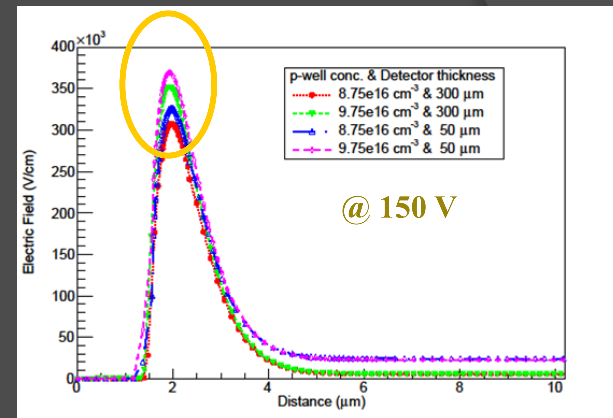
Effect of Detector Thickness – Non-irradiated



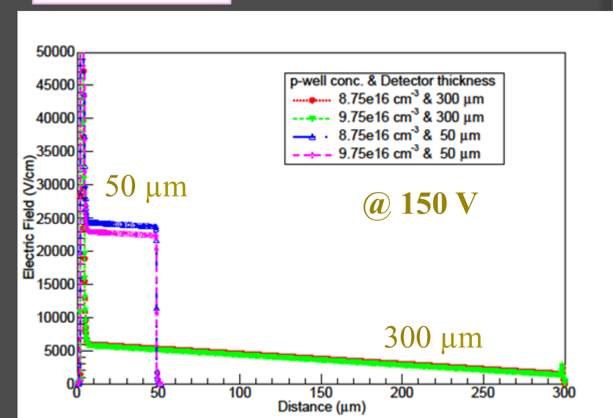
CC of Thin detector, with higher p-well conc ~ CC of Thick detector, with lower p-well conc

Because: Higher p-well conc. Implies higher peak e.field, larger avalanche multiplication. And also for thick detectors, e.field in the detector bulk is very low.

Peak E.field

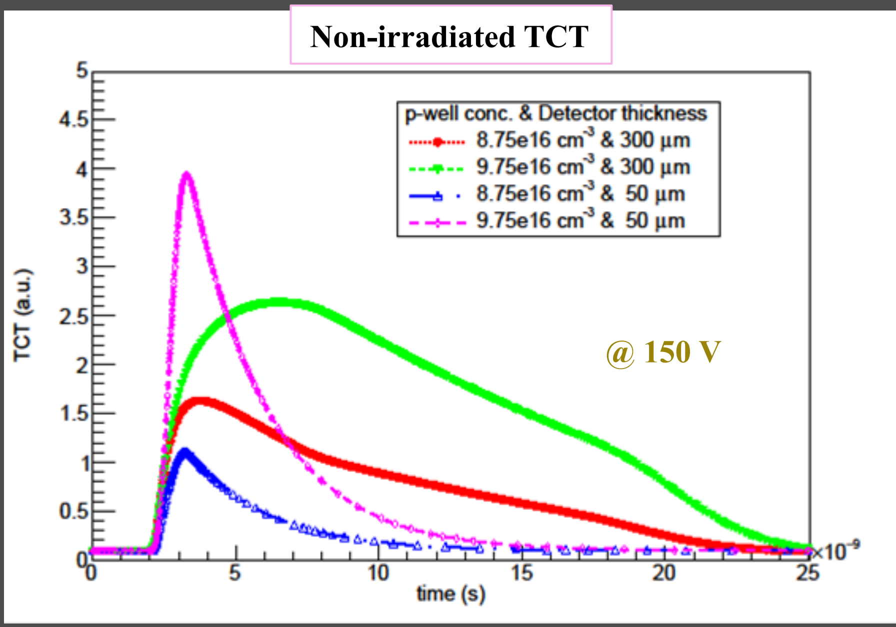


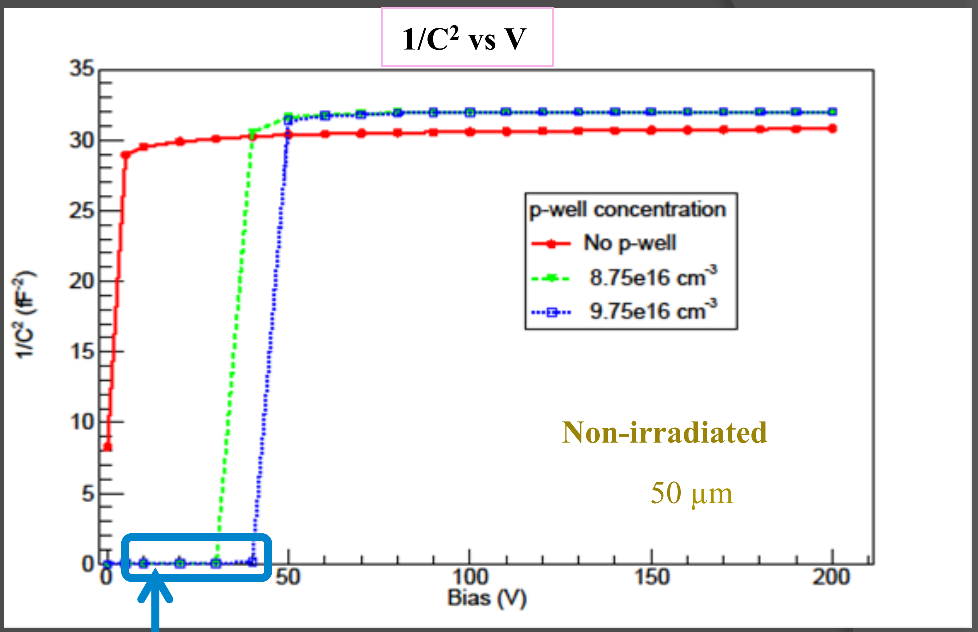
Bulk E.field



Thin detectors are better over Thick detectors!
Because: 1. Less material → Good tracking.
2. May have Faster charge collection
3. Smaller bias voltage required for depletion.

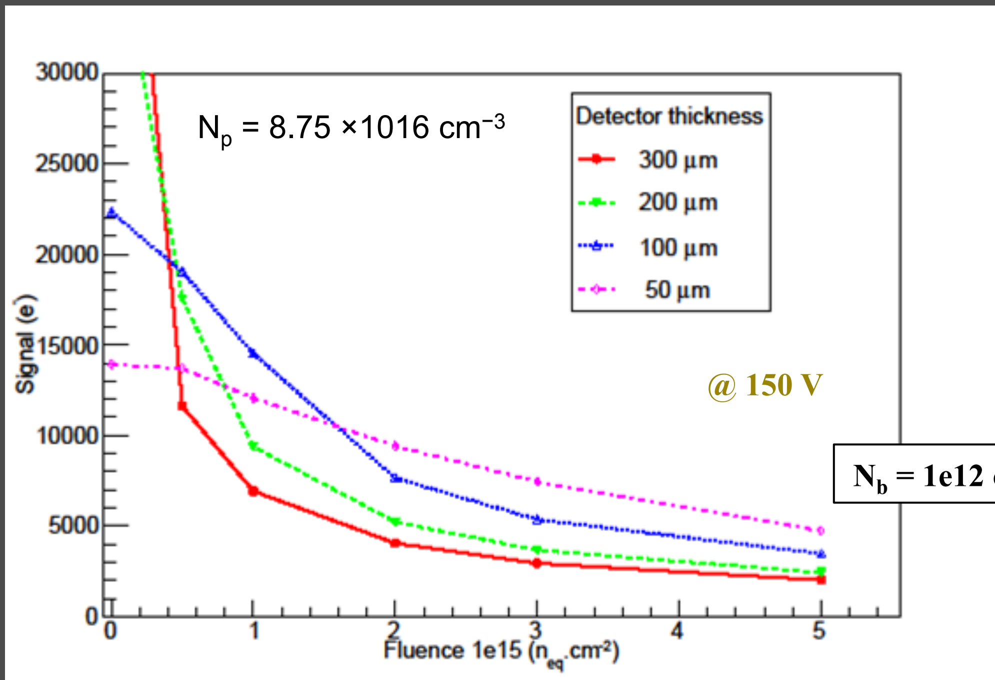
TCT Signal & Full depletion voltage





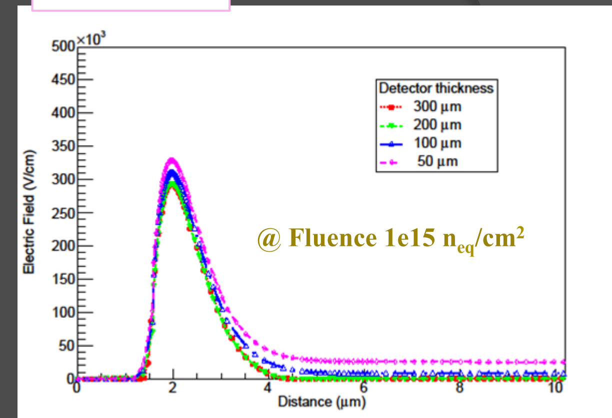
Voltage foot of 30V, 40V for p-well conc. of 8.75e16cm^{-3}, 9.75e16cm-3. This is the depletion voltage of the p-well. <u>Multiplication starts in the device for operating voltage greater than the voltage foot.</u>

Effect of Detector Thickness - Irradiated

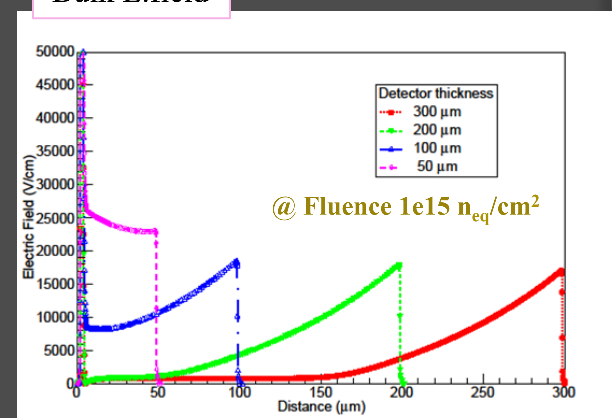


N_b = 1e12 cm^{-3}

Peak E.field



Bulk E.field



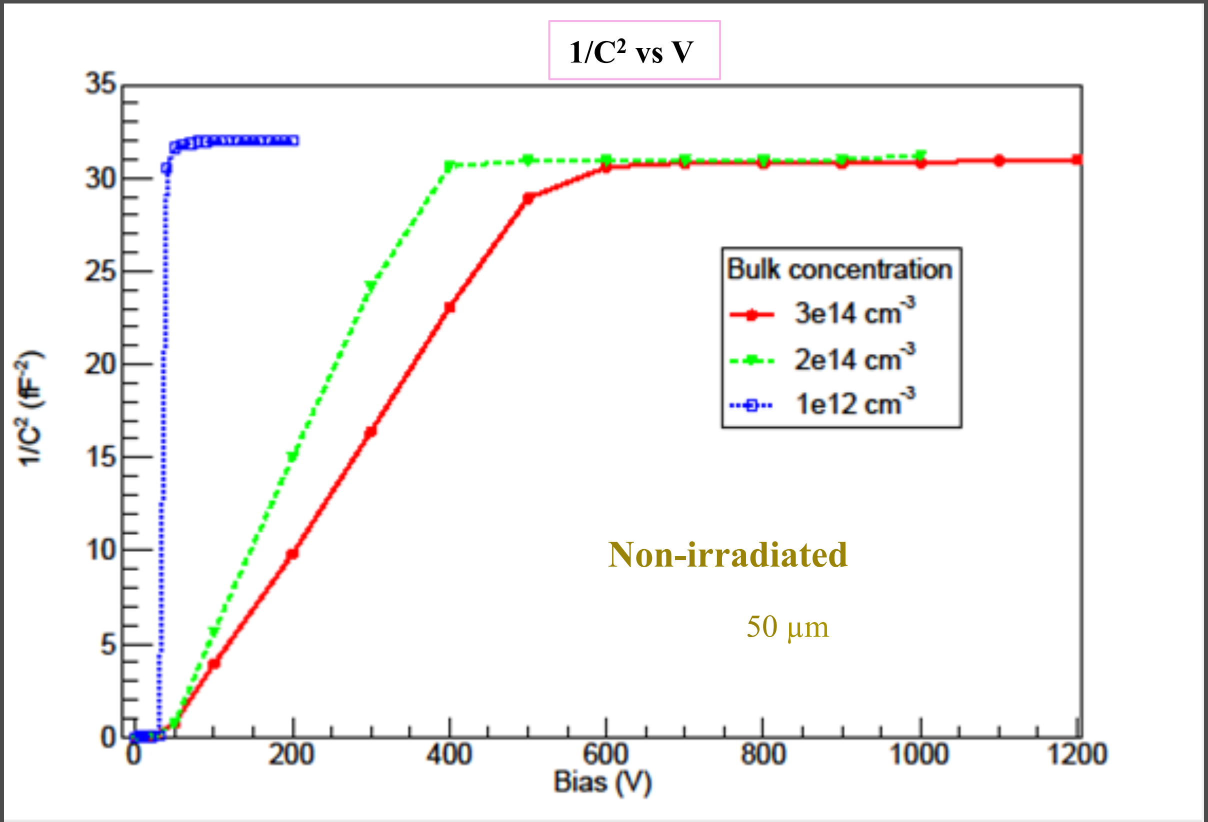
Simulated CC falls slowly with fluence, for thin detectors than thick detectors.
At 5e15 neq/cm^2 fluence & at a bias voltage of 150 V, CC for thick detectors is below the threshold CC value. And for thin detectors a little above the threshold.

→ Increased CC in high fluence condition for thin detectors!!

Electric field is nearly zero in the bulk after irradiation in thick detectors.
Thin detector CC will be faster.

Effect of bulk resistivity

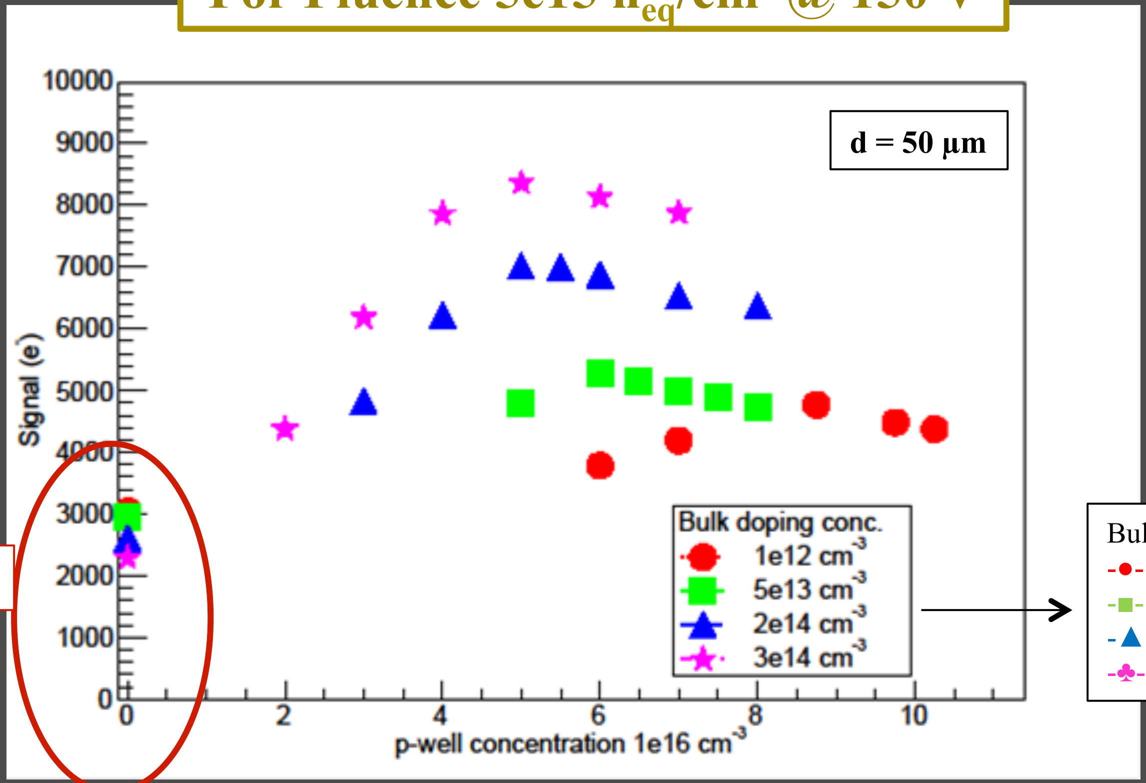
Capacitance Plot of Non-Irradiated Thin LGAD



Even though the operating voltage chosen (150 V) is less than the full depletion voltage of low resistivity bulk, but since it is greater than the voltage foot, a significantly high charge multiplication occurs.

Effect of Bulk Resistivity

For Fluence 5e15 n_{eq}/cm^2 @ 150 V

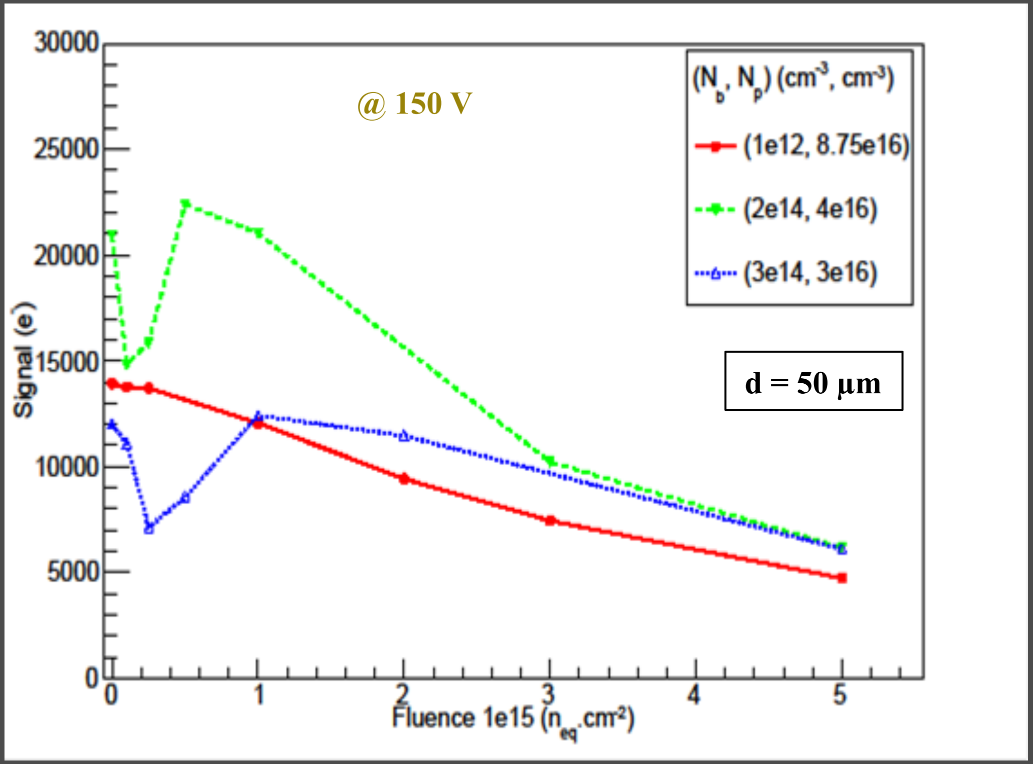


n-on-p PAD Detector

Bulk resistivity
- 13.3 kΩ.cm
- 266 Ω.cm
- 67 Ω.cm
- 45 Ω.cm

- ❖ Increase in p-well concentration, increases CC because peak electric field grows!
- ❖ Further increase in p-well concentration decreases CC because higher bias required to deplete it.
- ❖ With optimized value of bulk doping concentration & p-well concentration, CC can be as high as 8 ke-s even at a very high fluence of 5e15 n_{eq}/cm^2.

LGAD CC with Fluence



Signal can be enhanced for a highly irradiated detector by choosing an optimum value of the bulk resistivity concentration and peak p-well concentration.

Summary

- LGAD signal studied for four parameters – doping profile of p-well (N_p, d_p), doping profile of n^+ implant (N_n, d_n), substrate concentration (N_b), detector thickness (d).

- Parameter variation that favours increase in LGAD gain at high fluence are –
  - Increase in N_p, Increase in d_p
  - Decrease in N_n, Decrease in d_n
  - Decrease in d.
  - Increase in N_b

- Optimization of LGAD parameters can provide signal sufficiently higher than the threshold signal.

  Also, the device can sustain longer in radiation environment.

Future Work

- Understand the behaviour of thin LGADs: Check Neff & E field profile
- Leakage current & Junction Capacitance performance after irradiation of thin LGAD
- Rise time studies are to be performed
- Suggestions from collaboration & Some Directions


THANK YOU FOR YOUR ATTENTION
ANY QUESTIONS?
memegenerator.net

Backup

Peak E.field

Bulk E.field

50 µm Thin LGADS @ Fluence 1e15 n_{eq}/cm^2 p-well conc. 8.75e16 cm^{-3}