Ultrafast Imaging and Tracking Instrumentation, Methods and Applications

Palo Alto, 13 – 16 March 2023

ULITIMA 2023

Overview of Radiation Effects on LGADs

Evangelos – Leonidas Gkougkousis

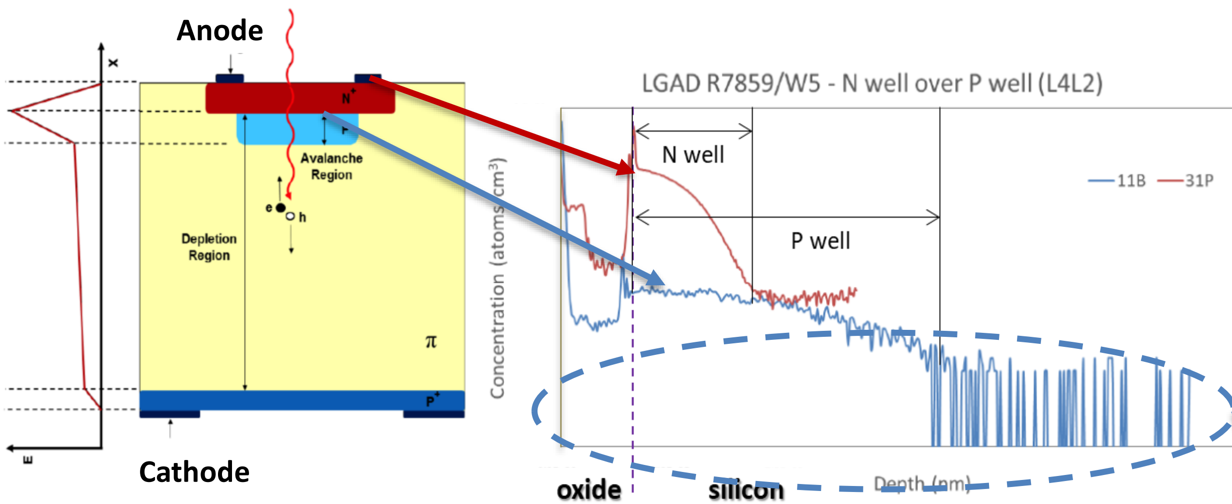
~~(CERN)~~

SLAC – March 13th, 2023

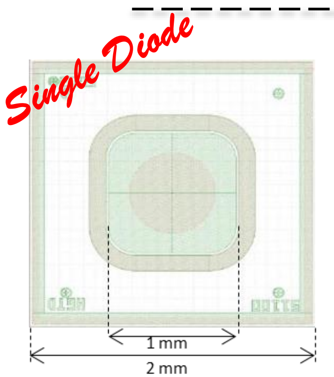
•Introduction I

LGAD Technology

- ✓ Invented at CNM, initially considered for tracking by IFAE, proposed for timing by UCSC
- ✓ HPK, CNM, FBK, MiCRON, BNL (USA), NDL (China), CiS, Teledyne (UK)



- ✓ Requires precise diffusion control for layer thickness:
  - ✓ Thin highly doped n-well layer (~ 1 – 1.5 μm)
  - ✓ Gain layer ~ 2 μm
  - ✓ p-stop ~3 -3.5 μm
- ✓ Different gain layer species possible:
  - ✓ Boron (standard)
  - ✓ Gallium
  - ✓ Boron +Carbon



- ➢ 4" Si-on-Si wafers (High Resistivity ~2 kΩ•cm)
- ➢ 50 μm thickness on 250 μm support wafer
- ➢ Different implantation species
- ➢ Single diodes of active area 0.7 x 0.7 mm
- ➢ 5 Neutron and proton fluences tested up to $6 \times 10^{15}\ n_{eq}/cm^2$

Standard Boron
Boron + Carbon Spray
Gallium

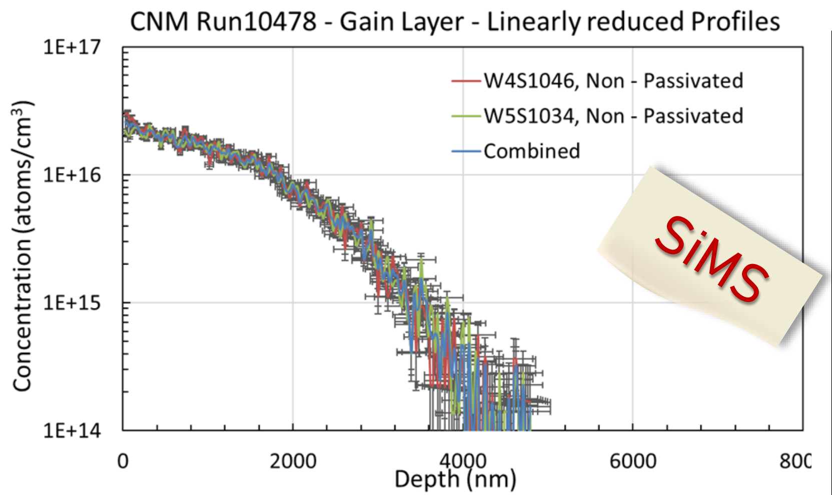
•Introduction III

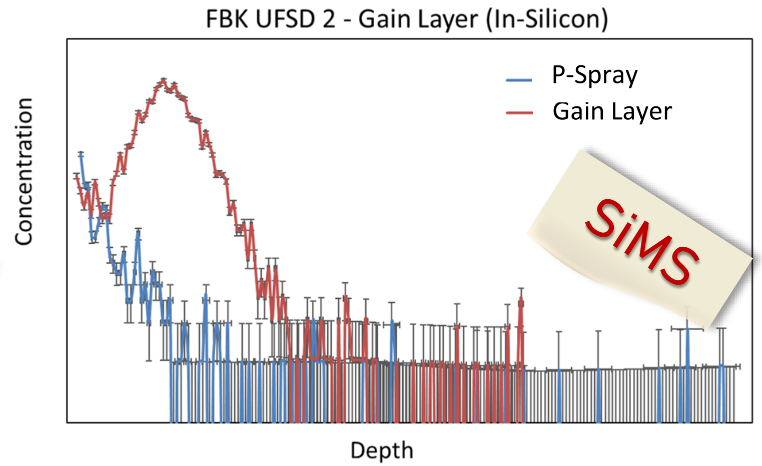
E. - L. Gkougkousis: - 17th Trento workshop (2022)
"Detailed process characterization of carbonated LGADs through Secondary Ion Mass Spectroscopy"

Doping Profiles - Carbon

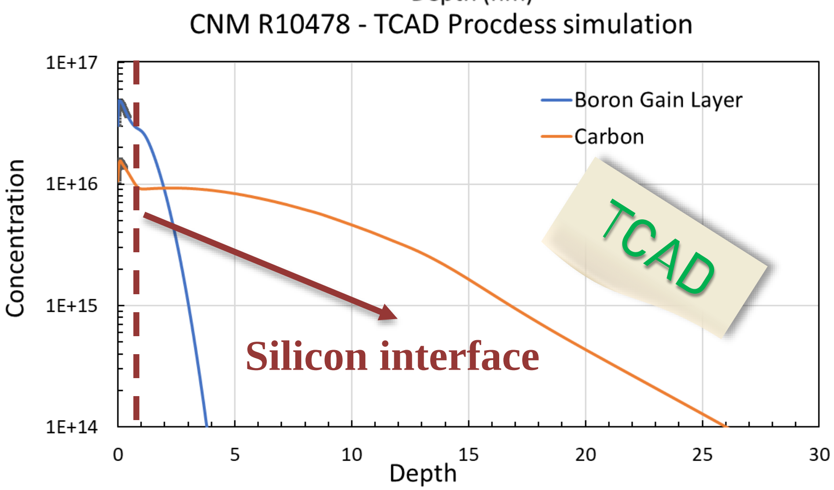
Best ever recorded resolution

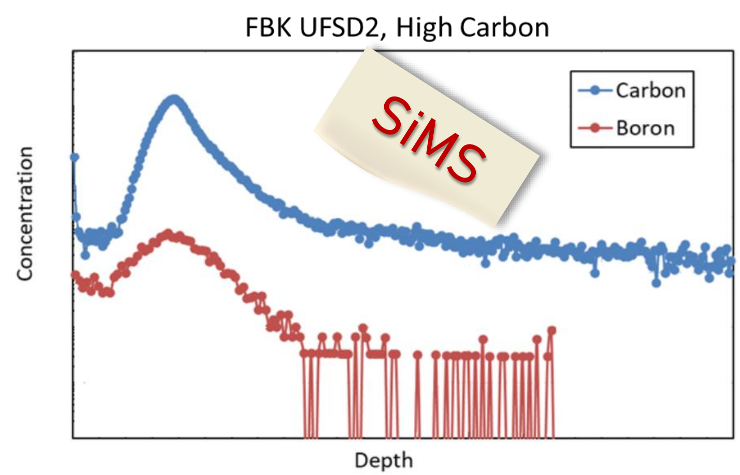
Element	Sensitivity (atoms/cm^3)
Carbon	$(2.22 \pm 0.08) \times 10^{16}$
Boron	$(1.35 \pm 0.58) \times 10^{14}$





Boron



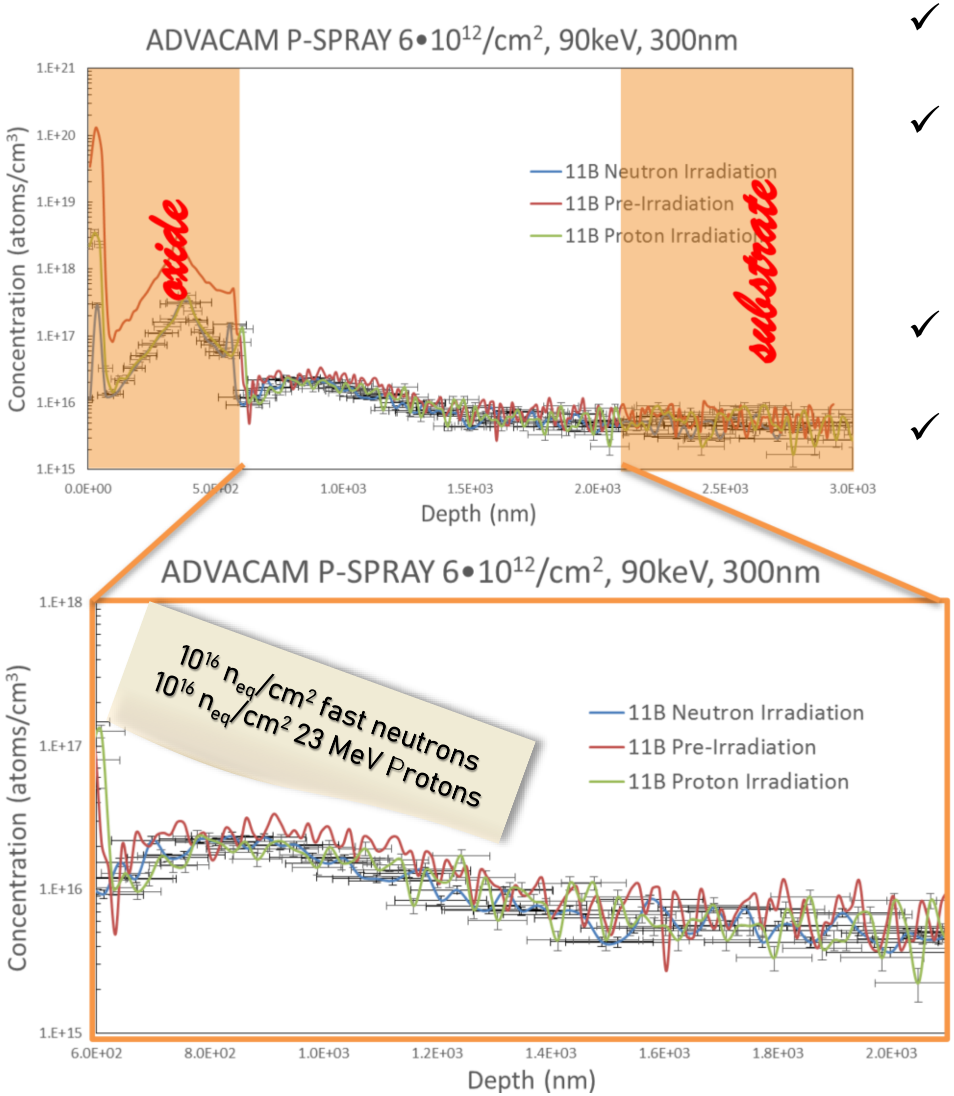


Carbon

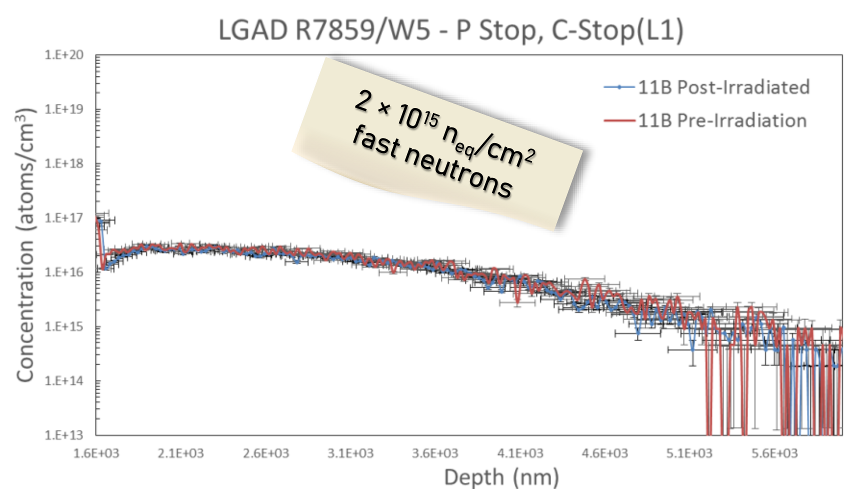
•Introduction IV

E. - L. Gkougkousis: [28th RD50 Workshop, Torino)]
“Neutron Irradiated doping profile evaluation”
June 2016

Post-Irradiation Doping Profiles



- ✓ SiMS on irradiated boron implanted structures with high sensitivity
- ✓ High (> 2 kOhm×cm) and low resistivity samples (< 2 Ohm×cm) p-type substrates tested under both proton and neutron irradiation (high resistivity is non-oxygenated, low is oxygenated)
- ✓ Up to fluences of 1×10^{16} n_{eq}/cm^2 no dopant redistribution was observed
- ✓ Boron DOES NOT diffuse (even as interstitial) under standard operation in sensors, neither does phosphorus



•Radiation Effects I

The Hamburg N_{eff} Model

G. Lindstrom et al., NIM A 466(2001) 308-326
"Radiation damage in silicon detectors"

Radiation damage modeling		
Constant Damage Terms	**Acceptor Introduction**	$\frac{dN_{acc.}^{con.}(t)}{dt} = g_{C_A} \times \Phi_{eq}(t)$
	Donor Introduction	$\frac{dN_{don.}^{con.}(t)}{dt} = g_{C_D} \times \Phi_{eq}(t)$
	Acceptor Removal	$\frac{dN_{acc.}^{rem.}(t)}{dt} = -c_{C_A} \times \Phi_{eq}(t) \times N_{acc.}^{rem.}(t)$
	Donor Removal	$\frac{dN_{don.}^{rem.}(t)}{dt} = -c_{C_D} \times \Phi_{eq}(t) \times N_{acc.}^{rem.}(t)$
Short term annealing	Acceptor Reduction	$\frac{dN_{acc.}^{short.}(t)}{dt} = g_A \times \Phi_{eq}(t) - k_A(T) \times N_{acc.}^{short.}(t)$
Long term annealing	Max Introducible Acceptors	$\frac{dN_{acc.}^{Max.long.}(t)}{dt} = g_y \times \Phi_{eq}(t) - k_Y(T) \times N_{acc.}^{Max.long.}(t)$
	Acceptor Introduction	$\frac{dN_{acc.}^{long.}(t)}{dt} = k_Y(T) \times N_{acc.}^{Max.long.}(t)$

• Radiation Effects II

E. - L. Gkougkousis: *TIPP2021, May 2021*
"Comprehensive technology study of radiation hard LGADs"

Four main disruptive mechanisms:

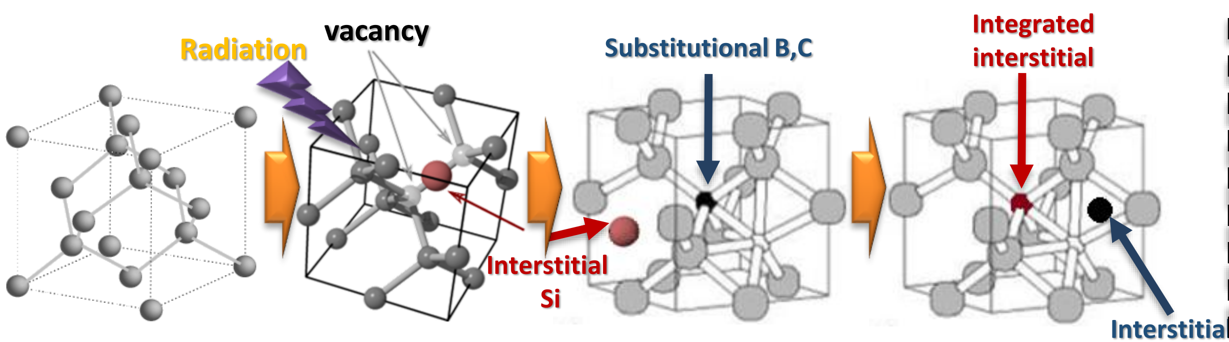
Substrate

1. **Reduced primary charges induced in substrate** → $1/\tau = \beta \times \Phi$
2. **Acceptor re-introduction rate** → $N_{Act.} = g_A \times \Phi$

The ROSE collaboration

Gain Layer

3. **Reduced active implant through acceptor removal** → $N_{G_\Phi} = f \times N_{G_0} e^{-c\Phi}$
4. **Reduced mobility within gain layer through trapping** → **Gain reduction larger than anticipated from acceptor removal**



Face centered Cubic Si (2-atom base) | **Interaction with incoming particle** | **Interstitial Diffusion** | **Substitutional Replacement**

Acceptor removal, Defect Kinetics (simplified ☺)

$Rad + Si_s \rightarrow Si_i + B_s \rightarrow B_i + O \rightarrow B_iO_i$

$Rad + Si_s \rightarrow Si_i + C_s \rightarrow C_i + O \rightarrow C_iO_i$

Gain layer de-activation
too many interstitials, cannot modify

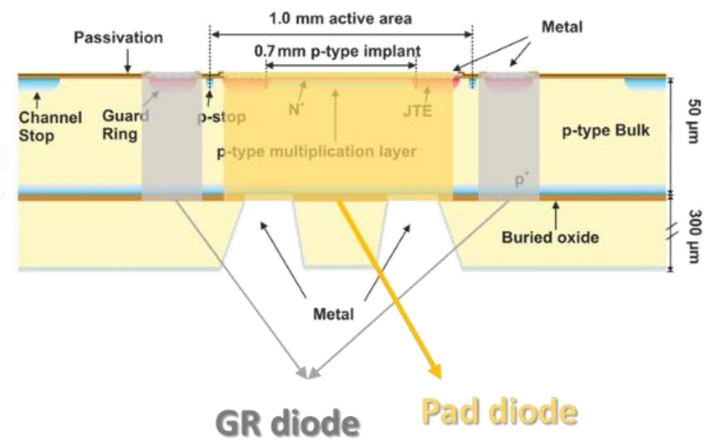
Charge trapping
Can be engineered by oxygen trapping

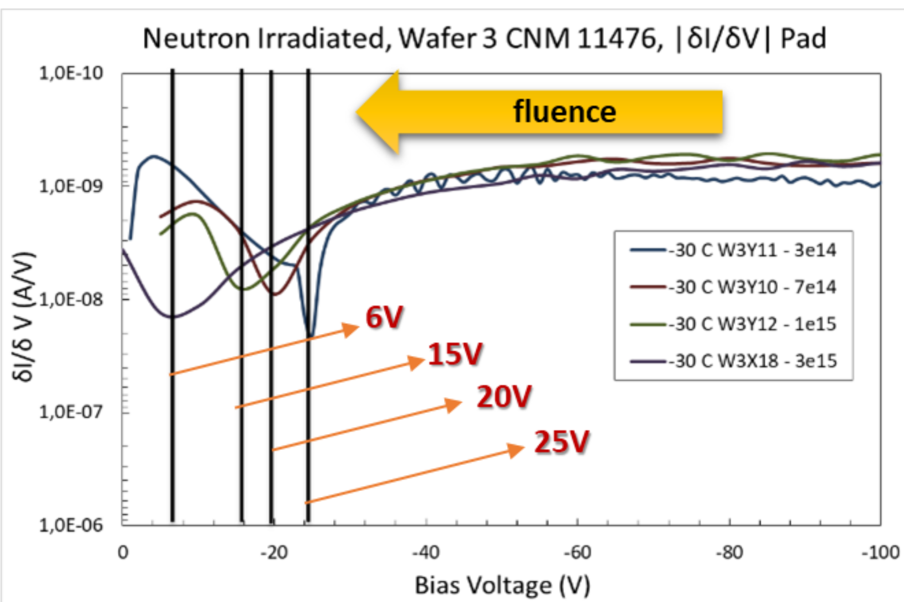
•The Leakage Current Transition Method (LCT) - I

$$f(V) = \left|\frac{\partial I_{pad}}{\partial V}\right|$$

E. - L. Gkougkousis et al.: "Comprehensive technology study of radiation hard LGADs"
J. Phys.: Conf. Ser. 2374 012175

- ✓ Probe active implant via depletion voltage
- ✓ Additional p-implantation gain layer creates secondary depletion region
- ✓ Mott–Schottky equation → **leakage current variation at gain layer depletion**
- ✓ Form of $\left|{}^{\partial I}/_{\partial V}\right|$ at depletion point corresponds to dopant transition function convoluted with instrument resolution (Gaussian X Gaussian)
- ✓ Depletion voltage determined Gaussian fit at depletion voltage for -10ºC, -20ºC & -30ºC





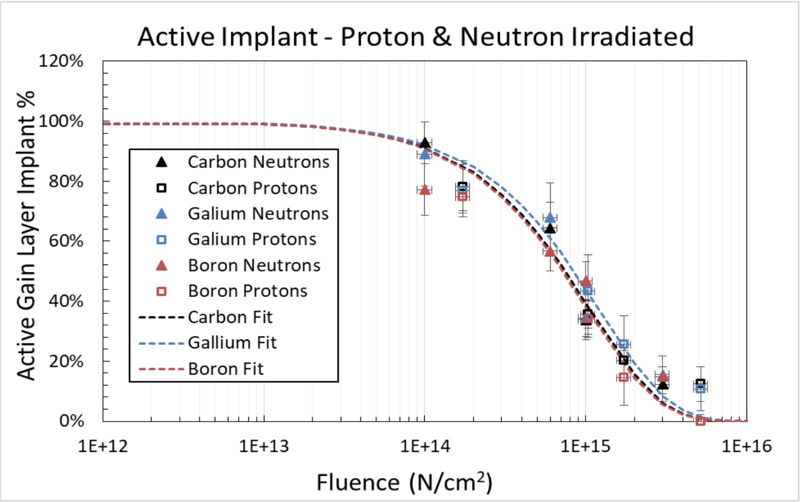
- Independent Gaussian fit for temperature
- Uncertainties estimated from propagation on fit sigma
- Fluences up to $3 \cdot 10^{15}$ n_{eq}/cm^2 in p^+ and n^0

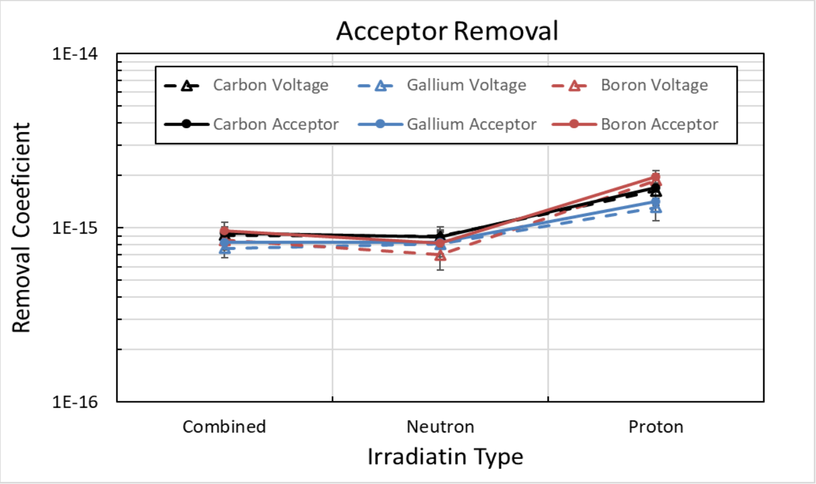
$$V_d = \frac{\sum_{T=-10\ ^oC}^{-30\ ^oC} V_{d,T_i}}{n_T}$$

$$\delta V_d = \sqrt{V_{d,sys} + V_{d,stat}}$$

Average of fit sigma — Standard deviation of V_d

•The Leakage Current Transition Method (LCT) - I





- Linear dependence assumption between V_{GL} and active implant
- Normalized exponential reduction fit model on gain and V_{GL}

$$G(\%) = e^{-C_G \Phi}$$

- Linearity hypothesis tested with independent C_v and C_G fits – full compatibility
- Constraints imposed on initial values to reflect charge measurements

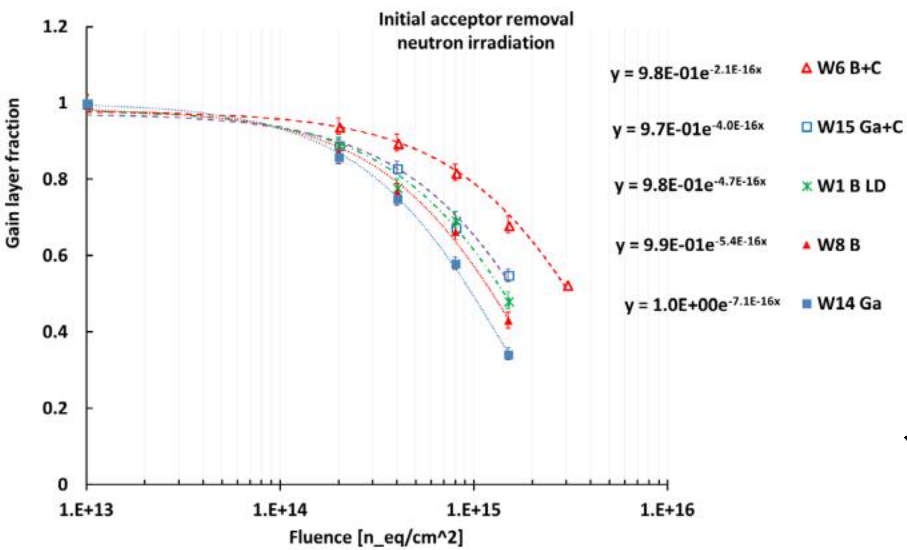
Results

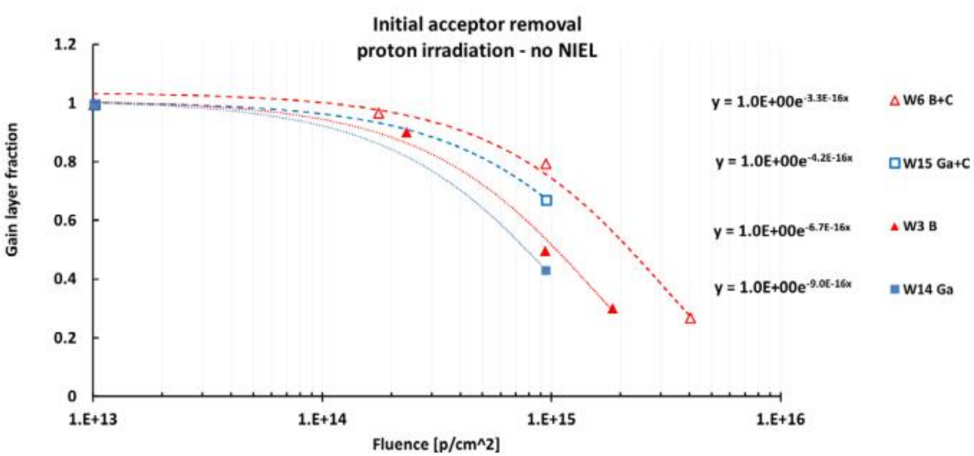
- **Compatible acceptor removal coefficients between all implants**
- Slight Ga advantage in p^+ irradiation (23 GeV/c PS), higher mass reduces displacement probability in coulomb-only (far-field) interactions
- Quasi-identical performance for neutron irradiated (fast ~ 10MeV neutrons)
- **Identical gain layer de-activation for all dopants with fluence**

Acceptor Removal Coefficient	
Gallium	$(8.25 \pm 0.80) \times 10^{-16}$
Boron + Carbon	$(9.33 \pm 0.78) \times 10^{-16}$
Boron	$(9.69 \pm 1.04) \times 10^{-16}$

•The other side of the coin – FBK Carbonated

M. Ferrero et al.: "Radiation resistant LGAD design"
NIMA, Volume 919, 1 March 2019, Pages 16-26





- ✓ Carbon is directly implanted at the gain layer only with comparable concentrations
- ✓ An improvement is seen on the acceptor removal coefficient by a factor of 2

What does this mean?

- ✓ Irradiated Implants do not diffuse (to the nm level)
- ✓ Carbon only helps in acceptor removal when close to boron

Acceptor removal is a local process

- ✓ The fact that proton and neutron irradiations fit in the same curve means that this is a point defect sensitive effect

• Radiation Hardness

Gain Layer Engineering

- ✓ First approximation: gain equivalent to charge in parallel plane capacitor:

  $$G \sim e^{a*d}$$

  d: distance (gain layer thickness)

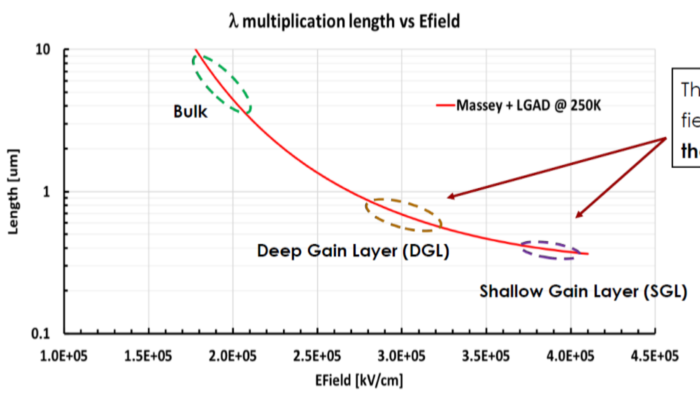
  a function equivalent to inverse of mean free path (1/λ)
- ✓ In irradiated silicon, λ depends on fluence, temperature and field
- ✓ Higher fields mean shorter distances to acquire same kinetic energy
- ✓ Presence of scattering centres has to be compensated with higher fields

$$G(E,T,\emptyset,d) \propto e^{\alpha(E,T,\emptyset)*d}$$

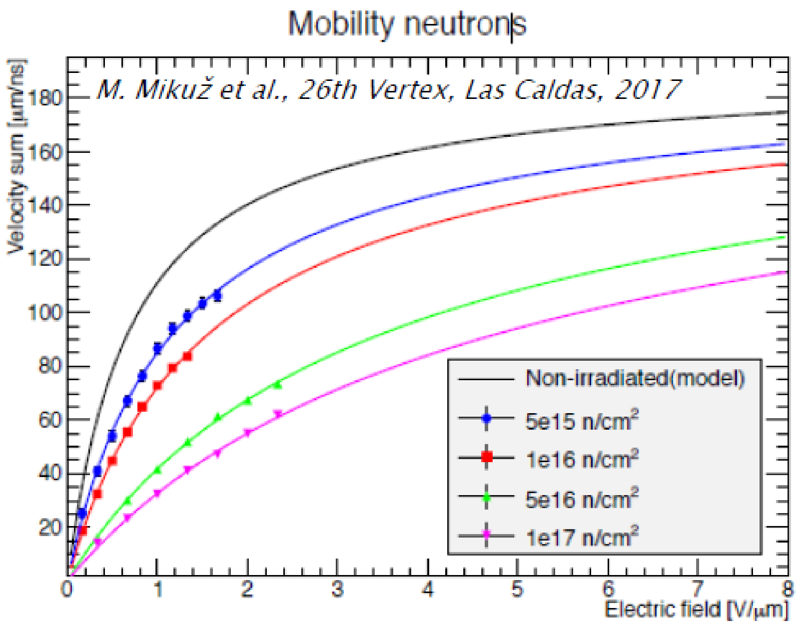
α(E,T, ϕ) impact ionization coefficient

d = length of high E field

Gain depletion not enough

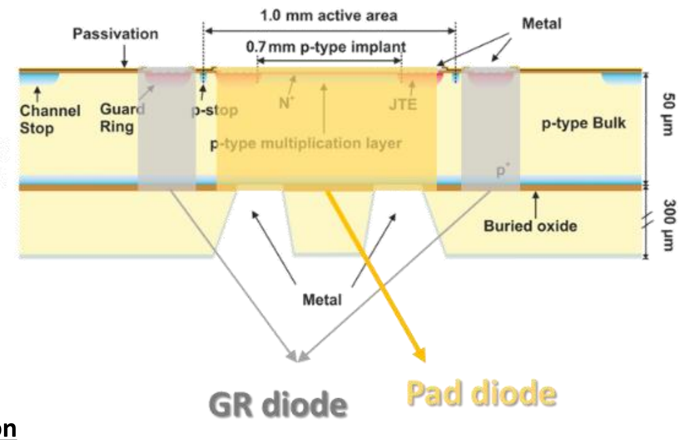


The position of the GL determines the field working point: **the deeper it is, the lower the field is**



•Comparative Current to Gain Method (CG2C) - I

- ✓ Acceptor removal only gives information about active dopant, not gain
- ✓ Gain also depends on **trapping levels & doping profiles**
- ✓ Effects after irradiation for different defect concentrations
- ✓ For same amount of acceptor removal, different gain reduction expected



Before Irradiation | **After Irradiation**

Geometry factor — Gain Current — Generation Current

Pad Leakage Current

Before irradiation: $I_{pad}^{\Phi=0} = S \times I_s \times \left(e^{\frac{eV}{nkT}} - 1\right) \times \mathbf{G(e^V, T, 0)}$

After irradiation: $I_{pad}(\Phi) = S \times (I_{GR}^{\Phi=0} + \alpha\Phi) \times \mathbf{G(e^V, T, \Phi)}$

Guard Ring Leakage Current

Before irradiation: $I_{GR}^{\Phi=0} = I_s \times \left(e^{\frac{eV}{nkT}} - 1\right)$

After irradiation: $I_{GR}(\Phi) = I_{GR}^{\Phi=0} + \alpha\Phi$

$$= f(V, \Phi)$$

Expected substrate current increase

If we divide the two then:

$$f(V, \Phi) = \left|\frac{I_{pad}}{I_{GR}}\right|$$

Normalize with uneradicated →

$$\frac{f(\Phi)}{f(\Phi = 0)} \sim G(e^V, T, \Phi)$$

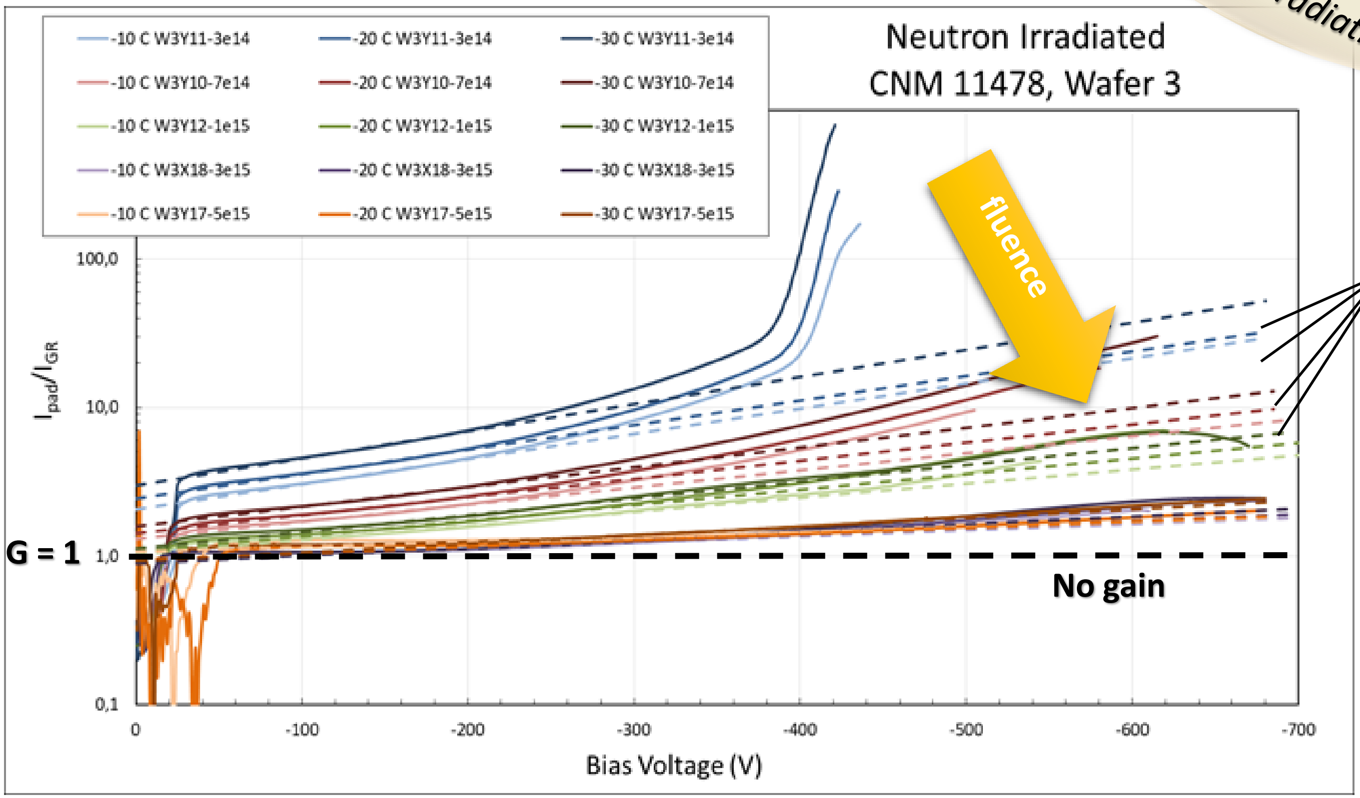
1. GR and pad on same substrate, all non-gain related irradiation effects can be normalized
2. Assumption that differences between GR n-type implant and pad n-type implant have minimal effects

•Comparative Current to Gain Method (CG2C) - II

E. - L. Gkougkousis: "Review of neutron irradiated 6" SoI LGAD sensors CNM 11486"
35th RD50 Workshop, November 2019

✓ I_{GR}/I_{PAD} linear at the semi-log plane
✓ Gain Coefficient probed by slope of linear fit
✓ Different fits per temperature, reputed at -10 °C, -20 °C and -30 °C

Repeat for all implants and radiation types

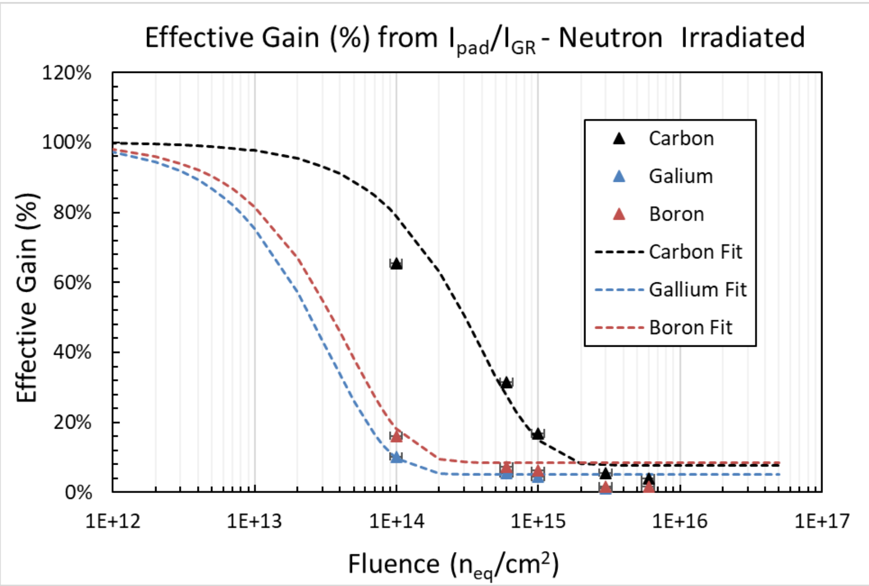


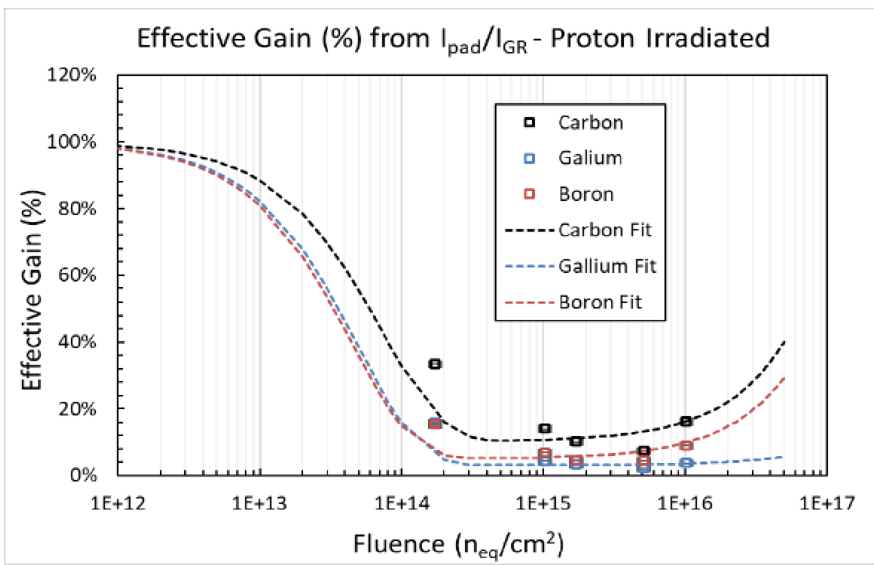
$$I_{pad}/I_{GR} = m \times a^{V}$$

× 6

(3 implants, n and p irradiated)

•Comparative Current to Gain Method (CG2C) - III





Acceptor level introduction rate

$$N_{eff}(\Phi) = N_{eff_0} - N_c\left(1 - e^{-c\Phi}\right) + g_c\Phi$$

Effective dopant concentration

Initial dopant concentration

Removable dopant

Gain extraction constant

Gain Reduction Coefficient	
Irrad. Type	**C ± δC**
Gallium	
n^0	$(3.01 \pm 0.9) \times 10^{-14}$
p^+	$(2.02 \pm 0.11) \times 10^{-14}$
Boron + Carbon	
n^0	$(2.57 \pm 1.1) \times 10^{-15}$
p^+	$(1.37 \pm 0.24) \times 10^{-14}$
Standard Boron	
n^0	$(2.25 \pm 0.39) \times 10^{-14}$
p^+	$(2.25 \pm 0.28) \times 10^{-14}$

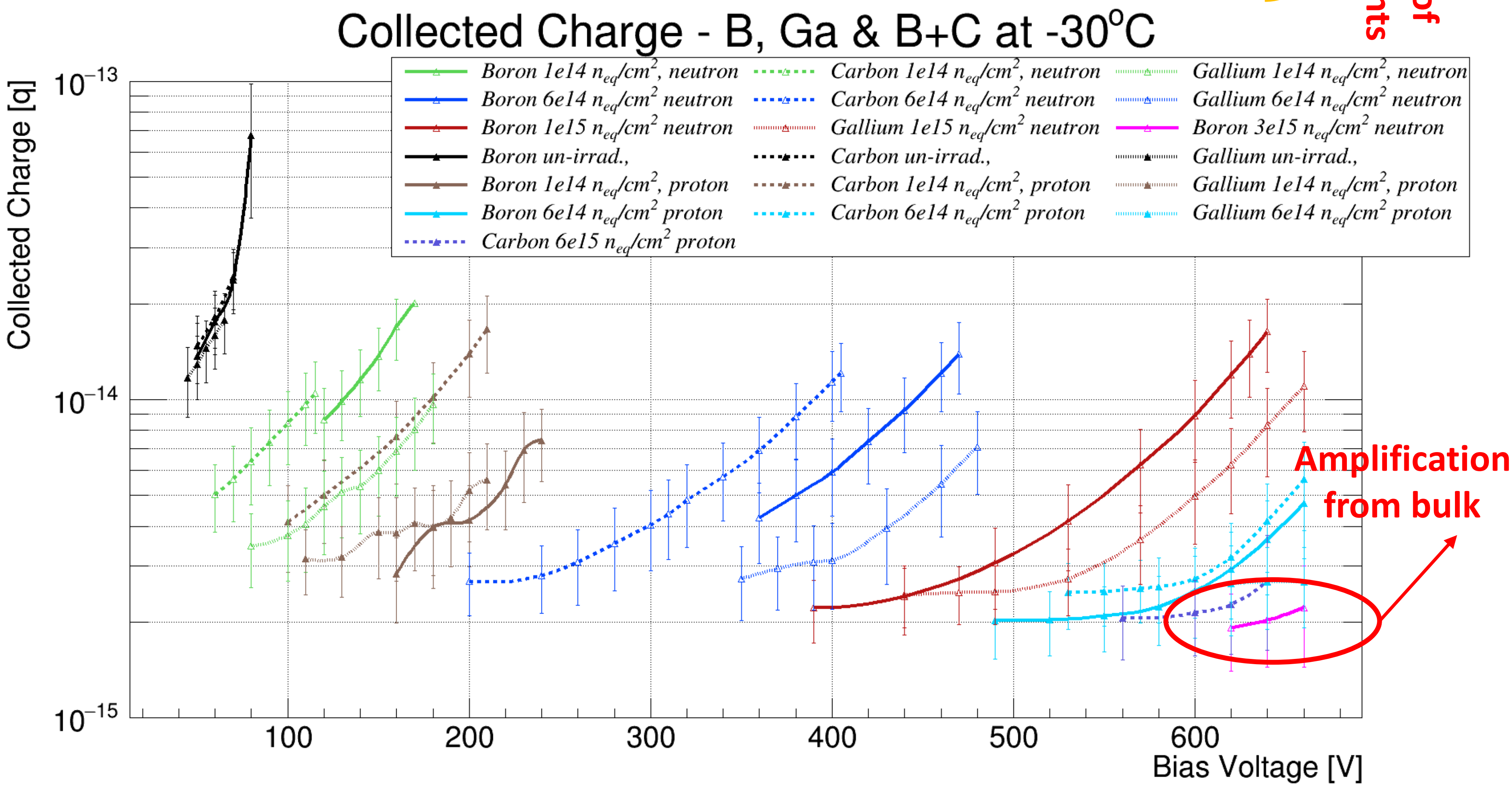
Results

- Gallium and Boron perform similarly
- **Carbon + Boron is up to 2 times better in proton and up to 7-8 times better in neutron irradiation**
- Significant variation with implant type
- **Gain reduction coefficients are up to 10 x the previously estimated acceptor removal**

•Collected Charge I

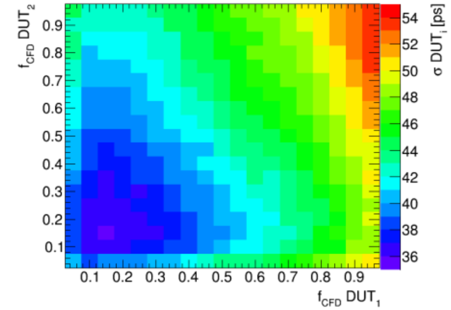
- ✓ Each point corresponds to MPV of Landau x Gauss fit on 5k recorded events
- ✓ Measurements repeated for -10ºC, -20ºC & -30ºC (see the backup)
- ✓ Gallium yields always 20% less charge for same voltage, carbonated 20% more

~940 series of measurements



•Time Resolution

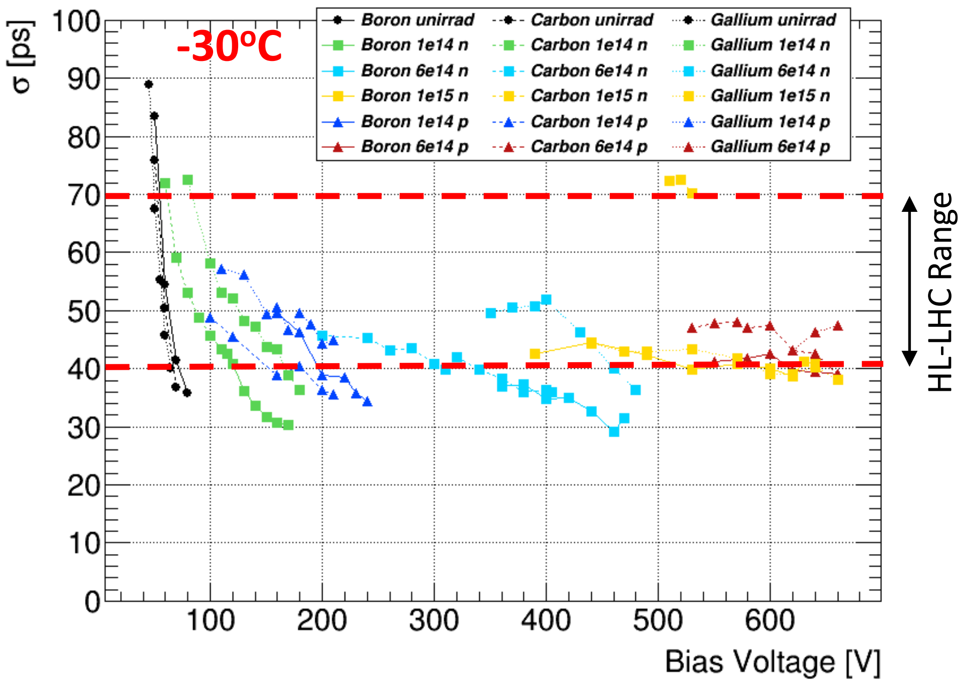
E. - L. Gkougkousis: "Acceptor removal and gain Reduction in proton and neutron irradiated LGADs"
36th RD50 Workshop, June 2020

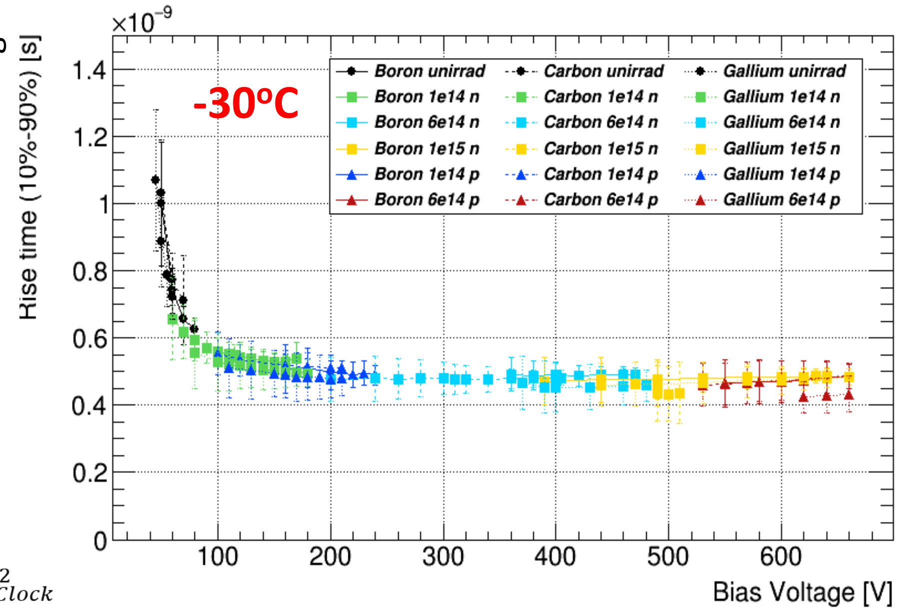


CFD Level optimization

$$(\sigma_{\mathrm{Dut}})_{CFD_{ij}} = \sqrt{(\sigma^2_{\mathrm{Tot}})_{CFD_{ij}} - (\sigma^2_{\mathrm{Ref}})_{CFD_i}}$$

2D optimization plot – 0.5% binning





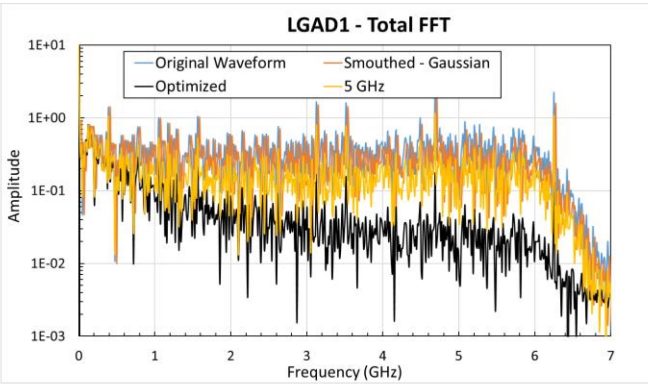
Time Resolution: $\sigma^2_{tot} = \sigma^2_{timewalk} + \sigma^2_{jitter} + \sigma^2_{conversion} + \sigma^2_{Clock}$

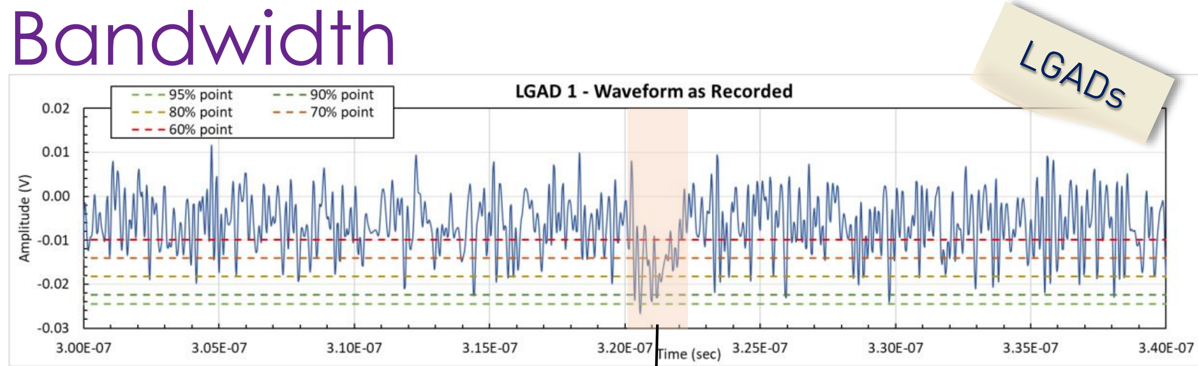
- $\sigma^2_{timewalk}$: $\sigma^2_{Dist.} + \sigma^2_{Landau}$
- σ^2_{jitter}: $\left(\frac{t_{rise}}{S/N}\right)^2$
- $\sigma^2_{conversion}$: $\left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2$
- σ^2_{Clock}: *Fixed Term ~ 5-7 psec*

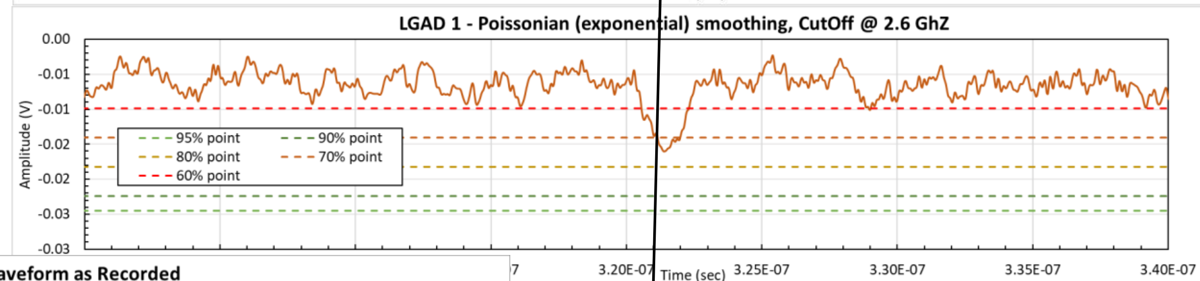
1. Similar behavior in terms of signal shape on all implants
2. Time resolution follow charge trend
3. Charge vs σt identical for all gain layer variations

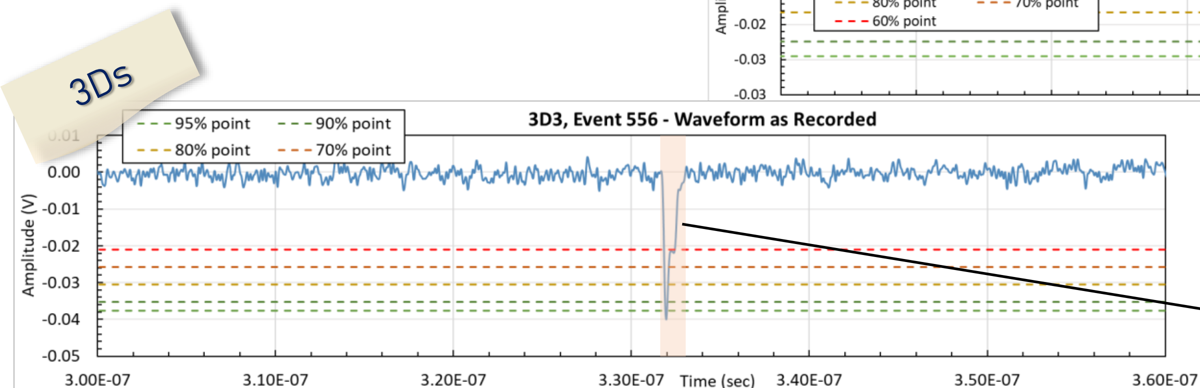
• Signal Analysis

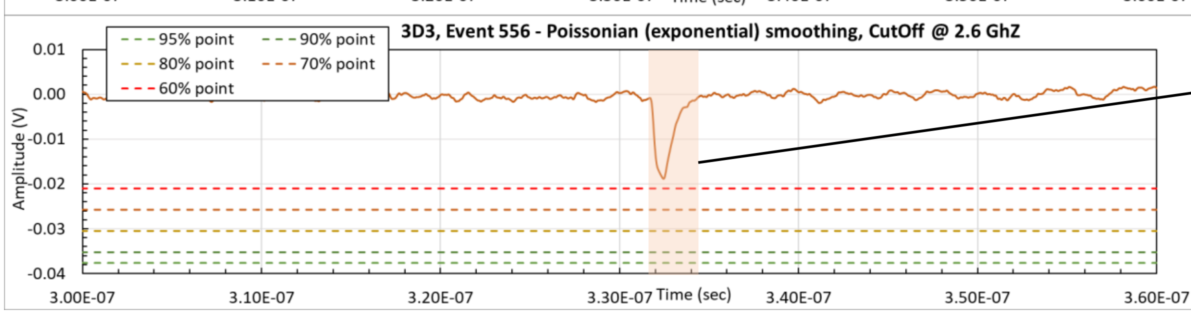
The importance of Bandwidth

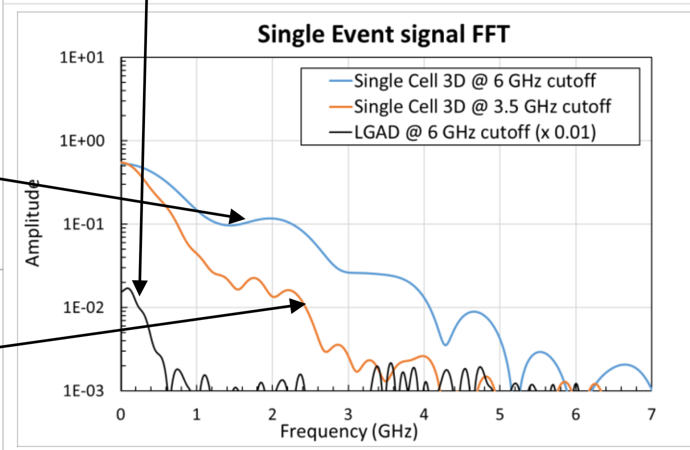












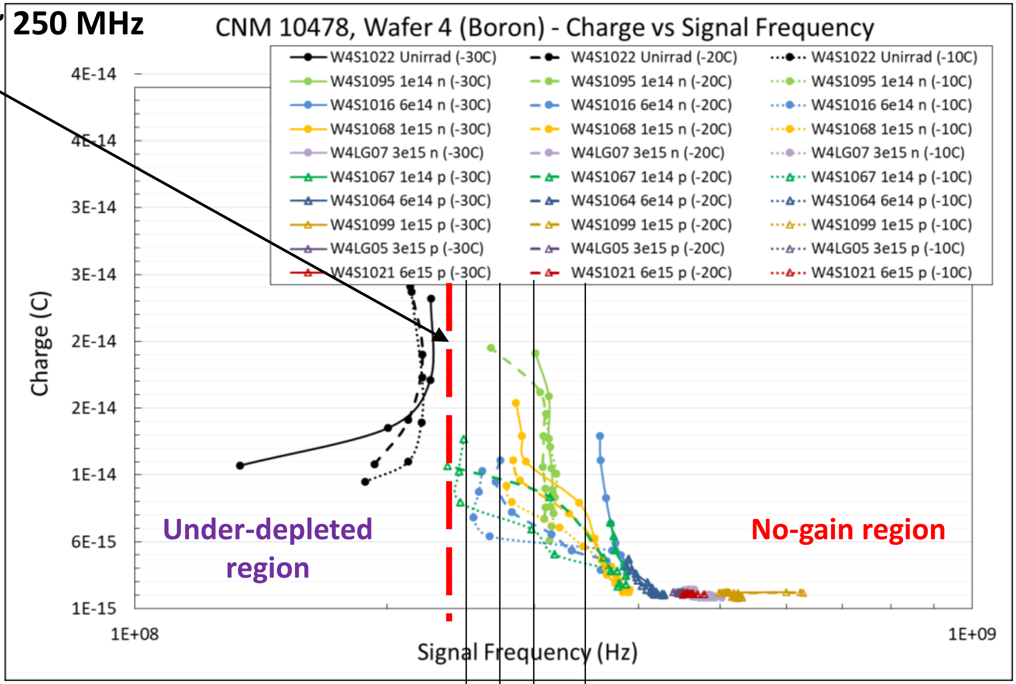
60 % less amplitude
20 % more charge

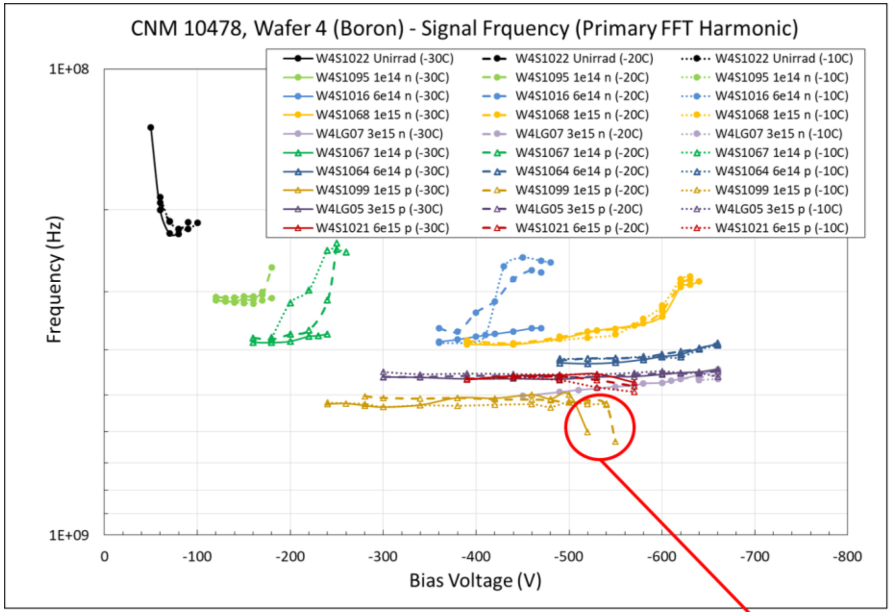
• Signal Analysis

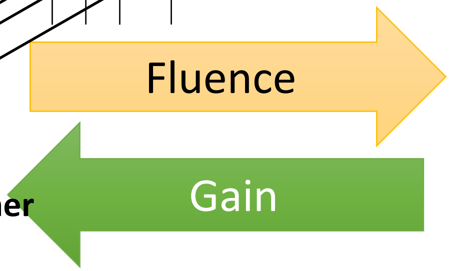
FFT

- ✓ FFT vs Voltage presents an asymptotic behavior towards a frequency
- ✓ Asymptotic frequency depends on fluence and remaining gain
- ✓ Signal frequency increases with voltage and decreases on the onset of multiplication

Asymptotic point ~ 250 MHz







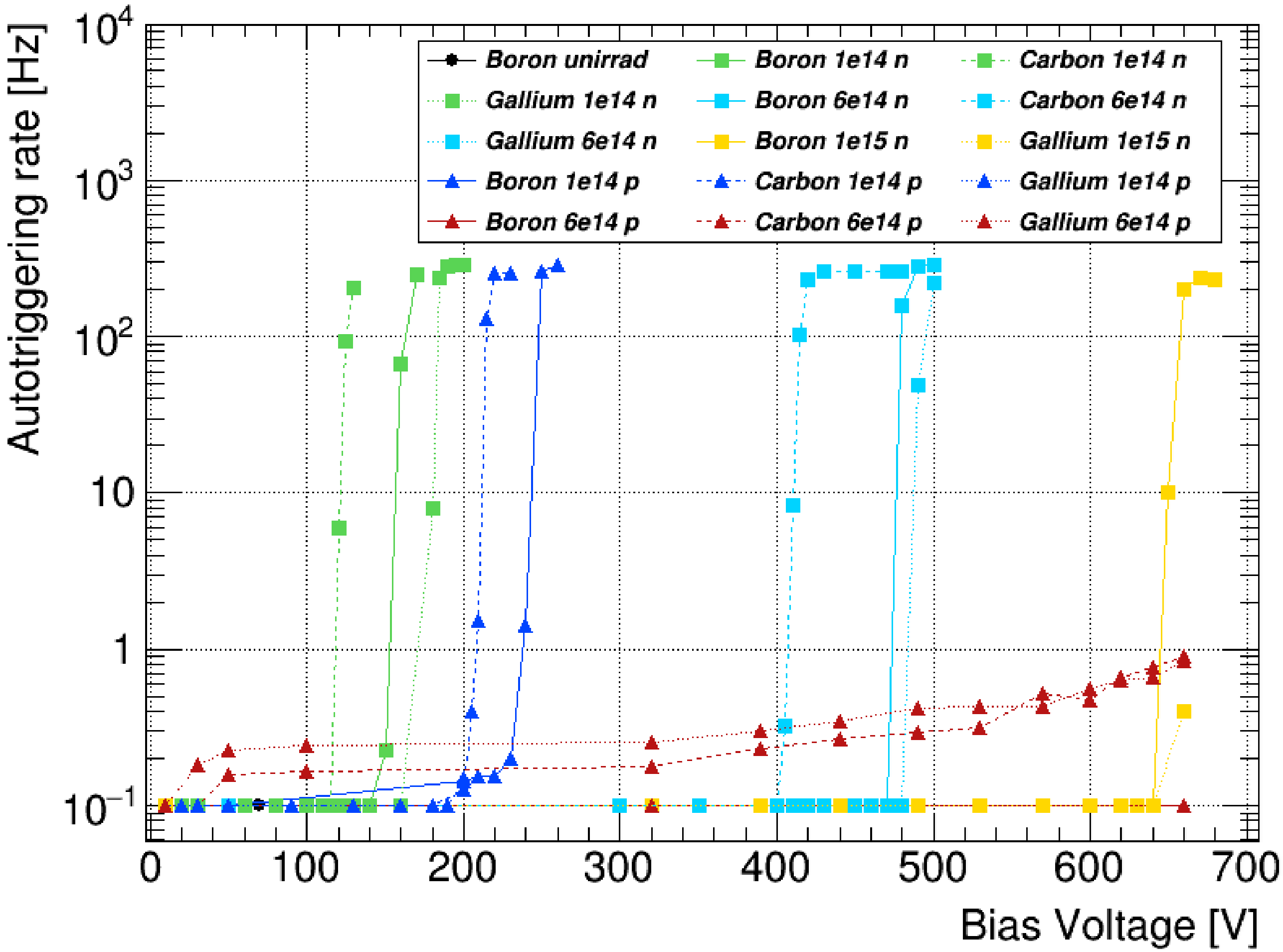
Asymptotics move to higher and higher frequencies as gain decreases and fluence increases

High Frequency noise, sensor in breakdown

• Sensor Stability

Dark Rate

- ✓ All sensors with gain present dark rate at high field values
- ✓ Dark rate events result out of thermally induced electron-hole pairs drifting picked up by the field
- ✓ Random in nature, follow a Poisson distribution
- ✓ An inverted s-curve study for each sensor defines the stable region or the acceptable level of shot noise.

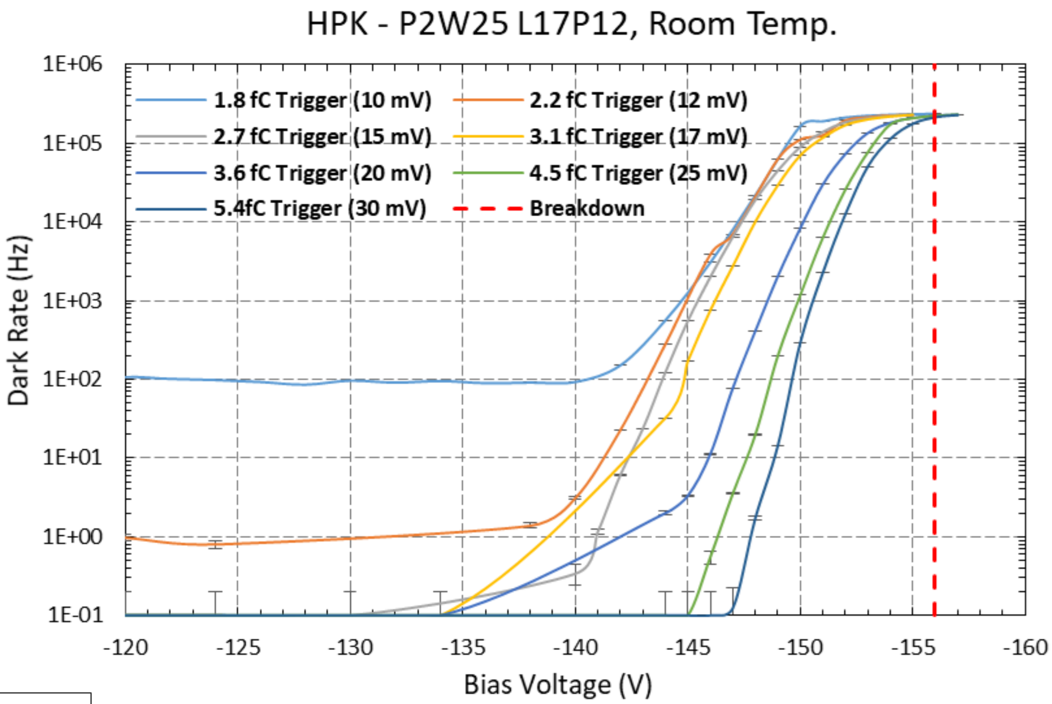


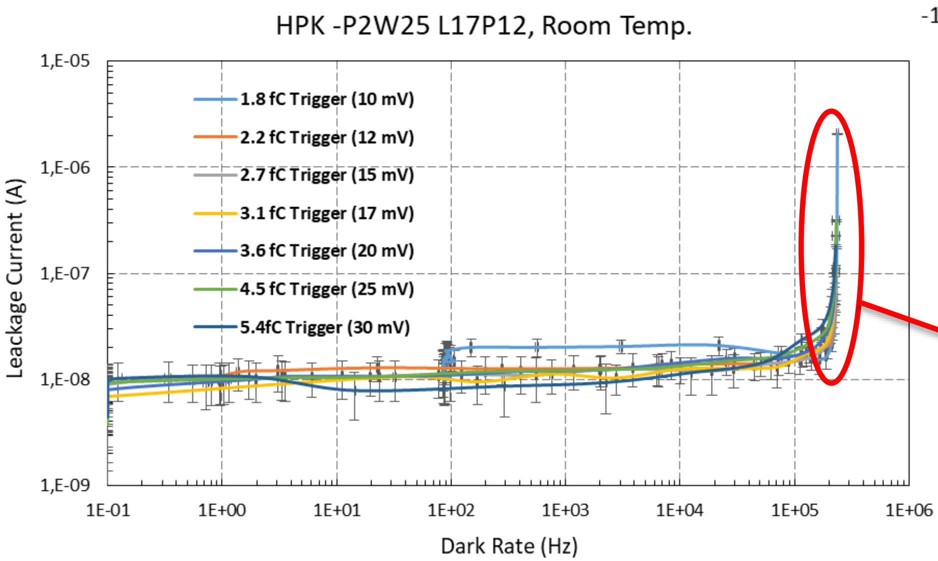
• Stability vs Threshold

Dark Rate

Threshold effect

- Un-irradiated HPK P2
- Breakdown ~156 V
- Measured at room temp
- Different Constant threshold triggers (1.8 – 5.4 fC) applied
- Bayesian Uncertainties
- Max saturation rate 230 kHz





Leakage Current effect

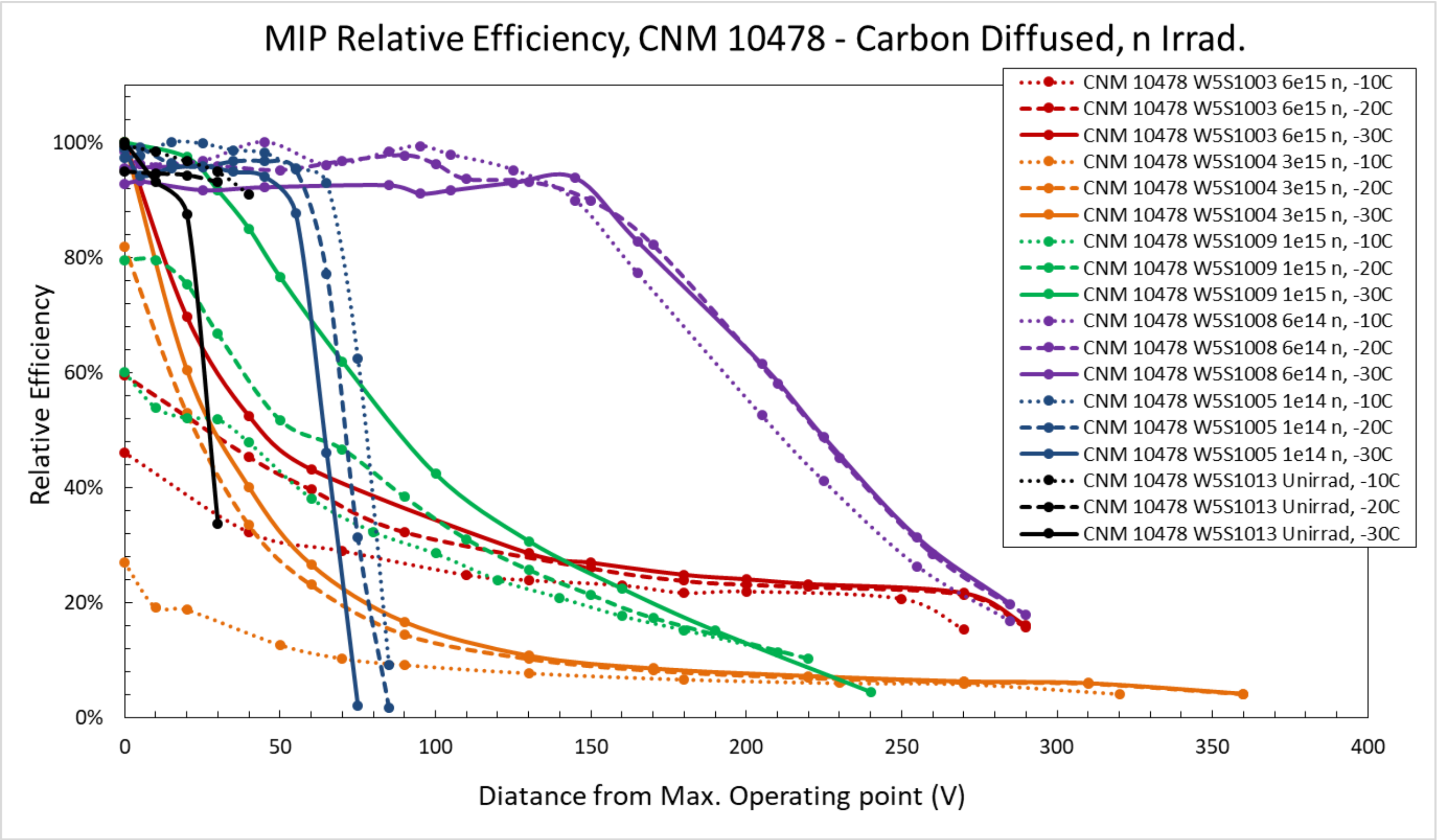
- Sensor far from breakdown
- Leakage current not demonstrate significant variation
- Stationary leakage current at exponential rate increase, breakdown over 1e5 Hz

• Efficiency

Head Room

- ➢ Measurements with radioactive ^{90}Sr source
- ➢ Define stable operation points satisfying the following conditions:

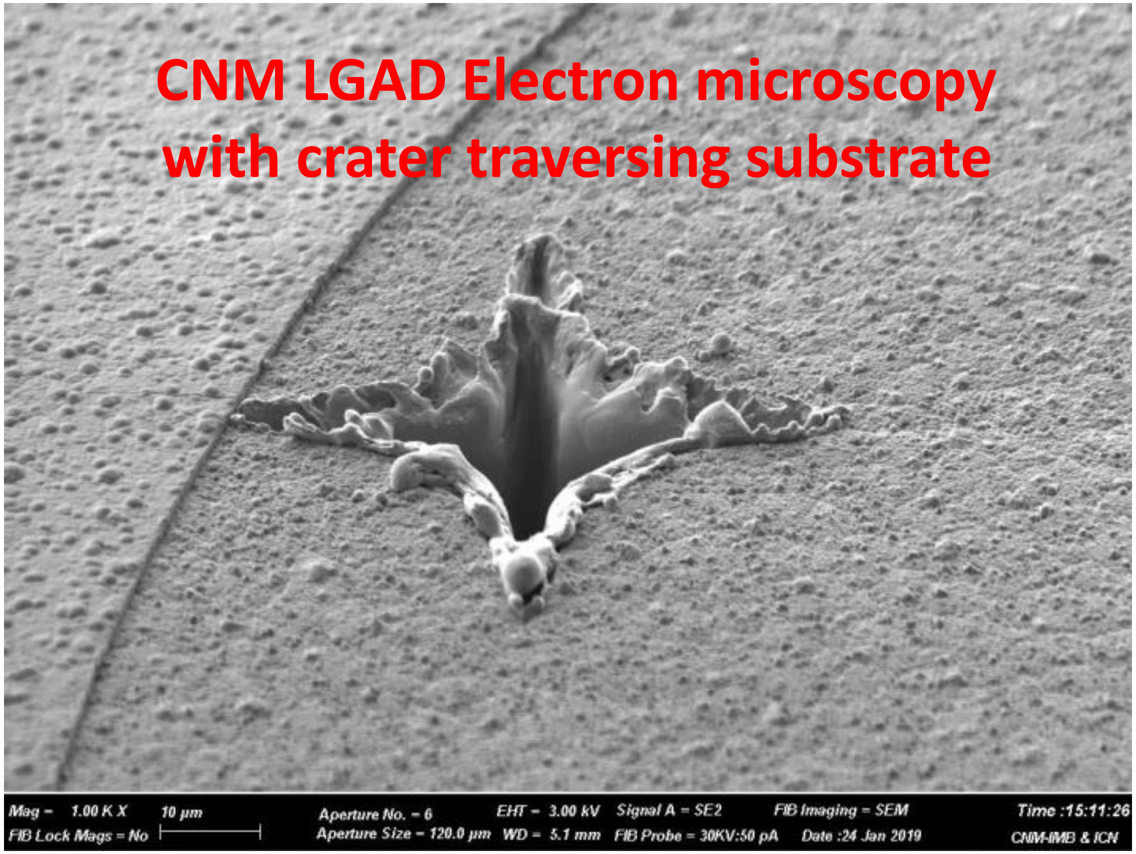
Sensor not in breakdown
Mean field inside sensor < 13.4 V/µm
Autro-trigger rate < 1% of source trigger



•Single Event Burn-Out

Catastrophic failure

- Catastrophic breakdown events occur at mean bias voltages of ~ 12 V/µm for planar structures
- Effect observed on LGADs and planar pixels after irradiation
- High energy deposition close to a tap cluster creating a highly localized field variation which leads to high gain
- Observed in SPS test beams in 2017 and verified by lasers at ELI beamlines

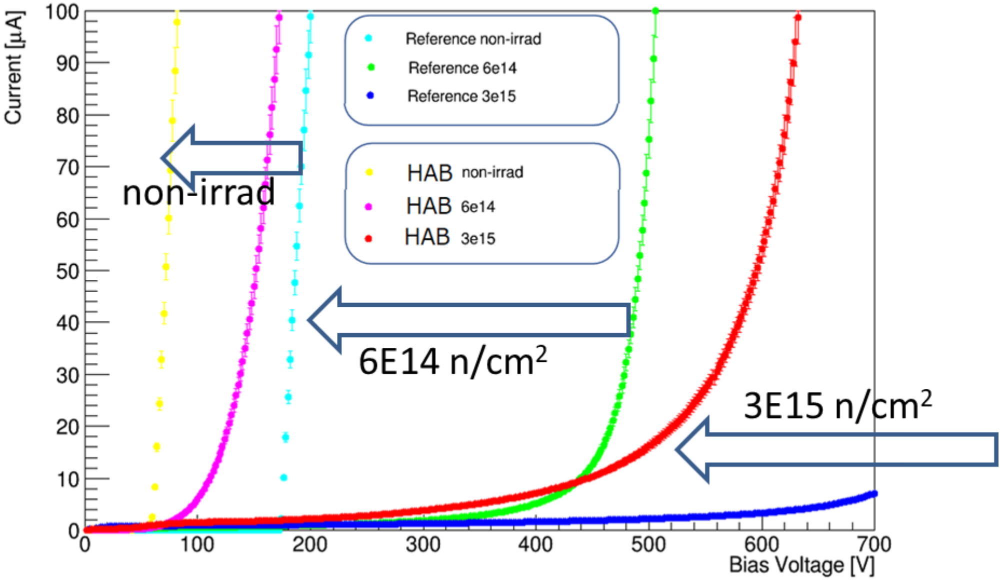


•Future developments

HAB = Half Activated Boron

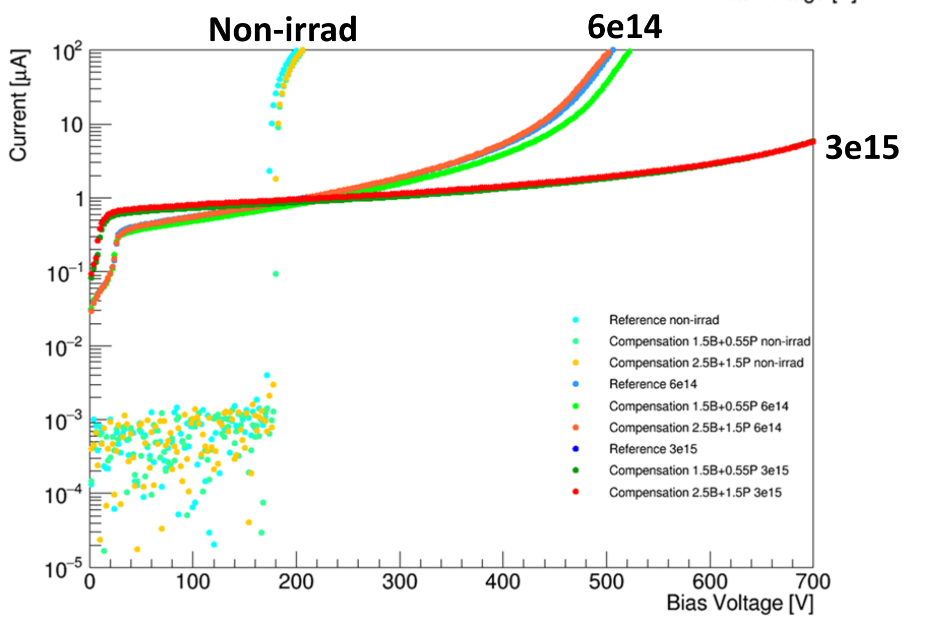
- Stop O_2 boron deactivation pathway by increasing amount of non-activated boron.
- Bi will capture the Oi before it encounters a substitutional boron
- Extremely promising first results

K. Hara et al.: [“Improvement of timing resolution and radiation tolerance for finely segmented AC-LGAD sensors”]() Trento 2023



Compensation

- Increase boron concentration but add some type of n-implant to maintain N_{eff} to acceptable levels
- If $C_D < C_A$ additional acceptors are disengaged to participate to the Neff with irradiation
- First results not promising

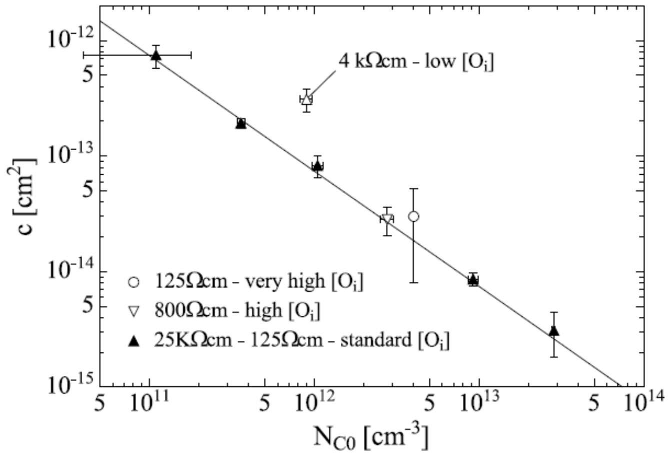


•Future developments

M. Moll: "Displacement Damage in Silicon Detectors for High Energy Physics"
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 65, NO. 8,

Removal Coefficients

- ✓ Removal coefficient dependent on initial acceptor concentration
- ✓ Almost complete removal for high N_{eff}, ~ 40 % removal for high resistivity substrates



Acceptor removal part

$$N_{C.}(\Phi_{eq.}) = g_c \times \Phi_{eq.} - f_c \times N_{eff.}(0)\left(1 - e^{-c_A \Phi_{eq.}}\right)$$

Re-Introduction rate g_c

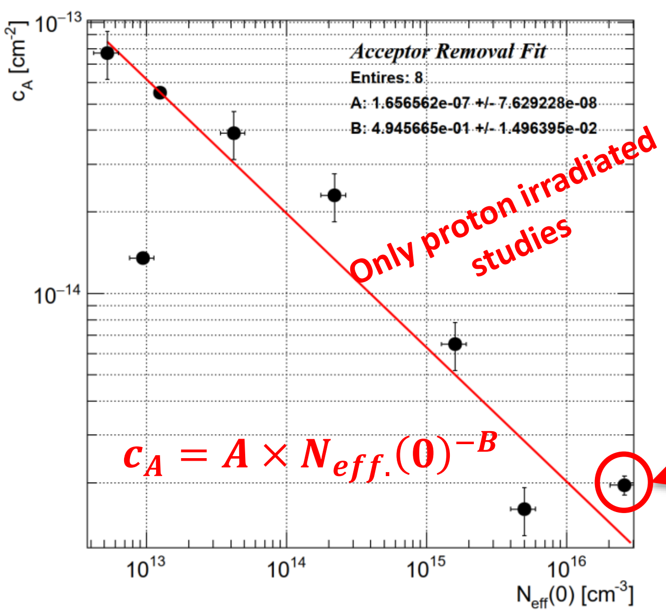
- ✓ > 0 primarily acceptor introduction
- ✓ < 0 primarily donor introduction

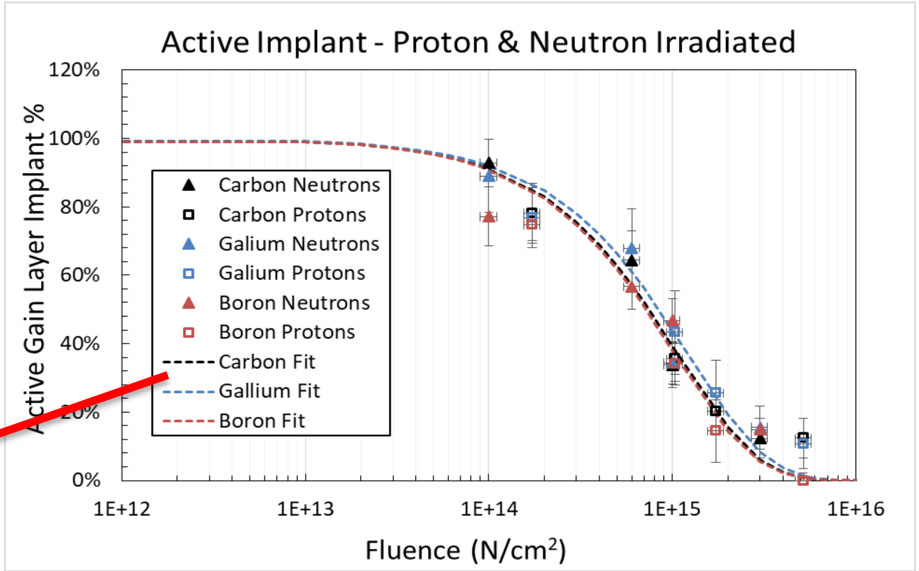
Original doping concentration

Acceptor Removal Coefficient

Removable Fraction

Acceptor Removal Coefficient





•Future developments

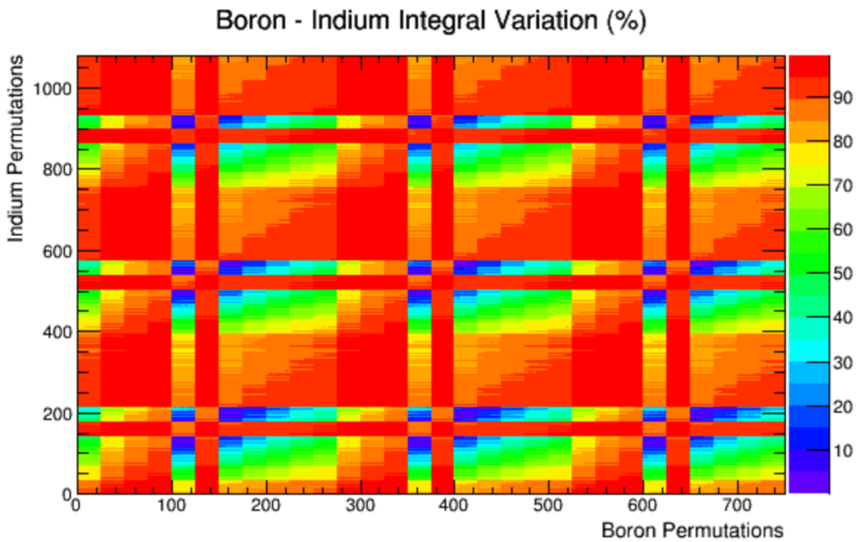
Alternative dopants

E. – L. Gkougkousis: "Parametric process optimization for Indium, Gallium and Boron dopants using TCAD simulation modelling"
16th Trento Workshop

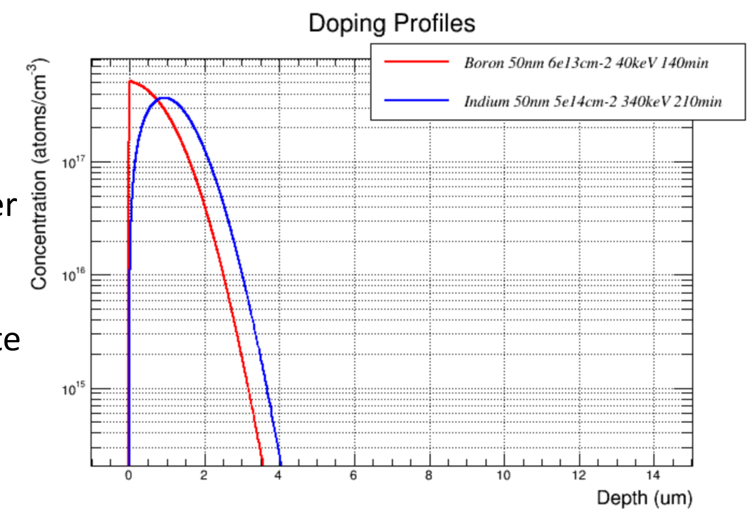
- ✓ Radiation damage lead to acceptor removal though defect kinematics
- ✓ Modify gain layer implants to generate beneficial defects for gain (**gain regulation**):

- **Lithium co-implantation:**
  - Boron with Lithium co-implantation demonstrates better neutron radiation hardness
- **Replace Boron with Indium**
  - Indium higher mass and lower reaction cross-section expected to generated less O_i defect clusters

- ✓ Implantation energy and doping profiles already optimized via TCAD simulations



- Lithium co-implantation ONLY on p-implant layers
  - Lithium is n-type but in low doses should not impact p layer
  - Proven to improve radiation hardness of solar cells after 1MeV neutron irradiation
  - Lowers annealing temperature when implanted in substrate
  - Defect engineering at low temperatures E. Oliviero et Al. (link)
  - Original Solar cell study Weinberg et Al. (link)



• Conclusions

Thoughts and discussion

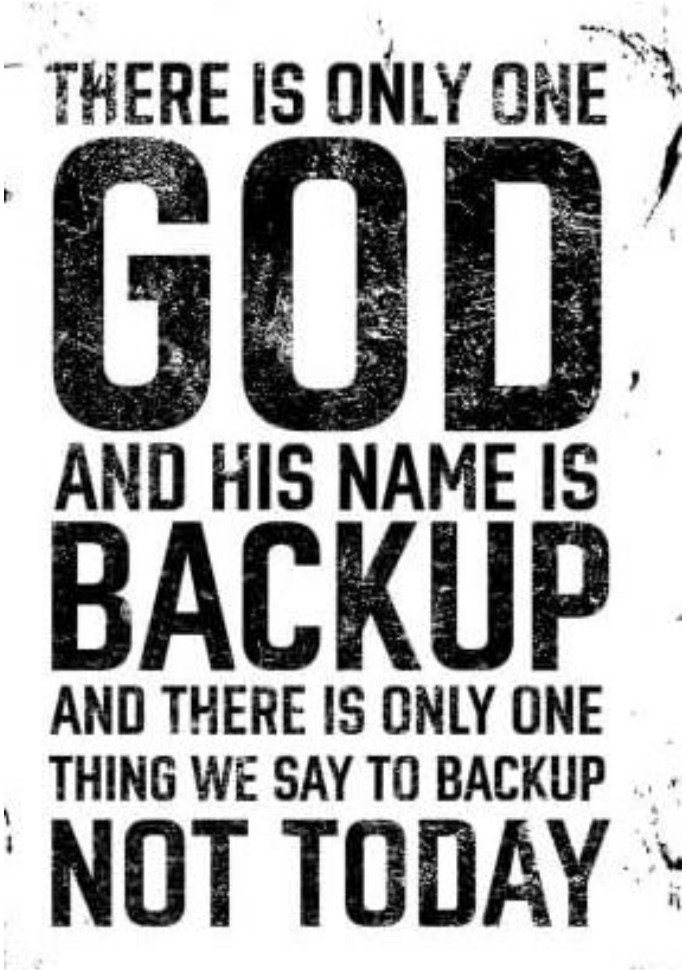
- Three methods of radiation hardness:

1. **Active Gain Implant:** No measureable improvement wrt different implants
2. **Effective Gain Estimation:** Gallium-Boron behave similarly
   Carbon up to 2x better in neutrons / protons
3. **MIPs Charge collection:** 20 % improvement in required bias for Carbon
   20 % degradation for Gallium

Consistent with defect kinetics theory and an exponential field -gain dependence
Results consistent in all temperatures (-10°C, -20°C, 30°C)

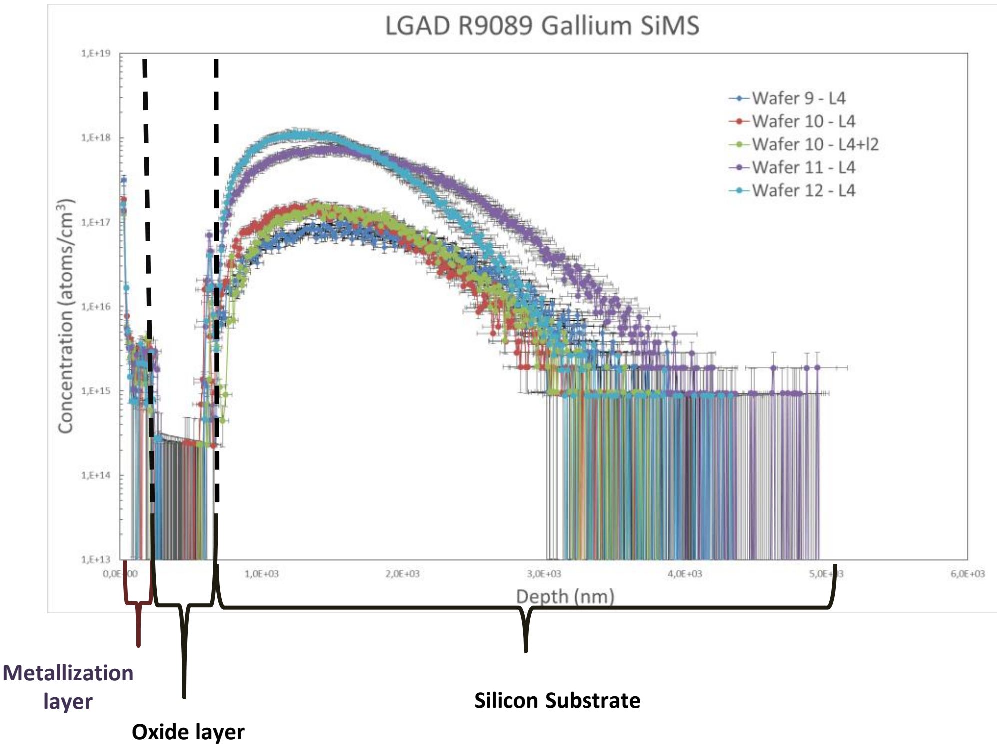
- No degradation in leakage current
- 15% degradation on available headroom in Carbon samples
- 15% degradation in stability of Carbon samples
- No effect on signal properties, efficiency, noise or timing
- In and Li co-implantation as next steps on defect engineering

- **Backup**


THERE IS ONLY ONE
GOD
AND HIS NAME IS
BACKUP
AND THERE IS ONLY ONE
THING WE SAY TO BACKUP
NOT TODAY

•Standard Candle Process

Typical Profiles



- ✓ New process optimization require standard profile as a reference
- ✓ Use Secondary Ion Mass Spectroscopy (SiMS)profiles form LGAD gain layers
- ✓ Target Boron and Gallium process (well understood)
- ✓ Accuracy of 1e15/cm^3

Gallium Nominal Parameters			
Nominal Dose [atoms/cm^2]	Anealing Temp [°C]	Anealing Time [min]	Implant. Energy [KeV]
1,00E+14	1100	180	
1,00E+14	1100	100	
1,00E+14	1100	100	195
1,00E+15	1100	180	
1,00E+15	1100	100	

Target optimization parameters

- ✓ Implantation energy
- ✓ Implantation dose
- ✓ Screen oxide layer thickness
- ✓ Diffusion Time
- ✓ Tilt Angle

•Carbon Calibration Profiles

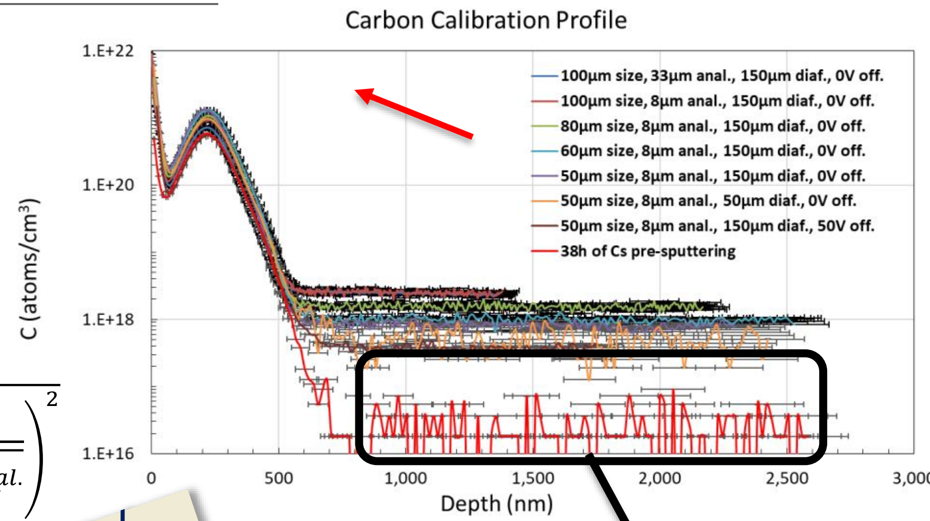
Sensitivity Optimization

- ✓ The implant concentration is estimated in each case following:

$$C = RSF \times \frac{i_i^{cal.}}{i_M^{cal.}}$$

$$\delta C = \sqrt{\left(\frac{i_i^{cal.}}{i_M^{cal.}} \times \delta RSF\right)^2 + \left(\frac{RSF}{i_M^{cal.}} \times \frac{1}{\sqrt{i_i^{cal.}}}\right)^2 + \left(RSF \times \frac{i_i^{cal.}}{(i_M^{cal.})^2} \times \frac{1}{\sqrt{i_M^{cal.}}}\right)^2}$$

- ✓ Without any additional optimization, a resolution of $(4.71 \pm 0.03) \times 10^{16}$ atoms/cm^3 can be achieved
- ✓ The resolution increased for smaller raster sizes while maintain same beam intensity, resulting in higher observant signal intensity
- ✓ Downside of such an approach higher abrasion speed, lees points
- ✓ In essence this is the equivalent in measurement terms of statistical smoothing of profiles.
- ✓ Points recorded every 17 nm, limit of feature size one can probe for achieving such resolution



Gaussian fit on point projection to estimate resolution form σ

Best Recorded Resolution for SiMS on Carbon

Beam Parameters	Abrasion Speed v (nm/sec)	Scaling Factor RSF (atoms/cm³)	Sensitivity S (atoms/cm³)
100µm size, 33µm reg., 150µm dia., 0V off.	4.35 ± 0.20	$(2.77 \pm 0.06) \times 10^{22}$	$(4.85 \pm 0.11) \times 10^{16}$
100µm size, 8µm reg., 150µm dia., 0V off.	4.43 ± 0.21	$(3.61 \pm 0.08) \times 10^{22}$	$(1.80 \pm 0.01) \times 10^{17}$
80µm size, 8µm reg., 150µm dia., 0V off.	6.93 ± 0.34	$(2.62 \pm 0.06) \times 10^{22}$	$(1.48\ 0.005) \times 10^{17}$
60µm size, 8µm reg., 150µm dia., 0V off.	12.11 ± 0.65	$(1.82 \pm 0.04) \times 10^{22}$	$(7.89 \pm 0.02) \times 10^{16}$
50µm size, 8µm reg., 150µm dia., 0V off.	14.64 ± 0.84	$(1.45 \pm 0.03) \times 10^{22}$	$(7.44 \pm 0.01) \times 10^{16}$
50µm size, 8µm reg., 50µm dia., 0V off.	15.55 ± 0.91	$(1.05 \pm 0.02) \times 10^{22}$	$(1.78 \pm 0.002) \times 10^{17}$
50µm size, 8µm reg., 150µm dia., 50V off.	17.00 ± 1.04	$(5.56 \pm 0.14) \times 10^{21}$	$(4.71 \pm 0.03) \times 10^{16}$
38 h Cesium Pre - Sputtering	**16.79 ± 1.02**	$\mathbf{(6.04 \pm 0.14) \times 10^{21}}$	$\mathbf{(2.22 \pm 0.07) \times 10^{16}}$

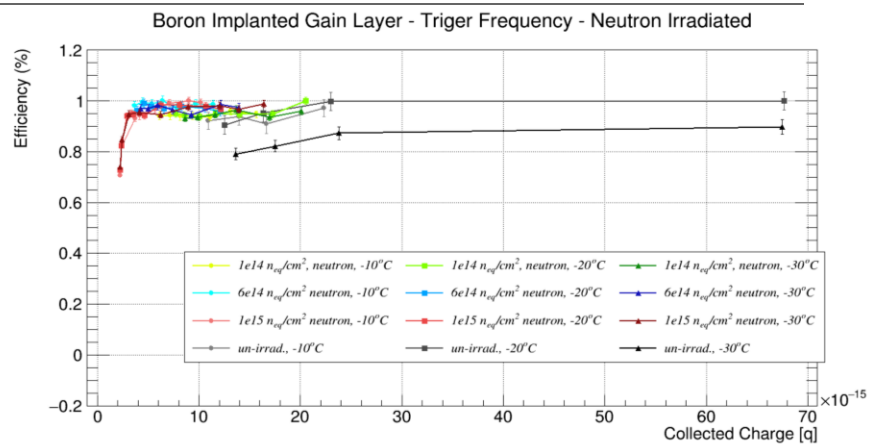
•Carbon implant simulation

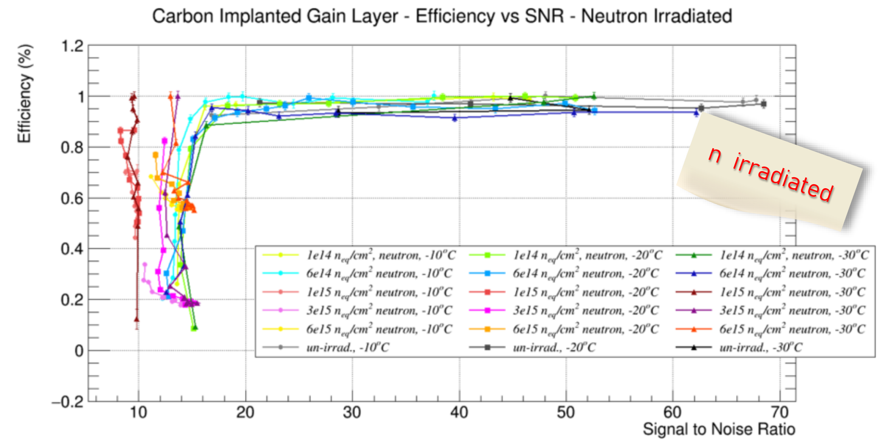
Dopant Defect Cluster Models

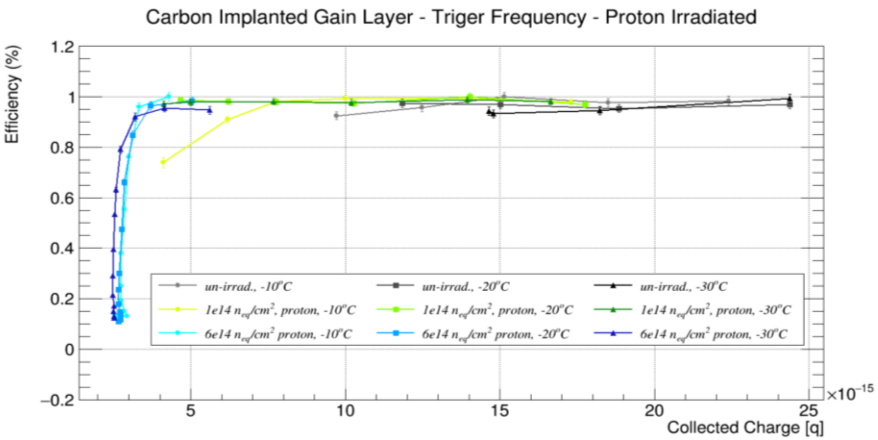
Complex Cluster and BIC (boron interstitial) models

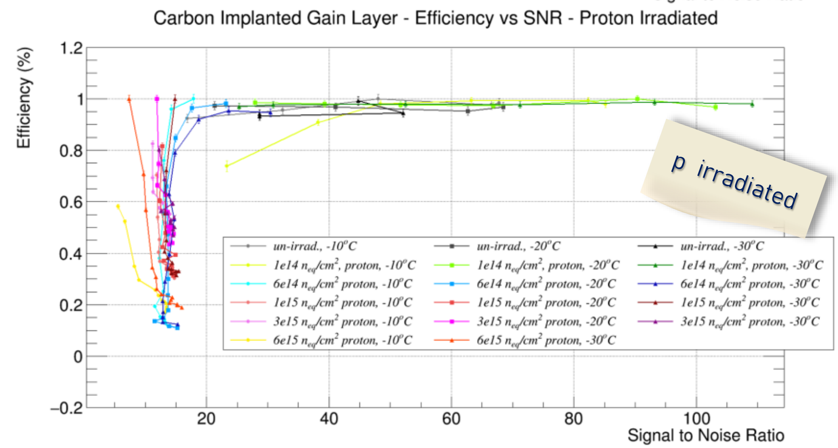
- **Boron activation model:**
  - Boron activation is mainly interstitial driven
  - BIC (**B**oron **I**nterstitial **C**luster) model simulates the process via clustering reactions: $\mathbf{B_i\, I_j + V/I \rightarrow B_i\, I_{j-1} / B_i\, I_{j+1}}$ $\mathbf{B_i\, I_j + BI \rightarrow B_{i+1}\, I_{j+1}}$
  - User demined cluster sizes to consider: $\mathbf{B, BI, BI_2, B_2I_1, B_3I_1, B_3I_2}$
  - Reaction rates can be set by user for each reaction (eg 0.3×10^{-10})
- **Carbon activation model:**
  - The Carbon Cluster or Neutral Cluster Model sets initial cluster concentrations to 0 unless in amorphous regions
  - No charged clusters are considered, solutions to $A_iI_j + I \leftrightarrow A_iI_{j+1}$ $A_iI_j + AI \leftrightarrow A_{i+1}I_{j+1}$ $A_iI_j + V \leftrightarrow A_iI_{j-1}$
  - For Carbon, the following dedicated clusters are computed: C_3I_2, C_4I_2, C_4I_3, C_5I_3, C_5I_4
- **Boron/Carbon activation/deactivation models:**
  - The ComplexCluster Model considers cluster formation between dopants and Vacancies / Interstitials in Si
  - Such process can be described generally as: $\mathbf{n_1 \times Imp.A + n_2 \times Imp.B + n_3 \times V/I + n_4 \times e^- \rightarrow A_{n1}B_{n2}(V/I)n_5 + n_6e^-}$
  - In the carbon/boron case, the simplest reaction to consider is: $C + B + I \rightarrow BCI + e$
  - A final charge of 1.0 is expected in such a case
  - For the moment using the Initial concentration as provided after MC implantation by Crystal Trim

•Comparative Studies - Efficiency





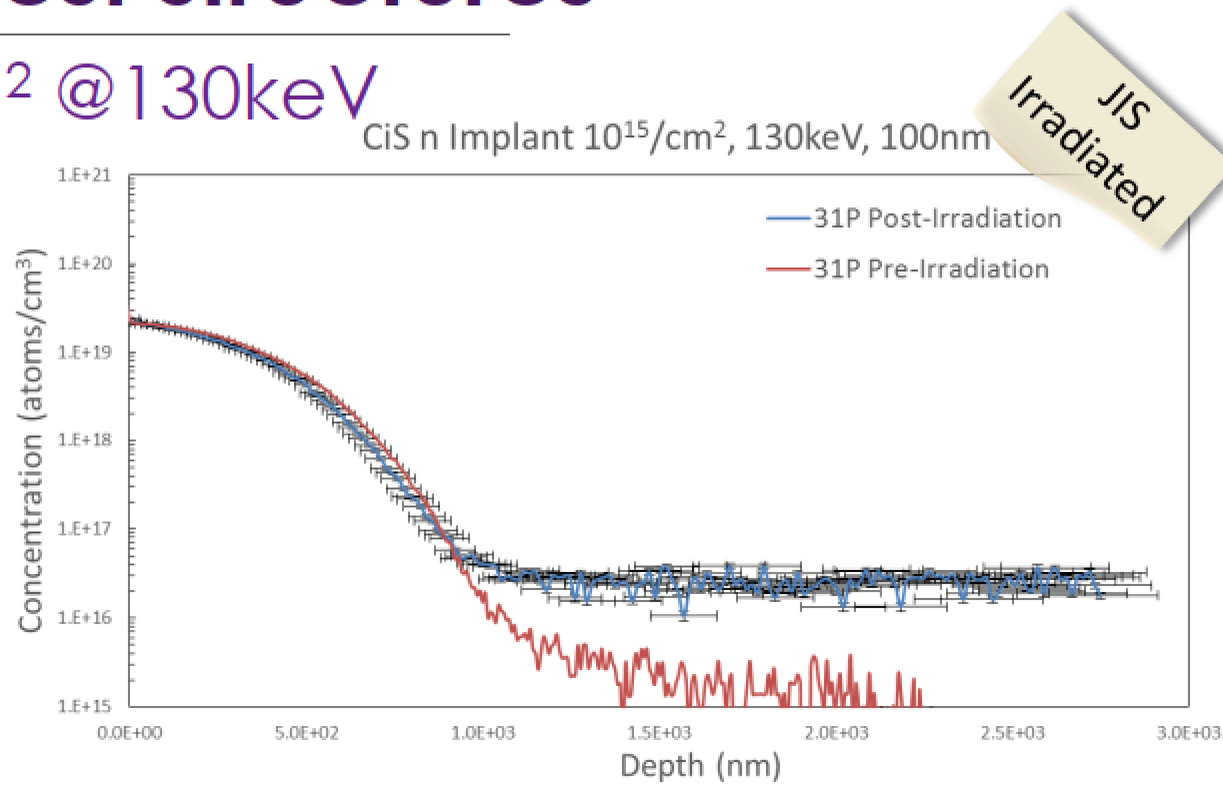




•Phosphorus Test structures

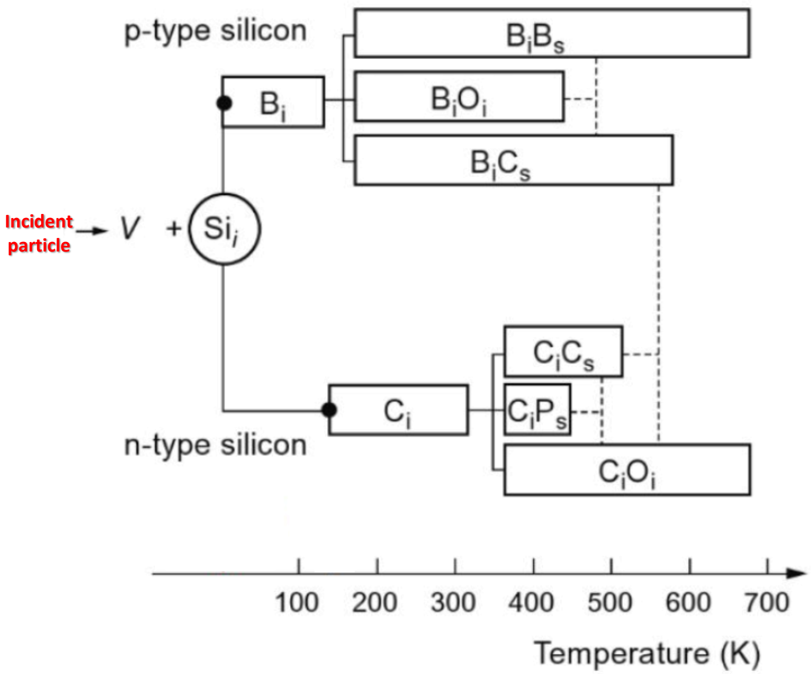
Cis n-in-n $10^{15}/cm^2$ @130keV

- ✓ Fluence of 10^{16} n_{eq}/cm^2
- ✓ Thermal neutrons
- ✓ Cooled during storage and transport



- The bopping profile o the neutron irradiated samples seems unaffected
- Agreement within uncertainties
- Higher detection limit due to timing constraints induces deviations at lower part of the profiles

•Radiation Effects



Acceptor removal, Defect Kinetics (simplified ☺)

- Incident particle hits silicon atom and created Vacancy (V) and Interstitial Silicon (Si_i)
- Si_i Propagates and can transform substitutional Boron/Carbon to B_i/C_i (interstitial),
- B_i/C_i can form several defects, but the most prominent in high resistivity silicon is:

$$Si_i + B_s \rightarrow B_i + O \rightarrow B_iO_i$$

or

$$Si_i + C_s \rightarrow C_i + O \rightarrow C_iO_i$$

Change type of final defects but not amount of active implant

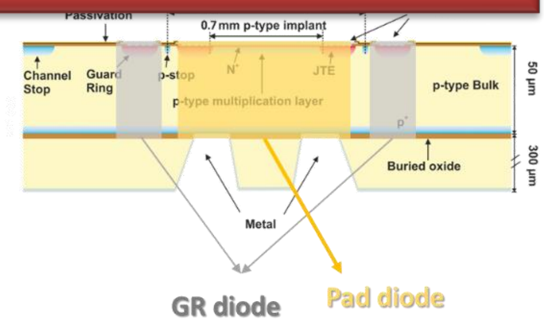
- Since B_i and C_i both compete for the same Si_i, if we introduce more Carbon we would expect to from less B_iO_i defects and more C_iO_i
- If we exchange Boron with a less mobile (heavier) atom (Ga), then we should also enhance C_iO_i defects instead of Ga_iO_i

•The Derive and Fit Method - I

Gkougkousis V., RD50 Workshop Talk, November 2019: link

$$f(V) = \left|\frac{\partial I_{pad}}{\partial V}\right|$$

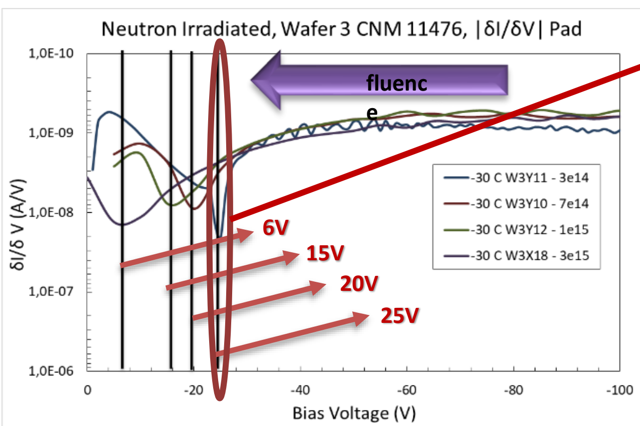
- ✓ Probe active implant by depletion voltage
- ✓ Additional p-implantation gain layer creates secondary depletion region
- ✓ Mott–Schottky equation → **leakage current variation at gain layer depletion**
- ✓ Form of $\left|{}^{\partial I}/_{\partial V}\right|$ at depletion point corresponds to dopant transition function convoluted with instrument resolution (Gaussian X Gaussian)
- ✓ Depletion voltage determined Gaussian fit at depletion voltage for -10°C, -20°C & -30°C

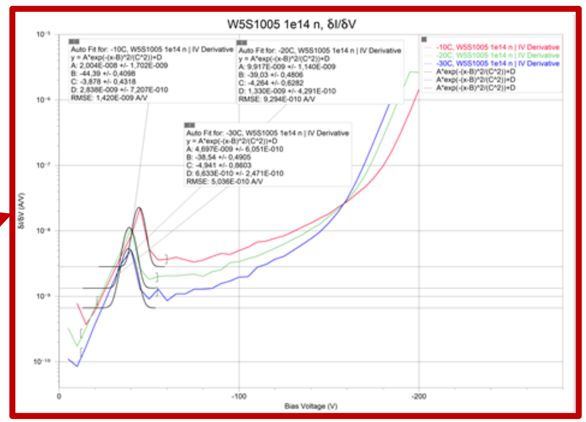


$$V_d = \frac{\sum_{T=-10\,^oC}^{-30\,^oC} V_{d,T_i}}{n_T}$$

$$\delta V_d = \sqrt{V_{d.sys} + V_{d.stat}}$$

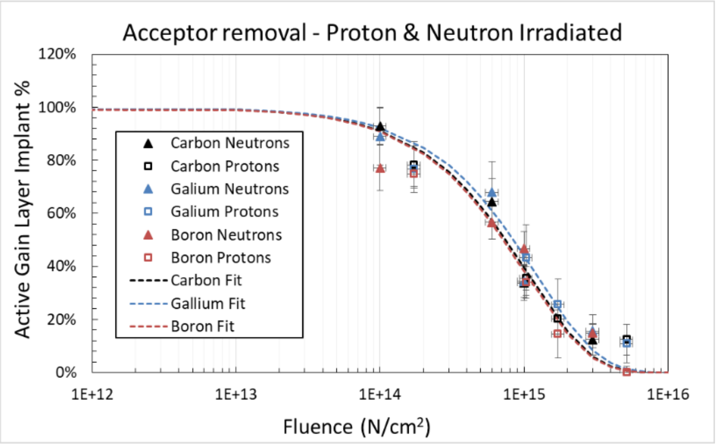
Average of fit sigma — Standard deviation of V_d

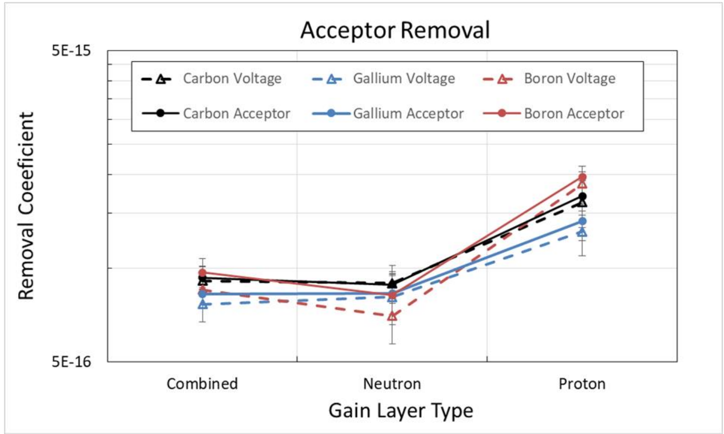




- Independent Gaussian fits for each temperature
- Uncertainties estimated from propagation of fit sigma
- Fluences up to $3{\cdot}10^{15}$ n_{eq}/cm^2 in p^+ and n^0

•The Derive and Fit Method - II





- Linear dependence assumption between V_{GL} and active implant
- Normalized exponential reduction fit model on gain and V_{GL}

$$G(\%) = e^{-C_G \Phi}$$

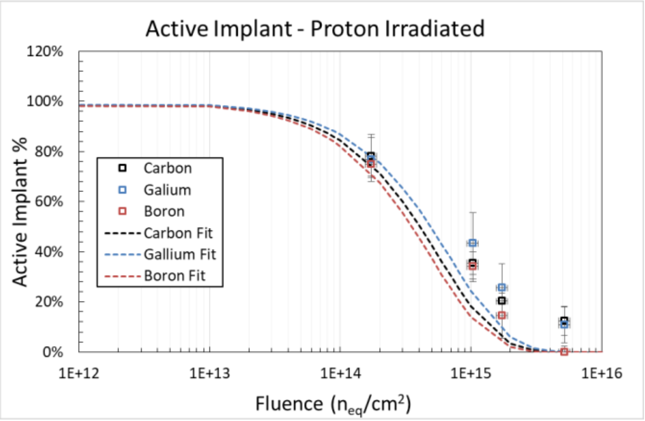
- Linearity hypothesis tested with independent C_v and C_G fits – full compatibility
- Constraints imposed on initial values to reflect charge measurements

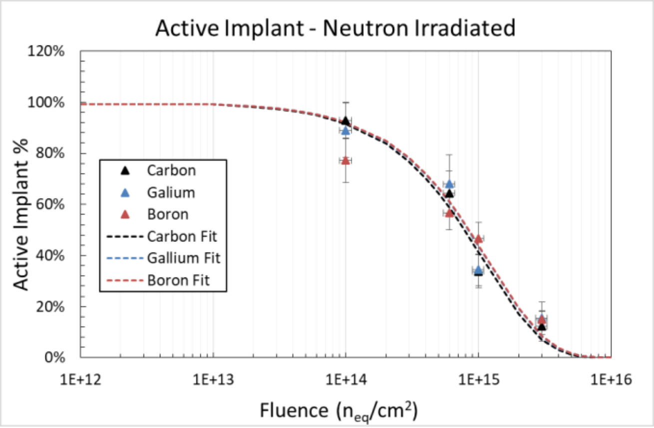
Results

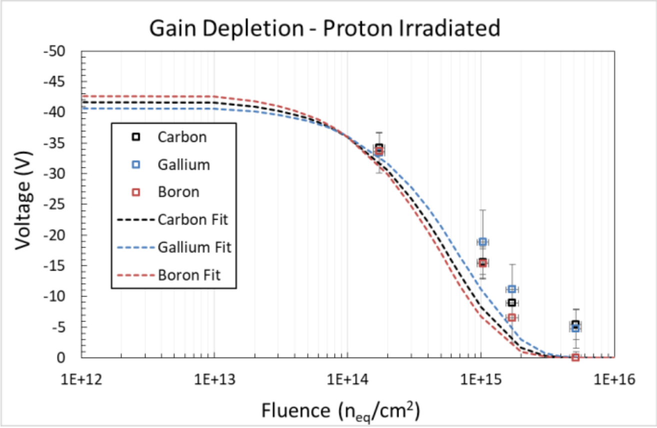
- Compatible acceptor removal coefficients between all implants
- Slight Ga advantage in p^+ irradiation (23 GeV/c PS), higher mass reduces displacement probability in coulomb-only (far-field) interactions
- Quasi-identical performance for neutron irradiated (fast ~ 10MeV neutrons)
- **Identical gain layer de-activation for all dopants with fluence**

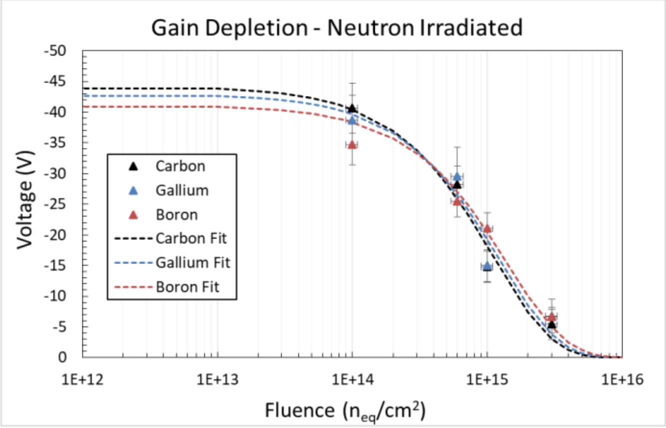
Acceptor Removal Coefficient		
Irrad. Type	**C**	**δC**
Gallium		
Combined	8.25E-16	7.98E-17
n^0 irradiated	8.28E-16	1.16E-16
p^+ irradiated	1.41E-15	1.88E-16
Boron + Carbon		
Combined	9.33E-16	7.78E-17
n^0 irradiated	8.85E-16	8.76E-17
p^+ irradiated	1.70E-15	2.23E-16
Standard Boron		
Combined	9.69E-16	1.04E-16
n^0 irradiated	8.19E-16	1.35E-16
p^+ irradiated	1.96E-15	1.60E-16

•The Derive and Fit Method - II









•Comparative Studies II - Stability

Self-trigger time: $$\Delta T^{i}_{trig} = \frac{\sum_{j=1}^{n-1}(T^{trig}_{j+1} - T^{trig}_{j})}{n}$$

Self-trigger Rate: $$F^{i}_{trig} = \frac{1}{\Delta T^{i}_{trigg}}$$

X 1000

Median of several rate measurements $$\widetilde{F_{trig}} = \frac{F_{trig\ \lfloor(\#k+1)\div 2\rfloor} + F_{trig\ \lceil(\#k+1)\div 2\rceil}}{2}$$

Uncertainty on trigger rate:

$$\delta\widetilde{F_{trig}}(\%) = \sqrt{\frac{(N_{over}+1)\times(N_{over}+2)}{(N+2)\times(N+3)} - \frac{(N_{over}+1)^2}{(N+2)^2}}$$

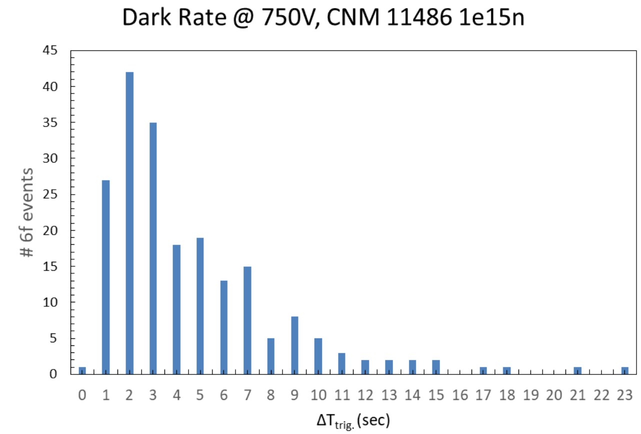
Efficiency is a binary magnitude, Bayesian approach implemented

Sigmoid Dark rate Fit: $$R_{Dark\ Rate} = \frac{R_{max}}{1 + e^{C\times(V_{50\%} - V)}} + R_{BaseLine}$$

Max, recordable rate Inst. saturation point

50% of maximum voltage point

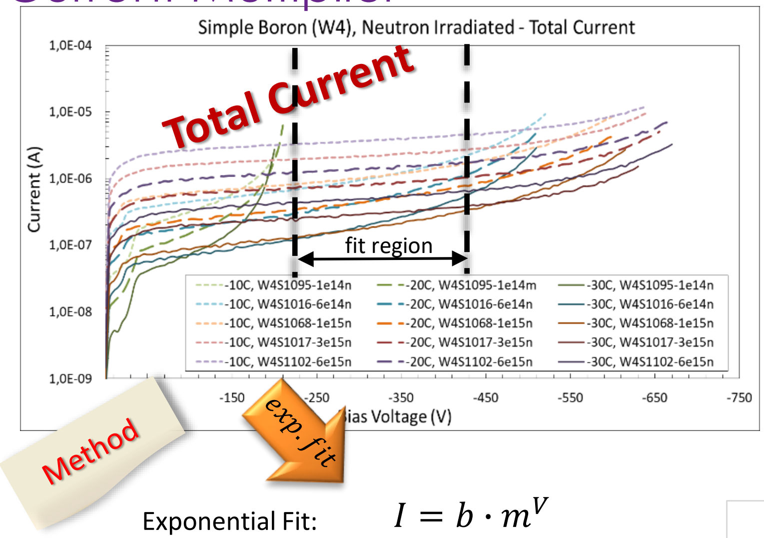
Baseline trigger rate (noise, radioactivity)



- ✓ Sensors with intrinsic gain present dark rate at higher biases
- ✓ Brownian thermal electrons following Poisson distribution
- ✓ As gain increases, the amount of charge necessary for an event to cross trigger threshold decreases
- ✓ Shot thermal noise increases with voltage
- ✓ Evaluation performed at the 2 fC threshold
- ✓ Values estimated from Poissonian fit on event frequency distribution (1000 events)

•Breakdown Voltage

Current Multiplier



Exponential Fit: $I = b \cdot m^V$

Acceptance Criteria: $R^2 \geq 99\%$

Expected current: $I_{norm} = b \cdot m^{V_i}$

Current Multiplier: $M(V) = \left| \frac{I_{pad} + I_{GR}}{I_{norm}} \right|$

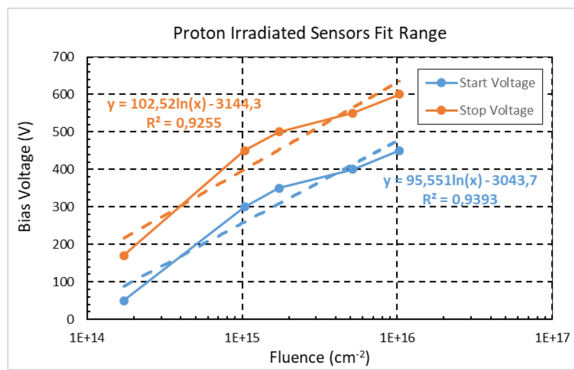
Breakdown: $V_{brw} \rightarrow M(V) > 2$

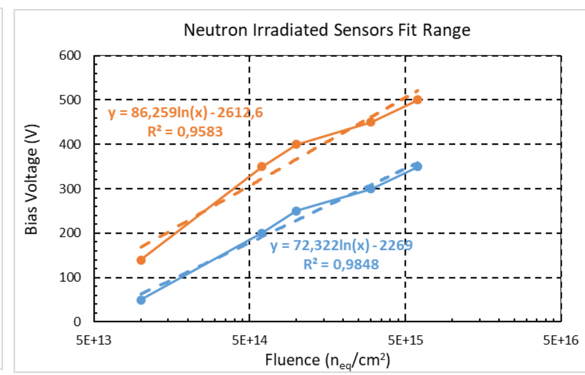
- ✓ Measure total leakage current (-10ºC, -20ºC, -30ºC)
- ✓ Select a stable voltage range where behaviour follows exponential law
- ✓ Define common for all temperatures stable voltage range, after depletion and much before breakdown
- ✓ Perform exponential fit requesting $R^2 \geq 99\%$ (same range as in the gain reduction fits - same constraints)
- ✓ Calculate the multiplier with respect to the expected current
- ✓ **Define breakdown in multiplier value (Is it really exponential??)**

Un-irradiated: $I_{pad}^{\Phi=0} = I_s \times \left(e^{\frac{eV}{nkT}} - 1\right) \times G(e^V, T)$

Irradiated: $I_{pad}(\Phi) = (I_{pad}^{\Phi=0} + \alpha\Phi) \times G^*(e^V, T, \Phi)$

Function of acceptor removal, exponential to fluence and voltage plus a linear term

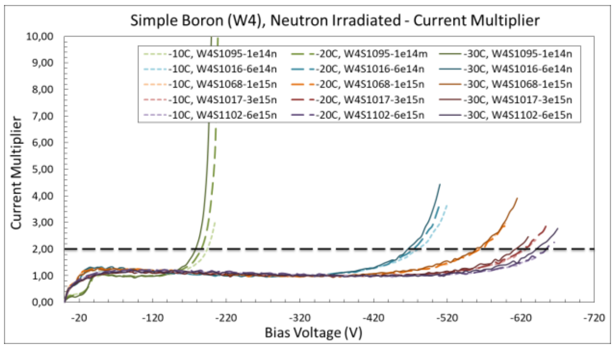


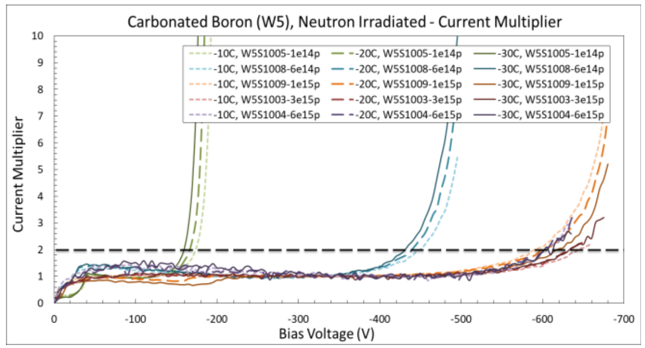


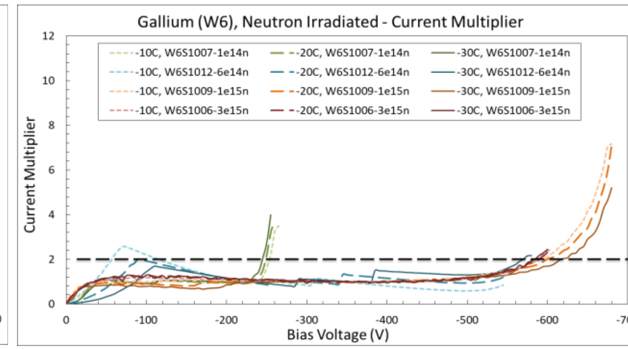
•Breakdown Voltage

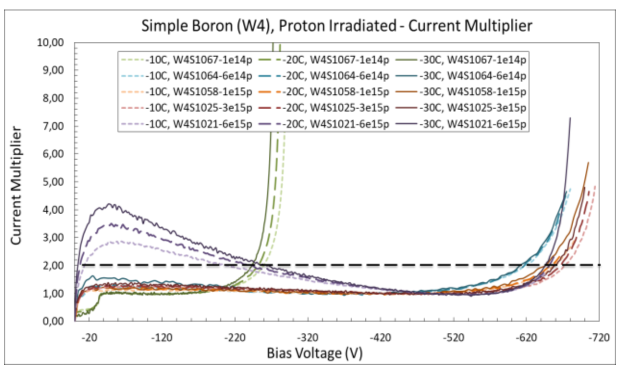
- ✓ Independent fit for each temperature
- ✓ Identical fit regions across all temperatures
- ✓ Identical fit regions for same fluence across all three implants

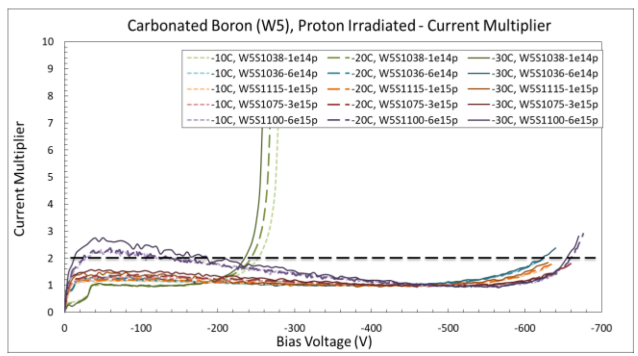
Constraints

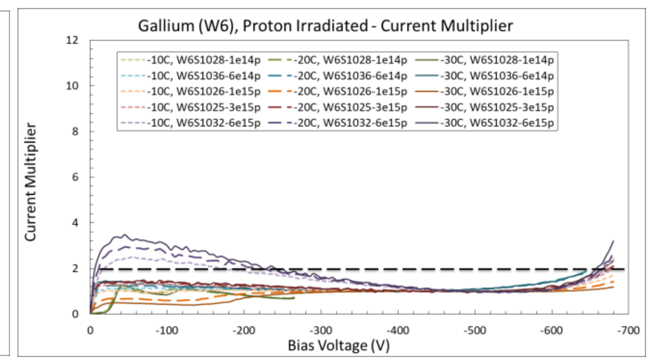












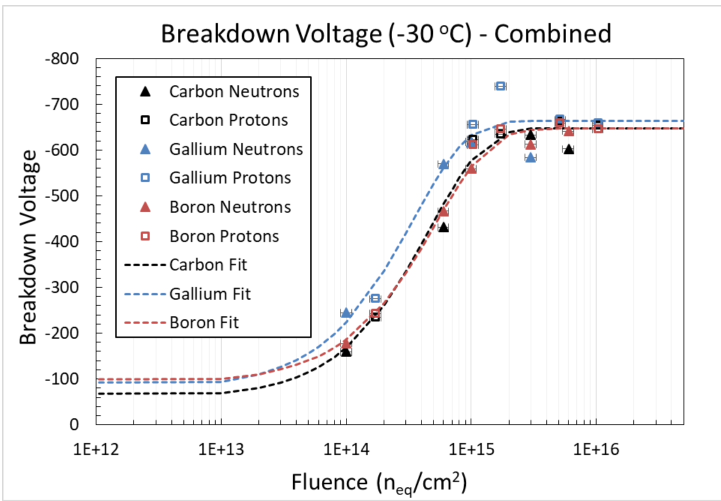
•Breakdown Voltage

Model

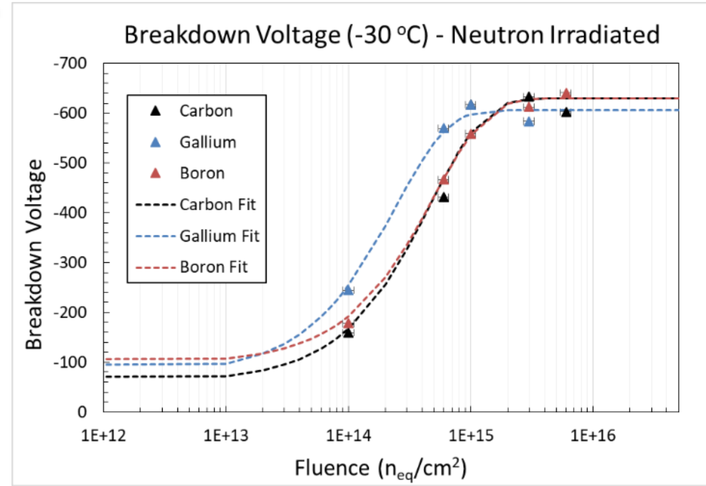
Breakdown of PIN

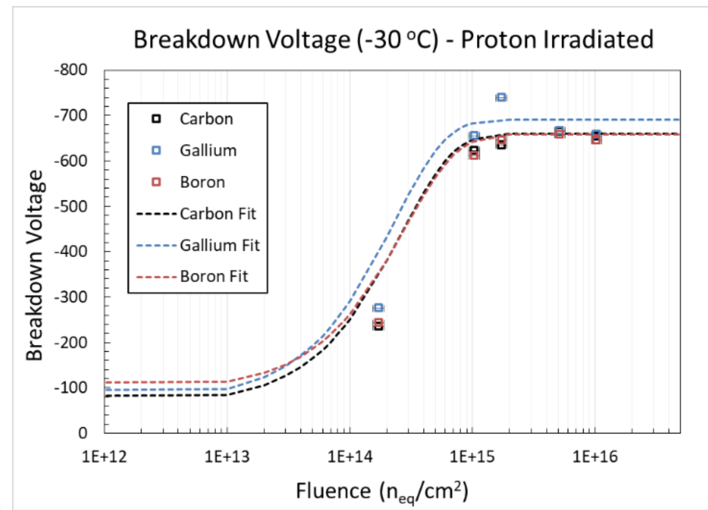
Un-irradiated breakdown voltage

$$V_b = (V_{max} - V_0)\left(1 - e^{-c\Phi}\right) + V_0$$



- ✓ Carbon and boron are compatible
- ✓ Gallium presents higher breakdown voltage (most possibly due to process variation)
- ✓ All implants compatible with sigmoid approach
- ✓ Highest breakdown voltage after irradiation independent of gain – exclusively process dependent





• Introduction il

Timing Concepts

Time Resolution: $\sigma_{tot}^2 = \sigma_{timewalk}^2 + \sigma_{jitter}^2 + \sigma_{conversion}^2 + \sigma_{Clock}^2$

$\sigma_{Dist.}^2 + \sigma_{Landau}^2$

$\left(\frac{t_{rise}}{S/N}\right)^2$

$\left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2$

Fixed Term

~ 5-7 psec

$\frac{t_{rise}}{S/N} \approx \frac{N}{dV/dt}$

$[\frac{V_{th}}{S/t_{rise}}]_{RMS} \propto \left[\frac{N}{\frac{dV}{dt}}\right]_{RMS}$

$\left(\left[\frac{V_{thr}}{S/t_{rise}}\right]_{RMS}\right)^2$

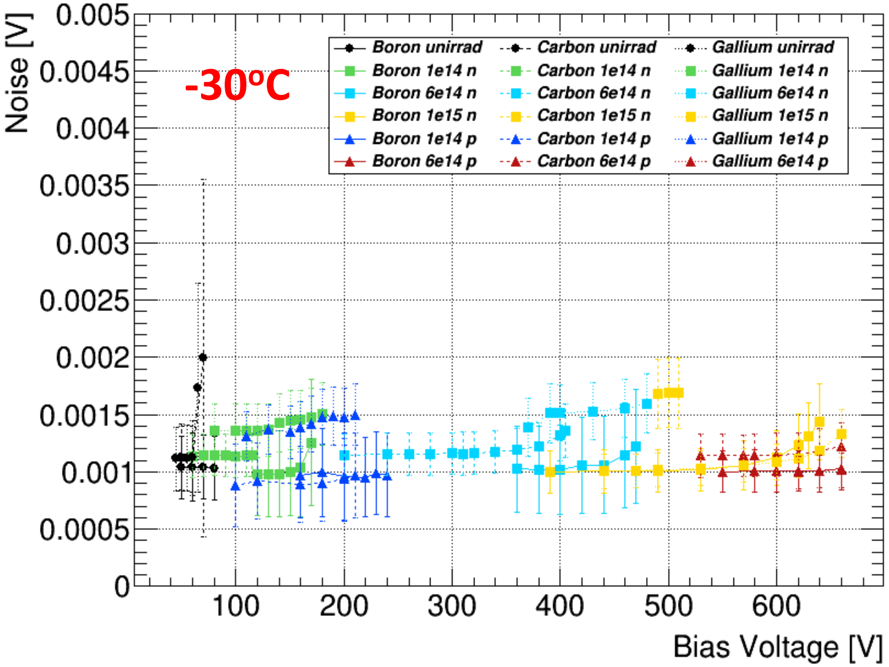
Where: S signal
N noise
$\boldsymbol{V_{th}}$ CFD threshold
t_{rise} *rise time*

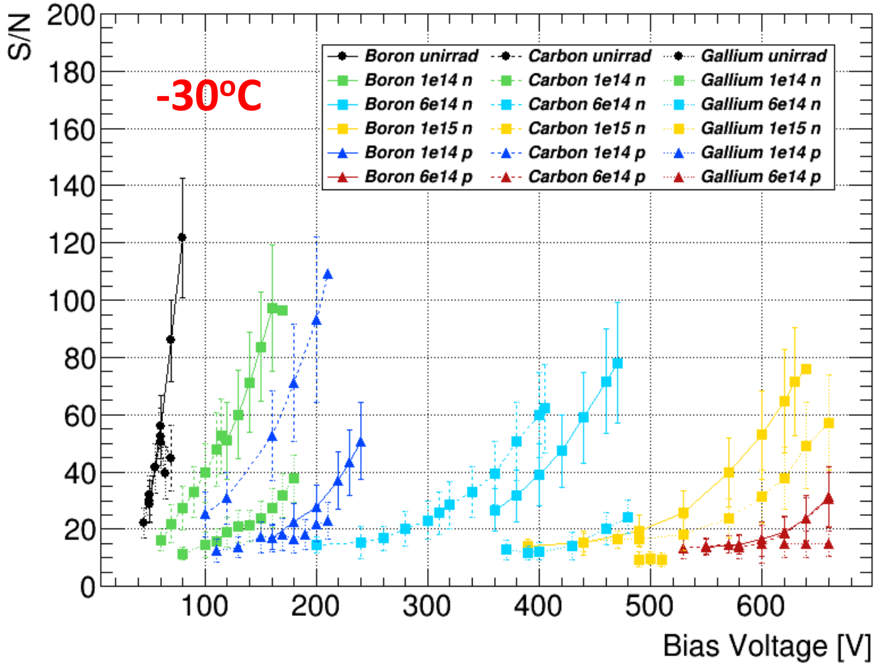
Fast time resolution:

- ✓ Maximize slope (large fast signals)
- ✓ Minimize noise to minimize jitter
- ✓ Implement time walk correction (CFD, ToT, ToA, ect)
- ✓ Uniform field with to minimize distortion term

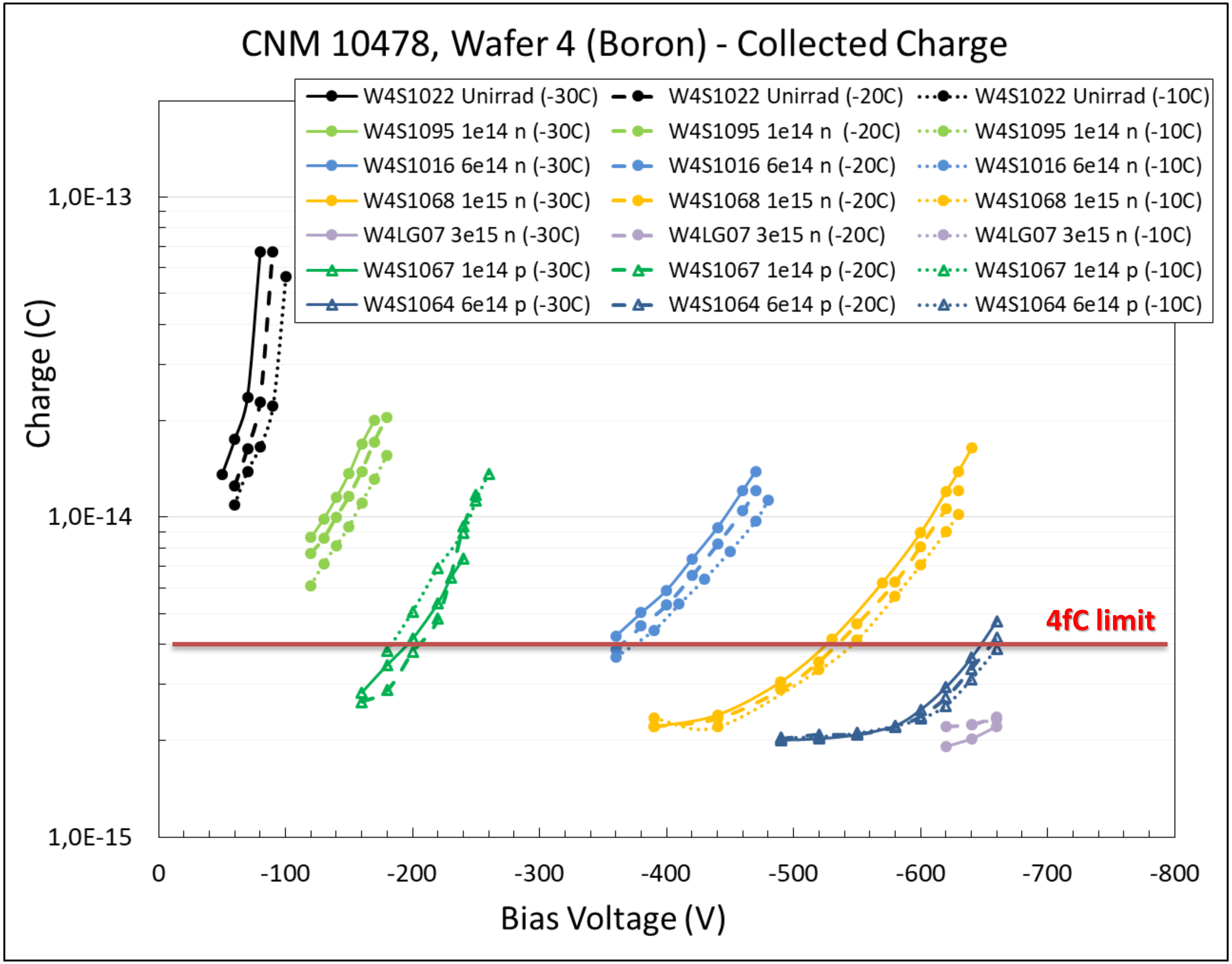
Thin silicon sensors with internal gain

•Noise and S/N Ratio

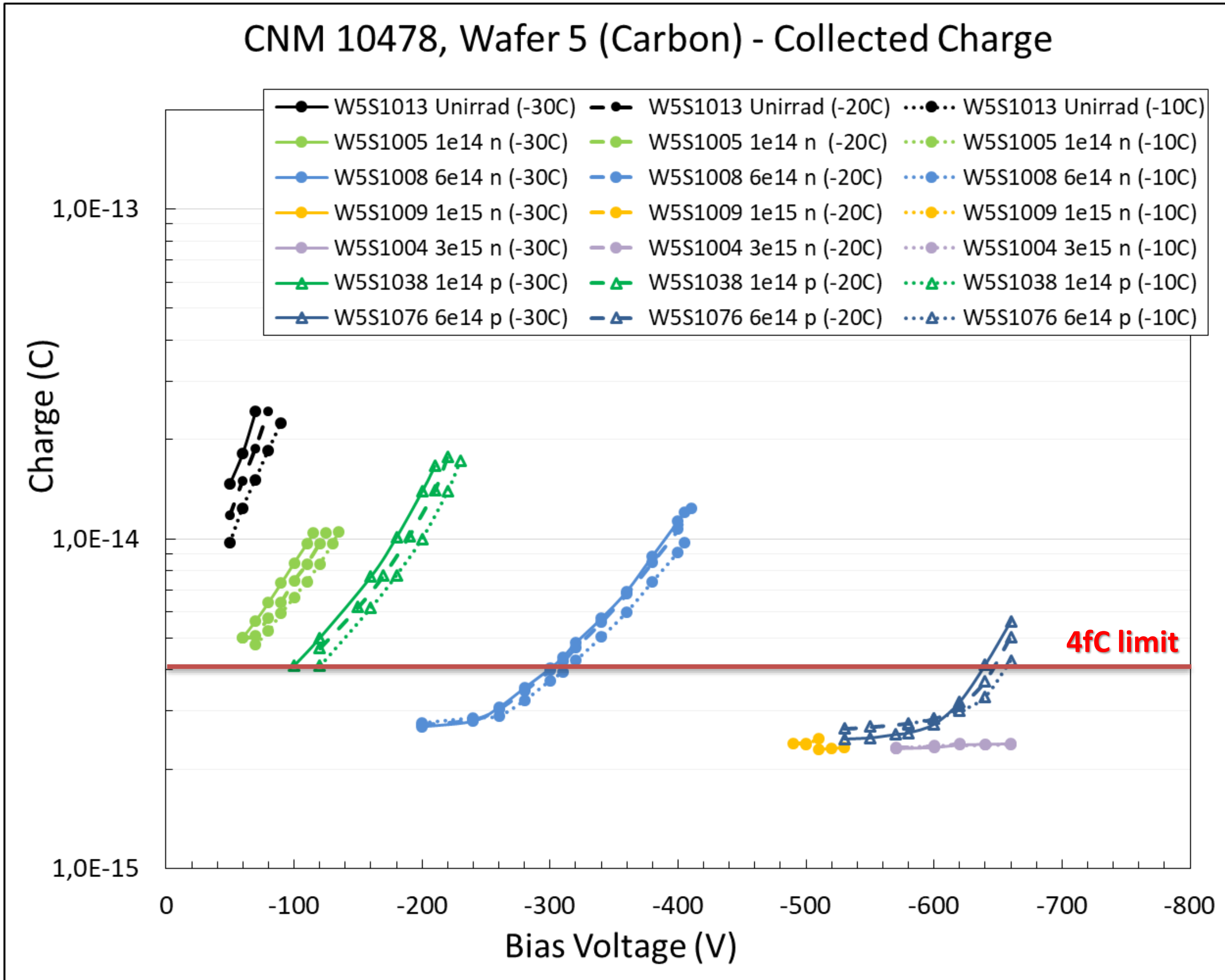




•Collected Charge - Boron



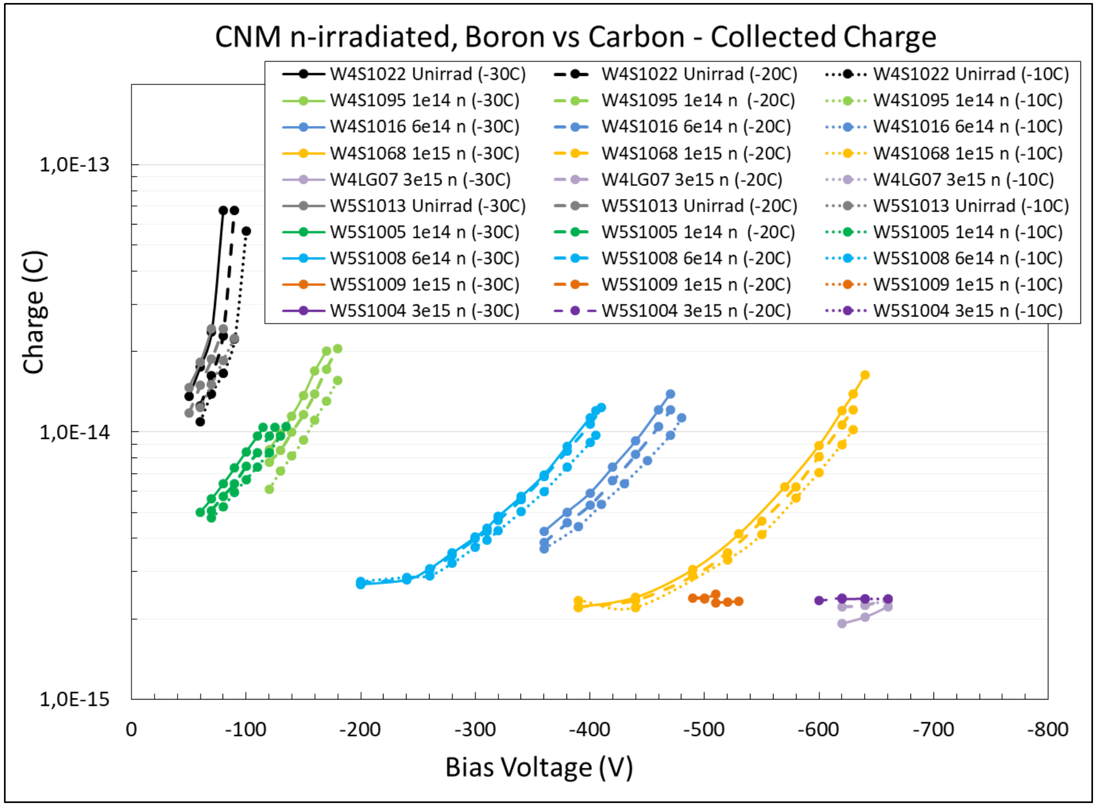
•Collected Charge – Boron + Carbon



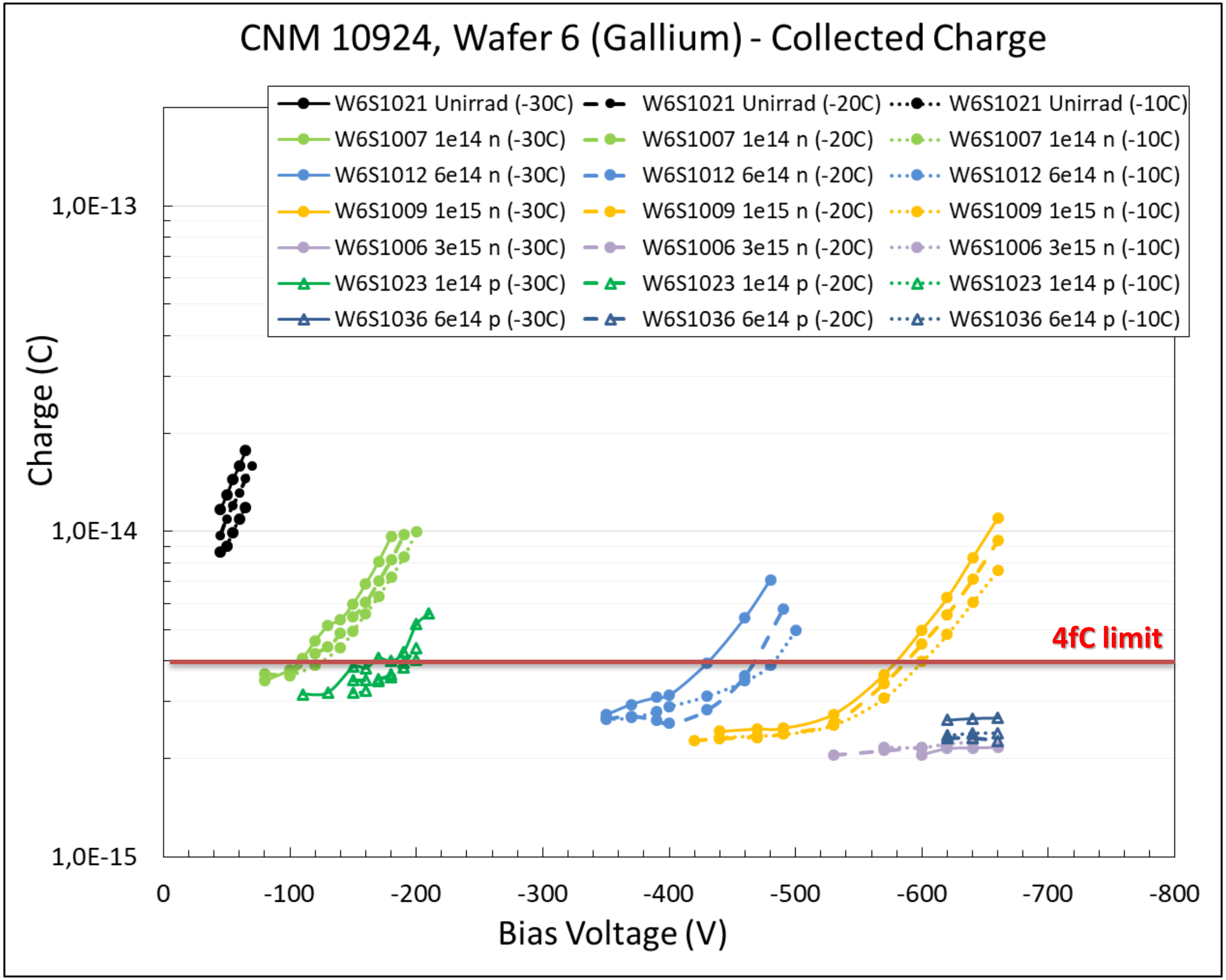
• Sensor R&D

LGADs – Charge collection

- ✓ Unirradiated gain tuned to be identical for boron/gallium/carbon implanted sensors fro accurate comparison
- ✓ Irradiated Carbon infused sensors present higher charge at lower HV
- ✓ Gallium implanted sensors are 10% worse than standard process boron
- ✓ Carbon is 20% better across the spectrum with respect to boron



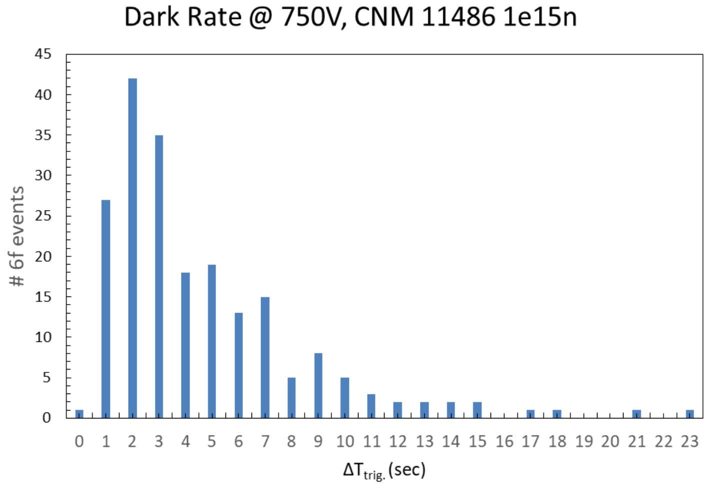
•Collected Charge – Gallium



•Dark Rate

Concepts & Methods

- ✓ Sensors with gain present dark rate at high enough voltages
- ✓ Dark rate events result of thermal movement and random in nature
- ✓ Follow the Poisson distribution



Quantification

- ✓ Study the time between consecutive self-triggering
- ✓ Use mean of 4 events (3 values) to reject cosmic background

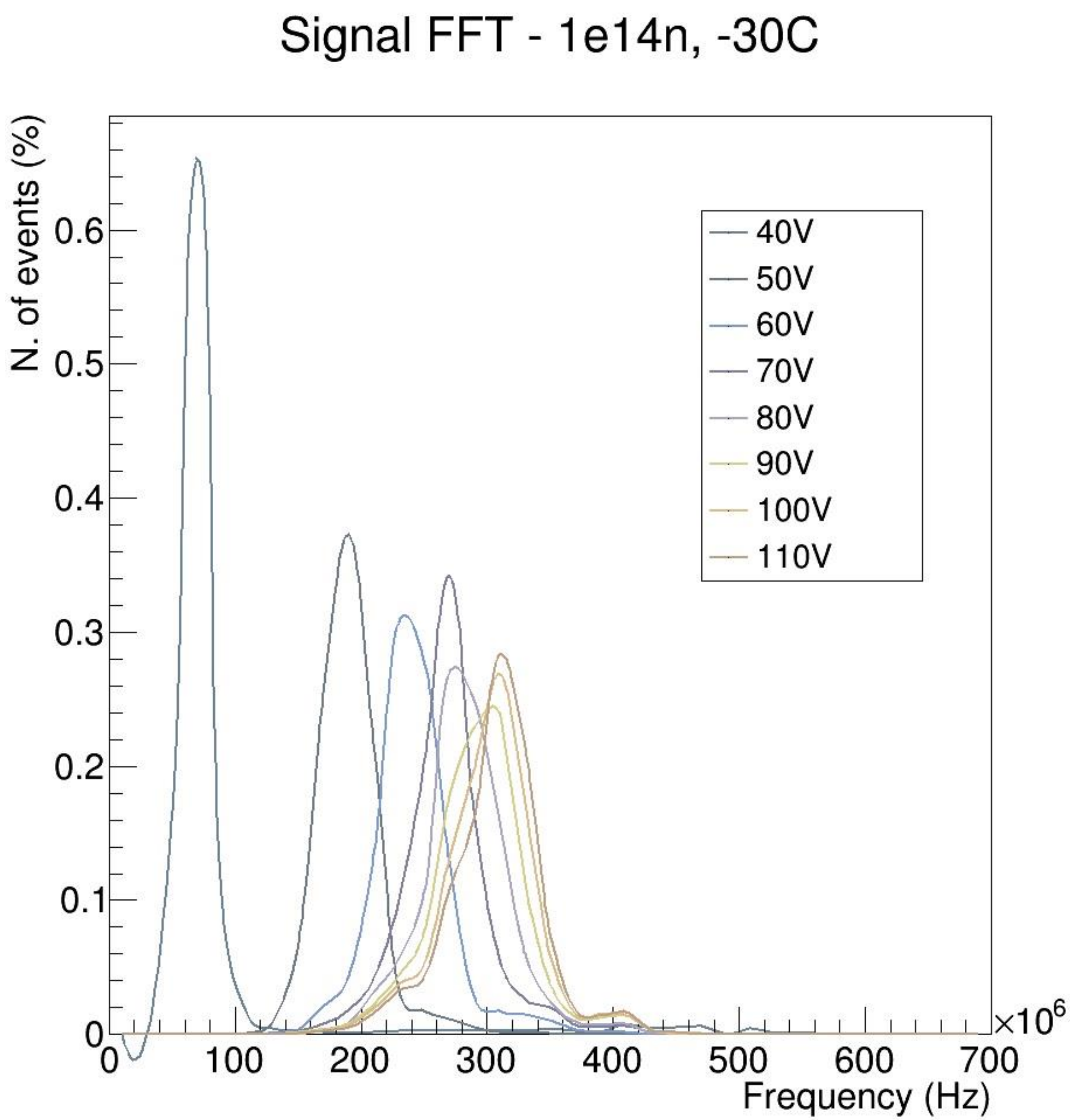
Self-trigger time:

$$\Delta T^{i}_{trig} = \frac{\sum_{j=1}^{n-1}(T^{trig}_{j+1} - T^{trig}_{j})}{n}$$

Self-trigger Rate:

$$R^{i}_{trig} = \frac{1}{\Delta T^{i}_{trigg}}$$

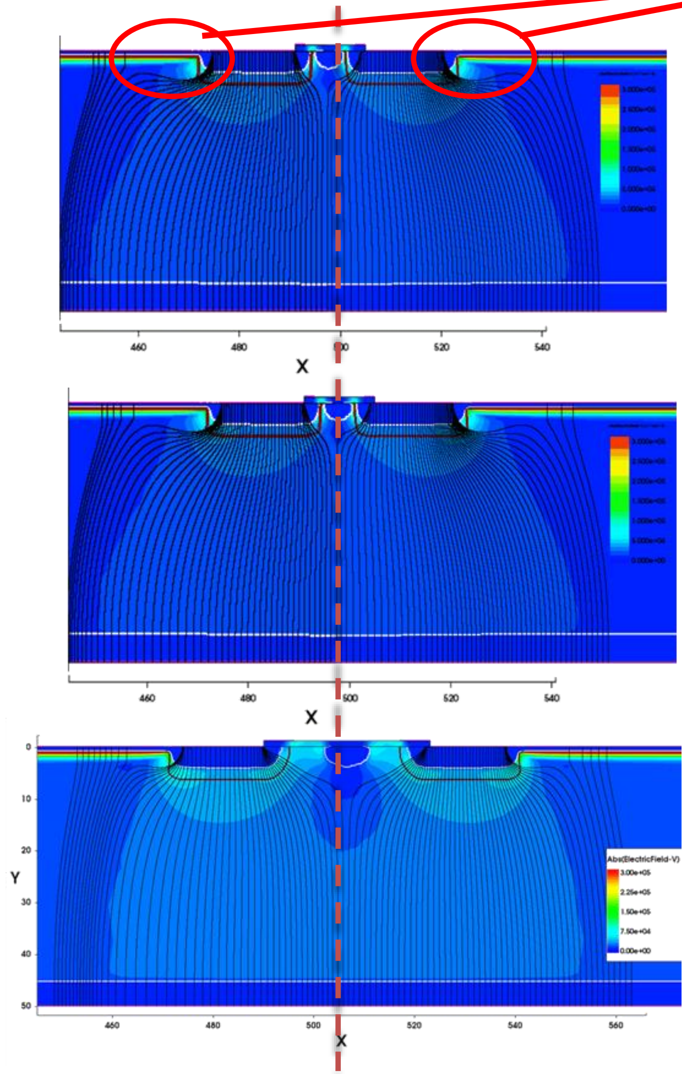
•Signal Evolution with bias in LGADs

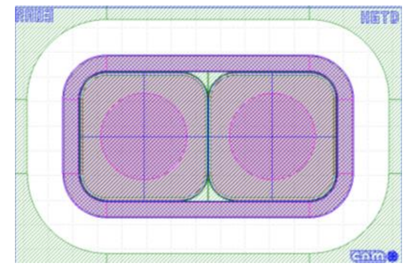


• Main Development Points

Inter-pad region

“no-field” region





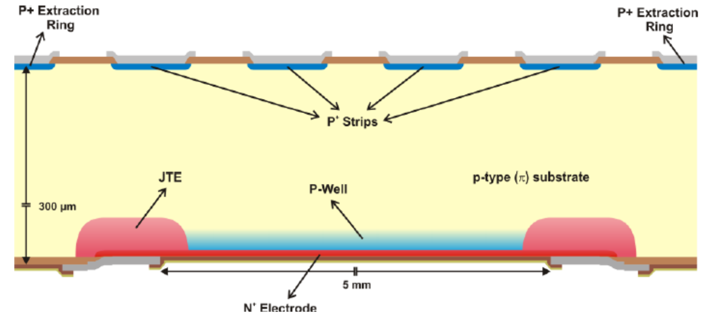
2-pad test structure

- Deeper JTE implant with respect to multiplication layer
- Effective no-field region created next to the boarder
- As voltage increase and gain field become more significant, “no-filed” region decreases
- Effect will never completely disappear
- In a perfect approach, JTE would be:
  - exactly as deep as gain layer
  - concentration gradient tuned to match gain layer

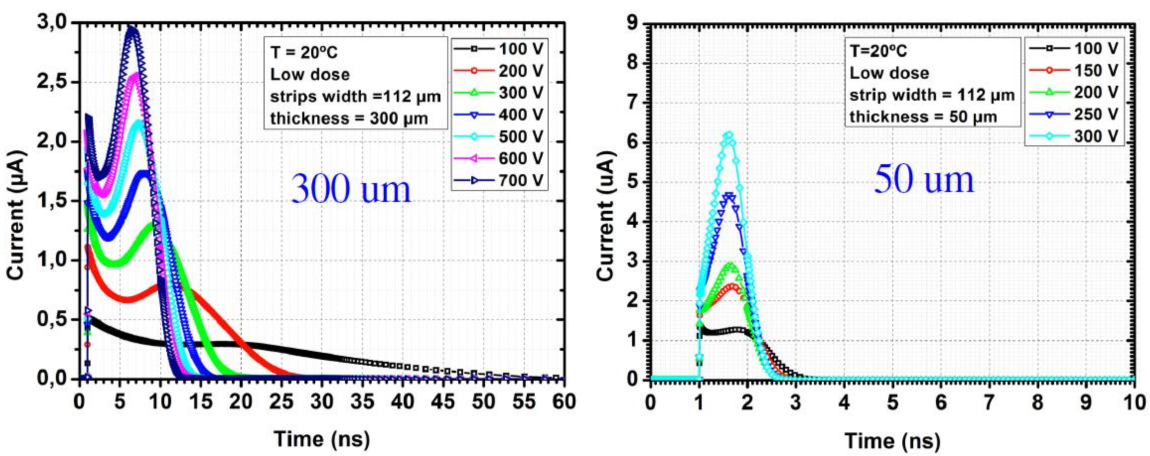
Nominal IP	Voltage	Measured IP	IP efficiency (%)
25 µm	45	103.0 ± 1.3	2,2
	50	91.8 ± 1.3	10,1
	60	69.2 ± 2.4	17,4
15 µm	40	111.9 ± 4.9	14.8
	60	70.2 ± 4.8	29.4
45 µm	120	68.4 ± 4.6	55.1

• Geometric efficiency

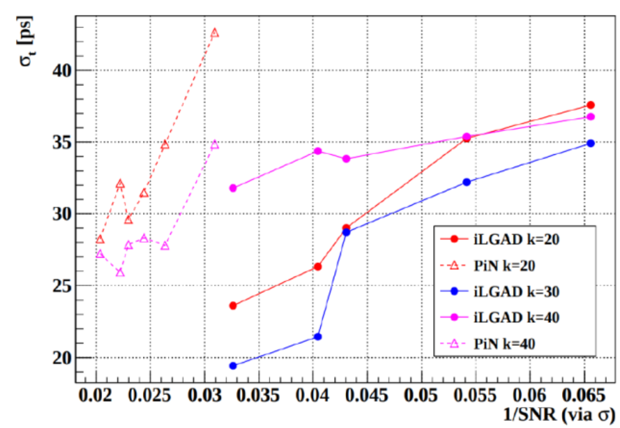
Inter-pad region, i-LGADs



- Approached based on non-segmentation of gain layer
- Double sided process with **NO** possibility for support structures (thin sensors extremely difficult)
- Multiplication layer multiplies carriers
- Two contribution signal, primary electron collection and subsequent multiplication of holes
- Distance between two signals depends on drift time, thinner sensors (<50µm) should be usable for time



- Typical pulse duration ~ 10 – 20 times of equivalent thickness LGAD
- Very good for timing, bad in SNR terms
- Need too go to 50 µm thick devices for any realistic applications



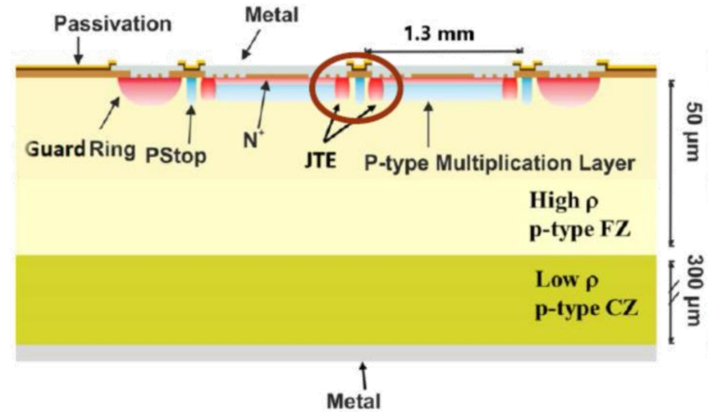
• Inter-pad area

Inactive regions

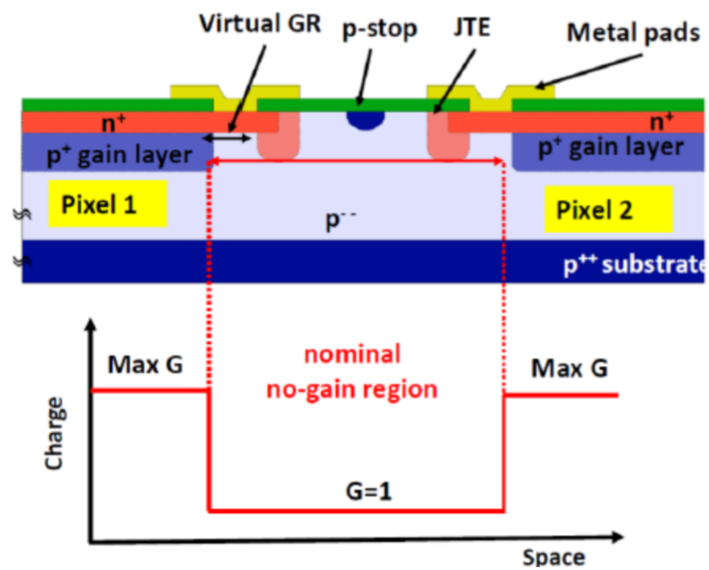
- ✓ High Field region in the gain layer
- ✓ Field needs to be controlled in pad edges where values increase due to geometry
- ✓ Introduction of electrical isolation implant JTE (Junction Termination Extension)
- ✓ Typical JTE geometries introduce 50 – 150 µm inactive area between adjacent gain layers
- ✓ Dead area varies with field (bias voltage) in a non-linear way (see next slide)
- ✓ Overall fill factor reduction at 1mm pads:

JTE size	Fill Factor reduction
50µm	~ 10 %
150µm	~ 30 %

CNM Technology

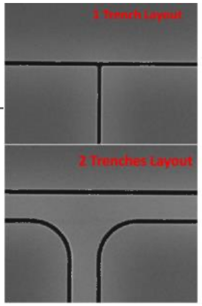


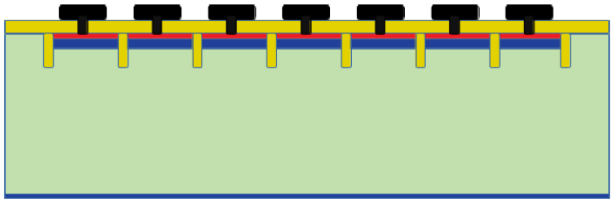
FBK Technology



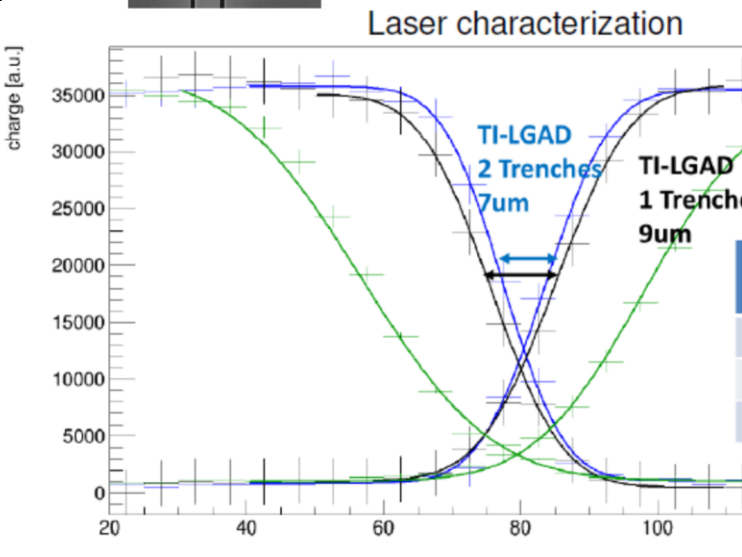
• Inter-pad area

Inter-pad region, Ti-LGADs



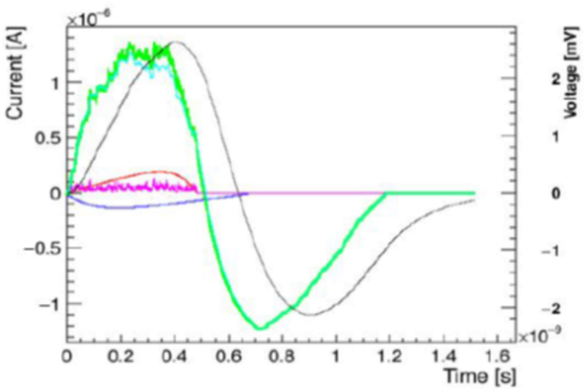


- Approach based on removing JTE completely
- Using trenches as electron diffusion barrier and field containment (JTE and p-stop)
- DRIE trenches comparable to SIPM processes ~ 1μm thick, filled with oxide
- Relatively understood process
- Based on the distance from the edge an opposite polarity signal present on adjacent pad (probably dependent on trench depth)

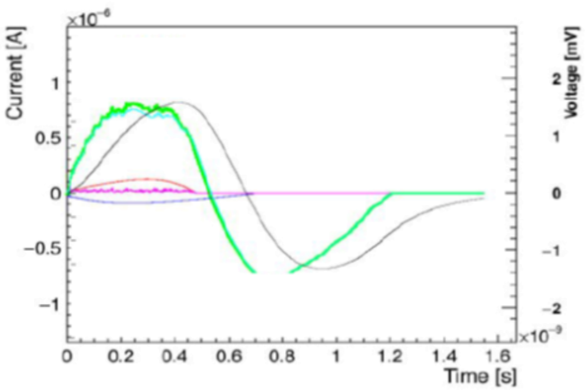


Layout	Effective inter-pad
STD-LGAD	~ 38 um
1 Trench	9 ± 1um
2 Trenches	7 ± 1 um

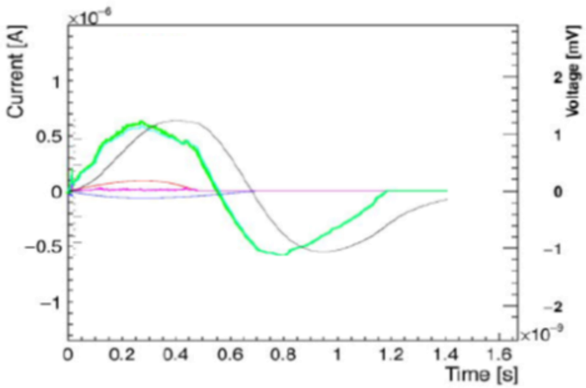
(a) 35 μm from mid gap



(b) 65 μm from mid gap

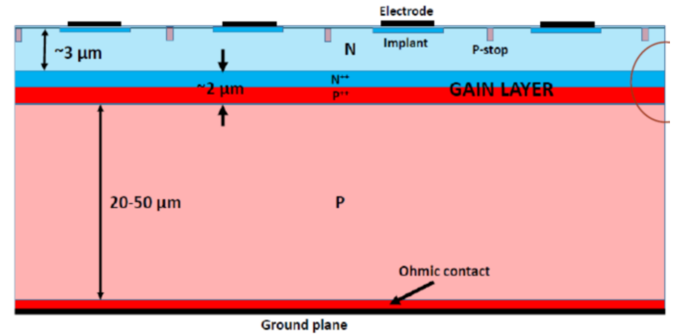


(c) 95 μm from mid gap

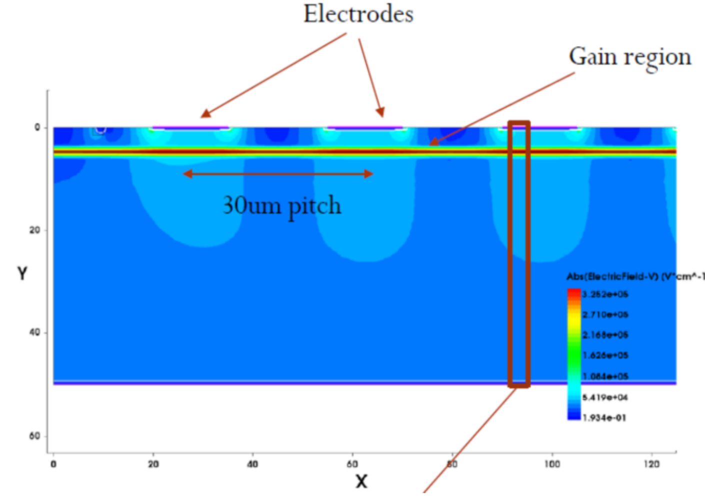


• Inter-pad area

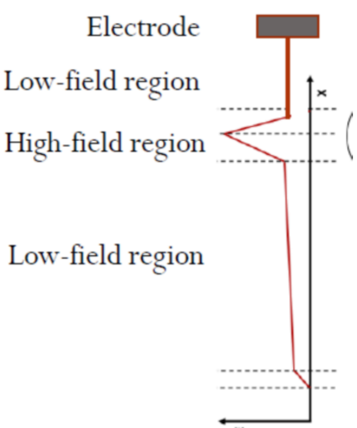
Deep Junction LGADs



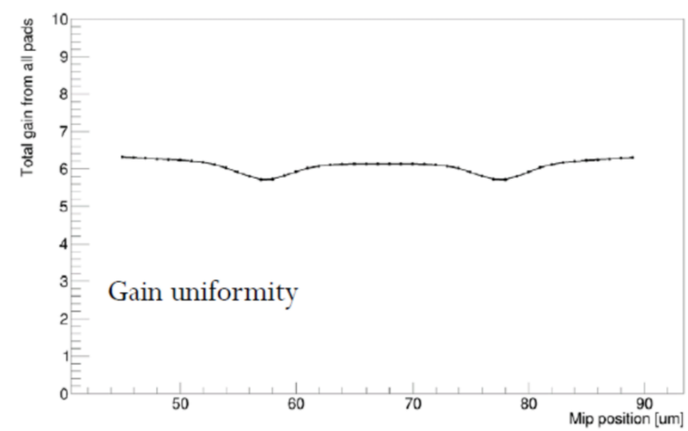
- ➢ Based on the non-segmentation of the gain region
- ➢ Move the gain layer away from the surface and deeper into the substrate
- ➢ Requires not one but two implants in a relatively deep region (~ 5 µm) from surface
- ➢ Top implant has to be lower concentration than deeper gain implants, leading to deposition rather than impanation techniques



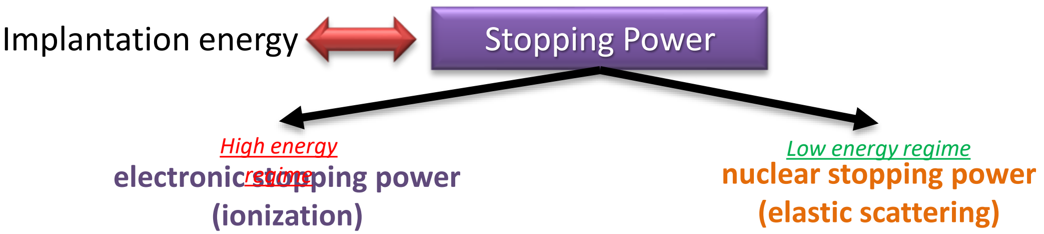
Status and issues



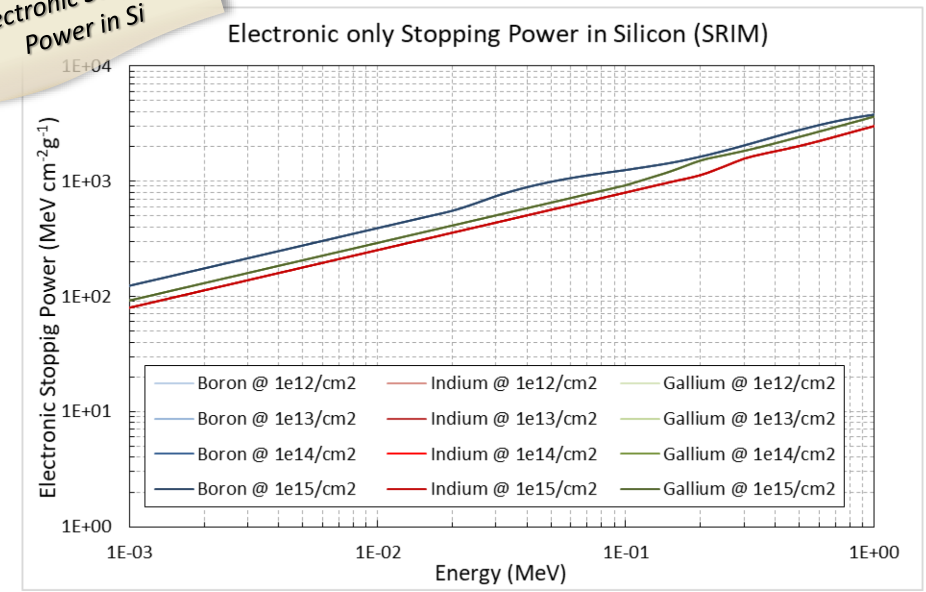
- ➢ Opposite sign signal on adjacent pad
- ➢ Only theoretical simulations from UCSC, BNL will work on a process
- ➢ Susceptible to crosstalk, but dependent probably on gain layer positioning
- ➢ Increase in process complications



•Implantation Parameters – Energy 1



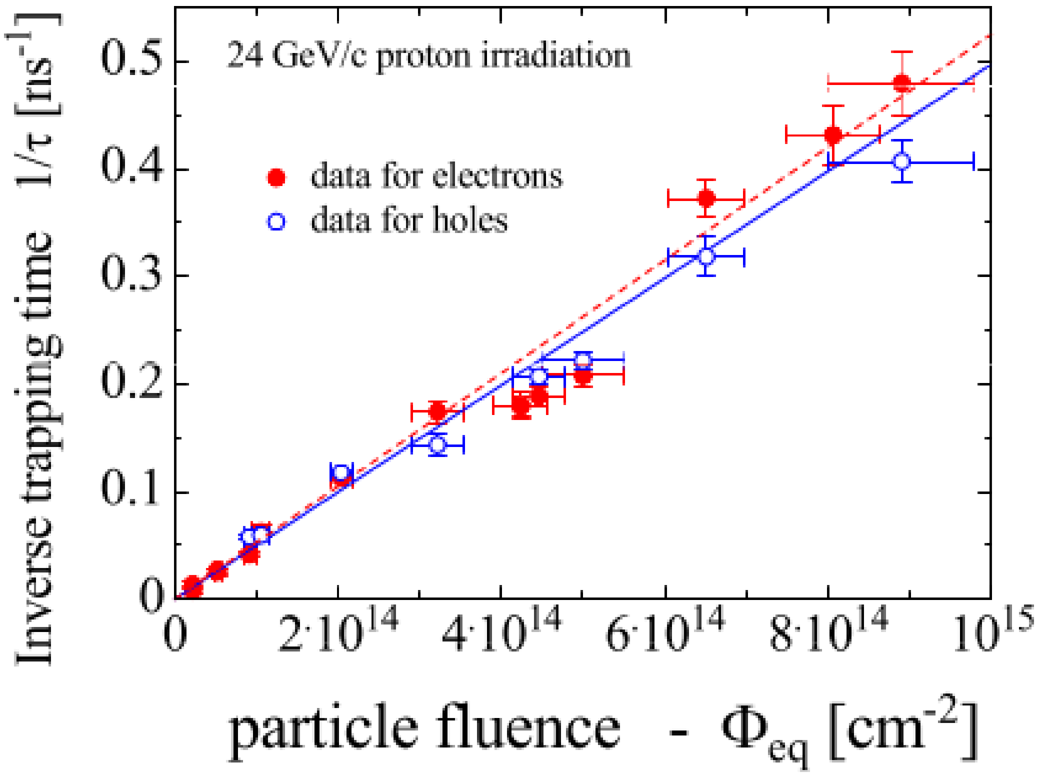
Electronic Stopping Power in Si



Electronic stopping power (ionization) consistency

- ✓ Varies with incident particle dose
- ✓ Typical doses in range of 10^{12} cm^{-2} – 10^{15} cm^{-2}
- ✓ Simulate with:
  - Real time implementation of SRIM (2013 version)
  - Implantation in pure ^{14}Si
  - No delta-ray assumption
  - Four different implantation doses tested (10^{12}, 10^{13}, 10^{14}, 10^{15})
  - Energy range 1 keV – 1MeV
- ✓ No variation for any of the three implants in the dose rate of interest

• Mobility & Trapping



• Mobility & Trapping

N_{eff} – Dynamic Model

Radiation damage modeling		
Constant Damage Terms	Acceptor Introduction	$N_{acc.}^{con.}(t) = g_{c_A} \times \int_0^t \Phi_{eq.}(\tau)\partial\tau$
	Donor Introduction	$N_{don.}^{con.}(t) = g_{c_D} \times \int_0^t \Phi_{eq.}(\tau)\partial\tau$
	Acceptor Removal	$N_{acc.}^{rem.}(t) = f_{c_A} \times N_{eff.}(0)\left(1 - e^{-c_{c_A}\int_0^t \Phi_{eq.}(\tau)\partial\tau}\right)$
	Donor Removal	$N_{don.}^{rem.}(t) = f_{c_D} \times N_{eff.}(0)\left(1 - e^{-c_{c_D}\int_0^t \Phi_{eq.}(\tau)\partial\tau}\right)$
Short term annealing	Acceptor Reduction	$N_{acc.}^{short.}(t_i) = g_A \times \int_{t_{i-1}}^{t_i} \Phi_{eq.}(\tau)\partial\tau \Big/ \delta t \times \frac{\left(1 - e^{-k_a(T_i)\times\delta t}\right)}{k_a(T_i)} + N_{acc.}^{short.}(t_{i-1}) \times e^{-k_a(T_i)\times\delta t}$
Long term annealing	Max Introducible Acceptors	$N_{acc.}^{Max.\,long.}(t_i) = g_Y \times \int_{t_{i-1}}^{t_i} \Phi_{eq.}(\tau)\partial\tau \Big/ \delta t \times \frac{\left(1 - e^{-k_Y(T_i)\times\delta t}\right)}{k_Y(T_i)} + N_{acc.}^{Max.\,long.}(t_{i-1}) \times e^{-k_Y(T_i)\times\delta t}$
	Acceptor Introduction	$N_{acc.}^{long.}(t_i) = N_{acc.}^{long.}(t_{i-1}) + g_Y(T) \times \frac{\int_{t_{i-1}}^{t_i} \Phi_{eq.}(\tau)\partial\tau \big/ \delta t}{k_Y(T)} \times \left(k_Y(T) \times t + e^{-k_Y(T)t} - 1\right) + N_{acc.}^{Max.\,long.}(t_i) \times \left(1 - e^{-k_Y(T)t}\right)$