Technology and Instrumentation In Particle Physics
TIPP - 2021

Comprehensive technology study of radiation hard LGADs

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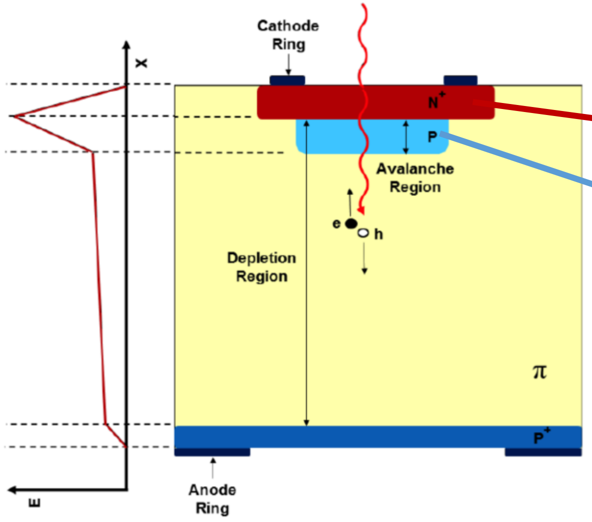
•Overview

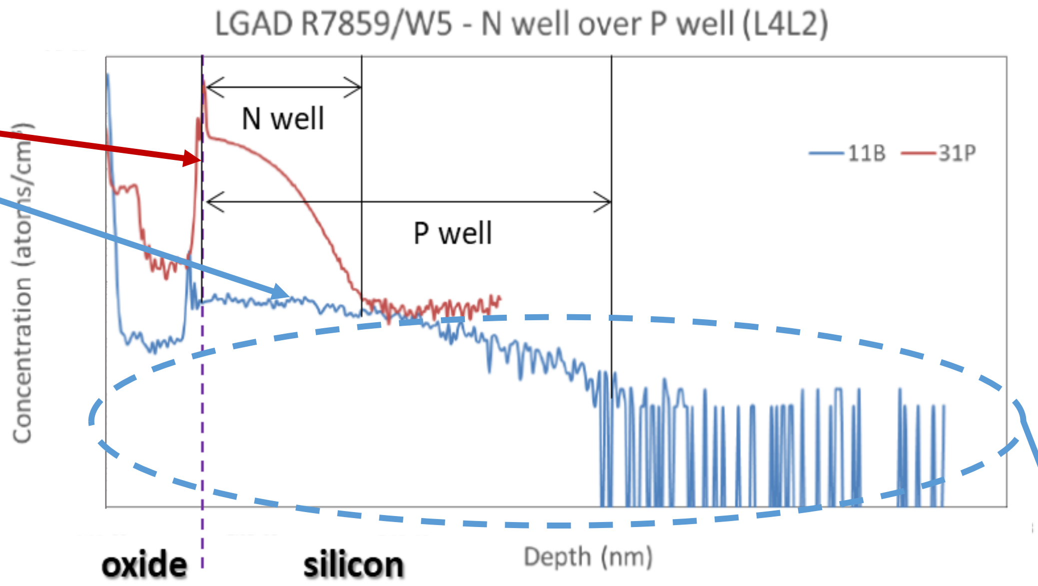
- *Introduction*
- *Radiation effects*
- *Active Gain Layer – Act I*
- *Effective Gain – Act II*
- *Collected Charge – Act II*
- *Comparative studies*
- *Conclusions*

3 complementary methods of radiation hardness evaluation

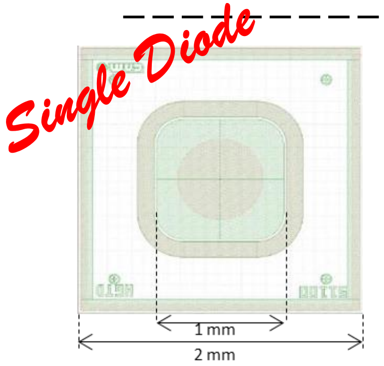
•Introduction – LGAD Technology

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





- ✓ 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

Standard Boron
Boron + Carbon Spray
Gallium

•Introduction – Use in HEP

ATLAS HGTD

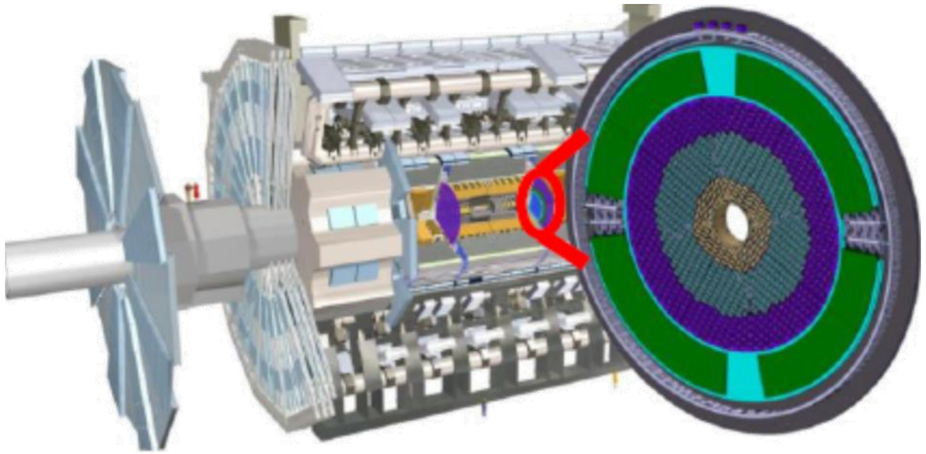
See Irena's talk : link

Sensors

- 15 x 30 LGAD arrays of 1.3 x 1.3 mm^2
  - 10% max estimated occupancy (120 mm radius)
  - Reduced (~ 20) μm inter-pad regions
  - Low sensor capacitance (~2pf)
- Operation temperature -30 ^oC (CO_2 cooling)
- **σ_t = 35 – 70 psec per hit**
- **Radiation tolerance to $2.5 \cdot 10^{15}$ n_{eq}/cm^2**

Geometry

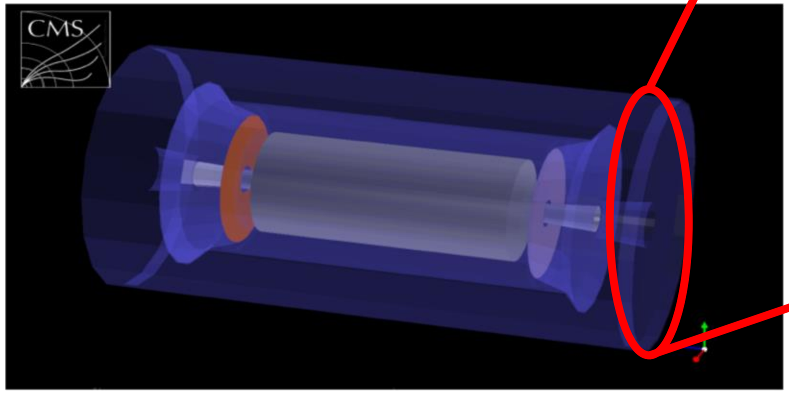
- 2 disks per side, 2 sensor layers per disk
- $2.4 < |\eta| < 4.0$, 12 cm < R < 64 cm

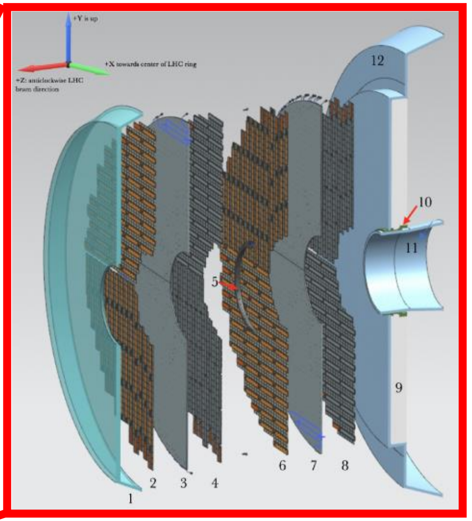


CMS MDT

Link to TDR: link

- ThiN LYSO Crystal + SiPM layer in the barrel (BTL), LGADs in the end caps (ETL)
- **30 psec MIP timing up to $|\eta|<3.0$** (LGADs at $1.6 < |\eta| < 3.0$)
- **Radiation requirements up to $2 \cdot 10^{15}$ n_{eq}/cm^2 for LGADs**
- 50 μm thick sensors on 300 μm SoI wafers, slim edge design
- Operation at -30 ^oC





•Radiation Effects

Four main disruptive mechanisms for irradiated LGADs :

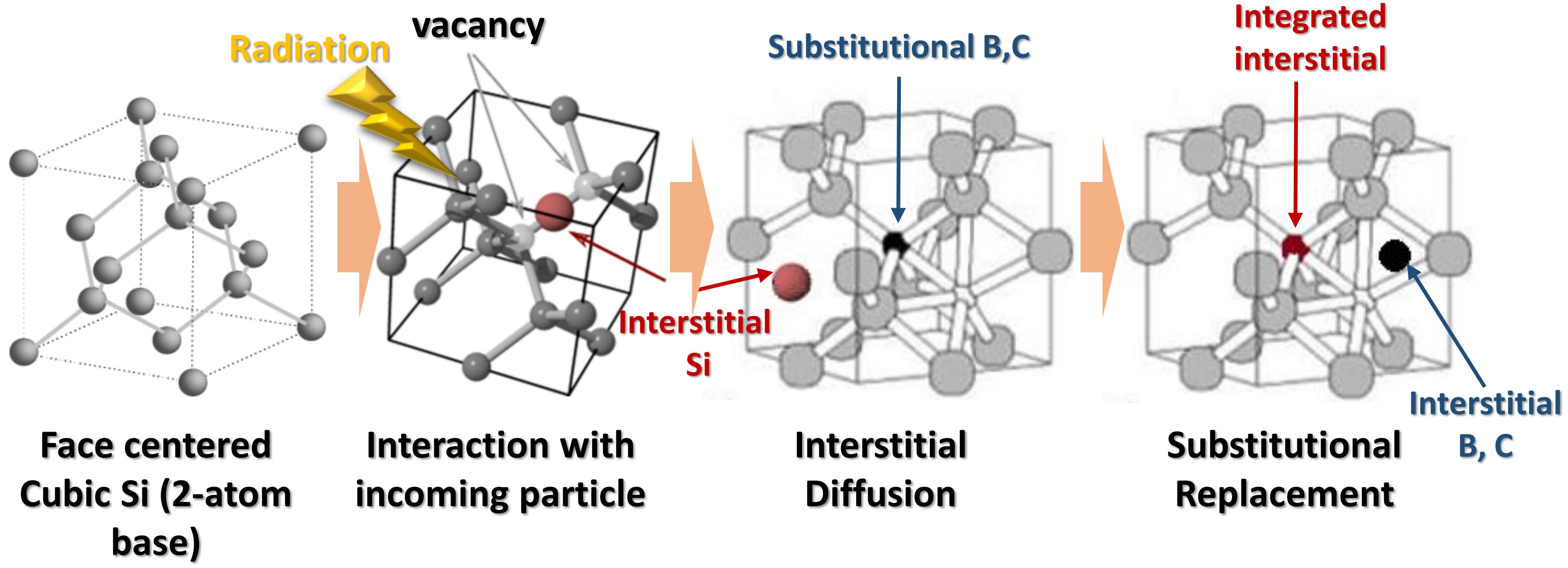
Substrate

1. Reduced primary charges induced in substrate (reduced lifetime) → $1/\tau = \beta \times \Phi$
2. Acceptor re-introduction rate → $N_{Act.} = G \times \Phi$

The ROSE collaboration

Gain Layer

3. Reduced active implant in gain layer through acceptor removal → $N_{G_\Phi} = N_{G_0} e^{-c\Phi}$
4. Reduced mobility within gain layer through trapping → Gain reduction larger than anticipated from acceptor removal (~factor of 3)



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

•Part I - The Active Gain Layer

Substrate

1. Reduced primary charges induced in substrate (reduced lifetime) → $1/\tau = \beta \times \Phi$
2. Acceptor re-introduction rate → $N_{Act.} = G \times \Phi$

Gain Layer

3. **Reduced active implant in gain layer through acceptor removal** → $N_{G_\Phi} = N_{G_0} e^{-c\Phi}$
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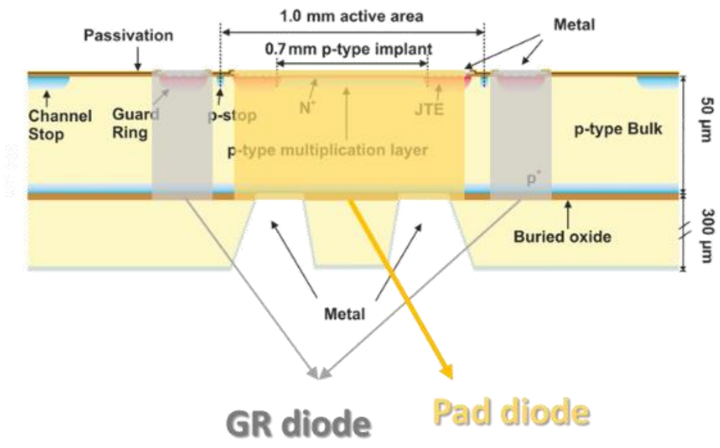
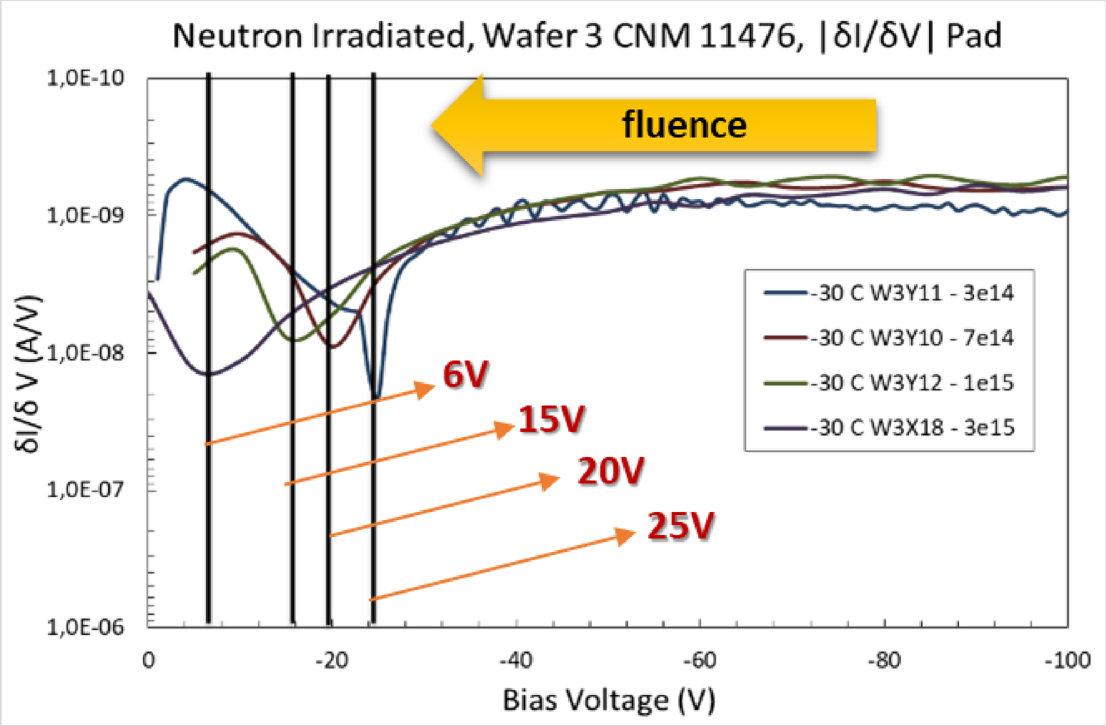
•The Derive and Fit Method - I

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 -10ºC, -20ºC & -30ºC





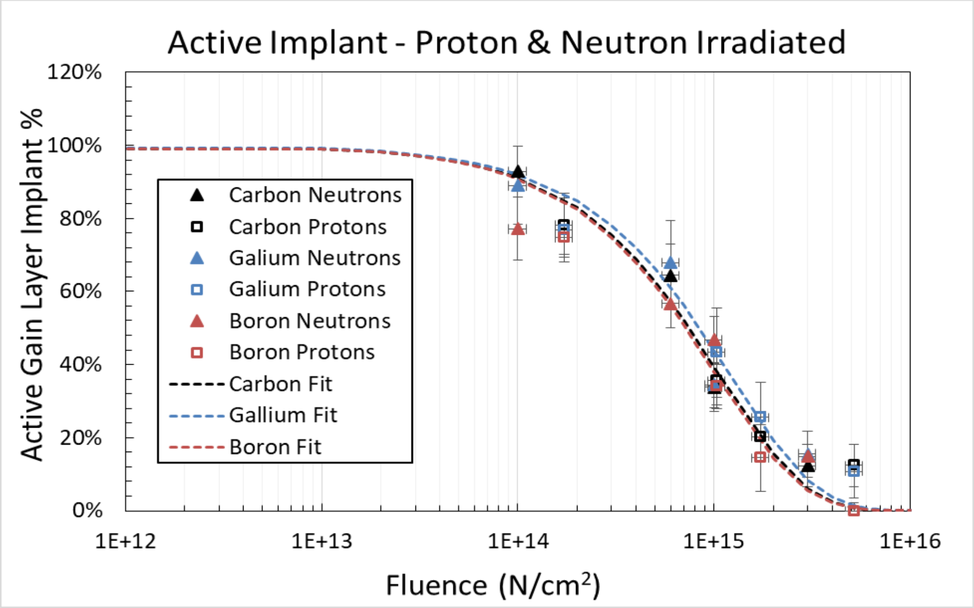
- Independent Gaussian fit for temperature
- Uncertainties estimated from propagation on fit sigma
- Fluences up to $3 \cdot 10^{15}$ n_{eq}/cm^2 in p^+ and n^0

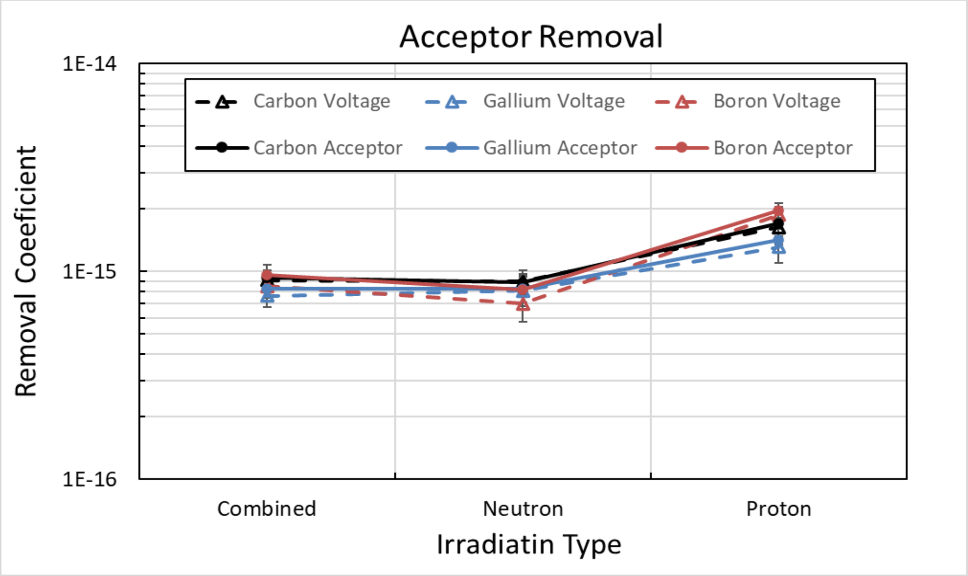
$$V_d = \frac{\sum_{T=-10\,^oC}^{-30\,^oC} V_{d,T_i}}{n_T}$$

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

Average of fit sigma ($V_{d,sys}$); Standard deviation of V_d ($V_{d,stat}$)

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

•Part II - Effective Gain

Substrate

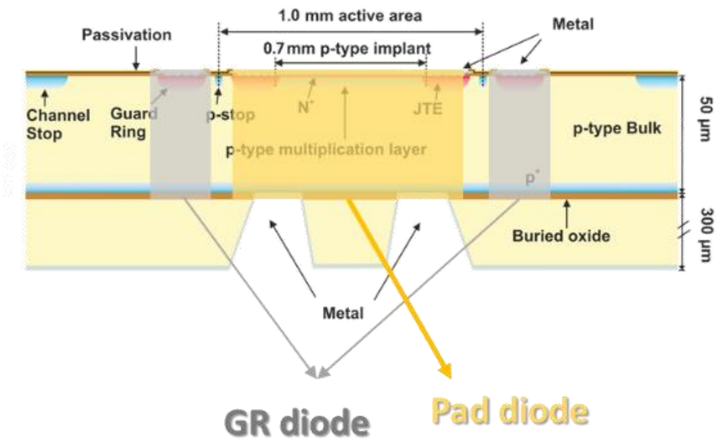
1. Reduced primary charges induced in substrate (reduced lifetime) → $1/\tau = \beta \times \Phi$
2. Acceptor re-introduction rate → $N_{Act.} = G \times \Phi$

Gain Layer

3. Reduced active implant in gain layer through acceptor removal → $N_{G_\Phi} = N_{G_0} \mathrm{e}^{-c\Phi}$
4. Reduced mobility within gain layer through trapping → Gain reduction larger than anticipated from acceptor removal (~factor of 3)

•GR Vs Pad Method - I

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



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

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

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 →

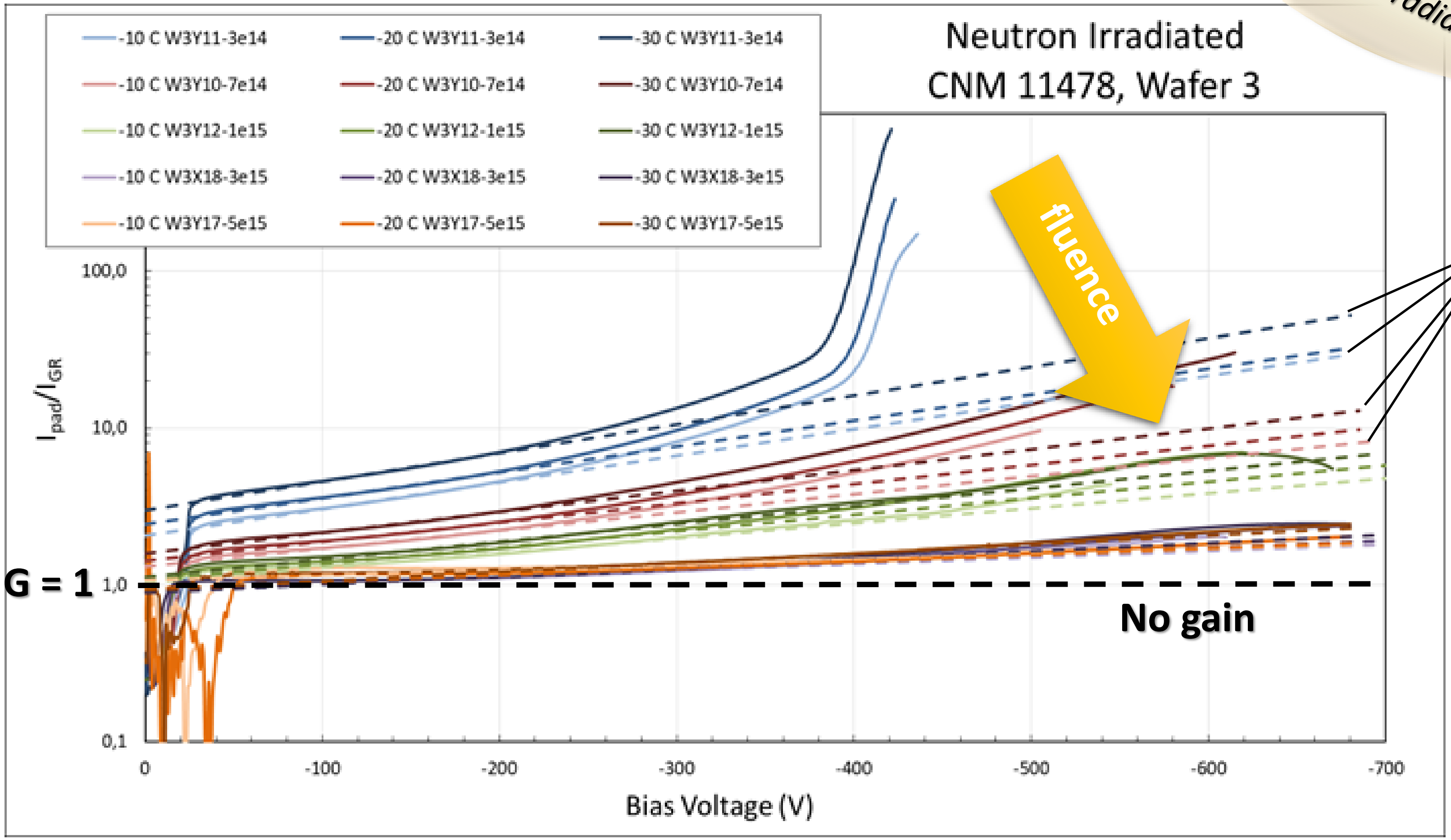
$$\frac{f(\Phi)}{f(\Phi = 0)} \sim G(e^{V}, T, \Phi)$$

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

•GR Vs Pad Method - II

- ✓ 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

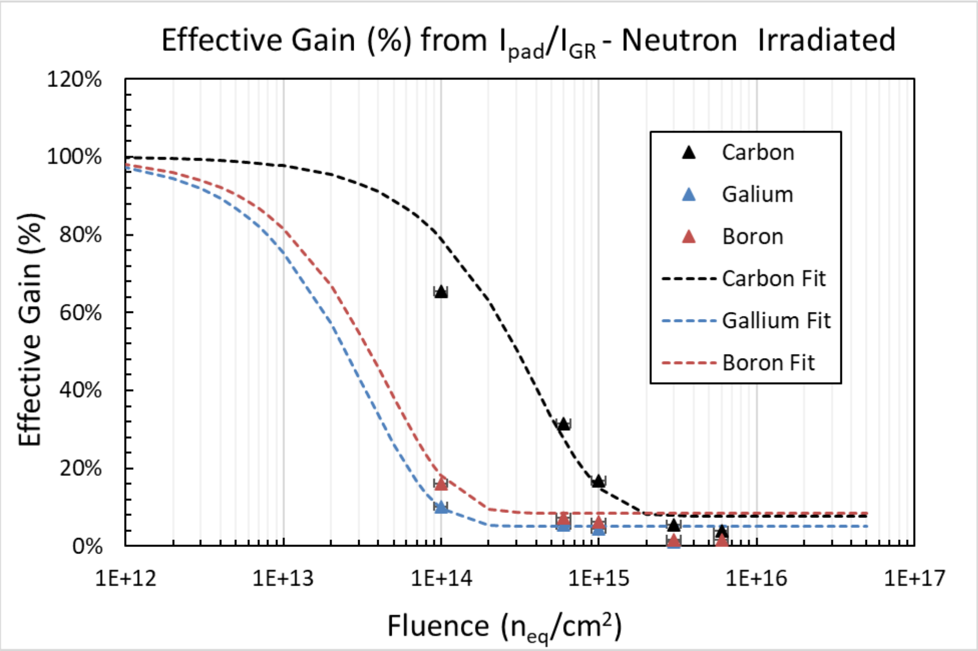
Repeat for all implants and radiation types

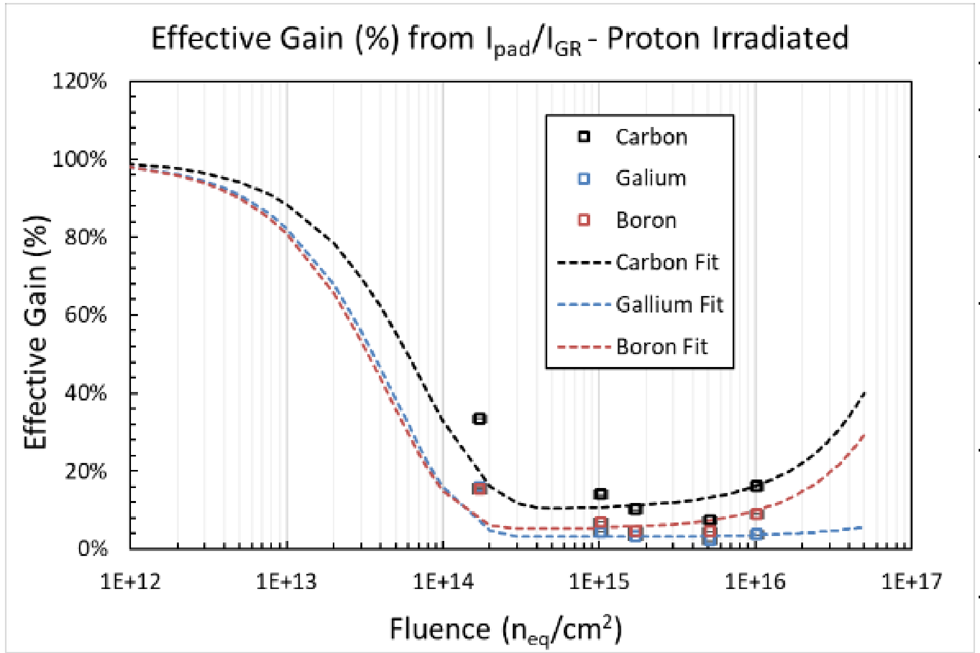


$$I_{pad}/I_{GR} = m \times a^{V}$$

× 6

•GR Vs Pad Method - III





Gain Reduction Coefficient	
Irrad. Type	$C \pm \delta C$
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^+	$(2.25 \pm 0.28) \times 10^{-14}$

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

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**

•Part III - The Actual Gain

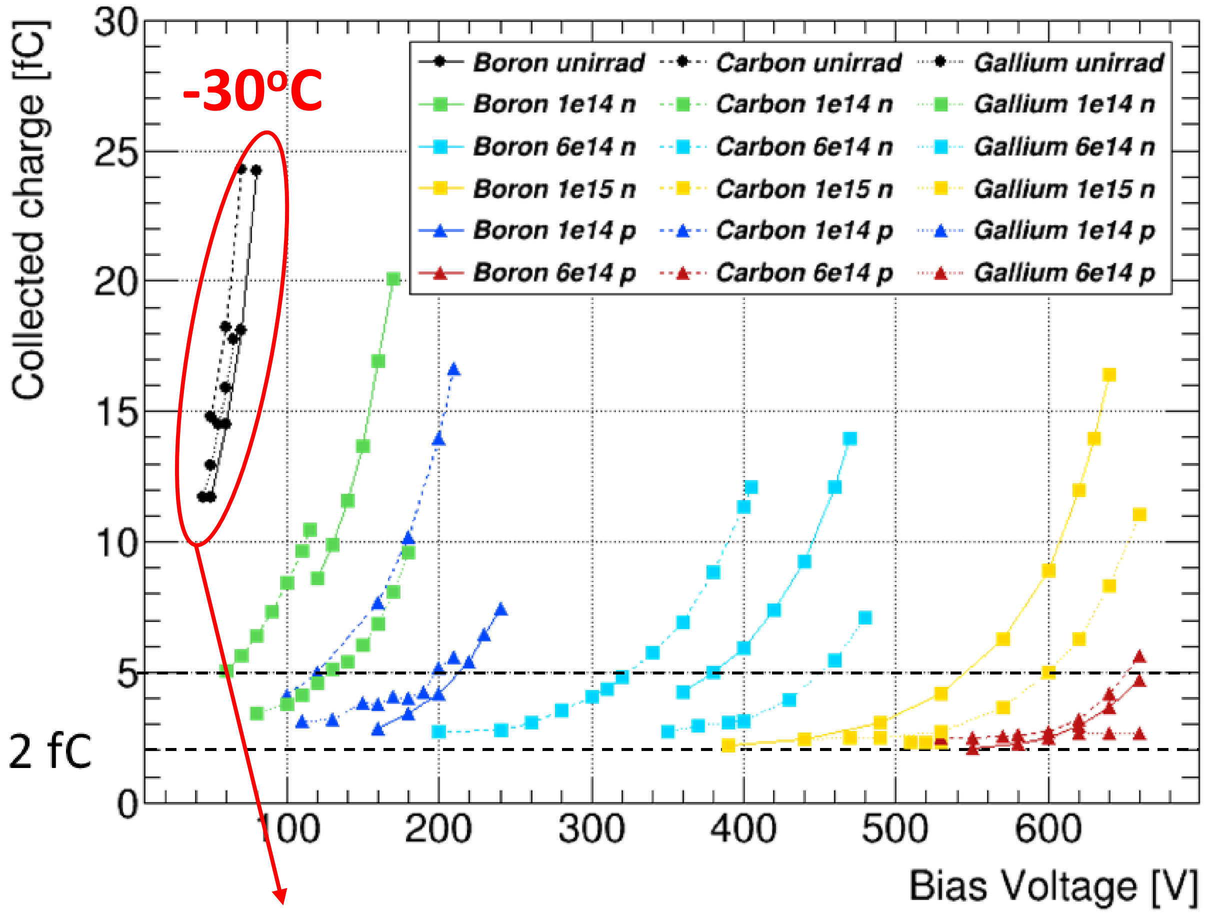
Substrate

1. Reduced primary charges induced in substrate (reduced lifetime) → $1/_{\tau} = \beta \times \Phi$
2. Acceptor re-introduction rate → $N_{Act.} = G \times \Phi$

Gain Layer

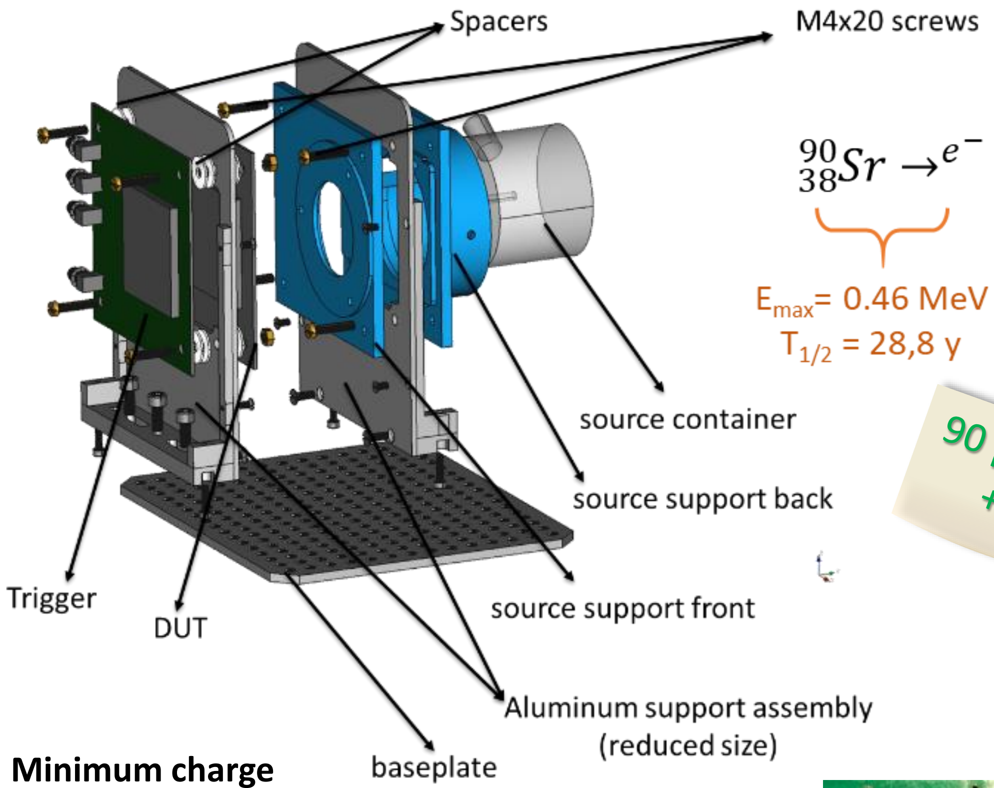
3. Reduced active implant in gain layer through acceptor removal → $N_{G_{\Phi}} = N_{G_0} \mathrm{e}^{-c\Phi}$
4. Reduced mobility within gain layer through trapping → Gain reduction larger than anticipated from acceptor removal (~factor of 3)

•Collected Charge - I



Minimum charge for good timing

5 σ from noise

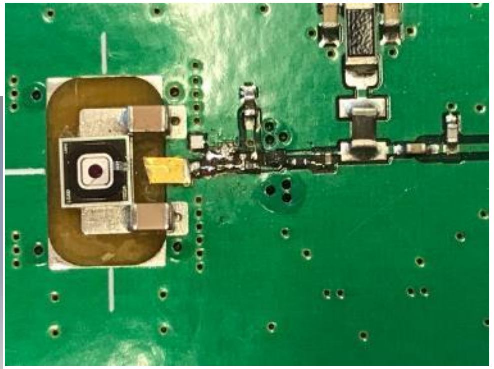


$^{90}_{38}Sr \rightarrow^{e^-} {}^{90}_{39}Y \rightarrow^{e^-} {}^{90}_{40}Zr$

E_{max}= 0.46 MeV
$T_{1/2}$ = 28,8 y

E_{max}= 2.28 MeV
$T_{1/2}$ = 64 h

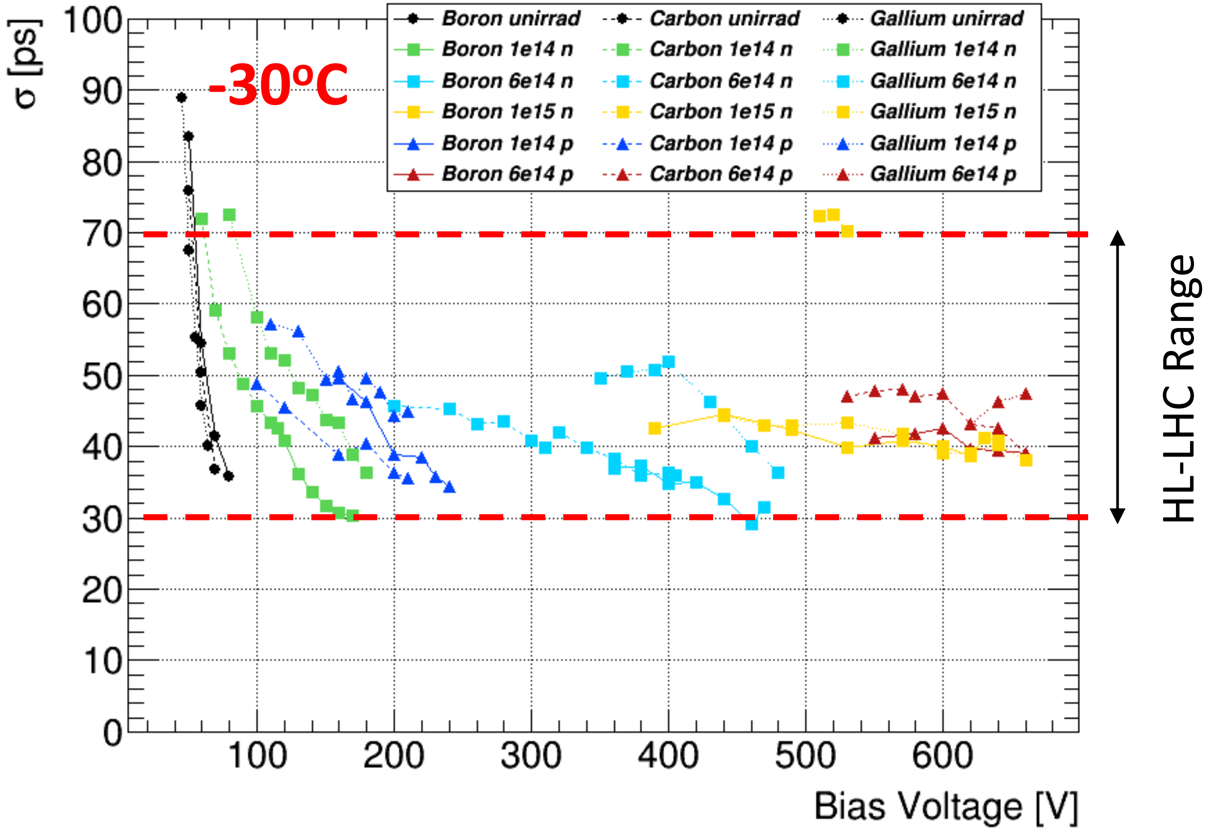
90 μm Al absorber
+ 500 μm Si



- Before irradiation all implants yield exactly same gain – charge
- With fluence increase:
  - Carbonated sensors require 20% less bias for same gain
  - Gallium implanted sensors require 20% more bias for same gain

- High frequency SiGe (~2GHz) amplifier
- Mean sensor + amplifier noise < 1.5 mV
- 5000 recorded events per point

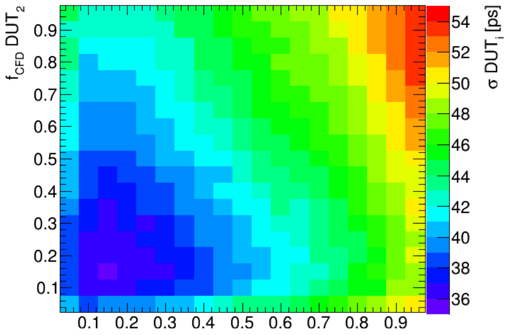
•Collected Charge - II

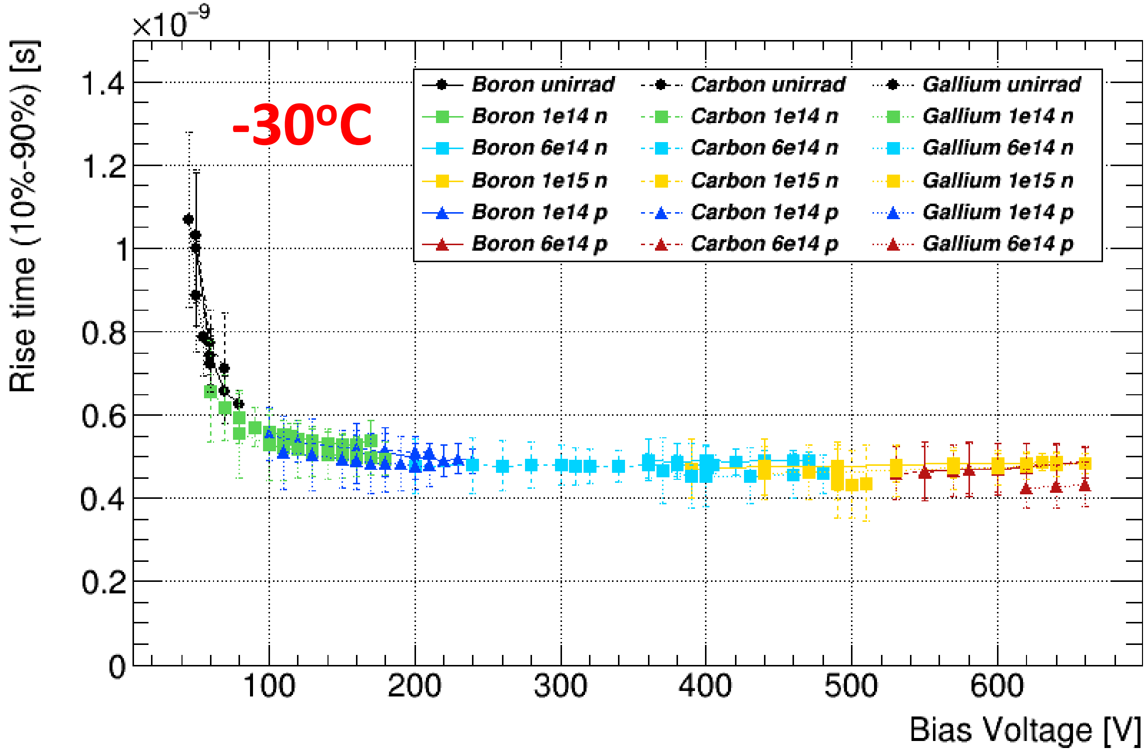


CFD Level optimization

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

2D optimization plot – 0.5% binning





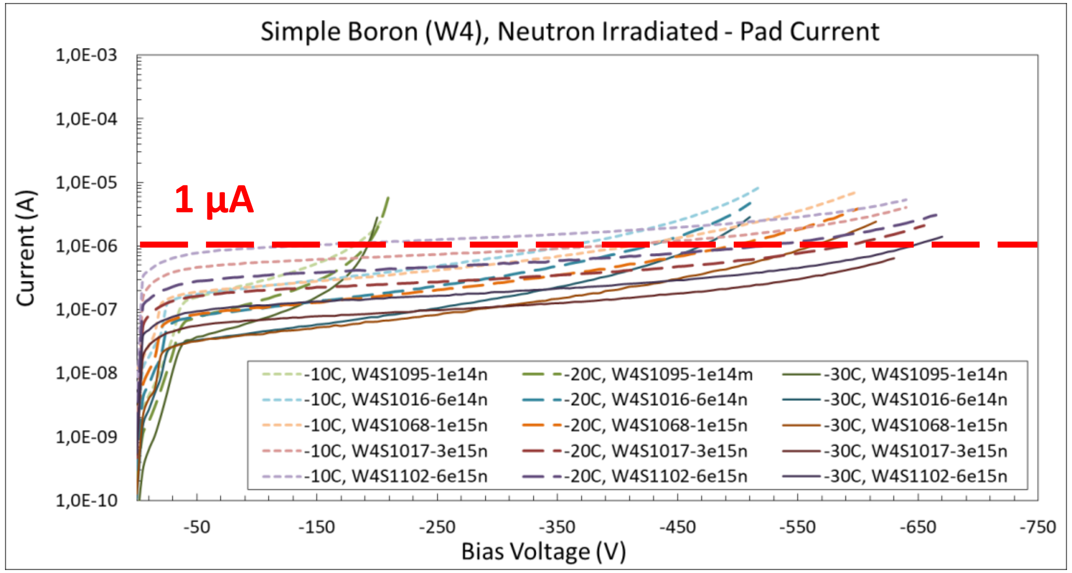
Time Resolution: $\sigma^2_{tot} = \sigma^2_{timewalk} + \sigma^2_{jitter} + \sigma^2_{conversion} + \sigma^2_{Clock}$

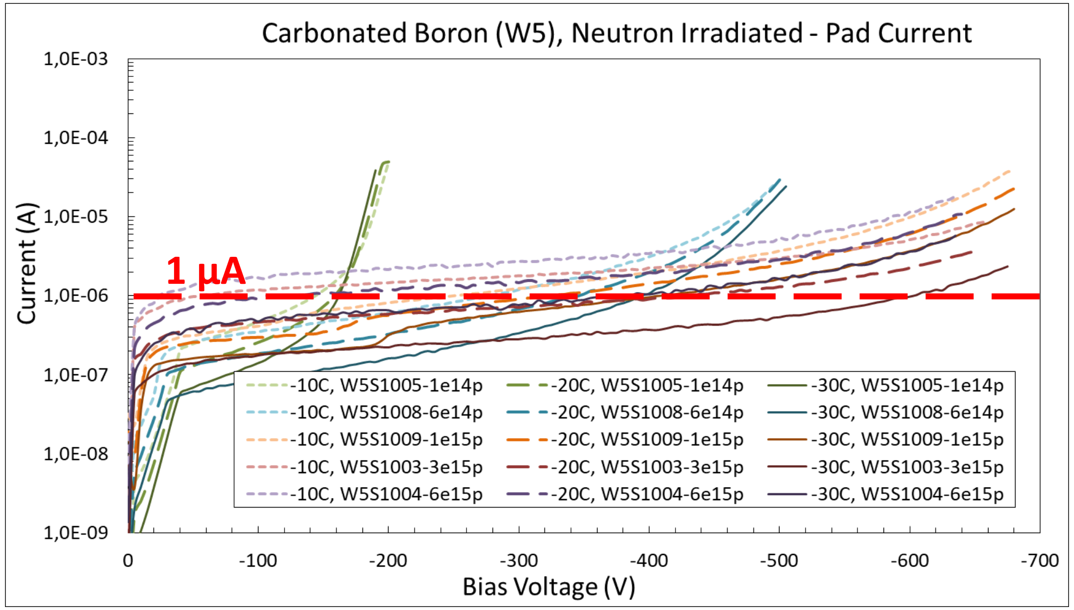
- $\sigma^2_{timewalk}$: $\sigma^2_{Dist.} + \sigma^2_{Landau}$
- σ^2_{jitter}: $\left(\frac{t_{rise}}{S/N}\right)^2$
- $\sigma^2_{conversion}$: $\left(\frac{TDC_{bin}}{\sqrt{12}}\right)^2$
- σ^2_{Clock}: *Fixed Term ~ 5-7 psec*

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

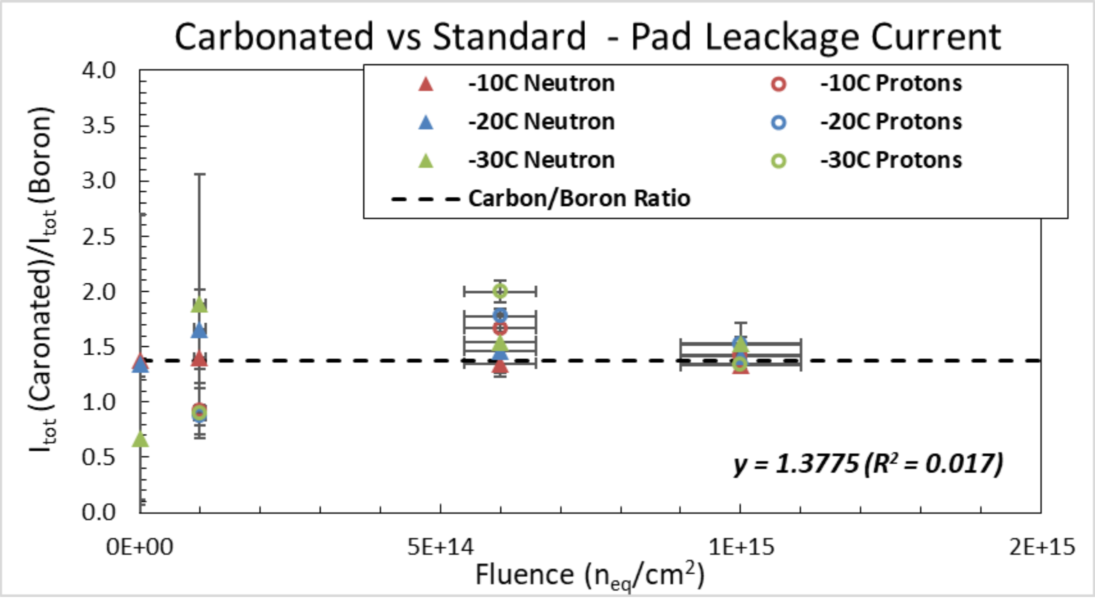
Gkougkousis V., RD50 Workshop Talk, June 2020: link

•Comparative Studies I – Leakage Current



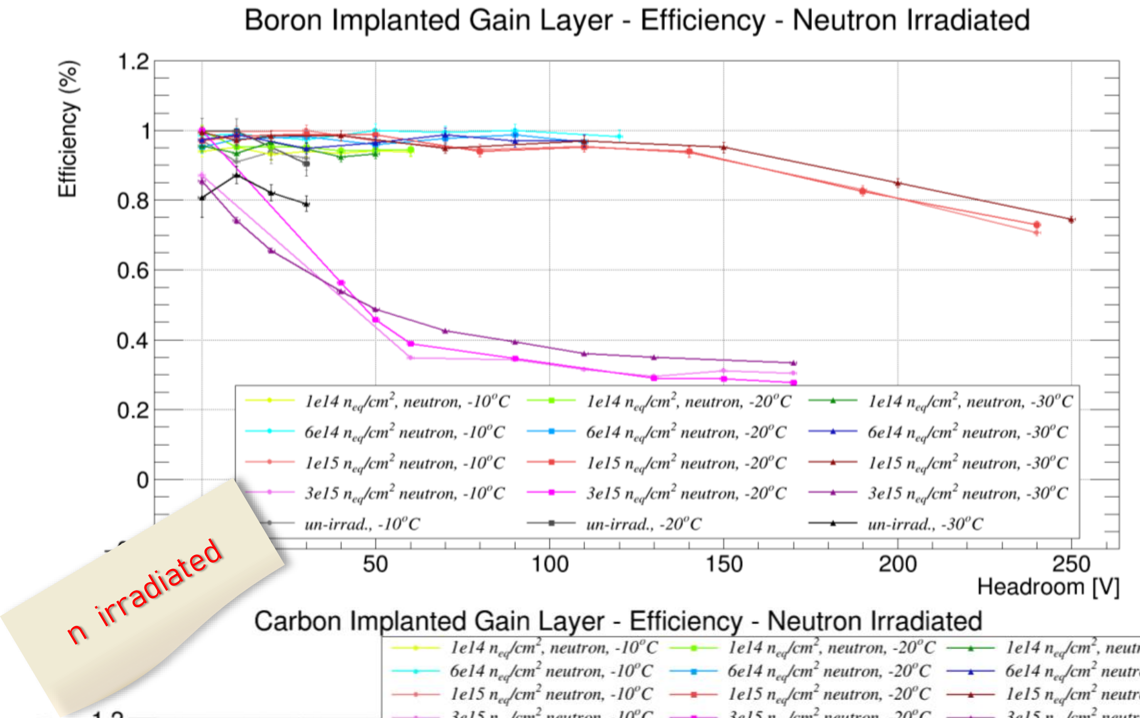


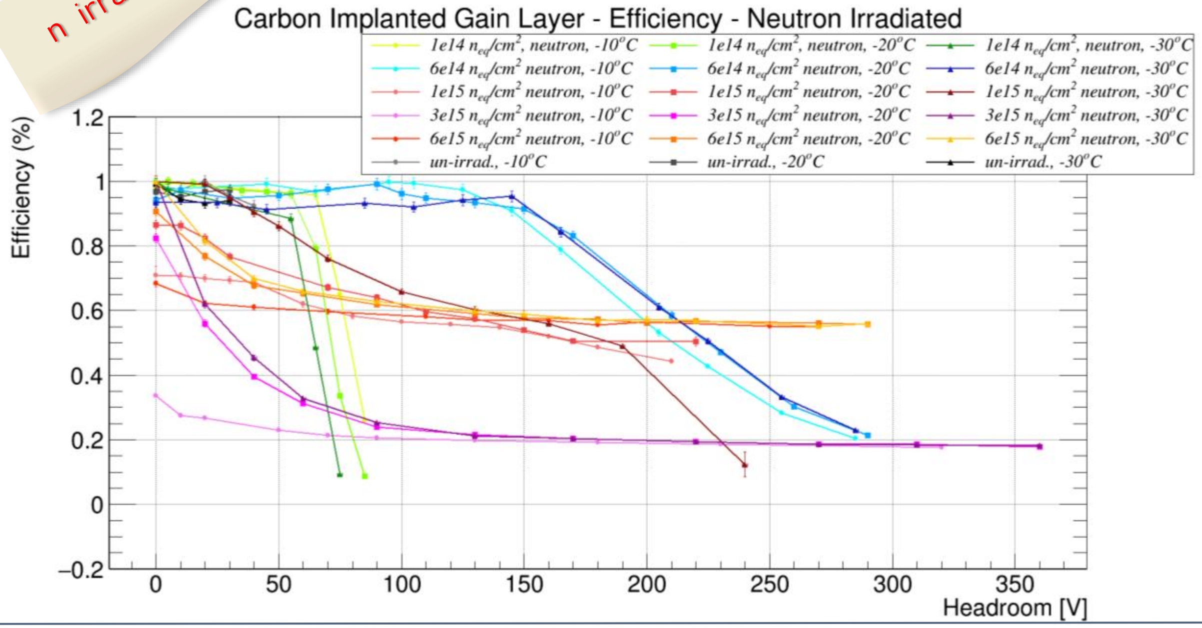
- (I_C/I_B) presents a 33 % increase
- Established though fits on non-gain regions
- Behaviour unchanged up to 1e15 n_{eq}/cm^2 in proton and neutron irradiated
- Consistent behavior with temperature (-30ºC, -20ºC, -10ºC)
- Leakage current increase in Gallium implanted samples but effect traced back to process issues



•Comparative Studies II – Efficiency vs Headroom

Gkougkousis V. , RD50 Workshop, November 2020: [link]

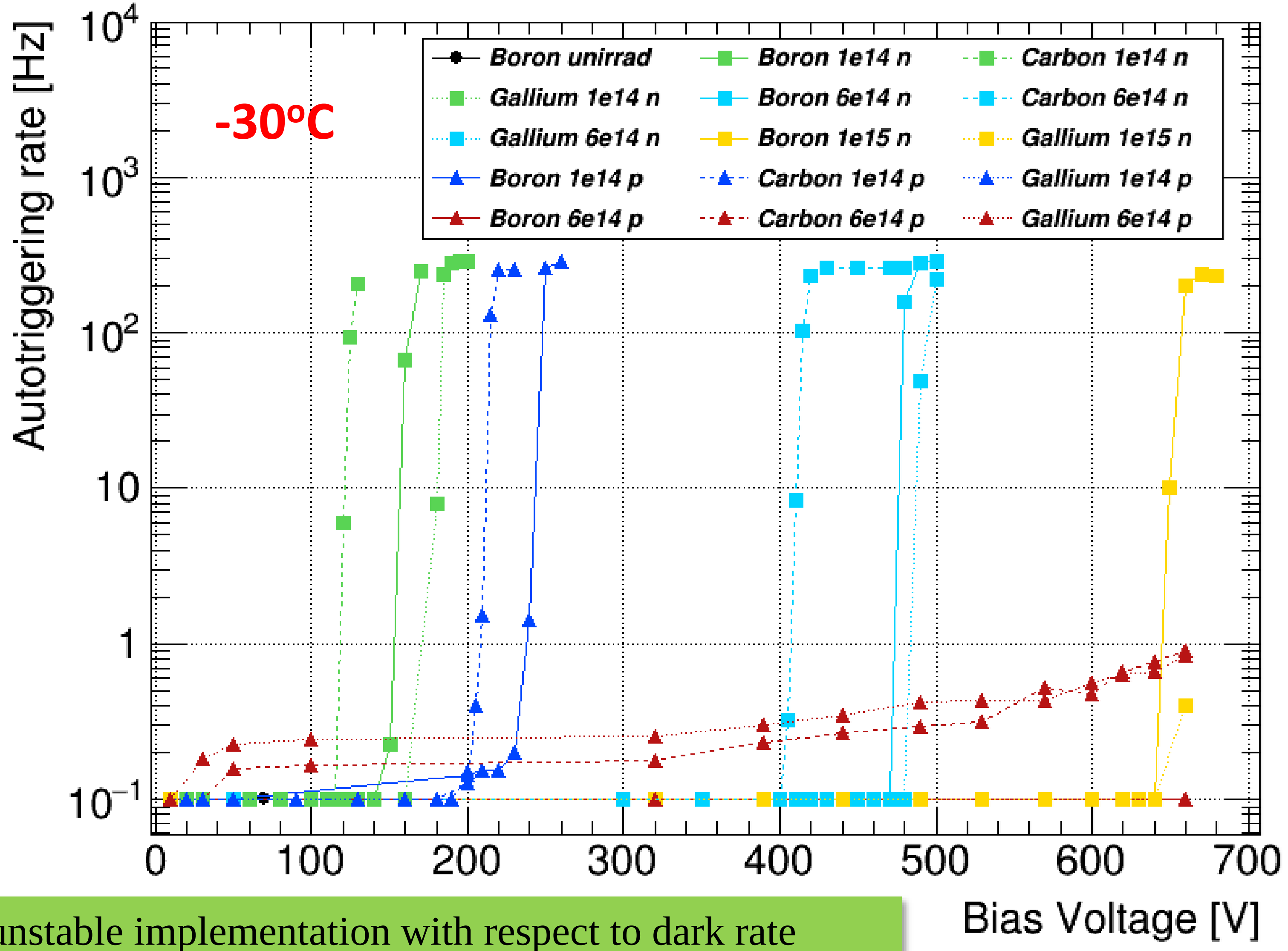




Headroom = V_{max} - $V_{bias\ at\ 100\%\ efficiency}$

- ~100 % efficiency for Carbon + Boron for 1e15 n_{eq}/cm^2 at neutron irradiation
- ~ 100 % efficiency at 1e15 n_{eq}/cm^2 for Boron only sensors at proton irradiation
- Boron only at 3e15 n_{eq}/cm^2 neutron is close to a 100 %, but more validation points needed
- Boron only sensors provide larger headroom at 100 % efficiency that Boron + Carbon combination
- In best case scenario (boron at 3e15 n_{eq}/cm^2 neutrons) no safety factor available

•Comparative Studies II - Stability

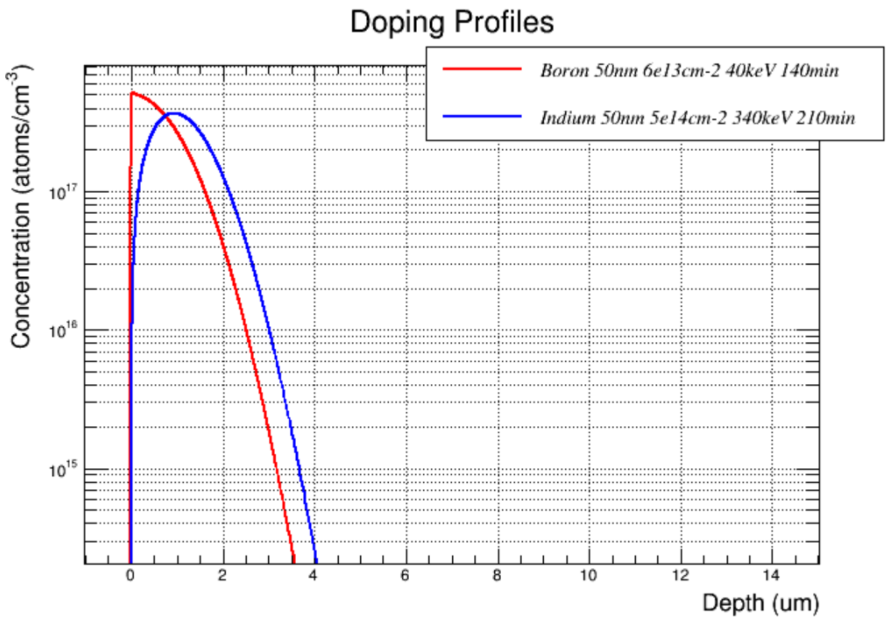


- ✓ Carbon presents the most unstable implementation with respect to dark rate
- ✓ Boron is the better solution across the board with higher stability points

•Outlook – Lithium, Indium

Gkougkousis V. , 16th Trento Workshop (2021): link

- Indium doped gain layers
  - No acceptor removal improvement anticipated
  - Idea from thin solar cell community, (D.J. Paez et. al., link) and space applications
  - Demonstrated to have larger radiation resistance in electron radiation
  - Because of higher atomic mass, should be less mobile (in theory, practice will be different….)



Boron **50 nm screen oxide, 6e13 cm^{-2} at 40 keV with 140 min diffusion time**

Indium **50nm screen oxide 5e14 cm^{-2} at 340 keV with 210 min diffusion time**

- 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)

RD50 founded Project: RD50-2021-03

•Conclusions

- 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^{o}C, -20^{o}C, 30^{o}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

•Overview

Introduction

- LGAD Technology
- HEP Applications – ATLAS & CMS

Radiation effects

- Primary Mechanisms
- Acceptor Removal

Gain Layer Depletion

- The Derive & Fit method
- Gain layer de-activation

Gain Extraction

- The GR vs Pad method
- Removal Coefficients and substrate re-introduction rates

Collected Charge

- Charged Particle measurements
- Performance after neutron-proton irradiation
- Gain modelisation

3 complementary methods of radiation hardness evaluation

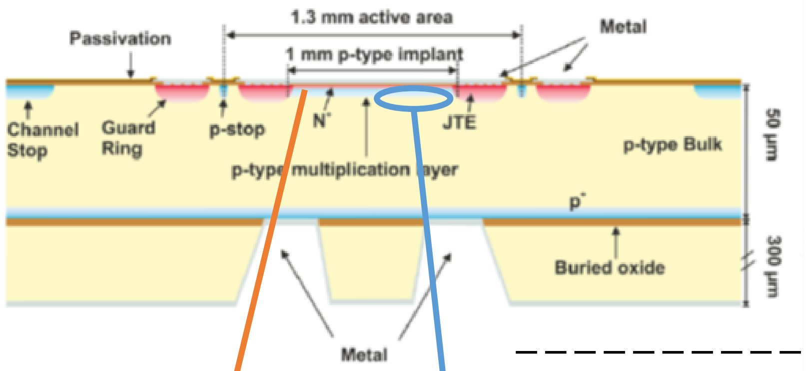
Comparative studies

- 3-method evaluation
- Leakage current across all spices
- Efficiency studies in different spices
- Stability across different implants

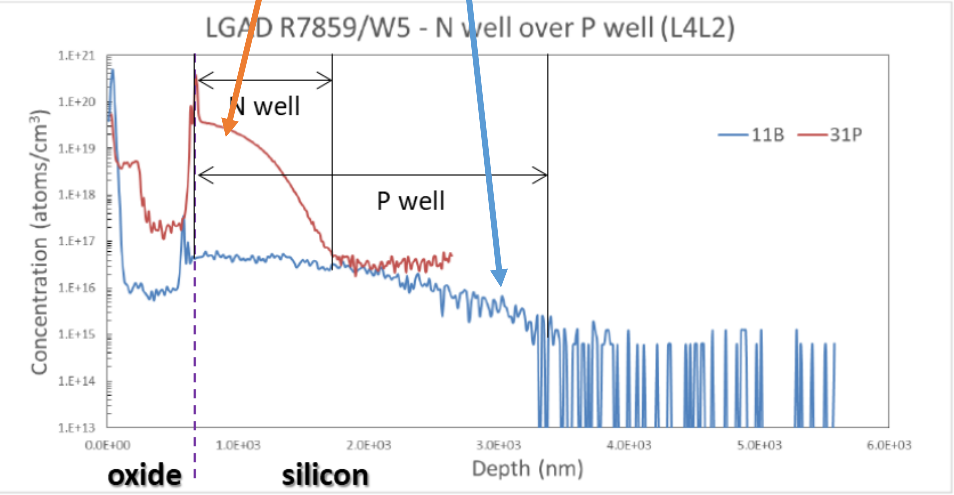
Conclusions

- Lithium – Indium
- Conclusions and Outlook

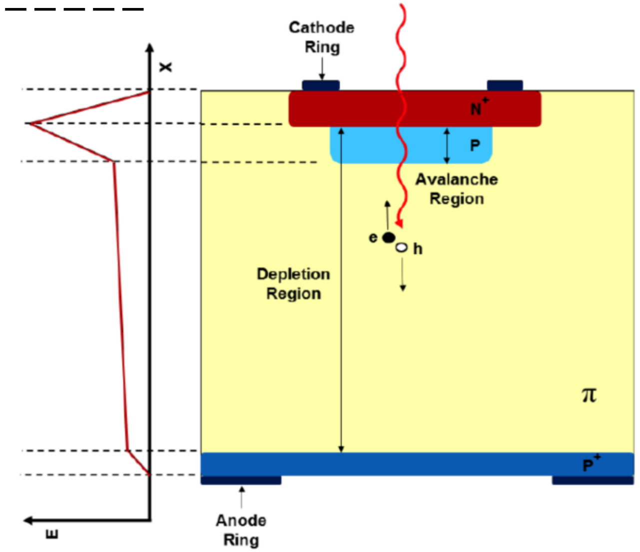
•Introduction – LGAD Technology

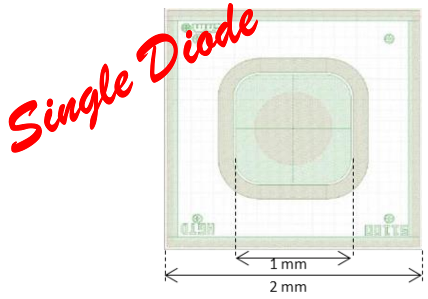


- ✓ Invented at CNM, initially considered for tracking by IFAE, proposed for timing by UCSC
- ✓ Secondary p implant under collection electrode introducing moderate gain (10 -50)
- ✓ Up to 35 µm thickness on SoI or wafer to wafer bonding (typically 50 µm)
- ✓ HPK, CNM, FBK, MiCRON, BNL (USA), NDL (China)



- ✓ 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

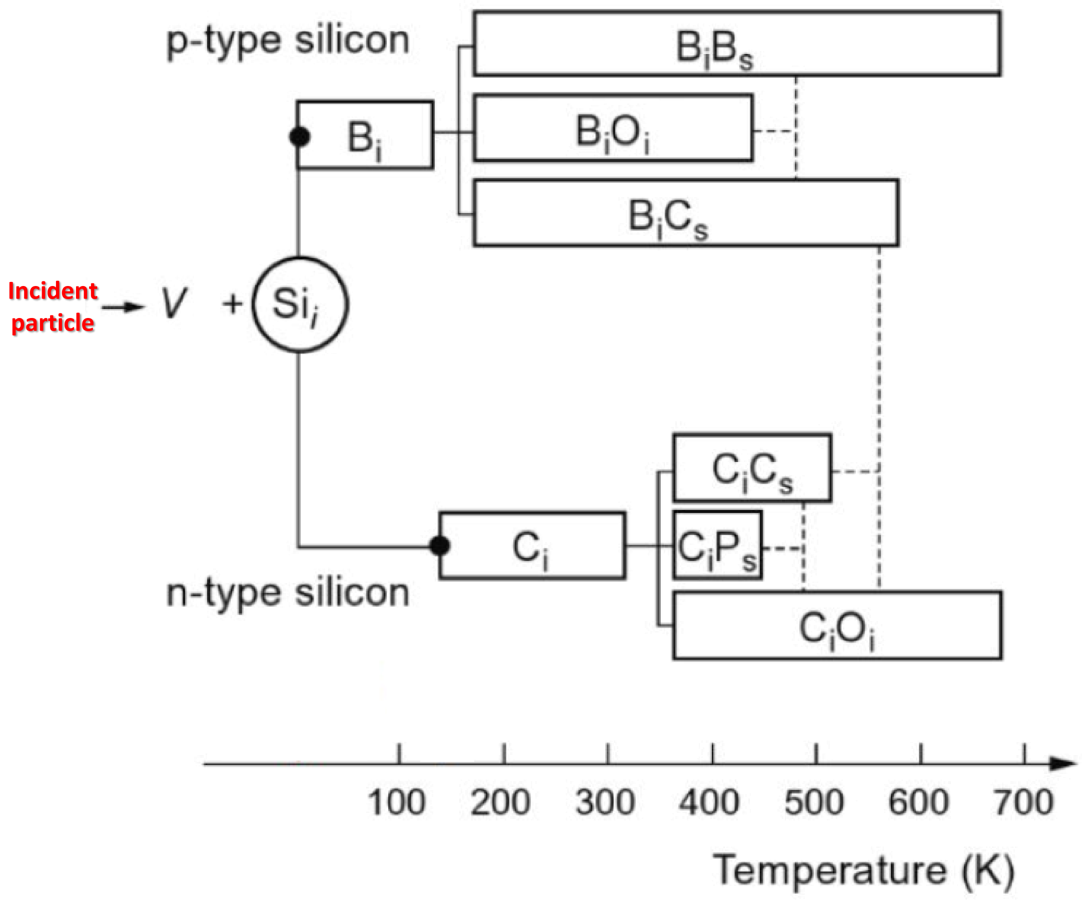




- ➢ 4” Si-on-Si wafers (High Resistivity ~2 kΩ•cm)
- ➢ 50 µm thickness on 250 µm support wafer
- ➢ Different implantation species
- ➢ Single diodes of active area 0.7 x 0.7 mm

Standard Boron
Boron + Carbon Spray (not confined)
Gallium

•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:

$$\mathbf{Si_i + B_s \rightarrow B_i + O \rightarrow B_iO_i}$$

or

$$\mathbf{Si_i + C_s \rightarrow C_i + O \rightarrow C_iO_i}$$

Change type of final defects but not amount of active implant

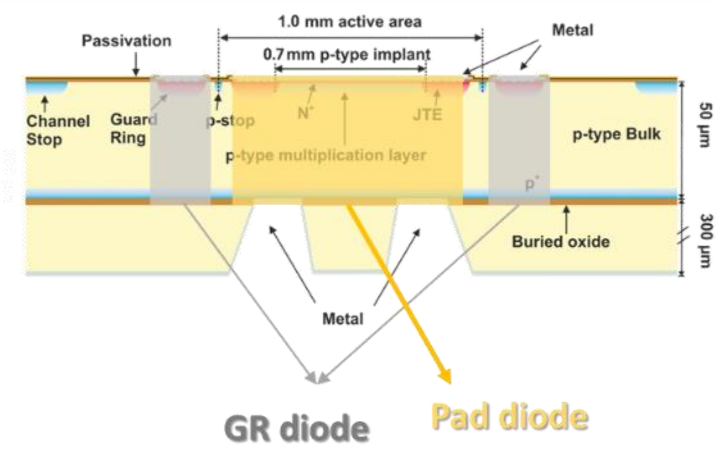
- Since B_i and C_i both compete for the same Si_i, if we introduce more Carbon we would expect to from less B_iO_i defects and more C_iO_i
- If we exchange Boron with a less mobile (heavier) atom (Ga), then we should also enhance C_iO_i defects instead of Ga_iO_i

•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 -10ºC, -20ºC & -30ºC

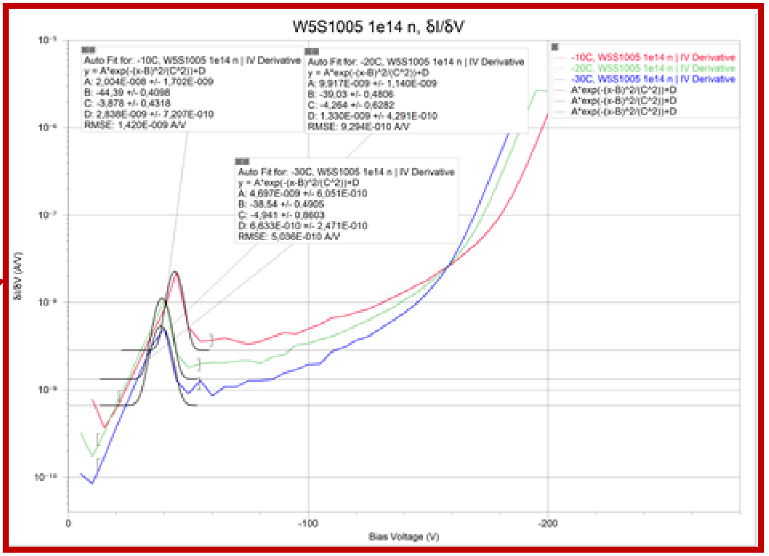


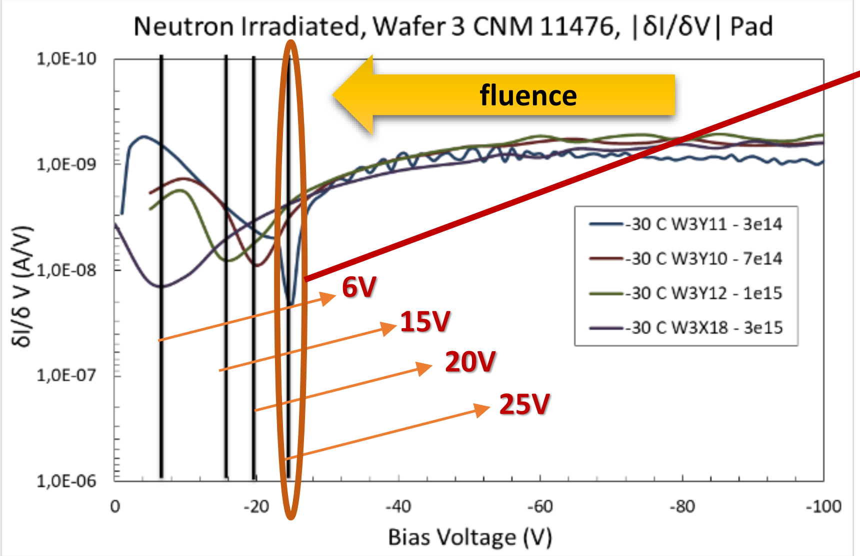
$$V_d = \frac{\sum_{T=-10\ ^oC}^{-30\ ^oC} V_{d,T_i}}{n_T}$$

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

Average of fit sigma

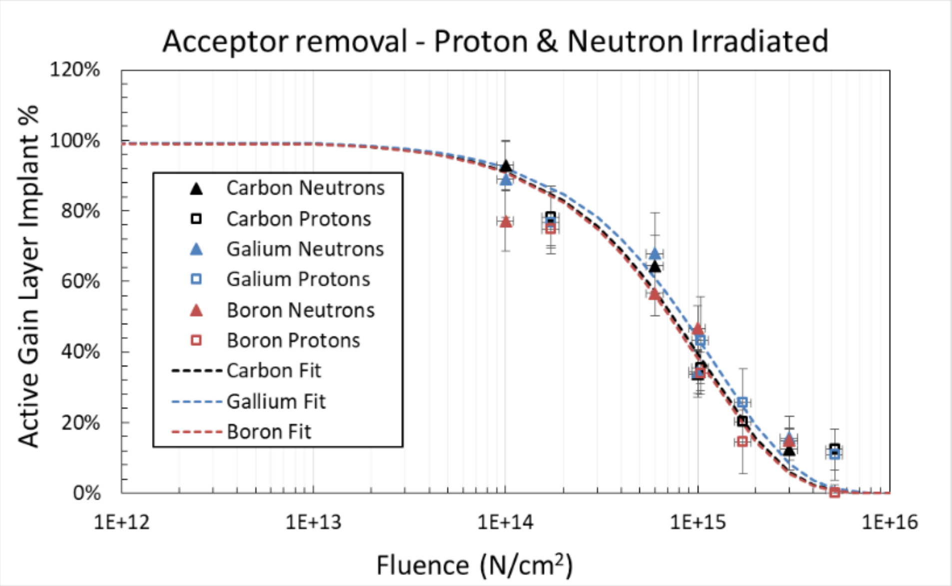
Standard deviation of V_d

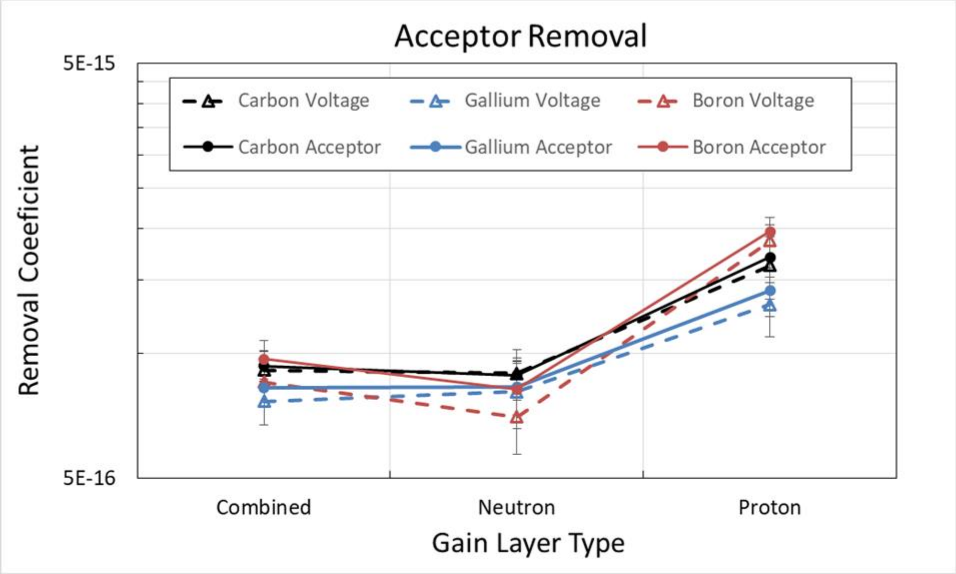




- Independent Gaussian fits for each temperature
- Uncertainties estimated from propagation of fit sigma
- Fluences up to $3\cdot10^{15}\ n_{eq}/cm^2$ in p^+ and n^0

•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}

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

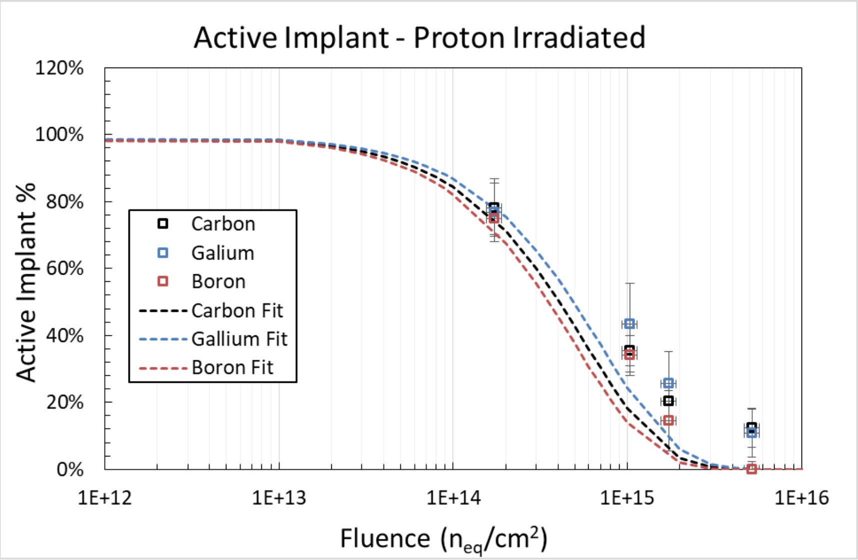
- Linearity hypothesis tested with independent C_v and C_G fits – full compatibility
- Constraints imposed on initial values to reflect charge measurements

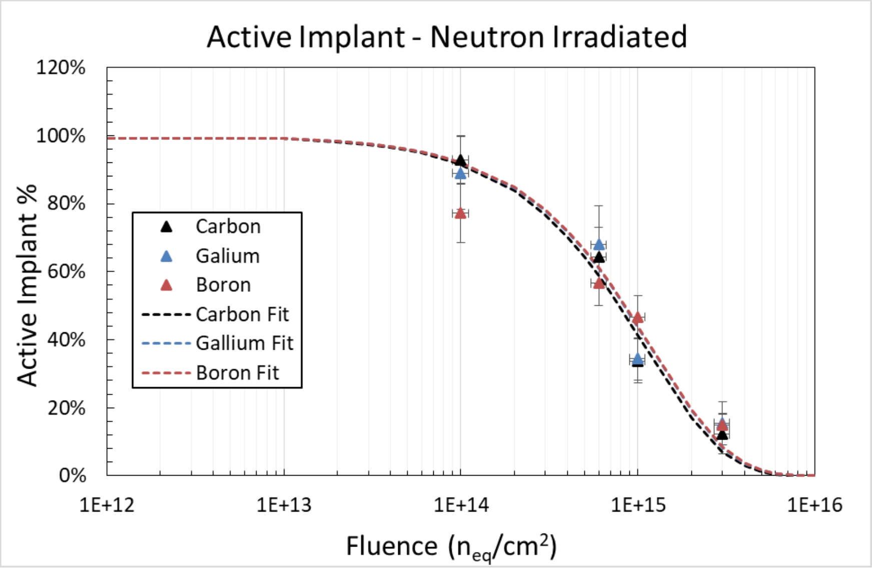
Results

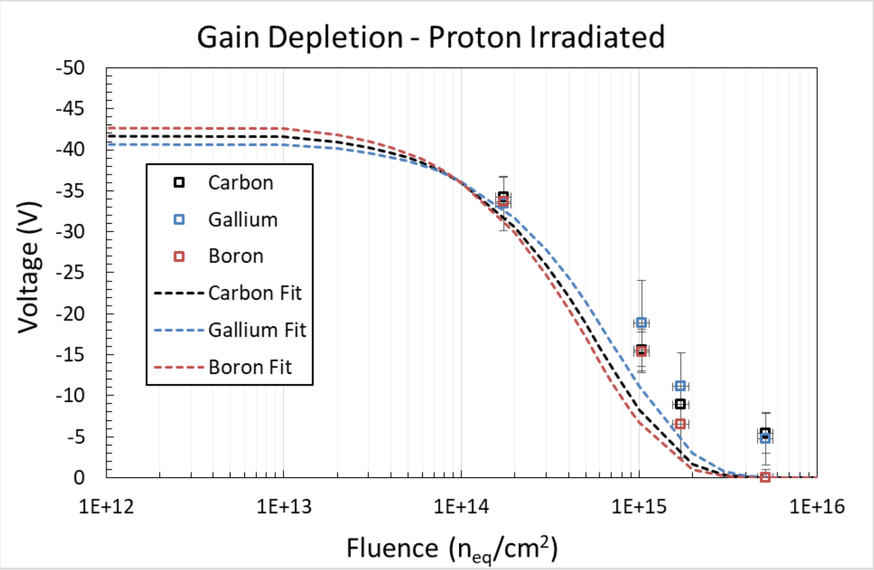
- Compatible acceptor removal coefficients between all implants
- Slight Ga advantage in p^+ irradiation (23 GeV/c PS), higher mass reduces displacement probability in coulomb-only (far-field) interactions
- Quasi-identical performance for neutron irradiated (fast ~ 10MeV neutrons)
- **Identical gain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

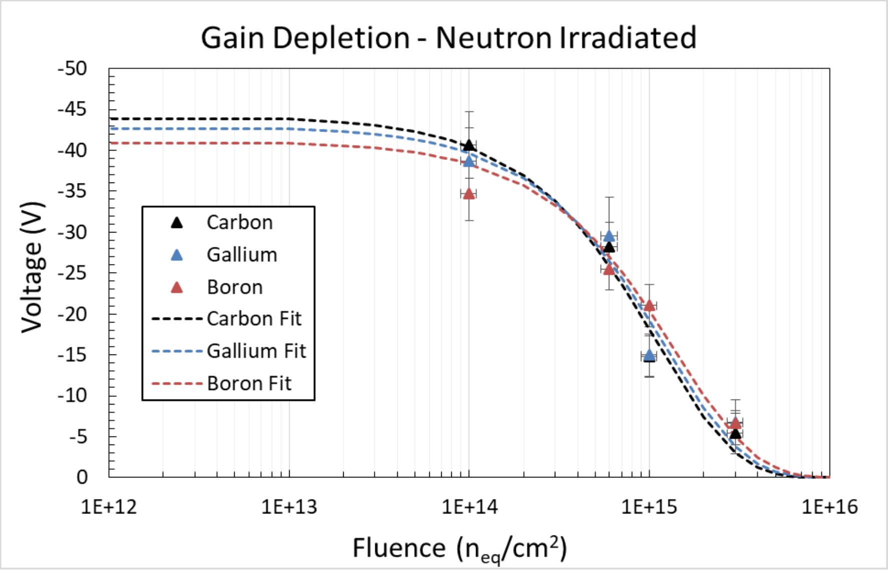
Acceptor Removal Coefficient		
Irrad. Type	**C**	**δC**
Gallium		
Combined	8.25E-16	7.98E-17
n^0 irradiated	8.28E-16	1.16E-16
p^+ irradiated	1.41E-15	1.88E-16
Boron + Carbon		
Combined	9.33E-16	7.78E-17
n^0 irradiated	8.85E-16	8.76E-17
p^+ irradiated	1.70E-15	2.23E-16
Standard Boron		
Combined	9.69E-16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

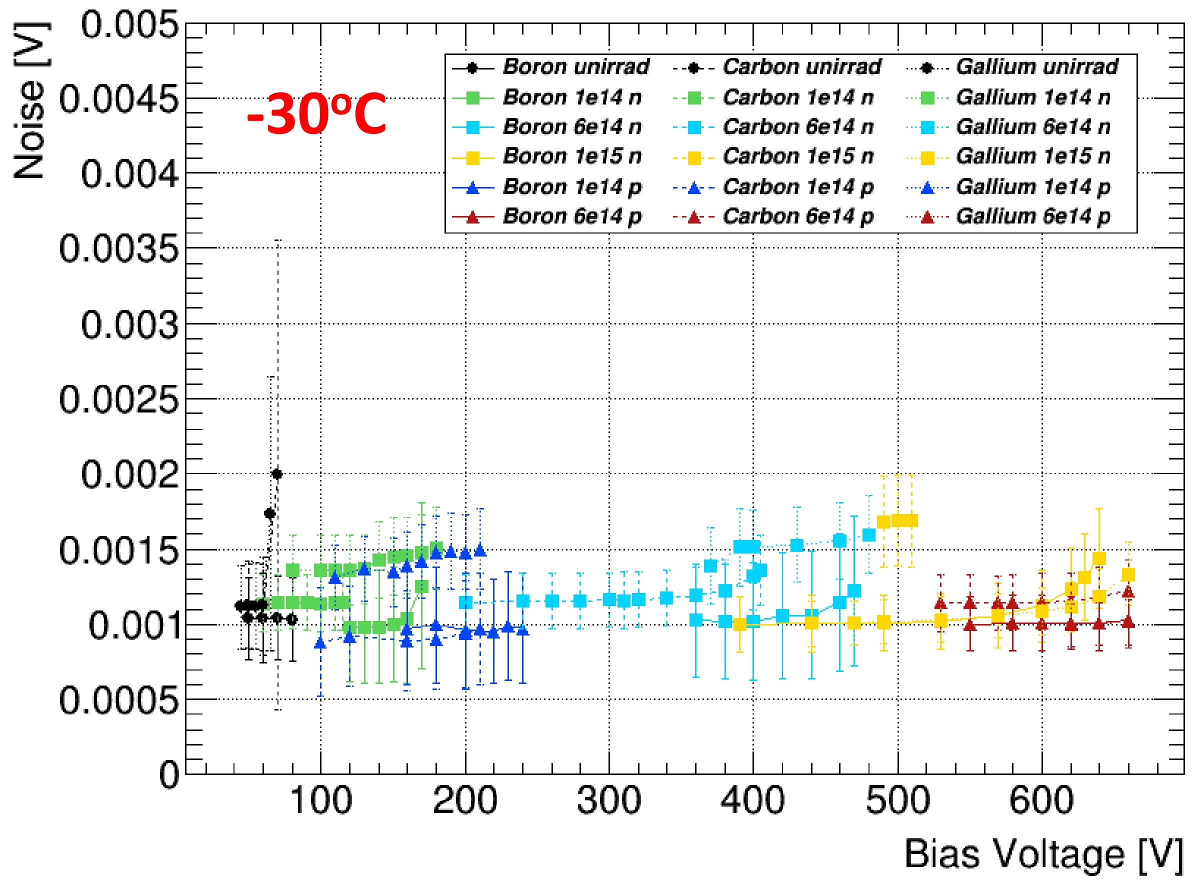


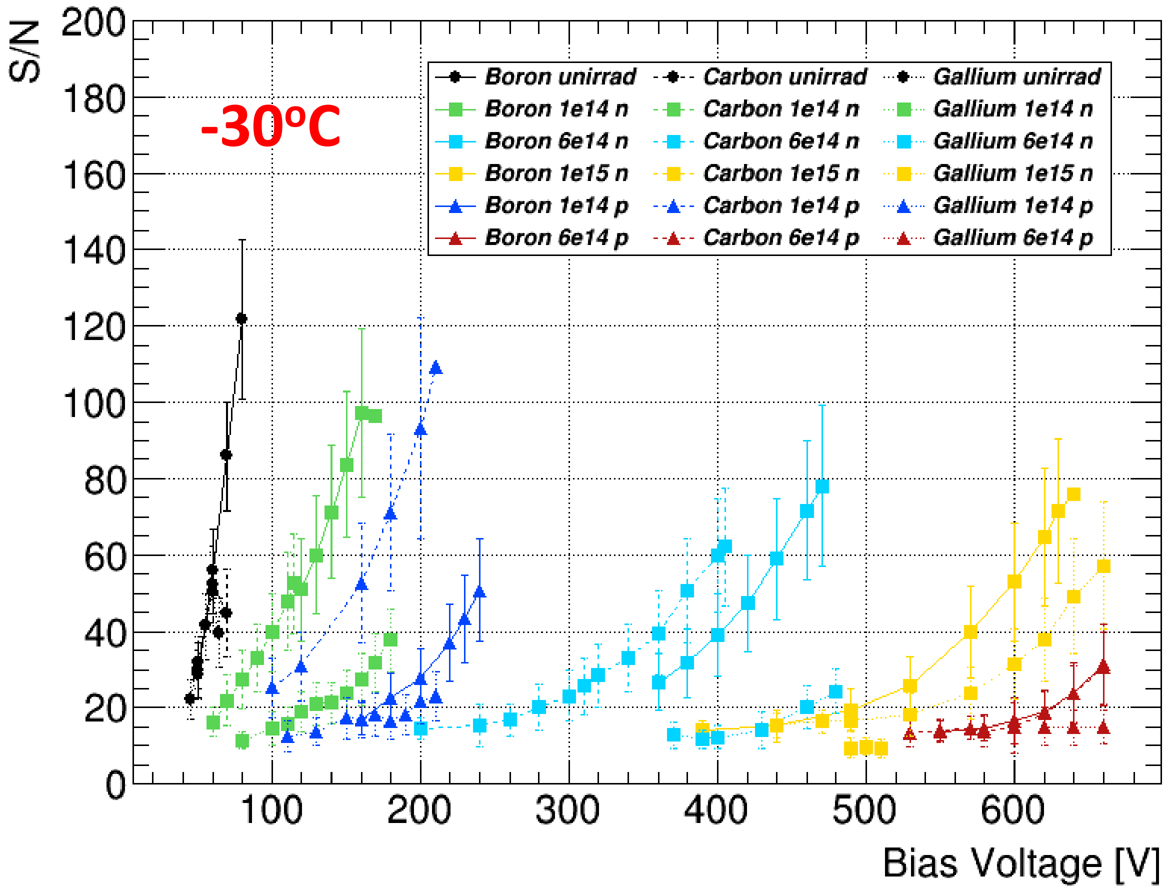




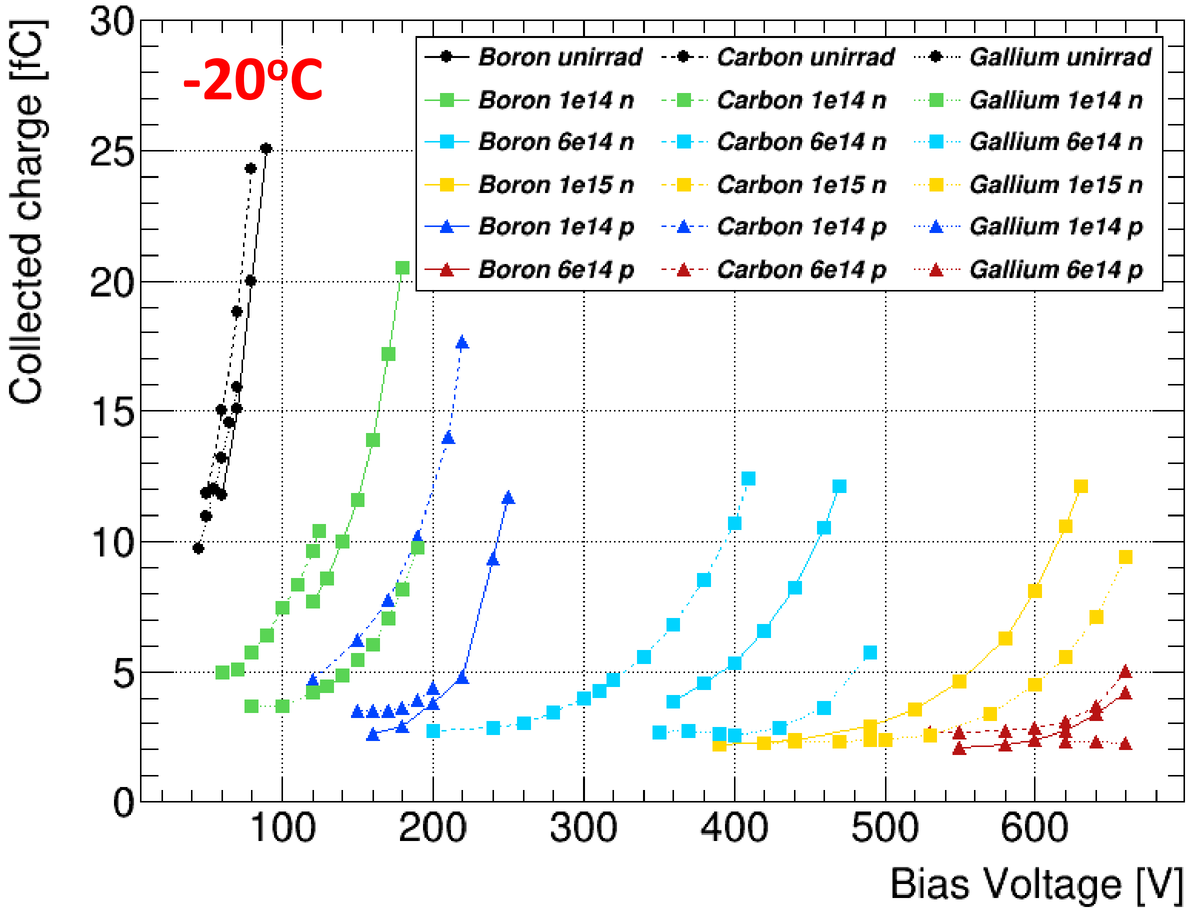


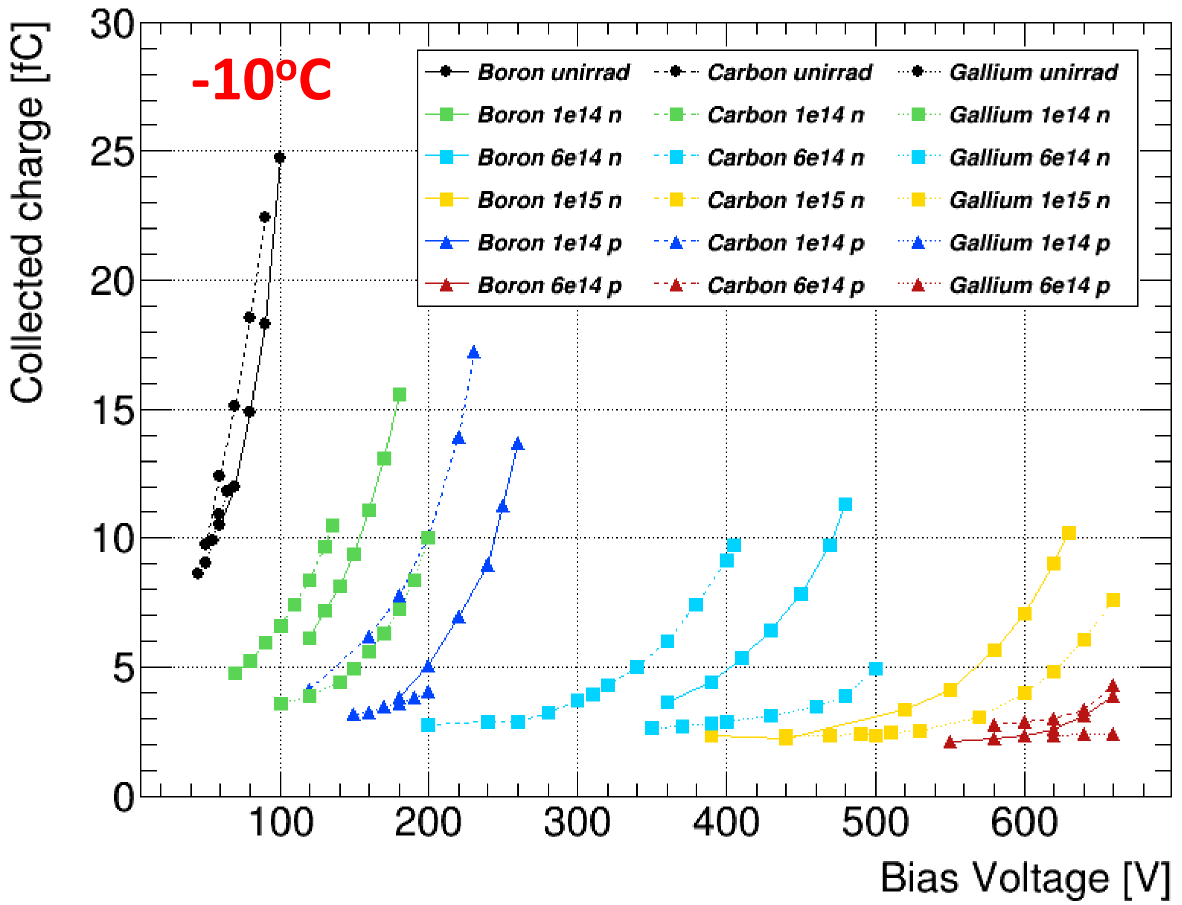
•Charge at -20°C and -10°C



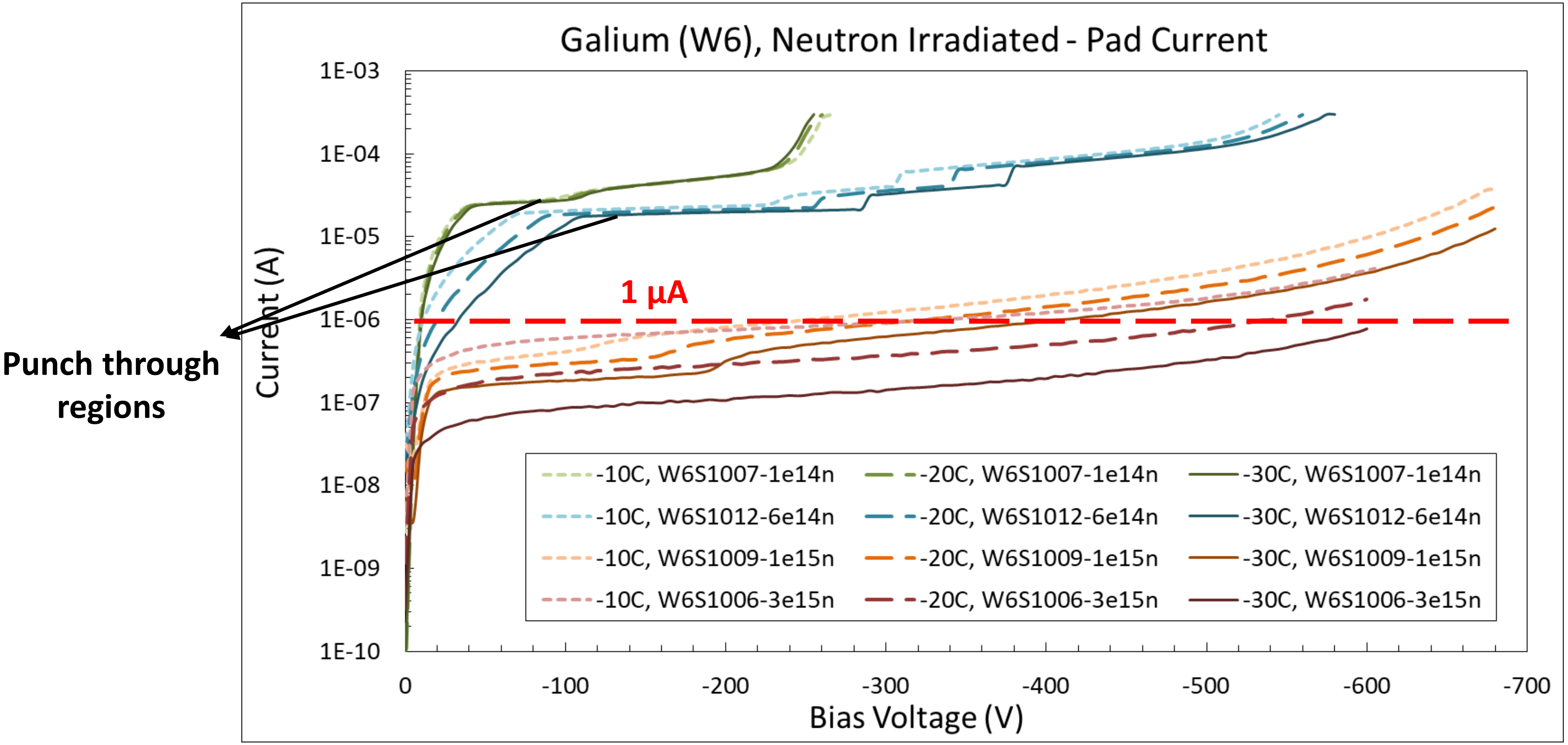


•Noise


-20°C
Boron unirrad
Carbon unirrad
Gallium unirrad
Boron 1e14 n
Carbon 1e14 n
Gallium 1e14 n
Boron 6e14 n
Carbon 6e14 n
Gallium 6e14 n
Boron 1e15 n
Carbon 1e15 n
Gallium 1e15 n
Boron 1e14 p
Carbon 1e14 p
Gallium 1e14 p
Boron 6e14 p
Carbon 6e14 p
Gallium 6e14 p
Collected charge [fC]
Bias Voltage [V]


-10°C
Boron unirrad
Carbon unirrad
Gallium unirrad
Boron 1e14 n
Carbon 1e14 n
Gallium 1e14 n
Boron 6e14 n
Carbon 6e14 n
Gallium 6e14 n
Boron 1e15 n
Carbon 1e15 n
Gallium 1e15 n
Boron 1e14 p
Carbon 1e14 p
Gallium 1e14 p
Boron 6e14 p
Carbon 6e14 p
Gallium 6e14 p
Collected charge [fC]
Bias Voltage [V]

•Gallium Leakage Current



•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

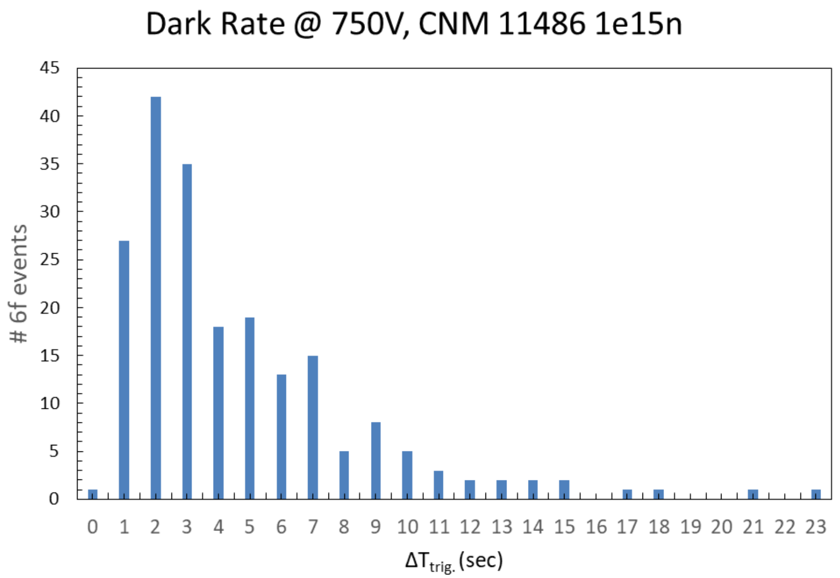
Sigmoid Dark rate Fit:

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

Max, recordable rate Inst. saturation point

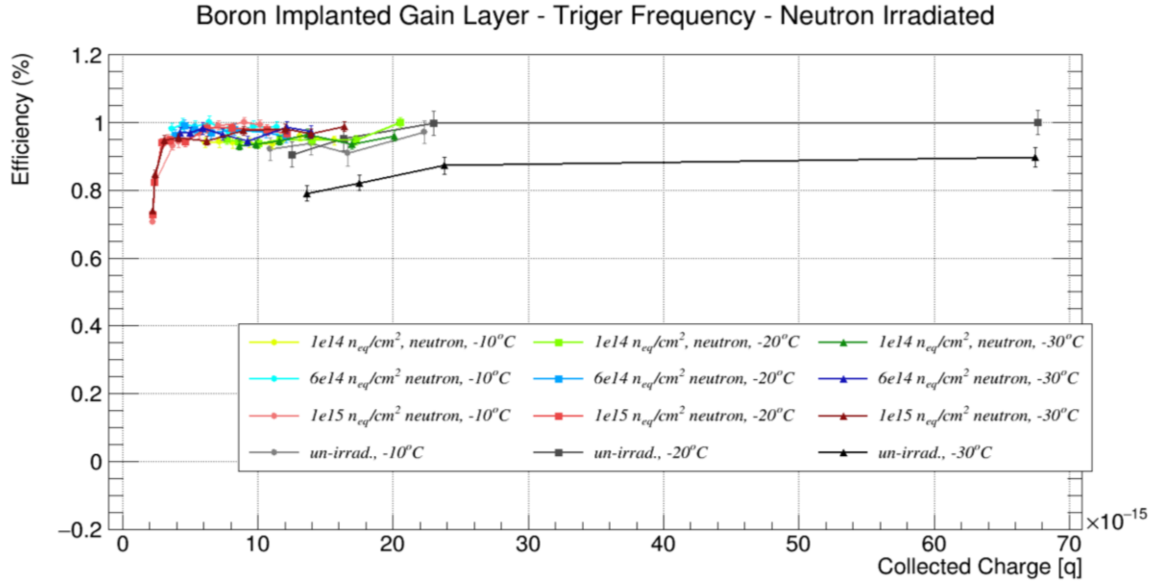
50% of maximum voltage point

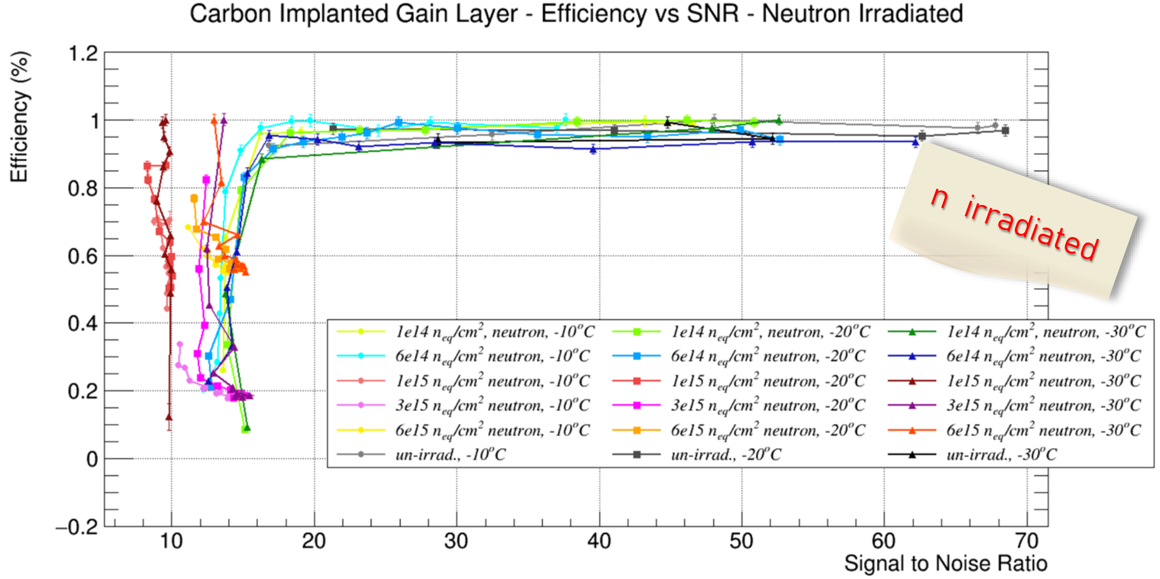
Baseline trigger rate (noise, radioactivity)

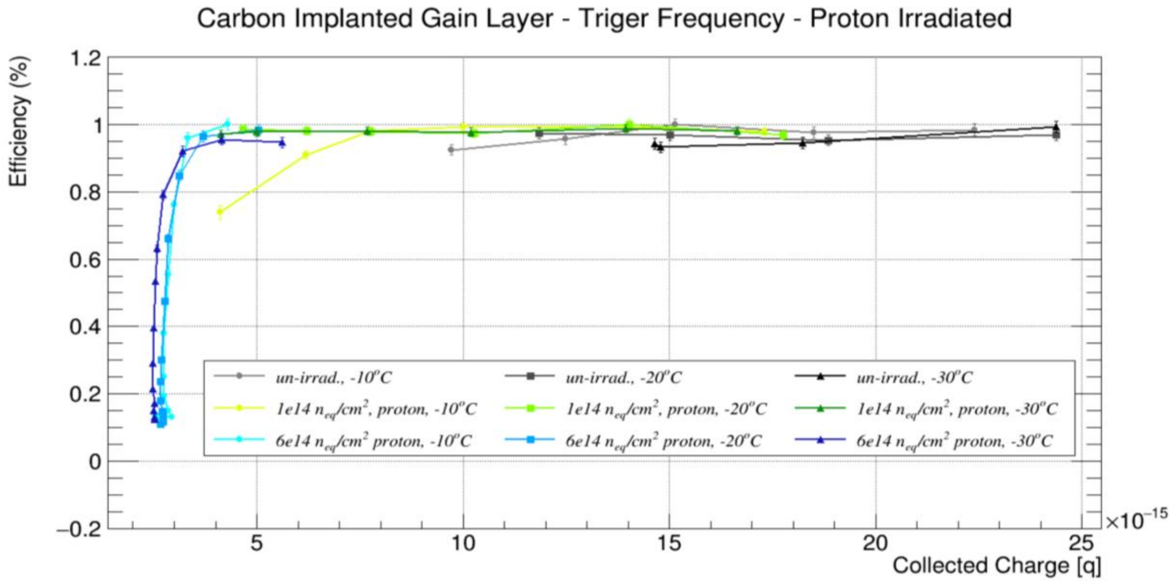


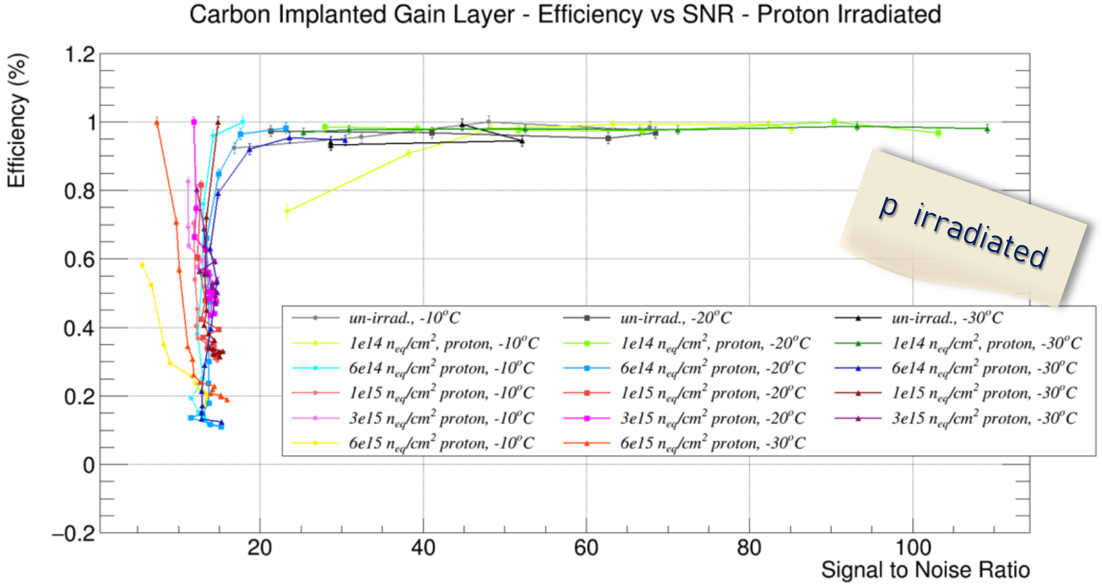
- ✓ Sensors with intrinsic gain present dark rate at higher biases
- ✓ Brownian thermal electrons following Poisson distribution
- ✓ As gain increases, the amount of charge necessary for an event to cross trigger threshold decreases
- ✓ Shot thermal noise increases with voltage
- ✓ Evaluation performed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

•Comparative Studies - Efficiency



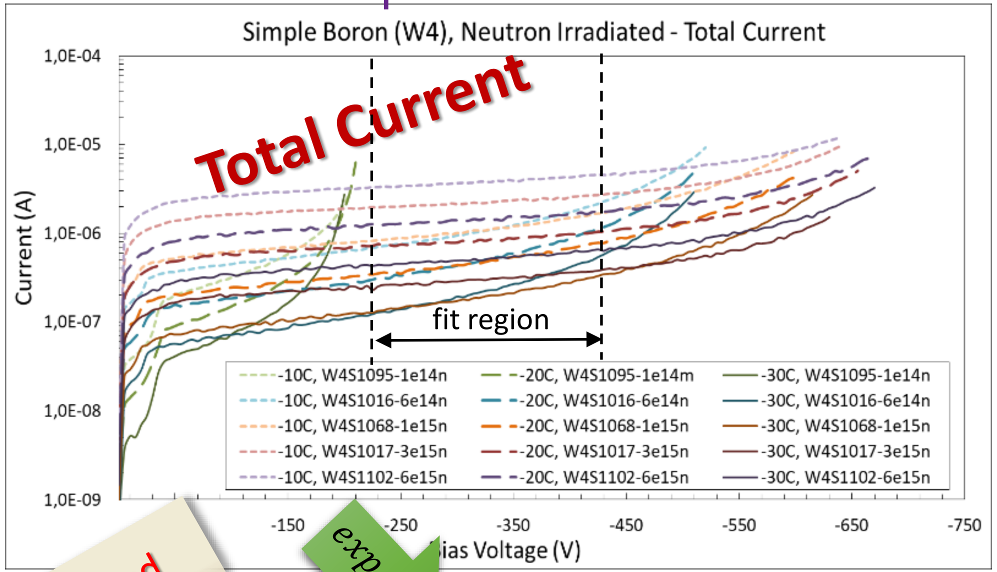






•Breakdown Voltage

Current Multiplier



Method

exp. fit

- ✓ 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

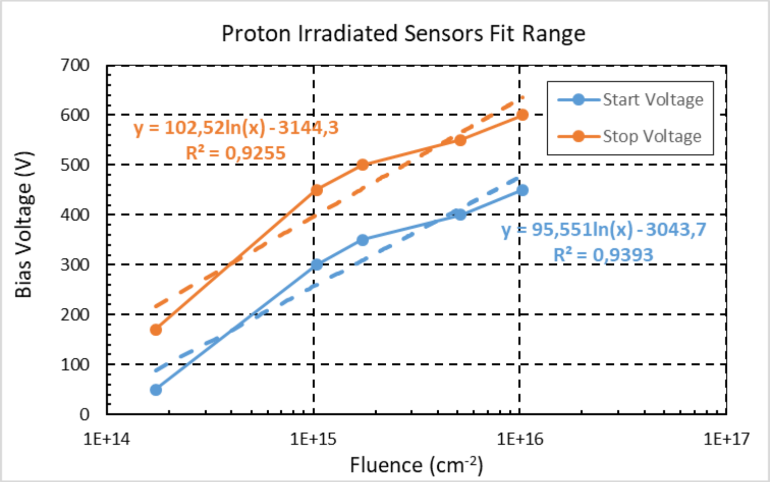
Exponential Fit: $I = b \cdot m^V$

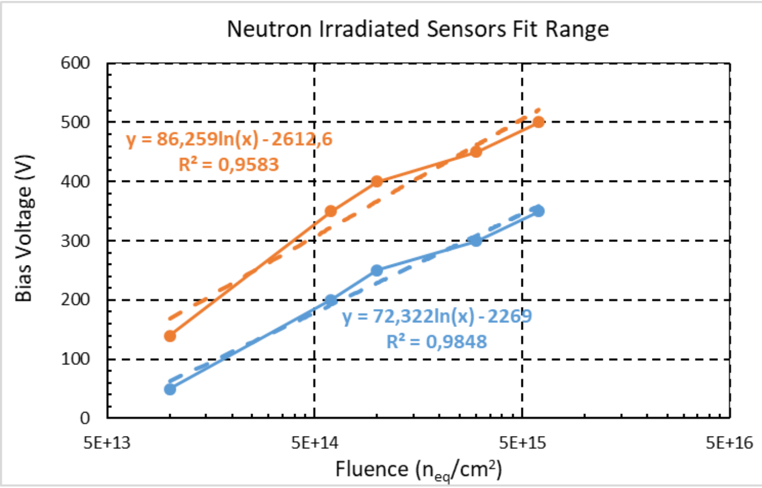
Acceptance Criteria: $R^2 \geq 99\%$

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

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

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

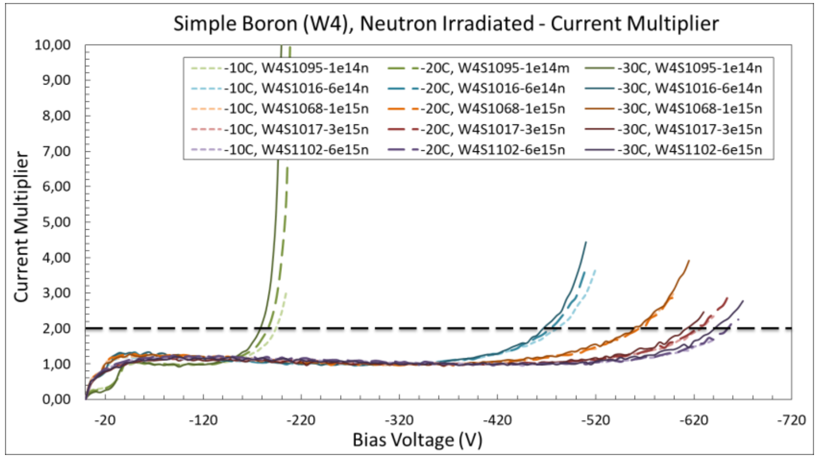


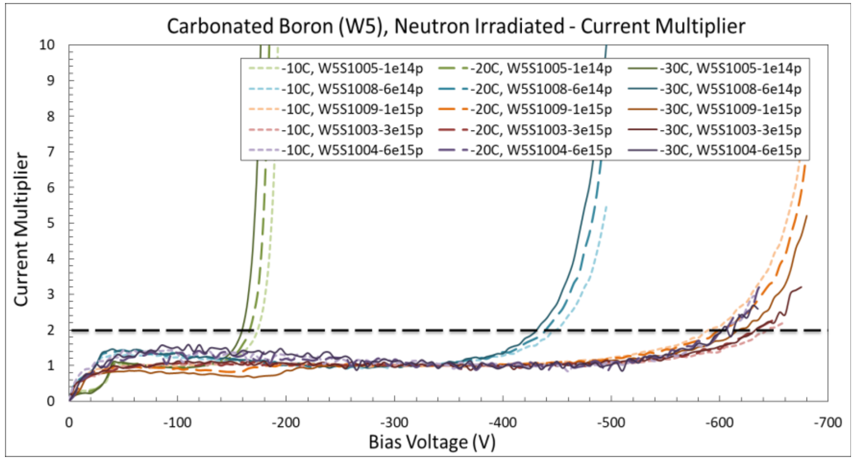


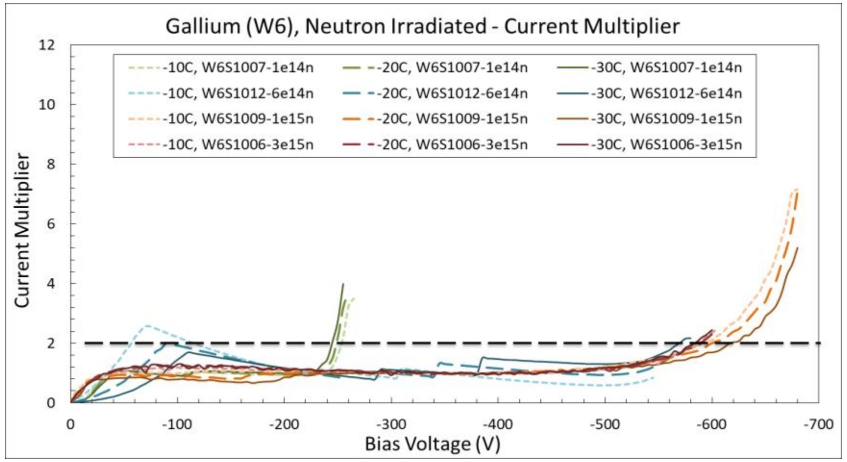
•Breakdown Voltage

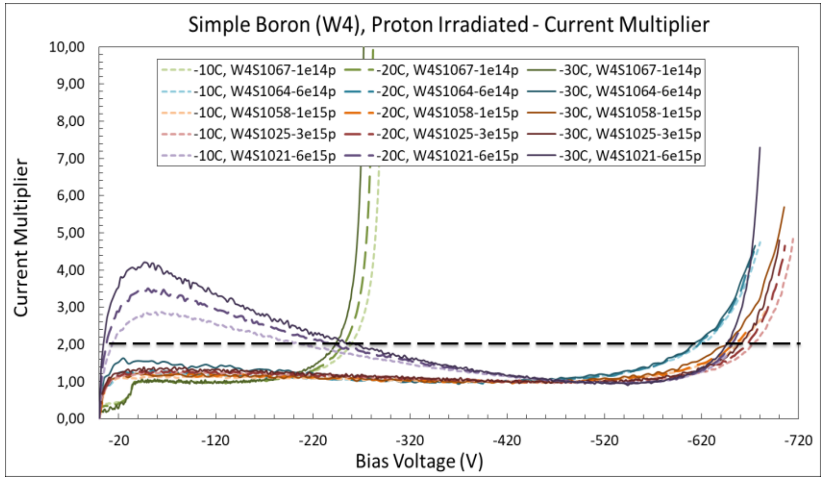
- ✓ Independent fit for each temperature
- ✓ Identical fit regions across all temperatures
- ✓ Identical fit regions for same fluence across all three implants

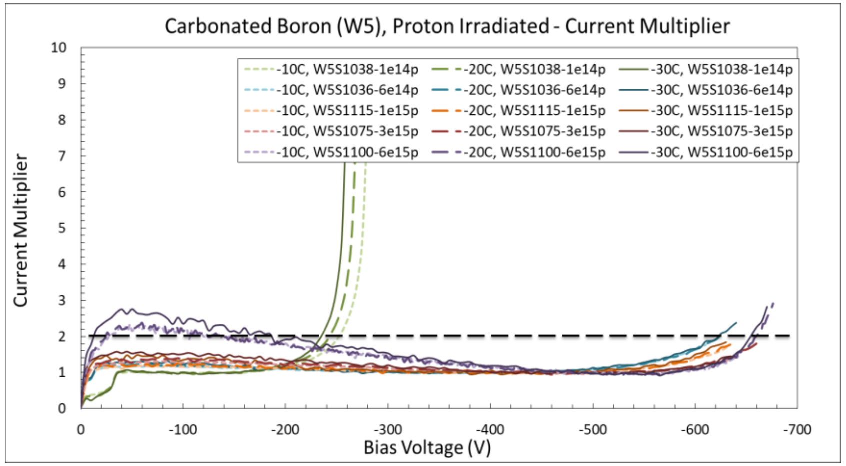
Constraints

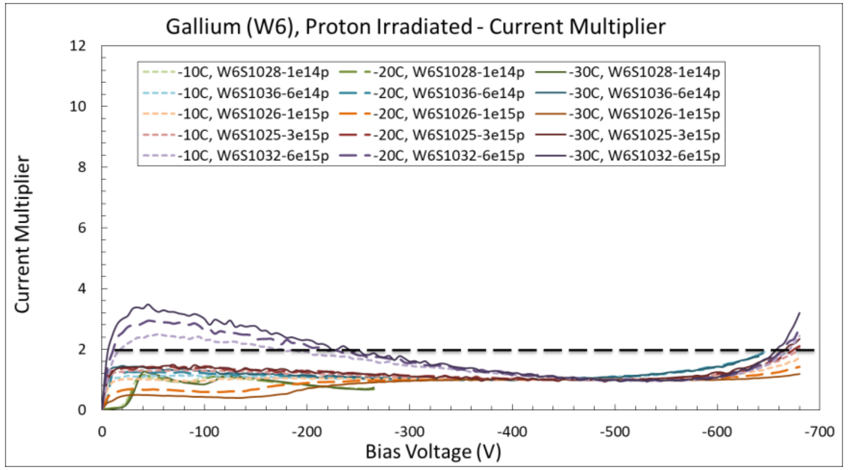












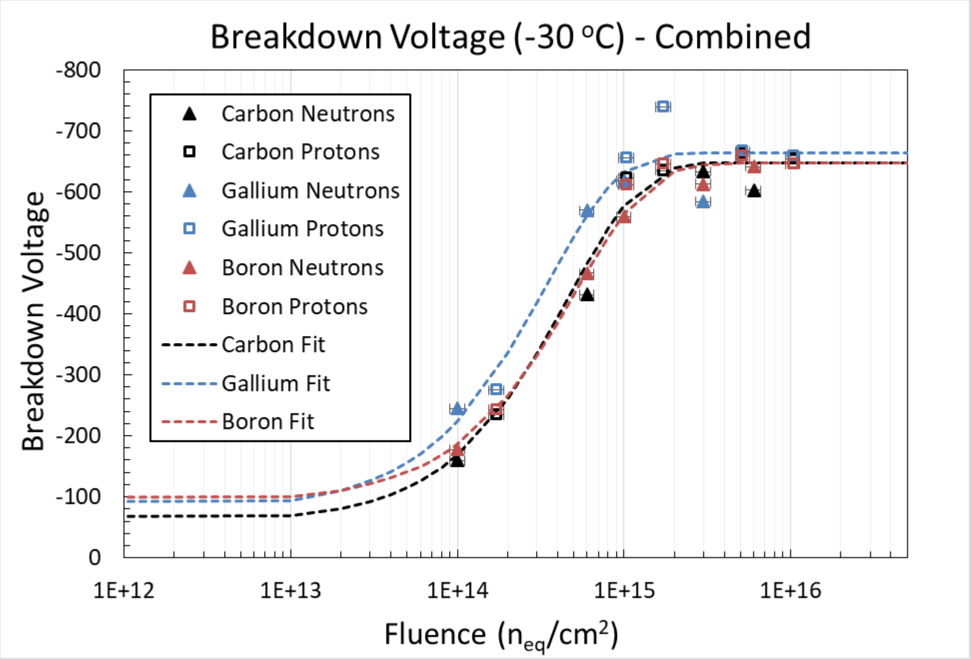
•Breakdown Voltage

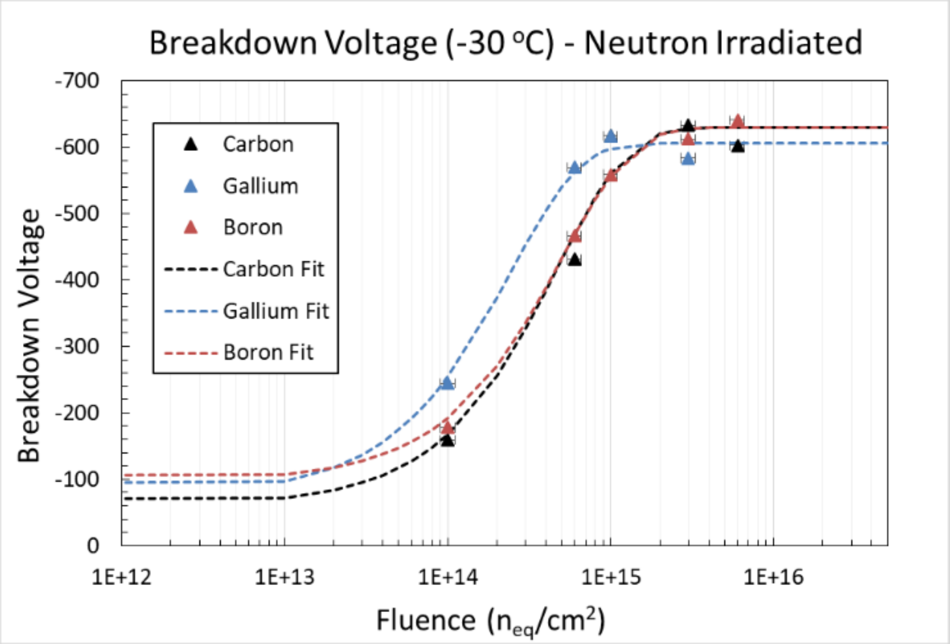
Model

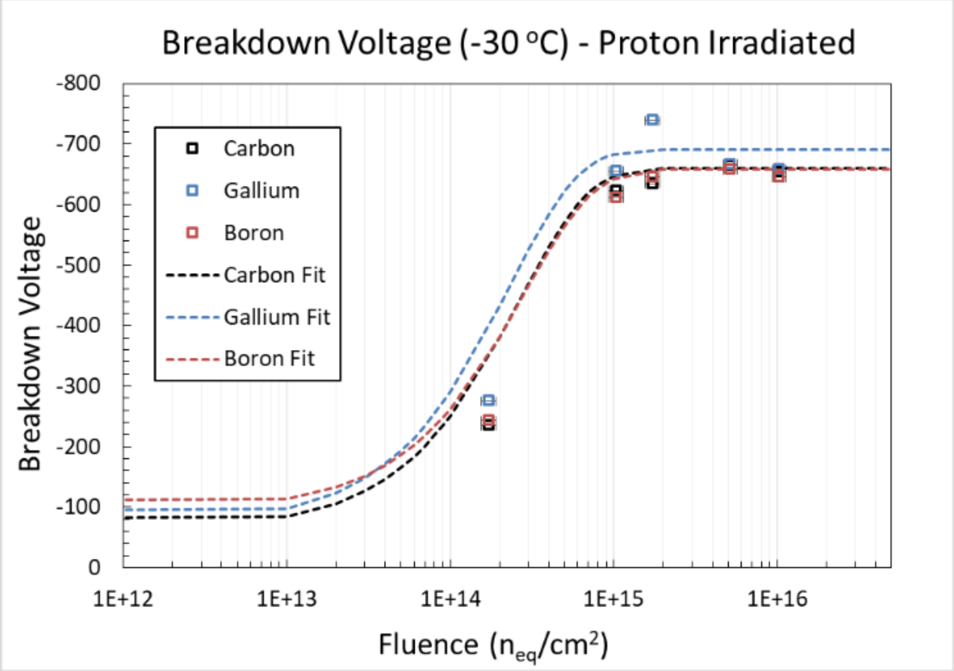
Breakdown of PIN

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