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

(Images of diagrams and text)
• Introduction – Use in HEP

**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 °C (CO$_2$ cooling)
- $\sigma_t = 35 – 70$ psec per hit
- Radiation tolerance to 2.5•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

See Irena's talk: [link]

**CMS MDT**
- 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•10$^{15}$ n$_{eq}$/cm$^2$ for LGADs
- 50 μm thick sensors on 300 μm SoI wafers, slim edge design
- Operation at -30 °C

Link to TDR: [link]
Radiation Effects

Four main disruptive mechanisms for irradiated LGADs:

1. Reduced primary charges induced in substrate (reduced lifetime)

\[ \frac{1}{τ} = β × Φ \]

\[ N_{Act.} = G × Φ \]

2. Acceptor re-introduction rate

\[ N_{GΦ} = N_{G0}e^{-cΦ} \]

Gain reduction larger than anticipated from acceptor removal (~factor of 3)

3. Reduced active implant in gain layer through acceptor removal

4. Reduced mobility within gain layer through trapping

Acceptance removal, Defect Kinetics (simplified 😊)

- Face centered Cubic Si (2-atom base)
- Interaction with incoming particle
- Interstitial Si
- Substitutional B,C
- Integrated interstitial
- Substitutional Replacement
- Gain layer de-activation too many interstitials, cannot modify
- Charge trapping Can be engineered by oxygen trapping
Part I - The Active Gain Layer

1. Reduced primary charges induced in substrate (reduced lifetime)
   \[ \frac{1}{\tau} = \beta \times \Phi \]

2. Acceptor re-introduction rate
   \[ N_{Act.} = G \times \Phi \]

3. Reduced active implant in gain layer through acceptor removal
   \[ N_{G\Phi} = N_{G0} e^{-c\Phi} \]
   Gain reduction larger than anticipated from acceptor removal (~factor of 3)

4. Reduced mobility within gain layer through trapping
The Derive and Fit Method - I

- Probe active implant by depletion voltage
- Additional p-implantation gain layer creates secondary depletion region
- Mott–Schottky equation \( \rightarrow \) leakage current variation at gain layer depletion
- Form of \( \left| \frac{\partial I}{\partial V} \right| \) 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

\[
V_d = \sum_{T=-30°C}^{-10°C} V_{d,T_i} n_T
\]

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

- Independent Gaussian fit for temperature
- Uncertainties estimated from propagation on fit sigma
- Fluences up to \(3 \times 10^{15}\) \(n_{eq}/cm^2\) 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 $V_{GL}$

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

- 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**

<table>
<thead>
<tr>
<th>Acceptor Removal Coefficient</th>
<th>Gallium</th>
<th>Boron + Carbon</th>
<th>Boron</th>
</tr>
</thead>
<tbody>
<tr>
<td>($8.25 \pm 0.80) \times 10^{-16}$</td>
<td>($9.33 \pm 0.78) \times 10^{-16}$</td>
<td>($9.69 \pm 1.04) \times 10^{-16}$</td>
<td></td>
</tr>
</tbody>
</table>
Part II - Effective Gain

1. Reduced primary charges induced in substrate (reduced lifetime)\[ \frac{1}{\tau} = \beta \times \Phi \]

2. Acceptor re-introduction rate\[ N_{Act.} = G \times \Phi \]

3. Reduced active implant in gain layer through acceptor removal\[ N_{G\Phi} = N_{G0} e^{-c\Phi} \]

4. Reduced mobility within gain layer through trapping

Gain reduction larger than anticipated from acceptor removal (~factor of 3)
- GR Vs Pad Method - I

- 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

\[ f(V, \Phi) = \frac{I_{pad}}{I_{GR}} \]

Geometry factor

**Before Irradiation**

- \[ I_{pad}^{\Phi=0} = S \times I_S \times \left( \frac{e^V}{e^{nkT}} - 1 \right) \times G(e^V, T, 0) \]

- \[ I_{GR}^{\Phi=0} = I_G \times \left( \frac{e^V}{e^{nkT}} - 1 \right) \]

Gain Current

**After Irradiation**

- \[ I_{pad}(\Phi) = S \times (I_{GR}^{\Phi=0} + \alpha \Phi) \times G(e^V, T, \Phi) \]

- \[ I_{GR}(\Phi) = I_{GR}^{\Phi=0} + \alpha \Phi \]

Gain Current

If we divide the two then:

\[ f(V, \Phi) = \frac{I_{pad}}{I_{GR}} \sim G(e^V, T, \Phi) \]

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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

![Graph showing $I_{pad}/I_{GR} = m \times a^V$]
**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**

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**Gain Reduction Coefficient**

<table>
<thead>
<tr>
<th>Irrad. Type</th>
<th>C ± δC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gallium</td>
<td></td>
</tr>
<tr>
<td>(n_0)</td>
<td>((3.01 ± 0.9) \times 10^{-14})</td>
</tr>
<tr>
<td>(p^+)</td>
<td>((2.02 ± 0.11) \times 10^{-14})</td>
</tr>
<tr>
<td>Boron + Carbon</td>
<td></td>
</tr>
<tr>
<td>(n_0)</td>
<td>((2.57 ± 1.1) \times 10^{-15})</td>
</tr>
<tr>
<td>(p^+)</td>
<td>((1.37 ± 0.24) \times 10^{-14})</td>
</tr>
<tr>
<td>Standard Boron</td>
<td></td>
</tr>
<tr>
<td>(n_0)</td>
<td>((2.25 ± 0.39) \times 10^{-14})</td>
</tr>
<tr>
<td>(p^+)</td>
<td>((2.25 ± 0.28) \times 10^{-14})</td>
</tr>
</tbody>
</table>

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**Effective Gain (%) from \(I_{pad}/I_{GR}\) - Neutron Irradiated**

**Effective Gain (%) from \(I_{pad}/I_{GR}\) - Proton Irradiated**

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**Acceptance level introduction rate**

\[
N_{eff}(\Phi) = N_{eff 0} - N_c \left( 1 - e^{-c\Phi} \right) + g_c \Phi
\]

- Effective dopant concentration
- Removable dopant concentration
- Gain extraction constant

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**GR Vs Pad Method - III**

- Gain Reduction Coefficient

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**E. L. Gkougkousis**

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27 / 5 / 2021
Part III - The Actual Gain

1. Reduced primary charges induced in substrate (reduced lifetime)\[1/\tau = \beta \times \Phi\]

2. Acceptor re-introduction rate\[N_{Act.} = G \times \Phi\]

3. Reduced active implant in gain layer through acceptor removal\[N_{G\Phi} = N_{G0} e^{-c\Phi}\]

4. Reduced mobility within gain layer through trapping

Gain reduction larger than anticipated from acceptor removal (~factor of 3)
Collected Charge - I

• 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

-30°C

Minimum charge for good timing
5 σ from noise

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

-30°C

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CFD Level optimization

\[
\left(\sigma_{\text{Dut}}\right)_{\text{CFD}_{ij}} = \sqrt{\left(\sigma_{\text{Tot}}^2\right)_{\text{CFD}_{ij}} - \left(\sigma_{\text{Ref}}^2\right)_{\text{CFD}_{i}}}
\]

2D optimization plot – 0.5% binning

Time Resolution:

\[
\sigma_{\text{Tot}}^2 = \sigma_{\text{Timewalk}}^2 + \sigma_{\text{Jitter}}^2 + \sigma_{\text{Conversion}}^2 + \sigma_{\text{Cloci}}^2
\]

\[
\sigma_{\text{Dist.}}^2 + \sigma_{\text{Landau}}^2 = \frac{\left(t_{\text{rise}} / S/N\right)^2 \left(TDC_{\text{bin}} / \sqrt{12}\right)^2}{\text{Fixed Term \~ 5-7 psec}}
\]

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

Gkougkousis V., RD50 Workshop Talk, June 2020: [link]
• Comparative Studies I – Leakage Current

- $\frac{I_C}{I_B}$ presents a 33% increase
- Established though fits on non-gain regions
- Behaviour unchanged up to $1\times10^{15}$ $n_{eq}$/cm$^2$ in proton and neutron irradiated
- Consistent behavior with temperature ($-30^\circ C$, $-20^\circ C$, $-10^\circ C$)
- Leakage current increase in Gallium implanted samples but effect traced back to process issues
• Comparative Studies II – Efficiency vs Headroom

➢ ~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

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

  - 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....)

  - 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])

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**RD50 founded Project:** RD50-2021-03
Conclusions

Three methods of radiation hardness:

1. **Active Gain Implant:** No measurable 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
• Overview

- LGAD Technology
- HEP Applications – ATLAS & CMS

- Primary Mechanisms
- Acceptor Removal

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

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

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

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

- Lithium – Indium
- Conclusions and Outlook
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
• Radiation Effects

Acceptee 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:

  $\text{Si}_i + \text{B}_s \rightarrow \text{B}_i + \text{O} \rightarrow \text{B}_i\text{O}_i$

  $\text{Si}_i + \text{C}_s \rightarrow \text{C}_i + \text{O} \rightarrow \text{C}_i\text{O}_i$

- 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$_i$O$_i$ defects and more C$_i$O$_i$
- If we exchange Boron with a less mobile (heavier) atom (Ga), then we should also enhance C$_i$O$_i$ defects instead of Ga$_i$O$_i$
The Derive and Fit Method - I

- 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 $|\partial I/\partial V|$ 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

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

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

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

- Independent Gaussian fits for each temperature
- Uncertainties estimated from propagation of fit sigma
- Fluences up to $3 \times 10^{15} \text{n}_{eq}/\text{cm}^2$ in p⁺ and n⁰
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

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<th>$\delta C$</th>
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<tr>
<td>Gallium</td>
<td>Combined</td>
<td>8.25E-16</td>
<td>7.98E-17</td>
</tr>
<tr>
<td></td>
<td>$n^0$ irradiated</td>
<td>8.28E-16</td>
<td>1.16E-16</td>
</tr>
<tr>
<td></td>
<td>$p^+$ irradiated</td>
<td>1.41E-15</td>
<td>1.88E-16</td>
</tr>
<tr>
<td>Boron + Carbon</td>
<td>Combined</td>
<td>9.33E-16</td>
<td>7.78E-17</td>
</tr>
<tr>
<td></td>
<td>$n^0$ irradiated</td>
<td>8.85E-16</td>
<td>8.76E-17</td>
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<tr>
<td></td>
<td>$p^+$ irradiated</td>
<td>1.70E-15</td>
<td>2.23E-16</td>
</tr>
<tr>
<td>Standard Boron</td>
<td>Combined</td>
<td>9.69E-16</td>
<td>1.04E-16</td>
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<tr>
<td></td>
<td>$n^0$ irradiated</td>
<td>8.19E-16</td>
<td>1.35E-16</td>
</tr>
<tr>
<td></td>
<td>$p^+$ irradiated</td>
<td>1.96E-15</td>
<td>1.60E-16</td>
</tr>
</tbody>
</table>
The Derive and Fit Method - II

**Active Implant - Proton Irradiated**

- Carbon
- Gallium
- Boron

**Active Implant - Neutron Irradiated**

- Carbon
- Gallium
- Boron

**Gain Depletion - Proton Irradiated**

- Carbon
- Gallium
- Boron

**Gain Depletion - Neutron Irradiated**

- Carbon
- Gallium
- Boron
• Charge at -20°C and -10°C

![Graph 1: Noise vs. Bias Voltage at -30°C](image1.png)

![Graph 2: SN vs. Bias Voltage at -30°C](image2.png)
-20°C

-10°C
Galium Leakage Current

Punch through regions

Galium (W6), Neutron Irradiated - Pad Current

1 μA

Bias Voltage (V)

Current (A)
Comparative Studies II - Stability

Self-trigger time:
\[ \Delta T_{\text{trig}}^i = \frac{\sum_{j=1}^{n-1} (T_{j+1}^{\text{trig}} - T_j^{\text{trig}})}{n} \]

Self-trigger Rate:
\[ F_{\text{trig}}^i = \frac{1}{\Delta T_{\text{trig}}^i} \]

Median of several rate measurements
\[ \bar{F}_{\text{trig}} = \frac{F_{\text{trig}} \lfloor (\#k+1)/2 \rfloor + F_{\text{trig}} \lceil (\#k+1)/2 \rceil}{2} \]

Uncertainty on trigger rate:
\[ \delta F_{\text{trig}}(\%) = \frac{\sqrt{(N_{\text{over}} + 1) \times (N_{\text{over}} + 2) - (N_{\text{over}} + 1)^2}}{(N + 2) \times (N + 3) - (N + 2)^2} \]

Efficiency is a binary magnitude, Bayesian approach implemented

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

- 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

- Boron Implanted Gain Layer - Trigger Frequency - Neutron Irradiated
- Carbon Implanted Gain Layer - Efficiency vs SNR - Neutron Irradiated
- Carbon Implanted Gain Layer - Trigger Frequency - Proton Irradiated
- Carbon Implanted Gain Layer - Efficiency vs SNR - Proton Irradiated
• Breakdown Voltage

Current Multiplier

- Measure total leakage current (-10°C, -20°C, -30°C)
- 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: $I_{pad}(\Phi) = (I_{pad}^{\Phi=0} + \alpha\Phi) \times G^*(e^V, T, \Phi)$

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

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Constraints

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• Breakdown Voltage

Model

\[ V_b = (V_{max} - V_0)(1 - e^{-c\Phi}) + V_0 \]

- Breakdown of PIN
- Un-irradiated breakdown voltage

✓ 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