Radiation Tolerance of Oxygenated n-strip Read-out Silicon Detectors

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Phil Allport
Gianluigi Casse
Ashley Greenall
Introduction

- Radiation damage to silicon detectors increases reverse currents, creates interface trapped charge, introduces traps, reducing charge collection efficiencies changes the effective doping concentrations.

- Studies of the effective doping changes have shown reduced susceptibility to charged hadron irradiation when high concentrations of interstitial oxygen are introduced (RD48).

- However, the other effects, in particular the trapping, do not seem to show corresponding improvements in radiation tolerance.
Introduction

- Effective doping concentration, $N_{\text{eff}}$, for a diode of thickness, $w$, is derived from the voltage needed to fully deplete the diode, $V_{\text{fd}} (\gg V_{\text{bi}})$, through the equation:

$$V_{\text{fd}} = \frac{1}{2} e w^2 \frac{N_{\text{eff}}}{\varepsilon_{\text{Si}}}$$

- Since $C \propto 1/w$, $V \propto 1/C^2$ for $V \ll V_{\text{fd}}$ allowing $N_{\text{eff}}$ to be extracted from $C(V)$

- Because of the effects of trapping, the charge collection efficiency (CCE) as a function of voltage does not saturate at $V_{\text{fd}}$ and for segmented detectors read out from the p-side, CCE($V$) continues to rise, well above $V_{\text{fd}}$

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Evaluation of Trapping Effects

- Corresponding Charge Collection Efficiency vs Voltage

Normalised (to $Q_M$) charge collection for (a) non-irradiated and (b) oxygen-enriched detector after $5.1 \cdot 10^{14} \text{ p cm}^{-2}$

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Evaluation of Trapping Effects

- The effects of trapping can be parameterised in terms of effective trapping time \((Kramberger et al.)\) or, equivalently, velocity dependent attenuation length \((Marti i Garcia et al.)\).
- In both cases, trapping is highest where the field is lowest.
- These parameterisations assume timescales such that the total untrapped charge is collected, integrating over transient effects.
- Both analyses give values of \(\beta\) (averaged over \(e\) and \(h\)) that agree. \(\beta_{e,h} \times \Phi_{eq} = 1/\tau_{eff\ e,h}\) (trapping \(\propto\) flux)

\[\beta_{e,h} \sim 5 \times 10^{-16} \text{ cm}^2/\text{ns}\]

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Annealing of Irradiated Detectors

- Oxygenated and non-oxygenated detectors with both p-side and n-side read-out have been studied.
- These have been irradiated in the CERN-PS and annealed to the minimum of the $N_{\text{eff}}$ vs time annealing curve.
Charge Collection Efficiency Studies

- We have previously reported excellent fits to the CCE(V) for irradiated detectors based on the parameterisation of Marti i Garcia et al. using attenuation length $\lambda \propto v_{\text{drift}}$ up to $v_{\text{saturation}}$

- Free parameters:
  - attenuation length $\lambda$
  - depletion voltage $V_{\text{FD}}$
  - total generated charge $Q_0$

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Charge Collection Efficiency Studies

![Graphs showing charge collection efficiency against bias voltage for oxygenated and non-oxygenated samples.](image)

- Oxygenated:
  - $2.9 \times 10^{14}$ p/cm$^2$

- Non-oxygenated:
  - $5.1 \times 10^{14}$ p/cm$^2$

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## Charge Collection Efficiency Studies

<table>
<thead>
<tr>
<th>Detector label</th>
<th>Fluence [p cm$^{-2}$]</th>
<th>Oxygen enrichment</th>
<th>$V_{FD}$ [V] (From C-V)</th>
<th>$V_{FD}$ [V] (From CCE)</th>
<th>$\lambda$ [$\mu$m]</th>
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<tbody>
<tr>
<td>NI</td>
<td>Non irr.</td>
<td>No</td>
<td>49 ± 2</td>
<td>50 ± 2</td>
<td></td>
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<tr>
<td>SO1</td>
<td>$1.9 \pm 0.1 \cdot 10^{14}$</td>
<td>Yes</td>
<td>100 ± 7</td>
<td>90 ± 2</td>
<td>1338 ± 15</td>
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<tr>
<td>SN1</td>
<td>$1.9 \pm 0.1 \cdot 10^{14}$</td>
<td>No</td>
<td>150 ± 8</td>
<td>137 ± 2</td>
<td>1407 ± 220</td>
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<tr>
<td>SO2</td>
<td>$2.9 \pm 0.2 \cdot 10^{14}$</td>
<td>Yes</td>
<td>121 ± 7</td>
<td>130 ± 2</td>
<td>1224 ± 138</td>
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<tr>
<td>SN2</td>
<td>$2.9 \pm 0.2 \cdot 10^{14}$</td>
<td>No</td>
<td>218 ± 15</td>
<td>214 ± 4</td>
<td>1313 ± 122</td>
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<td>SO3</td>
<td>$5.1 \pm 0.4 \cdot 10^{14}$</td>
<td>Yes</td>
<td>181 ± 15</td>
<td>196 ± 3</td>
<td>731 ± 84</td>
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<tr>
<td>SN3</td>
<td>$5.1 \pm 0.4 \cdot 10^{14}$</td>
<td>No</td>
<td>320 ± 20</td>
<td>348 ± 7</td>
<td>781 ± 55</td>
</tr>
</tbody>
</table>

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Charge Collection Efficiency Studies

- The fitted values of \( V_{FD} \) agree with each other and with oxygenated data from RD48 (CERN LHCC 2000-009) taking account of the proton damage factor.

- The fitted values of \( Q_0 \): 18.1±0.3, 18.2±0.3, 17.7±0.3, 18.1±0.6, 18.2±0.4 and 18.3±0.4 are all consistent and agree with the pre-irradiation value 17.9±0.3.
Because high resistivity n-type bulk detectors become effectively p-type after heavy hadron irradiation, read-out using segmentation of the n-implants allows charge to be collected on the high field side, giving higher CCE at lower $V$.

Comparison of p-type and n-type detectors using $^{106}$Ru $\beta$-source after $3 \times 10^{14}$ p/cm$^2$ (SCT-128A read-out)
Detectors for the LHC-b Experiment

- The LHC-b vertex locator VeLo uses oxygenated 200\(\mu\)m thick detectors.

- Prototypes have been fabricated using both p-strip and n-strip readout and irradiated at the CERN PS.
Detectors for the LHC-b Experiment

LHC-b uses back-to-back half disks for \( r \) and \( \varphi \) plus double-metal routing to the electronics mounted at the rim.

\( \sigma(B_s) = 340 \mu m \)
\( \sigma_t(B_s) = 43 \text{ fs} \)
Detectors for the LHC-b Experiment

- LHC-b and the pixel systems of ATLAS and CMS need to maximise their survival, given expected maximum doses approaching $10^{15}$ p/cm$^2$ and 10s of Mrad.

- Super-LHC is proposed with a factor of 10 increased luminosity.

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Detectors Studied

- Studies have been carried out with full-sized LHC-b prototypes using SCT-128 analogue readout and miniature (cm×cm) micro-strip detectors using SCT-128 or wide bandwidth (Phillips 6954) current amplifier.

- CCE(V) has been studied using a $^{106}$Ru β-source and a 1064nm light spot (where the latter is tuned to give an energy deposit about 3 times that of a minimum ionising particle).

- All give comparable results.

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CCE(V) for irradiated, 200μm thick, LHC-b n-in-n full-size prototype detector with laser data (normalised to value at 400V) superimposed.
LHC-b Prototype CCE(V) Results

- From fits to the CCE(V), the depletion voltages for the different regions of the detector can be extracted.
- These detectors were processed by Micron Semiconductor Ltd to Liverpool designs on oxygenated (> $10^{17}$ cm$^{-3}$) FZ 200μm thick 6” wafers.
- Given the thickness, the depletion voltages agree well with previous proton irradiation measurements, corroborating the dose estimates.

CCE(V) extracted depletion voltages vs strip number for non-uniformly irradiated n-strip LHC-b ‘$\phi$-detector’
LHC-b Prototype CCE(V) Results

- The CCE(V) values at high voltage for n-side read-out with respect to the non-irradiated value show limited signal loss even after $7 \times 10^{14}$ p/cm$^2$.

- The tracking parts of ATLAS and CMS are designed for an integrated dose after 10 years equivalent to $3 \times 10^{14}$ p/cm$^2$ although their pixel vertex detectors and the LHC-b VeLo have to survive much more.

- Should Super-LHC go ahead, the ATLAS and CMS trackers will need to be affordably upgraded

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n-side vs p-side read-out

- For simple one dimensional structures e.g. large area diodes, little difference is expected between the signals seen on the n-side or the p-side.
- However, for segmented detectors as designed for experiments, the key issue is the operating voltage for a given CCE after heavy irradiation.
- Direct comparisons of n-side and p-side detectors with the same masks fabricated on the same material confirm the superiority of n-side read-out after irradiation.

1060nm laser CCE(V) for the highest dose regions of an n-in-n (7.10^{14} p/cm^{2}) and p-in-n (6.10^{14} p/cm^{2}) irradiated LHC-b full-size prototype detector.
Conclusions

- Operationally, for position resolution and tracking efficiency the key parameter is the signal/noise.
- After irradiation, at the LHC, although other effects may raise the noise, the key deterioration as a position sensitive detector is in terms of the collected charge.
- The charge collected at a given voltage is reduced both by the trapping and by the changes to the effective doping concentration.
- The former is addressed by n-side read-out while the latter can be helped by using an oxygen enhanced substrate.
- Combining the techniques of n-side read-out (to reduce the influence of trapping) and enhanced interstitial oxygen should yield tracking detectors good to $10^{15} \text{p/cm}^2$ at least.