Charge Multiplication Properties in Highly-Irradiated Epitaxial Silicon Detectors

Jörn Lange¹, Julian Becker¹, Eckhart Fretwurst¹, Robert Klanner¹, Gregor Kramberger², Gunnar Lindström¹, Igor Mandić²

¹ University of Hamburg
² Jožef Stefan Institute, Ljubljana

Vertex 2010, Loch Lomond, 8 June 2010
Introduction

- Trapping: most limiting factor at S-LHC fluences ($\approx 10^{16}$ cm$^{-2}$)
  ⇒ Degradation of Charge Collection Efficiency (CCE)

- But at high fluences and voltages: CCE > 1
  ⇒ Trapping overcompensated by Charge Multiplication (CM)

- Can CM be used for highly damaged S-LHC detectors?
  ⇒ Detailed understanding of the formation and properties of CM in irradiated sensors needed
Investigated Material

- Epitaxial (Epi) Si on Cz substrate: candidate for superior radiation hardness
  - **Device Engineering:** Thin (25 - 150 µm)
  - **Defect Engineering:**
    - High O concentration in standard material (ST): \(<[O]> = (4.5 - 9.3) \times 10^{16} \text{ cm}^{-3}\)
    - Further O enrichment possible (DO): \(<[O]> = (1.4 - 6.0) \times 10^{17} \text{ cm}^{-3}\)
  - After irradiation with charged hadrons:
    - \(N_{\text{eff}}\) increase at high fluences due to predominant donor introduction
    - n-type: no space charge sign inversion!

- n-type
- 75 µm, 100 µm, 150 µm thickness
- Pad detectors produced by CiS: 5 x 5 mm\(^2\) and 2.5 x 2.5 mm\(^2\)
- 24 GeV/c proton irradiation (CERN PS) up to \(\Phi_{\text{eq}} = 10^{16} \text{ cm}^{-2}\)
- 30 min at 80 C annealing
Experimental Methods

- **Transient Current Technique, TCT (Hamburg)**
  - Front illumination ($\approx 10^6$ e-h pairs deposited)
  - Current-sensitive amplifier
  - Integral of current pulse = collected charge $Q$
  - Charge collection efficiency obtained by normalising $Q$ wrt. unirradiated diode: $\text{CCE} = \frac{Q}{Q_0}$
  - Measured at -10 C
  - Radiation with different penetration:
    - 5.8 MeV $\alpha$-particles, optional absorbers
    - 670, 830, 1060 nm laser light
  - $^{90}$Sr-beta setup (Ljubljana)
    - MIP-like particles
    - Charge-sensitive amplifier, 25 ns shaping time
    - Measured at -29 C

![Image of diode with laser and alpha particles](image.png)

**Creation of e-h Pairs as a Function of Detector Depth**

- 5.8MeV $\alpha$-particles (SRIM)
- 5.8MeV $\alpha$-particles + 12µm PE absorber
- 5.8MeV $\alpha$-particles + 24µm PE absorber
- mips/$\beta$ (x100), 1060nm laser ($\lambda=1$mm, a.u.)
- 670nm laser ($\lambda=3$µm, a.u.)
- 830nm laser ($\lambda=13$µm, a.u.)

- Bragg peak
Development and Localisation of the CM Region

Linear field model: $N_{\text{eff}} = \text{const}$
(Modifications at high fluences, e.g. double peak)

Due to irradiation:
$N_{\text{eff}}$ increases $\rightarrow E_{\text{max}}$ at front side increases $\rightarrow$ CM possible

$\rho_i = eN_{\text{eff}}$

$p^+\quad n \quad n^+$

$N_{\text{eff},2} = 2N_{\text{eff},1}$

$W_2 = \frac{W_1}{\sqrt{2}}$

$|E|$

Due to irradiation:
$N_{\text{eff}}$ increases $\rightarrow$ $E_{\text{max}}$ at front side increases $\rightarrow$ CM possible

Comparison of $I_{\text{rev}}$ and CCE for different sources

- n-EPI-ST 75\,\mu m, $\Phi_{eq} = 1 \times 10^{16}\,\text{cm}^{-2}$
  - CCE (670nm laser)
  - CCE (830nm laser)
  - CCE (1060nm laser)
  - CCE ($\alpha$-particles)
  - CCE ($\alpha$-part. + 12\,\mu m PE abs.)
  - CCE ($\alpha$-part. + 24\,\mu m PE abs.)
  - $I_{\text{rev}}$ (arb. normalised)

Smaller penetration depth
$\rightarrow$ stronger CM

$\Rightarrow$ Thin CM region located at the front side
Linearity of Measured Charge

Measured charge vs. deposited charge

n-EPI-ST 75μm, $10^{16}$cm$^{-2}$, 670nm; Fits: $y=a_0+a_1x$

- 900V, $a_0=5.8e-001$, $a_1=6.5$
- 700V, $a_0=8.5e-002$, $a_1=2.4$
- 500V, $a_0=3.6e-002$, $a_1=1.1$
- 300V, $a_0=3.1e-002$, $a_1=0.6$

⇒ Proportional mode
not Geiger mode

⇒ E too small for contribution of holes to impact ionisation
Spatial Uniformity and Long-Term Stability

Example: 800V

**Uniformity**
- x-y-scan with 660 nm laser: beam spot $\sigma_{\text{beam}}=20 \, \mu\text{m}$, 200 $\mu\text{m}$ step width
  - $$\Rightarrow$$ very uniform
    ($\sim 0.5 – 1 \%$ standard deviation)

**Stability**
- Repeated measurements at constant voltage, temperature
  - $$\Rightarrow$$ stable in time
- Limiting factor at high voltages: micro discharges
  - $$\Rightarrow$$ improvement of device technology desirable
Collected Charge with $^{90}\text{Sr}$ $\beta$-Setup

- At least 2500 single waveforms taken
  - Most Probable Value (MPV) determined by Landau-Gauss fit to spectrum: not possible for highly-irradiated diodes due to noise
  - Mean determined by averaging waveforms: also for low Signal-to-Noise Ratio (SNR) possible

- Unirradiated diodes:
  - Collected charge proportional to thickness
    - MPV: 80 e-h/µm
    - Mean: 97 e-h/µm
    - MPV/Mean $\approx 0.75 – 0.85$
    - Noise $\approx 2000-3300$ e (pad diodes!) depending on size, thickness

Charge as a Function of Thickness

- Mean
- MPV

---

Jörn Lange – Charge multiplication in EPI Si diodes

8 June 2010, Vertex 2010, Loch Lomond
Charge for Different Materials and Thicknesses at Highest Fluence

- $Q(75\mu m) > Q(100\mu m) > Q(150\mu m)$
  
  due to higher $E$-field and weighting field in thin diodes
  
  $\Rightarrow$ less trapping effects, more CM

- $Q(DO) < Q(ST)$ below the CM regime,
  $Q(DO) > Q(ST)$ in the CM regime
  
  due to higher donor introduction rate in DO
  
  $\Rightarrow$ smaller depleted region at low voltages; higher $E_{\text{max}} \rightarrow$ higher CM

- For all materials/thicknesses:
  
  - More than 9000 e possible at high voltages
  - More than 5000 e at 500 V
    (mean values)
Current and Noise

- CM expected to increase signal, current and noise
- Current and noise increase strongly
- Same material and thickness dependence as signal
  - Larger for thinner diodes
  - Larger for DO

\[ Q = M Q_{M=1} \]
\[ I = M' I_{M'=1} \]
\[ \sigma_{\text{shot}} = M' \sqrt{F' \sigma_{\text{shot},M'=1}} \]
\[ \sigma_{\text{noise}} = \sqrt{\sigma_{\text{shot}}^2 (M') + \sigma_{\text{noise}}^2} \]

RMS Baseline Noise

\[ \Phi_{eq} = 10^{16} \text{cm}^2 \]

- n-EPI-ST 75 μm
- n-EPI-DO 75 μm
- n-EPI-ST 100 μm
- n-EPI-DO 100 μm
- n-EPI-ST 150 μm
- n-EPI-DO 150 μm
Signal-to-Noise Ratio

- \[ \text{SNR} = \frac{Q}{\sigma_{\text{noise}}} = \frac{MQ_{M=1}}{\sqrt{M^2 F'M'^2 \sigma^2_{\text{shot},M'=1} + \sigma^2_{\text{noise}}}} \]

- Depends on relative size of different terms whether CM can improve SNR

- **TCT setup:**
  - \( \sigma_{\text{noise}} \) large
  - \( \Rightarrow \) SNR improves up to 900 V

- **\( \beta \)-setup:**
  - \( \sigma_{\text{noise}} \) smaller
  - \( \Rightarrow \sigma_{\text{shot}}(M') \) dominates early and increases faster than signal
  - \( \Rightarrow \) SNR decreases after maximum at 300 – 500 V

- What about pixels?
  - Lower I
  - Threshold \( >> \) noise (unirr.)
  - \( \Rightarrow \) noise increase tolerable?
Fluctuations due to CM might increase spectrum width

No significant increase of noise-corrected relative width with voltage

⇒ no significant impact of CM fluctuations observed
Summary

- Properties of charge multiplication in proton-irradiated EPI diodes investigated with
  - TCT (laser light, α-particles)
  - $^{90}$Sr β-setup with charge-sensitive amplifier, 25 ns shaper
- Thin CM region at the front side
- Proportional mode
- Uniform
- Stable
- β-setup: strong noise increase ⇒ SNR decreases at high voltages
- No significant increase of noise-corrected relative width of charge spectrum
  ⇒ no impact of CM fluctuations

High signals at S-LHC fluences possible!
Can noise increase be controlled or tolerated in segmented detectors?
Depletion Voltage (from CV at 10 kHz)

- CV/IV measurable up to $4 \times 10^{15}$ cm$^{-2}$ at room temperature
- Annealing curve at 80 C (isothermal) → no type inversion
- Stable Damage (8 min at 80 C): first donor removal, then donor introduction with $g_C(\text{DO}) > g_C(\text{ST})$

Annealing curve:

$T_a=80^\circ$C

- CV/IV measurable up to $4 \times 10^{15}$ cm$^{-2}$ at room temperature
- Annealing curve at 80 C (isothermal) → no type inversion
- Stable Damage (8 min at 80 C): first donor removal, then donor introduction with $g_C(\text{DO}) > g_C(\text{ST})$
Laser - TCT Setup

- **Laser Controller**: Picoquant Sepia II
- **PC Control and Data Acquisition**: Kei 2700
- **Temperature**: Kei 5077A
- **V-Source I-Meter**: Kei 6517A
- **Oscilloscope**: Tektronix DPO7254 (2.5GHz, 40GS/s)

General Diagram:
- **Trigger Line**
- **670nm Laser Diode**
- **Filter Box**
- **Amp**: Phillips Scientific Model 6954, 10x
- **Light-Wave Cable**
- **Detector Mounting**

Additional Details:
- **Picosecond Pulse Lab 5531 Bias-T**
- **2kΩ, 100nF, 2kΩ**
- **3kΩ, 2.2nF**

8 June 2010, Vertex 2010, Loch Lomond
Jörn Lange – Charge multiplication in EPI Si diodes

Noise and SNR (TCT with Laser)

![Graph showing Baseline Noise and SNR vs. Mean Collected Charge Q]

- 670 nm laser, unirradiated
- 670 nm laser, $10^{16}$cm$^{-2}$
- 1060 nm laser, unirradiated
- 1060 nm laser, $10^{16}$cm$^{-2}$
Width of Charge Spectrum

- Fluctuations in the CM process might increase spectrum width: \( \sigma_{sp} = M \sqrt{F} \sigma_{sp,M=1} \)

- Laser light \((\approx 10^6 \text{ e-h})\): Relative width of charge spectrum not increasing \(\Rightarrow\) no fluctuations in CM process

- \(\alpha\)-particles: Strong increase of relative width due to fluctuating fraction of charge deposited in the CM region

### Relative Width of Charge Spectrum

- 670 nm laser, unirradiated
- 670 nm laser, \(10^{16}\text{ cm}^{-2}\)
- 1060 nm laser, unirradiated
- 1060 nm laser, \(10^{16}\text{ cm}^{-2}\)
- \(\alpha\)-particles, unirradiated
- \(\alpha\)-particles, \(10^{16}\text{ cm}^{-2}\)
Sr Beta Setup

n-EPI-ST 150 µm, unirr., 333 V

Ljubljana setup for pad diodes:

- Charge-sensitive preamplifier (Ortec 142B) + shaper (25 ns shaping time)
- Scintillator → high purity trigger ⇒ signals with SNR<1 measurable
- T between -25°C and -29°C
- Calibrated with $^{241}$Am, cross-checked with 300 µm diode
- Single waveforms taken with oscilloscope
- Averaged waveform:
  Peak determination possible even for low SNR
  ⇒ for highly-irradiated diodes mean is considered instead of most probable value (MPV)
- Micro discharges in certain samples at high voltages (independent of fluence)
Collected Charge for Different Fluences

- Charge multiplication at high fluences and voltages
Current and Noise

- CM expected to increase signal, current and noise
- Current and noise increase strongly
- Same material and thickness dependence as signal
  - Larger for thinner diodes
  - Larger for DO

\[ Q = M' Q_{M=p} \]
\[ I = M' I_{M=p} \]
\[ \sigma_{\text{shot}} = M' \sqrt{F' \sigma_{\text{shot},p}} \]
\[ \sigma_{\text{noise}} = \sqrt{\sigma_{\text{shot}}^2 (M')} + \sigma_{\text{noise}}^2 \]
Width of Charge Spectrum

- Fluctuations due to CM might increase spectrum width
- No significant increase of noise-corrected relative width with voltage

⇒ no significant impact of CM fluctuations
CCE Dependence on Annealing

In the CM regime:

- Maximum of CCE at 8 min
- CCE annealing curve shows the same behaviour as the one of $U_{dep}$, $N_{eff}$

$N_{eff}$ higher $E_{max}$ → higher CM