TCT measurements of n-type MCz diodes after irradiation with 70 MeV protons and 300 MeV pions

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Background and motivation

N-in-N MCz detectors show peculiar properties:

- No space charge sign inversion for 23 GeV protons
- Relatively stable $V_{fd}$ for 200 MeV pions
- Additive space charge characteristics might enable the usage of cancelling effects to keep $V_{fd}$ low/stable
  - Optimal $N_{eff}$ stability at 2 parts proton and 1 part neutron radiation. Potential compensation of Neff for intermediate radii in ATLAS/CMS for n-in-n MCz.
- Results from: Kramberger et al., NIM A 612 (2010) 288 and NIMA A 609 (2009) 142
From previous results we know that 24 MeV proton irradiated n-in-n MCz behave like FZ silicon, while 23 GeV proton irradiation do not.

- LHC background energy spectrum peaks around 100-200 MeV
- 70 MeV proton irradiated samples acquired to investigate their behavior.
  - 1e13 n_{eq}/cm^2, 1e14 n_{eq}/cm^2, 5e14 n_{eq}/cm^2
- 200 MeV pion literature results showing ambiguous behavior.
- 300 MeV pion irradiated samples acquired to see if the results can be clarified
  - 1e13 n_{eq}/cm^2, 1e14 n_{eq}/cm^2, 2.76e14 n_{eq}/cm^2, 4.26e14 n_{eq}/cm^2
TCT+ setup at CERN

- Red Laser illumination possible from top and bottom side of DUT
- 2.5 GHz Agilent Scope
- Flushing with dry air
- Computer controlled peltier cooling down to -20°C
- Bias voltage up to 1000V

Pulsed laser with a trigger frequency of 200Hz

Red (660nm)  IR (1064nm)
Particulars TCT setup at Lancaster University

- IR pulsed laser
  - 20 kHz
  - \( \leq \) ns pulse length
- Adjusted to CERN’s PCB
- 2.5 GHz Tektronix DPO
- Nitrogen for flushing
- Peltier for cooling down to \(-20^\circ C\)
- Keithely 2410 for bias voltage up to 1100V
70 MeV Proton samples
IV curve

- IV measurements taken by Rebecca Carney with IV/CV measurement setup at CERN
- Clearly increasing leakage current with fluence, as to be expected
70 MeV Proton samples
Waveforms

Electrons – 1e13 n$_{eq}$/cm$^2$

Holes – 1e13 n$_{eq}$/cm$^2$

Electrons – 5e14 n$_{eq}$/cm$^2$

Holes – 5e14 n$_{eq}$/cm$^2$
70 MeV Proton samples Waveforms

• Waveforms highlight summarized below
• Both n-side and p-side show clearly shows a gradient sign change for the $5 \times 10^{14}$ $n_{eq}/cm^2$ sample.
• Most likely suggests SCSI
70 MeV Proton samples
Depletion voltage

- $V_{fd}$ calculated with TCTana, same method as 300 MeV pion samples
- Together with waveforms, most likely type inversion occurs slightly above $1 \times 10^{14}$ n$_{eq}$/cm$^2$

$V_{fd}$ calculation from CCE example
70 MeV Proton samples
Annealing study

- Annealing done at 60° C
- After 1e14:
  - Initially reverse followed by beneficial annealing
- After 5e14:
  - Initially beneficial annealing
  - After approx. 70 min at 60° C reverse annealing is dominating
- Analogous to DOFZ -> no compensation

<table>
<thead>
<tr>
<th>Annealing step</th>
<th>Time in oven (min)</th>
<th>Compensated time (min)</th>
<th>Total annealing time (min)</th>
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<tr>
<td>1</td>
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<td>13.5</td>
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<td>250</td>
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<tr>
<td>4</td>
<td>988</td>
<td>931.5</td>
<td>1225</td>
</tr>
</tbody>
</table>

Depletion voltage vs annealing time, MCz silicon 1E14 proton irradiation

Depletion voltage vs annealing time, MCz silicon 6E14 proton irradiation
**300 MeV pion samples**

**IV curves**

- **$V_{fd}$ values used from results with IR laser**
- **$I_{L2}$** is $I_{\text{leak}}$ at temperature $T$.
- **$I_{L1}$** is $I_{\text{leak}}$ at temperature $T + \Delta T$.
- Used to calculate $I_{\text{leak}}$ at different $T$

\[ \frac{I_{L2}}{I_{L1}} \approx \exp \left[ \left( \frac{3}{\eta T} + \frac{E_G}{\eta T E_T} \right) \Delta T \right], \quad (\eta=2, \ E_G=1.12\text{eV}, \ E_T=0.0259\text{eV}) \]
300 MeV pion samples
Waveforms (IR)

$1 \times 10^{13}$ n$_{eq}$/cm$^2$

TCT Measurement @ T=+14 C

$1 \times 10^{14}$ n$_{eq}$/cm$^2$

TCT Measurement @ T=+11 C

$2.76 \times 10^{14}$ n$_{eq}$/cm$^2$

TCT Measurement @ T=+11 C

$4.26 \times 10^{14}$ n$_{eq}$/cm$^2$

TCT Measurement @ T=+09 C
300 MeV pion samples
CCE and $V_{fd}$

• Results hint at increasing $N_{eff}$ with increasing fluence
• Systematically too low $V_{fd}$ for two lowest fluences, due to overshoot.
• Unsure of overshoot origin (only seen in low fluences and unirradiated MCz)
  • Any ideas?

Depletion voltage vs fluence
300 MeV Pion samples
Red Laser comparison (holes)

- Hints at possible SCSI or strong double junction forming between 1e14 n$_{eq}$/cm$^2$ and 2.76e14 n$_{eq}$/cm$^2$

1e13 n$_{eq}$/cm$^2$

300 MeV Pion samples
Red Laser comparison (holes)

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1e14 n$_{eq}$/cm$^2$

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300 MeV Pion samples
Red Laser comparison (holes)

- Hints at possible SCSI or strong double junction forming between 1e14 n$_{eq}$/cm$^2$ and 2.76e14 n$_{eq}$/cm$^2$
300 MeV Pion samples
Red Laser comparison (electrons)

- No suggestion at SCSI from electron drift, rather seems to hint at a double junction

Data taken by Isidre Mateu at CERN
Conclusion

- n-in-n MCz still puzzling
- 70 MeV protons cause SCSI (like DOFZ, like reactor neutrons and 24 MeV protons in n-in-n MCz)
- 200 MeV pions looked somewhat ambiguous in literature
- 300 MeV pions looked even more ambiguous in our measurements:
  - red laser TCT data indicate SCSI or at least formation of a strong double junction
  - IR laser TCT data suffers from overshoot of slow moving charge (where from?) for low fluences, indicates rather no SCSI
- Outlook:
  - CV measurements on 300 MeV pion-irradiated diodes
  - annealing study
  - add more irradiations in relevant energy region:
    - slow down 800 MeV protons at LANCSE or pions at PSI?
    - more additive studies?