Characterisation of irradiated silicon sensors with the Transient Current Technique

Claudia Merlassino
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Future of the LHC

In collider experiments a large amount of data is needed for:
- precision measurements
- sensitivity to processes with low cross section

The second run of the LHC is exceeding any expectation:
- new record of peak luminosity: $1.74 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- integrated luminosity $52 \text{ fb}^{-1}$, for now ;)

The upgrade project already started: **High Luminosity LHC**

- up to 200 collisions per bunch crossing
- peak luminosity $> 7.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$
- integrated luminosity $> 3000 \text{ fb}^{-1}$
Consequences on the ATLAS tracking detectors

Tracking detectors will need major upgrades to cope with the new conditions whilst providing:

- separation of primary vertices in a busy environment
- efficient readout
- tolerance to high radiation doses

Focusing on the radiation problem:

- tracking detector mostly effected
  - close to the interaction point
- present ATLAS Inner Detector not designed for these conditions
  - all subsystems will be replaced
  - full silicon
Expected dose for the ATLAS tracker upgrade

The total expected dose is studied with simulations and all the technologies are being tested in those conditions focus on HV-CMOS, sensors candidate for the 5th pixel layer.

TDR for the ATLAS Inner Tracker Strip Detector
http://inspirehep.net/record/1614102
Transient Current Technique (TCT)

- injection with µm precision
- possibility of injection from the edge

→ probe charge collection at different levels of the sensor depth
Charge collection maps

The measurements of the charge collected moving the laser along the sensor edge allow to create a 2D map of the active area.

edgeTCT map - single pixel

HV-CMOS pixel schematics
Depletion region

Signal of a particle that passes through the sensor $\propto$ to the depletion region $\rightarrow$ important parameter to have under control to be fully efficient!

Evolution with the bias voltage

- 2D maps collected at different level of voltage
- good agreement with the expected evolution

$$d = \sqrt{\frac{2\varepsilon}{q} \left( \frac{1}{C_A} + \frac{1}{C_D} \right) \Delta V}$$

$C_{A/D} = \text{concentration of acceptors/donors}$
Evolution after irradiation with protons

The sensor is irradiated with **18 MeV protons** at the Bern cyclotron
(see A. Fehr’s presentation)
and characterised after each step of irradiation

**Graph: 200Ω cm resistivity**

**Observations:** strong increase of the depth at low dose, then slow decrease
The depletion region depends on the acceptor concentration:

\[
d = \sqrt{\frac{2\varepsilon}{q} \left( \frac{1}{C_A} + \frac{1}{C_D} \right) \Delta V} = \sqrt{\frac{2\varepsilon}{q} \frac{1}{N_{eff}} \Delta V}
\]

And the fluence \( \Phi \) introduces two competitive effects:

\[
N_{eff} = N_{eff0} - N_C \cdot (1 - \exp(-c \cdot \Phi)) + g_c \Phi
\]

Our measurements quantitatively assess the two effects in proton irradiation.
Conclusions

Upgrade of the ATLAS tracker detector for the High Luminosity LHC
- new frontier for radiation hard silicon detectors
- test on proton irradiated sensors prototypes
- edge-TCT studies for depletion depth evolution due to radiation dose
- parametrisation of the doping concentration VS fluence

Additional measurements:
- dependence on the initial doping concentration (sensor resistivity)
- dependence on radiation source

Thank you!
Backup slides
ATLAS Inner Detector now

The Inner Detector provides the reconstruction of charged particle tracks:

- transverse momentum measurement
- collision and decay vertex identification

→

- high segmentation
- long lever arm
- as close as possible to the interaction point

Pixel Detector + IBL
Silicon sensors
highly segmentated, close to the beam pipe

SCT
Larger silicon strips

TRT
Gaseous detector, covers a large area
Detecting particles with silicon

Silicon is a semiconductor

- energy released by charged particle creates electron-hole pairs
- small band gap
  hard to discriminate from thermal excitation

Solution: p-n junction

- created by joining n-type and p-type doped silicon
- charge migration creates a region without free charges (depletion zone)
- the depletion zone can be enlarged by applying a reverse bias voltage
New monolithic sensors proposed for the outer pixel layers

- CMOS technology embedded in each pixel
- shielded by a deep n-doped region

Pros:
- possibility of industrial production $\rightarrow$ lower cost
- small depletion zone $\rightarrow$ radiation hardness
Protons give two different kind of radiation damage:

- total ionising dose (TID)
  fully recovered in the silicon bulk,
  important for the front-hand electronics
- nuclear collisions responsible for the non-ionising energy loss (NIEL)
  (expressed in $1 \text{ MeV n}_{eq}/\text{cm}^2$ to compare different particles)

Effects:

- change of effective doping concentration
  $\rightarrow$ higher operation voltage to obtain the same performances
- increase of the leakage current
- defects in the lattice $\rightarrow$ charge trapping
TID - NIEL conversion

\[
\begin{align*}
\text{fluence} &= D(E) \times \frac{n_p}{\text{cm}^2} \\
TID &= \frac{dE}{\rho dX} \times \frac{n_p}{\text{cm}^2}
\end{align*}
\]

Hardness factor \( \approx 3 \) from database:
http://www.sr-niel.org

(http://rd50.web.cern.ch/RD50/NIEL/default.html used for cross-checks)

![Graph showing ionising dose vs. fluence](image)