Macroscopic Radiation Damage in Semiconductor Detectors

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Outline

• Motivations
• Principle of operation of semiconductor detectors
• Macroscopic radiation effects on detector systems
• Possible radiation mitigating techniques
• LHC Silicon detector experience
• Future HI-LHC detectors
• This lecture will cover Silicon pixel and strip detectors only
Why?

- Silicon is, among the materials used to build particle detectors, the one which is most similar to a stone.
- But nevertheless its crystal structure is delicate when exposed to high intensity particle fluxes.
But this is where we want to use it

https://cmsinfo.web.cern.ch/cmsinfo/Media/Publications/CMStimes/2007/02_19/images/Luminosity.gif
The requests for future Silicon based detectors

- High Intensity LHC (HI-LHC) will eventually reach instantaneous luminosity close to $10^{35}\text{cm}^{-2}\text{s}^{-1}$
- To extract good physics data at this luminosity the detectors should cope with a flux of particles which is $\geq 10$ higher than now, so we need
  - Higher granularity
  - Higher number of channels
  - Higher power
  - Better cooling
- Scaling with the luminosity the radiation damage produced by the particle flux accumulates at a higher rate
- In HI-LHC detectors we expect a flux 10 times the one expected when the present LHC experiments were designed
- Some 100 times the one accumulated during the first two years of operation
- No way: the tracking detectors should be replaced after the first ten years or even before
Principle of operation of a Silicon detector

- Reverse diode detectors: a short remind
- Signal formation
- Segmented detectors
- Noise of the detector system: Sensor plus Electronics
Semiconductor detector scheme

- High resistivity (\(\sim k\Omega\,\text{cm}\)) Silicon layer + ohmic contact + reverse biased asymmetric junction

\[ V_{dep} = \frac{q_0}{\varepsilon \varepsilon_0} |N_{eff}| d^2 \]

For \(d=300\mu m\), \(N_{eff}=10^{12}\,\text{cm}^{-3}\)
\(\rho=4.4\,\text{K}\Omega\,\text{cm}\)
\(V_{dep}=70V\), \(E_{max}=4.6\text{KV/cm}\)

\[ V_{bias} > V_{dep} \]
Full depletion
Segmented (microstrip) detector
Signal

- **Deposited energy** / Mean excitation energy

The energy loss of a charged particle has a minimum at $p \sim 4mc \rightarrow$ Minimum Ionizing Particles [MIP]

MIP mean energy loss
\[ \text{d}E/\text{d}x \text{ (Si)} = 388 \text{ eV/µm} \]

$\Rightarrow$ 116 KeV for 300µm thickness

Signal

- Deposited energy / Mean excitation energy

Event-by-event energy loss fluctuations ‘follow’ the Landau distribution

Signal

• **Deposited energy** / Mean excitation energy

The most probable energy loss depends on detector thickness:
About 60-70% of the mean dE/dx

Most probable energy loss in 300µm thick Si
For a MIP is:
≈ 0.67 × mean
⇒ 81 keV

Signal fluctuation visualization

55\(\mu\)m pixels \(\rightarrow\) measured most probable value = 14 KeV/55\(\mu\)m = 255 eV/\(\mu\)m (as expected)

Cosmic ray track viewed by Timepix detector

\[\text{Data are fit by convolution of Landau and Gauss distributions.}\]

Signal

- Deposited energy / Mean excitation energy

The average energy to produce an electron-hole pair in Silicon is ~ 3.6 eV

Most probable MIP Signal in 300µm of Silicon $\rightarrow$ 22500 [e\textsuperscript{-}] or 3.6 fC (75 e-h couples / µm)

Average MIP Signal in 300µm of Silicon $\rightarrow$ 32200 [e\textsuperscript{-}] or 5.2 fC (107 e-h couples / µm)

Simulated Current Density

Ionizing particle with 45° angle \( t=0 \) s
t=1 ns
t=1.1 ns
Simulation Thomas.Eichhorn@kit.edu

\[ t = 1.2 \text{ ns} \]
t = 1.3 ns
t=1.4 ns
$t = 1.6 \text{ ns}$
t = 1.7 ns
t=1,9 ns
$t=3 \text{ ns}$
Mind all electrons collected

$t=7\text{ ns}$
Current pulses in strip detectors (track traversing the detector)

Depletion voltage = 60V  Bias voltage = 90V

The duration of the electron and hole pulses is determined by the time required to traverse the detector as in a parallel-plate detector, but the shapes are very different.
Strip Detector Signal Charge

In both electrodes the induced current must be integrated over the full collection time to optimize energy resolution.
Noise

- What is important to characterize the quality of a detector is its ‘signal-to-noise ratio’
- In a 300μm thick Silicon microstrip detector the minimum charge produced by a MIP is about 70% of the MPV
- If an electronic noise of about MPV/8 is superimposed the minimum charge can mix to the pedestal (signal when no particle crosses the detector) by 3 sigma
- In this condition the detector efficiency starts to decrease and/or the noise contamination becomes relevant
Electronic noise

\[ C_d = \text{detector capacitance} \]
\[ I_b = \text{bias current} \]
\[ R_p = \text{bias resistor} \]
\[ R_s = \text{strip resistance} \]
\[ V_{na}^2 = \text{Preamplifier noise} \]

\[ ENC_{parallel}^{I_b} \approx 108 \cdot \sqrt{I_b (\mu A) \tau (ns)} e^- , \]
\[ ENC_{parallel}^{R_p} \approx 24 \cdot \sqrt{\tau (ns) / R_p (M\Omega)} e^- , \]
\[ ENC_{series}^{R_s} \approx 24 \cdot C_{tot} (\text{pF}) \cdot \sqrt{R_s (\Omega) / \tau (ns)} e^- \]

+ front end electronics: \( ENC_{fe} = a + bC_d \)

\[ Noise = \sqrt{\sum (ENC_i)^2} \]
Radiation damage

• **Surface damage**
  – accumulation of charge in the oxide (SiO$_2$), traps at Si/SiO$_2$ interface
  – Depends on the ionization energy loss (Dose [rad])

• **Volume damage**
  – displacement damage → crystal defects
  – Depends on the non-ionization energy loss (NIEL, fluence normalized to 1 MeV neutron)
Surface damage

• This effect is due to the presence in the SiO₂ and SiO₂-Si interface of positive charges
  1. Fixed charges → from production process
  2. Mobile positive impurity ions → same as 1.
  3. Trapped holes → from irradiation

• The trapped holes (less mobile than electrons) are generated by ionization
  – Heavy charged particles → high ionization density → high recombination
  – Electrons/photons → low ionization density → low recombination → dominates

• This charged layer changes the electric properties of the segmented side of the detector
  – Increases the interstrip capacitance (C_{int})
  – Increases the surface current
  – Reduce the breakdown voltage

• Depends on the crystal orientation
• Important for Linear Collider and Xfel experiments
Surface damage $<111>$ vs $<100>$

The $C_{\text{int}}$ (main contribution to $C_d$) increases with irradiation in $<111>$ silicon but stays constant in $<100>$ one.

Dangling bonds at the SiO$_2$-Si interface play an importante role.

$w =$ strip width
$p =$ strip pitch

Yellow = no irradiation
Blue and green = $4 \times 10^{14}$ p/cm$^2$

S. Braibant et al., CMS NOTE 2000/011
Volume damage

• Volume (Crystal) damage is due to (scales with) Non Ionizing Energy Loss (NIEL) and results in:
  1. Change of effective doping concentration (higher depletion voltage, leading possibly to under-depletion)
  2. Increase of leakage current (increase of shot noise, thermal runaway)
  3. Increase of charge carrier trapping (charge collection efficiency decreases)

• Signal-to-noise ratio could then be reduced substantially

• The sensor total depletion could not be reached

• Safe detector operation is jeopardized by the possible thermal runaway (sensor temperature increased by the bias current, which is increased by temperature, which ... ) → Positive feedback
It is defined as the amount of energy released into the material by an incident particle which is not loss in ionization.

This is the energy which breaks the crystal lattice and introduce defects in the material.

Different particles have different effectiveness in releasing NIEL; to compare irradiation a possible solution is to normalize to the NIEL of a 1 MeV neutron.

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NIEL

Damage relative to 1 MeV neutrons

LHC spectra

NIM A 335 (1993) 580-582
Microscopic view...

The damaged lattice ‘zoo’

J. Zhang
Change of depletion voltage

Before inversion, in p-in-n sensors, the junction is on the segmented side (the depletion starts from there). After inversion the junction moves on the back side and the depletion starts from there. 

p+ and n+ layers are unaffected by radiation because their doping concentrations are very high.

Donor removal +  
Acceptor generation

Accepter generation

Keep in mind that ‘resonable’ bias voltages should be less than 1000V (…and what IV means)
N_{eff} annealing

- After irradiation the lattice defects and interstitials start to interact eventually leading to a change in the $N_{eff}$ with time and temperature $\rightarrow$ annealing

- Essentially two annealing are present:
  - Short term beneficial annealing
  - Long term reverse annealing
    - Time constant 500 years at -10 °C $\rightarrow$ 500 day at 20 °C $\rightarrow$ 21 hours at 60 °C
- Irradiated sensors should be kept cool all times
Oxigen enriched silicon

Introducing oxigen in the silicon bulk material a reduced sensitivity to the NIEL released by charged hadrons is obtained

NIEL scaling violation

RD48 Status Report CERN/LHCC 2000-009
Change of leakage current

- The leakage current of a sensor, at constant temperature, increase with the NIEL
- The damage parameter doesn’t depend on Silicon resistivity, bulk type, fabrication technology, ...

\[ \alpha = \frac{\Delta I}{V \cdot \Phi_{eq}} \]

Current change
NIEL normalized Fluence
Detector depleted volume
Leakage current annealing

- Also the leakage current is subject to an annealing process
- The measurement of $\alpha$ should be done after a well defined annealing process (temperature and duration)
- Std procedure 80 minutes at 60 °C
- The leakage current has a strong dependence on the sensor temperature: each 7 °C increase of a factor two →
- Irradiated detector should be operated at low temperature
Change of charge collection efficiency

• The irradiation introduces defects which act as trapping center for the charge generated by an ionizing particle
• This reduce the overall signal thus affecting the detector efficiency

\[ Q_{e,h}(t) = Q_{0e,h} \exp \left( -\frac{1}{\tau_{\text{eff},e,h}} \cdot t \right) \]

\[ \frac{1}{\tau_{\text{eff},e,h}} = \beta_{e,h}(T, t) \Phi_{eq} \]

• When the effective trapping time becomes of the order of the electron/hole drift time (5-20ns) the charge integrated at the electrodes by the front-end electronics is reduced
The trapping time too is subject to an annealing process but with different behaviour for the two carries: the electrons get better, the holes get worse.
Radiation hard Silicon detector

• Approach on two sides
  – Microscopic: material engineering (Oxigenated Silicon, crystal grown: FZ-MCz-Epi)
  – Macroscopic: device engineering
    • p-type sensors
    • Thin sensors
    • 3D sensors
**p-type detectors**

- The electrons mobility in Silicon is higher (factor ~3) than the holes one
- The charge trapping times (see slide 47) are more or less the same (remember that annealing help electrons)

Using a detector configuration with a signal produced mainly by electrons should reduce the radiation induced trapping effects

http://www.hephy.at/user/friedl/diss/html/node11.html
Signal formation (i)

- The current pulse shape originating from a MIP orthogonally crossing the sensor is very different in n-in-p with respect to p-in-n devices.
Signal formation (ii)

- For p-in-n detectors the signal is mainly produced by the electron drifting to the strips.
- For p-in-n detectors the majority of the signal is produced by the holes and it is much slower than the other.

![Graphs showing signal charge over time for n- and p-strips with symbols for electron (e) and hole (h).]
Device engineering

- **p-in-n detectors**
  - After some value in fluence the bulk type is inverted

- **n-in-p or n-in-n detectors**
  - No inversion at all

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**p-on-n silicon, under-depleted:**
- Charge spread – degraded resolution
- Charge loss – reduced CCE

**n-on-p silicon, under-depleted:**
- Limited loss in CCE
- Less degradation with under-depletion
- Collect electrons (fast)

*Be careful, this is a very schematic explanation, reality is more complex!*

M. Moll
n side read-out behaviour

15000 e⁻ signal:
from $3 \times 10^{14}$ 1MeV $n_{eq}$/cm² in p-in-n up to
$2 \times 10^{15}$ 1MeV $n_{eq}$/cm² n-in-n
Thin sensors

- Very thin (100µm) n-in-p pixel sensors have been tested resulting in an almost full efficiency at $5 \times 10^{15} \, \text{n_{eq}} / \text{cm}^2$
3D sensors

• So far planar technology applied to sensor:
  – J.A. Hoerni (Fairchild Semiconductors) 1957-58
  – Signal proportional to detector thickness
  – A planar detector is depleted starting from junction towards the opposite side (whole thickness)

• 3D technology:
  – Signal proportional to detector thickness
  – Depletion from column to columns (different type) with a distance decoupled from detector thickness
  – Example: 300µm thick sensor and (order of) 50µm columns pitch
3D sensors layout

Depletion voltages order of 10V or less even at high fluences
Fast charge collection when the read-out is connected to n+ columns

Some dead volumes inside the columns → not critical if the particle trajectories are not too collimated and orthogonal to the sensor (tilted detectors)
Some regions with low electric field, poor charge collection
High intercolumn capacitance, higher noise


M. Boscardin, Trento 2015
How to ‘drill’ a hole into Silicon?

Deep Reactive Ion Etching

Ace V Spot Mag WD 5 μm
5.00 kV 3.0 5000x 21.8 mhp closed

"Bosch process PILLAR" by Pgalajda - Own work. Licensed under Public Domain via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Bosch_process_PILLAR.jpg#/media/File:Bosch_process_PILLAR.jpg
The 3D column structure

3D-STC detectors - FBK technology

- Hole etching with Deep-RIE technology
- Wide superficial n+ diffusion in which the contact is located
- Passivation of holes with oxide

- Si High Resistivity, p-type, <100>
- Surface isolation: p-stop or p-spray
- Holes are "empty"

3D: from pixels to strips

3D-STC detectors - Strip detectors

Different strip-detector layouts:
- Number of columns from 12000 to 15000
- Inter-columns pitch 80-100 μm
- Holes Ø 6 or 10 μm

3D pixel efficiency and irradiation

Pixel cell efficiency after irradiation

FBK_11_37_01 (1x10^{15} n_{eq}/cm^2)

Preliminary

1 readout column not enough to fully collect charge in the side regions

Efficiency vs Bias Before Irradiation

Efficiency > 98.5% at V_{bias} > 5 V

Efficiency vs Bias After Irradiation

F. Ravera, Trento 2015
Radiation effects measured on LHC Silicon detectors

- A review of the status of the Silicon detectors, pixel and strips, installed in Atlas, CMS and LHCb experiments
- Mainly data from leakage current and depletion voltage measurements
- LHC Integrated luminosity near to 30 fb\(^{-1}\)
Atlas Pixel Detector

- 3 barrel layers and 3+3 endcap disk
- Coverage $|\eta|<2.5$
- Innermost barrel layer at $r=5\text{cm}$
- n+-in-n 250 $\mu\text{m}$ thick, oxigenated Silicon material
- 1744 modules with $80\times10^6$ pixels, for a total of 1.7 $\text{m}^2$
- 8 $\mu\text{m}$ resolution $r-\phi$
- 75-80$\mu\text{m}$ resolution in $z$
- Evaporative $\text{C}_3\text{F}_8$ cooling (average temperature -13 $^\circ\text{C}$)
- Additional layer (IBL) in 2015: mixed technology planar + 3D sensors
Leakage current evolution

- The Atlas pixel sensors have been kept at -13 °C during most of the time with some periods at room temperature (annealing is clearly visible)
- The measured leakage current is compatible with the predictions
10 years forecast on Leakage current

- The evolution of the leakage current with the following scenario: 10 days at 20 °C every year, otherwise -13 °C
- The temperature is of paramount importance
- Annealing is an important ingredient too
Atlas Semiconductor Tracker (SCT)

- 4 barrel layers and 9+9 endcap disks
- Coverage $|\eta|<2.5$
- 4088 p-on-n microstrip modules, 285$\mu$m thick
- $6.2\times10^6$ channels, 61 m$^2$ of active area
- -7°C operating temperature
Atlas fluence estimation

1 MeV $n_{eq}$ fluence [particles / cm$^2$]

- 1 MeV neutron equiv. /cm$^2$ for 1fb$^{-1}$ of integrated luminosity

Pixel

- After 500fb$^{-1}$: $10^{15}$ $n_{eq}$cm$^{-2}$
- After 500fb$^{-1}$: $10^{14}$ $n_{eq}$cm$^{-2}$

ATLAS Simulation

SCT

2014 JINST 9 P08009
Atlas SCT: leakage current evolution

- Also in SCT the leakage current is in agreement with the expectations
- Annealing during the LHC shutdowns and technical stop periods is visible
SCT noise performance

- The radiation effects are still very low: the noise is practically unaffected and the efficiency is close to full

Koichi Nagai, Vertex 2014
CMS Pixel detector

- 3 barrel layers and 2+2 endcap disks
- Coverage $|\eta|<2.5$
- Barrel layers at $r = 4.3, 7.2, 11$ cm
- n+-on-n
- 10 $\mu$m resolution $r-\phi$
- 100x150$\mu$m² pixel size
Total leakage current vs luminosity

Leakage current vs $\phi$ (off-center detector position)

CMS pixel position $s$ seen from nuclear interaction vertices
CMS Pixels: Depletion voltage evolution

- Method: measure the Voltage at which the Hit Finding Efficiency is 99% of the plateau value
- Plot it as function of the integrated luminosity
- At least for layer 1 the type inversion point has been reached
Lorentz angle vs fluence

- The Lorentz angle depends on the fluence
- Should be constantly monitored because it has an influence on the local hit position reconstruction

24/03/2015 C. Civinini INFN - Firenze
CMS strip tracker

- 4+6 barrel layers
- 3+9 endcap disks
- 200 m² of silicon
- p-on-n sensors
- 15148 modules, 320-500µm thick
- 9.6*10⁶ channels
CMS strip leakage current

- The detector has been operated at +4 °C (dew point in tracker quite high)
- In some cases already 30% of the HV power supply limit (12mA)
- After an intervention to seal the tracking volume now -20°C could be reached (-15°C has been chosen for operation)
CMS strip: foreseen depletion voltage

Projected depletion voltage at 700fb⁻¹ when running with
-15°C cooling plant set point before LS2 and -20°C afterwards

CMS simulation
L=700fb⁻¹

TID

+Z

TEC

TIB L2
TIB L4
TOB L2
TOB L4
TOB L6

TIB L1
TIB L3
TOB L1
TOB L3
TOB L5

-z

LHCb

- Single arm spectrometer for b physics
- \(2 < \eta < 5\)
- Silicon strip detectors:
  - VELO
  - TT/IT
- Less luminosity than Atlas/CMS
LHCb Vertex Locator (VELO)

- Two single-sided sensors (r-strips, \(\phi\)-strips) glued back-to-back
- Sensors: n+-in-n, n+-in-p on the most upstream modules
- 300\(\mu\)m thick
- Double metal for signal routing
- \(T=-10^\circ\) C

Two halves opened during LHC filling and acceleration phases, then closed for data taking
LHCb Tracker Turicensis (TT)

- p+-in-n sensors
- 500µm thick
- 183µm pitch
- Long readout strips (up to 37 cm → 60pF)
- T=8° C
- 144k channels, 8m²

http://lhcb.physik.uzh.ch/
LHCb: Inner Tracker (IT)

- p+-in-n sensors
- 12 layers
- 320/410μm thick
- 198μm strip pitch
- 130k channels, 4.2m²
- T=8° C
VELO leakage current

- Current normalized to -7°C
- In agreement with predictions

A. Affolder et al 2013 JINST 8 P08002
VELO Depletion Voltage

- n+-in-n sensors invert bulk type after \((7÷10)\times10^{12}\) \(n_{eq}/cm^2\)
- The few n+-in-p sensors have a depletion voltage which increase (as expected p type bulk material)
LHCb: IT Depletion Voltage
LHCb: TT and IT leakage current
HL-LHC

- LHC is an evolving infrastructure which will be improved over decades to exploit its full potential
- During these days the machine is restarting after a period of two years during which the magnet electrical connections have been redone to permit reaching both the energy and luminosity design specifications

LHC / HL-LHC Plan

https://cds.cern.ch/record/1975962/files/new_timeplan_24Sept2014_1_image.png
CMS Phase 1 Pixel upgrade

- The present CMS pixel detector was designed to sustain 500 fb$^{-1}$
- But the instantaneous luminosity evolution will soon exceed the rate capability of read-out chips and data links
- The new detector will have the same sensor type (n-in-n), a new read-out chip (evolution of the present one) and more redundancy → one more barrel layer (4) and one more disk per side (3+3)
- The new beam pipe with a radius of 22.5mm, instead of 30mm, will allow to place the innermost barrel layer at 29mm, instead of 43mm) with important improvements on the b-tagging capabilities of the system
CMS Phase 2 Pixel upgrade

- After 500 fb$^{-1}$ also the phase 1 detector starts to lose some of its key performance on tracking
- A full replacement of the pixel detector, together with the external microstrip detector, is foreseen starting from 2022

M. Musich, Vertex 2014
CMS phase 2 pixel layout

- Improve the resolution at high $p_t$ → higher granularity
- Improve the resolution at low $p_t$ → reduce the material
- Increase acceptance up to $|\eta|<4$ → 10+10 endcap disks
- Pixels dimensions: 25x100 $\mu m^2$ (50x200 $\mu m^2$ external layers)
- Sensor choice: planar n-in-p thin or 3D
The phase 2 tracker upgrade

- Aside the radiation problems, at HI-LHC luminosities the whole CMS level-1 muon trigger system will not be more able to reduce the rate selecting high $p_T$ events.
- The phase 2 tracker should be able to provide information already at level 1 trigger (within few $\mu$s from the interaction time).

G. Sguazzoni, Vertex 2014
\( p_t \) module concept

- The \( p_t \) discrimination is done locally using appropriate hit position correlation in two closely spaced detectors
- Only interesting data are sent out at 40MHz to ease an online fast track reconstruction
**$p_t$ modules**

- Two kind of modules: strip-strip (outer), strip-pixel (inner)
- Fluences up tp $1.5 \times 10^{15} \text{n}_{eq}/\text{cm}^2$
- Probably n+-in-p 200$\mu$m thick sensors

G. Sguazzoni, Vertex 2014
The Phase 2 CMS tracker

- 6 barrel layers
- 5+5 endcap disks
The Phase 2 CMS tracker: performance