R&D of silicon detectors for HEP experiments

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ØMIC detector workshop,
Copenhagen, Denmark, 10. 12. 2012
Segmented Si detectors in HEP:

- Used for ~30 years
- Fundamental part of modern HEP experiments (ATLAS, CMS.. at LHC)
- Fast signal formation times, superior spatial resolution → accurate measurement of charged particle momentum in magnetic field
- Favorite choice for tracker (Strip) and vertex (Pixel) detectors → positioned close to interaction point → radiation damage (CERN RD50 collaboration)

ATLAS strip sensors

ATLAS tracker

Si strip sensors

Hybrid with ASICs

TPG baseboard with BeO facings

Resolution ~50μm

p+-in-n+
LHC: signal degradation

- **LHC**: $L \approx 10^{34}\text{cm}^{-2}\text{s}^{-1}$, expected to accumulate $\sim 350\text{fb}^{-1}$
- **High Luminosity (HL) LHC**: $L = 5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$, aiming to accumulate $3000\text{fb}^{-1}$, planned for $\sim 2022$

![Graph showing signal degradation for LHC and HL-LHC](image)

**HL LHC challenges:**
- Higher radiation damage
- Higher multiplicity
- Triggering
- Connectivity
- Cooling
- Powering

Note: Measurements taken at partially different conditions; lines just to guide the eye

References:
1. p/n-FZ, 300μm, (-30°C, 25ns), strip [Casse 2008]
2. n/n-FZ, 285μm, (-10°C, 40ns), pixel [Rohe et al. 2005]
HL LHC: radiation field

- **Pixel detector:**
  pion radiation damage dominating (neutrons ~10%)
- **Strip detector:**
  damage mostly due to neutrons

![Graph showing fluence for pixel and strip layers.](http://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/RADIATION/RadiationTF_document.html)
Radiation damage

- **Surface damage due to IEL (Ionising Energy Loss)**
  - accumulation of + charge in the oxide (SiO2) and at the Si/SiO2 interface
  - affects interstrip capacitance (noise), breakdown behavior
  - can be controlled by proper design and manufacturing process

- **Bulk damage due to NIEL (Non Ionising Energy Loss):**
  - Results in defects in crystal lattice → new energy levels in the band gap
    - $E_{k,\text{recoil}} > 25\text{eV}$: Si atom displaced out of its lattice site to form interstitial I and vacancy V (Frenkel pair), which can react with other defects to form new type of point defects (VO, V2, ...)
    - $E_{k,\text{recoil}} > 5\text{keV}$: cluster of displacements possible
  - nuclear reactions: resulting high energy fragments involved in the damage process

- **Comparing the damage:**
  - $\Phi_{\text{eq}} =$ equivalent fluence → fluence of 1MeV neutrons needed to cause the same NIEL

- **NIEL scaling hypothesis:** “Observed damage in Si bulk scales with energy deposited in the NIEL interactions” → Does not hold in all cases (see later)!

- **Effects on detector performance:**
  - Change of effective dopant concentration $N_{\text{eff}}$ → change in full depletion voltage $V_{\text{FD}}$
  - Increase of leakage current (increased noise, high power consumption)
  - Increase of effective trapping time (deterioration of charge collection efficiency CCE)
Rad-hard solid state detector development

Strategies
(1) Material engineering
(2) Detector engineering
(3) Change of detector operation

✦ Defect engineering
  ✦ introduction of defects, impurities in silicon bulk to improve radiation hardness
  ✦ Example: oxygen rich silicon (MCz, Cz, EPI, DOFZ)

✦ New materials
  ✦ Silicon Carbide (SiC), Gallium Nitride (GaN), Gallium Arsenide: strong rad. damage observed, no potential for HL-LHC
  ✦ Diamond (CERN RD42 Collaboration)

✦ Detector engineering
  ✦ p-type silicon detectors
  ✦ thin detectors, epitaxial detectors
  ✦ 3D detectors
  ✦ Monolithic devices

CERN RD39 collaboration
“Cryogenic Tracking Detectors” operation at 100-200K to reduce charge loss
Leakage current

Change of leakage current

... with particle fluence

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

- constant over several orders of fluence
- independent of Si impurity
- independent of particle type (except $\gamma$)

\[ I \propto \exp \left( - \frac{E_g}{2k_B T} \right) \]

⇒ cooling during operation needed!

Example: \[ I(-10^\circ C) \sim 1/16 \, I(20^\circ C) \]
Full depletion voltage

Change of $V_{FD} (N_{eff})$ in standard n-type FZ detectors

- "Type inversion": Neff changes from positive to negative (Space Charge Sign Inversion – SCSI)
- acceptor generation

$V_{FD} = \frac{\varepsilon_0 D}{2\varepsilon_0 \varepsilon_{Si}} \frac{N_{eff}}{N_{eff}}$

- Short term: “Beneficial annealing”
- Long term: “Reverse annealing”
  - time constant depends on temperature:
    - ~ 500 years (-10°C)
    - ~ 500 days (20°C)
    - ~ 21 hours (60°C)

$\Rightarrow$ Detectors must be cooled even when the experiment is not running!
Trapping

- CCE degradation due to partial depletion (underdepletion) and trapping
- Trapping is described by effective trapping probability for holes and electrons $1/\tau_{\text{eff}, \text{e,h}}$

$$Q_{\text{e,h}}(t) = Q_{\text{e,h}}(0) \exp \left( -\frac{t}{\tau_{\text{eff}, \text{e,h}}} \right) \frac{1}{\tau_{\text{eff}, \text{e,h}}} \propto N_{\text{traps}}$$

$1/\tau_{\text{eff}, \text{e,h}}$ dependence on fluence

- After irradiation: trapping stronger for holes than electrons; charged hadrons induce more trapping compared to neutrons (NIEL violation)
- Common to all materials after irradiation (apart from $\gamma$): same increase of trapping (electrons and holes) within ~20%
- Annealing: increases trapping for holes, decreased for electrons

... and annealing time
Oxygen rich Si: proton irradiation

Irradiation with 24GeV/c protons

- **Standard FZ silicon**
  - *type inversion* at ~ $2 \times 10^{13}$ p/cm$^2$
  - strong $N_{\text{eff}}$ increase at high fluence

- **DOFZ silicon (is oxygen rich)**
  - *type inversion* at ~ $2 \times 10^{13}$ p/cm
  - smaller $N_{\text{eff}}$ increase at high fluence

- **Cz, MCz silicon (is oxygen rich)**
  - “no type inversion” in the overall fluence range
  - Comment: there is no “real” type inversion, a more clear understanding of the observed effects is obtained by investigating directly the internal electric field; look for (“double junction” effects, see later)

[M.Moll, 11th ICATPP]
Oxygen rich Si: neutron vs. proton irradiation

EPI silicon (EPI-DO, 72µm, 170Ωcm) irradiated with 24GeV/c protons and reactor neutrons

- SCSI (“Type Inversion”) after neutrons but not after protons
- Acceptor generation after neutron irradiation (as in standard FZ)
- Donor generation enhanced after proton irradiation (only in oxygen rich Si)
Why the difference in proton and neutron damage?

- **Clusters vs. Point defects:**
  - Charged hadrons create less point defects with increasing energy
  - At given particle energy, neutrons create more clusters then protons

- **A ‘simplified’ explanation for difference between proton and neutron damage:**
  - Defect clusters produce predominantly **negative space charge** – acceptors
  - Point defects produce predominantly **positive space charge** – donors (in ‘oxygen rich’ silicon)
  - Comment: note NIEL violation

Initial distribution of vacancies after incidence of $10^{14}$ particles/cm$^2$
[Mika Huhtinen NIMA 491(2002) 194]
Oxygen rich Si: mixed irradiations

- MCz and Fz n-type devices exposed to mixed irradiations:
  - step 1: proton (or pion) irradiation
  - step 2: neutron irradiation
- Result: damage additive! Can we profit from that in real experiment?

FZ-n (low O concentration) accumulation of damage

MCz-n (high O concentration) compensation of damage

[G.Kramberger et al., NIMA, 609 (2009), p142]
Device engineering: p-type devices

**p⁺-n detector**
- n-type silicon after high fluence
- “type inversion”
- p⁺ strips

**n⁺-p detector**
- p-type silicon after high fluence
- still p-type

- **Undepleted region**
- **Active region**

- Traversing particle
- • High el. field region on the back (non-segmented side)
- • Underdepleted
  - • charge spread (resolution deterioration)
  - • charge loss (CCE deterioration)

- **Comment:**
  - ✗ this is just a schematic explanation, reality is much more complex (see next slide)
  - ✗ Instead of n-on-p also n-on-n devices could be used

- **High el. field region stays on the front**
  - (segmented side → weighting and real field stay aligned)
- • Limited loss of CCE, less deterioration with underdeplition
- • Limited deterioration of resolution
- • Collecting electrons (3-times faster than holes)
Determination of electric field

Edge-TCT (transient current technique)
- Technique pioneered by Gregor Kramberger, Ljubljana [1]
- Sensor (strip detector) is illuminated with pulsed IR laser from the side, light focused under one of the strips
- Scan across detector thickness and record induced current signal waveforms as function of depth
- Reconstruction of drift velocity electric field, detector efficiency (also trapping probability?) profile across the detector thickness


Highly irradiated detectors:
- “Double junction” form of electric field can be observed: field peak both on the back and front
- Example of drift velocity profile in: MCz-p, irradiated with 24GeV/c protons ($\Phi_{eq} = 6.2 \times 10^{15} n_{eq}/cm^2$)
CCE measurements of irradiated FZ p-type strip devices

- 100% CCE observed even after $3 \times 10^{15}$ n/cm², also even CCE > 100% was observed
- Extrapolation of charge trapping parameters obtained at lower fluences would predict much lower signal
- Origin: ‘Charge multiplication effects’ due to high electric fields close to the strips

[Graph showing bias voltage vs. most probable signal for different fluences]

I. Mandić, RESMDD08
Device engineering: 3D Si sensors

- **Electrodes:**
  - narrow columns along detector thickness,
  - diameter: 10mm, distance: 50 – 100mm
- **Lateral depletion:**
  - lower depletion voltage needed
  - thicker detectors possible
  - fast signal
  - radiation hard (short drift path minimizes the trapping)

- promising results
- processing of 3D sensors challenging, though many good devices with reasonable production yield produced
- main drawback is the resulting high channel capacitance
- 3D sensors will be part of ATLAS IBL detector!

first proposed by S.I. Parker et al. [NIMA 395(1997) 328]
# New materials: diamond

<table>
<thead>
<tr>
<th>Property</th>
<th>diamond</th>
<th>Si</th>
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</thead>
<tbody>
<tr>
<td>Band gap [eV]</td>
<td>5.5</td>
<td>1.12</td>
</tr>
<tr>
<td>Intrinsic resistivity @ RT [Ωcm]</td>
<td>&gt;$10^{11}$</td>
<td>2.3x10^5</td>
</tr>
<tr>
<td>e(h) mobility [cm^2/Vs]</td>
<td>1900 (2300)</td>
<td>1350 (480)</td>
</tr>
<tr>
<td>e(h) sat. velocity [cm/s]</td>
<td>1.3(1.7)x10^5</td>
<td>1.1(0.8)x10^5</td>
</tr>
<tr>
<td>Dielectric constant</td>
<td>5.7</td>
<td>11.9</td>
</tr>
<tr>
<td>Displacement energy [eV/atom]</td>
<td>43</td>
<td>13-20</td>
</tr>
<tr>
<td>Thermal conductivity [W/m K]</td>
<td>~2000</td>
<td>150</td>
</tr>
<tr>
<td>Energy to create e-h pair [eV]</td>
<td>13</td>
<td>3.61</td>
</tr>
<tr>
<td>MIP Ionization loss [Mev/cm]</td>
<td>4.7</td>
<td>3.21</td>
</tr>
<tr>
<td>Avrg. MIP signal/100µm [e_0]</td>
<td>3602</td>
<td>8892</td>
</tr>
</tbody>
</table>

⇒ low leakage current (low noise, no cooling)
⇒ fast signal
⇒ low capacitance
⇒ radiation hard
⇒ heat spreader
⇒ low signal

<table>
<thead>
<tr>
<th></th>
<th>poly-CVD (16 chip ATLAS pixel module)</th>
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<tbody>
<tr>
<td></td>
<td>single crystal CVD diamond (few cm)</td>
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</table>

Diamond sensors heavily used in LHC experiments for Beam Monitoring
**BCM (Beam Conditions Monitor)**
- Purpose: protection, luminosity
- Based on TOF measurement
- 4 modules (pCVD diamond pad) on each side of interaction
  \((z=\pm183.8\text{cm}, r=5.5\text{cm} (\eta \approx 4.2))\)

**BLM (Beam Loss Monitor)**
- Purpose: protection
- Based on beam induced current measurement
- 6 modules (pCVD diamond pad sensor) on each side of interaction
  \((z \approx 3450\text{mm}, r \approx 65\text{mm})\)
ATLAS BCM: principle of operation

Time of flight measurement to distinguish between collisions and background events (beam – gas, halo, TAS scraping)

- measurement every proton bunch crossing (25ns)
- 2 detector stations at z=±1.9m
- particles from collisions reach both stations at the same time (~6ns after collisions)
- secondary particles from downstream background interactions reach nearest station 12.5ns before particles from collisions (~6 ns before collisions)
- use coincident “in time hits” to monitor luminosity
- use “out of time hits” to identify background events

Requirements:
- fast and radiation hard detector & electronics:
  - rise time ~1ns
  - pulse width ~3ns
  - baseline restoration ~10ns
  - ionization dose ~0.5 MGy,
  - $10^{15}$ particles/cm² in 10 years
- MIP sensitivity
Sensors for HL-LHC

Fluences $\Phi_{eq} < 10^{15}$ cm$^{-2}$ (outer layers – strip sensors)
- Underdepletion is dominant cause for CCE degradation
- $n$-MCz silicon detectors: good performance in mixed fields due to compensation of charged hadron and neutron damage (more work needed)
- p-type Si microstrip detectors: encouraging results (“base line option” for the ATLAS SCT upgrade)

Fluences $\Phi_{eq} > 10^{15}$ cm$^{-2}$ (innermost tracking layers – pixel sensors)
- CCE degradation mostly due to trapping -> active thickness is significantly reduced
- Collection of electrons at electrodes essential: Use n-on-p or n-on-n detectors!
- Presently three options under investigation: planar Si (thin, p-type), 3D Si, Diamond

Questions to explore:
- Can we control multiplication effects in order to profit from them?
- Can we profit from compensation effects in mixed fields (i.e. MCz-n)?
- Can we understand detector performance on the basis of simulations?

A comparison of technologies in terms of collected charge (signal)

Note:
- measurement at partly different conditions...
- only an indication of what could be used
- for specific applications SNR crucial! (also important: efficiency, availability, price, reliability, cooling, track resolution...)

**Silicon Sensors**
- p-in-n (EPI), 150 µm [7,8]
- p-in-n (EPI), 75µm [6]
- n-in-p (FZ), 300µm, 500V, 23GeV p [1]
- n-in-p (FZ), 300µm, 500V, neutrons [1]
- n-in-p (FZ), 300µm, 500V, 26MeV p [1]
- n-in-p (FZ), 300µm, 800V, 23GeV p [1]
- n-in-p (FZ), 300µm, 800V, neutrons [1]
- n-in-p (FZ), 300µm, 800V, 26MeV p [1]
- p-in-n (FZ), 300µm, 500V, 23GeV p [1]
- p-in-n (FZ), 300µm, 500V, 26MeV p [1]
- Double-sided 3D, 250 µm, simulation! [5]

**Other materials**
- SiC, n-type, 55 µm, 900V, neutrons [3]
- Diamond (pCVD), 500 µm [4] (RD42)

References: