Development of radiation tolerant silicon detectors for the Super - LHC

... with strong focus on the results of the RD50 collaboration

Michael Moll (CERN/PH)
Outline

• Motivation to develop radiation harder detectors
  • Super-LHC and expected radiation levels at the Super-LHC
  • Radiation induced degradation of detector performance

• Radiation Damage in Silicon Detectors
  • Macroscopic damage (changes in detector properties)
  • Microscopic damage (crystal damage)

• Approaches to obtain radiation hard sensors
  • Material Engineering
    • Silicon materials – FZ, MCZ, DOFZ, EPI
    • Other semiconductors
  • Device Engineering
    • p-in-n, n-in-n and n-in-p sensors
    • 3D sensors and thin devices

• Silicon Sensors for the LHC upgrade and open questions
  • Collected Charge – Signal to Noise – Avalanche effects
  • Mixed irradiations

• Summary
LHC example: CMS inner tracker

CMS – “Currently the Most Silicon”
- **Micro Strip:**
  - ~ 214 m\(^2\) of silicon strip sensors, 11.4 million strips
- **Pixel:**
  - Inner 3 layers: silicon pixels (~1m\(^2\))
  - 66 million pixels (100x150\(\mu\)m)
  - Precision: \(\sigma(\rho \phi) \sim \sigma(z) \sim 15\mu m\)
  - Most challenging operating environments (LHC)

<table>
<thead>
<tr>
<th>Total weight</th>
<th>12500 t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>15m</td>
</tr>
<tr>
<td>Length</td>
<td>21.6m</td>
</tr>
<tr>
<td>Magnetic field</td>
<td>4 T</td>
</tr>
</tbody>
</table>
The challenge: Super LHC - visually

LHC nominal luminosity

SLHC luminosity ≈ 300-400 interactions/bx
Future Plans: Towards sLHC

The peak luminosity over time is shown with two lines:
- Red line: no PHASE II upgrade
- Blue line: including PHASE II upgrade

Key milestones:
- 2008: Linac4 + IR upgrade phase 1
- 2012: Collimation phase 2
- 2016: New injectors + IR upgrade phase 2

R. Garoby - LHCC - July 2008 - "Upgrade Plans for the CERN Accelerator Complex"
Future Plans: Towards sLHC

- Timeline shifting

Peak Luminosity \([10^{34} \text{ cm}^{-2} \text{s}^{-1}]\)

- R.Garoby - LHCC - July 2008 - "Upgrade Plans for the CERN Accelerator Complex"
- F.Zimmermann - Feb. 2009 - "SLHC Machine Plans"

- Planning 2009
Future Plans: Towards sLHC


- **Phase I upgrades:**
  - CMS: New Pixel Detector
    - 4 layers 4-16 cm + 6 disc
  - ATLAS: IBL – Insertable b-layer
    - (add layer at 3.5 cm)

- **Phase II upgrades:**
  - CMS: Tracker replacement
  - ATLAS: New ‘all silicon’ tracker
    - 4 pixel, 3 short & 2 long strip layers
      - (3.5 cm to 95 cm)

- **Timeline shifting**

**SLHC (ATLAS) goal:** 3000 fb\(^{-1}\) recorded

Integrated Luminosity [fb\(^{-1}\)]

Year

- no PHASE II
- normal ramp
Future Plans: Towards sLHC

2009
Start of LHC
Ramp up luminosity to few $10^{32}$ cm$^{-2}$s$^{-1}$
Energy of 3.5 TeV per beam (50%)
• 19. March 2010 – Beams accelerated to 3.5 TeV
• 30. March 2010 – First collisions at 2 x 3.5 TeV … run for 2 years

2012
Modify splices … go to 7 TeV
Run at 7 TeV per beam and ramp up luminosity to ~30% nominal

2016
New Linac 4 injector and full collimation scheme
Small upgrades to ATLAS and CMS
Ramp up luminosity even slightly beyond nominal

~2020
sLHC: New LHC focusing magnets, CRAB cavities, …
Major Upgrades of ATLAS and CMS
Collect data until > 3000 fb$^{-1}$

Planning 2010
(very uncertain at the moment)
new timeline in June 2010 ?

New Pixel
New Tracker

Use this value for further discussions
Radiation levels after 3000 fb$^{-1}$

- **Radiation hardness requirements (including safety factor of 2)**
  - $2 \times 10^{16}$ neq/cm$^2$ for the innermost pixel layers
  - $7 \times 10^{14}$ neq/cm$^2$ for the innermost strip layers

**Radial distribution of sensors determined by Occupancy**

- **Long Strips** (up to $4 \times 10^{14}$ cm$^{-2}$)
- **Short Strips** (up to $10^{15}$ cm$^{-2}$)
- **Pixels** (up to $10^{16}$ cm$^{-2}$)

**B-layer (R=3.7 cm):** $2.5 \times 10^{16}$ neq/cm$^2 = 1140$ Mrad
**2nd Inner Pixel Layer (R=7 cm):** $7.8 \times 10^{15}$ neq/cm$^2 = 420$ Mrad
**1st Outer Pixel Layer (R=11 cm):** $3.6 \times 10^{15}$ neq/cm$^2 = 207$ Mrad
**Short strips (R=38 cm):** $6.8 \times 10^{14}$ neq/cm$^2 = 30$ Mrad
**Long strips (R=85 cm):** $3.2 \times 10^{14}$ neq/cm$^2 = 8.4$ Mrad

Dominated by pion damage

Dominated by neutron damage

Signal degradation for LHC Silicon Sensors

Pixel sensors:
max. cumulated fluence for LHC

Strip sensors:
max. cumulated fluence for LHC

FZ Silicon
Strip and Pixel Sensors
- n-in-n (FZ), 285 μm, 600 V, 23 GeV p
- p-in-n (FZ), 300 μm, 500 V, 23 GeV p
- p-in-n (FZ), 300 μm, 500 V, neutrons

References:

Note: Measured partly under different conditions!
Lines to guide the eye (no modeling)!
Signal degradation for LHC Silicon Sensors

Strip sensors:
max. cumulated fluence for LHC and SLHC

Pixel sensors:
max. cumulated fluence for LHC and SLHC

FZ Silicon Strip and Pixel Sensors
- n-in-n (FZ), 285µm, 600V, 23 GeV p
- p-in-n (FZ), 300µm, 500V, 23 GeV p
- p-in-n (FZ), 300µm, 500V, neutrons

References:
[1] p/n-FZ, 300µm, (-30°C, 25ns), strip [Casse et al. 2008]

Note: Measured partly under different conditions! Lines to guide the eye (no modeling)!

SLHC will need more radiation tolerant tracking detector concepts!

Boundary conditions & other challenges:
Granularity, Powering, Cooling, Connectivity, Triggering, Low mass, Low cost!
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**Reminder: Reverse biased abrupt p⁺-n junction**

Poisson’s equation

\[ - \frac{d^2 \phi(x)}{dx^2} = \frac{q_0}{\varepsilon \varepsilon_0} \cdot N_{eff} \]

Positive space charge, \( N_{eff} = [P] \)
(ionized Phosphorus atoms)

**Electrical charge density**

**Electrical field strength**

**Electron potential energy**

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

**depletion voltage**

**effective space charge density**

Full charge collection only for \( V_B > V_{dep} \)!
Macroscopic Effects – I. Depletion Voltage

Change of Depletion Voltage $V_{\text{dep}} (N_{\text{eff}})$

**with particle fluence:**

- **Type inversion**: $N_{\text{eff}}$ changes from positive to negative (Space Charge Sign Inversion)

- Short term: “Beneficial annealing”
- Long term: “Reverse annealing”
  - time constant depends on temperature:
    - $\sim 500$ years (-10°C)
    - $\sim 500$ days (20°C)
    - $\sim 21$ hours (60°C)
  - Consequence: Detectors must be cooled even when the experiment is not running!

**with time (annealing):**

- $N_{\text{eff}}$ changes with annealing time at 60°C [min]

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Radiation Damage – II. Leakage Current

- Change of Leakage Current (after hadron irradiation)

Damage parameter $\alpha$ (slope in figure)

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

Leakage current per unit volume and particle fluence

- $\alpha$ is constant over several orders of fluence and independent of impurity concentration in Si

$\Rightarrow$ can be used for fluence measurement

Leakage current decreasing in time (depending on temperature)

Strong temperature dependence

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

Consequence:

Cool detectors during operation!

Example: $I(-10^\circ\text{C}) \sim 1/16 I(20^\circ\text{C})$

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Deterioration of Charge Collection Efficiency (CCE) by trapping

Trapping is characterized by an effective trapping time $\tau_{\text{eff}}$ for electrons and holes:

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

where

$$\frac{1}{\tau_{\text{eff} e,h}} \propto N_{\text{defects}}$$

Increase of inverse trapping time $(1/\tau)$ with fluence

and change with time (annealing):

![Graph showing increase of inverse trapping time with fluence](image1)

![Graph showing change with time (annealing)](image2)

For 24 GeV/c proton irradiation, $\Phi_{\text{eq}} = 4.5 \times 10^{14} \text{ cm}^{-2}$

[M.Moll; Data: O.Krasel, PhD thesis 2004, Uni Dortmund]
Two general types of radiation damage to the detector materials:

- **Bulk (Crystal) damage due to Non Ionizing Energy Loss (NIEL)**
  - displacement damage, built up of crystal defects –
  
    I. Change of **effective doping concentration** (higher depletion voltage, under- depletion)
  
    II. Increase of **leakage current** (increase of shot noise, thermal runaway)
  
    III. Increase of **charge carrier trapping** (loss of charge)

- **Surface damage due to Ionizing Energy Loss (IEL)**
  - accumulation of positive in the oxide (SiO₂) and the Si/SiO₂ interface –
  - affects: interstrip capacitance (noise factor), breakdown behavior, …

Impact on detector performance and Charge Collection Efficiency
(depending on detector type and geometry and readout electronics!)

- Signal/noise ratio is the quantity to watch
  - **⇒ Sensors can fail from radiation damage!**

Influenced by impurities in Si – Defect Engineering is possible!

Same for all tested Silicon materials!

Can be optimized!
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Impact on detector properties can be calculated if all defect parameters are known:

- $\sigma_{n,p}$: cross sections
- $\Delta E$: ionization energy
- $N_t$: concentration

charged defects $\Rightarrow N_{eff}, V_{dep}$
e.g. donors in upper and acceptors in lower half of band gap

Trapping (e and h) $\Rightarrow$ CCE
shallow defects do not contribute at room temperature due to fast detrapping

generation leakage current
Levels close to midgap most effective

Impact on Defects on Detector Properties

Shockley-Read-Hall statistics

$E_C$  
+ donor  

$E_V$  
acceptor  

electrons  

holes  

$\Rightarrow CCE$

shallow defects do not contribute at room temperature due to fast detrapping
Defect Characterization - Methods

Methods used by RD50 Collaboration
RD50-WODEAN project
guided by G. Lindstroem (HH):

- C-DLTS (Capacitance Deep Level Transient Spectroscopy)
- I-DLTS (Current Deep Level Transient Spectroscopy)
- TSC (Thermally Stimulated Currents)
- PITS (Photo Induced Transient Spectroscopy)
- FTIR (Fourier Transform Infrared Spectroscopy)
- RL (Recombination Lifetime Measurements)
- PC (Photo Conductivity Measurements)
- PL (Photo Luminescence)
- EPR (Electron Paramagnetic Resonance)
- TCT (Transient Charge Technique)
- CV/IV (Capacitance Voltage and Current Voltage Characteristics)

Further interesting methods:

- Positron Annihilation, TEM, TSCAP, .....
Correlation: Microscopic and Macroscopic data

- TSC and CV measurements (Isothermal annealing after $2 \times 10^{14}$ n/cm$^2$)

TSC-results (EPI-ST)

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>TSC-signal (µA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>0</td>
</tr>
<tr>
<td>50</td>
<td>10</td>
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<tr>
<td>75</td>
<td>15</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
</tr>
<tr>
<td>125</td>
<td>30</td>
</tr>
<tr>
<td>150</td>
<td>40</td>
</tr>
<tr>
<td>175</td>
<td>50</td>
</tr>
<tr>
<td>200</td>
<td>50</td>
</tr>
</tbody>
</table>

- E(30)K
- V$_O$
- H(140)K
- H(116)K
- V$_e$ ±?
- H(152)K

Comparison to $\Delta N_{eff}$

[Alexandra Junkes, Hamburg University, RD50 Workshop June 2009]
Summary – defects with strong impact on the device properties at operating temperature

Point defects

- \( E_{i}^{BD} = E_c - 0.225 \) eV
- \( \sigma_n^{BD} = 2.3 \cdot 10^{-14} \text{ cm}^2 \)
- \( E_{i}^{I} = E_c - 0.545 \) eV
  - \( \sigma_n^{I} = 2.3 \cdot 10^{-14} \text{ cm}^2 \)
  - \( \sigma_p^{I} = 2.3 \cdot 10^{-14} \text{ cm}^2 \)

Cluster related centers

- \( E_{i}^{116K} = E_v + 0.33 \text{ eV} \)
- \( \sigma_p^{116K} = 4 \cdot 10^{-14} \text{ cm}^2 \)
- \( E_{i}^{140K} = E_v + 0.36 \text{ eV} \)
- \( \sigma_p^{140K} = 2.5 \cdot 10^{-15} \text{ cm}^2 \)
- \( E_{i}^{152K} = E_v + 0.42 \text{ eV} \)
- \( \sigma_p^{152K} = 2.3 \cdot 10^{-14} \text{ cm}^2 \)
- \( E_{i}^{30K} = E_c - 0.1 \) eV
- \( \sigma_n^{30K} = 2.3 \cdot 10^{-14} \text{ cm}^2 \)


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Silicon Growth Processes

- **Floating Zone Silicon (FZ)**
  - Poly silicon
  - RF Heating coil
  - Single crystal silicon
  - Float Zone Growth

- **Czochralski Silicon (CZ)**
  - The growth method used by the IC industry.
  - Difficult to produce very high resistivity

  ![Czochralski Growth](image)

- **Epitaxial Silicon (EPI)**
  - Basically all silicon tracking detectors made out of FZ silicon
  - Some pixel sensors out of DOFZ Diffusion Oxygenated FZ silicon
  - Chemical-Vapor Deposition (CVD) of Si
  - up to 150 μm thick layers produced
  - growth rate about 1μm/min
## Silicon Materials under Investigation by RD50

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness [μm]</th>
<th>Symbol</th>
<th>$\rho$ (Ωcm)</th>
<th>$[O_i]$ (cm⁻³)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard FZ (n- and p-type)</strong></td>
<td>50, 100, 150, 300</td>
<td>FZ</td>
<td>1–30×10³</td>
<td>&lt; 5×10¹⁶</td>
</tr>
<tr>
<td><strong>Diffusion oxygenated FZ (n- and p-type)</strong></td>
<td>300</td>
<td>DOFZ</td>
<td>1–7×10³</td>
<td>~ 1–2×10¹⁷</td>
</tr>
<tr>
<td><strong>Magnetic Czochralski Si, Okmetic, Finland (n- and p-type)</strong></td>
<td>100, 300</td>
<td>MCz</td>
<td>~ 1×10³</td>
<td>~ 5×10¹⁷</td>
</tr>
<tr>
<td><strong>Czochralski Si, Sumitomo, Japan (n-type)</strong></td>
<td>300</td>
<td>Cz</td>
<td>~ 1×10³</td>
<td>~ 8–9×10¹⁷</td>
</tr>
<tr>
<td><strong>Epitaxial layers on Cz-substrates, ITME, Poland (n- and p-type)</strong></td>
<td>25, 50, 75, 100, 150</td>
<td>EPI</td>
<td>50 – 100</td>
<td>&lt; 1×10¹⁷</td>
</tr>
<tr>
<td><strong>Diffusion oxyg. Epitaxial layers on CZ</strong></td>
<td>75</td>
<td>EPI–DO</td>
<td>50 – 100</td>
<td>~ 7×10¹⁷</td>
</tr>
</tbody>
</table>

- **DOFZ silicon** - Enriched with oxygen on wafer level, inhomogeneous distribution of oxygen
- **CZ/MCZ silicon** - high Oi (oxygen) and $O_{2i}$ (oxygen dimer) concentration (homogeneous)
  - formation of shallow Thermal Donors possible
- **Epi silicon** - high O₁, $O_{2i}$ content due to out-diffusion from the CZ substrate (inhomogeneous)
  - thin layers: high doping possible (low starting resistivity)
- **Epi-Do silicon** - as EPI, however additional O₁ diffused reaching homogeneous O₁ content
FZ, DOFZ, Cz and MCz Silicon

- Strong differences in $V_{\text{dep}}$
  - Standard FZ silicon
  - Oxygenated FZ (DOFZ)
  - CZ silicon and MCZ silicon

- Strong differences in internal electric field shape
  (space charge sign inversion, no inversion, double junction effects,…)

- Different impact on pad and strip detector operation!
  - e.g.: a lower $V_{\text{dep}}$ or $|N_{\text{eff}}|$ does not necessarily correspond to a higher CCE for strip detectors (see later!)

Common to all materials (after hadron irradiation, not after $\gamma$ irradiation):
- reverse current increase
- increase of trapping (electrons and holes) within $\sim 20\%$
Correlation: Microscopic and Macroscopic data

- Epitaxial silicon irradiated with 23 GeV protons vs reactor neutrons

Development of $N_{eff}$ for EPI-DO after neutron and proton irradiation

TSC results after neutron and proton irradiation

- SCSI after neutrons but not after protons
- donor generation enhanced after proton irradiation
- microscopic defects explain macroscopic effect at low $\Phi_{eq}$

[I. Pintilie, et al., to be published.]

[A.Junkes, Hamburg University, RD50 Workshop June 2009]
Mixed irradiations – Change of $N_{\text{eff}}$

- Exposure of FZ & MCZ silicon sensors to ‘mixed’ irradiations
  - First step: Irradiation with protons or pions
  - Second step: Irradiation with neutrons

FZ: Accumulation of damage

MCZ: Compensation of damage

Why is proton and neutron damage different?

- Particle $\rightarrow S_i$ $\rightarrow E_K > 25$ eV
- $E_K > 5$ keV point defects and clusters of defects

**Simulation:**
Initial distribution of vacancies in $(1 \mu m)^3$ after $10^{14}$ particles/cm$^2$ [Mika Huhtinen NIMA 491(2002) 194]

- 10 MeV protons, 36824 vacancies
- 24 GeV/c protons, 4145 vacancies
- 1 MeV neutrons, 8870 vacancies

- A ‘simplified’ explanation for the ‘compensation effects’
  - Defect clusters produce predominantly negative space charge
  - Point defects produce predominantly positive space charge (in ‘oxygen rich’ silicon)

For the experts: Note the NIEL violation
Advantage of non-inverting material
p-in-n detectors (schematic figures!)

Fully depleted detector
(non – irradiated):

- p⁺ strips
- Hole drift
- Electron drift
- n⁺ layer
- Traversing particle
### Advantage of non-inverting material

#### p-in-n detectors (schematic figures!)

---

**Fully depleted detector (non – irradiated):**

- **Inverted to “p-type”, under-depleted:**
  - Charge spread – degraded resolution
  - Charge loss – reduced CCE

- **Non-inverted, under-depleted:**
  - Limited loss in CCE
  - Less degradation with under-depletion

---

*Be careful, this is a very schematic explanation, reality is more complex!*
**Device engineering**  
*p-in-n versus n-in-p (or n-in-n) detectors*

**n-type silicon after high fluences:**  
(type inverted)

- **p⁺on-n**
  - **p⁺strips**
  - Undepleted region
  - **Electron drift**
  - **Hole drift**
  - **n⁺layer**
  - Traversing particle

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

**n⁺on-p**
- **n⁺strips**
- Undepleted region
- Traversing particle

**p-type silicon after high fluences:**  
(still p-type)

- **n⁺on-p**
  - **n⁺strips**
  - Active region
  - **Hole drift**
  - **Electron drift**
  - **p⁺layer**

**n-on-p silicon, under-depleted:**
- Limited loss in CCE
- Less degradation with under-depletion
- Collect electrons (3 x faster than holes)

**Comments:**
- Instead of *n-on-p* also *n-on-n* devices could be used
Reality is more complex: *Double junctions*

- Dominant junction close to n+ readout strip for FZ n-in-p
- For MCZ p-in-n even more complex fields have been reported:
  - no “type inversion” (SCSI) = dominant field remains at p implant
  - “equal double junctions” with almost symmetrical fields on both sides
FZ n-in-p microstrip detectors (n, p, π – irrad)

- **n-in-p microstrip p-type FZ detectors** (Micron, 280 or 300µm thick, 80µm pitch, 18µm implant)
- **Detectors read-out with 40MHz** (SCT 128A)

[A.Affolder, Liverpool, RD50 Workshop, June 2009]

- **CCE:** ~7300e (~30%) after ~1×10^{16}cm^{-2} 800V
- **n-in-p sensors are strongly considered for ATLAS upgrade** (previously p-in-n used)
**FZ n-in-p microstrip detectors (n, p, π – irrad)**

- **n-in-p microstrip p-type FZ detectors** (Micron, 280 or 300μm thick, 80μm pitch, 18μm implant)
- **Detectors read-out with 40MHz** (SCT 128A)

**Signal (10^3 electrons)** vs **Fluence (10^{14} n_{eq}/cm^2)**

**CCE: ~7300e (~30%)**
after ~ 1×10^{16}cm^{-2} 800V

**n-in-p sensors are strongly considered** for **ATLAS upgrade** (previously p-in-n used)

**no reverse annealing in CCE measurements** for neutron and proton irradiated detectors
Why do planar silicon sensors with n-strip readout give such high signals after high levels (>10^{15} \text{ cm}^{-2} \text{ p/cm}^2) of irradiation?

- Extrapolation of charge trapping parameters obtained at lower fluences would predict much lower signal!
- Assumption: ‘Charge multiplication effects’ as even CCE > 1 was observed

FZ Silicon Strip Sensors

- n-in-p (FZ), 300\,\mu m, 500V, 23GeV p [1]
- n-in-p (FZ), 300\,\mu m, 500V, neutrons [1,2]
- n-in-p (FZ), 300\,\mu m, 500V, 26MeV p [1]
- n-in-p (FZ), 300\,\mu m, 800V, 23GeV p [1]
- n-in-p (FZ), 300\,\mu m, 800V, neutrons [1,2]
- n-in-p (FZ), 300\,\mu m, 800V, 26MeV p [1]
- n-in-p (FZ), 300\,\mu m, 1700V, neutrons [2]
- p-in-n (FZ), 300\,\mu m, 500V, 23GeV p [1]
- p-in-n (FZ), 300\,\mu m, 500V, neutrons [1]

References:
(p/n-FZ, 300\,\mu m, (-30^\circ\text{C}, 25ns)
(p-FZ, 300\,\mu m, -20^\circ\text{C} to -40^\circ\text{C}, 25ns)

Which voltage can be applied?
Charge Multiplication – Epi Diodes

- Epi diodes, 75 and 150 μm thick
- Measured trapping probability found to be proportional to fluence and consistent with values extracted in FZ
- Multiplication effect stronger for 75 μm diodes
- Smaller penetration depth (670 nm laser) → stronger charge multiplication

[J.Lange et al., 14th RD50 Workshop, June 2009]
Annealing studies on strip sensors

[I. Mandic, 15th RD50 Workshop, Nov. 09 – Measured on HPK ATLAS sensors]

- p-type strip sensor; $\Phi_{eq} = 5 \times 10^{15} \text{ cm}^{-2}$ (neutrons) [ATLAS – HPK – sensors]

Michael Moll – Instrumentation Seminar, Hamburg 26.3.2010
Further annealing studies
[G.Casse, Trento Workshop, Feb.2010 – Measured on HPK ATLAS sensors]

- p-type strip sensor; [ATLAS – HPK]
- $\Phi_{eq} = 1 \times 10^{15} \text{n}_{eq} \text{cm}^{-2}$ (26MeV protons)

Stable operation of n-in-p sensors without cooling during maintenance periods seems feasible
Still long way to fully understand high voltage operation of highly irradiated sensors
3D detector - concept

- **“3D” electrodes:**
  - narrow columns along detector thickness,
  - diameter: 10μm, distance: 50 - 100μm

- **Lateral depletion:**
  - lower depletion voltage needed
  - thicker detectors possible
  - fast signal
  - radiation hard

Not discussed here in detail:
Seminar on 9. April dedicated entirely to 3D sensors
Example: Testbeam of 3D-DDTC

- DDTC – Double sided double type column

- Testbeam data – Example: efficiency map
  [M.Koehler, Freiburg Uni, RD50 Workshop June 09]

- Processing of 3D sensors is challenging, but many good devices with reasonable production yield produced.

- Competing e.g. for ATLAS IBL pixel sensors

40V applied
~98% efficiency
3D-DDTC – Study after irradiation

- DDTC sensors irradiated with 26 MeV protons

- Signal scales with leakage current

- Avalanche effects in 3D sensors

- Signal to Noise

[M.Koehler, Trento Workshop, Feb. 2009]  
\[1 \times 10^{25} \text{ n}_{\text{eq}} /\text{cm}^2\]
### Use of other semiconductor materials?

<table>
<thead>
<tr>
<th>Property</th>
<th>Diamond</th>
<th>GaN</th>
<th>4H SiC</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_g$ [eV]</td>
<td>5.5</td>
<td>3.39</td>
<td>3.3</td>
<td>1.12</td>
</tr>
<tr>
<td>$E_{\text{breakdown}}$ [V/cm]</td>
<td>$10^7$</td>
<td>$4\cdot10^6$</td>
<td>$2.2\cdot10^6$</td>
<td>$3\cdot10^5$</td>
</tr>
<tr>
<td>$\mu_e$ [cm$^2$/Vs]</td>
<td>1800</td>
<td>1000</td>
<td>800</td>
<td>1450</td>
</tr>
<tr>
<td>$\mu_h$ [cm$^2$/Vs]</td>
<td>1200</td>
<td>30</td>
<td>115</td>
<td>450</td>
</tr>
<tr>
<td>$v_{\text{sat}}$ [cm/s]</td>
<td>$2.2\cdot10^7$</td>
<td>-</td>
<td>$2\cdot10^7$</td>
<td>$0.8\cdot10^7$</td>
</tr>
<tr>
<td>e-h energy [eV]</td>
<td>13</td>
<td>8.9</td>
<td>7.6-8.4</td>
<td>3.6</td>
</tr>
<tr>
<td>e-h pairs/X$_0$</td>
<td>4.4</td>
<td>~2-3</td>
<td>4.5</td>
<td>10.1</td>
</tr>
</tbody>
</table>

- **Diamond**: wider bandgap  
  ⇒ lower leakage current  
  ⇒ less cooling needed

- **Signal produced by m.i.p:**  
  Diamond 36 e/$\mu$m  
  Si 89 e/$\mu$m  
  ⇒ Si gives more charge than diamond

- **GaAs, SiC and GaN**:  
  ⇒ strong radiation damage observed  
  ⇒ no potential material for sLHC detectors  
  *(judging on the investigated material)*

- **Diamond (RD42)**:  
  ⇒ good radiation tolerance *(see later)*  
  ⇒ already used in LHC beam condition monitoring systems  
  ⇒ considered as potential detector material for sLHC pixel sensors

- poly-CVD Diamond  
  −16 chip ATLAS pixel module

- single crystal CVD Diamond of few cm$^2$

Diamond sensors are heavily used in LHC Experiments for Beam Monitoring
Are diamond sensor radiation hard?

Most published results on 23 GeV protons

70 MeV protons 3 times more damaging than 23 GeV protons

25 MeV protons seem to be even more damaging (Preliminary: RD42 about to cross check the data shown to the left)

In line with NIEL calc. for Diamond

Outline

- Motivation to develop radiation harder detectors
  - Super-LHC and expected radiation levels at the Super-LHC
  - Radiation induced degradation of detector performance

- Radiation Damage in Silicon Detectors
  - Macroscopic damage (changes in detector properties)
  - Microscopic damage (crystal damage)

- Approaches to obtain radiation hard sensors
  - Material Engineering
    - Silicon materials – FZ, MCZ, DOFZ, EPI
    - Other semiconductors
  - Device Engineering
    - p-in-n, n-in-n and n-in-p sensors
    - 3D sensors and thin devices

- Silicon Sensors for the LHC upgrade
  - Collected Charge – Signal to Noise – Avalanche effects
  - Mixed irradiations

- Summary
Silicon materials for Tracking Sensors

- Signal comparison for various Silicon sensors

![Graph showing signal comparison for various Silicon sensors](image)

**Silicon Sensors**
- p-in-n (FZ), 300μm, 500V, 23GeV p [1]
- p-in-n (FZ), 300μm, 500V, neutrons [1]

**Other materials**

References:

[5] 3D, double sided, 250μm columns, 300μm substrate [Pennicard 2007]

Note: Measured partly under different conditions!
Lines to guide the eye (no modeling)!
Silicon materials for Tracking Sensors

- Signal comparison for various Silicon sensors

![Graph showing signal comparison for various Silicon sensors](image)

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]
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- p-in-n (FZ), 300µm, 500V, 23GeV p [1]
- p-in-n (FZ), 300µm, 500V, neutrons [1]

Other materials
- SiC, n-type, 55 µm, 900V, neutrons [3]

References:
[5] 3D, double sided, 250µm columns, 900µm substrate [Pennicard 2007]

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- SiC, n-type, 55 μm, 900V, neutrons [3]

**References:**
1. p/n-FZ, 300 μm, (-30° C, 25 ns), strip [Casse 2008]
2. p-FZ, 300 μm, (-40° C, 25 ns), strip [Mandic 2008]
3. n-SiC, 55 μm, 2 μs, pad [Moscatelli 2006]
4. CVD Diamond, scaled to 500 μm, 23 GeV p, strip [Adam et al. 2006, RD42]
5. 3D, double sided, 250 μm columns, 300 μm substrate [Pennicard 2007]
6. n-EPI, 75 μm, (-30° C, 25 ns), pad [Kramberger 2006]
7. n-EPI, 150 μm, (-30° C, 25 ns), pad [Kramberger 2006]
8. n-EPI, 150 μm, (-30° C, 25 ns), strip [Messineo 2007]

Note: Fluctuations normalized with damage factor for Silicon (0.62)

- LHC SLHC
- highest fluence for strip detectors in LHC: The used p-in-n technology is sufficient

Note: Measured partly under different conditions!
Lines to guide the eye (no modeling)!

Michael Moll – Instrumentation Seminar, Hamburg 26.3.2010
Silicon materials for Tracking Sensors

- Signal comparison for various Silicon sensors

- All sensors suffer from radiation damage
- Presently three options for innermost pixel layers under investigation:
  - 3-D silicon sensors (decoupling drift distance from active depth)
  - Diamond sensors
  - Silicon planar sensors

Silicon Sensors
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- p-in-n (EPI), 75μm [6]
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- p-in-n (FZ), 300μm, 500V, 23GeV p [1]
- p-in-n (FZ), 300μm, 500V, neutrons [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:
[5] 3D, double sided, 250μm columns, 300μm substrate [Pennicard 2007]

Beware:
Signal shown and not S/N!

Higher Voltage leads to charge multiplication

Note: Measured partly under different conditions!
Lines to guide the eye (no modeling)!
Ongoing Work / Open Questions
- Performance of MCZ silicon in mixed fields -

- Is MCZ silicon (n- and p-type) an option for SLHC detectors?
  - Protons induce predominantly defects that are positively charged
  - Neutrons induce predominantly defects that are negatively charged
  - Mixed Fields: Compensation?

- Mixed irradiations:
  - (a) $\Phi_{eq} = 5 \times 10^{14}$ neutrons
  - (b) $\Phi_{eq} = 5 \times 10^{14}$ protons

- FZ (n-in-n)
- MCZ (n-in-n)

[T.Affolder et al. RD50 Workshop, Nov.2008]
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● FZ (n-in-n)
  Mixed Irradiation:
  Damage additive!

● MCZ (n-in-n)
  Mixed Irradiation:
  Proton damage
  “compensates” part of neutron damage ($N_{eff}$)

More charge collected at 500V after additional irradiation!!!
Summary – Radiation Damage

- **Radiation Damage in Silicon Detectors**
  - Change of **Depletion Voltage** (internal electric field, “type inversion”, reverse annealing, …) (can be influenced by defect engineering!)
  - Increase of **Leakage Current** (same for all silicon materials)
  - Increase of **Charge Trapping** (same for all silicon materials)

  **Signal to Noise ratio is quantity to watch** (material + geometry + electronics)

- **Microscopic defects & Defect Engineering**
  - Good understanding of damage after γ-irradiation (point defects)
  - Defects after hadron damage still to be better understood (cluster defects) although enormous progress in last 5 years a big question remains: Which are the defects responsible for the charge trapping?

- **Approaches to obtain radiation tolerant devices:**
  - **Material Engineering:** explore and develop new silicon materials
  - **Device Engineering:** 3D, thin sensors, n-in-p, n-in-n, …

⇒ **To obtain ultra radiation hard sensors a combination of material and device engineering approaches depending on radiation environment, application and available readout electronics will be best solution**
Summary – Detectors for SLHC

- **At fluences up to** $10^{15}$cm$^{-2}$ (outer layers of SLHC detector):
  - The change of the depletion voltage and the large area to be covered by detectors are major problems.
    - **MCZ silicon detectors**: n-MCZ show good performance in mixed fields due to compensation of charged hadron damage and neutron damage ($N_{\text{eff}}$ compensation) (more work needed)
    - **p-type silicon** microstrip detectors show very encouraging results:
      - CCE $\approx 6500$ e; $\Phi_{\text{eq}} = 4 \times 10^{15}$ cm$^{-2}$, 300$\mu$m, immunity against reverse annealing!
      - This is presently the “most considered option” for the ATLAS SCT upgrade

- **At fluences >** $10^{15}$cm$^{-2}$ (Inner SLHC layers or innermost upgraded LHC pixel)
  - The active thickness of any silicon material is significantly reduced due to trapping.
    - Collection of electrons at electrodes essential: Use n-in-p or n-in-n detectors!
  - **Recent results show that planar silicon sensors might still give sufficient signal**, (still some interest in epitaxial silicon and thin sensor options)
  - **3D detectors**: looks promising, drawback: technology has to be optimized!
    - Many collaborations and sensor producers working on this.
  - **Diamond** has become an interesting option (*Higher damage due to low energy protons?*)

- Questions to be answered:
  - a) Can we profit from the avalanche effects and control them?
  - b) Can we profit from MCZ (mixed field operation?)
Acknowledgements

- Some material taken from the following summary talks:
  - RD50 presentations on conferences: http://www.cern.ch/rd50/
  - Nigel Hessey: Eiroforum RADHARD 2010 Workshop, Lisbon 16-18 March 2010 (Path to upgrade)
  - Anthony Affolder: Presentations on the RD50 Workshop in June 2009 (sATLAS fluence levels)
  - Frank Hartmann: Presentation at the VCI conference in February 2010 (Diamond results)
  - … most references to particular works given on slides.

Further information about RD50 activities: http://cern.ch/rd50/
Further R&D: RD42, RD39, ATLAS & CMS detector upgrade meetings, ATLAS IBL

… or go to DESY bldg. 67b …

…. where you will find the

Particle Physics & Detector Development Group

.. and more expertise in this research field than I can offer.