Cryogenic Silicon Detectors

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Outline

• (Radiation Damage in Silicon)

• Silicon at Cryogenic Temperatures:
  ✓ Known Properties
  ✓ The Lazarus Effect

• Experimental Results on Diodes

• Position Resolution of a “Resurrected” Detector

• Irradiation in the Cold

• First Application of a Cryogenic Silicon Tracker in a High-Energy Physics Experiment
Working Principle of a Si detector

- Charged particle generates charge by ionization
- External field → detect signal induced on the electrodes by the charge carriers that drift in the depleted region $W$

\[
W \propto \sqrt{V_{\text{bias}}} \\
Q_{\text{induced}} = q \frac{\Delta x}{d}
\]

- For a non-irradiated detector (the non-depleted region is metal-like):
  
  - $CCE = 100\% \Rightarrow$ need to apply $V_{\text{bias}}$ such that $W = d$

$$CCE \equiv \frac{Q_{\text{measured}}}{Q_{\text{generated}}} \propto \frac{W}{d}$$

$$V_{\text{bias}} = V_{\text{dep}} = \frac{q}{2\varepsilon_0 \varepsilon_s} N_D d^2$$

$V_{\text{dep}}$ : depletion voltage

$N_D$ : density of impurities (donors, $\sim 10^{12} \text{cm}^{-3}$)
Radiation Damage in Si

- Non-ionizing energy loss
  → displacement of lattice atoms, creation of a Frenkel pair
  (vacancy + interstitial)

- Vacancies and interstitials move around and combine with lattice impurities
  → stable defects, which appear as deep energy levels in the forbidden band gap of silicon

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Vacancies and interstitials move around and combine with lattice impurities, creating stable defects. These defects appear as deep energy levels in the forbidden band gap of silicon.

Radiation induced levels:
- Conduction band
- Valence band
Radiation Damage in Si

Macroscopic observables:

- Leakage current increases linearly with dose
  - increase of detector noise
  - power dissipation in the sensor

- Trapping and de-trapping of carriers
  - signal loss

- At equilibrium, a certain fraction of defects are filled and therefore charged, so they contribute to the effective doping concentration \( N_D \rightarrow N_{\text{eff}} \)

- Experimental observation: under irradiation, space charge become more and more negative
  - dramatic increase of depletion voltage \( V_{\text{dep}} \propto N_{\text{eff}} d^2 \)

- Annealing: \( N_{\text{eff}} \) changes also after irradiation
  - need to keep the detector at -10°C
Under bias, space charge is negative, \( \rightarrow \) bulk behaves like a \textit{p-type} material.

The junction develops from \( n^+ \)

Heavily irradiated detector
\( \rightarrow \) the non-depleted region behaves like an insulator
\( \Rightarrow \) \( Q_{\text{induced}} \propto W/d \)

\[ CCE \propto \left( \frac{W}{d} \right)^2 \]

\( W/d = 70\% \rightarrow CCE = 50\% \) !!!

Experimental observation: there is trapping
\( \rightarrow \) even for a fully depleted detector \( CCE < 100\% \)
Known Properties of Si at Cryogenic Temperatures
Silicon at Cryogenic Temperatures

Higher Mobility

- Fast signals

Less Carriers

- Higher bulk resistivity
- Lower depletion voltage
Leakage Current vs Temperature

Exponential Decrease of Leakage Current

Irradiated detector

I < 1 nA up to ±500 V!

→ low noise

→ no power dissipation in the sensor
Is there anything else ?
• Experimental observation: heavily irradiated Si detector no longer operational at room temperature “resuscitate” when cooled down to cryogenic temperatures
Is there anything else?

The Lazarus Effect
The Lazarus Effect


- By cooling, we manipulate the Si bulk properties
  - Most relevant:
    - charge carrier density
    - de-trapping probability
  - Cooling \( \Rightarrow \) fraction of charged traps decreases
    - \( \Rightarrow |N_{\text{eff}}| \) decreases
Results on Diodes
Conventional Operation

Time Dependence

Reduced Stable Values

300 μm + 10^{15} n/cm^2 @ 130 K @ 250 V \implies 5'000 e^{-}

T = 80 K
Forward Bias Operation

300 μm + $10^{15}$ n/cm² @ 130 K @ 250 V $\Rightarrow$ 15’000 e⁻

No Time Dependence !!!
Operation in Presence of Light

- Short wavelength light absorbed in few $\mu$m $\Rightarrow$ only positive charge flows through the bulk, compensating negative space charge:
  
  $\Rightarrow |N_{eff}|$ becomes smaller

G. Lutz, NIM A 377 (1996) p. 242:
“Partial charging of defects can be influenced by increasing the carrier density of one type against the other by e.g. providing a surface generated current (e.g. illumination of one side of the detector). Reducing the full depletion voltage of a detector by this method may work only in unpractical conditions (as e.g. very low temperature or high current)…”
The CCE at cryogenic temperatures does not depend on the annealing status of the detector

- need to cool only during operation !!!
Cryogenic silicon is a (kind of) new material ... ...what can we do with it?
“Double P” Detector

Before Irradiation

\[ p^+ \rightarrow n \rightarrow n^- \]

After Irradiation

\[ p^+ \rightarrow p \rightarrow n^- \]

\[ \text{Bias Voltage (V)} \]

CCE (%)

400 µm + \(10^{15}\) n/cm\(^2\) @ 130 K @ 500 V \(\Rightarrow 27'000\) e\(^-\)
The charge is back, but what about position resolution?
The DELPHI Microstrip Detector

- 3.2 \times 11.5 \text{ cm}^2 \text{ double sided detector}
- 1 \text{ module} = 1280 \text{ channels}
- strip pitch: p-side 25 \mu m, n-side 42 \mu m
- AC coupling
- readout: MX6, 3 \mu m CMOS, 1 ms peaking time

irradiated with
3.5 \times 10^{14} 24 \text{ GeV protons / cm}^2

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K. Borer et al, NIM A 440 (2000) 17
Cryogenic cooling of a segmented detector results also in recovering the position resolution!
What happens when irradiating in the cold?
Si Detector Irradiated at 83 K

Irradiation with (400 GeV) protons

No significant differences compared to room temperature!
## 260 K vs 130 K

<table>
<thead>
<tr>
<th></th>
<th>260 K</th>
<th>130 K</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Leakage current</strong></td>
<td><img src="image.png" alt="Image" /></td>
<td><img src="image.png" alt="Image" /></td>
</tr>
<tr>
<td>detector noise</td>
<td>OK @ $10^{14}$ n/cm$^2$</td>
<td>OK @ $2 \times 10^{15}$ n/cm$^2$</td>
</tr>
<tr>
<td>power in the sensor</td>
<td>~100μW/mm$^2$</td>
<td>(~1μW/mm$^2$)</td>
</tr>
<tr>
<td><strong>CCE (trapping + depletion)</strong></td>
<td><img src="image.png" alt="Image" /></td>
<td><img src="image.png" alt="Image" /></td>
</tr>
<tr>
<td>reverse bias</td>
<td>3×$10^{14}$ n/cm$^2$ : 65% @ 500V</td>
<td>100% @ 250V</td>
</tr>
<tr>
<td></td>
<td>2×$10^{15}$ n/cm$^2$ : ?</td>
<td>20% @ 250V</td>
</tr>
<tr>
<td>forward bias</td>
<td>2.8×$10^{14}$ n/cm$^2$ : 70% @ 50V</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(I = 6μA / mm$^2$)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1×$10^{15}$ n/cm$^2$ :</td>
<td>70% @ 250V</td>
</tr>
<tr>
<td></td>
<td>(I &lt; 1nA / 5×5mm$^2$)</td>
<td></td>
</tr>
<tr>
<td><strong>Annealing</strong></td>
<td>need to keep the detector at -10ºC</td>
<td>cooling only during operation</td>
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The first application: Cryogenic Heavy Ion Beam Tracker for the NA60 Experiment
The NA60 Experiment

- Study $\mu^+\mu^-$ production in heavy ion collisions
- Signals related to phase transition from hadronic matter to Quark-Gluon Plasma
- First measurement of charm production in heavy ion collision
Charm Measurement in NA60

Need to measure the transverse coordinates of the interaction point

✓ Good position resolution: ~20 µm
✓ Good timing: two-pulse resolution < 5 ns
✓ Extreme radiation hardness: ~100 Grad
The Beamscope

- Vacuum chamber (beam windows: 100 µm of stainless steel)
- Cryogenic Module
- Readout Cards
- Beam
- 200 mm
The Cryogenic Module

- Low mass cooling pipe ($\varnothing = 1\text{mm}, 100\mu\text{m}$ thick)
- Integrated thermo-electrical design improves performance
- Temperature can be adjusted between 80K and 300K by adjusting the LN$_2$ flow and the power dissipated through a heater placed on the PCB

- 24 narrow strips (50 $\mu$m pitch)
- 2x4 wide strips (500 $\mu$m pitch)
The Beamscope Readout

- Narrow strips
- Wide strips
- Back-plane
- Discriminator
- Amplifier
- Current to frequency converter
- MHTR
- Memory
- Scaler
- Oscilloscope
**Test Beam Conditions**

**November 1999:** detector concept
- Exposed for 3 days to 40 A GeV Pb beam
- Average beam intensity: $5 \times 10^6$ ions per 4.5 s burst
- Total dose: $\sim 1$ Grad

**October - November 2000:** radiation tolerance
- Parasitic to NA50
- Exposed **4 days** to 40 A GeV and **38 days** to the 158 A GeV Pb beam
- Average beam intensity: $7 \times 10^7$ ions per 4.5 s burst
- Total fluence: $5\pm2 \times 10^{14}$ ions/cm$^2$ ($90 \pm 40$ Grad)
- Electronics suffered much from radiation in the beam area...
True (unshaped) Pb Ion Signal

Non-irradiated

- Very fast rise time (< 500ps)
- Very long tail (~20ns)

After 20 days (40 ± 20 Grad)

- Signal is broader
- Amplitude ~20 times lower… but we see it!

200 V
8 Gs/s

200 V
2 Gs/s
Beam Profile

Day 1

Day 38 (~85 Grad)

horizontal

vertical

strip number

strip number

1.2 mm
MHTR Timing

Time of arrival wrt the trigger of the hits in one strip integrated over several spills

ions coming before or after the trigger
MHTR Timing & Cluster Correlation

Time of arrival wrt the trigger of the hits in all strip integrated over several spills, normalizing to the same mean time.

\[ \sigma = 1.0 \pm 0.1 \text{ ns} \]

Correlation of clusters in plane 2 and 4 (only hits within 3 \( \sigma \))

\~200 \( \mu \)m misalignment
Cluster Size

- Contrary to what is expected in segmented Si detectors, cluster size increases with Vbias.
- Different charge generation process of Pb vs MIPs?
• After 40 Grad no dependence of the pulse height on the bias voltage.

• To be checked: possible bias of signal shaping
Conclusions

- Work to be done to understand the detail of the phenomenon. Nevertheless, data clearly show that:
  - CCE dramatic improves at T ~ 130 K
  - If charge is back, the position resolution is also recovered

→ Cryogenic Operation is a robust technique to extend the lifetime of Si trackers by more than order of magnitude

- For heavy ions, where very large signals are obtained, Cryogenic Silicon can work up to several tens of Grad
  - Cooling must be integrated in the mechanical design
  - Thermal design is easier at 80 K than at 250 K
  - 2-phase nitrogen is an excellent coolant

- Future:
  - Cryogenic Detectors for TOTEM
  - Beamscope for NA60 (also for protons)
  - Vertex Tracker of COMPASS