Radiation Hard Cryogenic Silicon Detectors: The Lazarus Effect

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on behalf of the CERN-RD39 Collaboration
http://www.cern.ch/RD39
Outline

- Known facts about silicon detectors operated at cryogenic temperatures
- Electric passivation of radiation induced defects in silicon: the Lazarus effect
- Silicon detectors optimized for the cold
- Position resolution of a “resurrected” detector
- “Low mass” cryogenic cooling systems
- First application of a cryogenic silicon tracker in a high energy physics experiment
- Innovative concepts
- Conclusions
Known facts about silicon detectors operated at cryogenic temperatures ...
Properties of Silicon at Cryogenic Temperatures

Higher Mobility

Less Carriers
Radiation Induced Leakage Current Reduction with Temperature

Exponential Decrease

At 77 K, detectors irradiated above $5 \times 10^{14}$ n/cm$^2$ show less than 1 nA current in the bias range $\pm$ 500 V

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Is there anything else?

...
Electric Passivation of Radiation Induced Defects

$T = 300 \text{ K}$

- Electron trapping
- Electron de-trapping
- Hole trapping
- Hole de-trapping

$T = 77 \text{ K}$

- Electron trapping
- Electron de-trapping
- Hole trapping
- Hole de-trapping

- Trap filled

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Conventional Operation

\[
\left\{ 300 \mu m \times 10^{15} \frac{n}{cm^2} + 130K + 250 V = 25000 e^- \cdot 20\% = 5000 e^- \right\}
\]
The Lazarus Effect !
Is cryogenic silicon a new material?

if yes ... what can we do with it?
Non-Conventional Operation

Forward Bias

\[
\left\{ \begin{array}{l}
300 \mu m \times 10^{15} \text{ n/cm}^2 + 130K + 250V = 25000 \ e^- \cdot 60\% = 15000 \ e^-
\end{array} \right.
\]
“Double P” Detector

\[
\{ 400 \mu m \times 10^{15} \text{ n/cm}^2 + 130 K + 500 V = 33000 e^- \cdot 80\% = 27000 e^- \} 
\]

K. Borer et al. (the RD39 Collaboration), NIM A 462 (2001) 474

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The charge is back, but what about position resolution?
The Cooled DELPHI Microstrip Detector Module

3x12 cm$^2$; 1280 Channels CMOS readout

K. Borer et al, NIM A 440 (2000) 17

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Cryogenic cooling of a segmented detector results also in recovering the tracking position resolution!
Is a “low mass” cryogenic system feasible?
Towards a “Low Mass” Cooling System

The cooling pipe is “low mass” (1 mm \(\Theta\) 100 \(\mu m\) thick)

Integrated thermal/electric design for the PCB/Hybrid improves performances
No dissipation in the sensor means no need for cooling

Liquid nitrogen is a very good coolant

For 130 K operation, foam isolation (30 mm thick) plus dry gas atmosphere is sufficient
The first application:
The BeamScope for the CERN NA60 Experiment...
... Installed in the Beam Line!
The CERN SPS High Intensity Pb-Ion Beam as seen by the BeamScope

Using a strip pitch of 50 $\mu$m, we have measured the beam profile with unprecedented resolution.

Using the trigger of the experiment as a reference, we could tag every single ion in the beam spill (containing $5 \times 10^7$ ions!).

L. Casagrande et al, NIM A in press
Radiation Damage...
Which radiation hard readout electronics for the cold?
The Proton Beamscope

A new front-end chip by CERN EP-MIC group manufactured in 0.25 μm radiation-tolerant CMOS technology:

- 2×4 mm²; 32 channels
- Peaking: ~3.6 ns at 130 K
- Good S/N down to 2500e
- Power dissipation: ~300 mW

Improved module:
- Optimized microstrips
- New PCB design
- 0.5 mm diameter pipes

G. Anelli et al, NIM A in press

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How Protons Look Like...

Single proton signal as seen by a fast digital oscilloscope after front-end chip and shaping stage. Extremely fast signal with good S/N.

Beam intensity $10^9$ protons per burst: many protons can be measured on a single detector strip without significant pile-up.

G. Anelli et al, NIM A in press
Innovative concepts:
Solid-State Ionization Beam Monitor

Using a simple scheme we were able to precisely measure the position and the intensity of the CERN SPS proton beam.
Before and After Irradiation ...

The Si pad is perfectly functional after a dose of 50 Mrad and provides relative measurements over more than three orders of magnitude of beam intensity.
Absolute measurements of beam intensity are affected by radiation damage. However a nice linear behaviour is observed.
Conclusions

- **Cryogenic cooling dramatically improves radiation hardness of silicon detectors**
  - A universal optimal temperature of 130 K is found for the Lazarus effect. At this temperature, after irradiating a 400 μm thick Si detector with $1 \cdot 10^{15}$ n/cm$^2$, a m.i.p. most probable signal of 27000 e$^-$ is measured at 500 V. This corresponds to 80% CCE;
  - Segmented devices show a corresponding recovery of the position resolution when the CCE is restored;

- **Liquid nitrogen cooling can be made low-mass**
  - Foam isolation is sufficient for operation at 130 K;

- **Innovative concepts can take advantage of the properties of silicon at cryogenic temperature**
  - Solid-state ionization beam monitor can operate up to very high intensity ($10^{10}$ protons per burst) and doses (50 Grad)