Assessment of photodetection performance of analog and digital SiPMs when exposed to cold neutrons

June 14, 2018 | Daniel Durini\textsuperscript{1,2,*}, Shashank Kumar\textsuperscript{1}, David Arutinov\textsuperscript{1}, Carsten Degenhardt\textsuperscript{1}, Stefan van Waassen\textsuperscript{1,3}

\textsuperscript{1}Central Institute of Eng., Electronics and Analytics ZEA-2 – Electronic Systems, Forschungszentrum Jülich, Germany
\textsuperscript{2}National Institute of Astrophysics, Optics and Electronics (INAOE), Tonantzintla, Puebla, Mexico
\textsuperscript{3}Faculty of Engineering, Communication Systems (NTS), University of Duisburg-Essen, Duisburg, Germany

* d.durini@fz-juelich.de
Table of Contents:

• Motivation
• Radiation Hardness of SiPMs: Dark Signal Issues
• Radiation Hardness of SiPMs: PDE Issues
• Conclusions and Outlook
Motivation

Small-angle neutron scattering (SANS):

- Soft matter investigations
- No electric charge → nuclear reactions
- Neutron magnetic moment → investigation of magnetic properties of matter
- Thermal and cold neutrons (1 – 25 meV) deposit only minimum amounts of energy into the investigated sample

We need:

- Higher spatial resolutions (< 1 mm²)
- Higher count rates (to match any future neutron source)
- Compatibility with magnetic fields
- Modular 4-side tileable detectors
- Lower power consumption and heat generation
We propose…

SANS solid-state pixelated and modular scintillation detectors using Ce-doped $^6$Li-glass scintillator and an underlying array of SiPM photodetectors:

- Near single photon counting $\rightarrow$ high $\eta_n$
- Low bias voltages (20-70 V)
- Acceptable space resolution (< 1 mm sq.)
- Neutron counting rates $\sim$ 100 Mcps/m²
- Insensitivity to magnetic fields up to several Tesla

\[ \bar{Q} = |\bar{Q}| = \sqrt{k^2 + k'^2 - 2kk' \cos 2\theta} \quad \text{yields} \quad |\bar{Q}| = \frac{4\pi}{\lambda_n} \sin \theta \]
Typical operating conditions for SANS experiments

PMT based Anger-camera scintillation detector installed at the KWS-1 instrument of the MLZ in Garching, Germany. The detector has an active area of 60 x 60 cm²:

Scale-up factor of 7.9 used for the maximum amount of neutrons expected at the instrument in the future.

Technical data of the KWS-1 instrument:
- \( Q = 0.0007 - 0.5 \text{ Å}^{-1} \)
- Maximal neutron flux: \( 1.5 \times 10^8 \text{ n·cm}^2\cdot\text{s}^{-1} \)
- Neutron velocity selector (chopper, FWHM 10%): \( \lambda_n = 4.5 \text{ Å} - 12 \text{ Å} \); typically \( \lambda_n = 5 \text{ Å} \Rightarrow E_n = 3.27 \text{ meV} \)

Source: Durini et al., NIMA 835 (2016) 99–109

June 14, 2018

Graphical presentation of the amount of neutrons detected during 240 days (between August 2014 and October 2015) across all kinds of experiments and setups available at the instrument.
Main concern: Radiation Hardness of SiPMs

Radiation damage for SiPMs:

- Ionizing damage (mainly due to high-energy gamma photons)
- Displacement damage (DD): 25 eV for a Si atom to be displaced → 175 keV neutrons for generation of Frenkel pairs (silicon interstitial and vacancy) to be produced
- Single event effects (SEE): range of effects caused by ionization from a single, high energy particle

Effective damage to Silicon detectors relative to 1 MeV neutron (irradiated with white neutrons):

The equivalent damage is expected to be 3 - 4 orders of magnitude lower than the one caused by 1 MeV neutrons


Durini et al. ICA SiPM 2018
Main concern:

Radiation Hardness of SiPMs

Nuclear transmutation processes initiated by thermal neutron \((n)\) capture:

\[ ^{30}\text{Si} + n \rightarrow ^{31}\text{Si} \rightarrow ^{31}\text{P} + \beta^- \]

Damage introduced into silicon by thermal/cold neutrons is primarily in form of point defects, approximately 2-5 defects per absorbed neutron remaining at room temperature.

Increase in the dark signal of the SiPMs!

Source: Durini et al., “CMOS Technology for SPAD / SiPM. Results from the MiSPiA Project”, 7th IMS Workshop, 2014
We investigated the dark signal and PDE performances of 3 SiPM technologies under irradiation with cold neutrons.

For dark signal deterioration assessment, we measured it during irradiation with cold neutrons both, with and without a scintillator material covering the photodetector arrays.
# Table of Contents:

- Motivation
- Radiation Hardness of SiPMs: Dark Signal Issues
- Radiation Hardness of SiPMs: PDE Issues
- Conclusions and Outlook
Radiation Hardness of SiPMs: Dark Signal

<table>
<thead>
<tr>
<th>Investigated SiPM technologies</th>
<th>SensL Series-C</th>
<th>Hamamatsu 8 x 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array format</td>
<td>12 x 12 PCB</td>
<td>8 x 8</td>
</tr>
<tr>
<td>Pitch of each individual</td>
<td></td>
<td></td>
</tr>
<tr>
<td>detector, mm</td>
<td>4.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Array package size (4-side</td>
<td>50.2 x 50.2</td>
<td>22.4 x 25.8</td>
</tr>
<tr>
<td>tileable), mm²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active area of each</td>
<td></td>
<td></td>
</tr>
<tr>
<td>individual sensor (pixel),</td>
<td>3 x 3</td>
<td>3 x 3</td>
</tr>
<tr>
<td>mm²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microcell size, µm</td>
<td>35</td>
<td>50</td>
</tr>
<tr>
<td>No. of micro-cells</td>
<td>4774</td>
<td>3584</td>
</tr>
<tr>
<td>Micro-cell fill-factor, %</td>
<td>64</td>
<td>62</td>
</tr>
<tr>
<td>Detector fill-factor, %</td>
<td>51</td>
<td>87.9</td>
</tr>
</tbody>
</table>

SensL Series-C I-V curve and $V_{br}$ analysis

Variations of up to 0.2 V
Radiation Hardness of SiPMs: Dark Signal

Source: Durini et al., NIMA 835 (2016) 99–109

June 14, 2018

Durini et al. ICA SiPM 2018
Radiation Hardness of SiPMs: Dark Signal

**Philips DPC3200-22-44**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Array format</td>
<td>8 × 8 SiPM</td>
</tr>
<tr>
<td>Pitch of each individual SiPM detector</td>
<td>4.0 mm</td>
</tr>
<tr>
<td>Array package size (4-side tiltable)</td>
<td>32.6 × 32.6 mm²</td>
</tr>
<tr>
<td>Active area of each individual sensor</td>
<td>3.2 × 3.8 mm²</td>
</tr>
<tr>
<td>Microcell size</td>
<td>59.4 × 64 μm²</td>
</tr>
<tr>
<td>No. of micro-cells</td>
<td>3200 1</td>
</tr>
<tr>
<td>Micro-cell fill-factor</td>
<td>74 %</td>
</tr>
</tbody>
</table>

**Graph:**
- Average DCR per photoactive cell over 1 die (4 Pixels or 12,800 photoactive cells) + 1σ Standard Deviation @ 90% activated photoactive cells
- Interpolated DCR

**Measurements:**
- Average DCR [cps]
- Thermal Neutron Dose [n/cm²]

- 134 kcps
- Factor 226 increase

- **592 cps**
- **T = 23.78 ± 0.72 °C**

---

*June 14, 2018*

*Durini et al. ICA SiPM 2018*
Radiation Hardness of SiPMs: Dark Signal

Active Area Related Detector (Pixel) DCR [kcps/mm²]

Neutron Dose [n/cm²]

One year equivalent dose
Ten year equivalent dose

T = 23°C

No Irradiation

Normalized the aSiPM dark currents:

$$DCR = \frac{I_{dark}}{q \cdot G \cdot A_{active}} \left( \frac{100 - XT - AP}{100} \right)$$

June 14, 2018

Durini et al. ICA SiPM 2018
Radiation Hardness of SiPMs: Dark Signal

SensL SiPM detectors with $3 \times 3$ mm² photoactive areas, biased at $(V_{br} + 2.5)$ V @ T = 23°C:

1 mm Ce-doped $^6$Li-glass Scintillator
Approx. Transmission: ~5%

Hamamatsu MPPC $3 \times 3$ mm² photoactive area detectors, biased at $(V_{br} + 2.4)$ V @ T = 23°C

1 mm Ce-doped $^6$Li-glass Scintillator
Approx. Transmission: ~12%

Philips DPC detectors with $4 \times 4$ mm² photoactive areas, biased at $(V_{br} + 3)$ V @ T = 23°C:

1 mm Ce-doped $^6$Li-glass Scintillator
Approx. Transmission: ~5%

Assumption for future work: approx. 10% of impinging neutrons get absorbed in the scintillator.
Table of Contents:

• Motivation
• Radiation Hardness of SiPMs: Dark Signal Issues
• Radiation Hardness of SiPMs: PDE Issues
• Conclusions and Outlook
Radiation Hardness of SiPMs: PDE issues

Opto Measurement System Setup

- Peltier element & Ref. diode
- Monochromator & Optical fibre
- Xenon lamp housing & Controller
- Chopper control & Lock-in Amp.
- Cooling system controller & PC
- Thermochiller

0.8m 1.8m 2.3m
Radiation Hardness of SiPMs: PDE issues

Example of repeated irradiance measurements using a reference photodiode:

Resulting system uncertainty (including the uncertainty of the ref. PD): 16.6 %

Illumination spot uniformity (8 x 8 mm²):
Radiation Hardness of SiPMs: PDE issues

Optimizing the measurement system for “single-photon counting” devices is never easy…

Max. neutron dose: 1.9x10^{12} n/cm²

Max. neutron dose: 2x10^{12} n/cm²

Max. neutron dose: 6x10^{12} n/cm²

Source: Kumar et al. (2018) JINST Vol. 13

Durini et al. ICA SiPM 2018
Table of Contents:

• Motivation
• Radiation Hardness of SiPMs: Dark Signal Issues
• Radiation Hardness of SiPMs: PDE Issues
• Conclusions and Outlook
Conclusions and Outlook:

• SiPM technology is viable for solid-state pixelated scintillation detectors to be used in SANS applications having over 10-year life-times

• *Hamamatsu* MPPCs showed higher radiation hardness than *SensL Series-C* and *Philips DPC* → all three technologies remained within goal specifications

• An annealing effect at room temperature was observed and will be investigated further (also using active heating or illumination)

• The relative deterioration in PDE (λ = 420 nm) after irradiation with 5 Å cold neutrons is proportional to the increase in the DCR → remained within goal specifications

• We chose the *Philips DPC technology* and developed and characterized the first SANS PDPC based solid-state scintillation detector demonstrator yielding:
  
  • Count-rate (linearity > 90%): >110 Mcps for 60 x 60 cm²
  • Neutron Detection Efficiency: 75 ± 5 % @ 5 Å
  • Spatial resolution: ≥ 1x1 mm² for monolithic scintillator glass
  • A prototype detector of 13 x 13 cm² is currently under development
Conclusions and Outlook:

- SiPM technology is viable for solid-state pixelated scintillation detectors to be used in SANS applications having over 10-year life-times

- *Hamamatsu* MPPCs showed higher radiation hardness than *SensL Series-C* and *Philips DPC* → all three technologies remained within goal specifications

- An annealing effect at room temperature was observed and will be investigated further (also using active heating or illumination)

- The relative deterioration in PDE ($\lambda = 420$ nm) after irradiation with 5 Å cold neutrons is proportional to the increase in the DCR → remained within goal specifications

- We chose the *Philips DPC technology* and developed and characterized the first SANS PDPC based solid-state scintillation detector demonstrator yielding:
  - Count-rate (linearity > 90%): >110 Mcps for 60 x 60 cm²
  - Neutron Detection Efficiency: 75 ± 5 % @ 5 Å
  - Spatial resolution: $\geq 1x1$ mm² for monolithic scintillator glass
  - A prototype detector of 13 x 13 cm² is currently under development

Thank you very much for your attention!

…any questions?