TIMING RESOLUTION OF SIPM TECHNOLOGIES BEFORE AND AFTER NEUTRON IRRADIATION

2019.07.10 | S. KUMAR¹, L. NIRAULA¹, M. HERZKAMP¹, D. ARUTINOV¹, S. VAN WAASEN¹,²

¹CENTRAL INSTITUTE OF ENGINEERING, ELECTRONICS AND ANALYTICS ZEA-2 – ELECTRONIC SYSTEMS, FORSCHUNGSZENTRUM JÜLICH GMBH, GERMANY
²FACULTY OF ENGINEERING, COMMUNICATION SYSTEMS (NTS), UNIVERSITY OF DUISBURG-ESSEN, GERMANY

Email: s.kumar@fz-juelich.de

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MOTIVATION

Neutron Time of Flight Scattering:
- Study neutron-nucleus interaction
- Conservation of momentum
- Kinetic energy determination
- Time of fly measurement

Scientific Applications:
- Material science
- Medicine
- Chemistry etc.

State-of-the-art detector: \(^3\)He tubes

Schematic of a Small Angle Neutron Scattering (SANS) experiment with scintillation detector

Photodetectors in scintillation based detector:
- Photomultiplier Tube (PMT)
- **Silicon Photomultipliers (SiPM)**
**SILICON PHOTOMULTIPLIERS (SIPM)**

- Semiconductor photo sensor working in Geiger mode
- Array of Single Photon Avalanche Diode (SPAD)
- Parallel connected SPAD current output

<table>
<thead>
<tr>
<th>Photodetector</th>
<th>SiPM</th>
<th>PMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Form factor</td>
<td>😊</td>
<td>😞</td>
</tr>
<tr>
<td>Operating voltage</td>
<td>~ Tens of V</td>
<td>~ Kilos of V</td>
</tr>
<tr>
<td>Magnetic field insensitivity</td>
<td>😊</td>
<td>😞</td>
</tr>
<tr>
<td>Time resolution</td>
<td>~ tens of ps</td>
<td>~ hundreds of ps</td>
</tr>
<tr>
<td>Radiation hardness</td>
<td>?</td>
<td>😊</td>
</tr>
</tbody>
</table>

Conversion of light into current in SPAD

Excess voltage = $V_G - V_{BD}$ (Breakdown voltage) (Operation voltage)

Current vs. Voltage characteristics of SPAD

SiPM output as sum of SPAD current

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RADIATION HARDNESS OF SiPM

Concern of prolonged neutron exposure to SiPM:

- Increase in electron concentration
  \[ ^{30}\text{Si} + n \rightarrow ^{31}\text{Si} \rightarrow ^{31}\text{P} \text{ (donor atom)} + \beta \]
  (Nuclear transmutation doping)
- Increase in defects in silicon crystal

\[ |I_{\text{dark}}| = \alpha_p q A_n \left( \frac{n_i^2}{N_D} \sqrt{\frac{D_p}{\tau_{r-p}}} + N_{\text{def}} W_{\text{SCR}} \sigma_n c_n T^2 e^{\frac{E_c - E_r}{k_B T}} \right) \]

D. Durini et al., Nucl. Instr. and Meth. A 835, p. 99 (2016)

Increase in dark current (noise) of SiPM?
Effect on Photon Detection Efficiency (PDE) of SiPM?
Effect on Timing Resolution (TR) of SiPM?
SIPM MODULES UNDER INVESTIGATION

Analog SiPM arrays

- **SensL C-series (12×12)**
  - Active area: 3mm×3mm
  - SPAD size: 35µm×35µm
  - Breakdown voltage: ~25V

- **Hamamatsu (8×8)**
  - Active area: 3mm×3mm
  - SPAD size: 5µm×5µm
  - Breakdown voltage: ~65V

Digital SiPM array

- **Philips Digital Photon Counter (8×8)**
  - Active area: 3.8mm×3.2mm
  - SPAD size: 59.4µm×64µm
  - Breakdown voltage: ~23V

SiPMs covered with B$_2$C, during irradiation with neutrons ($\lambda = 5\text{Å}$, $E = 3.27\text{meV}$) up to a dose of $6 \times 10^{12} \text{n/cm}^2$, performed in 2015 at the KWS-1 instrument at *Heinz Maier Leibnitz Zentrum (MLZ)*, Germany.
Under 10 year of constant operation (estimated total neutron dose \(\sim 10^{11}\) n/cm\(^2\)) in a typical small angle neutron scattering (SANS) experiments:

<table>
<thead>
<tr>
<th>SiPM Arrays</th>
<th>Increase factor in dark current (in 2016)</th>
<th>Relative change (%) in PDE (in 2018)</th>
<th>Received overall neutron dose ((\times 10^{12}) n/cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Philips DPC</td>
<td>1.5</td>
<td>0</td>
<td>1.85</td>
</tr>
<tr>
<td>SensL</td>
<td>1.3</td>
<td>-4.9</td>
<td>1.9</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>1.1</td>
<td>-11.3</td>
<td>6</td>
</tr>
</tbody>
</table>

Table: Comparison of SiPM performance after irradiation with neutron (\(\lambda = 5\)Å)

D. Durini et al., Nucl. Instr. and Meth. A 835, p. 99 (2016)
S. Kumar et al., JINST, 13C01042 (2018)

Increase in dark current (noise) of SiPM? 😊
Change in Photon Detection Efficiency (PDE) of SiPM? 😊
Change in Timing Resolution (TR) of SiPM? 😊
TIMING RESOLUTION OF SIPM

Jitter in time for the arrival of photon on SiPM and its detection

Histogram of variation of output pulse with time:

\( \sigma \) of this histogram is TR

Temporal characteristics of an SensL output signal recorded in oscilloscope:

Rise time = \( \sim10 \) ns
Fall time = \( \sim100 \) ns

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TIME RESOLUTION MEASUREMENT

- Correlation of SiPM signal with a reference (sync) signal
- Thresholding
- Histogramming
- Measurement of $\sigma$

Approaches:
- Time Correlated Single Photon Counting (TCSPC) device: Reference signal rise time not compatible
- Oscilloscope

Fig: Illustration of time resolution measurement using oscilloscope.
MEASUREMENT SETUP

Pilas Laser Diode
Central wavelength: 403 nm
Pulse duration: 45 ps
Pulse peak power: 300 mW

- Pulsed Laser
- Laser head
  - Pulse width: 9 ns
  - Pulse rise time: 4.2 ns
- Electrical sync signal
- TTL to NIM
- Power Supply
- Reference signal
- SiPM output signal
- Oscilloscope
  - Keysight
    - Bandwidth: 13GHz
    - Max Sample Rate: 40 GSa/s
    - ADC Bits: 8 bits

Dark box
- Neutral density filter
- Front end board
- Pinhole
- Neutral density filter
- SiPM
MEASUREMENT

\[ \sigma_{measured} = \sqrt{\sigma^2_{SiPM} + \sigma^2_{setup} + \sigma^2_{laser} + \sigma^2_{noise}} \]

Pulsed Laser \rightarrow TTL to NIM \rightarrow Splitter \rightarrow Oscilloscope

- Laser
  - Optical pulse width = 3ps
  - Electronic to optical signal jitter

Short cable: Trigger signal
Long cable: TR test signal
Thresholding: 50%

\[ \sigma_{setup} = 26\text{ps} \]

\[ \sigma_{noise} = \frac{V_{noise}}{dV/dt} \]

Recorded image in oscilloscope for the time resolution measurement of the set up.
Comparison of four pixels of **Hamamatsu SiPM** at 21°C and at 50% thresholding

Comparison of four pixels of **SensL SiPM** at 21°C and at 50% thresholding
CONCLUSION AND OUTLOOK

- SiPMs are feasible for cold neutron time of flight applications (ps range)
- Small degradation in TR observed due to surface damage leading to noise increment

<table>
<thead>
<tr>
<th>SiPM arrays under investigation</th>
<th>Increase factor in Dark Current (2015)</th>
<th>Decrease (%) in PDE (2016)</th>
<th>Timing Resolution</th>
<th>Received overall neutron (5Å) dose ($\times 10^{12}$ n/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SensL</td>
<td>1.3</td>
<td>4.9</td>
<td>Non-Irradiated</td>
<td>Irradiated</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>38ps</td>
<td>39ps</td>
</tr>
<tr>
<td>Hamamatsu</td>
<td>1.1</td>
<td>11.3</td>
<td>67ps</td>
<td>73ps</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

Table: Quantitative comparison of performance of SiPM technologies after neutron (5Å) irradiation ($6\times 10^{12}$ n/cm$^2$). No significant change in TR at 3V excess voltage is observed under measurement uncertainty of 4ps.

- Investigation of TR change for Philips (digital SiPM) will be reported in near future
- Interesting to study the changes within shorter time after neutron irradiation

Thanks for your attention!