Tissue-Equivalent Radiation Dosimeter-on-a-chip

Erik Johnson
Christopher Stapels, Radia Sia and James Christian
Radiation Monitoring Devices, Inc.

Eric Benton
Oklahoma State University

Adam Rusek and Michael Sivertz
Brookhaven National Laboratories

NASA SBIR: X13.01-9313
Use a tissue-equivalent scintillating material.
Use CMOS technology for optical device and readout.
The scintillator is the limiting factor for the dosimeter size.
Compact, low-power, low-mass.
Provides rates, accumulated dose and spectra.
SSPMs are built as an array of Geiger Photo-Diodes (GPD).

- GPD is a reversed biased photodiode operated beyond the diode breakdown voltage.
- Single pixel detection efficiency = Quantum Efficiency • Geiger Probability
- Quantum Efficiency is the potential for incident light to generate electron-hole pairs in the silicon.
- Geiger Probability is the potential of an electron-hole pair to generate a self-sustained avalanche.
- Avalanche is quenched using a voltage sensing resistor.
Solid-State Photomultipliers

- **Dark Counts**
  - Equivalent to dark current
  - Uncorrelated random events

- **Resolution**
  - Light intensity distribution: \( \sqrt{N} \)
  - Single pixel: \( \sqrt{N} \cdot \sigma_{\text{pixel}} \)
SSPM Dosimeter

- Prototype device to evaluate at the NSRL at Brookhaven.
- 780 pixel device is coupled to a plastic scintillator covered in Teflon.
- Responded to alpha particles
- Mounted in plastic box for NSRL tests.
NSRL Spectral Results

- Spectra obtained for low-LET and high-LET particles.
- Large dynamic range demonstrated.
- Thermal background (dark counts) do not obscure the 1-GeV protons (minimum ionizing).

WRMISS 2007
Radiation Damage

- Dose in scintillator is approximately equal to dose in silicon.
- No effect on spectrum for this exposure.

\[ Dose \propto \frac{dE}{dx} \cdot \frac{L}{\rho \cdot A \cdot L} = \frac{dE}{\rho \cdot A} \]

\[ \rho_{Si} \approx 2 \cdot \rho_{scint} \]

\[ \frac{dE}{dx_{Si}} \approx 2 \cdot \frac{dE}{dx_{scint}} \]

\[ A_{Si} = A_{scint} \]

\[ Dose_{Si} \approx Dose_{scint} \]

<table>
<thead>
<tr>
<th>26 rads</th>
<th>Exposed SSPM</th>
<th>Control SSPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>1.6 MHz</td>
<td>1.6 MHz</td>
</tr>
<tr>
<td>After</td>
<td>2.3 MHz</td>
<td>1.6 MHz</td>
</tr>
</tbody>
</table>

Minimal Effects on Spectrum from 16 Rads of Exposure
Advantages of an SSPM with a high pixel density for spectral based dosimetry.

- Better energy resolution
- Larger dynamic range
- Better separation between the baseline noise and the signal.

Q1: Type 12
Fill Factor = 19%
1020 pixels

Q2: Type 12
Fill Factor = 29%
700 pixels

Q3: Type 4
Fill Factor = 29%
700 pixels

Q4: Type 12
Fill Factor = 29%
576 pixels

P1: Q1 pixels (Type 12)
P2: Q2 pixels (Type 12)
P3: Q3 pixels (Type 4)
P4: Hyper-dense square pixel (Type 12)
Imaging the Active Area

1) P1 (Type 12)

2) P2 (Type 12)

3) P3 (Type 4)

4) Hyper-dense Pixel

Good quantum efficiency uniformity.
Device Characterization

- Fill Factor: Ratio of active to dead area of an array
  - Low-density SSPM: 7%
  - High-density SSPM: 19% and 29%
  - Hyper-density SSPM: 50%

- Dark counts influences the spectral baseline.
  - Quadrants show similar behavior to low-density prototype used at NSRL.
  - Hyper-density pixel has similar DCR to nominal design.

- Detection efficiency is the product of the QE and Geiger probability.
  - Geiger probability is dependent on the excess reverse bias.
  - Excess bias is bias above breakdown.
  - Hyper-dense pixel operates similar to the nominal pixel.

Detection efficiency is the product of the QE and Geiger probability.

- Geiger probability is dependent on the excess reverse bias.
- Excess bias is bias above breakdown.
- Hyper-dense pixel operates similar to the nominal pixel.
Energy Resolution

Illustration of the strong dependence energy resolution has with DE.

Equivalent performance to PMTs.
Summary

- Low-density array has an excellent response to protons and silicon ions for simulating space radiation.
- Radiation damage in the SSPM will have minimal effects on the spectrum for the high-density SSPM.
- High-density SSPM compared to the low-density array
  - Similar dark count rates.
  - Improved range of operation.
  - Improved energy resolution, close to PMT.
- Demonstrated feasibility of using an SSPM for a space radiation dosimeter-on-a-chip.
- Plan to develop chips with integrated readout.
Pixel Types

Type 4

Guard ring

p-substrate

n⁺

Type 12

p⁺
n-well

p-substrate
Energy resolution depends on the number of triggered pixels.

There will be no noticeable effects in the energy resolution until the single pixel pulse height width is greater than one.
Assume damage (dark count rate) increases linearly with exposure.

Simulate 300 rad of dose in SSPM.

DCR increases from 5 kHz/pixel to 10.4 kHz/pixel.

For the high-density chip, 1-GeV protons will still be sufficiently above the noise floor.
Quantum Efficiency

Design 12: 42%
Design 4: 58%

BC-430 Emission
High-Density SSPM
Quadrant Energy Resolution

Energy (MeV)

Normalized Counts

Q1
Q2
Q3
Q4

WRMISS 2007