Feasibility of PET Detector Readout by High-Density Silicon Photomultipliers with Epitaxial Quenching Resistors

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9th International workshop on Semiconductor Pixel Detectors for Particles and Imaging, December 10 -14, 2018, Taipei
Outline

● Motivation
● NDL SiPM Technology
● Experimental setup
● Results & discussions
● Summary
Silicon Photomultipliers, SiPMs

- High gain
- Photon number discrimination
- Insensitive to magnetic field
- Low bias voltage
- Excellent timing properties
- Small volume and robustness

SiPMs replace PMTs and APDs in many low level light detection and sensing applications: particle physics, nuclear physics, nuclear medical imaging, etc.
**Positron Emission Tomography** (PET)

**PET = Positron Emission Tomography**

**principle of operation**

1. **Inject radiotracer**
2. **Detect** (scintillation detectors) two annihilation photons in coincidence
3. **Defines line** along which annihilation lies
4. **Collect** $\sim 10^7$-$10^8$ events
5. **Use reconstruction algorithms** to compute image of radiotracer distribution using multiple views of projection data
6. **Analyze data**
   - **Lesion detection**
   - **Quantify radiotracer distribution**
   - **Tracer kinetics**

State-of-the-art ToF PET Scanners based on Silicon Photo-Multiplier (SiPM)

**PHILIPS**

**GE**

**SIEMENS Healthineers**

**Vereos**

**Signa PET/MR**

**Biograph Vision**

**TOF 345ps**

**TOF 380ps**

**TOF 249ps**

*Courtesy by S.Dolinsky, GE*
Features of NDL SiPMs

Features
- The bulk resistor under each APD cell in the epitaxial layer is used as the quenching resistors
- A continuous cap resistive layer at the surface to connect all the micro APD cells

Advantages
- Small micro cell and high micro cell density (thus large dynamic range) while retaining high fill factor and photon detection efficiency, fast response to even a single photon.
- No extra fabrication processes for quenching resistors are needed, thus simple fabrication technology and cost effective.
- Easy to implement charge division mechanism to realize a position-sensitive SiPM.
## High-Density SiPMs with Epitaxial Quenching Resistors

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<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td><strong>Active area (mm²)</strong></td>
<td>3.0 × 3.0</td>
<td><strong>Microcell density</strong></td>
<td>90000 / mm²</td>
</tr>
<tr>
<td><strong>Gain</strong></td>
<td>≥ 2×10⁵</td>
<td><strong>Dark count rate</strong></td>
<td>700 kHz / mm²</td>
</tr>
<tr>
<td><strong>Peak PDE</strong></td>
<td>34% @ 420 nm</td>
<td><strong>Optical crosstalk</strong></td>
<td>~8 %</td>
</tr>
<tr>
<td><strong>Breakdown voltage</strong></td>
<td>27.5 ± 0.4 V</td>
<td><strong>Temperature coefficient for V&lt;sub&gt;b&lt;/sub&gt;</strong></td>
<td>25 mV/°C</td>
</tr>
<tr>
<td><strong>Recovery time</strong></td>
<td>~ 4 ns</td>
<td><strong>Single photon time resolution</strong></td>
<td>81 ps</td>
</tr>
</tbody>
</table>
Experimental setup

LYSO → SiPM → Readout Board → Oscilloscope → LYSO

FDG

L < 10 cm
- Energy resolution (ER) of \(~10.1\%\), with the \(2.84\times2.84\times6\) mm\(^3\) LYSO

![Graph showing energy resolution](image)
• Energy resolution (ER) of ~10.6 %, with the 2.84×2.84×10 mm³ LYSO
Coincidence timing resolution (CTR) of ~195 ps (FWHM), with the 2.84×2.84×6 mm³ LYSO.
NDL has been developing an unusual SiPM technology. It employs bulk resistor under each APD cell in the epitaxial layer as the quenching resistors, and a continuous cap resistive layer at the surface to connect all the micro APD cells.

Its main advantages include:

- Small micro cell, high micro cell density (thus large dynamic range) while retaining high fill factor and photon detection efficiency.
- No extra quenching resistors and trenches fabrication steps, thus simple fabrication technology and cost effective.
- Saturation effects involved in most commercial SiPM with limited micro cells is negligible. These results verify that EQR-SiPM is promising in applications of PET imaging.
- Easy to implement charge division mechanism to realize a PS-SiPM.

It is very suitable for applications such as preclinical PET and small animal PET, safety & security, and scientific researches, etc.
About Us

(NDL) Novel Device Laboratory, Beijing)

Affiliated to Beijing Normal University and Cooperated with Photoelectric Instrument Factory of Beijing Normal University, Beijing, China

Is committed to R&D of Silicon Photomultipliers for Low-Level-Light Detection Innovation

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http://www.ndl-sipm.net/device.html
<table>
<thead>
<tr>
<th></th>
<th>NDL SiPM</th>
<th>SensL SiPM</th>
<th>Hamamatsu MPPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effective Active Area</td>
<td>11-3030 C-S/T, 3.0x3.0 mm²</td>
<td>C-30020-SMT, 3.0x3.0 mm²</td>
<td>S12572-010-C/P, 3.0x3.0 mm²</td>
</tr>
<tr>
<td></td>
<td>11-1010 C-S/T, 1.0x1.0 mm²</td>
<td>C-10010-SMT, 1.0x1.0 mm²</td>
<td>S12571-010-C/P, 1.0x1.0 mm²</td>
</tr>
<tr>
<td>Effective Pitch</td>
<td>10 μm</td>
<td>28 μm</td>
<td>10 μm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18 μm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 μm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 μm</td>
<td></td>
</tr>
<tr>
<td>Micro-cell Number</td>
<td>90000</td>
<td>10998</td>
<td>90000</td>
</tr>
<tr>
<td></td>
<td>10000</td>
<td>2880</td>
<td>10000</td>
</tr>
<tr>
<td>Fill Factor</td>
<td>40%</td>
<td>48%</td>
<td>33%</td>
</tr>
<tr>
<td></td>
<td>40%</td>
<td>28%</td>
<td>33%</td>
</tr>
<tr>
<td>Breakdown Voltage (V&lt;sub&gt;b&lt;/sub&gt;)</td>
<td>27.5±0.4V</td>
<td>24.2-24.7</td>
<td>65±10V</td>
</tr>
<tr>
<td></td>
<td>27.5±0.4V</td>
<td>24.2-24.7</td>
<td>65±10V</td>
</tr>
<tr>
<td>Measurement Overvoltage (V)</td>
<td>5</td>
<td>2.5</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>2.5</td>
<td>4.5</td>
</tr>
<tr>
<td>Peak PDE</td>
<td>31%@420nm</td>
<td>24%@420nm</td>
<td>10%@470nm</td>
</tr>
<tr>
<td></td>
<td>31%@420nm</td>
<td>24%@420nm</td>
<td>10%@470nm</td>
</tr>
<tr>
<td>Max. Dark Count (kcps)</td>
<td>~6000</td>
<td>860</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>~500</td>
<td>96</td>
<td>200</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Gain</td>
<td>2x10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>1x10&lt;sup&gt;6&lt;/sup&gt;</td>
<td>1.35x10&lt;sup&gt;5&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>2x10&lt;sup&gt;5&lt;/sup&gt;</td>
<td>1x10&lt;sup&gt;6&lt;/sup&gt;</td>
<td>1.35x10&lt;sup&gt;5&lt;/sup&gt;</td>
</tr>
<tr>
<td>Temp. Coef. For V&lt;sub&gt;b&lt;/sub&gt;</td>
<td>25mV/°C</td>
<td>21.5mV/°C</td>
<td>60mV/°C</td>
</tr>
<tr>
<td></td>
<td>25mV/°C</td>
<td>21.5mV/°C</td>
<td>60mV/°C</td>
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**Potential Applications**

**High Energy Physics:** Scientific Researches, such as scintillating fiber tracker (SciFi Tracker), hadronic calorimeter (HCAL) and electromagnetic calorimeter (ECAL) in high energy physics, need huge amount of SiPMs with large dynamic range and high resolution.

**Preclinical PET:** High density (10000/mm$^2$) SiPMs as PET detector readout, energy resolution (ER) of $\sim$10.1% and coincidence timing resolution (CTR) of $\sim$195 ps (FWHM) were obtained with LYSO crystals.

**Small Animal PET:** 511keV gamma ray is detected by coupling a 5×5 array of 0.45×0.45×6 mm$^3$ LYSO crystals to the NDL PS-SiPM with an active area of 2.77×2.77 mm$^2$.

**Safety & Security:** NDL SiPM is attractive in safety and security area due to its large dynamic range ($10^4$/mm$^2$ micro cells) and linearity of high energy detections.
Thank You for Your Attentions!