Characterization of silicon photomultipliers

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Outlook

1. Introduction
   1.1. What is a silicon photomultiplier (SiPM)?
   1.2. Properties
   1.3. Afterpulsing and crosstalk
   1.4. Applications

2. GAE-UCM activities on SiPM characterization
   2.1. Characterization technique
   2.2. Characterization results
   2.3. Model of optical crosstalk
   2.4. Model of afterpulsing and delayed crosstalk

3. Concluding remarks
   3.1 Future plans
   3.2 Take home message
1. Introduction
1.1. What is a silicon photomultiplier (SiPM)?

- Solid-state detector with **single photon sensitivity** (~$10^6$ gain)
- Many developers: single units (1-16 mm$^2$) or matrixes (4-256 channels), pin or SMD packages, blue or red enhanced, etc.
- Promising substitutes of conventional photomultiplier tubes
1.1. What is a silicon photomultiplier (SiPM)?

- Building block: Geiger mode avalanche photodiode (GM-APD)
- Reverse bias greater than breakdown voltage
- Self-sustaining breakdown avalanches quenched by the voltage drop across a series resistor
- Standard saturated signal when fired by a photon (no proportionality)
1.1. What is a silicon photomultiplier (SiPM)?

- A SiPM comprises many GM-APDs connected in parallel (100 – 2000 pixels/mm²)
- Output signal = sum of “digital” signals of fired pixels
- Excellent potential photon counting capability

Output pulses recorded by an oscilloscope in persistence mode
## 1.2. Properties

<table>
<thead>
<tr>
<th>Green</th>
<th>Red</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Small size</td>
<td>• Low cost</td>
</tr>
<tr>
<td>• Not damaged by ambient light</td>
<td>• Insensitive to magnetic fields</td>
</tr>
<tr>
<td>• High gain (~10^6)</td>
<td>• Not bad photon-detection efficiency</td>
</tr>
<tr>
<td>• Room temperature operation</td>
<td>• Low bias operation (&lt;100 V)</td>
</tr>
<tr>
<td>• Low power consumption</td>
<td>• Compact and robust</td>
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<tr>
<td>• Excellent time resolution (~100 ps)</td>
<td>• Excellent photon-counting capability</td>
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<tr>
<td>• Room temperature operation</td>
<td>• High dark-count rate (0.1 – 1 MHz)</td>
</tr>
<tr>
<td>• Not damaged by ambient light</td>
<td>• Efficiency depends on bias voltage</td>
</tr>
<tr>
<td>• Small active area</td>
<td>• Gain and efficiency depend on temperature</td>
</tr>
<tr>
<td>• Small active area</td>
<td>• Correlated noise: afterpulsing and crosstalk</td>
</tr>
</tbody>
</table>
1.3. Afterpulsing and crosstalk

- Afterpulsing: secondary avalanche in the same pixel due to delayed release of carriers trapped in crystal defects during the primary avalanche.
- Optical crosstalk: almost simultaneous avalanche in a neighboring pixel fired by secondary IR photons emitted in the primary avalanche.
1.3. Afterpulsing and crosstalk

- Secondary photons absorbed in the Si substrate generate carriers that can diffuse back to the active layer, contributing to both afterpulsing (same pixel) and delayed crosstalk (different pixel)
1.4. Applications

- Any application that needs high sensitivity
- Setups with small-size requirements
- Experiments using magnetic fields
- Fast timing measurements
1.4. Applications

- CTA foresees the use of SiPMs for some/all telescopes
- The High Energy Group at UCM is highly involved in technology developments for CTA

L.A. Tejedor, patent WO2012123604 A1

2. GAE-UCM activities on SiPM characterization
2.1 Characterization technique

Measurements in coincident with pulsed illumination

- Pulse identification from deconvolution
- ~6 ns resolution to distinguish pulses
- Pulse amplitude $\propto$ deconvolution peak

- We have started collaboration with Hamamatsu
- First publication: L. Gallego et al., JINST 8 (2013) P05010, cited by
  - V. Boccone et al. (CTA)
  - F. Nagy et al. (STMicroelectronics)
2.1 Characterization technique

Measurements in coincident with pulsed illumination

- N$_2$ laser
- Absorber
- Power supply
- Fast amplifier AD8367 (500MHz)
- Digital Oscilloscope TDS5032B (350MHz)

Calculation of pulse height with baseline subtraction

- More precise measurement of amplitude as pulse height with baseline subtraction

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2.2. Characterization results

**Afterpulses**
- Without cuts
- With cuts
- Gaussian fit

**CT-opt**

**Proportional to gain**

**Breakdown voltage**

**Hamamatsu SiPMs**

**Quadratic behavior**

**Dark conditions**

**Deconvolution peak (a.u.)**

**Breakdown voltage proportional to gain**

**Quadratic behavior**

**Dark counts**

**Afterpulses**

**CT-diff**
2.3. Model of optical crosstalk

- Statistical model including geometrical considerations and dead time effects
- Analytical expressions for application to photon counting

L. Gallego et al., JINST 8 (2013) P05010
2.4. Model of afterpulsing and delayed crosstalk

- Statistical model including diffusion mechanisms and experimental considerations
- Model supported by Monte Carlo simulations
- Preliminary results sent to publication: J. Rosado et al., NIM A (2014), in press

\[
P(t)dt = \exp\left\{-R_{DC}(t - t_{\text{min}}) - \sum_{i} \lambda_{i} \int_{t_{\text{min}}}^{t} f_{i}(s)ds\right\} \\
\times \left[R_{DC} + \sum_{i} \lambda_{i} f_{i}(t)\right]dt
\]

- \(t_{\text{min}} = 10 \text{ ns} : \text{minimum } t \text{ (analysis limitations)}\)
- \(R_{DC}: \text{dark count rate}\)
- \(\lambda_{i}: \text{average number of secondary pulses of type } i \text{ per primary avalanche}\)
- \(f_{i}(t): \text{normalized time distribution of secondary pulses of type } i\)
3. Concluding remarks
3.1. Future plans

- Extending our characterization and modeling studies
- Hamamatsu provided us with two exclusive models (not marketed yet)

S13081-050CS  S13082-050CS

- Collaboration with other technology companies and research groups
- Application to medical imaging (e.g., PET)
- Application to astroparticle physics (e.g., CTA)

Characteristics Vover Dependence

- Essays with scintillator crystals
- Gamma event detected by FACT

Hamamatsu specifications
3.2. Take home message

- GAE-UCM involved in characterization studies of SiPMs focused on afterpulsing and crosstalk
- Models of the electrical response of SiPMs
- Collaboration with Hamamatsu (and other companies)
- Planning application to medical imaging and astroparticle physics developments

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