Silicon Photomultiplier

Operation, Performance & Possible Applications

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Introduction

Very high intrinsic gain together with minimal excess noise make silicon photomultiplier (SiPM) a possible choice of a photodetector in those applications where the input light is in the photon-counting range.
Introduction

This webinar is a high-level review of SiPM’s structure, operation, and opto-electronic characteristics, followed by a discussion of some possible applications.
Outline

• Structure and operation
• Opto-electronic characteristics
• Applications
  + Automotive ToF LiDAR
  + Flow cytometry
  + Radiation detection and monitoring
• Summary and conclusions
SiPM

Structure and Operation of a SiPM

Portraits of SiPMs (images not to scale)
SiPM structure

SiPM is an array of microcells

Top view

Side view

Single microcell

electrical equivalent circuit of a microcell

$\pi$

$\text{n}^+$

$\text{p}^+$

$\text{p}^+$

R$_Q$

oxide
SiPM structure

All of the microcells are connected in parallel
SiPM specifications

Active area: 1.3×1.3 – 6×6 mm²

Microcell size (pitch): 10×10, 15×15, 25×25, 50×50, 75×75 μm²

Number of microcells: (active area)/(microcell size), from 100’s to 10,000’s

Overvoltage: ΔV = V_{BIAS} − V_{BD}; recommended by the manufacturer
SiPM operation

Example of single-photoelectron waveform (1 p.e.)

Gain = area under the curve in electrons
SiPM operation

RC time constant of the slow component depends on microcell size (all else being equal).

Recovery time $t_R \approx 5$ times the RC time constant.

$t_R$ is on the order of 10’s to 100’s ns but in practical situations, it is also a function of detection bandwidth.
SiPM operation

The output of an SiPM is a chronological superposition of current pulses

SiPM also outputs current pulses even in absence of light: dark counts (dark current)
Dark Counts

Current pulses due to photons and dark counts are indistinguishable

Dark-count pulses are indistinguishable from those due to photons

The rate of dark counts depends on overvoltage, temperature, and size of the active area
Crosstalk

Primary discharge can trigger a secondary discharge in neighboring microcells. This is crosstalk.

Crosstalk probability depends on overvoltage.
Operation

If the pulses are distinguishable, SiPM can be operated in a photon counting mode.

If the pulses overlap, the SiPM can be operated in an analog mode. The measured output is voltage or current.
SiPM detection circuits

![SiPM detection circuits diagram]
SiPM

Performance and characteristics
Characteristics of a SiPM

- Photon detection efficiency
- Gain
- Temperature effects
- Crosstalk probability
- Dark current & dark counts
- Linearity & dynamic range
Photon detection efficiency (PDE) is a probability that an incident photon is detected. It depends on:
- wavelength
- overvoltage
- microcell size

Peak PDE 20% – 50%
Photon detection efficiency

Examples of PDE curves for SiPMs optimized for NIR, VIS, and UV response.
• Gain of SiPM is comparable to that of a PMT.

Excess noise very low:
F ~ 1.1, mostly due to crosstalk

• Gain depends linearly on overvoltage
Gain *versus* temperature

Does gain of an SiPM depend on temperature?

**Yes** – if the bias voltage is fixed

![Graph showing gain versus reverse bias voltage for different temperatures.](Otte et al. (2016))
Gain versus temperature

Does gain of an SiPM depend on temperature?

No – if the overvoltage is fixed

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Fixed overvoltage

Fixed bias

Temperature [°C]

Gain variation [%]
Crosstalk

$P_{CT}$ increases with overvoltage

Crosstalk is the main contributor to excess noise

$F \approx (1+P_{CT})$
Dark Current

Example of dark current versus overvoltage

\[ DCR = \frac{I_D}{e\mu} \]

\[ I_D = 1 \times 10^{-7} \text{ A (at 7 V)} \]

\[ \mu = 1.2 \times 10^6 \text{ (at 7 V)} \]

\[ \Rightarrow DCR \approx 520 \text{ kHz} \]

or once per about 2 \( \mu \text{s} \)
Linearity and dynamic range

Example of output current versus incident light level.

Photon irradiance (at 850 nm) = $4.3 \times 10^{18} \times P[W]$

$P = 10^{-8} \text{ W} \rightarrow 4.3 \times 10^{10}$ photons per second

Linearity depends on the number of microcells for a given active area
SiPM, PMT & APD

This webinar will compare and contrast SiPM with a photomultiplier tube (PMT) and APD.

Let’s briefly review the operation of a PMT and APD.

Examples of a PMT (left) and APD (right).
Operation of a PMT

Typical voltage divider  V ~ 1000 V
SiPM versus PMT

- Solid state *versus* vacuum tube technology
- Comparable gains
- Comparable excess noise
- Dark count rate per unit active area larger in SiPM
- E & B field immunity in SiPM

- Comparable photosensitivity in the spectral overlap region
- Greater optimization for PMTs
Operation of an APD

APD biased below breakdown voltage

Single photon can lead up to about 100 of electron-hole pairs

Thus gain up to ~100

Avalanche is self-quenching
SiPM versus APD

- Differ in construction
- \( \text{Gain}_{\text{SiPM}} \gg \text{Gain}_{\text{APD}} \)
- \( F_{\text{SiPM}} \ll F_{\text{APD}} \)

![Graph showing the comparison between SiPM and APD](image-url)
Possible applications of SiPMs

• Automotive time-of-flight LiDAR
• Flow cytometry
• Radiation detection and monitoring
Automotive time-of-flight LiDAR

How far is this tree?

LiDAR = Light Detection and Ranging
Automotive ToF LiDAR: basic concept

- "start" pulse
- "fast" photodetector
- emission optics
- laser
- beam splitter
- timer
- "stop" pulse
- collection optics
- returned pulse after Δt

$w = c\tau$

to target
Automotive ToF LiDAR: basic concept

Measure round-trip time-of-flight $\Delta t$

Range (distance to the reflection point) = $c\Delta t/2$; here $c$ is the speed of light

By scanning the surroundings, a 3D map can be constructed
Characteristics of received light

- Wavelength: 905 nm or 1550 nm
- Pulse: duration 2 – 5 ns
- No. of photons per returned pulse: 100’s – 10,000’s on detector’s active area
- Repetition frequency: kHz - MHz
- DC photon background
Photodetector requirements

• High quantum efficiency at 905 nm and/or 1550 nm (affects detection range)
• High detector (intrinsic) gain (reduces importance of electronic noise)
• Small excess noise (affects timing error)
• Small time jitter (affects distance resolution)

APD has been a default detector. Could SiPM be a better choice?
Photosensitivity

(Ta=25 °C, Vop=VBR + 7)

S13720 SiPM
S13720 series
S13360-1325CS

Quantum efficiency [%]

S10341 Si APD

(Typ. Ta=25 °C)

Photon detection efficiency [%]
Intrinsic gain

(Ta=25 °C)

Gain

S13720 SiPM

(Typ. λ=800 nm)

Gain

S10341 Si APD
Excess noise

\[ F \approx 1 + P_{CT} = 1.06 \]

\[ F \approx (\text{Gain})^{0.3} = 3.2 \text{ for gain } = 50 \]
Time jitter

There are two contributions to timing jitter:

1. “Classical” jitter – variation in response time, often reported for a single photon illumination. This contribution is on the order of 100 ps for SiPMs and APDs

2. Time-walk effect. For a constant trigger level, timing depends on gain variation and signal intensity.
Time jitter

For a given light level SiPM has smaller time-walk effect because of its lower excess noise.
Take-away points

1. SiPMs are likely to compete successfully with APDs at 905 nm because of their higher gain and much lower excess noise. Empirical evidence is forthcoming.

2. Sensitivity at 905 nm will improve in a new generation SiPMs.

3. SiPMs with sensitivity at 1550 nm are being developed.
Flow cytometry

Studying biological cells with light
Flow cytometry (basic concept)

[Diagram showing a laser, forward-scatter photodetector, side-scatter photodetector, and data processing.]
Flow cytometry also uses fluorescence tagging to study cells.
Flow cytometry

• Used to study and sort biological cells
• Side-scatter signal vs. forward scatter signal depends on cell properties
• Fluorescence is also employed (dyes attached to cells) to produce a variety of plots using fluorescence signal(s)
• The optical system employs a combination of lasers (different wavelengths), optical filters, and photodetectors
Flow cytometry data

Side scatter vs. forward scatter plot – the most fundamental in flow cytometry

Cell’s characteristics such as size, complexity, or refractive index affect the relative strengths of side scatter and forward scatter signals.
Characteristics of received light

- Wavelength: can be selected depending on cell sizes and fluoresce
- Pulses – duration dependent on sheath flow speed and cell size and is on the order of $\mu$s.
- No. of photons per pulse varies from few to thousands
- Rate of pulses in kHz
Side-scatter photodetector requirements

- High photodetection efficiency (affects S/N of detection)
- High intrinsic gain (reduces importance of electronic noise)
- Minimal excess noise (affects accuracy of the scatter plots; random noise)
- High linearity (affects accuracy of the scatter plot; systematic errors)
- High dynamic range (affects accuracy of the scatter plot; systematic errors)

PMT is commonly used. Could SiPM be a better choice?
Photosensitivity

S13360
3×3 mm², 25 μm
14,400 microcells

PDE [%]

Wavelength [nm]

Cathode radiant sensitivity [mA/W]

Wavelength [nm]

QE ≈ 28% at 450 nm
Excess Noise

\[ F \approx 1 + P_{CT} \quad \text{(SiPM)} \]

Excess noise \textit{increases} with gain.

\[ F \approx \frac{\delta}{(\delta - 1)} \quad \text{(PMT; } \delta \text{ – gain of the first dynode)} \]

Excess noise \textit{decreases} with gain.
**Linearity/dynamic range (PMT)**

- **10% nonlinearity**: 75 mA, $T_P = 500$ ns
- **Gain**: $2 \times 10^6$, **QE**: 28%
- **No. of incident photons at 450 nm**: $4.2 \times 10^5$
Linearity/dynamic range (SiPM)

\[
\bar{N}_{\text{fired}} = N_{\text{tot}} \left( \frac{T_P}{t_r} \right) \left( 1 - \exp \left( \frac{-N_\gamma PDE}{\left( \frac{T_P}{t_r} \right) N_{\text{tot}}} \right) \right)
\]

\[N_{\text{tot}} = 14,400; \ PDE = 25\%, \ t_r = 50 \text{ ns}\]

\[N_\gamma \cdot PDE = 1.1 \times 10^5 \text{ (ideal response)}\]

\[N_{\text{fired}} = 0.75 \times 10^5 \text{ or } 32\% \text{ below an ideal response}\]
Take-away points

1. The major weakness of SiPMs in flow cytometry is limited dynamic range and linearity.

2. However, out of dozens of optical channels in a flow cytometer, SIPM can be suitable for some.

3. There is a great interest in using SiPMs in flow cytometry but little published work on this subject exists.
Radiation monitoring and spectroscopy
Radiation monitoring (basic idea)

An event is registered if the output signal exceeds the threshold level.
Radiation monitoring (basic idea)

- Used to detect the presence of specific radiation
- Monitoring devices are often portable and hand-held.
- Information provided: radiation rate (flux can be derived)
Characteristics of received light

- Wavelength dependent on the choice of scintillator often in the 300 nm – 500 nm range
- Pulses
- Number of photons per pulse depends on energy of ionizing radiation and type of scintillator
- Duration of the pulse depends on the size and type of the scintillator (decay time constants range from ns to μs)
- Frequency of pulses depends on the rate of incoming radiation
Photodetector requirements

• High photodetection efficiency
• High intrinsic gain
• Large active area
• Ability to couple to a scintillator
• Suitable for portable hand-held devices
Radiation spectroscopy

Ionizing radiation

Scintillator

Photodetector

Charge integrator

C

R
Radiation spectroscopy (basic idea)

Resolution is affected by the properties of the photodetector and the scintillator.
Photodetector requirements

- High photodetection efficiency (affects S/N of the detection and thus resolution)
- High intrinsic gain (reduces the importance of electronic noise and, thus, better count rate and measurable lower energy levels)
- Low excess noise (affects energy resolution)
- High linearity (affects systematic errors and energy range)
- Ability to couple to a scintillator
Radiation detection photodetectors

PMTs used to dominate the detector choice in radiation detection, monitoring, and spectroscopy.

SiPMs are becoming a viable alternative.

Due to a multitude of possible detection scenarios, it is best to perform a side-by-side comparison between an SiPM and a PMT.
SiPM vs. PMT in γ-ray detection

## SiPM vs. PMT in γ-ray detection

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy [keV]</th>
<th>CeBr₃</th>
<th>NaI:TI</th>
<th>CsI:TI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>FWHM/centroid, [%]</td>
<td>Energy resolution after correction</td>
<td>FWHM/centroid, [%]</td>
</tr>
<tr>
<td>²²Na</td>
<td>511</td>
<td>7.1 ± 0.4</td>
<td>7.6 ± 0.4</td>
<td>5.6 ± 0.2</td>
</tr>
<tr>
<td>¹³⁷Cs</td>
<td>662</td>
<td>5.9 ± 0.3</td>
<td>6.4 ± 0.3</td>
<td>4.9 ± 0.2</td>
</tr>
<tr>
<td>²²Na</td>
<td>1275</td>
<td>4.2 ± 0.2</td>
<td>5.1 ± 0.3</td>
<td>3.7 ± 0.1</td>
</tr>
<tr>
<td>PuBe</td>
<td>3416</td>
<td>3.4 ± 0.2</td>
<td>4.9 ± 0.3</td>
<td>3.8 ± 0.1</td>
</tr>
<tr>
<td>PuC</td>
<td>5116</td>
<td>2.1 ± 0.1</td>
<td>3.5 ± 0.2</td>
<td>2.3 ± 0.1</td>
</tr>
</tbody>
</table>

Take-away points

1. SiPMs provide comparable performance to PMTs in radiation monitoring and spectroscopy

2. It is likely that the majority of hand-held devices will employ SiPMs

3. Side-by-side comparison is the best approach in deciding if an SiPM or a PMT should be used for a given detection application
Summary and conclusions

- High gain, low excess noise, magnetic immunity, and ease of use are some of the highly desirable characteristics of SiPMs.
- There is a great interest in using SiPMs instead of APDs and PMTs in a variety of applications.
- New generation SiPMs will have improved characteristics making the transition more likely.
Visit Booth #521 & Presentations at PW18

Development of an InGaAs SPAD 2D array for Flash LIDAR
Presentation by Takashi Baba, January 29, 2018 (11:00 AM - 11:30 AM)

Development of an InGaAs MPPC for NIR photon counting applications
Presentation by Yusei Tamura, January 30, 2018 (5:50 PM - 6:10 PM)

Photodetectors, Raman Spectroscopy, and SiPMs versus PMTs
One-day Workshop with Slawomir Piatek, January 31, 2018 (8:30 AM - 5:30 PM) – Free Registration Needed

Development of a Silicon hybrid SPAD 1D array for LIDAR and spectrometers
Poster session with Shunsuke Adachi, January 31, 2018 (6:00 PM - 8:00 PM)
Thank you for listening!

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