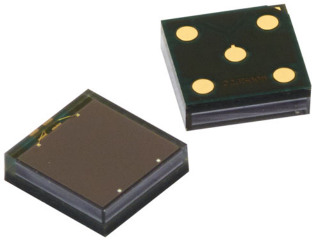
White Paper

AFBR-S4

SiPMs in Life Sciences: Overcoming Limitations of PMTs



Overview

Photomultiplier tubes (PMTs) have been the detector of choice for detecting dim signals, for example fluorescence, in life science applications such as the following:

- Laser scanning/fluorescence/multiphoton microscopy
- Flow cytometry
- Fluorescence lifetime imaging
- Microplate readers

Silicon photomultipliers (SiPMs), solid-state-based single-photon detectors, have overcome some of the key limitations imposed by PMTs in various life science applications.

Advantages of SiPMs over PMTs

- Superior sensitivity up to the NIR
- Superior signal-to-noise ratio (SNR) due to lower excess noise factor (ENF)
- Higher dynamic range at high count rates or quasi-DC illumination
- Single gain setting to accommodate full dynamic range
- No damage by bright light exposure
- No recovery time after exposure to ambient light

Efficiency and Sensitivity

SiPM efficiency is expressed as PDE (photon detection efficiency) and the parameter to compare to a PMT's quantum efficiency (QE).

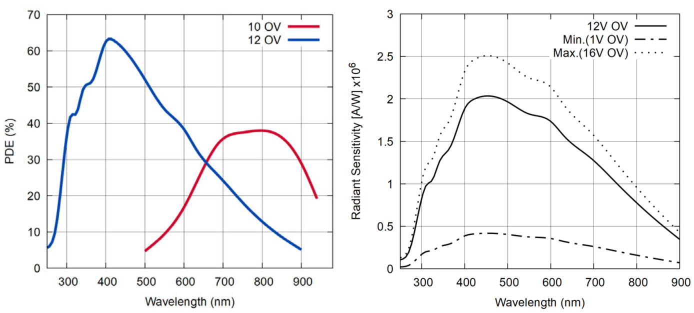
With a PDE of 63% at 420 nm (NUV SiPM) and a PDE of 38% at 800 nm (NIR SiPM), Broadcom SiPMs achieve an efficiency superior to most available PMTs (Figure 1, left).

From the efficiency, the radiant sensitivity derives from:

$$S = \frac{e\lambda}{hc} \cdot PDE\ (\lambda)\ \cdot Gain\ \cdot (1 + CT + AP)$$

With *e* the elementary charge, *h* the Planck constant, *c* the speed of light, *CT* the crosstalk of the SiPM, and *AP* the afterpulsing probability of the SiPM (Figure 1, right)

Figure 1: SiPM PDE (Left for Broadcom NUV and NIR SiPMs) and Radiant Sensitivity (Right for NUV SiPMs)



Signal-to-Noise Ratio

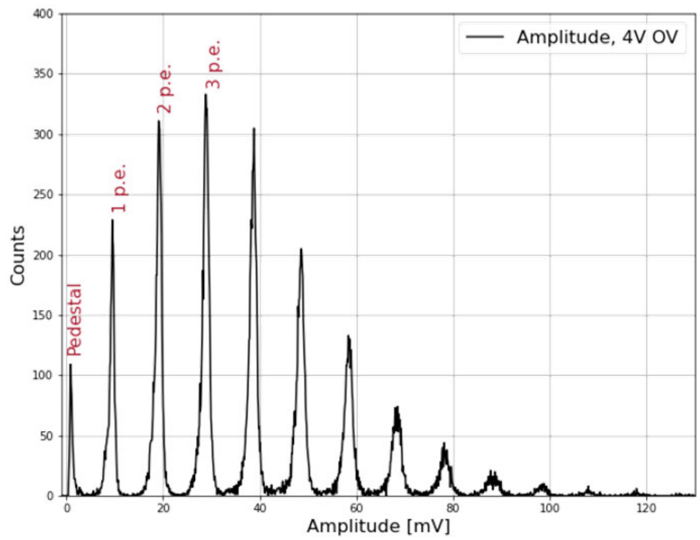
The excess noise factor (ENF) yields a good estimate of the signal-to-noise ratio, especially in a single-photon regime. Due to a different amplification process for SiPMs compared to PMTs, the ENF of SiPMs is substantially smaller than in PMTs, with an achievable ENF close to 1. Using the ENF, a noise-corrected efficiency can be calculated to allow comparing different types of single-photon detectors.

Detector	PDE/QE [%] at 550 nm	ENF	Noise-Corrected PDE [%]
GaAsP PMT	40	1.35	30
NUV-MT SiPM	42	1.14	36

At 420 nm, the Broadcom NUV SiPM achieves a noise-corrected PDE of 52%. The Broadcom NIR SIPM reaches a noise-corrected PDE of 37% at 800 nm.

The low ENF and Geiger-mode operation of SiPMs result in clear single-photon spectra with individual peaks, representing a discrete number of detected photons (Figure 2).

Figure 2: Single-Photon Spectrum



Dynamic Range

The dynamic range of PMTs is typically limited by the maximum current. For high repetition rates or bright signals, PMTs are operated at a low gain setting. For dim signals (such as fluorescence signals), a high gain setting is used. In practice, this requires operating the PMT at varying bias voltages and, hence, limiting the dynamic range from either the bottom or top side. Depending on the sample under investigation, recalibration is one of the consequences for users.

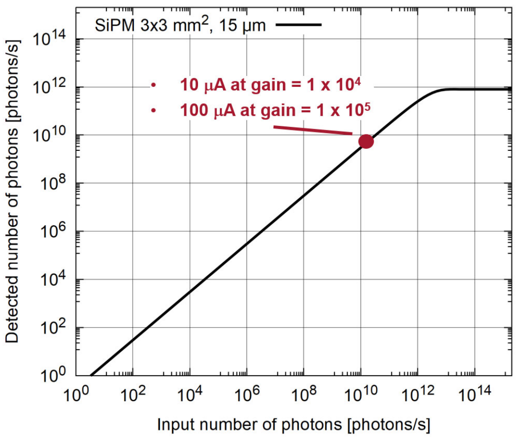
SiPMs have no intrinsic requirement to limit the current; and the dynamic range is limited only by the number of microcells available and, for longer light pulses (greater than a few tens of ns), by the recharge time constant.

When using higher count rates or even in CW (continuous wave; it should not be DC), the dynamic range of SiPMs is higher than that of PMTs.

Consequently, SiPMs can achieve the following:

- They can reach a dynamic range of 7 orders of magnitude per pulse (for µs pulses).
- They can tolerate photon fluxes (photons/s) of 12 orders of magnitude (Figure 3).

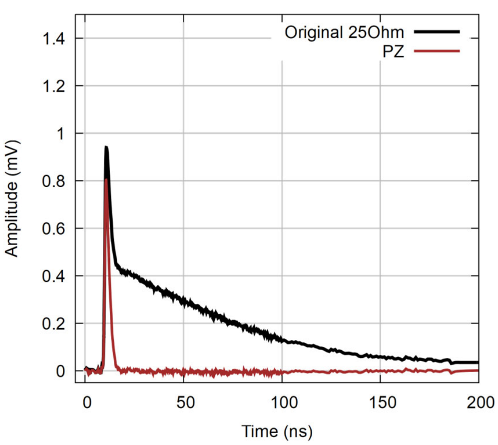
Figure 3: Dynamic Range of a SiPM with 15-µm microcells (The red dot indicates where a signal current of 100 µA and 10 µA is reached.)



Pulse Shape and Dead Time

The pulse shape of SiPMs is dominated by the recharge of the microcells that detected photons. With several tens to hundreds of nanoseconds, the pulse duration is longer than that of PMTs. The recharge time can be reduced by using small microcells (for example, 15-µm pitch), but at the cost of reduced efficiency. Therefore, electronic pulse shaping, for example by pole-zero cancellation, is an adequate solution. Figure 4 shows a regular single-photon response of a NUV SiPM (black) and the short pulse after pole-zero cancellation.

Figure 4: SiPM Single-Photon Pulse



Device Examples: SiPM TIA Module

Broadcom offers a SiPM TIA module that allows for a 1-to-1 replacement of PMT modules.

The module comprises the following:

- HV generation on board (from 5V input)
- Adaptable SiPM overvoltage for fine-tuning the gain
- Amplified/shaped SiPM signal (Gain = 35, BW = 12.5 MHz)

Summary

Table 1: Key Advantages of SiPMs over PMTs in Life Sciences

Characteristic	PMT	SiPM	System Implications
Operating Voltage	800V–2000V	< 50V	Safety, simpler design
Efficiency (QE/PDE)	Up to 40%	Up to 65%	Improved SNR
Excess Noise Factor	Medium	Low	Improved SNR
Dynamic Range	Limited by max. current	Determined by the number of SPADs (and recharge)	Operation at a single-gain setting with SiPMs
Compact and Mechanical Robustness	No	Yes	Compact design, many readout channels
Long-term Stability	Deteriorates over time	Good	Reduction in system recalibration
High Granularity	No	Yes	Compact design, many readout channels
Uniformity	Good	Excellent	Measurement accuracy, easy to calibrate