BROADCOM®

Application Note

# AFBR-S4XX

## Brief Introduction to Silicon Photomultipliers


## Abstract

Light-sensing applications are rapidly penetrating more and more aspects of life and technology. Light-sensing applications are found in a range of industries including communication, consumer, medical, life sciences, safety and security, and automotive. In many of these industries, a rather insensitive and slow photodetector is sufficient. In other industries, however, sensitivity and speed are essential parameters. Some of these applications include biomedical (for example, DNA sequencing, flow cytometry, and immunoassay analysis), medical imaging (for example, X-ray, CT, and molecular imaging), safety and security (radiation spectrometry), 3D ranging (LiDAR), and high-energy physics experiments. In these cases, special photodetectors such as the silicon photomultiplier (SiPM) play a crucial role.

This document is intended to discuss silicon photomultipliers and whether the device may be useful to specific light-sensing applications. For additional detailed information, contact Broadcom directly at sipm@broadcom.com.

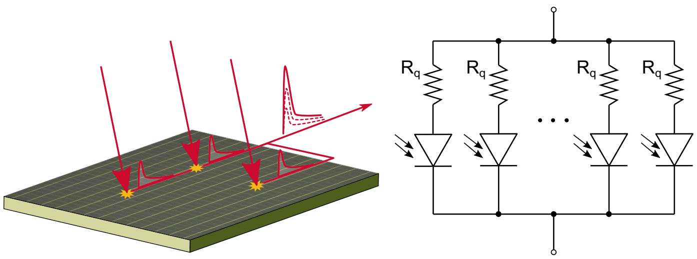

## Overview

A silicon photomultiplier is a highly sensitive solid-state photodetector. An internal amplification process allows it to achieve a very high signal-to-noise ratio, enabling the detection of individual photons with excellent time resolution. Compared to conventional light detection, SiPMs provide sharp, quasi-digital pulses that correspond to each individual photon.

Considering a classical photodiode, each photon creates one electron and one hole, which are collected at the electrodes. The overall noise in the detection system is larger than the signal induced by one carrier on the electrode, meaning that a single photon cannot be discriminated in such conditions. Increasing the reverse bias voltage (and implementing a proper doping structure), a carrier multiplication regime can be reached (for an avalanche photodiode, or APD). At this voltage, the electric field in the photodiode is high enough that an initial electron is accelerated to a velocity (creating energy) so high that further electrons can be ionized. These electrons are again accelerated and can ionize more electrons, and an avalanche is started. However, due to the limited probability of ionization, the avalanche dies after some time. In such a way, the single photo-generated carrier creates a finite number of carriers internally in the device, which is called gain. The gain and signal amplification in the APD regime can be up to a few hundred. As the multiplication of carriers is a statistical process and fluctuates from event to event, an APD shows increased noise compared to a normal photodiode (excess-noise factor).

Increasing the reverse bias further, the breakdown voltage is reached. Beyond this voltage, the ionization is so high that a single electron can trigger a self-sustaining avalanche; once started, the avalanche would last forever. To stop it, a quenching resistor is connected in series to the diode. After some time, in the order of a few tens of nanoseconds, the diode is fully reset and can detect another photon. Contrary to classical photodiodes, the electric field of the diode junction is optimized to work well beyond the breakdown voltage. Such detectors are called single-photon avalanche diodes (SPADs).

**Figure 1: A SPAD Arrangement and SiPM Signal Formation with Schematic**




Biasing the SPAD above the breakdown is also referred to as Geiger-mode operation. This is because the SPAD always gives the same output signal regardless of whether one, two, or hundreds of photons hit the SPAD at the same time (similar to a Geiger-Müller counter). Therefore, a SPAD is either on or off, and the on-state is always the same even if 1 or 100 photons start the avalanche. To overcome this problem, multiple SPADs are arranged in an array and are connected in parallel, as in Figure 1. Such an array of SPADs is called a silicon photomultiplier (SiPM).

# PMT vs. SiPM

Until recently, the photomultiplier tube (PMT), a vacuum tube device available since the 1940s, has been the only choice for low-light-level/photon-counting applications. However, its vulnerability to ambient light, fragile and bulky housing, sensitivity to magnetic fields, and requirement for high voltage make this sensor difficult to use in many applications. When fast timing, high granularity and sensitivity, robustness, and compactness (for handhelds) are considered, the silicon photomultiplier offers significant advantages. Since its introduction a few decades ago, the SiPM has replaced PMTs due to advantages such as higher sensitivity, good timing performance, the possibility to build arrays with high granularity, compactness and ruggedness, insensitivity to magnetic fields, and low required bias voltage and power. See the following table for a detailed comparison.

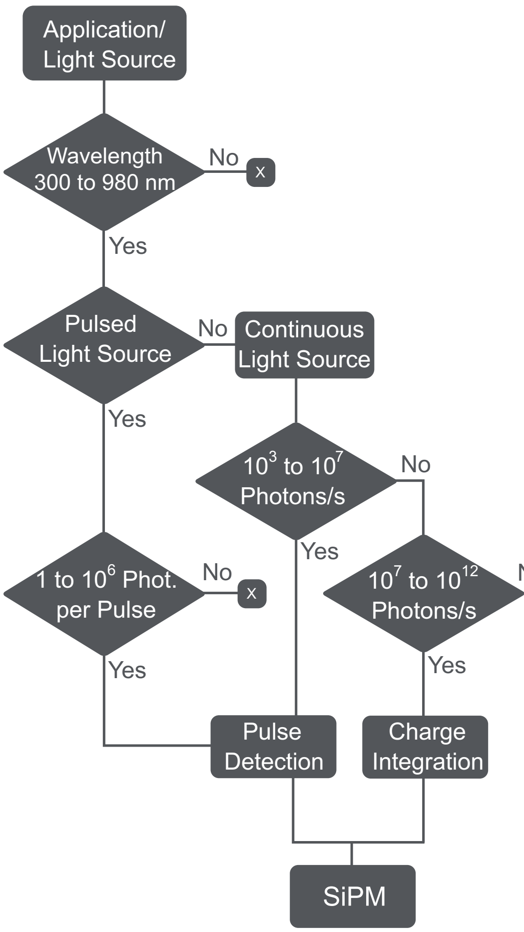
**Table 1: Comparison of PMTs and SiPMs**

| Characteristic | Photomultiplier Tube (PMT) | Silicon Photomultiplier (SiPM) |
|---|---|---|
| Sensitivity | Single photon | Single photon |
| Gain | To $10^7$ | To $10^6$ |
| Operation voltage | 800V to 20,00V | 30V to 50V |
| Large area | Yes | Yes, scalable |
| High-density arrays | No | Yes |
| High granularity/ resolution | No | Yes |
| Dark noise | Low | Medium |
| Uniformity | Good | Excellent |
| Response time | Fast | Very Fast |
| Photon-counting resolution | Good | Excellent |
| Temperature sensitivity | Low | Medium |
| Immunity to ambient light | No | Yes |
| Immunity to magnetic fields | No | Yes |
| Compactness and light weight | No | Yes |

# A Quick Selection Guide

Figure 2 shows a basic decision tree on the suitability of an SiPM for a specific application. It is based on a selection of the wavelength of light to be detected, the type of light source (pulsed/continuous), the light intensity, and the frequency of light pulses. Depending on the application, a photon/pulse counting, a charge integration, or a combination of both can be the readout solution.

**Figure 2: SiPM Application Decision Tree**




If the application is within the given requirements, the SiPM is a promising candidate for accomplishing photon-detection tasks. Additional requirements can be geometrical considerations (photosensitive area, volume of device), robustness against ambient light, number of channels, granularity (that is, the number of channels per unit area), magnetic fields, or mechanical ruggedness.

Further technical details on Broadcom® SiPM sensors can be found at broadcom.com.

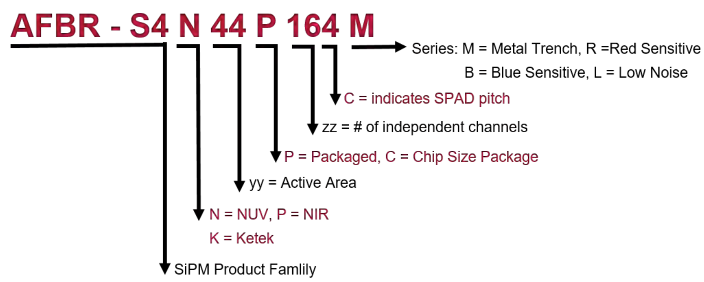
# Broadcom SiPM Product Numbers

Broadcom offers two types of SiPM products:

- **NUV SiPM**: The individual SPADs are realized in a p-on-n design to optimize the sensitivity for photons in the NUV to the blue range of the EM spectrum.
- **NIR SiPM**: The individual SPADs are realized in an n-on-p design to optimize the sensitivity for photons in the red to NIR range of the EM spectrum.

The P/N of the corresponding products contains further details on the device:

**AFBR-S4XyyPzzCW**




| | |
|---|---|
| **AFBR-S4:** | P/N for Broadcom's SiPM products. |
| **X:** | Can be either the **N** or **P** (for p-on-**n** or n-on-**p**) structure of the SPAD's pn-junction and therefore the peak sensitivity regime. |
| **yy:** | Refers to the active area of the die in **(y × y)** $mm^2$. |
| **P:** | Indicates a packaged device. |
| **zz:** | Refers to the number of independent channels on the device. |
| **C:** | Indicates the SPAD pitch on the die (can be rounded to the next decimal or double digit). |
| **W:** | **(Optional)** Indicates a front-end series. |

**Example: Broadcom's AFBR-S4N66P024M**

This SiPM array is for a NUV/blue-light optimized SiPM (AFBR-S4**N**66P024M), with an active die area of 6 × 6 $mm^2$ (AFBR-S4N**66**P024M). The packaged device contains two independent channels (AFBR-S4N66P**02**4M) with a 40-µm SPAD pitch (AFBR-S4N66P02**4**M). The **M** for this type of SiPM indicates that the front-end belongs to Broadcom's NUV-**MT** technology.

# SiPM Basic Electrical Model

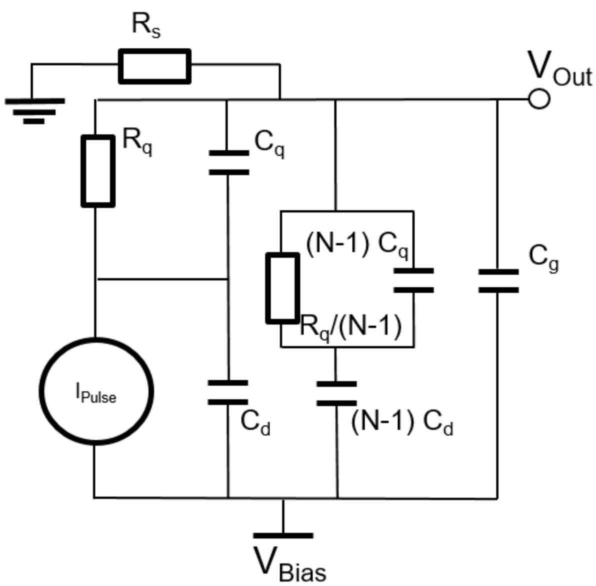
Figure 3 shows a basic SiPM electrical model. The SiPM current pulse (signal) of one firing SiPM SPAD can be modeled by a current source.

The main parameters of the model are as follows:

- $C_d$: Capacitance of the single SPAD
- $R_q$: Quenching resistor
- $C_q$: Parasitic capacitance of the quenching resistor
- $C_d$: Parasitic capacitance of the grid

For specific information on the electrical characteristics and parameters of Broadcom SiPM, contact sipm@broadcom.com.

**Figure 3: SiPM Basic Model**[1]




$C_d$ is not only determined by the microcell design (like the SPAD pitch) but also strongly depends on the level of depletion of the active volume.

# Glossary of SiPM Terms

As with the introduction of the SiPM, new terms for describing its characteristics are as follows:

- **afterpulse (AP)**: A form of correlated noise. Charge carriers of an avalanche can be trapped in the silicon and released after some time. As the SPAD is already (partly) recovered, a second delayed pulse can be observed next to an initial one.
- **breakdown voltage**: Above this reverse voltage, the avalanche is self-sustaining. It must be quenched (typically with a quenching resistor).
- **crosstalk (CT)**: A form of correlated noise. During the avalanche process in a SPAD, optical photons can be emitted. These photons can propagate through the silicon or the protective glass layer of the SiPM and trigger a neighboring cell. As a consequence, a double-pulse is observed at the output.
- **dark count rate (DCR)**: Even without any light pulses, signals can still be observed. These signals are caused by thermal electrons triggering an avalanche. Therefore, the DCR is dependent on the temperature and usually doubles with every 10°C increase.
- **dark current ($I_D$)**: The dark current is the cumulated charge originating from the DCR, CT, and AP. It can be estimated using the gain with the following equation:

$$I_D \approx q \cdot DCR \cdot gain \cdot (1 + CT + AP)$$

**NOTE:** Higher orders of CT will also contribute to the dark current.

- **dynamic range**: The dynamic range is given by the number of SPADs per SiPM.
- **fill factor (FF)**: The FF gives the ratio of insensitive area to sensitive area.
- **gain**: The number of electrons (charge carriers) ionized during an avalanche after a trigger. In other words, the number electrons forming an SiPM signal in response to a photon. For example, if the gain is $10^6$, one million electrons can be collected at the SiPM output for each photon.

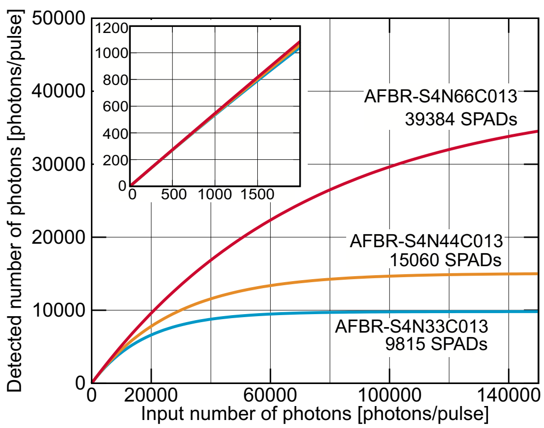
1. Adapted from F. Corsi *et al.*, Modelling a silicon photomultiplier (SiPM) as a signal source for optimum front-end design, NIM A 572 1 pp. 416-418, 2007.

- **linearity/saturation**: Assuming spatial distribution, the photons impinging on an SiPM are stochastic. If the intensity per light pulse is increasing, and the probability that two photons are hitting the same SPAD is increasing but giving the signal of just one photon, a nonlinear response of the SiPM is observed saturating at the number of SPADs of an SiPM. The response curve, meaning the number of fired SPADs ($N_{fired}$), is described by the input number of photons, $N_{photons}$, the number of SPADs ($N_{SPADs}$), and the photon detection efficiency (PDE):

$$N_{\text{fired}} = N_{\text{SPADs}} \cdot \left(1 - e^{-\frac{N_{\text{photons}} \cdot PDE}{N_{\text{SPADs}}}}\right)$$

Figure 4 shows the typical saturation response for the three available form factors of NUV-HD SiPMs.

**Figure 4: Linearity, Saturation Effect, and Dynamic Range of SiPMs—Data at 7V Overvoltage (54% PDE)**




**NOTE:** This curve is valid if the input photons are impinging the SiPM simultaneously (within a few ps) as a light pulse or flash.

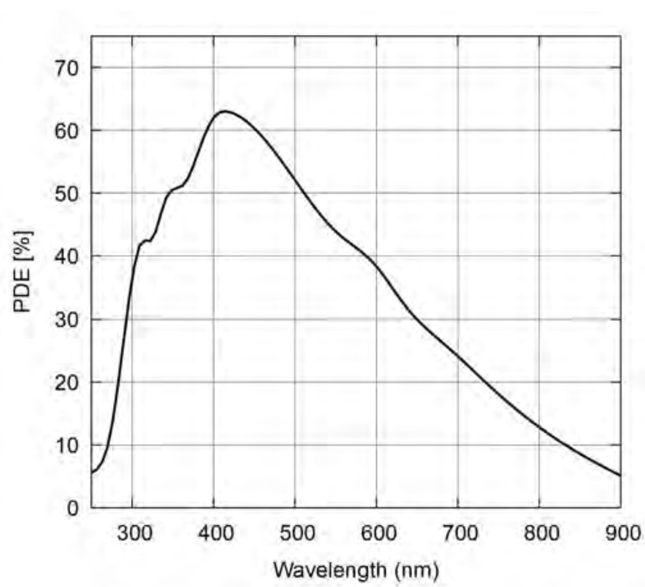
- **photon detection efficiency (PDE)**: The optical sensitivity of the SiPM (similar to quantum efficiency). The PDE depends on the wavelength of the incident light and increases with increasing overvoltage. The PDE is mainly the product of the quantum efficiency and the fill factor. For example, a PDE of 40% means that only 4 out of 10 photons can be detected. In a simplified picture, the PDE is the product of the quantum efficiency, the trigger probability (that is, the probability that an electron is triggering an avalanche), and the fill factor.
- **quenching resistor**: A resistor for stopping the electron avalanche.
- **recharge time constant (τ)**: The recharge of a SPAD follows an exponential behavior proportional to $e^{(-t/\tau)}$. After the recharge time, the signal is back to 1/e = 37%, and after five time constants, the signal is back below 1% of the peak amplitude.

  As shown, the dynamic range of the SiPM is given by the number of SPADs. However, sensitivity can be reduced by decreasing the overvoltage (OV), and thus the response curve can be adjusted within some limits.
- **silicon photomultiplier (SiPM)**: An array of SPADs connected in parallel.
- **single-photon avalanche diode (SPAD)**: The name of a single-diode structure working in Geiger mode above the breakdown voltage.
- **single-photon time resolution (SPTR)**: The SPTR, typically measured in full-width-at-a-half-maximum (FWHM), is the accuracy in time at which a single photon can be measured. If more than one photon is detected within a single pulse, the time resolution usually improves with ~$1/(\sqrt{n})$, where $n$ is the number of detected photons within the pulse.

## Spectral Sensitivity

The spectral sensitivity of the Broadcom NUV-MT SiPMs ranges from below 250 nm up to and beyond 900 nm and peaks at 420 nm (see Figure 5). Tuning the overvoltage, the overall sensitivity (that is, the PDE) can be increased (with a trade-off of increasing DCR and crosstalk).

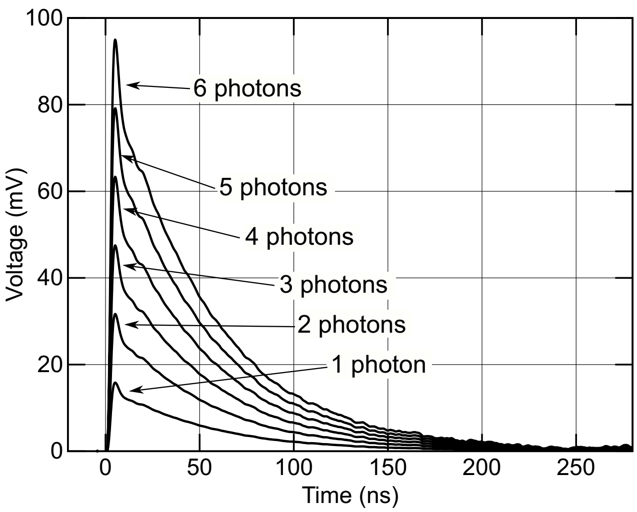
**Figure 5: Spectral Sensitivity of the Broadcom NUV-MT SiPMs**



# Typical SiPM Signals

The high intrinsic gain of the SiPM allows distinguishing even single photons and thus enables the SiPM to be used in photon-counting applications. Despite the intrinsic gain, however, the signals must usually be amplified using a preamplifier stage. Figure 6 shows typical SiPM signals after amplification using a transimpedance amplification circuit with a gain of 2V/A.

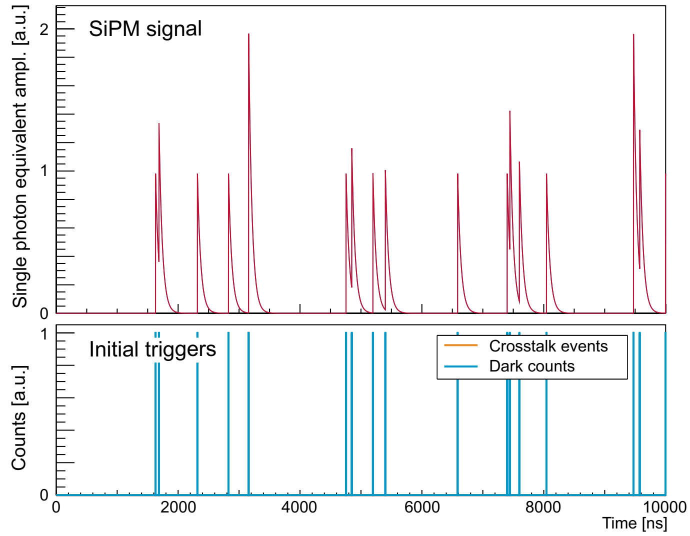
**Figure 6: Pulse Response to a Different Number of Photons**




In a first-order approximation, the signal can be described using a double-exponential function with a rise-time constant of a few hundred picoseconds and a recharge time constant of about 50 ns (for the NUV-HD technology).

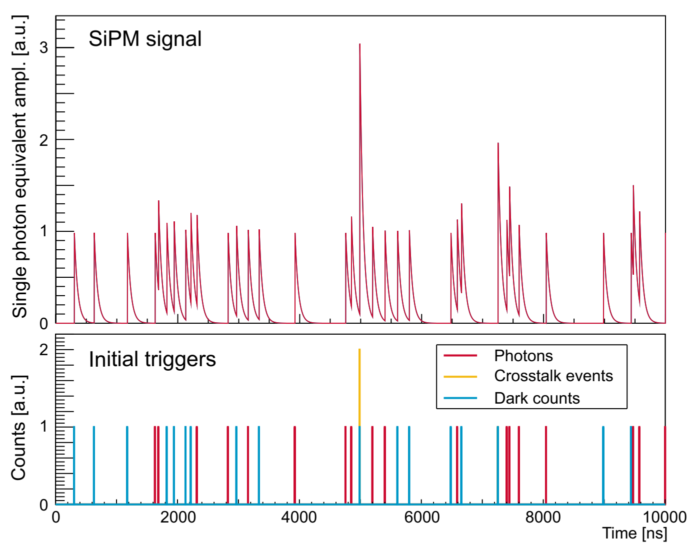
To visualize and better understand the influence of dark counts and crosstalk, a few SiPM signal waveforms have been simulated. Doing so, not only the signal itself but also the origin of the signal can be demonstrated. Figure 7 shows such a simulation result. This case shows the signal under dark conditions for the AFBR-S4N44C013 SiPM at an overvoltage of 3V. At this bias, the DCR is 1.7 Mcps (at 25°C), the crosstalk probability is 9%, and the PDE is 43%.

**Figure 7: Simulated SiPM Signal (Top) and Initial Triggers (Bottom) in the Dark for AFBR-S4N44C013 at 3V OV and 25°C**



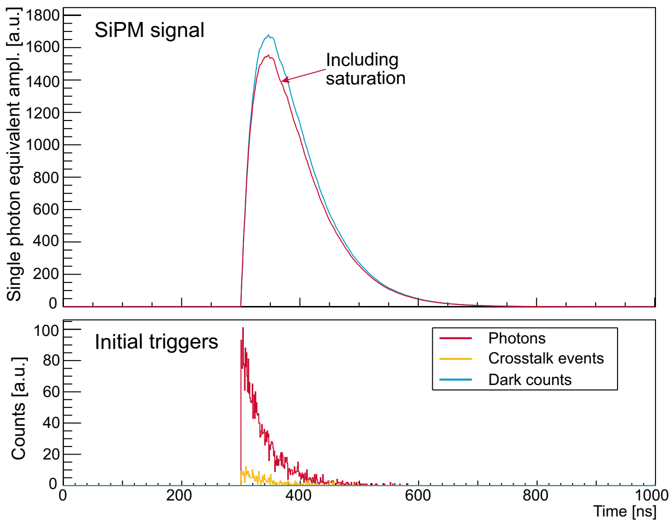

In another case, CW light is added in the simulation. The power of the light source is 2 pW shining on the sensitive area of an AFBR-S4N44C013 SiPM (that is, 3.72 × 3.72 $mm^2$). Figure 8 shows the result. It can be seen that the number of pulses caused by dark counts is about the same as the number of pulses caused by real photons. In this scenario, if pulse counting is used as the readout mode, about double the DCR (3.4 Mcps) would be obtained as a result.

**Figure 8: Simulated Signal and Triggers as CW Light Response**



Additionally, a scintillation event has been simulated. To do so, parameters of a high-energy photon absorption event in an LSO:Ce are used. More precisely, in this scenario an energy of 511 keV is deposited in a scintillation material with a light yield of 32 photons/keV and a decay time constant of 40 ns. Figure 9 shows the obtained signal.

**Figure 9: Simulated SiPM Signal and Triggers from a 511-keV Gamma Ray (Using an LSO:Ce Scintillator)**




In this figure, most of the signal originates from real photons; however, a small fraction is caused by crosstalk. The effect of dark events on the estimation of the number of photons is negligible. Two signals have been simulated: one with and the other without consideration of the saturation effect. Saturation plays a role in this illumination condition because the saturated signal amplitude and area are smaller than without saturation.

# Typical Readout Modes

In a first instance, the readout mode is mainly chosen by the type of light signal that should be detected—either a pulsed light source or a continuous or slowly changing signal. Therefore, photon counting can be realized in two ways:

- For pulsed-light sources (that is, a scintillator or pulsed laser), a combination of preamplifier (for example, a transimpedance amplifier) and discriminator/comparator circuit is realized. If the signal exceeds a threshold, the amplitude or preferably the integral of the signal can be measured (for example with a charge-integrator). Dividing the integral by the integral of a single photon results in the number of photons of the pulse (correction for crosstalk may be necessary).

  While intense flashes of light can be measured by applying a high threshold value and measuring the signal amplitude, low threshold settings for weaker signals, for example, of scintillators, can lead to an unwanted acquisition of dark-count and crosstalk events. In this case, pulse integration methods should be applied. An alternative to pulse integration is the so-called time-over-threshold method where the time above a given threshold is related to the intensity of the pulse.

  Alternatively, in research environments, the signal is often digitized after the preamplification stage and the obtained waveforms are analyzed offline, allowing full flexibility on the measurement method and data correction algorithms.
- For continuous-wave light sources (CW lasers, LEDs, fluorescence, or other luminescence modes), the light intensity can be measured by photon counting, measuring the current, or a combination of both.
  - Photon counting is typically realized by measuring a photon rate. To do so, the threshold of a comparator (or discriminator) is typically set to half the single photon amplitude. The number of threshold crossings per unit of time provides a photon rate (in this case, corrections for DCR and CT should be applied).

    The dynamic range of this detection mode is limited on the lower end by the DCR and on the higher end by pile-up due to a given recovery time. As a rule, the lower limit is about 10% of the DCR. Measures to widen the dynamic range can be taken. Lowering the overvoltage or cooling the SiPM increases sensitivity in the lower limit by reducing the DCR; whereas, for example, pole-zero cancellation circuits can be applied to extend the dynamic range on the high end.
  - An alternative solution is to measure the current drawn by the SiPM. By doing so, the dynamic range can be extended on the high end by going beyond the limits of signal pile-ups. Measures for temperature stabilization should be considered when approaching values of mA.
  - A combination of photon counting and current measurement can be applied to obtain optimum results in the lower and higher end of the dynamic range.

# Relating Responsivity, Quantum Efficiency, and Photon Detection Efficiency

The photon detection efficiency (PDE) is a sensitivity parameter usually used for SiPMs and can be directly compared with the QE of photodiodes, APDs, and PMTs.

Often, the radiant sensitivity is provided as a parameter of the sensitivity of a photodetector. To compare the sensitivity of various detectors, the quantum efficiency (QE) at a given wavelength, λ (in nanometers), can be calculated from the responsivity (or radiant sensitivity S [A/W]) using the following equation:

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

With *e* being the electron charge, $\lambda$ the wavelength of light, the Planck's constant *h,* and the speed of light in vacuum *c*. Typically, the sensitivity of SiPMs is given as photon detection efficiency (PDE). The PDE can be approximated using PDE = QE × FF × $\varepsilon$, with FF being the geometrical fill factor and $\varepsilon$ being the avalanche trigger probability. For PMTs and photodiodes, FF equals 1, so the QE has the same value as the PDE. Note that for a comparison of photosensors with and without gain (photodiodes, APDs, PMTs, SiPMs), QE and PDE are more useful parameters than the radiant sensitivity S. This is due to the fact that gain and noise parameters are included in the preceding equation. For example, an SiPM with very poor PDE can show a huge radiant sensitivity when the gain or correlated noise is very high.

The gain of the sensors is one for photodiodes, tens to hundreds for APDs, and millions for SiPMs and PMTs.

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