BROADCOM® FAQ

AFBR-S4XX

Broadcom SiPM Frequently Asked Questions

What is an SiPM?

Related application note: *AFBR-S4XX – Brief Introduction to Silicon Photomultipliers*

A silicon photomultiplier (SiPM) is a semiconductor device that can detect light (photons) and convert it into a current signal. Its basic building blocks are single photon avalanche diodes (SPADs), also referred to as Geiger-mode avalanche photo diodes (GM-APD). GM-APDs are biased with a reverse voltage that is high enough to create a Geiger discharge when a photon is absorbed in the active (high field) region of the diode. The minimum voltage at which the Geiger breakdown occurs is referred to as breakdown voltage (V_{BD}). The Geiger discharge provides a high multiplication factor (gain) and a well defined charge output, resulting in excellent single-photon resolution. To stop the discharge current (and the self-sustainable current), quenching is necessary. In an analog SiPM, this is conventionally realized by using a quenching resistor (Rq) in series to the SPAD. Once an avalanche occurs in the SPAD, the voltage drop across Rq effectively reduces the voltage across the diode below its breakdown voltage. Subsequently, the SPAD recharges over Rq and is ready to detect photons again.

A SPAD with its dedicated Rq is often referred to as a microcell. An SiPM is an array with several ten to several ten thousand microcells connected in parallel. The microcell density of an SiPM depends on the SPAD pitch, which is typically between 10 µm to 100 µm. The resulting size of the SPAD (partially) determines many electro-optical performance parameters of the SiPM, such as the photon detection efficiency (PDE) and the gain.

What are SiPMs suitable for?

SiPMs are best suited to detect light (photons) from the near UV over the visible to the near infrared electromagnetic spectrum.

Higher-energy photons, such as X-rays and gamma-rays, can be detected using scintillators. Scintillators convert high-energy photons into a number of UV or visible photons that are proportional to the energy of the incoming X-ray or gamma-ray.

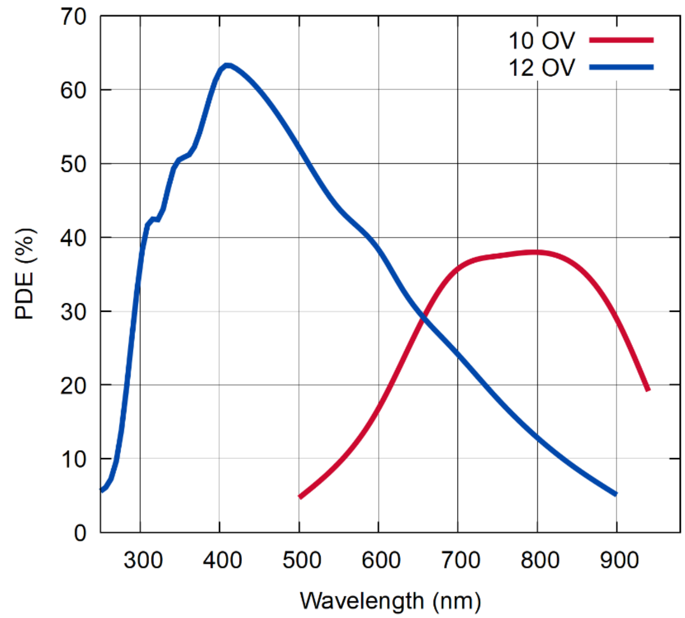
SiPMs are applied in a large variety of applications in fields such as the following:

- Medical imaging (PET, gamma cameras)
- Radiation detectors and dosimeters
- Microscopy (for example, confocal laser scanning microscopy, two-photon microscopy, fluorescence microscopy)
- Astrophysics
- High-energy physics (HEP)
- X-ray imaging
- Biophysics (for example, fluorescence detection, cytometry)
- LiDAR

If you are unsure if SiPMs are a suitable detector in your application, contact our application team via sipm@brodcom.com.

At which wavelengths are SiPM sensitive?

The sensitivity of Broadcom® SiPMs ranges from 250 nm to 980 nm, with the exact PDE spectrum determined by the technology. Therefore, SiPMs are best suited to detect light (photons) from the near UV over the visible to the near infrared electromagnetic spectrum.



Broadcom's SiPM portfolio offers dedicated solutions for the detection of UV/blue/green (NUV-MT SiPM) light and for yellow/red/IR (NIR SiPM) light.

- The PDE spectrum of Broadcom's NUV-MT SiPM ranges from 250 nm to 900 nm.
- The PDE spectrum of Broadcom's NIR SiPM ranges from 500 nm to 980 nm.

Besides the peak sensitivity and spectral sensitivity, both technologies differ in the other key parameters, such as noise characteristics and the dynamic range.

If you are unsure which technology is best suitable for your application, contact our SiPM applications team via sipm@brodcom.com.

Can SiPMs detect X-rays and gamma-rays?

Although SiPMs can directly detect X-rays, the efficiency is very low and signal generation is dominantly based on scattering. However, SiPMs can be used with the majority of scintillators, and, therefore, they can be used to detect X-rays and gamma-rays with high efficiency.

We have broad experience in the field or X-ray and gamma-ray detection and can support your application-specific needs.

I am unsure whether SiPMs can work in my application. Can you help me?

Sure, our applications team has extensive experience with SiPMs in various applications and works closely with our customers. We are happy to support your requests. Contact sipm@brodcom.com to get in touch with our SiPM applications team.

Are SiPMs easy to damage or destroy?

SiPMs are very robust devices both mechanically and optically. When the recommended current limit is obeyed, SiPMs are virtually indestructible. Accidental illumination, daylight illumination, or the wrong bias polarity is usually not critical and does not damage SiPMs. Furthermore, SiPMs can be used immediately after being exposed to bright light and need no time to recover.

What is the size of an SiPM?

Related product briefs:

- *AFBR-S4N Series – Broadcom High-Sensitivity NUV Silicon Photomultipliers*
- *AFBR-S4 SiPM Family – Silicon Photomultipliers*

Depending on the technology, Broadcom offers various SiPM form factors and channel areas.

NUV-MT SiPMs:

NUV-MT SiPMs are available in three active area variants:

- 2x2 mm^2 (AFBR-S4N**22**P014M)
- 4x4 mm^2 (AFBR-S4N**44**P014M)
- 6x6 mm^2 (AFBR-S4N**66**P014M)

The 4x4 mm^2 SiPMs are also available as SiPM arrays in the following arrangements:

- 2 x 2 (AFBR-S4N44P**04**4M)
- 4 x 4 (AFBR-S4N44P**16**4M)

The 6x6 mm^2 SiPMs are available in a 2 x 1 array configuration (AFBR-S4N66P**02**4M).

All Broadcom NUV-MT SiPMs use a SPAD technology with a 40-µm pitch, providing an optimal balance between efficiency and linearity.

NIR SiPMs:

Broadcom's high-sensitivity NIR SiPMs (AFBR-S4P11P012R) are available in a 2 x 1 dual-channel package. The channels are integrated in a monolithic array of 1 x 0.5 mm^2 active area per channel. The package design allows connecting the two individual cathodes on a customer PCB to obtain a 1x1 mm^2 SiPM.

Broadcom's fast NIR technology is designed for dTOF and LiDAR applications and is available in the following configurations:

- 1 x 24 monolithic line array with a 1.1 x 0.233 mm^2 channel area (AFBR-S4P0124P3TA)
- 1 x 2 monolithic line array with a 0.5 x 1.0 mm^2 channel area (AFBR-S4P0102L3R)

Broadcom NIR SiPMs provide ultra-high SPAD densities with a pitch of 12.5 µm, resulting in excellent dynamic range.

What do breakdown voltage and overvoltage mean?

Related application notes:

- *AFBR-S4XX – Brief Introduction to Silicon Photomultipliers*
- *AFBR-S4XX – Working with Broadcom SiPMs*

SiPMs are arrays of single photon avalanche diodes (SPADs) in a parallel circuit.

Breakdown voltage refers to the minimum voltage that is required to cause a Geiger breakdown in the SPADs; in other words, the minimum voltage that must be applied to an SiPM to operate it properly.

Overvoltage is the excess voltage above the breakdown voltage. Most SiPM parameters are a function of the applied overvoltage.

The overall bias voltage supplied to an SiPM is $V_{Bias} = V_{breakdown} + V_{OV}$.

What is the maximum voltage that can be applied to SiPMs?

The maximum voltage that can be applied to SiPMs depends on the technology.

- For Broadcom's NUV-MT SiPMs, the maximum overvoltage is 16V, resulting in a maximum bias voltage of 48.5V at 25°C.
- Broadcom's NIR SiPMs can be operated at up to 12V overvoltage.

For details, refer to the data sheet of your device.

Which bias polarity do you recommend?

Related application note: *AFBR-S4XX – Working with Broadcom SiPMs*

Depending on the connection scheme and therefore the used polarity of the SiPM bias, the signal can be obtained from the anode or the cathode. However, Broadcom recommends using the following convention for readout:

- Broadcom SiPMs with *AFBR-S4N* and *AFBR-S4K* serial numbers (p-on-n substrate), such as NUV-MT SiPMs, prefer the *anode* for signal extraction and therefore *a positive bias via the cathode*.
- Broadcom SiPMs with *AFBR-S4P* serial numbers (n-on-p substrate), that is NIR SiPMs, prefer the *cathode* for signal extraction and *a negative bias via the anode*.

What is photon detection efficiency?

Related application note: *AFBR-S4XX – Brief Introduction to Silicon Photomultipliers*

Photon detection efficiency (PDE) is the SiPM parameter that refers to sensitivity and is the ratio of detected (primary) photo-electrons and the number of incident photons.

An SiPM's PDE is given as follows:

$$PDE = QE \times FF \times \varepsilon$$

With QE the quantum efficiency, FF the geometric fill factor given by the ratio between the sum of the SPADs' active area and the total SiPM area, and ε the probability of triggering an avalanche.

Broadcom SiPMs provide best-in-class PDE:

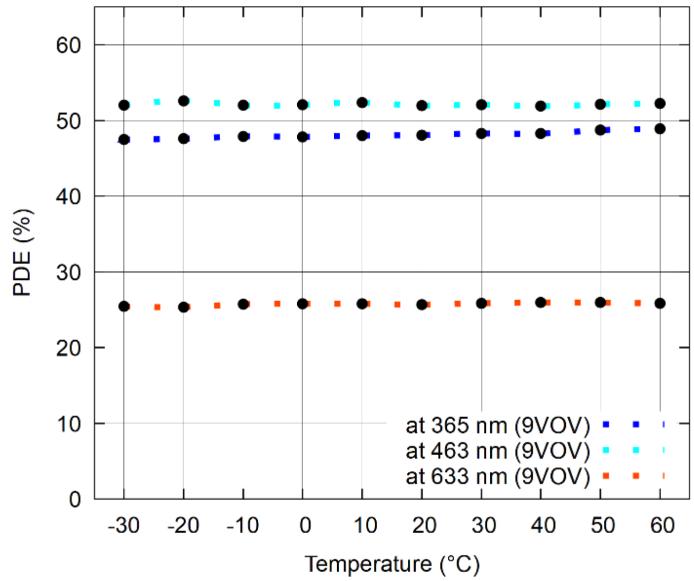
- 63% at 420 nm for NUV-MT SiPMs
- 37% at 750 nm for high-sensitivity NIR SiPMs

Does the PDE change with temperature?

Yes, there is a measurable influence of the SiPM temperature on its PDE. The exact temperature behavior depends on the underlying technology.

The temperature coefficient of the PDE depends on the wavelengths and applied overvoltage and tends to increase for longer wavelengths. More details on the NUV-MT temperature behavior of the PDE are given in Schmailzl et al. 2022 JINST 17 P12009.

The plot shows the measured PDE at three wavelengths (365 nm, 463 nm, and 633 nm) at 9V overvoltage in the temperature range between –30°C and 60°C. Overall, the temperature coefficient of the PDE is a small value and in the order of 10^{-3}/°C.



How do you calculate the responsivity of SiPMs?

Related application notes:

- *AFBR-S4XX – Brief Introduction to Silicon Photomultipliers*
- *AFBR-S4NxxPyy4M – SiPM Characteristics for PMT Users*

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.

However, often, the radiant sensitivity is provided as a parameter of the sensitivity of a photodetector. The radiant sensitivity (S [A/W]) of an SiPM can be calculated from the PDE, gain, and correlated noise components (P_{CT}: crosstalk probability and P_{AP}: afterpulsing probability) using the following equation:

$$\boldsymbol{S[A/W] = \frac{e\lambda}{hc} \cdot PDE(\lambda) \cdot Gain \cdot (1 + P_{CT} + P_{AP})}$$

With *e* being the electron charge, *λ* being the wavelength of light, *h* being the Planck's constant, and *c* being the speed of light in a vacuum.

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 the gain and noise parameters are included in the preceding equation.

For example, a sensor with very poor PDE can show a huge radiant sensitivity when the gain or correlated noise is very high. This, however, would not translate into an acceptable signal-to-noise ratio.

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

What is crosstalk in SiPMs?

Related application note: *AFBR-S4XX – Brief Introduction to Silicon Photomultipliers*

Crosstalk (CT) in SiPMs is a form of correlated noise. During the avalanche process in a SPAD, optical photons (from recombination) can be emitted. These photons can propagate through the silicon or the protective layer of the SiPM package and trigger a neighboring cell. As a consequence, the pulse amplitude (and charge) is increased by the contribution of additionally triggered SPADs.

What is afterpulsing in SiPMs?

Related application note: *AFBR-S4XX – Brief Introduction to Silicon Photomultipliers*

Afterpulsing (AP) in SiPMs is 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.

What is the recovery/recharge time of an SiPM?

Related application note: *AFBR-S4XX – Brief Introduction to Silicon Photomultipliers*

The recharge of a SPAD follows an exponential behavior proportional to $e^{-t/T}$ with τ being the recharge time constant. After the recharge time, the signal is back to 1/e = 37%, and after (approximately) five time constants, the signal is back below 1% of the peak amplitude.

The recharge time constant is determined by the capacitance of the SPAD and the quenching resistor value. Smaller SPADs tend to have shorter recharge times and therefore provide a higher rate capability.

- For Broadcom NUV-MT SiPMs, τ is 55 ns.
- For Broadcom NIR30 SiPMs, τ is 15 ns.

How can I evaluate Broadcom SiPMs?

Related application note: *AFBR-S4E001 – Evaluation Kit for the AFBR-S4NxxPyy4M SiPM Family*

Our AFBR-S4E001 NUV SiPM evaluation kit includes an SiPM of all three available active area variants (2x2 mm^2, 4x4 mm^2, and 6x6 mm^2). In addition, it ships with two types of readout PCBs:

- A DC readout without amplifier for direct access of the SiPM pulse
- An amplifier PCB with an amplified energy channel and a pole-zero filtered timing output

If you want to evaluate our NIR SiPM or need further information on evaluation options, contact our application team via sipm@broadcom.com.

What do I need to operate an SiPM?

SiPMs are simple to test and evaluate.

The AFBR-S4E001 SiPM evaluation kit comprises an amplified energy and pole-zero filtered timing output. For applications with high dynamic range requirements and bright signals, it is shipped with a DC readout PCB that allows reading out the SiPM directly without amplifier or bandwidth limitation.

A voltage supply (~ 50V) and an oscilloscope are all the equipment you need to test the SiPM with its evaluation kit. If you also want to use the amplifier PCB, you will need a dual-source voltage supply to (5V) to bias the amplifiers.

NOTE: Cables are not shipped with the evaluation kit and must be provided by customers.

Can I buy SiPMs in interposer PCBs?

Broadcom does not sell single SiPMs on an interposer PCB. The Broadcom AFBR-S4E001 evaluation kit includes three SiPMs on an interposer PCB to be used with the dedicated amplifier and/or readout PCB.

If you need additional SiPMs on an interposer PCB to be used with your evaluation kit, contact sipm@broadcom.com.

Can you supply the footprints for your SiPMs?

Yes, contact our application team at sipm@broadcom.com.

What does an SiPM pulse look like?

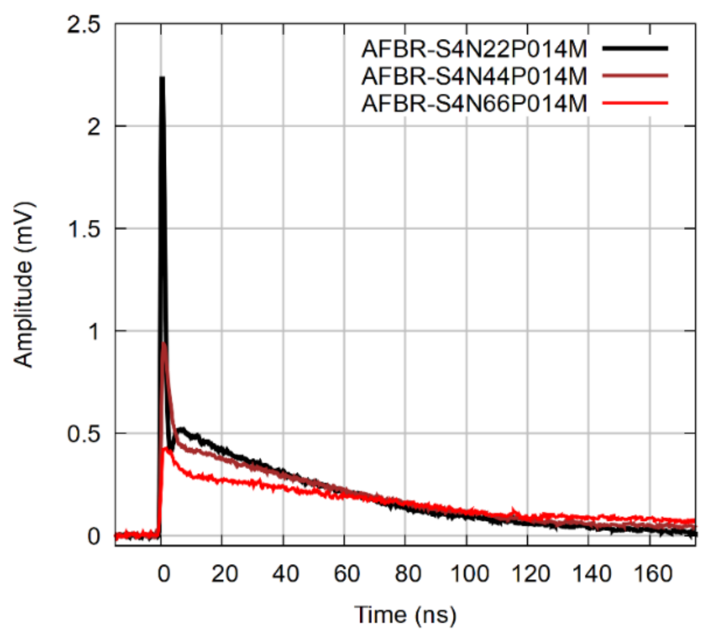
Related application note: *AFBR-S4NXX – SiPM Waveform and Bandwidth Consideration*

The rising edge of an SiPM signal is caused by the Geiger discharge and is determined by the diode resistance in a conducting state.

The falling edge of the signal is determined by the recharge of the SPAD (and parasitics) and is characterized by two exponential decays (a fast and a slow component).

The following figure shows the response to a single photon for an SiPM with Broadcom's NUV-MT technology with three different active areas (without amplifier).

Furthermore, the effective pulse measured at the output of the SiPM also depends on the detected light pulse and is a convolution of the SiPM pulse shape with the light pulse.



What is the dynamic range of an SiPM?

Related application note: *AFBR-S4NxxPyy – SiPM Dynamic Range, Linearity, and Saturation*

The dynamic range of an SiPM addresses the maximum number of photons that can be detected by the SiPM and depends on the properties of the incident light pulse.

- For short light pulses (approximately < recharge time constant), the dynamic range is determined by the number of SPADs and the PDE.
- For light pulses longer than the recharge time constant and CW light, SPADs can recharge and be triggered by further photons, which effectively increases the dynamic range.

Does the SiPM gain change with temperature?

The gain of an SiPM does not change with temperature if the bias voltage is adapted such that the temperature coefficient of the breakdown voltage is accounted for (meaning that the SiPM is operated at a constant overvoltage).

However, customers may see a reduced signal amplitude/charge pulse response at high temperatures due to saturation effects. This effect can be prominent in NIR SiPMs, which are qualified at high temperatures and show higher DCR compared to NUV SiPM: At high temperatures (for example above 80°C) a non-negligible number of SPADs can be triggered by dark counts. This is observed by a DC current offset of the signal baseline. In numerous applications where high temperatures (and often also bright ambient light conditions) must be handled, AC coupling is used to suppress this DC baseline component. The high DCR at high temperatures effectively reduces the dynamic range by occupying SPADs. These SPADs cannot contribute to the overall SiPM signal when a signal light pulse is detected by the SiPM. The reduced number of contributing SPADs results in a reduced signal amplitude/charge output.

Broadcom NIR SiPMs use a 12.5-µm SPAD pitch, providing excellent dynamic range and a target to minimize saturation effects under bright ambient light and/or high-temperature conditions.

Can I operate an SiPM in ambient light?

An SiPM is a highly sensitive photon detector and thus will saturate when exposed to bright ambient light. However, exposing an SiPM to ambient light will not damage the SiPM if a suitable current compliance limit is applied.

If SiPMs are required to be operated under bright ambient light, narrow-band pass filters can be used to suppress the ambient light of wavelengths different from the signal wavelength.

Follow these tips to operate an SiPM in ambient light:

- Always use a current compliance limit (of a few mA; the exact value depends on the type of SiPM).
- Use a narrow-optical-band-pass filter matched to the signal wavelength to suppress a broad spectrum of ambient light.
- AC coupling (for example, using a high-pass filter or balun transformer) can suppress a DC offset caused by frequent SiPM triggers by ambient light.

Note that ambient light will constantly trigger SPADs on the SiPM, which effectively reduces the available dynamic range of the detector. In an AC readout scheme, the increasing saturation with increasing ambient light brightness may appear to reduce the signal amplitude (given a constant signal power). This signal amplitude reduction is not due to gain changes; rather, it is caused by a reduced dynamic range (similar to the effect caused by high DCR at high temperatures, Q 1.23).

Do you have tips for testing your SiPMs?

Related application notes:

- *AFBR-S4XX – Working with Broadcom SiPMs*
- *AFBR-S4NxxPyy4M – Single-Photon Measurements*
- *AFBR-S4NxxPyy4M – NUV-MT SiPM Performance Correlation*

SiPMs are easy to use and to test. The following are a few tips for first-time users:

- **Current compliance**: Make sure to apply a current compliance limit to the SiPM to prevent high currents to the device when involuntarily applying wrong bias polarities of exposing the SiPM to ambient light. To start with, you can use 3 mA as the current compliance limit.
- **Consistency checks**: It is good practice to ensure proper measurement conditions:
  - Firm cable connections
  - Dark conditions
  - Correct oscilloscope settings

  Before starting a detailed test, a brief setup consistency check can be performed, such as the following:
  - Does the SiPM behave like a diode (diode test on multimeter)?
  - Is the SiPM dark current reading on an SMU (if used) reasonable?
  - Can dark pulses be observed on an oscilloscope?
- **Operational point**: SiPMs are complex sensors with most of their performance parameters depending on the applied overvoltage. To find the best operation point in your application, we strongly recommend a bias sweep over the full specified overvoltage range.

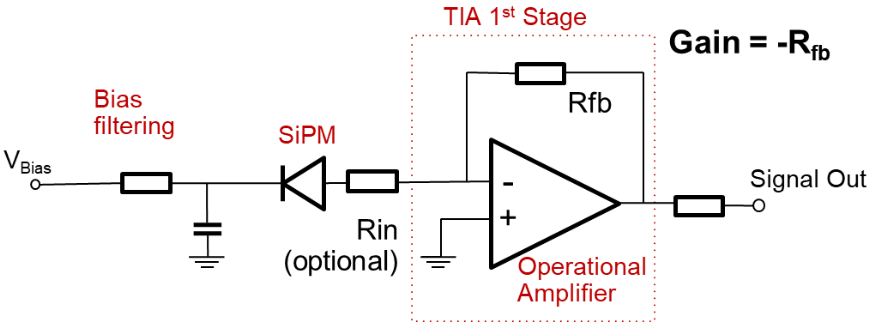
What are the most common ways to read out an SiPM?

The ideal way to read out an SiPM strongly depends on the application and its requirements in the signal. The SiPM can be DC or AC coupled; impedance matching and filtering may be necessary; and signal amplitudes can be increased using amplifiers or even reduced using attenuators.

In most applications, the SiPM signal is amplified and filtered/shaped. A very common readout design therefore comprises a transimpedance amplifier (TIA). TIAs can be realized based on a wide range of operational amplifiers. The choice of operational amplifier should be based on the performance requirements in the end application.

The SiPM signal can be coupled to the TIA input DC or AC, and each variant has its own advantages and complications.

If only moderate gain (few tens of V/A) and/or low bandwidth is required, a single-stage transimpedance amplifier can be used:



If the required gain at a given bandwidth cannot be achieved by a single-stage TIA, a second amplification stage can be implemented. For the second stage, a TIA design can be used, but other options, such as voltage amplifier designs, are also suitable options.

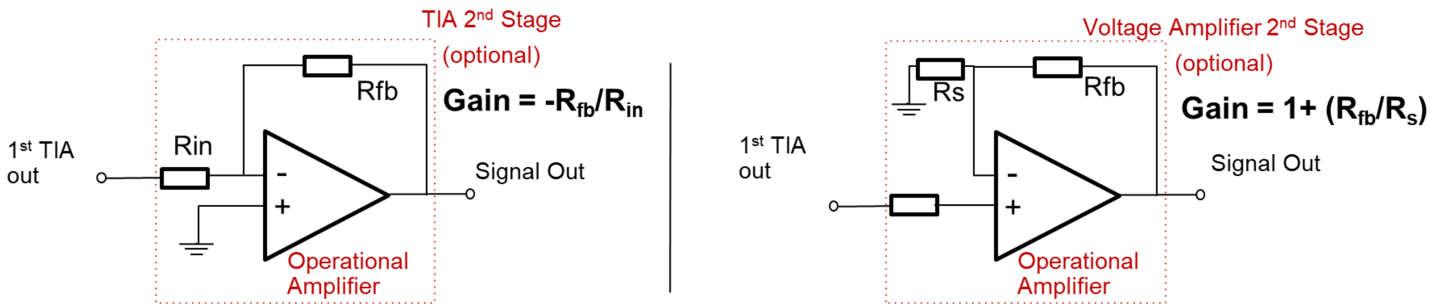
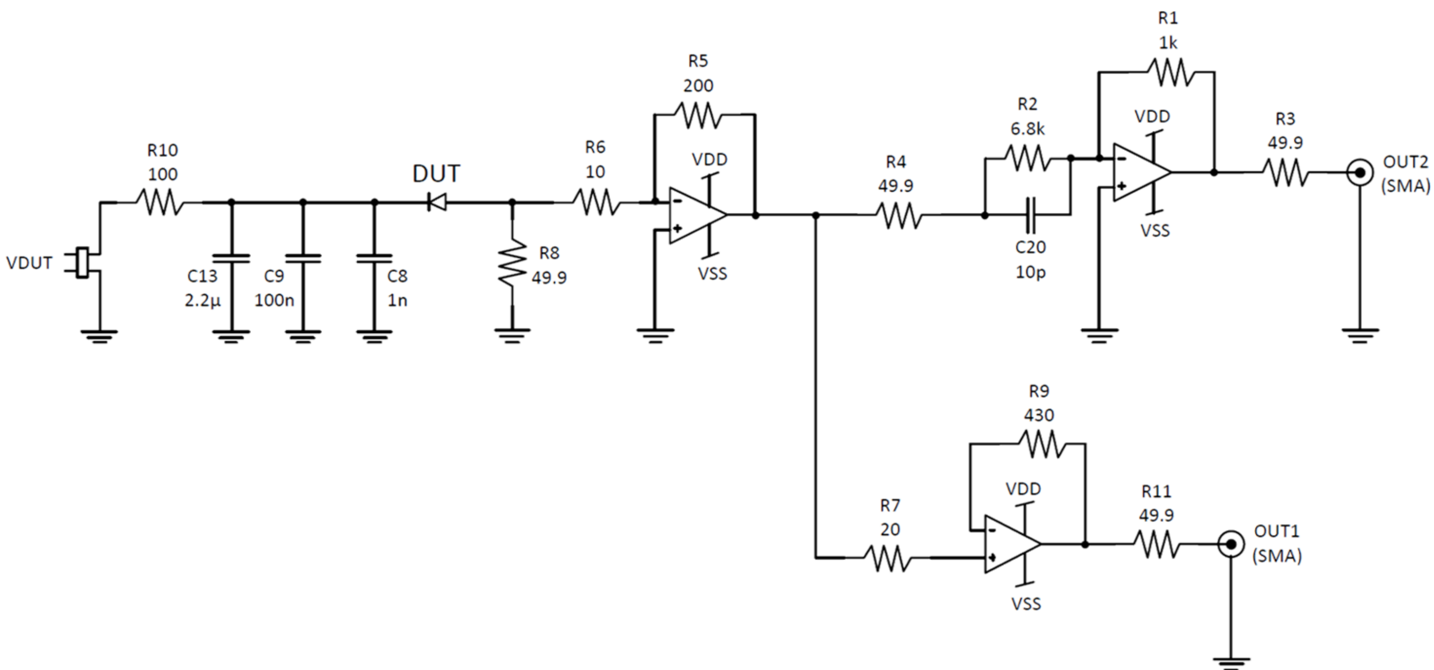


Figure 1: Example: Simplified Readout Scheme of the Broadcom AFBR-S4E001



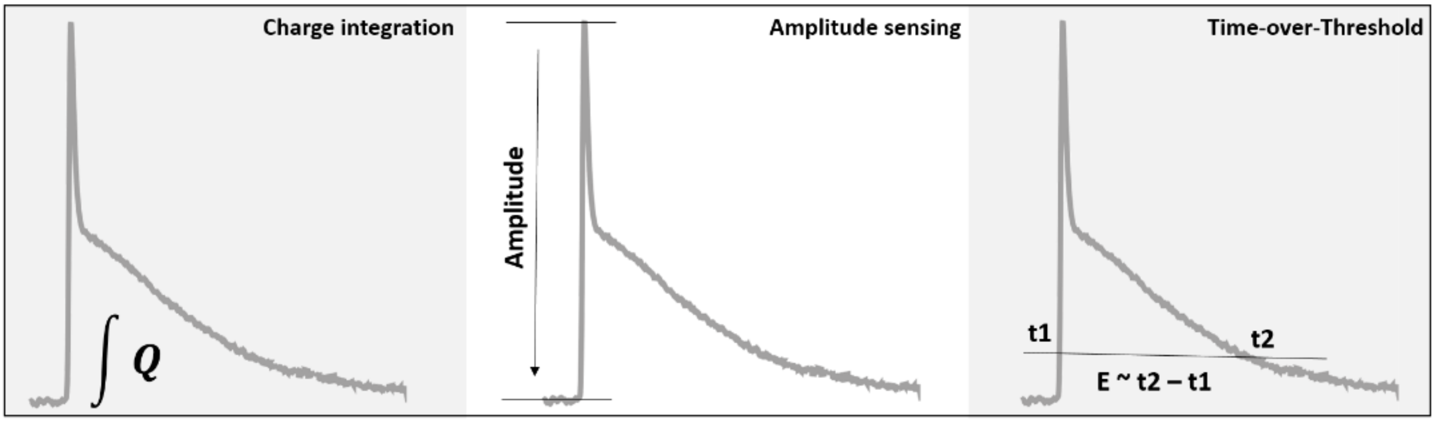
The SiPM is biased via its cathode with buffer caps used in the bias line. The SiPM signal is first fed into a current divider (R6 and R8), which effectively reduces the gain of the first TIA stage. With a TIA gain of 200 (given by the feedback resistor R5) and the current divider, the gain of the first stage is 82 V/A. The pre-amplified voltage signal is subsequently split into two channels. The “energy” signal (full DC signal via OUT1) is fed into a voltage follower (unity gain), whereas “timing” (pole-zero filtered via OUT2) is fed into a second TIA stage.

Both outputs are impedance matched to 50Ω.

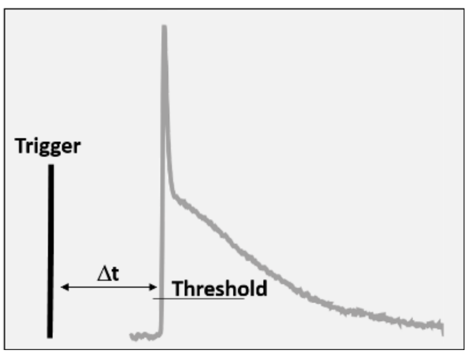
How do I digitize an SiPM signal?

The SiPM current signal is typically digitized by either of the following:

- Charge integration or amplitude sensing
- Time-over-threshold measurements if the energy must be assessed



For timing measurements, the typical time at which the signal exceeds a predefined threshold (for example, versus a trigger or second detector) is used.



What is the fill factor of Broadcom SiPMs (arrays)?

The fill factor within the active area is included in the PDE.

The achievable fill factor of SiPM arrays, meaning the ratio between the active area of the SiPM channel and the overall covered area, depends on the used product. Generally, SiPMs with larger active areas also result in a higher fill factor if single-channel devices are considered. However, the fill factor can be increased by using Broadcom SiPM arrays. Highest fill factors are achieved with the Broadcom 16-channel NUV-MT array (AFBR-S4N44P164M).

The following table provides an overview of the device fill factor for Broadcom NUV-MT SiPM products.

	AFBR-S4N44P**014**M	AFBR-S4N44P**044**M	AFBR-S4N44P**164**M	AFBR-S4N66P**014**M	AFBR-S4N44P**024**M	AFBR-S4N22P**014**M
Active area of SiPM [mm^2]	3.72 x 3.62	3.72 x 3.62	3.72 x 3.62	6.00 x 6.00	6.00 x 6.00	2.00 x 2.00
# of channels	1	4	16	1	2	1
Active area per device [mm^2]	13.47	53.88	215.52	36	72	4
$\text{Dimension}_{\text{vertical}}$ [mm]	4.31	8.26	16	6.71	6.54	2.48
$\text{Dimension}_{\text{horizontal}}$ [mm]	4.18	8.26	16	6.48	13.54	2.71
Package outer dimension [mm^2]	18.02	68.23	256	43.48	88.55	6.72
Fill Factor [%]	**74.77**	**78.97**	**84.19**	**82.80**	**81.31**	**59.5**

*values rounded to two decimal places

Broadcom NIR SiPM arrays are based on a different technology and on monolithic arrays; that is the channels are implemented in a single Si die. This allows a fill factor of close to 100% for the single array (without package).

How can I buy Broadcom SiPMs?

If you need smaller quantities of SiPMs (< few tens of SiPM arrays, < 100 for single-channel SiPMs), you can order Broadcom SiPMs directly from the following vendors:

- Digikey
- Mouser
- Farnell

For larger-quantity orders and/or repeated orders, Broadcom works with its distribution partner Avnet. Contact your Avnet/EBV sales contact, your local Broadcom sales representative, or the SiPM sales team via sipm@broadcom.com for volume quotations.

Contact sipm@broadcom.com if you have any questions, and we can work on finding the distribution channel that best fits to your needs.

I would like to learn more about Broadcom SiPMs. Where can I get more information?

The Broadcom SiPM website provides numerous application notes with topic-specific information on the performance and usage of our SiPMs.

The application team is also happy to support your requests and can provide further information. Contact sipm@broadcom.com to get in touch with our SiPM application team.

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