WHITE PAPER

How to Evaluate and Compare Silicon Photomultiplier Sensors

October 2015

The Silicon Photomultiplier (SiPM) is a single-photon sensitive light sensor that combines performance characteristics that exceed those of a PMT, with the practical advantages of a solid state sensor. The SiPM is formed of a summed array of closely packed SPAD sensors with integrated quench resistors, thus transforming multiple binary devices into a single analog sensor. An in depth introduction to the technology can be found here [1].

SiPM sensors were first commercially available in 2005, and since then many improvements have made and more manufacturers are producing sensors commercially. Selecting the optimum sensor for a given application can seem daunting given the increasing choice in the market. This document discusses some of the primary factors to be considered in this selection. As well as performance, this document will discuss packaging, system performance, application specific performance, uniformity and reliability and the support available for the product.

Contents

Raw Performance Parameters

Photon Detection Efficiency (PDE) and Responsivity

In a large number of applications, the photon detection efficiency (PDE) will be the first parameter to review. It is a measure of the sensitivity of the sensor and is defined as the percentage of incident photons that will go on to be amplified by the high internal gain and produce a measurable signal. Best-in-class SiPM sensors are now approaching, or in SensL's case, exceeding, a peak PDE of >50%. PDE is a function of wavelength (Fig. 1), and also varies with bias voltage (Fig. 2). The PDE of sensors from different vendors varies considerably and even between those from the same vendor, depending on the sensor type (see the microcell section in [1]). It is also important to consider the responsivity of the sensor which is shown in Fig. 3. Due to the high internal gain of the SiPM the responsivity remains high across a wide wavelength range.

Points to consider:

- *Does the sensor have enough sensitivity at the required wavelengths? Optimal sensor performance will be obtained at the wavelengths where the PDE/ responsivity peaks, but with the high responsivity of a SiPM, operation outside of the peak region works extremely well.*
- *What overvoltage is needed to achieve the PDE and how does this impact on other performance parameters?*

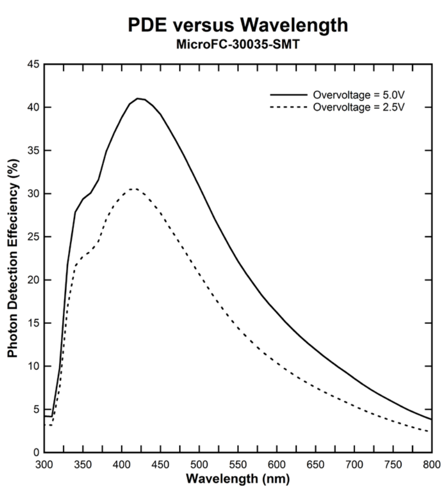


Figure 1, PDE as a function of wavelength and bias.

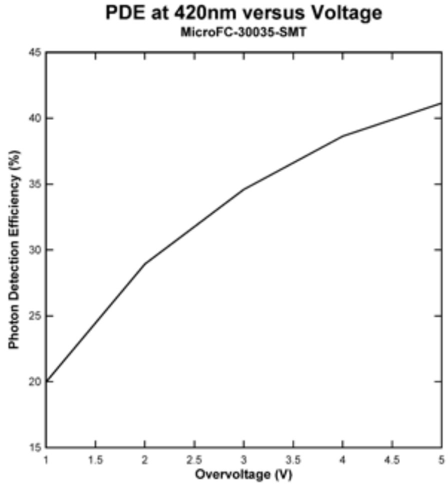


Figure 2, PDE as a function of overvoltage.

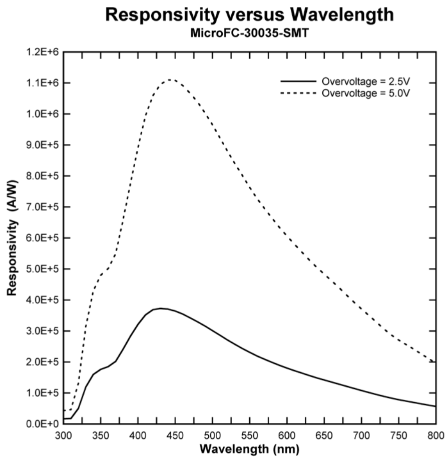


Figure 3, Responsivity as a function of wavelength and bias.

Dark Count Rate (DCR)

The DCR is the primary source of noise in a SiPM sensor. It is defined as the rate of counts at the single photon level that are due to thermally generated electrons in the active volume of the silicon, rather than the incident light source. The DCR is especially important for low-light applications or those with long integration times. However, in any application, the DCR will impact the signal-to-noise ratio (SNR). Typical DCR values for SensL sensors are ~30kHz/mm^2. It is important to express the rate per area, as this noise will scale with the overall sensor size. The DCR is also a function of overbias (Fig. 4) and temperature.

Points to consider:

- *Is DCR quoted per mm^2 or for the whole sensor area?*
- *Is the DCR sufficiently low to achieve the required SNR for the application?*
- *The DCR varies with overbias and temperature – check the value when these are taken into account?*
- *Is the DCR quoted based on “binned” devices available at a higher price, or typical of all products in the line?*

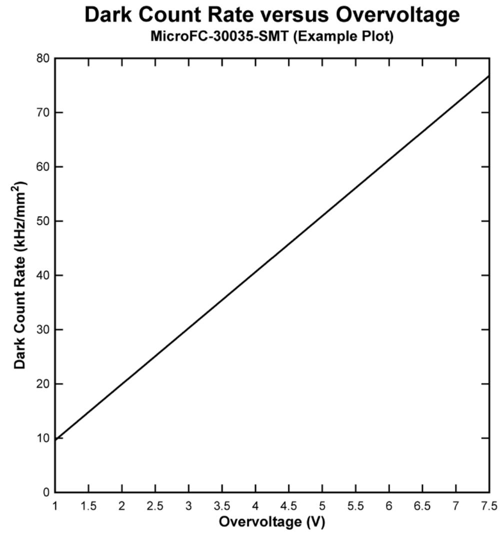


Figure 4, DCR as a function of overvoltage.

Crosstalk & Afterpulsing

Crosstalk and afterpulsing are two types of noise events that cause unwanted noise. An explanation of both can be found in [1]. Both phenomena are quoted as the percentage chance of them occurring, for each detected photon event. Measurements can be degraded if the values of these parameters are too high, although it is highly dependent upon the application. Recent research shows that cross-talk may be minimally important for CRT measurements in PET, but it is vitally important in the new large Cherenkov telescope arrays.

Both crosstalk and afterpulsing increase with overbias and microcell size [1]. There is a huge variation in these parameters between manufacturers. Some manufacturers have been successful in implementing 'trench' technology, that was previously believed to be the best route to crosstalk reduction. However, some of the lowest crosstalk values on the market today have no trenches.

Points to consider:

- *Is the crosstalk or afterpulsing important to the application?*
- *Do not assume that the presence of trenches guarantees the best crosstalk.*

Rise Time & Recovery Time

The rise time of the microcell in a SiPM is very fast, however the observed output signal is dominated by the impedance of the overall SiPM array. Manufacturers optimize this to provide the fastest signal timing. Typical rise times are in nanoseconds for a fast SiPM.

The recovery time, or decay time of the pulse, is primarily determined by the microcell reset period, given by the product of the effective capacitance of the microcell and the value of the quench resistor. Since the capacitance of the microcell will depend upon its area, the reset time will vary for different microcell sizes. An additional factor that can affect the recovery time is the series resistance from the rest of the sensor that will be more significant in larger sensors.

To provide the best timing possible, SensL has added a third terminal (in addition to the anode and cathode), which provides a dedicated Fast Output for achieving the fastest signal rise times, Fig. 5. The fast output is capacitively coupled to each microcell, with the output signal being the derivative of the internal fast switching of the microcell in response to the detection of a single photon. These fast output signals typically have rise times of 300ps - 1ns and pulse widths of 600ps - 3ns FWHM (dependent on sensor size only). A typical fast output pulse can be seen alongside a standard output pulse in Fig. 5. This signal can be used to make ultra-fast timing measurements, using the ability to clearly distinguish the arrival time of the first photon in the pulse, and also provide higher count rate ability or capability for second photon timing. In addition to the timing improvements, the fast output also has considerably lower capacitance which can be beneficial when designing readout systems for the sensor. The fast output from a 1mm sensor has a capacitance of 1pF, whereas, reading out from the anode or cathode would have about 100pF.

Points to consider:

- *Is timing or count rate critical to the application? Fast output should be considered. If not, careful study of the various sensor sizes, and/or microcell sizes should be carried out.*

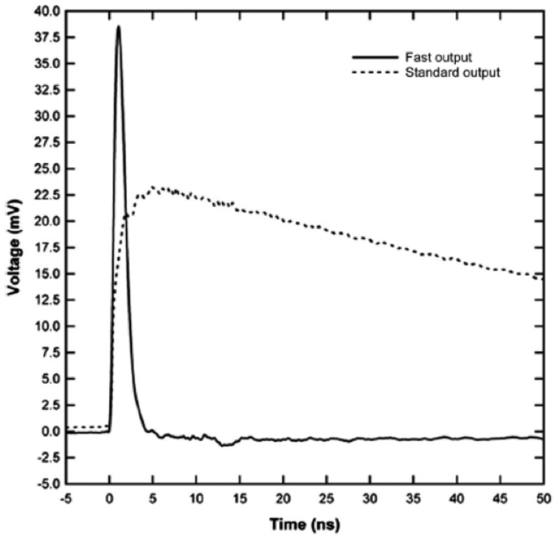


Figure 5, The fast and standard output signals from a SensL SiPM.

System Performance

Breakdown Voltage and Operating Bias

The breakdown voltage (Vbr) is the bias point at which the electric field strength generated in the depletion region is sufficient to create a Geiger discharge. A typical Vbr in SensL sensors is around 24.5V. SensL recommends an applied bias voltage (Vbias) of between 1V and 5V above the Vbr. Therefore for SensL sensors, Vbias is <30V, which contrasts with some SiPM sensors that have a Vbias of anywhere from 50V to more than 100V. The benefit of a low bias voltage is that the SiPM complies to the “extra low voltage” directive.

Another factor relating to bias is the uniformity of bias over large numbers of sensors. This uniformity can be tightly constrained using high quality manufacturing, and for SensL sensors is ±250mV for all sensors shipped [5]. This is particularly important if a large number of sensors are required for a single system. If the Vbias varies too much, individual adjustment of bias will be required.

Points to consider:

- *Is there an advantage to have low bias?*
- *Are multiple sensors being used in a single system, where they could be powered from a single bias source?*
- *If a manufacturer has agreed to provide sensors within a narrow range of Vbr, is this from binning/selecting detectors, and if so has the selection increased the cost?*
- *Has the impact of the power supply on the design and power requirements been considered?*

Temperature

Temperature affects both the breakdown voltage and the DCR.

SensL’s SiPM sensors has a narrow depletion layer and uses doping levels which result in a low Vbr. Temperature is known to affect the breakdown voltage of the silicon diodes, and lower voltage Vbr sensors are far less susceptible to temperature than sensors with high Vbr. All SensL SiPM sensors vary only 21.5mV/°C, whereas a SiPM with a higher Vbr will have a stronger variation with temperature, as in Fig. 6.

Since the DCR is due to the thermal generation of electrons, this noise will also increase with temperature and is one of the limiting factors of the use of these sensors in applications that operate at elevated temperature. Conversely, cooling the sensor will reduce the DCR, with every drop of 20°C providing a factor 10 reduction. Some interesting recent work showed that at liquid argon temperatures*, the DCR was <10Hz/mm² @ Vbr+5V [2].

Temperature compensation circuits can be used to adjust for the change in overbias with changing temperature, but the increase in DCR can only be reduced by active cooling.

Points to consider:

- *Will temperature fluctuations in the application require a bias compensation circuit?*
- *If higher temperatures are to be encountered, is the increase in DCR tolerable?*

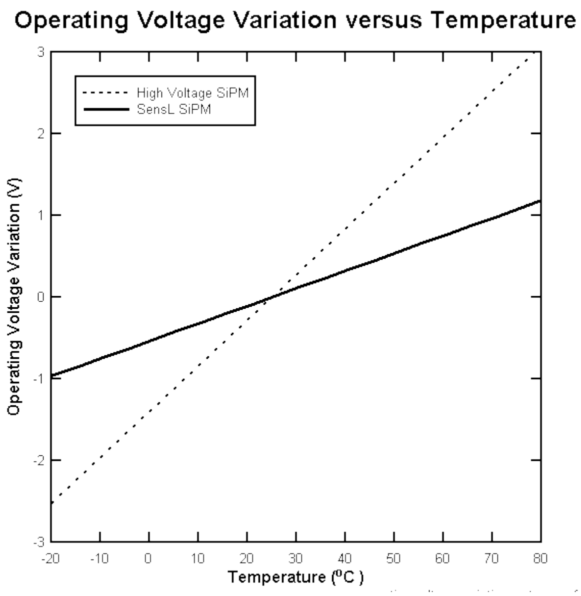


Figure 6, Temperature coefficients comparing SensL and a high voltage SiPM.

** Please consult the product datasheet for the recommended operating temperature range.*

Application Specific Performance

In addition to the considerations discussed here, the selection of a particular sensor may ultimately come down to a performance parameter that is specific to a given application. Some examples are:

- Coincidence resolving time (CRT) in positron emission tomography (PET) applications. The CRT will have an impact on the overall image quality of the system, and is becoming the most critical metric in commercial PET system design. PDE and the SPTR (single photon timing resolution) are the sensor parameters that have most impact here.
- Energy Resolution in gamma ray spectroscopy applications, such as those of hazard and threat detection. The best energy resolution allows for precise isotope identification. Good energy resolution is primarily dependent on having a sensor with high PDE, however, at low energies, low DCR and crosstalk can also be important.
- Ranging applications, such as LIDAR and gesture recognition, require exceptional timing accuracy in order to achieve the best distance resolution. In these applications, the numbers of returned photons can be small, so low noise and SPTR are the primary drivers.

Points to consider:

- *Are there any applications specific performance metrics that are important, and what raw SiPM performance parameters impact it?*

Packaging

Sensor packaging, (the structure in which the silicon chip is housed and has its terminals connected to), will have an impact on how the sensor can be used, and in some cases it's performance. Some packaging characteristics are summarized in Table 1.

Form Factor

The most obvious feature when discussing a sensor package is its form factor (shape and size), and the I/O type (pins or pads).

Points to consider:

- *Does it need to be compact to fit in a miniaturized system.*
- *Should the edge deadspace be minimized to allow for formation of a close-packed array [3]?*
- *Is there a preference for pins, which are generally hand-soldered, or pads that can be reflow soldered?*

Optical Transmission

The clear material used to encapsulate the sensor can have an impact on the PDE, as shown in Fig.7. The glass of the SensL TSV package offers significant advantages over the MLP package for UV wavelengths. This extension to UV wavelengths is achieved without the use of silicone resin or thin films.

Points to consider:

- *Does the application involve wavelengths that could be absorbed by the sensor encapsulant material?*

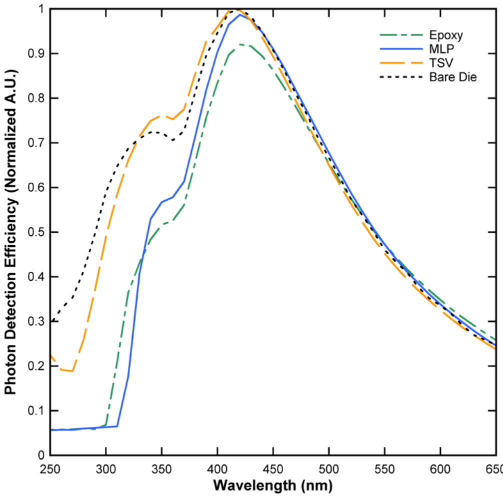


Figure 7, PDE curve of different packages.

Magnetics

In certain applications, the presence of magnetic material in the package can be an issue. One such application is PET-MRI, where magnetic fields of up to 3T are used. It has been shown that the SiPM sensors themselves are not affected by the magnetic field [5], but in some cases, ferrous metals in the sensor package can disrupt the magnetic field, causing slight distortions. However, SensL's TSV package has the benefit of being completely free of ferrous metals, e.g. nickel.

Points to consider:

- *Are there any magnetic fields in the application that may be affected by the ferrous materials in the package?*

Radiopurity

The material used to create a sensor package can contain trace radioactive elements, such as U^{238}, Ra^{226} and Th^{232} which will provide a small amount of background counts which, in certain low-light research applications, such as dark matter detection, this can be a problem. Recent work [4] has shown that SensL MLP packaged sensors have very high radiopurity, achieving the standards required for applications such as dark matter detection and double betaless decay experiments. It should be noted that the radiopurity is not an issue for the vast majority of applications.

Points to consider:

- *Will the presence of trace radioactive elements in the package impact the experiment?*

Delivery Format and MSL (Moisture Sensitivity Level)

There are practical considerations related to how the sensors are delivered and then stored until use. These matters are generally more important for high-volume usage of the sensors.

SensL MLP and TSV sensors are both delivered on tape and reel (3000 units each), that can be fit into standard reflow solder systems for automated usage. The MSL will determine how long the sensors can be out of their original sealed bag before they require and an additional bake procedure prior to soldering. The SensL MLP and TSV packages have a MSL rating of 3 which is the industry standard for integrated circuits.

It should be noted that poured epoxy packages have no MSL rating and can not be reflow soldered.

Points to consider:

- *Does the contract manufacturer have specific storage requirements prior to assembly that may impact the sensor package choice?*

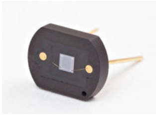
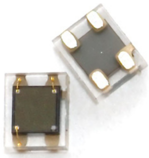
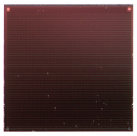
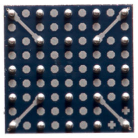
Parameter	Poured Epoxy 	Clear MLP 	TSV  
Array Fill Factor	Good	Good	Best
Optical Transmission	Poor	Good	Best
Output Impedance	Poor	Good	Best (subject of future work)
Operating Temperature	0°C - 40°C	-40°C - 85°C	-40°C - 95°C
Reliability	Manual processing: reduced reliability	Good	Best (subject of future work)
Service Life	Yellowing of potted epoxy is not well controlled	Good	Best (subject of future work)
Uniformity and Reproducibility	Poor	Good	Good (subject of future work)
Cost	Not recommended for use in volume. Suitable for research and prototype testing.	Low	Low, but higher than MLP per unit area when used in high density arrays using minimal spacing design rules

Table 1, Characteristics of different SiPM package types.

Manufacturability, Uniformity and Reliability

Manufacture and Testing

The sensor manufacture will have an impact on the device quality and reliability, and the testing will determine the likelihood of out-of-spec part reaching a customer.

SensL uses Tier 1 wafer production and packaging houses, which provide 100% testing of the sensors.

Wafer processing is carried out in a CMOS foundry using a standard CMOS, 8-inch process. Process control monitor (PCM) testing is carried out to ensure quality, with 1,000,000 product tests carried out per batch. Any failing sensors do not make it to packaging.

The packaging process is designed to be high volume, and also incorporates 100% end-of-line product test that includes a dark current measurement and optical inspection. Any sensors failing these tests are removed and destroyed. All qualifying sensors are shipped to SensL on tape and reel.

Points to consider:

- *Has the manufacture been carried out in a way that ensures a high-quality product?*
- *Does the manufacturing process meet the volume and uniformity requirements of the application needs when the product is in full production?*

Uniformity of Breakdown Voltage and Optical Current

The result of the high quality manufacture and 100% testing is a highly uniform product, both in terms of the spread in the breakdown voltage and the optical current under a given illumination. The plots in Fig. 8 and Fig. 9 show the results of over 100k sensors. The breakdown voltage shows uniformity of ±221mV, with optical uniformity of <±9%.

Points to consider:

- *If having a supply of sensors with similar breakdown voltages and other characteristics is necessary?*

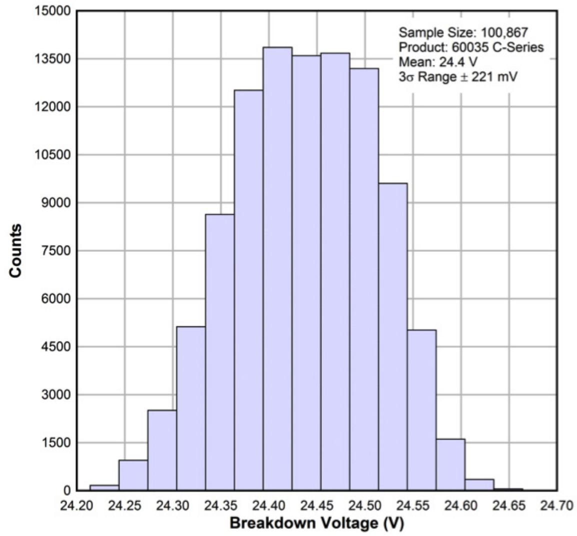


Figure 8, Vbr uniformity over 100k+ sensors.

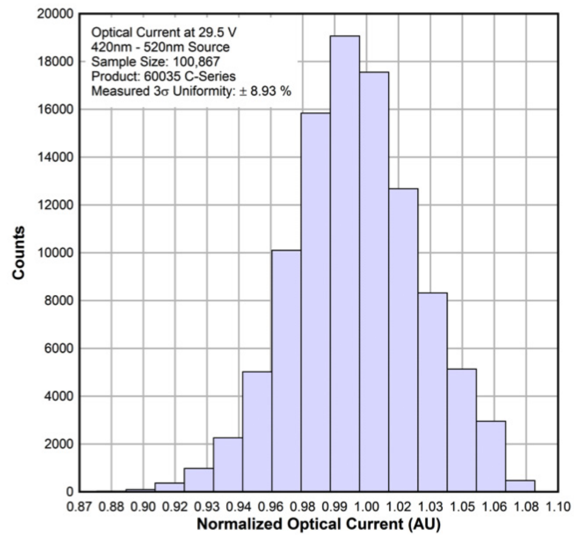


Figure 9, Optical current uniformity over 100k+ sensors.

Reliability

Reliability testing of the sensor product should be required by any user that intends to use incorporate the device into a system. The problem is that no standard reliability assessment program exists for SiPM or other optoelectronic sensors. SensL has decided to follow industry standard test flows designed for integrated circuits. The test flows are described in more detail in [6] and are performed on multiple wafer production and package assembly batches for each product type.

Points to consider:

- *Have the sensors undergone extensive reliability testing to integrated circuit standards like JEDEC?*

Support and Documentation

The optimum sensor will be selected based upon all of the factors described in this document: performance, packaging, reliability and uniformity. However, a final consideration is that of product support. SensL have a strong commitment to supporting the users of our products. This is achieved in a variety of ways: contact with a support team that have direct access to the product engineers, a variety of technical documentation from datasheets and user manuals to tech notes, and an online academic research library that collates all of the published journal papers that use our sensors.

Points to consider:

- *Is the product well supported in the event of a problem?*
- *If I have a question, do I have a support channel?*
- *I am a novice/expert. Is there documentation at my level?*

References

[1] SensL Introduction to SiPM Tech Note

[2] Catalanotti et al., Performance of a SensL-30035-16P Silicon Photomultiplier array at liquid argon temperature

[3] SensL Tech Note, SMT Array Design

[4] S. Cebrián et al., Radiopurity assessment of the tracking readout for the NEXT double beta decay experiment, Submitted to JINST, 2015

[5] J. J. Vaquero et al., Nuc. Inst. & Met. in Phy. Res. A, 702, pp. 83-87, 2013

[6] C. Jackson et al. “High-volume silicon photomultiplier production, performance, and reliability”, Opt. Eng. 53(8), 081909 (Aug 15, 2014).

Summary Table

Consideration	SensL C-Series MLP			
Peak PDE	41%			
Overvoltage	+5V			
DCR per mm^2	55 kHz			
Crosstalk	10%			
Afterpulsing	0.5%			
Trenches	No			
Fast output	Yes			
Bias voltage	<30V			
Is Vbr binning used?	No			
Temperature coefficient	21.5mV/°C			
Reflow solder compatible packages available?	Yes			
Packages compact enough to form arrays?	Yes			
Sensitivity <300nm?	No			
Ferrous-free?	No			
High radiopurity?	Yes			
MSL rating	3			
High volume production?	Yes			
Vbr uniformity	±250mV			
Optical current uniformity?	±10%			
Testing to standard such as JEDEC?	Yes			
Product support available?	Yes			
Well supported by documentation?	Yes			

www.sensl.com
sales@sensl.com
+353 21 240 7110 (International)
+1 650 641 3278 (North America)

All specifications are subject to change without notice