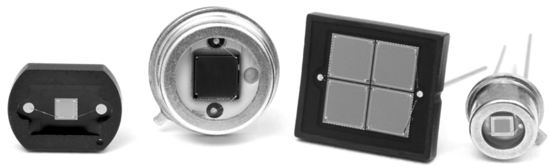
An Introduction to the Silicon Photomultiplier



The Silicon Photomultiplier (SPM) addresses the challenge of detecting, timing and quantifying low-light signals down to the single-photon level. Traditionally the province of the Photomultiplier Tube (PMT), Avalanche Photodiode (APD), or PIN photodiode with high-gain amplifier, the Silicon Photomultiplier now offers a highly attractive alternative that closely mimics the low light detection capabilities of the PMT while offering all the benefits of a solid-state device. The SPM offers low voltage operation, insensitivity to magnetic fields, mechanical robustness and excellent uniformity of response. Due to these traits, the SPM has rapidly gained a proven performance in the fields of medical imaging, hazard and threat detection, biophotonics, high energy physics and LiDAR.

This document provides an introduction to SPM, explaining how the device works and the primary performance parameters. It concludes with a brief comparison of the SPM with legacy low-light detectors (PMT, APD, PIN).

Photon Detection with Silicon Photomultipliers

When a photon travels through silicon, it can transfer its energy to a bound state (valence) electron, thereby transporting it into the conduction band, creating an electron-hole pair. The absorption length of a photon in silicon depends on its energy (or wavelength) and is shown in Figure 1. This illustrates that silicon is a good photo detector material in the spectral range form 350nm up to 800nm. Above 1000nm the absorption length becomes so large that a silicon based detector becomes too bulky, and below 350nm, too thin.

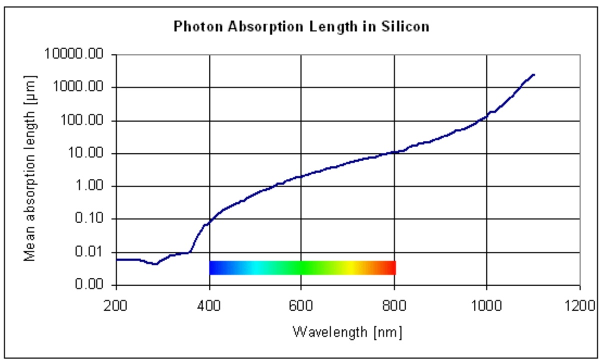


Figure 1 Photon Absorption Length in Silicon

Photon Absorption in Silicon

In an SPM photodiode this effect is exploited to detect incident light. Applying a reverse bias to a diode will counteract the diffusive force that draws negative and positive charge carriers (electrons and holes respectively) to the depletion region situated around the p-n junction. Under application of the reverse bias, an absorbed photon will result in a net current electrons through the n-type and holes through the p-type sides of the device.

The Geiger Mode in Silicon

When a sufficiently high electric field (> 5 x 10^5 V/cm) is generated within the depletion region of the silicon, a charge carrier created in this region will be accelerated to a point where it carries sufficient kinetic energy to create secondary charge pairs through a process called impact ionization. In this way, a single photoelectron can trigger an self-perpetuating ionization cascade that will spread throughout the silicon volume subjected to the field. The silicon will break down and become conductive, effectively amplifying the original photoelectron into a macroscopic current flow. This process is called Geiger discharge, in analogy to the ionization discharge observed in a Geiger-Müller tube. This process is illustrated in Figure 2.

A photodiode operated in Geiger mode employs this mechanism of breakdown to achieve a high gain. The *p-n* junction region is designed in such a way that it can sustain a reverse bias beyond its nominal breakdown voltage, creating the necessary high field gradients across the junction. Once a current is flowing it should then be stopped or 'quenched'. Using passive quenching

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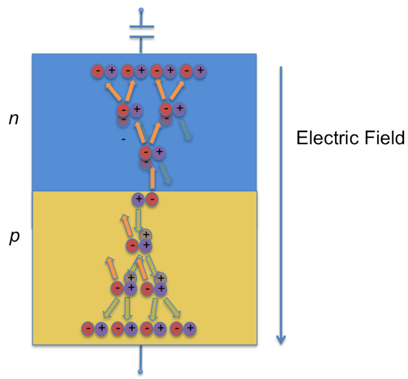

Figure 2 schematic of the Geiger mode as used in SPM operation

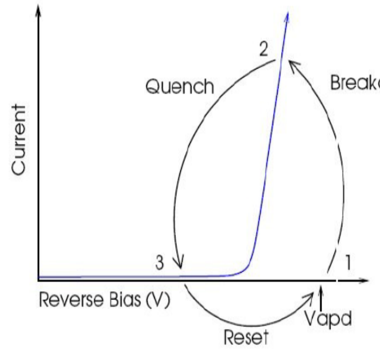

Figure 3a) Breakdown, quench and reset cycle of a photodiode working in the Geiger mode.

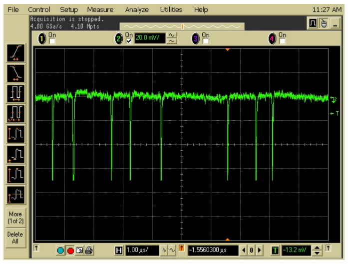

Figure 3b) "digital" pulse output from a photodiode working in the Geiger mode

(i.e. no active circuitry), this is achieved through the means of a series resistor R_Q which limits the current drawn by the diode during break down, and hence lowers the reverse voltage seen by the diode to a value below its breakdown voltage. This cycle of breakdown, avalanche, quench and subsequent reset of the bias to a value above the breakdown voltage is illustrated in Figure 3a.

In this way, a single photodiode device operated in Geiger-mode functions as a photon-triggered switch, in either an 'on' or 'off' state, and therefore cannot provide proportional information regarding the magnitude of an instantaneous photon flux. A 'binary' output such as that in Figure 3b would be the result. Regardless of the number of photons interacting within a diode at the same time, it will produce a signal of '1' photon.

The Silicon Photomultiplier

To overcome this lack of proportionality, the Silicon Photomultiplier integrates a dense array of small, electrically and optically isolated Geiger-mode photodiodes. Each photodiode element in the array is referred to as a "microcell". Typically numbering between 100 and 1000 per mm^2, each microcell has its own quenching resistor. The signals of all microcells are then summed to form the output of the SPM. A simplified electric circuit to illustrate the concept is shown in Figure 4. Each microcell detects photons identically and independently. The sum of the discharge currents from each of these individual binary detectors combines to form a quasi-anlog output, and is thus capable of giving information on the magnitude of an incident photon flux. The response to low-level light pulses is shown in Figure 5, and a spectrum of the same pulse is shown in Figure 6.

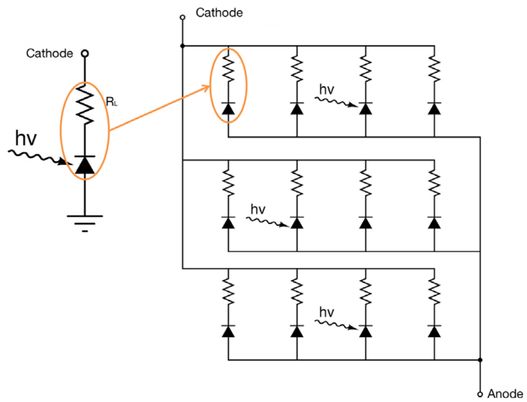

Figure 4 An array of microcells (photodiode plus quench resistor) with summed output

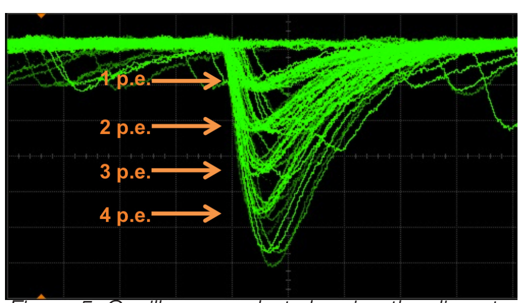

Figure 5 Oscilloscope shot showing the discrete nature of the SPM output when illuminated by brief pulses of low-level light.

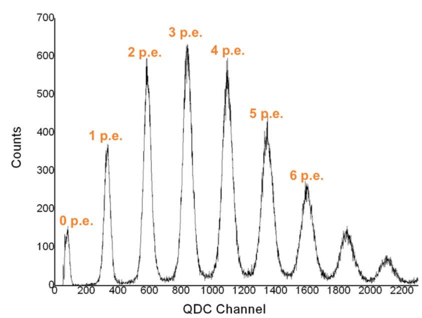

Figure 6 Photoelectron spectrum of the SPM, achieved using brief, low-level light pulses

Silicon Photomultiplier Performance Parameters

The users of SPM detectors will typically be interested in the following parameters: gain, PDE, noise, dynamic range, timing and temperature sensitivity. The following sections define these parameters, as well as giving some of the theory behind the parameter and also some typical values.

Over-Voltage

The breakdown voltage (V_{br}) is the bias point at which the electric field strength generated in the depletion region is sufficient to create a Geiger discharge. The point of breakdown is clearly seen on an I-V plot by the sudden increase in current, as in Figure 7. For optimized performance, SensL recommend a working bias voltage (V_{bias}) of 2V above the breakdown voltage for their devices. This 2V is referred to as the 'over-voltage' (ΔV) and is critical in defining the important performance parameters of the SPM.

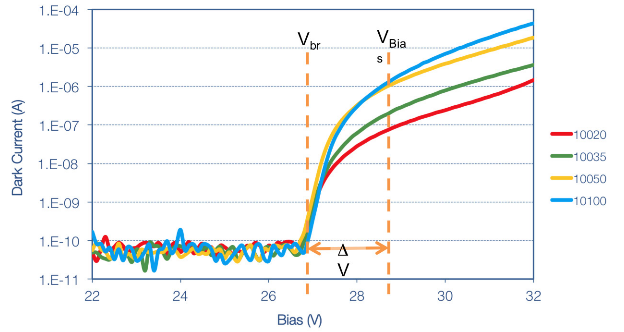

Figure 7 Dark current as a function of voltage for 1mm SPMs of various microcell size (20um, 35um, 50um, 100um).

Gain

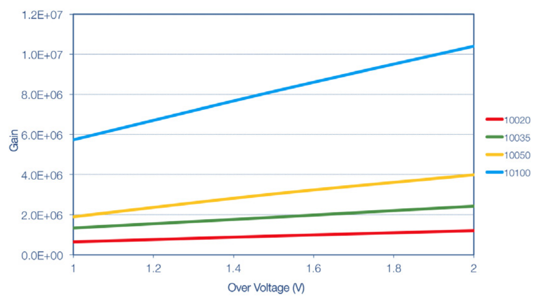

Figure 8 Gain as a function of over-voltage for different microcell size SPMs (20um, 35um, 50um, 100um)

Each microcell in an SPM is comprised of a Geiger-mode photodiode in series with an integrated quench resistor. Each microcell generates a highly uniform and quantized amount of charge every time the microcell undergoes a Geiger breakdown. The gain of a microcell (and hence the detector) is defined as the ratio of the output charge to the charge on an electron. The output charge can be calculated from the over-voltage and the microcell capacitance.

$$G = \frac{C \cdot \Delta V}{q}$$

Due to the unique way in which the SPM operates, each detected photon results in a highly quantized output pulse, as was shown in Figures 5. If such pulses are integrated by an ADC and a spectrum is formed, the peaks due to successive numbers of detected photons will be clearly visible. Such a spectrum is shown in Figure 6. The separation between each pair of adjacent peaks (in pC) is constant and corresponds to the charge from a single Geiger discharge. This can therefore be used to accurately calculate the gain, using the equation above. By repeating this procedure at different over-voltage values, a plot such as that in Figure 8 can be formed.

Photon Detection Efficiency

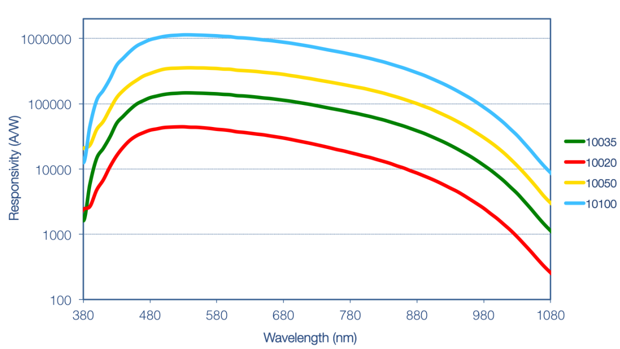

Figure 9 Responsivity as a function of wavelength for SPMs of different microcell size (20um, 35um, 50um, 100um)

The photon detection efficiency (PDE) of an SPM is the statistical probability that an incident photon will produce a Geiger pulse from one of the SPM microcells. It differs slightly from the quantum efficiency (QE) that is quoted for a PMT or APD, due to the microcell structure of the device. The PDE is a function of wavelength and bias and is given by

$$PDE(\lambda, V) = \eta(\lambda) \cdot \varepsilon(V) \cdot F$$

where $\eta(\lambda)$ is the quantum efficiency of silicon, $\varepsilon(V)$ is the avalanche initiation probability and F is the fill factor of the device. The avalanche initiation probability takes into account the fact that not all generated photoelectrons will go on to initiate an avalanche. The fill factor is the ratio of active to inactive area on the SPM, as a result of the gaps between the microcells.

The PDE is commonly calculated from the responsivity of the detector which is defined as the average photocurrent produced per unit optical power and is given by

$$R = \frac{I_p}{P_{op}}$$

where I_p is the measured photocurrent and P_{op} is the incident optical power at a particular wavelength over the detector area. The responsivity is typically expressed in units of Amps per Watt (A/W). A plot of the measured SPM responsivity is shown in Figure 9. The PDE can then be determined from the responsivity from the relation

$$PDE = \frac{R}{G} \cdot \frac{h \cdot c}{\lambda \cdot e}$$

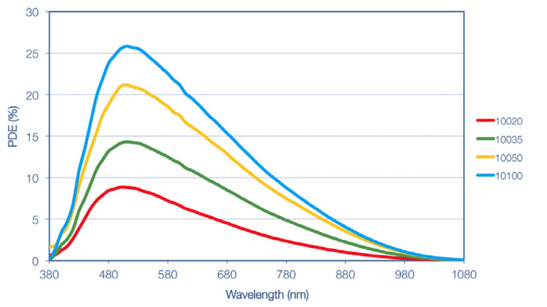

Figure 10 PDE as a function of wavelength for different microcell sizes (20um, 35um, 50um, 100um)

where *G* is the gain of the SPM microcells, *h* is the Planck constant, *c* is the speed of light, λ is the wavelength of the incident light and *e* is the electronic charge. In this method the gain of the SPM microcells should be accurately known and the SPM should be operated in its linear region. It should be noted that this method does not account for the contributions of cross-talk or after pulsing and therefore gives a slight over-estimation of the PDE. A plot of the PDE for SPMs with different microcell sizes is shown in Figure 10.

Noise

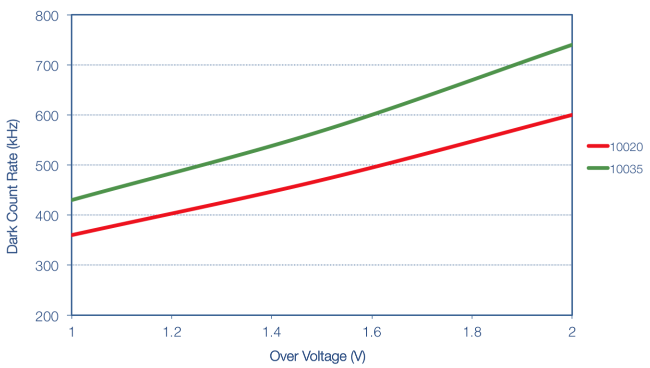

Figure 11 Dark count rate as a function of over-voltage for 1mm SPMs of two different microcell sizes (20um and 35um)

Noise is a general term that may cover all sources of unwanted signal in the system and is superimposed onto the measured signal. The noise ultimately imposes a limit on the smallest signal that can be measured.

The main source of noise in an SPM is the dark count rate (DCR), which is primarily due to thermally generated electrons that go on to create an avalanche in the high field region. The signals resulting from the breakdown of the cell, due to either photoelectrons or thermally generated electrons, are identical. Therefore, these electrons form a source of noise at the single photon level. If a threshold can be set above the single photon level, false triggers from the noise can be avoided, but the dark counts will always form a contribution to the measured signal.

Since this noise is comprised of a series of pulses, its magnitude is often quoted as a pulse rate, typically in kHz or MHz. For continuous or current integration measurements, it might be more convenient to consider the contribution as a ‘dark current’ in µA.

It should be noted that the magnitude of the DCR itself is not the noise contribution. If a given source of noise was always constant, then it could easily be subtracted from the signal. It is instead the fluctuations on the noise which degrade a measurement. The occurrence of the dark pulses is Poissonian in time and so the noise contribution can be taken as the square root of the DCR.

The DCR can be measured with a simple counting system, setting a threshold set at the 0.5p.e. level. The plots in Figure 11 show the noise as a function of over-voltage. In addition to the bias, the DCR is also a function of temperature, microcell size and overall detector area.

Optical Crosstalk

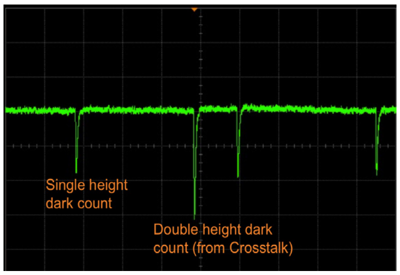

Figure 12 Oscilloscope shot showing dark counts

An additional component of SPM noise is that of optical cross-talk between microcells. When undergoing avalanche, carriers near the junction emit photons as they are accelerated by the high electric field. These photons tend to be in the near infrared region and can travel substantial distances through the device. Typically $2x10^5$ are emitted per electron crossing the junction. These photons can travel to neighboring microcells and may initiate a subsequent Geiger avalanche there. The crosstalk probability is the probability that an avalanching microcell will initiate an avalanche in a second microcell. The process happens instantaneously and as a consequence, single photons may generate signals equivalent to a 2, 3 or higher photoelectron event. This can be seen for the middle pulse shown in Figure 12 where the pulse height is equivalent to a 2-photon event. The optical crosstalk probability is a function of SPM over-voltage and the distance between neighboring microcells, and can be estimated by the ratio of the count rate at the second photoelectron level to the count rate at the single photoelectron level. Figure 13 shows the result of plotting the DCR as a function of threshold position, which produces a step-like curve. The flat regions of the curve correspond to the frequency of dark counts at the single, double, triple photoelectron level. Crucially, this plot shows that with a threshold level set to 5 p.e., the dark count trigger rate will be negligible.

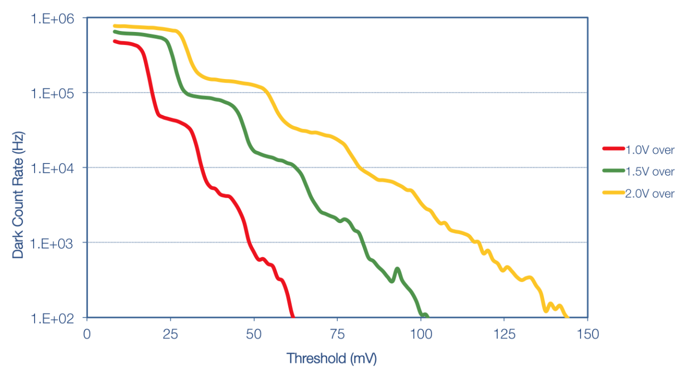

Figure 13 Dark count rate of a 1mm, 35um microcell SPM, as a function of counting threshold, for different over-voltages.

Dynamic Range and Linearity

The dynamic range of a detector can be defined as the optical signal level range over which the detector provides a useful output. For an SPM, this range extends from the lowest signal level detectable, to the optical signal level that results in all of the SPM microcells detecting photons simultaneously (within the microcell dead-time). At this point the output signal completely saturates since no more microcells are available to detect incoming photons, until some of the microcells have recovered back to their sensitive (charged) state.

The dynamic range of an SPM is therefore a function of the total number of microcells and the PDE of the device. Since the PDE of an SPM is a function of the SPM bias voltage and wavelength of the incident photons, the dynamic range of an SPM is also a function of these parameters. The number of microcells fired as a function of the number of incident photons can be approximated by the expression,

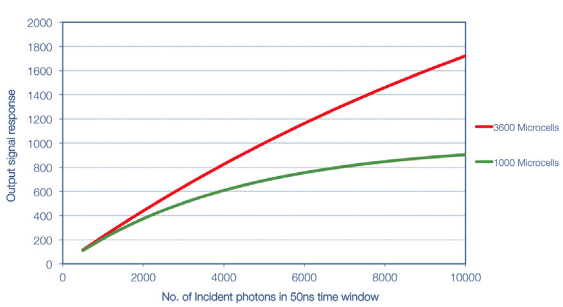

Figure 14 Linearity for SPMs with either 3600 or 1000 microcells

$$N_{fired}\left(M,V,\lambda\right)=M\left(1-\exp\left(-\frac{PDE(V,\lambda)\cdot N_{ph}}{M}\right)\right)$$

where N_{fired} is the number of microcell fired, N_{ph} is the number of incident photons, M is the number of SPM microcells and PDE is the SPM photon detection efficiency. The expression also assumes that the incoming photons are evenly distributed across the surface of the SPM. Above a certain signal level, and before saturation, the SPM response becomes sub-linear. This is because the output pulse of a single microcell is independent of the number of incident photons that initiated the output pulse. As the number of incident photons per microcell per second increases, the probability increases that two or more photons will interact in the same microcell at the same time. The SPM output begins to saturate when the number of detected photons begins to approach the number of microcells (*M*).

$$N_{ph} \cdot PDE \rightarrow M$$

In summary, at low optical signal levels the SPM photocurrent is proportional to the incident optical power, giving a linear detector response. As the optical power increases the SPM photocurrent begins to deviate from linearity due to the limited number of microcells, and finally saturates. Figure 14 shows a simulation of the response for a 3600 and 1000 microcell SPM when uniformly illuminated with 50ns duration light pulses of varying brightness.

Pulse Shape

A typical single photoelectron pulse for a 3mm, 35µm microcell SPM is shown in Figure 15. The rise time of the SPM is dependent upon the total area of device, and specifically, the capacitance resulting from the tracks that connect all of the microcells. The rise time varies from ~1ns for a 1mm device to ~10ns for a 6mm device.

The recovery time, or decay time of the pulse, is irrespective of the detector size, but is instead determined by the microcell reset period, given by

$$\tau_{reset} = R_Q \cdot C$$

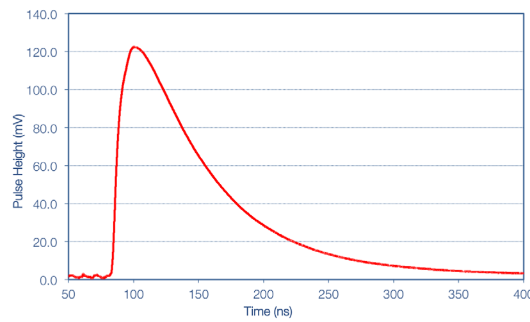

Figure 15 Typical pulse from a 3mm, 35um microcell SPM

where C is the effective capacitance of the microcell and R_Q 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, with a 100µm SPM having a signigicantly longer reset time than a 20µm SPM.

Temperature Dependency

The primary effects of temperature on the SPM are a change in the breakdown voltage of the diode and in the dark count rate.

The breakdown voltage changes as a function of temperature, as shown in Figure 16, and unless compensated for, this will result in a change in the effective over-voltage. Since the over-voltage affects many of the SPM's characteristics, it follows that for stable operation the detector should have its temperature regulated. Since the SPMs thermal mass is very small (the detector is only 500µm thick) it is a simple matter to cool or regulate the temperature with a Peltier device. If this is not possible, the bias voltage should be adjusted in order to maintain a constant over-voltage with respect to the altered breakdown voltage.

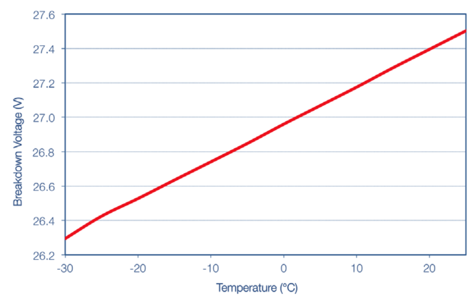

Figure 16 Breakdown voltage as a function of temperature

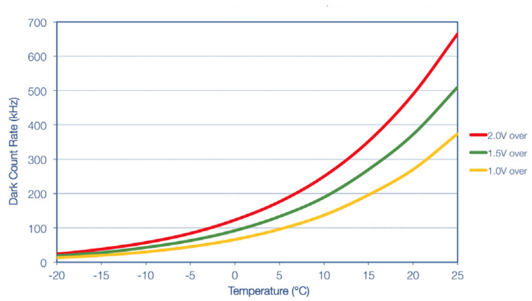

Figure 17 Dark count rate as a function of temperature and over-voltage, for a 1mm, 35um microcell SPM

If a constant over-voltage is maintained, many parameters, such as gain, PDE and timing, will remain the same as at room temperature. However, regardless of constant over-voltage, the DCR will be altered by a change in temperature, as shown in Figure 17.

An increase in temperature will increase dark rate, and the converse is also true: for every 10°C reduction in device temperature, there is a 50% decrease in the dark count rate. Thus, an SPM detector that is cooled with thermoelectric (Peltier) coolers, such as the MiniSL, opens up a range of new, low-light level applications that require very low noise detectors.

Comparison with Other Detector Technologies


Figure 18 A typical PMT

Low-light photon detectors constitute the enabling technology for a diverse and rapidly growing range of applications: Nuclear medical imaging, radiation detection, fluorescence analysis, spectroscopy, quality control or meteorology all require detectors that serve to quantify and/or time stamp light signals with anywhere from 1 to ~1000 photons per event. The ideal detector provides a response proportional to the incident photon flux and incorporates an internal gain mechanism, yielding signals of sufficient magnitude to be easily processed. It should offer sub-nanosecond response times and broad spectral sensitivity, be robust, easy to operate and only generate manageable amounts of noise or dark count rates.

To date the Photomultiplier tube (PMT), a well established and widely available vacuum tube device, has been the detector of choice for such applications. The semi-transparent photocathode deposited inside the entrance window inherently limits the PDE they can achieve, with typical PMTs having about 20% at 420nm. A gain of 1-10e^6 is achieved at the cost of a high bias voltage of 1-2kV, which requires the use of costly high-voltage power supplies. PMTs are generally stable and low noise but are bulky and delicate due to their vacuum tube structure. They can also be adversely affected by magnetic fields which will limit their suitability for some applications.

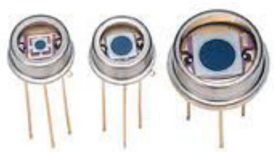
Figure 19 APD detectors

Solid state devices have many practical advantages over the PMT, and this led to the PIN diode being used in applications where PMTs were too bulky or delicate, or where high voltages were not possible. However, PIN diodes are severely limited by their complete lack of internal gain. The Avalanche Photodiode (APD) is a more recent technology, an extension of the simple PIN diode. Here the reverse bias is raised to a point where impact ionization allows for some internal multiplication, but is below the breakdown bias where the Geiger mode would take over. In this way, a gain of around a 100 is achieved for a bias of 100-200V. With special manufacture, it is possible for gains of several thousand to be reached using an HV bias of >1500V. Whilst the gain may be lower than that of a PMT, APDs have the advantage of a PDE which can be >65% and also a compact size, ruggedness and insensitivity to magnetic fields. Their main drawbacks are their excess noise (associated with the stochastic APD multiplication process) and in an important trade-off: The capacitance increases with increasing device area and decreasing thickness, whereas the transit times of the charge carriers increase with increasing thickness, implying a performance trade-off between noise and timing. They are limited in size to ~10mm diameter.

The SPM has high gain and moderate PDE (~20%), very similar to the PMT, but has the physical benefits of compactness, ruggedness and magnetic insensitivity in common with the PIN and APD. In addition, the SPM achieves its high gain (1e^6) with very low bias voltages (~30V) and the noise is almost entirely at the single photon level. Because of the high degree of uniformity between the microcells the SPM is capable of discriminating the precise number of photoelectrons detected as distinct, discrete levels at the output node. The ability to measure a well resolved photoelectron spectrum is a feature of the SPM which is generally not possible with PMTs due to the variability in the gain, or excess noise. Despite the fact that the SPM is sensitive to single photons, its dark count rate of ~100kHz/mm^2 at room temperature renders it unsuitable for use for applications at very low light levels. However, with the application of cooling (such as with the SensL MiniSL) a two order of magnitude reduction in the dark count rate is readily achievable. Further technical details on SensL's full range of SPMs can be found at

www.sensl.com/documentation.

	PIN	APD	PMT	SPM
Gain	1	10^2	10^6	10^6
Operational Bias	Low	High	High	Low**
Temp. Sensitivity	Low	High	Low	Low
Mechanical Robustness	High	Medium	Low	High
Ambient light exposure?	OK	OK	NO	OK
Spectral range	Red	Red	Blue/UV	Green
Readout / Electronics	Complex	Complex	Simple	Simple
Form factor	Compact	Compact	Bulky	Compact
Large area available?	No	No	Yes	Yes
Sensitive to magnetic fields?	Yes*	Yes*	Yes	No
Noise	Low	Medium	Low	High
Rise time	Medium	Slow	Fast	Fast

** Due to the requirement for the external electronics to be located close to the detector*
*** SPM from SensL, having an operational bias of 30V, meet the requirements of the Extra Low Voltage directive*

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