Chapter 2

Feasibility study of various detectors for TL/OSL system

2.1 Introduction

The major requirement of the light detector in a TL/OSL system is the ability to detect light at the photon counting level. This is required as the emitted luminescence can be of a very low level especially when used for geological and archeological applications. A high Signal to Noise Ratio (SNR) is required to achieve this. For high SNR the dark counts and other noises should be at a minimum level. At the same time there are also some samples which emit quite bright luminescence. Thus it is required that the light detector does not saturate at higher luminescence. This implies that the light detector should have a large dynamic range by which it can detect the faintest light and quite bright lights.

The sample will emit luminescence in all the directions. Since 180˚ area of the sample will be in contact with the sample plate and thus blocked from the detector, the luminescence emitted in this area will be lost. The Field of View (FOV) of the light detector should be large enough to be able to collect the luminescence form the remaining area. The other important qualities required in the photo-detector are high quantum efficiency, high internal gain, high photon detection efficiency, high sensitivity in UV-Visible region of the spectrum, low dark current, low overall noise, low to moderate dead time (high speed, high-moderate count rate), low rise-fall time and low after pulsing probability.

Traditionally Photo-Multiplier Tube (PMT) was the only light detector used for TL/OSL application due to its ability to detect very low level of light. However its many drawbacks like sensitivity to magnetic fields, bulky and fragile, requirements of high voltages of nearly 1000 volts or more and more power consumption makes its replacement preferable. In many of the applications the replacement of PMTs with solid state detectors having ruggedness, compactness, insensitivity to magnetic fields, low operating voltages, low power consumption and large production capabilities are explored.

Efforts have also been made to use an image sensor in some applications. Light detectors like PMT measure the emitted luminescence by integrating it while an image sensor gives the spatial distribution of luminescence. The spatial distribution of luminescence from the sample allows the mapping of luminescence from slices of materials. The luminescence behaviour of many individual grains of the sample can also be measured. In the following review both types of light detectors—the ones that measures integrated luminescence and the ones that measures the spatial distribution of the luminescence are discussed.

2.2 A short review of various light detectors

Since the replacement of PMT is sought, the following review begins with PMT.

2.2.1 Photo Multiplier Tube (PMT)

The working principle of PMT is different from other semiconductor detectors. It is a vacuum tube consisting of a photocathode on one side. Inside the tube there is a series of dynodes arranged in a specific pattern and connected with gradually increasing bias voltage. The last dynode is called the anode which is connected to external electronics circuit.

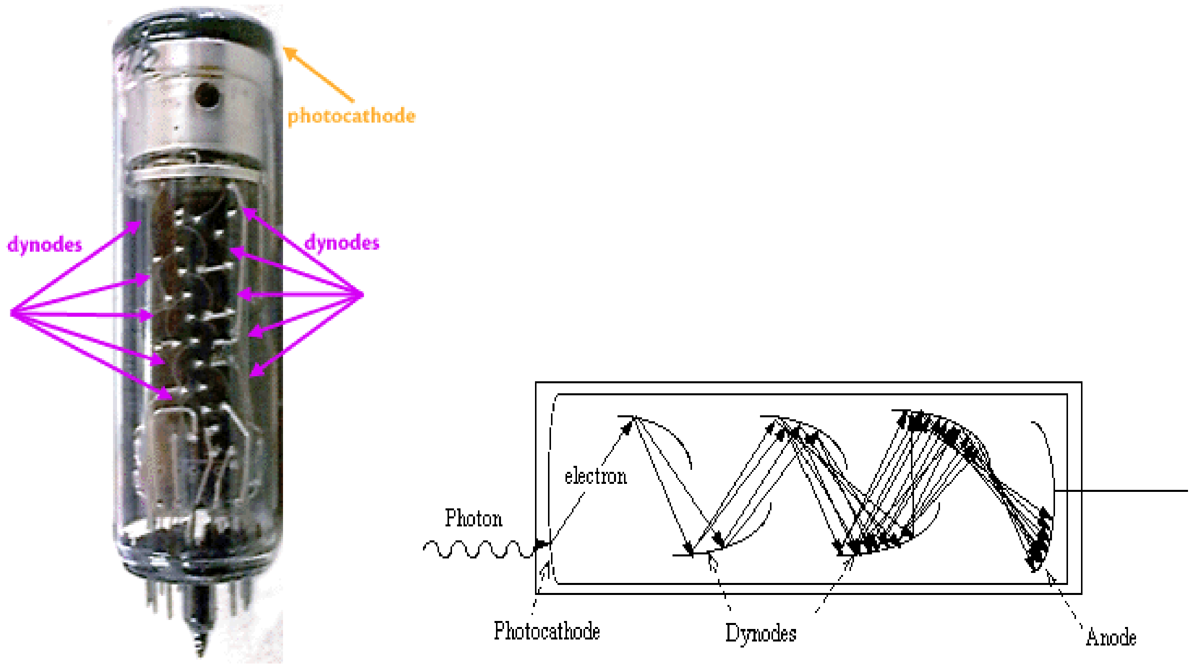

Figure 1. A basic PMT

(Image courtesy http://quarknet.fnal.gov/projects/pmt/student/dynodes.shtml, http://www.frankswebspace.org.uk/ScienceAndMaths/physics/physicsGCE/D1-5.htm)

When light photon strikes the photocathode of PMT, electrons are generated as a result of photoelectric effect. These electrons are accelerated to first dynode with high velocity in the presence of high electric filed. Owing to high kinetic energy, when these electron strikes the first dynode they generates more secondary electrons. These electrons are accelerated to the next dynode and the same process is repeated till the last dynode. Thus number of electrons gets multiplied. As a result, large gain of the order of 10^6 is achieved.

PMTs have been used for low level light detection since long due to its high gain and good overall Photon Detection Efficiency (PDE). It is also capable of single photon counting. The drawback of PMT is its low Quantum Efficiency (QE) of around 30%. In addition it has larger volume, more weight, complex mechanism, susceptibility to magnetic field and high voltage requirements with a divider circuit.

However, with advancement in technology, miniature PMTs are available in the market. This type of PMT has also low weight and low volume, but still needs high voltage and is susceptible to magnetic field.

2.2.2 P-N photodiode

P-N photodiode is basically a general purpose semiconductor P-N junction diode except that it has an optical window for penetration of light into the junction area. Light photons having sufficient energy (greater than 1.2 eV in the case of silicon) will interact with atoms in the junction area and generates electron-hole pair which forms electric current in the circuit.

P-N junction type photodiode is operated in two modes: photovoltaic (PV) and photo conductive (PC). PV mode has the benefit of low noise and good linearity while PC mode gives large dynamic range and bandwidth for fast changing light signal due to low junction capacitance. PC operation requires reverse bias voltage while the PV doesn't require it.

Due to its low noise PV is useful where light level is low. It also gives high degree of linearity. PC mode is useful in application where more dynamic range and high speed i.e. more bandwidth due to low capacitance is required. Photodiode has higher QE of around 80 to 90%, but due to low internal gain compared to average noise level of succeeding read-out electronics, its overall responsivity is very low.

2.2.3 P-I-N photodiode

It is similar to P-N photodiode except that an additional layer of intrinsic semiconductor between P and N layer is present. It is used in reverse biased mode (PC mode). This type of structure increases the size of the depletion region where photons interact resulting in higher overall collection efficiency and hence the sensitivity of the detector is enhanced. Additionally the low capacitance is conducive for high speed operation. Similar to P-N diode the P-I-N diode also lacks high overall responsivity due to reasons applicable for P-N photo diode.

2.2.4 Photo Transistor

It is a basic bipolar transistor whose base-collector junction can be exposed to light signal. It has a larger base and collector area compared to ordinary transistor. This is to optimize it for photo applications. Interaction of photon with reversed biased base-collector junction generates electron-hole pairs. The generated electrons-holes are swept by the electric field and cause base current. The base current is amplified by the transistor gain β, which could be as high as 50-100. Therefore, responsivity of phototransistor is higher than photodiode. The frequency response of the transistor is poor due to large capacitance of base-collector junction due to their large area. It has limited internal gain and consequently low overall SNR.

2.2.5 Avalanche Photo Diode (APD)

APD is a lightly doped semiconductor P-N diode operated in reverse bias voltage near the breakdown region. Due to its special doping pattern, the depletion region is long. Higher reverse voltage causes impact ionization process which leads to avalanche break down. As a result, the number of charge carriers for each photon interaction increases largely and overall gain of 100-500 can be achieved.

Even though APD has sizable amount of gain compared to previously discussed detectors, it is still not suitable for extremely low level light detection due to low SNR and variation in gain as a function of temperature and bias voltage.

2.2.6 Single Photon Avalanche Diode (SPAD)

A high electric field greater than 5 x 10^5 V/cm in the depletion region will cause the charge carrier created by the incident photons in this region to accelerate such that it carries the required kinetic energy to create secondary charge pairs by impact ionization. Thus a single photoelectron can cause an ionization cascade due to which the silicon will break down and become conductive causing a huge current flow. This process is called Geiger discharge. This high flowing current is then stopped by a quenching resistor which is a resistor connected in series with the diode, before it could damage the diode. This causes the lowering of the reverse voltage seen by the diode to a value below its breakdown voltage. Then it is ready to detect the next photon. Such a diode is called Single Photon Avalanche Diode (SPAD).

SPAD is a variant of APD with basic difference in doping profile and operating voltage. SPAD is operated with bias supply 15-20% more than the breakdown voltage. This extra electric field helps in achieving the gain of about 10^6 because of heavy impact ionization. The SPAD works in binary fashion i.e. ON or OFF. Interaction of photon/s gives a fixed magnitude output. In the applications where intensity of light is to be measured in a classical way (Analogue mode), SPAD is not suitable because input–output proportionality is lost. But for extreme low light detection, SPAD is the most preferable detector in single photon counting (digital mode) operation due to high SNR. The major disadvantage of SPAD is that its exposure area is very small. It is of the order of ~ 0.2 mm^2 or 0.5 mm diameter.

2.2.7 Hybrid Photo Detector (HPD)

It is a hybrid product of APD and PMT. The idea is to get more numbers of charge carriers per single photon using principle of electron-bombardment and avalanche breakdown together.

HPD consists of a vacuum tube having photocathode on one side similar to PMT. Inside the tube, there are focusing dynodes to focus the electrons generated by photo electric effect, directly to APD. For this the high voltage in the order of 8-10 kV is used. Due to high electric field, electrons get high kinetic energy and strike the substrate of APD, which generates lots of electron-hole pairs. These electrons then drift towards P-N junction and avalanche process starts, which again generates lots of charge carriers. Here electron bombardment gain of the order of 1600 and avalanche gain of the order of 100-500 can be achieved. So the total gain of the order of 10^5 can be achieved. It is also capable of doing single photon counting.

HPD has slightly lower gain than PMT but excellent pulse height, time resolution and response time. However, more weight, large volume, high voltage requirement and susceptibility to magnetic field are its drawbacks.

2.2.8 Charge Coupled Device (CCD)

A CCD camera consists of the CCD chip and associated electronics. The CCD chip is an image sensor whose active area is made up of a number of pixels. It is basically a Metal Oxide Semiconductor (MOS) capacitor When an image is incident on the detector area, the incoming photons get converted into charges by the pixel which is then sent to a shift register form where it is digitalized using an analogue to digital converter. The digitalized value will depend on the intensity of the light. It is a serial device where each pixel is read one at a time. Each pixel has limited charge holding capacity. If this is exceeded then the charges would spill over to the adjacent pixels.

The CCD image sensors are generally implemented in full-frame, frame-transfer, and interline architectures. In full-frame architecture a mechanical shutter is used to prevent the smearing of the image as the CCD is clocked. In frame-transfer architecture half of the detector area is covered by a mask. The image is speedily transferred to this opaque region from the active region with a small amount of smear. The image is read out from this area as a new image is formed in the detector region. The same principle is employed for the interline architecture. Here instead of masking half of the detector area, every alternate column of the detector area is masked for the purpose of storing image. This increases the speed but at the cost of lower fill factor. The fill factor is improved in later designs by using micro-lenses which re-directs the light falling on the inactive region to the active region.

2.2.9 Complementary Metal Oxide Semiconductor (CMOS) Sensors

CMOS image sensors integrate a number of processing and control functions directly onto the sensor integrated circuit. These features include timing logic, exposure control, analogue-to-digital conversion, shuttering, white balance, gain adjustment and initial image processing algorithms. The advanced CMOS designs are built using Active Pixel Sensor (APS) technology. In APS technology both the photodiode and readout amplifier are incorporated into each pixel. This enables the charge accumulated by the photodiode to be converted into an amplified voltage inside the pixel. It is then transferred in sequential rows and columns to the analogue signal processing portion of the chip.

Each pixel consists of a photodiode and a triad of transistors that converts accumulated electron charge to a measurable voltage, resets the photodiode, and transfers the voltage to a vertical column bus. The busses carry the timing signals to the photodiodes and return readout information back to the analogue decoding and processing circuitry housed away from the photodiode array. Due to this design individual pixels could be read which is not possible with the CCD sensors.

The presence of the supporting electronics in the pixel itself reduces the photon sensitive area of the pixel since the supporting electronics is like a dead area as far as photon sensitivity is concerned. This causes the fill factor of the sensor to be comparatively very small; decreases the sensitivity and a corresponding reduction in SNR, due to which the dynamic range is reduced.

The working of the CMOS sensor is as follows: a reset transistor drains the charge from the photosensitive region and reverse biases the photodiode. Next, the integration period begins, and light interacting with the photodiode region of the pixel produces electrons, which are stored in the silicon potential well lying beneath the surface. At the end of the integration period, the row-select transistor is switched on, connecting the amplifier transistor in the selected pixel to its load to form a source follower. This converts the electron charge in the photodiode into a voltage. The resulting voltage appears on the column bus and can be detected by the sense amplifier. This cycle is then repeated to read out every row in the sensor in order to produce an image. CMOS sensors are manufactured in the same plant which manufactures other chips unlike the CCDs which requires a specialised plant.

2.2.10 Intensified CCD (ICCD)

ICCD is formed by adding an image intensifier in front of a CCD. Image intensifiers could provide image amplification up to a thousand times. They are made by evacuated tube comprising of a photocathode, a Micro-Channel Plate (MCP) and a phosphor screen. An electron is generated when a photon is incident on the photocathode. This generated electron is attracted towards the MCP due to an electric field where it generates more electrons when it strikes the plates of the MCP. The output of this MCP is incident on the CCD. The image intensifier is very fast, but the low speed of the CCD makes ICCD a slow device for photon detection. It also suffers from low spatial resolution and high background noise.

2.2.11 Electron bombardment CCD (EBCCD)

EBCCD comprises of a back-illumination CCD sealed in a photoelectric vacuum tube. When photons strike the photocathode, it emits electrons which are detected by the internal CCD. The gain in the EBCCD is due to the electron bombardment multiplication which occurs within the CCD when accelerated electrons lose energy and generate much charge within the CCD. It has the drawback of not having a high dynamic range, high spurious noise due to secondary electrons and it is a delicate instrument which is very susceptible to damage.

2.3 Review of SiPM, dSiPM and EMCCD and its comparison with PMT

Silicon Photomultiplier (SiPM) are being developed for low level light detection since the last few decades by some companies. It is based on a technology originally invented in Russia [1]. A digitalised version named digital Silicon Photomultiplier (dSiPM) with improved performance has been developed by Philips. Electron Multiplying CCD (EMCCD) has also been recently introduced in the market by Andor Technology Ltd (Ireland). These recent technologies are quite promising as an alternative for PMT in TL/OSL applications.

2.3.1 Silicon Photo Multiplier (SiPM)

The Silicon PhotoMultiplier (SiPM) consists of a high-density (up to ~10^3 /mm^2) matrix of diodes connected in parallel on a common Si substrate. Figure 2 shows the equivalent circuit of a SiPM. Each diode is an SPAD operated in a limited Geiger-Müller regime connected in series with a quenching resistance, in order to achieve gain at level of 10^5 - 10^6. As a consequence, these detectors are sensitive to single photons (even at room temperature), feature a dynamic range well above 100 photons/burst and have a reasonable PDE.

These SPADs have extremely high internal amplification that allows single photon sensitivity at room temperature. The output of each micro-cell is an identical, fixed charge or current pulse for each single photon detected. Thus, SiPM has a single output which is a sum of all SPADs' output. This type of arrangement increases the collection area of the detector which is a major drawback of a single SPAD. SiPM can be operated in both analogue and digital mode. Since the outputs of all SPADs in SiPM are tied together in a single node and therefore have a moderate collection area, SiPM can detect photons which arrive simultaneously. In this case the output is proportional to number of triggered SPADs. This particular mode of operation is useful in pulse height analysis. In digital mode of operation, if incoming photon flux is low compared to SiPM's dead time, photon counting operation can be performed with high accuracy.

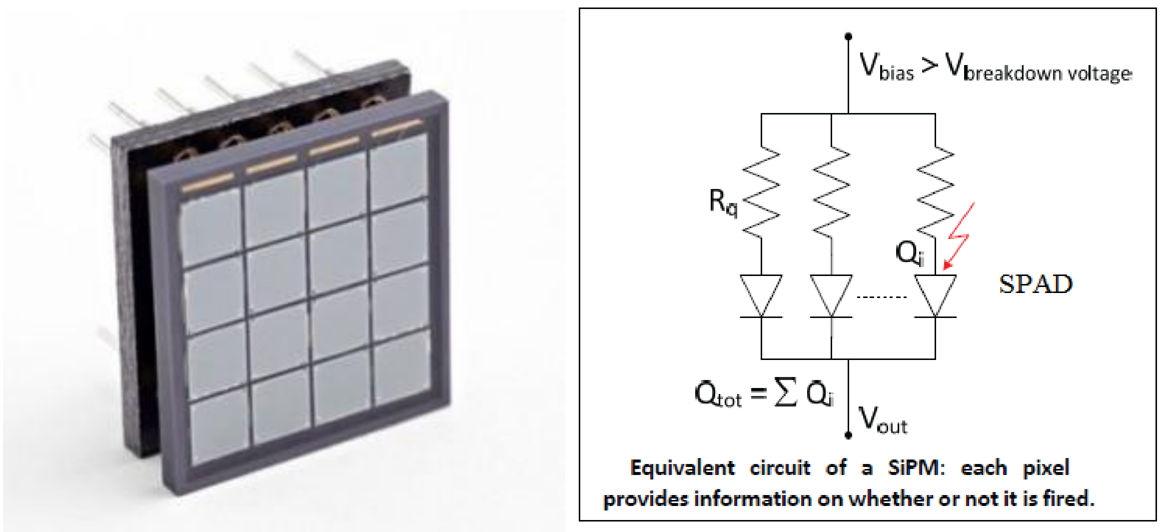

Figure 2. Silicon Photomultiplier with its equivalent circuit

(Image courtesy: http://sensl.com/products/silicon-photomultipliers/)

The uniform high gain across the array allows the single photoelectron peaks to be clearly resolved permitting both single photon detection and accurate calibration of the photon number. The main advantages of SiPMs are: standardized output pulses for single photoelectrons, large intrinsic gain 10^5–10^6, no need for sophisticated preamplifiers, fast rise–time pulses, very low operating voltages of 20–100 V, very low sensitivity to pickup noise and EMI, no damage when exposed to large photon fluxes, compactness, low power consumption and many other advantages. Along with these advantages they also suffer from the disadvantage of having dead area between the SPADs. Photons falling on this dead area are not detected. So unlike the PMT 100% of their detection area is not active.

SiPMs have been compared with PMT in order to replace them in various applications. For the Hamamatsu SiPM, the photon detection efficiency for green light was found to be twice or more than that of the PMT [2]. In the comparison between SiPM and PMT, for the use of SiPM as a possible front-end detector system for the electromagnetic barrel calorimeter of the GlueX Project at Jefferson Laboratory, USA, it was found that SiPM performs better when the light flux is more [3]. For very low light flux PMT is still the better option. Overall the studies present an encouraging picture of SiPM.

SiPM is known by different names like SPM: Silicon Photomultiplier (SensL), MPPC: Multi-Pixel Photon Counter (Hamamatsu), SSPM: Solid-State Silicon Photomultipliers (Voxtel, RMD, USA), MAPD: Micro-pixel Avalanche PhotoDiode (Zecotek).

In order to be of use in TL/OSL applications the SiPM detector area should be equal to or greater than the sample area. This will ensure efficient optical coupling. The sample area is generally approximately 10 mm x 10 mm, so the detector area should be around 12 mm x 12 mm. Most of the SiPM are of smaller area. This is due to the fact that as the detector area increases the dark noise also increases. In order to get larger area, an array is formed of SiPM. Hamamatsu has SiPM in the form of 1 x 4 array, 2 x 2 array and 4 x4 array with an active area of 4 x1, 6 x 6, 12 x 12 mm respectively. Thus, only the 4 x 4 array SiPM will be useful for TL/OSL applications.

S11064-025P and S11064-050P are the two SiPM available from Hamamatsu with the detection area of 12 mm x 12 mm. The difference between them is in their pixel sizes, fill factor, dynamic range, PDE and dark counts. The fill factor of the detector is equal to the ratio of the effective pixel size and the total pixel size. In other words it is the ratio of the sensitive area in the detector and the total detector area. Dynamic range is a measure of the brightest and faintest light that can be detected. For image detectors it is the brightest and the faintest light that can be detected in the same image. PDE is the ratio of number of photons detected and the total number of photons incident on the detector. All these factors are interrelated as follows: with the decrease in pixel size there are more pixels for the same detection area, causing an increase in the dynamic range and less dark counts but at the expense of reduced fill factor which decreases the PDE. With the increase in pixel size the number of pixel for the same detection area decreases, causing a reduction in dynamic range and increase in fill factor which increases the PDE. This relationship is demonstrated in table 1 [4].

	Pixel size (µm)	Fill factor	Dynamic range(= number of pixel)	PDE	Total dark counts
Hamamatsu 11064-025P	25 x 25	30.8%	230400	22 % at 440 nm	64000 to 128000 kcps
Hamamatsu 11064-050P	50 x 50	61.5%	57600	46 % at 440 nm	96000 to 160000 kcps

Table 1. Table showing the relationship between the different parameters of SiPM

11064-025P has 25 µm x 25 µm pixel size and S11064-050P has 50 µm x 50 µm pixel size. Due to this, S11064-25P has double the number of pixels than S11064-050P. Thus it has more dynamic range because the dynamic range is equal to the number of pixels. However, it has only 30.8 % fill factor as against 61.5% fill factor of S11064-50P. This is because the fill factor and pixel size are inversely proportional. Due to the low fill factor the PDE of S11064-025P is much lower than that of S11064-050P. The total dark count, obtained by adding the dark counts from each of SiPM from the 4 x 4 array, of S11064-025P is around 16000000 counts per second (cps) to 32000000 cps. Similarly for S11064-050P it is around 64000000 cps to 160000000 cps. This is not preferred for low light level applications. Even though the PDE of S11064-050P is reported in their literature [4] to be around 46% peak at 440 nm, it is not used for TL/OSL applications due to the high dark counts. Sensl's silicon photomultiplier also has similar high dark counts [5].

2.3.2 Digital Silicon Photomultiplier (dSiPM)

dSiPM, developed by Philips, is a digital implementation of SiPM. Here photons are detected directly by sensing the voltage at the anode of the Geiger-mode avalanche photodiode using a dedicated cell electronics block next to each diode. When there is an avalanche due to the detected photon/s, it is actively quenched using a dedicated transistor and is quickly recharged to its sensitive state using a different transistor. Photons are detected and counted as digital signals. This is opposed to the analogue SiPM where the output signal is the analogue sum of the output of each diode. Since it is an analogue signal it is more susceptible to temperature variations, interference, unstable baseline, noise and deterioration. Whereas in the dSiPM, due to the digitization immediately after the signal generation, the effect of noise is minimized, making it more immune to temperature variations and electronic noise.

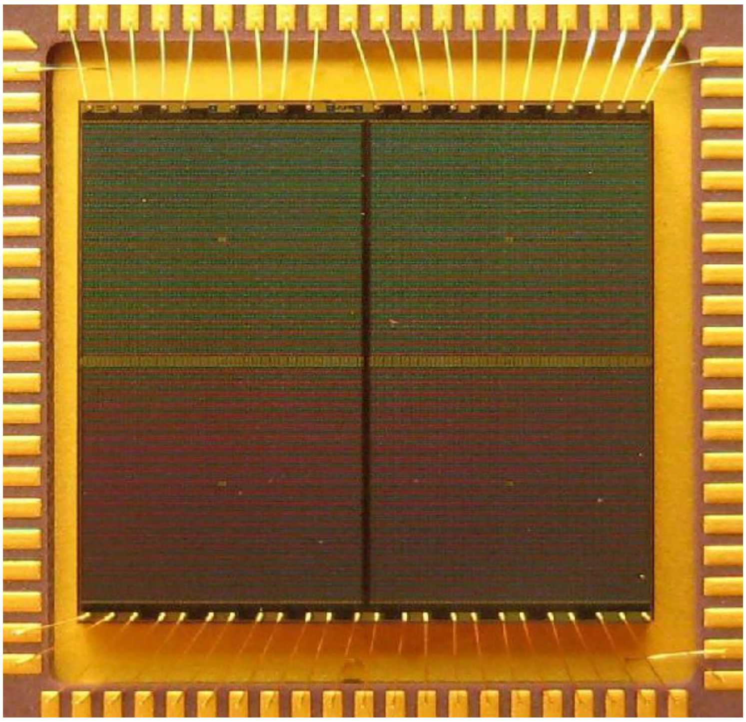

Figure 3. A Digital Silicon Photomultiplier

(Image courtesy: http://horizon.hadronphysics.eu/docs/presentations_ko_hph/WP32.pdf)

To eliminate a conventional SiPM's need for an external digitizing ASIC, dSiPM equips each individual avalanche photodiode with its own 1-bit on-chip Analogue to Digital Converter in the form of a CMOS inverter. Each micro-cell that experiences avalanche breakdown therefore produces its own digital output that is captured, along with the digital outputs from all other triggered micro-cells, by an on-chip counter. dSiPM therefore converts digital events (photon detections) directly into a digital photon count. As a result, it is capable of achieving significantly better resolution than conventional SiPMs.

Along with the photon counter, a timer is also integrated in the detector itself. When a photon hits the active area of the detector the photon counter is incremented by one. The timer measures the arrival time of the first photon per die. At the end of the detection process the value of the photon counter and the timer can be read out using a digital interface consisting of a dedicated FGPA board. By integrating both the sensor and the data processing into a single silicon chip, it will enable faster and more accurate photon counting in a wide range of applications where ultra-low light levels need to be measured. Detailed description of the operating principle and the intrinsic performance is given by Frach *et al.* [6].

In contrast to analogue SiPMs, in which parasitic capacitance and inductance degrade timing performance, all micro-cells in dSiPM are connected via a low-skew balanced trigger network to an on-chip time-to-digital converter. The timing resolution of this converter is 20 ps, thereby preserving the excellent intrinsic timing performance of the Geiger-mode avalanche photodiodes.

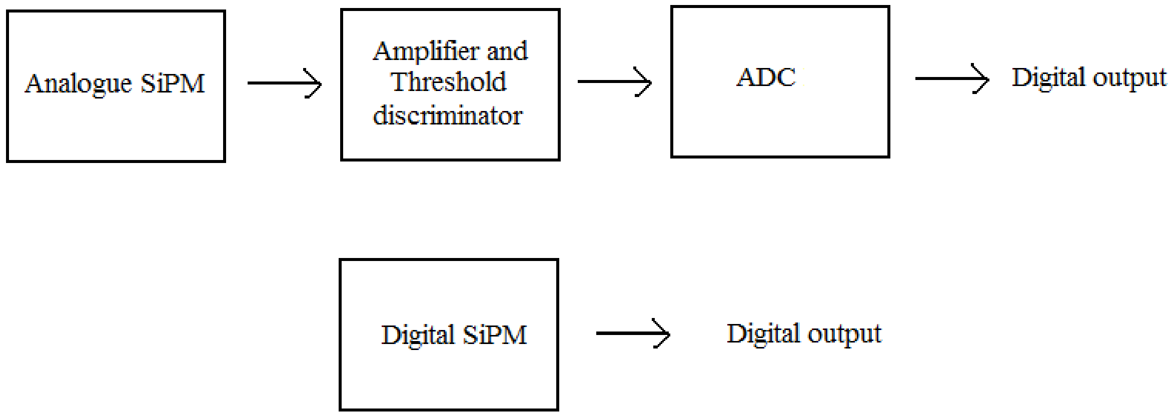

Figure 4. Block diagram of a system based on analogue SiPM and digital SiPM

Unlike the analogue SiPM, the individual pixel is accessible in the digital SiPM so spatial resolution is possible which can be used in imaging applications. As of now the spatial resolution is much below the spatial resolution provided by the CCD sensors. It may be improved in the future with the development of the technology.

2.3.3 Electron Multiplying Charge Coupled Device (EMCCD)

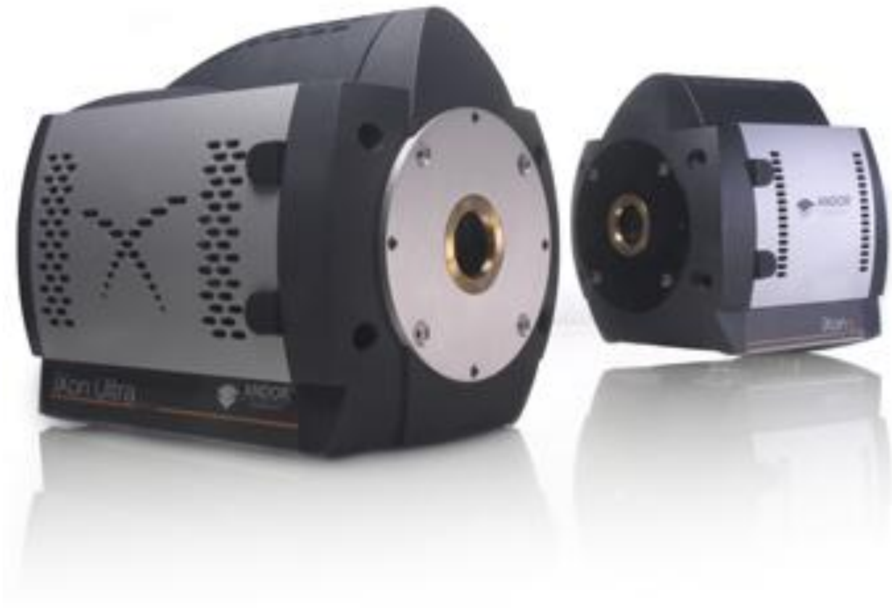

Figure 5. EMCCD cameras

(Image courtesy:http://www.andor.com/news/andor-technology-launches-ixon-ultra-897-emccd-camera-190112

EMCCD is an image sensor that is capable of detecting single photon events without an image intensifier, achievable by way of a unique electron multiplying structure built into the chip. It uses a conventional CCD structure, except that the shift register is extended with an additional section – the Gain Register. The gain register is essentially a chain of pixels across which the signal charge is transferred. Traditional CCD cameras, often referred to as 'slow scan' cameras, offers high sensitivity, with low readout noises but at the expense of slow readout. This fundamental constraint comes from the CCD charge amplifier. To have high speed operation the bandwidth of the charge amplifier needs to be as wide as possible. However the noise increases as the bandwidth of the amplifier increases. Slow scan CCDs have relatively low bandwidth and hence can only be read out at modest speeds typically less than 1 MHz. EMCCD cameras overcomes this fundamental physical constraint by amplifying the charge signal before the charge amplifier and hence maintain unprecedented sensitivity at high speeds. By amplifying the signal the readout noise is effectively by-passed and readout noise is no longer a limit on sensitivity [7]. EMCCDs can also be used as the traditional

CCDs by not activating its EM gain. They are also equipped with Peltier cooler which can cool it to -100˚C thereby drastically reducing the dark counts.

2.3.4 General comparison of PMT, SiPM, and dSiPM [5, 8-11]

A general comparison of some of the popular light detectors is shown in Table 2. The active area of the SiPMs used for this comparison is 12mm x 12mm; for bialkali PMT (EMI 9235QA) the diameter of the active area is 52 mm and for multi-alkali PMT (R943-02) it is 51 mm. With the decrease in the detector area there is a decrease in the dark counts which leads to a decrease in the minimum optical power required for valid reading.

	PMT (Bialkali)	**PMT (Multi - alkali)**	**dSiPM Philips**	**SiPM Hamamatsu 11064-025P**	**SiPM Hamamatsu 11064-050P**	**SiPM Sensl**
Spectral range (nm) (QE/PDE >5%)	320-620 (QE)	360-720 (QE)	350-720 (PDE)	330-780 (PDE)	330-860 (PDE)	400-1100 (PDE)
PDE/QE at peak wavelength (Percentage)	28% at 400nm (QE)	20% at 400 nm (QE)	30% at 430 nm (PDE)	22.75% at 460 nm (PDE)	46.16% at 460 nm (PDE)	5-20% over the range (PDE)
Dark counts (Counts/sec)	20 at 25^0C	20 to 50 at 25^0C	11040000 at 20^0C 1104000 at at 0^0C 73000 at -45^0C	64000000 to 128000000 at 25^0C	96000000 to 160000000 at 25^0C	32000000 at 25^0C
Fill factor	100 % However, whole area is not	100 % However, whole area is	50%	30.8%	61.5%	Not available

	equally sensitive [14]	not equally sensitive [14]				
Minimum detectable power at peak wavelength at 25 ^{0}C	0.0112 fW	0.0247 fW	7.210f W (0.589 fW at -45^{0}C)	30.300 fW	16.7 fW	Not availabl e For 12mm x 12mm detector area
Minimum number of photon/ second at peak wavelength at 25 ^{0}C	22	50	15619 (1275 at -45^{0}C)	70120	38637	Not availabl e For 12mm x 12mm detector area
Dynamic range	Up to 100,000	Upto 100,000	Upto 73,629	Upto 54,600	Upto 14,400	Upto 14560
Operating voltage	~1000 V	~2000V	~30V	~70V	~70V	~30V
Exposure to ambient or excess light	Harmful	Harmful	Not harmful	Not harmful	Not harmful	Not harmful
Effect of Magnetic field	Distortion	Distortio n	None	None	None	None

Table 2. General comparison of PMT, SiPM, and dSiPM.

The QE (for PMT) and PDE (for silicon detector) of the light detectors are shown graphically in figure 6.

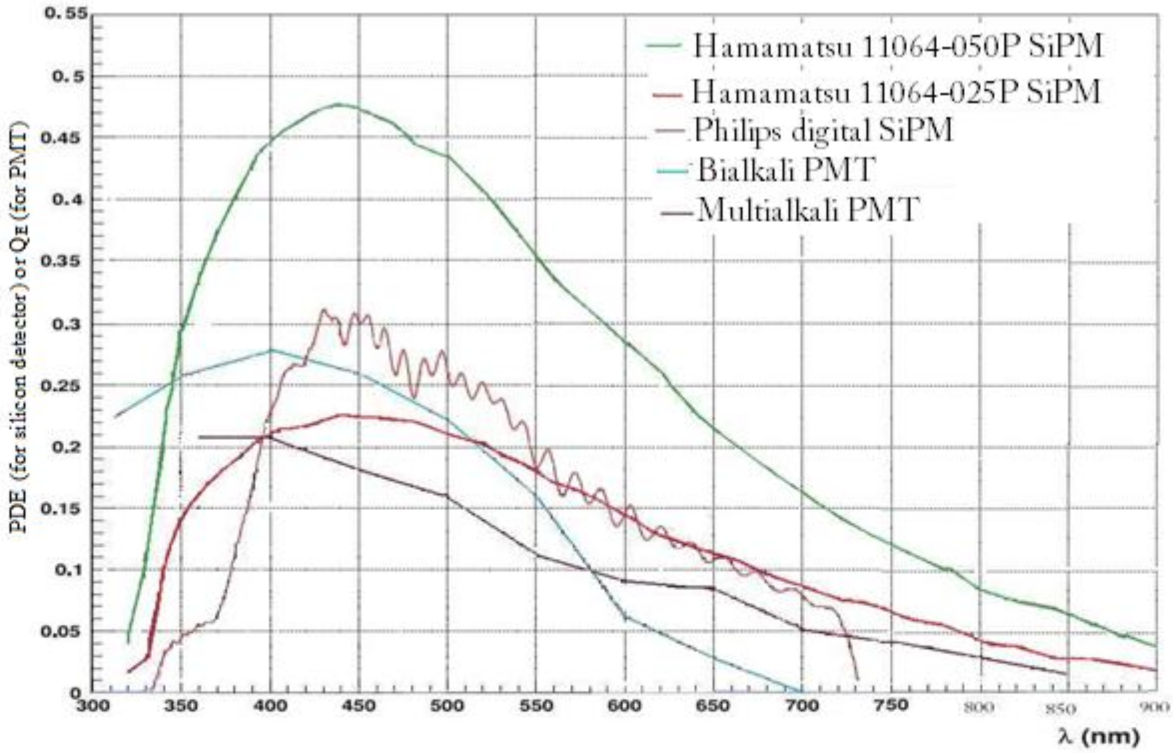

Figure 6. Comparison of QE/PDE of PMT, SiPM, and digital SiPM.

For PMT, the photon detection efficiency is actually quantum efficiency, whereas for SiPM it is less than that due to the ‘‘geometrical’’ efficiency. Figure 6 does not give the complete picture of the detector because two detectors having the same QE or PDE will differ in their capacity to detect low level light due to the difference in their dark counts. Thus a graph of minimum detectable power for different wavelength which accounts for the PDE/QE and the dark counts is plotted (figure 7). This graph gives a more realistic picture of the detector.

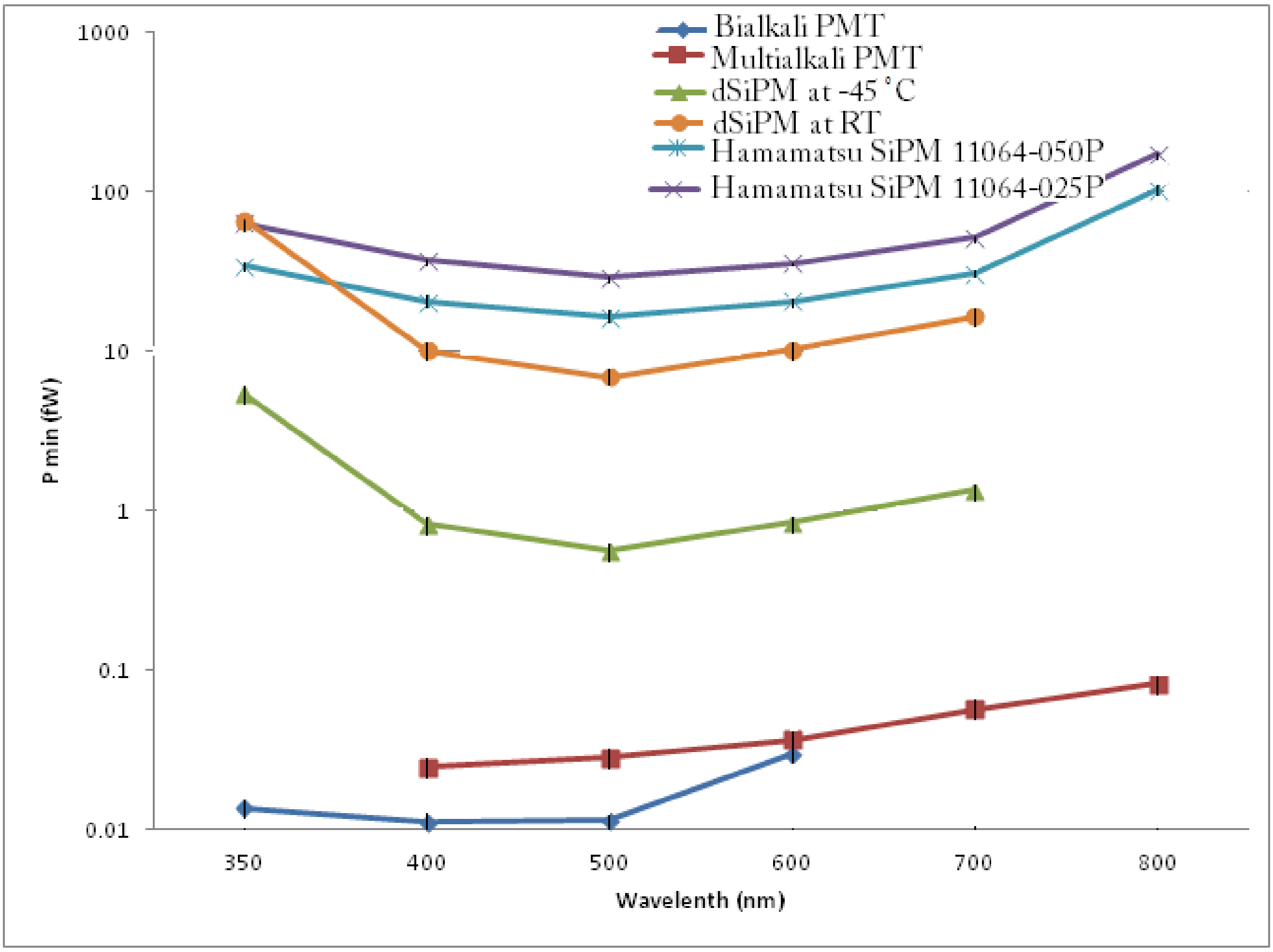

Figure 7. Minimum detectable power verses wavelength for bialkali (blue sensitivity) PMT, multialkali (red sensitivity) PMT, SiPM, and dSiPM

It is seen from the figure 7 that the minimum detectable power for dSiPM is about an order less than that of SiPM and more than that of PMT. This situation improves at low temperature.

The different parameters used for the comparison above are enumerated as follows:

2.3.4.1 Photon detection efficiency (PDE) of the detector

Quantum efficiency (QE) describes the probability to detect a photon of a certain wavelength. It is a measure of detector's capability to detect photons of different wavelength. PDE of specific detector depends upon several other characteristics of detector. For PMT, the PDE is defined as:

$$PDE = QE \times CE$$

Where QE is the quantum efficiency of the photocathode and CE is the electron collection efficiency of internal multiplying dynode structure of PMT. CE depends on the photocathode shape, dynode structure and voltage distribution for it. It is generally from 70% to 90% for head-on PMTs [12].

In the case of SiPM, PDE is defined as:

$$PDE = QE \times \mu \times A_p$$

Where QE is the quantum efficiency of front semiconductor material of avalanche diodes, μ is the fill factor of the detector which is equal to the ratio of the effective pixel size and the total pixel size, and A_p is the avalanche probability which is equal to the ratio of the number of excited pixels and the number of photon-incident pixels.

Fill factor gives a measure of the active area of the detector. It depends on the insensitive area between the pixels and can be improved by using micro-lenses and better fabrication. It can also be increased by increasing the size of the pixel but at the cost of reduction in the dynamic range of the detector. A_p gives the probability of junction breakdown due to avalanche caused by a carrier attracted into the high field region of the junction.

PDE gives a better idea than QE of the detector’s response to the incident photons. It is defined as the ratio of detected photons to the incident photons. Thus even for the detectors which have higher QE, its capability to detect photon could be low due to the other factors mentioned above.

2.3.4.2 Spectral range

The spectral response of PMT is determined by the photocathode material on long wavelength side and on short wavelength by the window material. Spectral response of SiPM/dSiPM depends on, among other factors, the thickness of the top layer as the depth in which the photons are absorbed depends on the wavelength of the photon. Longer wavelength penetrates deeper than the shorter wavelength. It also depends on the type of the substrate. For n type silicon, the maximum response is in the blue-green region while for p type silicon, maximum response is in the red region.

As mentioned earlier, QE represents the production probability of photoelectrons being emitted when one photon strikes the detector sensing area. However, this probability is different for photons with different wavelength. As a result, the detector responds to photons only in specific range of wavelength. Again this is not the final spectral response of detector, because other factors like collection efficiency (for PMT) and fill factor and avalanche probability (for SiPM) reduces the overall spectral response. The spectral range of available SiPMs from different manufacturers also differs. For Philip's dSiPM, the spectral range is from 350 nm to 720 nm, for Hamamatsu's SiPM, it is from 330 nm to 860 nm while for Sensl's SiPM, it is from 400 nm to 1100 nm.

2.3.4.3 Dark Count Rate

One of the main factors limiting the performance of the any detector is the dark rate. This is mainly because of the generation of electrons due to thermal energy. This process is called thermionic emission and the signal generated is called dark count signal. There are other processes like leakage current which also contribute to the dark count. Dark count is an unwanted signal which lowers the SNR and hence detection capability of detector.

In the case of PMT, they are generated in the photocathode as well as in dynodes, whereas in SiPM/dSiPM, they originate in the active volume and also in avalanche region due to tunnelling assisted process. The former contribution can be reduced by active cooling and the latter by a careful design of the avalanche region. In SiPM the dark rate results from thermally generated carriers which initiate a Geiger avalanche resulting in a current pulse that is indistinguishable from a pulse produced by the detection of a photon. This is particularly important for room temperature operation. The SiPM dark rate is the average frequency of the thermally generated Geiger avalanches from all the microcells in the array. In many applications the average dark rate can be measured and subtracted. However, the statistical variation in the dark rate cannot be subtracted and constitutes a noise source that determines the minimum detectable signal. In dSiPM, the individual diode's dark count could be measured. The diodes having high dark counts could be disabled. The effect of the dark counts can be decreased by the method described by Frach et al. [6]. This method involves switching off the cells producing excessive dark count at the expense of reduced PDE. Also a validation threshold up to 64 photons for an adjustable time period of 5 ns to 40 ns to distinguish valid photon events from dark counts could be set up [6].

2.3.4.4 Optical Cross-talk

In SiPM, optical crosstalk is caused by the photons which are generated in the avalanche discharge of the diode. They propagate within the SiPM and eventually are absorbed in the active volume of a neighbouring cell. Optical crosstalk is directly proportional to the current density in the high-field region of the junction of the avalanche diode. So it can be reduced by decreasing the current density. In the analogue SiPM, this leads to the decrease in gain which causes the reduction of SNR. In digital SiPM, the current is reduced by discharging the avalanche diode by dedicated quenching transistor, thus not decreasing the gain and SNR. Optical crosstalk can be directly measured in a digital SiPM [6]. Another approach to reduce optical crosstalk is to absorb the “crosstalk” photons between neighbouring pixels. Grooves between pixels for the absorption of crosstalk photons might introduce additional dead area. It can also be suppressed by optical isolation between the avalanche diodes. In the case of PMT there is no optical cross talk, but the whole detector area is not equally sensitive [14].

2.3.4.5 Temperature Sensitivity

The gain of the PMT is susceptible to temperature variations. Also, the photocathode’s resistivity increases with the decrease in temperature. This effect has to be taken into consideration when the PMT is cooled to very low temperatures. At very low temperatures, increase in the photocathode resistivity will cause a cathode current saturation effect resulting in loss of output linearity with respect to the incident light level. The ambient temperature, along with supply voltage and current, causes stress resulting in performance deterioration of the PMT called ‘fatigue’. PMTs need few hours to stabilize the dark counts and other noises after a change in the ambient temperature. It takes such a long time because heat travels very slowly in the interior of the PMT which is in vacuum. PMTs need to be stored at or below room temperature or else it will accelerate sensitivity variation [14].

Similarly the gain of the analogue SiPM is affected by temperature variations. It leads to a temperature drift of the breakdown voltage of the diode. This in turn will lead to a proportional change in the gain of SiPM as per the following equation [6].

$$G = \frac{C(V_{bias} - V_{bd})}{q}$$

Where G is the gain of the SiPM, C is the diode capacitance including any parasitic, V_{bias} is the bias voltage of the device, V_{bd} is the breakdown voltage, and q is the electron charge.

The dSiPM, due to the digitization of the voltage level at one of the diode terminals, is insensitive to any change in the breakdown voltage as long as the switching threshold of the gate is reached. There is a change in the PDE due to the temperature dependent avalanche initiation probability. The intrinsic temperature dependence of the dSiPM as measured with a laser light source was determined to be −0.3 %/°C [6]. Compared to values found in the literature for analogue SiPMs of −8 %/°C [13], the dSiPM is more than one order of magnitude less affected by temperature variations. This is due to the fact that the dSiPM does not rely on the gain of the individual Geiger-mode diodes. As long as the diodes break down with a sufficient drop in voltage, the breakdown is detected by the integrated electronics regardless of the individual gain of the diode. Also the measured drift is of 0.33%/°C in the average number of photons per pulse over a range of 15 ˚C to 25 ˚C. This drift is an order of magnitude lower compared to the analogue silicon photomultiplier [14]. However it can be compensated by adapting the bias voltage of the device. It might be possible to integrate the bias voltage generator in the same die [6].

For all the three detectors there is an increase in the dark counts with the increase in temperature. As a result there is a decrease in the SNR of the detector. This causes an increase in the minimum amount of optical power needed to get a valid reading. Thus it is important to maintain a low temperature.

2.3.4.6 Minimum detectable power

In extremely low level light detection applications, the main criterion is the minimum light power that can be detected by the detector with precision.

The light detector can be operated in either analogue mode or in digital mode. The digital mode or the photon counting mode gives a better SNR for low level of light [14]. The SNR should be minimum 1 in order to get reliable information from the signal. The minimum power of the incident light to get SNR as 1 is given by the following equation [16].

$$P_{\min} = \frac{hc\sqrt{2N'_d}}{\lambda\eta(\lambda)} W$$

Where h is Planck's constant 6.626 x 10^{-34} J/s, c is the velocity of light 3 x 10^{8} m/s. λ is the wavelength of the incident light in nano-meter and $\eta(\lambda)$ is its QE. $\sqrt{N'_d}$ is the square root of the ratio of dark count and measurement time. The above equations can also be applied to SiPM and dSiPM.

2.3.4.7 Minimum number of photons needed for $P_{min.}$

From the value of the minimum detectable power, the minimum number of photons per second can be obtained using the following equation for the power of photon per second [12]:

$$P = \frac{hc}{\lambda} \approx \frac{2x10^{-16}}{\lambda} W$$

The minimum number of photon required to give an accurate signal needs to be found out for applications like TL/OSL where the emitted light is normally expressed in terms of number of photons.

2.4 Important parameters for light detection

There are some important parameters in light detection which needs to be taken into account while designing an optimal light detector set-up. These parameters are enumerated below taking into account the associated electronic circuitry also. The quality of light detection depends very much on these parameters.

2.4.1 Signal-To-Noise Ratio (SNR)

To measure the intensity of light striking the photo-detector, the basic requirement is that detector should be able to generate some charge carriers (electrical signal) in proportion to the incident light. The magnitude of this electrical signal indicates the intensity of light. So it is desirable to have the electronic read-out circuit with the ability to read this signal with high degree of accuracy. However, some other sources within detector and electronics as well, generate additional and unwanted electrical signal, called the noise.

Variety of noise sources exists depending on several parameters like temperature, geometry of the detector, detector material, presence of other radiations, etc. For example, a thermal noise which depends upon the ambient temperature can be reduced by lowering the temperature.

If a steady state noise is present in the system under consideration, it is still not difficult to extract the signal information, which is mixed with noise. This is because basic input-output proportionality still exists. The only requirement is to have the detector with enough sensitivity so that smallest signal can still be sensed. In such a case, only appropriate calibration is required.

However, the main problem associated with the noise is its fluctuation in form of ac components superimposed on the signal. This is known as a Shot noise, originating from the statistical fluctuation in the signal. The fluctuation is due to discrete nature of the constituent (electrons-holes) of the electrical signal. As a result, the shot noise is generated not only from the noise sources but also from the signal itself.

The detection of the signal is not straight forward particularly in the initial stage of signal processing chain where the signal is just generated in the detector/transducer. This is due to relatively small magnitude of generated signal and the presence of noise. Signal detection process becomes more difficult if the magnitude of signal and noise are comparable. Generally, noise is superimposed upon the signal. As a result, the accuracy of the detected signal decreases.

The degree of accuracy in detecting the signal mainly depends on how strong the signal is compared to noise. The term used for this comparison is called Signal-to-Noise Ratio (SNR). High SNR gives result as close as actual, which is the prime requirement of any experiment. It cannot be achieved if the electrical signal generated by the light detector is very low. This happens in the case of some samples whose emission is very low. It is essential to search for the detector and read-out circuit with SNR as high as possible. Apart from other requirements, high SNR would be the main search criteria in finding the best suitable detector.

2.4.2 Effect of Quantum Efficiency (QE) and Detector Gain on SNR

SNR depends mainly on quantum efficiency (QE) and detector gain. The QE of the detector is the production probability of photoelectrons being emitted when one photon strikes the photocathode. In the single photoelectron state, the number of emitted photoelectrons per photon is only 1 or 0. Therefore QE refers to the ratio of the average number of electrons generated from the detector per unit time to the average number of photons incident on the detector. As QE increases, the production probability of charge carriers also increases and more photoelectrons will be available for each event. As a result, the statistical fluctuation involved in photoelectrons production decreases. This fluctuation appears as a noise in the system, which is referred as shot noise. For high QE, the shot noise will be less which leads to higher SNR.

Analogous to QE, the gain of the detector is also useful in making high SNR. Generally the read-out circuit connected to the detector does introduce additional noise in the signal coming out from the detector. In the case where the strength of detector's output signal is low or comparable to the noise level of read-out circuit, signal detection accuracy will be low. In fact, sometime it becomes almost impossible to extract exact signal information. The detector gain then becomes critical for the extraction of the signal form the noise.

The effect of read-out noise is minimized, if signal generated within detector is significantly multiplied by some mechanism before feeding to the read-out circuit. However, due to multiplication process itself additional noise is generated and additionally existing noise gets multiplied. The resulting shot noise will be low by several orders to the amplified signal. Detector having high QE but not having internal gain can fail to detect low level light due to the read-out noise of the electronics circuit.

2.4.3 Mode of operation (Analogue-Digital) and SNR

In light detection experiment, the intensity of light is detected using two different modes: analogue/current mode and digital/photon counting mode which is also known as photon counting mode. Digital mode of operation is possible because light is made up of stream of discrete component called photon which represents specific quanta of energy. In more intense light, the photons are coming at very high rate and hence time interval between them is extremely short. Therefore, it is difficult to count them individually. In contrast, if the intensity of light is low, the photons are relatively away from each other (in time domain), and hence can be detected individually.

Generally for moderate to high level of light signal, analogue mode of operation is used whereas for extremely low level light detection digital mode is more beneficial due to high SNR and stability.

In Analogue mode, the signal measured at the detector output is an average (analogue) current created by multitude of pulses as a result of interaction of photons. As the light level is high the pulses are overlapping and cannot be handled individually. The average signal collected at the output of detector is used to determine the intensity of light. In this mode, the information which is to be extracted is lying in the magnitude of the signal. There is high degree of probability that noise gets superimposed upon the signal. This unwanted signal in the form of noise changes the actual magnitude of signal, and deteriorates the signal detection accuracy. In other words, the noise is tightly bound with the signal. If the noise level is high, sometimes it becomes quite impossible to detect the genuine signal. When the incoming light intensity is high, corresponding signal strength would be high compared to the noise strength. In this situation, analogue mode of operation is preferable as percentage error is less and the detected signal will be close to its actual value.

Since the photon rate is high for high intensity light it is difficult to distinguish individual photons from each other. Due to this digital mode is not suitable for high intensity light. When light intensity is low, the signal is comparable to noise level and use of analogue mode leads to erroneous result. Photon counting mode of operation is more suitable in this case. In digital mode, the detector and electronics are tuned to count the numbers of photons striking the detector. The intensity of incoming light is directly proportional to the total number of photons counted in a specific time interval. However, the basic requisite of digital mode of operation is that light level should be low enough so that photon count rate is low and distinguishable in time.

In digital mode, the read-out circuit is tuned only to register the presence of the signal, not its magnitude. This is done by converting signal into digital pulses if its magnitude is above specific discrimination level. This level is called low level discriminator (LLD). The process of detecting the presence of the signal is not affected by a small variation in the magnitude of the signal resulting from the noise. This is not the case for analogue mode. Complete elimination of noise is not possible due to several reasons. It can be reduced considerably if

LLD is set at right value. In addition to LLD, upper level discrimination (ULD) can also be kept to eliminate the noise due to environmental radiation.

From the above discussions, it is clear that high SNR is the major requirement to detect extremely low level light. In other words, the PDE of the detector improves considerably if SNR is high.

2.5 Detail analysis of SNR, QE and detector gain

In the following**,** only the effect of shot noise on SNR is discussed in detail because shot noise is the most prominent component which significantly influences the SNR. For better understanding the interrelation of above parameters and their role in detecting extremely low level light, three different types of detectors are considered as follows.

1) Photo multiplier tube (PMT)
2) P-I-N photo diode (P-I-N)
3) Silicon Photo multiplier (SiPM)

2.5.1 Analogue Mode

The explanation given below has considered PMT only. However it is also applicable to other two detectors as well.

The shot noise (i_{ph}) generated by photo current (I_{ph}) produced by incident light is [12]:

$$i_{ph} = \sqrt{2eI_{ph}B} \text{ ....(1)}$$

Where

e = electron charge,

B = bandwidth of the measurement system

I_{ph} = Photo current = Pi QE α e/h ν

Where Pi = average light level entering the PMT,

QE = Quantum efficiency of photocathode,

α = collection efficiency of dynode chain

hν = energy of photon

Rearranging equation (1) we get,

$$SNR = \frac{I_{ph}}{i_{ph}} = \frac{\sqrt{I_{ph}}}{\sqrt{2eB}}$$

From this equation, it is clear that SNR is directly proportional to photo current $I_{ph.}$ It is more for high QE. Therefore, as QE increases SNR also increases. However, high QE improves SNR only for the noise which is originated due to signal shot noise. However in actual, the read-out electronics also adds to the noise. If all the noises i.e. signal shot noise, background shot noise, dark current shot noise and noise introduced by electronics are combined and signal is measured at the anode of PMT then [12],

$$SNR = \frac{I_{ph}}{\sqrt{2eFB\{I_{ph} + 2(I_b + I_d)\} + \frac{\left(\frac{4F_a kTB}{\mathrm{Re}\,q}\right)}{\mu^2}}}$$

Where

μ = Gain of PMT

F = Noise figure of PMT

I_b = Average background current produced by background light

I_d = Dark current generated due to ambient temperature

F_a = Noise figure of read-out electronics (generally amplifier)

T = Absolute temperature

B = Bandwidth of measurement system

Req = Input impedance of read-out electronics

From the above equation it is clear that if internal gain of PMT is high the term $\frac{\left(\frac{4F_a kTB}{\mathrm{Re}\,q}\right)}{\mu^2}$, which represent electronic circuit noise, can be ignored. Here detector gain plays an important role in improving the SNR. The detector with fair amount of internal gain has obviously upper hand compare to the detector without gain. As a side effect, the noise of the detector (shot noise) also gets amplified due to internal gain. However, the noise is amplified by the square root of gain ($\sqrt{\mu}$), whereas the actual signal is amplified by µ. If noise of read-out circuit is ignored, than above equation is simplified as follows [12].

$$SNR = \frac{I_{ph}}{\sqrt{2eFB\{I_{ph} + 2(I_b + I_d)\}}}$$

By substituting the value of I_{ph} the following equation is derived.

$$= \frac{Pi \times QE \times \alpha \times e \times G}{h\nu\sqrt{2eFBG\{I_{ph} + 2(I_b + I_d)\}}}$$

From the above equations, it is evident that high QE and high G improves SNR and hence the accuracy in signal detection.

If similar argument is applied to other two detectors i.e. P-I-N detector and SiPM, following equation can be derived [15]

For P-I-N Detector

$$SNR = \frac{I_{ph}}{\sqrt{2eB\{I_{ph} + 2(I_b + I_d)\}}}$$

For SiPM Detector

$$SNR = \frac{I_{ph}}{\sqrt{2eFB\mu\{I_{ph} + 2(I_b + I_d)\}}}$$

An experiment was undertaken [16] to verify above equation and to compare the output of the above three detectors. To provide common platform for comparison, a P-I-N diode with 1.2 mm diameter and SiPM with 1 mm^2 area was used. Also PMT (R7400, 8 mm diameter) was illuminated with a 1mm diameter light spot.

When SNR becomes unity, the signal intensity equals the noise. This term is expressed by Noise Equivalent Power (NEP). This is the minimum optical power which can be detected by detector. From the experiments, the minimum optical power for the detectors under consideration is as follows.

PMT: ~0.5 fW

SiPM: ~7.2 fW

P-I-N: ~90 fW

2.5.2 Digital Mode (Photon Counting mode)

In digital mode, signal pulses generated by randomly arriving photons which are of the appropriate amplitude set by the lower and upper discriminator levels are counted. The number of signal pulses detected during a certain time period will have a Poisson distribution since the emission and hence detection of photons follows Poisson statistics.

In Poisson statistics the number of observed occurrences fluctuates about its mean λ with a standard deviation $\sqrt{\lambda}$. As in analogue mode the amplifier noise can be ignored by operating the PMT gain at a higher level so that the discrimination level can be set at a level above the amplifier noise.

In photon counting mode the shot noise resulting from the signal photons is given by [12]

$$n_{ph} = \sqrt{N_{ph}}$$

Where N_{ph} is the number of counts resulting from detected photons.

The shot noise from background light is given by [12]

$$n_b = \sqrt{N_b}$$

Where N_b is the number of counts resulting from background photons.

The shot noise resulting from dark counts is given by [12]

$$n_d = \sqrt{N_d}$$

Where N_d is the number of dark counts.

In a photon counting measurement the number of counts due to signal photons is found by measuring the total number of counts (N_{ph} + N_b + N_d) and then subtracting the background and dark counts (N_b+N_d) measured over the same period of time by removing the signal light.

The noise associated with N_{ph} is then given by [12]

$$n_{tot} = \sqrt{N_{ph} + 2(N_b + N_d)}$$

Assuming each component is independent and random. The signal to noise ratio is then given by [12]

$$SNR = \frac{N_{ph}}{n_{tot}}$$

$$= \frac{N_{ph}}{\sqrt{N_{ph} + 2(N_b + N_d)}}$$

For a measurement time of *t* in seconds, the number of counts per second is given by [12]

$$N' = \frac{N}{t}$$

The signal to noise ratio can be written as [12]

$$SNR = \frac{N'_{ph}\sqrt{t}}{\sqrt{N'_{ph} + 2(N'_b + N'_d)}}$$

$$N'_{ph} \sim \sqrt{2N'_d} \qquad \text{for SNR} = 1,$$

At this point, the power of incident light is [12]

$$P_{\min} = hc\frac{\sqrt{2N_d^{'}}}{\lambda\eta(\lambda)} \text{ Watt}$$

$$P_{\min} = \frac{2.8\times10^{-16}\times\sqrt{N_d^{'}}}{\lambda\times\eta(\lambda)} \text{ Watt} \quad \text{...............(2)}$$

where η(λ) is the QE at wavelength λ

This is the lowest detectable optical power in digital mode for PMT.

SNR for SiPM can be derived just as it is derived for PMT [15].

$$SNR = \frac{N_{ph}^{'}\sqrt{t}}{\sqrt{N_{ph}^{'} + 2\left(N_b^{'} + N_d^{'}\right)}}$$

The minimum detectable optical power is given by [15]:

$$P_{\min} = hc\frac{\sqrt{2N_d^{'}}}{\lambda\eta(\lambda)} \text{ Watt}$$

$$P_{\min} = \frac{2.8\times10^{-16}\times\sqrt{N_d^{'}}}{\lambda\times\eta(\lambda)} \text{ Watt} \quad \text{.......................... (3)}$$

where η(λ) is the QE at wavelength λ

Equation 2 and 3 are similar and show that for higher quantum efficiency the minimum detectable power is low which is the basic requirement of low level light detection.

From the graph of SNR verses incident optical power for PMT and two different SiPM plotted in the technical note by Sensl [15], the minimum optical power for the detectors under consideration is as follows.

PMT: ~0.2 fW

SiPM Mini: ~2.7 fW

SiPM Micro: ~11 fW

In comparison to Analogue mode, the minimum detectable optical power of PMT and SiPM in digital mode is better.

2.6 Conclusion

A feasibility study of various light detectors was done to assess their suitability as photon detector for TL/OSL system. Light detectors capable of giving spatial distribution of luminescence and light detectors that integrate the detected luminescence were studied. This study highlights that PMT is a superior detector compared to all others in detecting extremely low level optical signal. The next most suitable detector is the digital SiPM. It has sufficiently large detection area but its minimum detectable power is high for TL/OSL applications. For the case of spatial analysis EMCCDs are found to be the best because of their spectral range, high photon sensitivity, and high speed along with other desirable features. In view of the above, EMCCD is used in the system developed for this study.

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