ISSN 1726-5479

SENSORS & TRANSDUCERS

vol. 139
4/12

MEMS and Modern Technologies

International Frequency Sensor Association Publishing

IFSA

Sensors & Transducers

Volume 139, Issue 4, April 2012 | **www.sensorsportal.com** | **ISSN 1726-5479**

Sensors & Transducers Journal (ISSN 1726-5479) is a peer review international journal published monthly online by International Frequency Sensor Association (IFSA).
Available in electronic and on CD.

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Volume 139
Issue 4
April 2012

www.sensorsportal.com

ISSN 1726-5479

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Sensors & Transducers Journal, Vol. 139, Issue 4, April 2012, pp. 52-62

Sensors & Transducers

ISSN 1726-5479

http://www.sensorsportal.com

A Feasibility Study of Analogue and Digital Silicon Photomultiplier as an Alternative to PMT for Low Light Level Applications

[1] Johnson MUNDUPUZHAKAL, [2] Yashwant ACHARYA, [2] Pranav ADHYARU, [1] Bishwajit CHAKRABARTY

[1] Department of Applied Physics, Faculty of Technology, M.S. University, Vadodara 390001, India
[2] Physical Research Laboratory, Navrangpura, Ahmedabad 380009, India
E-mail: johnsj73@gmail.com, yacharya@prl.res.in, pranav@prl.res.in, bschakrabarty@rediffmail.com

Received: 16 February 2012 /Accepted: 23 April 2012 /Published: 30 April 2012

Abstract: A new promising novel detector called digital silicon photomultiplier for low light level application is being introduced in the market. The comparison of various detectors namely Photomultiplier tube, Silicon photomultiplier and the new digital silicon photomultiplier for low light detection applications is presented in this work. The comparison is made mainly in terms of photo detection efficiency, spectral properties, minimum detectable power and its temperature dependence. There is also a brief review on the state of art in the development of digital silicon photomultiplier and their possible applications. *Copyright © 2012 IFSA.*

Keywords: Low-level light detection, Photomultiplier tube, Silicon photomultiplier, Digital silicon photomultiplier.

1. Introduction

Research and development work for low level light detectors is important because it has application in various fields such as particle physics experiments, PET systems, biomedical research and atmospheric pollution measurements, LIDAR (light detection and ranging), laser scanning microscopy, fluorescence correlation spectroscopy, Thermoluminescence, and Optically Stimulated Luminescence [1].

In order to meet the need of such varied applications the type of light detectors, both fully developed and under developmental stage, are numerous: P-N photo diode, P-I-N photo diode, Photo transistor, Avalanche photo diode (APD), Photo multiplier tube (PMT), Hybrid photo detector (HPD), Charge couple device (CCD), CMOS sensors, Electron multiplier CCD (EMCCD), Electron bombardment CCD (EBCCD), Intensified CCD (ICCD), Single photon avalanche diode (SPAD), Silicon photo multiplier (SiPM), digital Silicon Photo Multiplier (dSiPM), Nano-crystal solar cell, Super conductor based light detectors, visible-light photon counters (VLPC), superconductive transition edge sensors (TES), and time-multiplexed detectors. In spite of such a large number of light detectors, there is no ideal detector. So an optimal detector has to be chosen keeping the application in mind.

Usually a PMT is used for many low level light detection applications. During the past few decades, PMTs have been the work horse of all studies requiring quantitative measurement of photon fluxes. But they have many disadvantages like they are sensitive to magnetic fields, are bulky and fragile, require high voltages nearly 1000 volts or more, and consume more power. Due to this, 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 is desirable. Among the solid state detectors Silicon Photomultiplier (SiPM) stands out as the most suitable replacement for PMT.

SiPM are novel detectors for low level light detection based on arrays of avalanche photodiodes operating in Geiger mode. They offer good characteristics like fast response, high gain, photon counting capability, insensitivity to magnetic fields, and low voltage operation. Drawbacks are dark rate and optical cross talk. In order to overcome such drawbacks M/s Philips has introduced a variant of SiPM called digital Silicon Photo-Multiplier (dSiPM), which has on-chip dedicated electronics for each photodiodes (cell) with early digital signal processing and control. These additional circuits enable the device to have many performance improvisations like low electronic noise and less signal deterioration, less temperature susceptibility, reduced optical crosstalk and more importantly, low dark counts. In addition, there is a scope to use the device for imaging the low level light source due to direct access to individual photocell. This paper explores the feasibility of these detectors for low level light detection applications by comparing their different parameters.

1.1. Photomultiplier Tube (PMT)

PMT is a vacuum tube consisting of a photo-cathode on one side. Inside the tube, series of dynodes are arranged in a specific pattern and connected to gradually increasing bias voltage. The last dynode is called the anode which can be connected to external electronics circuit to process the signals. When a light photon strikes the photo cathode of PMT, electrons are generated as a result of the photoelectric effect. These electrons are accelerated to the first dynode with high velocity due to the presence of high electric filed. Owing to high kinetic energy, when these electron strikes the first dynode they generates more secondary electrons. Thus number of electrons gets multiplied. This process continues till the last dynode. As a result, large gain of the order of 10^6 is achieved.

1.2. Silicon Photomultiplier (SiPM)

SiPM is a two-dimensional array made of numbers of Single Photon Avalanche Diode (SPAD, also called as micro-cell) operating in Geiger mode. Each diode has its own quenching circuit. The outputs of all diodes are connected in parallel. These diodes 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. The SiPM connects this array of micro-cells in parallel and the summed output is proportional to the number of Geiger mode pulses and hence proportional to the incident photon flux. 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 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.

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 photomultiplier tube [2]. In the comparison between SiPM and PMT, 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).

1.3. 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 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.

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. 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 in [4].

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. 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. Parameters of the Light Detectors

2.1. Photon Detection Efficiency (PDE) of the Detector

PDE 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:

$$PDE = Q_E \text{ x } C_E \ , \tag{1}$$

where Q_E is the quantum efficiency of the photocathode, it gives the probability of photoelectrons being emitted when one photon strikes the detector sensing area; and C_E is the electron collection efficiency of internal multiplying dynode structure of PMT, it depends on the photocathode shape, dynode structure and voltage distribution for it. It is generally from 70 % to 90 % for head-on PMTs [5].

In the case of SiPM, PDE is defined as:

$$PDE = Q_E \text{ x } \mu \text{ x } A_p \ , \tag{2}$$

where Q_E 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 of detector's response to the incident photons. It is defined as the ratio of detected photons to the incident photons. It is obvious from these facts that even for the detectors having higher Q_E, its capability to detect photon could be low due to the other factors mentioned above.

2.2. Spectral Range

The spectral response of PMT is determined by photo cathode 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, Q_E 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 the three detectors is given in Table 1. The spectral range of available SiPMs from different manufacturers also differs. For the 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.

Table 1. General comparison of PMT, SiPM, and dSiPM.

	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/second)	20 at 2 5^0C	20 to 50 at 25 ^{0}C	11040000 at 2 0^0C; 1104000 at 0^0C; 73000 at -45^0C	64000000 to 128000000 at 25 ^{0}C	96000000 to 160000000 at 2 5^0C	32000000 at 25 ^{0}C
Fill factor	100 % However, whole area is not equally sensitive [6]	100 % However, whole area is not equally sensitive [6]	50 %	30.8 %	61.5 %	Not available
Minimum detectable power at peak wavelength at 25 ^{0}C	0.0112 fW	0.0247 fW	7.210 fW (0.589 fW at -45^0C)	30.300 fW	16.7 fW	Not available For 12 mm × 12 mm detector area
Minimum number of photon/ second at peak wavelength at 25 ^{0} C	22	50	15619 (1275 at -45^0C)	70120	38637	Not available For 12 mm × 12 mm detector area
Dynamic range	Up to 100,000	Up to 100,000	Up to 73,629	Up to 54,600	Up to 14,400	Up to 14560
Operating voltage	~1000 V	~2000 V	~30 V	~70 V	~70 V	~30V
Exposure to ambient or excess light	Harmful	Harmful	Not harmful	Not harmful	Not harmful	Not harmful
Effect of Magnetic field	Distortion	Distortion	None	None	None	None

2.3. Dark Count Rate

One of the main factors limiting the performance of the any detector is the dark rate. This is mainly because of 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 signal-to-noise ratio (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 tunneling assisted process. The former contribution can, in principle, 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 in [4]. 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 [4].

2.4. 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. This gives rise to "optical" crosstalk. It is directly proportional to the current density in the high-field region of the junction of the avalanche diode. So the optical crosstalk can be reduced by decreasing the current density. In the analogue SiPM, this leads to the decrease in gain which causes the reduction of signal to noise ratio. In digital SiPM, the current is reduced by discharging the avalanche diode by dedicated quenching transistor, thus not decreasing the gain and signal to noise ratio. Optical crosstalk can be directly measured in a digital SiPM [4]. 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.

2.5. 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 vacuum. PMTs need to be stored at or below room temperature or else it will accelerate sensitivity variation [6].

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 [4]:

$$G = \frac{C(V_{bias} - V_{bd})}{q}, \tag{3}$$

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 digital silicon photomultiplier, 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. But 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 [4]. Compared to values found in the literature for analogue SiPMs of −8 %/°C [7], the dSiPM is more than one order of magnitude less affected by temperature variations. This can be explained by 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 % per degree Celsius 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 [8]. 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 [4]. 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 Signal to Noise ratio (S/N) of the detector. This causes an increase in the minimum amount of optical power needed to get a valid reading. So it is important to maintain a low temperature.

2.6. 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. Thus the term “minimum detectable power” is of prime importance and should be investigated prior to other parameters to find the suitability of a detector in a particular application. The “minimum detectable power” eventually depends on several parameters of detector, which were discussed previously.

The light detector can be operated in either analogue mode or in digital mode (photon counting). The digital mode or the photon counting mode gives a better signal to noise ratio for low level of light [6]. The signal to noise ratio should be minimum 1 in order to get reliable information from the signal. The minimum power of the incident light to get S/N as 1 is given by [9]:

$$P_{\min} = \frac{hc\sqrt{2N'_d}}{\lambda\eta(\lambda)}W \,, \tag{4}$$

where h is Planck’s constant 6.626 × 10^{-34} J/S, c is the velocity of light 3 × 10^8 m/s. λ is the wavelength of the incident light in nano-meter and η(λ) is its QE. √ 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.

2.7. 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 power of photon per second:

$$P = \frac{hc}{\lambda} \approx \frac{2x10^{-16}}{\lambda}W \tag{5}$$

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

3. General Comparison of PMT, SiPM, and dSiPM [4, 10-13]

A general comparison of some of the popular light detectors is shown in Table 1. The active area of the SiPMs used for this comparison is 12 mm × 12 mm; 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.

The Q_E (for PMT) and PDE (for silicon detector) of the light detectors are shown in Fig. 1.

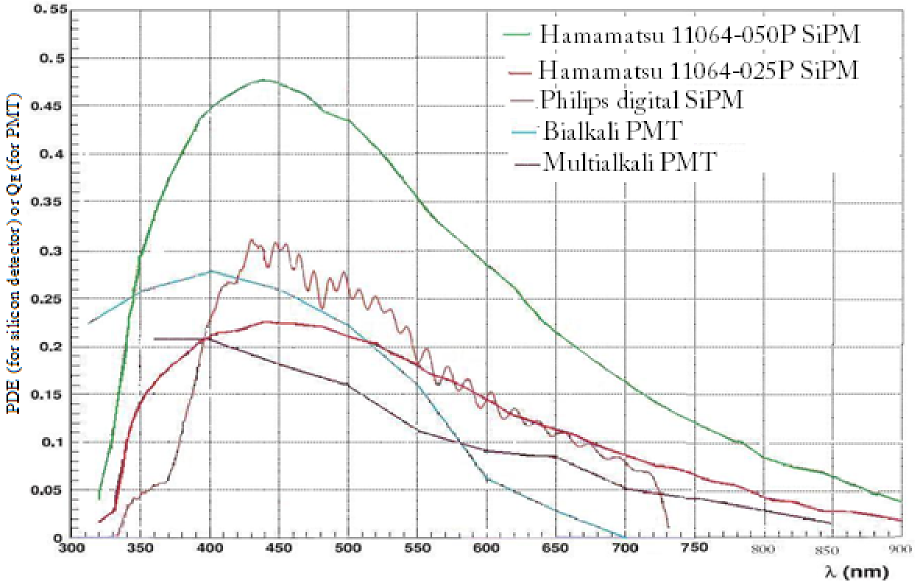

Fig. 1. Comparison of QE/PDE of PMT, SiPM, and digital SiPM.

In Fig. 1, one can see the comparison of photon detection efficiencies of vacuum and silicon devices. For PMT, the photon detection efficiency is actually quantum efficiency Q_E, whereas for SiPM it is less than that due to the ''geometrical'' efficiency. The SiPM (Hamamatsu 11064-025P) photon detection efficiency is for a time being at the level of PMT QE for blue light and more for yellow–red region, that is important for some applications. This graph 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. So a graph of minimum detectable power for different wavelength is plotted below. This graph takes into account the PDE or QE and the dark counts and thus gives a more realistic picture of the detector.

It is seen from the Fig. 2 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.

4. Suitability of dSiPM for Various Applications

Due to the above mentioned features, SiPMs are found to be suitable for various applications [14-17]. Even its use for space-based experiments has been explored [18-19]. The Sensl SiPM's performance was found to be well suited for cryogenic environments and it was also very resilience to repetitive thermal shock [20]. SiPM has triggered interest for many applications, like calorimeters, air-shower

Cerenkov telescopes, medical applications etc. Work has also been done on the application of SiPM technology for the development of radiation sensor [21]. Also in thermoluminescence and optically stimulated luminescence when the phosphor is bright, dSiPM can be used.

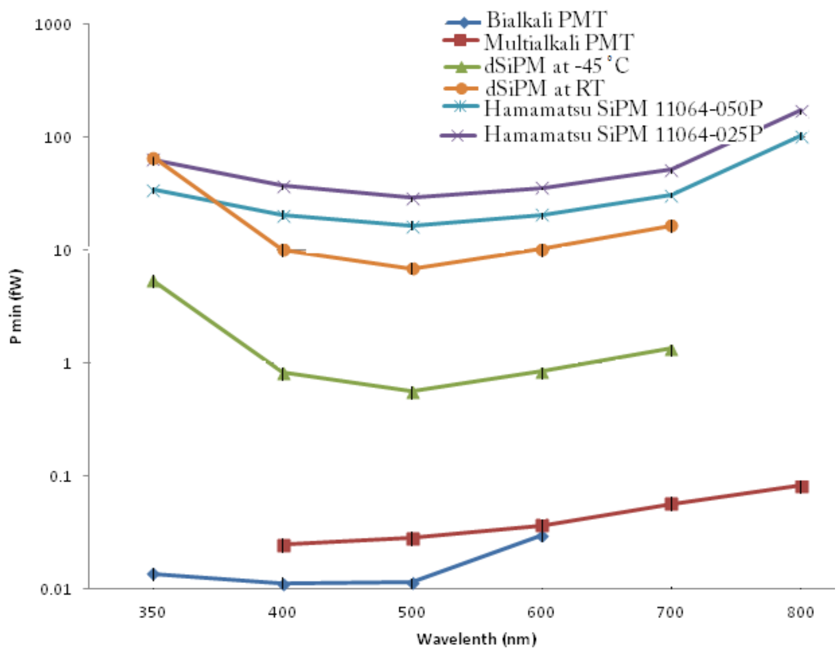

Fig. 2. Minimum detectable power verses wavelength for bialkali (blue sensitivity) PMT, multialkali (red sensitivity) PMT, SiPM, and dSiPM.

The use of SiPM for nuclear medical imaging applications has also been explored [22]. In applications like PET and radiation measurement, a scintillator is used to convert the radioactive emissions into light which is then detected by the light detector. Usually a PMT is used as the light detector. But SiPM is a better alternative for such applications because of their compact size, and because they have shown promising results in terms of energy and timing resolution when coupled to PET scintillator crystals [23]. In such applications the choice of the scintillator is important since the amount of light emitted depends on it. The different scintillator material like BGO, LSO, YSO, GSO, BaF_2, NaI emits 6, 29, 46, 10, 2, and 38 photons/KeV respectively. The PET camera should be able to detect coincident pairs of 511 keV annihilation photons. For this requirement dSiPM can be employed. For the 'time-of-flight' PET scanners, accurately determining the time at which the first photon arrives at the detector is extremely important. Philips' digital silicon photomultiplier prototypes achieve a timing accuracy for the detection of the first photon of around 190 ps (full-width, half-maximum using a standard scintillator crystal (LYSO) at 511 keV for two detectors in coincidence). The planar nature of the silicon photomultipliers allows them to be closely coupled to suitable scintillator materials for the detection of nuclear particles and high-energy electromagnetic radiation [24].

The dSiPM can replace SiPM in most of the applications due to its lower dark counts and other features. dSiPM can also be used to obtain the image of the light spread over the sensor area. Such facility can be used for applications like verification or fine-tuning of a light guide design [25]. As per the need of the application the detector area could be reduced by de-activating the excess area. This has the advantage of lowering the dark counts, as the dark counts are directly proportional to the detector active area.

Other applications for Philips digital silicon photomultipliers include fluorescence-based DNA sequencing, protein/DNA microarray assays, surveillance systems and night-vision systems [24]. In fact, dSiPM can be used for many applications that currently use photomultiplier tubes for the detection of moderate low light fluxes.

5. Conclusion

Silicon Photomultipliers (SiPMs) overcomes some of the drawbacks of other solid state detectors and PMTs, but still do not exploit the intrinsic performance of Geiger-mode cells due to parasitic capacitances and inductances of the interconnect, the influence of electronic noise and the sensitivity to temperature drifts. The Digital Silicon Photomultiplier (dSiPM) overcomes these problems by the early digitization of the Geiger-cell output and integrated electronics on chip. The development of digital silicon photomultiplier is still going on and with the advancement in technology; the dSiPM may prove to be a good alternative to PMT in many applications.

Acknowledgement

The authors would like to thank Prof. A. K. Singhvi at the Physical Research Laboratory, India for the valuable discussions on various light detectors.

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Guide for Contributors

Aims and Scope

Sensors & Transducers Journal (ISSN 1726-5479) provides an advanced forum for the science and technology of physical, chemical sensors and biosensors. It publishes state-of-the-art reviews, regular research and application specific papers, short notes, letters to Editor and sensors related books reviews as well as academic, practical and commercial information of interest to its readership. Because of it is a peer reviewed international journal, papers rapidly published in *Sensors & Transducers Journal* will receive a very high publicity. The journal is published monthly as twelve issues per year by International Frequency Sensor Association (IFSA). In additional, some special sponsored and conference issues published annually. *Sensors & Transducers Journal* is indexed and abstracted very quickly by Chemical Abstracts, IndexCopernicus Journals Master List, Open J-Gate, Google Scholar, etc. Since 2011 the journal is covered and indexed (including a Scopus, Embase, Engineering Village and Reaxys) in Elsevier products.

Topics Covered

Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

- Physical, chemical and biosensors;
- Digital, frequency, period, duty-cycle, time interval, PWM, pulse number output sensors and transducers;
- Theory, principles, effects, design, standardization and modeling;
- Smart sensors and systems;
- Sensor instrumentation;
- Virtual instruments;
- Sensors interfaces, buses and networks;
- Signal processing;
- Frequency (period, duty-cycle)-to-digital converters, ADC;
- Technologies and materials;
- Nanosensors;
- Microsystems;
- Applications.

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