SILICON PHOTOMULTIPLIERS AND THEIR APPLICATIONS FOR DETECTION OF LIGHT

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Silicon photomultiplier is a detector capable of detecting single-photon events. Its predecessors PIN and Avalanche photodiodes do not posses that ability; a Photomultiplier tube, while possessing that ability, has other disadvantages. This article deals with the evolution of photosensors from PMTs to SiPMs, differences in their construction and properties. As SiPMs have high noise signals, some solutions to minimize their impact on measurements are presented. At the end some applications using SiPMs are listed.

SILICIJEVE FOTOPOMNOŽEVALKE IN NJIHOVA UPORABA ZA DETEKCIJO SVETLOBE

Silicijeve fotopomnoževalke so detektorji, ki lahko zaznajo posamezne fotone. Njihovi predhodniki – PIN in plazovne fotodiode posameznih fotonov ne morejo zaznati, fotopomnoževalne tube pa lahko, vendar imajo druge slabosti. Članek predstavlja razvoj fotosenzorjev od fotopomnoževalk (PMT) do silicijevih fotopomnoževalk (SiPM) ter razlike v njihovi zgradbi in lastnostih. Ker pri SiPM detektorjih težavo predstavlja visok šum signala, je predstavljenih nekaj rešitev, kako zmanjšati njegov vpliv na meritve. Na koncu je navedenih še nekaj aplikacij, ki uporabljajo silicijeve fotopomnoževalke.

1. Introduction

Visible photons, created in nuclear or other physical reactions, can be detected with photodetectors. Although there are many different types of light sensors, all of them convert incident photons into electrical current. This article focuses on a photoemission type of photodetectors, more specifically on Photomultipliers.

The well known kind of such detectors are Photomultiplier tubes – PMTs. They have been around since 1930s [1] (commercially, the first patent dates to 1916 [2]), which provided their development with plenty of time for improvement. They are able to detect individual photons. Their disadvantages (e.g. complicated design and high-voltage requirement) gave incentive to further search for alternatives. Solid-state semiconductor detectors were next successful sensors (like PIN photodiodes and Avalanche photodiodes – ADPs), however their main fault is the inability to measure single photons since at least 100 for PIN and 20 photons for APD are required for such a measurement [2]. This article will focus on the most recent alternative, Silicon photomultipliers – SiPMs. Their lower cost and smaller size compared to PMTs makes them more accessible and therefore a good subject for research and use in applications even outside of physics.

2. Photomultiplier tubes

Photomultiplier tube is a vacuum phototube, which consists of a photocathode, focusing electrode, several dynodes and an anode (Figure 1). When a photon hits the photocathode, it emits an electron via the photoelectric effect. This electron, which is called a primary electron, is then directed through the focusing electrode to a series of dynodes. When a primary electron hits the first dynode, more electrons are emitted from the surface of the dynode via secondary emission – they are called secondary electrons. These electrons accelerate to the second dynode and each one of them emits more secondary electrons. The process is repeated several times and creates an avalanche of electrons with enough momentum to hit an anode and trigger a signal strong enough to be measured [1].

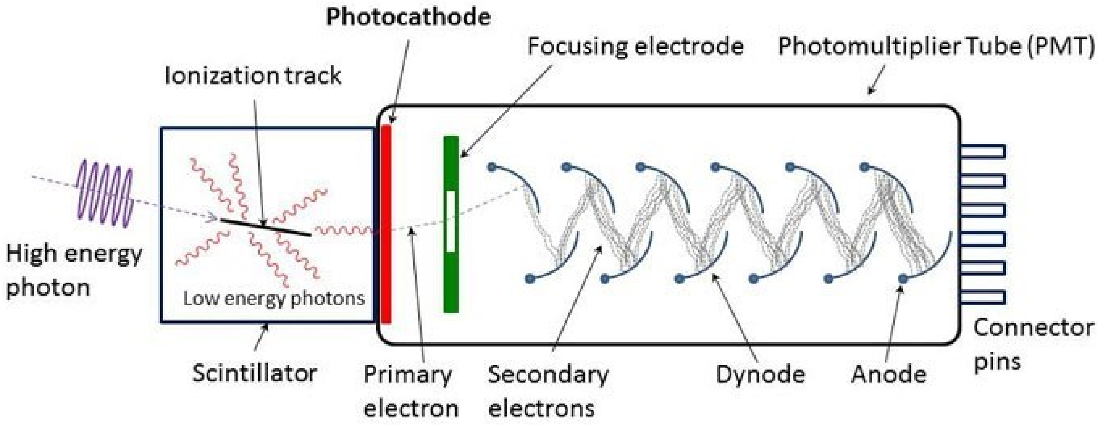

Figure 1. Photomulitplier tube coupled to a scintillator [1].

Primary electron, when emitted, has a low energy (around 3 eV), which is not enough to allow for emission of more electrons. The PMTs are under high negative voltage (order of 1000 V) so that electrons are accelerated between dynodes. Between each pair of dynodes is around 100 V of potential difference enabling the sufficient acceleration of each electron, so that it can hit around 5 secondary electrons out of dynode. That is how at the end a signal equivalent to approx. 10^6 electrons is obtained [1].

The height of the signal at the end is proportional with gain (G) and number of successfully detected photons. Twice as many photons means doubling the signal's height. Gain depends on number of dynodes (n) and secondary emission yield (g) – how many secondary electrons can one primary electron emit with secondary emission [3]. Dependence is exponential [4].

$$G = g^n \tag{1}$$

An important parameter when using photoelectric effect is quantum efficiency (QE). It expresses a number of photoelectrons ejected from photocathode per incident photons, which is dependent on energy of incident photon and material a photocathode is made of [5]. In the early stages of PMTs development the best detectors had a QE at order of 10–20% [1].

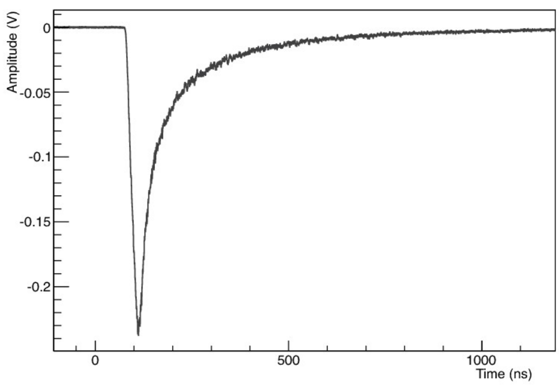

Figure 2. Example of a waveform of the PMT signal [6].

Another important factor of photo detectors is photo detection efficiency (PDE). It is defined as a product of

$$PDE = QE * CE, \tag{2}$$

where CE is a collection efficiency – probability of a primary electron to trigger an avalanche. PDE has a strong dependency on wavelength and for a typical PMT ranges from 20% to 50%.

One of the advantages that PMTs have is their fast response. A large number of electrons reaching the anode results in a pulse signal with a rise time of a few ns and a width of order of 10 ns (Figure 2) [7]. This fast reaction time allows for a detection of different incident photons and determination of single-photon events as just one photon is enough to trigger a signal of a few million electrons (because of a high gain property). Another advantage is having a wide spectrum of detection, from UV to the near infrared light [1]. This could mean a downside in measuring a specific type of light but can be fixed by adjusting the type of photocathode used in a PMT. A dependence of QE to wavelength (which corresponds with energy of an incident photon) of different materials can be used to detect a desirable wavelength (Figure 3).

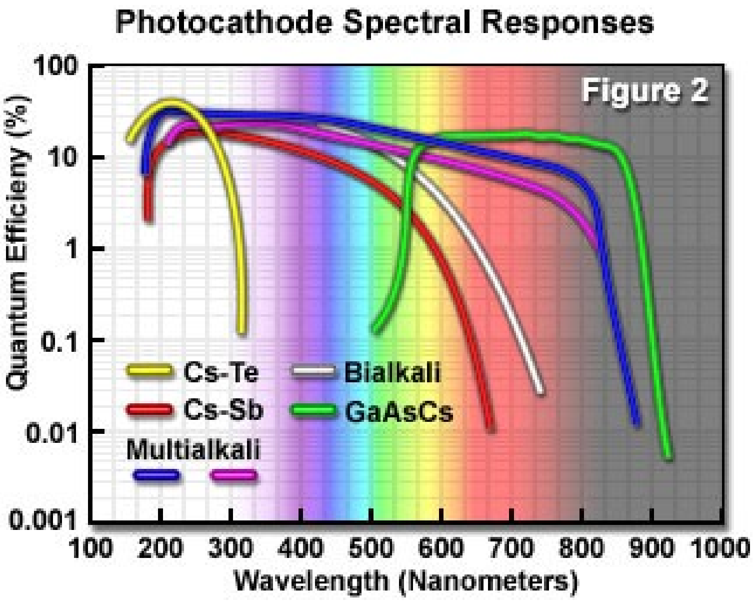

Figure 3. QE dependence to wavelength for a few photocathode materials [8].

The first disadvantage of Photomultiplier tubes is their size. PMTs are enclosed in vacuumed glass-to-metal sealed tubes in order to prevent any unwanted interaction between particles. Should some kind of gas got inside the tube, the electrons would hit gas molecules and cause them to ionize, which would result in ions corrupting the signal. Depending on an application PMTs can vary from a size of around 10 to more than 50 cm (experiment Kamiokande in Hida, Japan). Another downside can be their high voltage requirement. Since an electro-potential difference is used to accelerate electrons, these photomultipliers are called electrostatic. As a layout geometry of dynodes is important, tubes are not effective in a magnetic field which curves the path of electrons so they can miss the next dynode. To bypass that obstacle a research in magnetic photomultipliers was made to intentionally use magnetic field to direct electrons form dynode to dynode. That only happened in early ages of development, though [1].

In experimental physics, noise is always one of the problems. A photon background can trigger a detector even though the experiment did not produce any photons. Next, with photocathode under high voltage there is a possibility of photocathode emitting an electron even with no photon to trigger a photoelectric effect. That can be an effect of thermodynamic fluctuations [1]. Lastly, all the electronics used in PMTs can have their own noise sources. All these unwanted signals can be combined into what is called signal-to-noise ratio, which is defined as height of a signal divided by height of a noise signal. This quantity basically describes to what extent the noise is present. The problem of noise can be minimalized with a constant signal current running through PMT and with a low-pass filtering [4].

PMTs can be used in combination with scintillators for detection of gamma rays and other particles. As a high-energy particle enters into the scintillator (as shown in Figure 1), it produces low-energy photons with enough energy to be detected with PMT without causing any radiation damage to it. This kind of a coupled detector is commonly used in high-energy physics (particle experiments), medical physics (gamma cameras) and astrophysics (the previously mentioned Kamiokande experiment).

An interesting fact is that in the beginning of commercializing the production of photomultiplier tubes there were a few companies that made a name for themselves by producing and developing PMTs, for example RCA (Radio Corporation of America), Burle Industries (both in America, first in 1940s, second in 1980s) and Hamamatsu Photonics (Japan, the biggest manufacturer in this field, from 1950s) [1].

3. Before Silicon Photomultipliers

As mentioned in the introduction, researchers have been looking for an alternative to Photomultiplier tubes as they are excessively big and expensive. Evolution of photosensors lead to smaller semiconductor detectors. Such sensor uses a p–n junction to convert incident photons into electrical current. First semiconductor detectors used in experiments were PIN photodiodes (in 1950s), which have a wide intrinsic region between both parts of the junction for a better detection of photons. One photon equals to one emitted electron, therefore a lot of photons must be detected for a readable signal. Later, Avalanche photodiodes (APDs) were introduced as a first real analog to PMTs, using a multiplying effect. When a photon hits an electron in a valance band, it gains energy to jump into a conduction band (photoelectric effect), hence forming an electron-hole pair. As this primary electron accelerates due to a high reverse bias voltage (around 100 V), it causes impact ionization (also known as avalanche effect) – hitting another bound electron and promoting it into a conduction band, again creating an electron-hole pair. Repeating this process results in an avalanche of electrons giving a detectable signal.

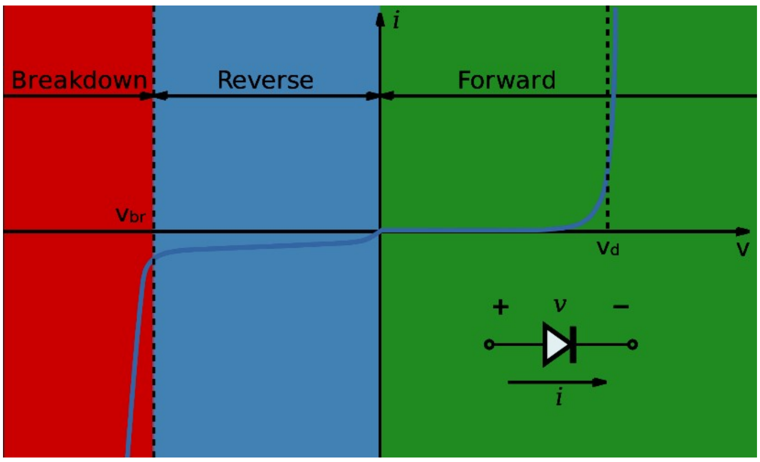

Figure 4. I(U) curve for a APD [10].

APDs have a gain of only around 10^2. Both PIN and APD are smaller and more robust than PMTs and require lower supply voltage. They operate in a so-called linear mode where gain is linearly proportional to increasing voltage (the blue zone in Figure 4) [9]. Their main disadvantage is inability to detect single-photon events [2].

Semiconductor detectors are sensitive to temperature changes. Because of thermal fluctuations the unwanted dark current appears – an electron starts an avalanche without external photon hitting it. That happens because of thermodynamics as room temperature offers enough energy to make electrons jump from valance to conduction band. This can happen as frequently as a few kHz. Therefore APD constantly leaks some current, which makes observation of experiments harder as more than just one photon emission is necessary to trigger a detectable signal (it needs to be distinct from noise).

In the 1970s Single-photon avalanche diodes (SPADs) started to show promising results [2]. The main difference between APD and SPAD is that the latter is designed to operate with reverse-bias voltage well above the breakdown voltage (V_{br}, the red zone shown in Figure 4). This kind of operation is called Geiger-mode [11]. SPADs are capable of triggering a short-duration but relatively large signal as they have a similar gain to PMTs (order of 10^6) [9]. The size of the detector became a whole scale smaller, to a mm and later to a few 100 μm [2].

A signal on a SPAD can be triggered by a single photon. An electron injected into a depletion layer triggers a self-sustaining avalanche. The current rises in less than a ns and remains at the steady level until the avalanche is quenched. This can be done passively by lowering the bias voltage with a resistor or actively with a fast discriminator which having sensed a step in current reduces the bias voltage below V_{br} and then relatively fast returns it back to the original. This active quenching can reduce the dead time (time required to wait before the next photon can be detected) [11]. Quenching is important as the maximum count rate (number of detectable events) with passive quench was smaller than 100 kHz. With active quenching count rate increases to over 1 MHz [2].

SPAD can be improved by applying a very thin layer of metal and a resistive layer (e.g. one of silicon oxides) on top of the sensor as an additional quenching area. Combining this kind of SPADs into an array (each SPAD is then called a cell and represents one pixel), implementing them onto a common silicon substrate and connecting them all in parallel via an 50 Ω resistor results in a SiPM sensor (Figure 5) [2].

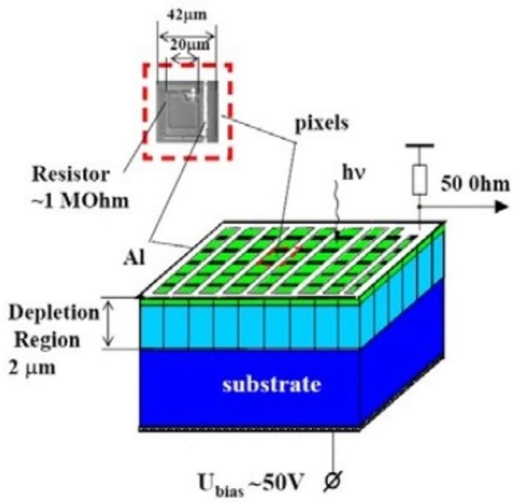

Figure 5. Structure of a SiPM [2].

4. SiPM

Silicon photomultipliers are detectors closest to Photomultiplier tubes in terms of quality. They are an ordered cluster of SPADs (in Figure 5 represented with pixels). The size of a single SPAD can vary from 10 to 100 µm so the whole SiPM sensor can be as small as a few mm [12]. Like PMTs, SiPMs are able to detect single-photon events which has been a major development in experimental photo-detection physics. They have the same or wider spectral range from UV to infra-red light.

Figure 6. Size comparison of a PMT and a SiPM [15].

Photo detection efficiency (PDE) is calculated differently for semiconductor detectors than for PMTs, namely as a product of

$$PDE = QE * FF * P_t, \tag{3}$$

where QE is a quantum efficiency of silicon, FF is a fill factor (sometimes marked as ε) – same as space efficiency (defined as an active area of a detector divided by the total area that the sensor takes) and P_t is probability of a photon to actually trigger the detection (not all the photons are detected) [2, 13, 14].

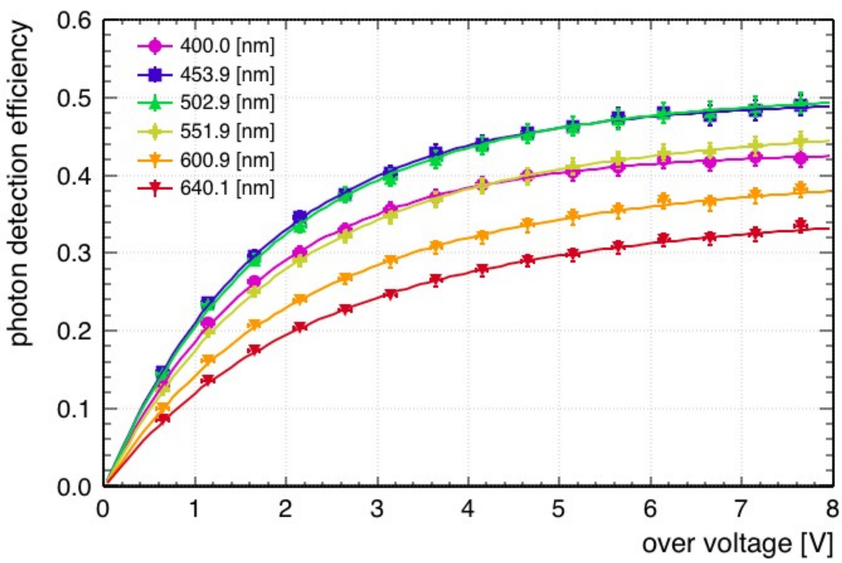

Figure 7. Dependence of PDE to overvoltage [16].

In comparison to a traditional PMT, a SiPM is much smaller (a few mm^2, see Figure 6), but the fill factor depends on size of a single cell and ranges from 30 to 80%. Maximum quantum efficiency of a SiPM can reach (depending on wavelength, of course) up to 90%, but overall PDE ranges from 20 to 35% and is thus comparable to PMTs. There is a notable difference in necessary power supply: while PMTs require a high voltage of $\sim$ 1000V, SiPMs need somewhere between 20V and 100V breakdown voltage (depending on the product). This means a lower power consumption and easier handling. Gain of a SiPM is similar to a PMT, being around 10^5, but it can be increased by adding higher voltage, so-called overvoltage (order of a few V, see Figure 7), resulting in a higher (and easier to detect) signal. Dependency is linear: doubling the overvoltage results in doubling the amplitude of the signal [2, 12, 13, 14].

SiPMs have a good time resolution of 100–300 ps, due to their small size (thin silicon layer) and active quenching. They are not affected by magnetic fields and their temperature dependence is not as significant as in previous detectors. Compared to PMTs, SiPMs are light, robust, extremely compact and easy to use. Their production is also very cheap, around 10 € per cm^2 [2, 12].

4.1 Disadvantages/problems

As simple and practical as SiPM sensors are, they are still far from perfect. Their biggest weakness is their high noise signal. Crosstalk, dark count and afterpulsing are one of parameters adding to the noise.

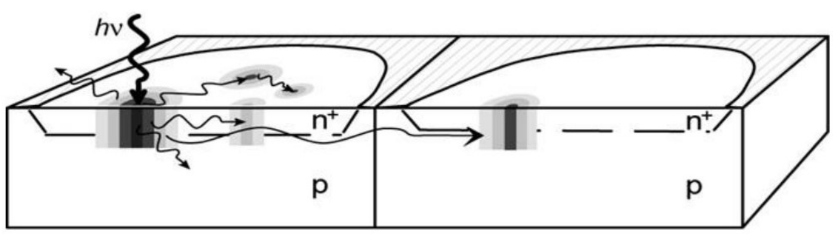

Figure 8. Optical crosstalk [2].

The small size of SiPMs and their array composition can result in what is called optical crosstalk (Figure 8). When a photon hits one cell, the resulting avalanche can emit more visible photons that can trigger the neighbouring cells. This is then mistakenly read as a signal equivalent to more photons even though there was only one external-photon hit. Putting a little extra isolating space between each cell can lower the possibility of crosstalk; these spaces are called tranches. This however worsens the fill factor of a detector. The other factor that can limit the crosstalk is lowering the temperature and gain; the bigger avalanche enhances the chances of producing more photons, therefore a limited gain has been shown to reduce the crosstalk [2, 13].

SiPMs are made of semiconductor silicon and in every semiconductor there are, naturally, thermodynamic fluctuations. A signal can be triggered by an incident photon or by generating a free charge carrier. The latter causes dark counts, and signals produced by them occur at rates of several MHz per mm^2, thus constituting the main factor of background noise. Although the gain increases with overvoltage, so does the dark count – when applying too much overvoltage the noise signal overshadows the photon one. This can become a problem in detectors with large surfaces ($\sim cm^2$) or in experiments with small light intensities. As this is due to the thermodynamics, the dark count can be significantly reduced by lowering the temperature. By putting the sensor in a liquid nitrogen ($\sim$ 77 K) the dark count of 1 MHz per mm^2 at room temperature is lowered to only 1 kHz per mm^2 [2, 14].

Afterpulsing (see Figure 9) is another noise factor. An additional signal can be caused if a charge carrier somehow traps itself bellow the conducting band and continues its path after a short time delay. It does not affect the signal as strongly as the previous two factors but it causes recovery time to prolong. Recovery time is, similarly to dead time, necessary waiting time before another photon can be detected. A cell, after an avalanche breakdown has been quenched down, needs to recharge. How fast can that happen mostly depends on the cell size and its resistivity. It can take up to a few µs for a SiPM to cool down enough for the next signal's height to reach 95% of the first signal's height [2]. Afterpusling and recovery time can be reduced by lowering the gain and using metal alloy with higher resistivity (e.g. FeCr) instead of a temperature-variable resistor like silicon [2, 12, 13, 14].

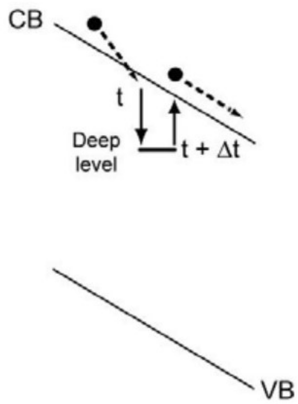

Figure 9. Mechanism of afterpulsing [2].

Like most photodetectors, SiPMs are used mainly in high energy physics (in experiments like LHC). In such environments detectors are exposed to large amounts of radiation dose, e.g. in upgraded LHC detectors are expected to receive a dose equivalent to $\sim 10^{14}$ neutrons per cm^2 in their lifetime [17]. As there are many particles running through sensors, the lattice structure of silicon and other components can get damaged, which can result in a change in a number of properties: gain and PDE are lower and higher overvoltages are necessary to achieve the same efficiency. The time resolution and amount of crosstalk do not change, but the height of the signal decreases. Meanwhile, the dark count and height of the noise signal increases. The change each property undergoes depends on a product itself [17, 18, 19].

4.2 Applications of SiPMs

As mentioned before, SiPMs are one of many detector types used in high energy physics experiments like LHC. Their low price and robust design makes them practical to use in tracking systems, calorimeters and basically everywhere where photosensors are needed; as their development progresses further their role is expected to become even more prominent. Since they are small and have fast response and quench time they offer a good spatial and time resolution. Even in highly radiated environment, where individual sensors might become damaged, it should be easy to substitute them with new ones. Apart from their role in colliders and accelerators, SiPMs are also used as photosensors in astrophysics: in telescopes for detection of cosmic rays, two examples being MAGIC telescope on Canary Islands and JEM-EUSO project on International Space Station.

SiPMs are also used in medicine physics: for the purpose of medical imaging in Positron emission tomography (PET) and Single-photon emission computed tomography (SPECT). PET helps radiologists in their detection processes by taking advantage of the ability to detect single-particle

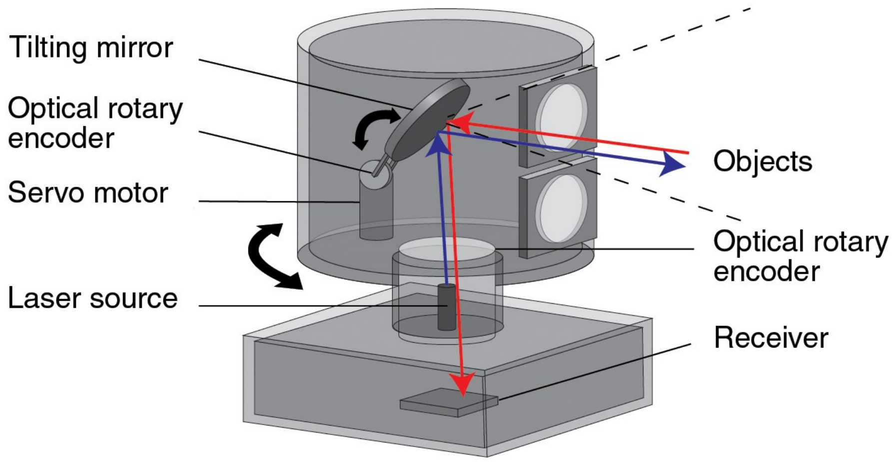

Figure 10. Optical sensor used in LIDAR [20].

emissions to detect positrons from radioactive decay of e.g. fluorine-18 in the body of a patient. SPECT uses high sensitivity of SiPMs to detect gamma rays from a gamma-emitting radioisotope that are inclined to bound to a certain type of tissue. SiPMs are used in gamma detectors, dose meters, isotope identifiers, x-ray scanners, neutron detectors etc.

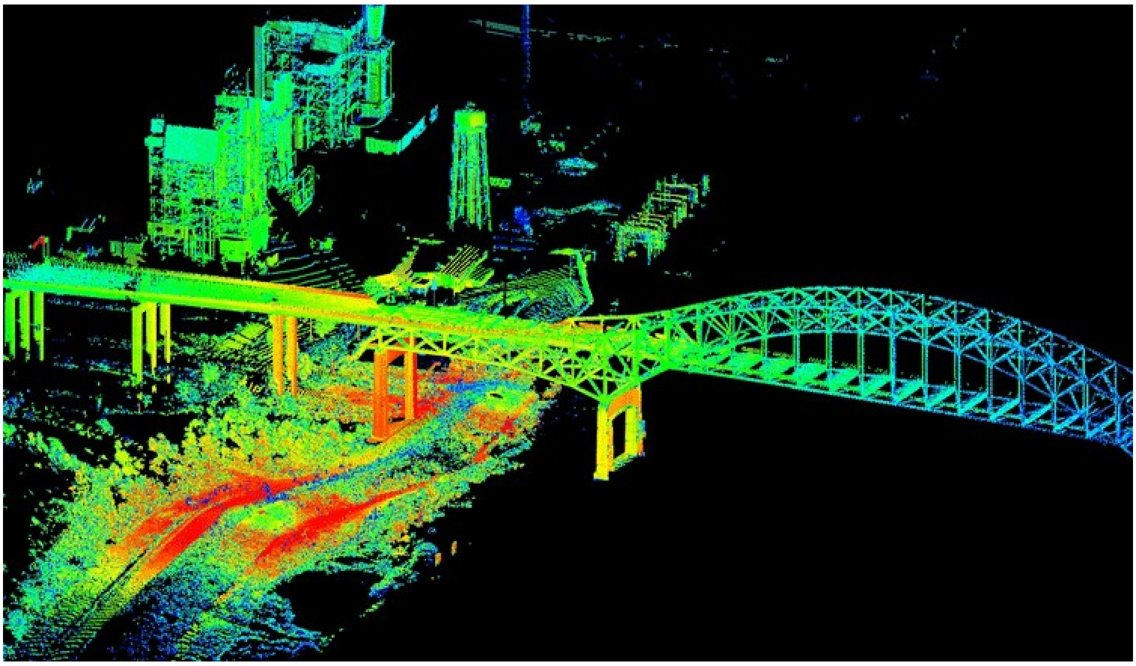

Figure 11. Picture made with LIDAR from a drone [23].

Another practically oriented use still waiting to be widely recognised is LIDAR (Light Detection and Ranging) technology and 3D ranging, which manufacturers hope to make mainstream. LIDAR scanning system (Figure 10) uses laser to shoot a photo beam which reflects from an object back into the scanner and can determine the distance of the object by calculating the travelled time. This kind of scanning uses single-photon sensitivity, fast response, low power consumption and low temperature dependence of SiPMs to enable long-distance ranging useful for autonomous vehicles, cartography, drones and robotics (Figure 11). One of the problems that needs to be taken care of is lowering the sensitivity of SiPMs in visible spectrum since detecting all the light would lead to overloading the detector [21, 22].

5. Conclusion

SiPMs represent an important step forward in photo detection physics as their high sensitivity and low cost both make them a fine substitute for Photomultiplier tubes, which have been in use for nearly a century. Some of their properties, e.g. dark current and radiation resistance, could be improved further, but even in the present state they still preform better that their predecessors APDs. Mainly used in particle physics (for detection of photons in experiments like LHC and KEK) they contributed greatly to improvements in medical physics, making procedures cheaper and medical equipment easier to manage. Manufacturers of SiPMs hope that over time their commercial use becomes important and widely implemented into everyday technology.

6. Acknowledgement

I would like to thank my mentor dr. Rok Pestotnik for explanations that helped me to better understand some physical principles as well as suggestions for improvements to the article's content and expanding the list of references.

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