The Silicon Photomultiplier - A new device for High Energy Physics, Astroparticle Physics, Industrial and Medical Applications

N. Otte
Max-Planck-Institut für Physik, Föhringer Ring 6, 80805 Munich, Germany

since a few years a novel photon detector concept is being developed which is based on a matrix of densely packed small avalanche photo diodes operating in the limited Geiger mode with a common readout line. In this paper I review the operation principle of the detector concept. I discuss characteristics of the device as well as some of the ongoing developments and one example of a very promising application, namely PET.

1. Introduction

Quite a few of the next generation experiments that are planned in high energy physics and astro particle physics will have a need for a large number of photon detectors. For example, the hadron calorimeter for the detector facility at the planned International Linear Collider needs more than 1,000,000 photon detectors for the necessary granularity of the detector [1]. Besides the large number of sensors, the requirements of single photon sensitivity, large dynamic range, inaccessibility during the lifetime of the experiment and others put additional constraints on the sensor:

- low sensitivity against temperature and bias fluctuations
- very compact
- very robust
- cheap
- insensitive to magnetic fields
- no aging over years
- radiation hard
- very low response to passing ionizing particles (low "nuclear counter effect")
- ...

Similar conditions have to be fulfilled by photon detectors for Astro Particle Physics Experiments like the ground based gamma ray experiment MAGIC [2] or possible future space missions like the proposed EUSO [3] mission for detecting cosmic rays with energies around the GZK cutoff (above 10^{19} eV). In both applications a very high Photon Detection Efficiency (PDE), in the near UV to the blue wavelength region, is needed.

A promising photon detector for the above requirements is the so-called Silicon Photomultiplier (SiPM) also called Geiger mode APD or Micropixel avalanche photon detector. This type of novel photon detector is still in its development phase. During the last two years this new device underwent major improvements. The development has reached a level at which many different groups now consider the application of SiPM in demanding physics application.

In this paper I will discuss the operation principle of this novel device and summarize some of the ongoing developments. In the last part I will as an example discuss the use of SiPM in another field, i.e. its application in positron emission tomography (PET); which has been receiving considerable interest in the last two years.

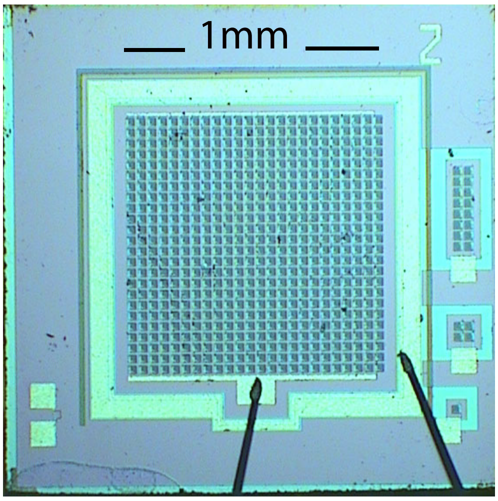

Figure 1: Picture of a SiPM. The pictured device consists of 24×24 small avalanche diodes. This device has been produced by MEPhI [4].

2. From the Single Cell limited Geiger Mode Avalanche Photon Detectors to the Silicon Photomultiplier

In this section I will describe the different operation modes of semiconductor avalanche photon detectors, and how the idea of the SiPM has evolved.

2.1. The classical APD operated in the proportional Mode

Avalanche Photo Diodes (APDs) in proportional mode are photon detectors with very high detection efficiencies, a large dynamic range and a gain ranging between 10 to a few hundred. The pn–junction of an APD is biased in reverse mode slightly below the breakdown voltage. APDs have an excess noise factor >2, due to the statistical nature of the multiplication process. The large excess noise factor allows by no means to separate the first photoelectron peak from the pedestal. The proportional mode is therefore only of constricted use in single photon counting applications.

APDs operated at high gain, i.e. close below breakdown, show a strong dependence of the gain on temperature and bias voltage (e.g. 3% change in gain per one volt difference in bias supply and -2.2% change in gain per one degree temperature difference both at a nominal gain of 50 [5]. This is a specific example. In general characteristics are strongly device dependent). This requires, in practice, very good temperature and bias voltage stability. Another constraining factor is the limited internal gain of proportional APDs ($<$ 1000), which requires low noise amplifiers for readout, restricted operation bandwidth, and special precautions to prevent pickup.

2.2. Small area APDs operated in the limited Geiger Mode

Limitations in gain and most of the stability problems can be avoided in small area APDs by operating them in the limited Geiger mode instead of in the proportional gain mode, i.e. by increasing the bias voltage slightly (10%–20%) above breakdown voltage. In this mode, a single electron can trigger a diverging avalanche multiplication process. In contrast to the proportional mode, where basically only electrons generate additional electron hole pairs, the avalanche in the limited Geiger mode is diverging because both electrons and holes actively participate in the multiplication process. A constant current is flowing through the junction. If the current is limited to below a critical value, the current flow is disrupted (quenched) due to statistical fluctuations within a few picoseconds after the breakdown has started. A simple way to achieve this is by inserting a high Ohmic resistor in series to the diode. After quenching, the resistor prevents an instantaneous recharge of the diode capacitance and an instantaneous reset to the initial bias above breakdown. Due to the diverging nature of the multiplication, any information about the primary signal (i.e. the number of generated photoelectrons) that initiated the breakdown is lost. The device is operating in a binary mode.

A different method of quenching the breakdown is by using a dedicated electronic circuit that lowers the bias voltage below the breakdown voltage for a certain period of time until the breakdown is quenched.

The limited Geiger mode is only useful for very small area avalanche diodes because besides free electrons being generated by the photoeffect, electron–hole pairs are constantly generated thermally. Thermal generation rates of 6×10^8 per second per cm^2 can be achieved at room temperature for 450μm thick fully depleted silicon. Traps are another source of charge carriers. In combination with the recovery time of the diode these effects set an upper limit to the area of the diode.

APDs operated in the Geiger mode have the advantage of large, well defined output pulses ($10^5 \ldots 10^7$ electrons, depending on the overvoltage and diode capacitance) per breakdown, and can be used for "single photon counting". Therefore, such APDs are often referred to as Single Photon Avalanche Counters (SPADs). SPADs have been commercially produced for approximately twenty years but have not achieved widespread use. In fact, SPADs are only found in applications that require low rate single photon counting, and where a small size detector is sufficient (typically 100 to 10,000 μm^2 sensitive area). Due to their inability to resolve the number of primary photons, respectively photoelectrons, SPADS can, e.g. not be in calorimetry. A more detailed discussion about the physics, quenching methods and history of APDs in Geiger mode can be found e.g. in [6].

2.3. The multicell APD operated in limited Geiger mode

In the 1990ies a new photon detector concept was invented (in the former Soviet Union) that made use of the advantages of limited Geiger mode and, at the same time, allowed to retain over a large dynamic range the information on the number of primary photoelectrons see [7–9] or for a recent review [10].

In this detector concept a densely packed array of typically 100 up to 10,000 SPADS per mm^2 is fabricated on the same substrate. Each SPAD has its own miniature, integrated quenching resistor. In addition, all SPAD–resistor combinations (called cells thereafter) are connected in parallel to a common bus (s. right panel in Figure 2). The output signal of the device is the analog sum signal of all "fired" cells. Figure 2 shows in the left panel the top view of four cells of such a device. Note that each photosensitive area is surrounded by some strip of insensitive material separating cells from each other. Figure 1 shows a photograph a (1×1)mm^2 device that comprises 576 such cells, each of $(42 \times 42)\,\mu$m^2 area.

Since the late 1990ies the development has diversified and many prototype devices exist nowadays. To

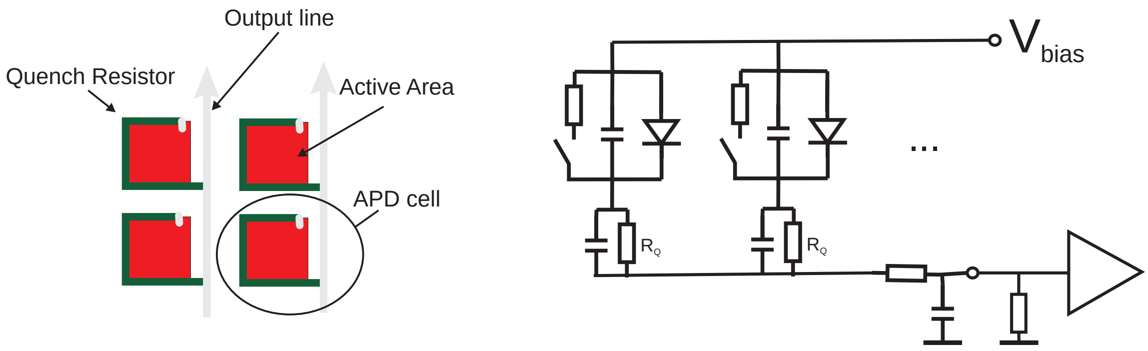

Figure 2: The left panel shows a sketch of 4 cells of a SiPM. Each cell consists of a photo diode and a quenching resistor that is connected in series between the diode and the readout line. The right panel depicts the simplified replacement circuit of a SiPM. Shown are two cells of a SiPM. The low pass filter on the lower right side pictures the network of aluminium lines for signal transmission within the SiPM. The amplifier and load resistor on the right side do not belong to the SiPM.

date the device has as many names as there are ongoing developments. Widely used are Metal Resistive layer Semiconductor (MRS-APD), Silicon Photomultiplier (SiPM), Multi Photon Pixel Detector (MPPD), Micro–Cell APD, Geiger APD, Digital Pixel Photo Diode (DPPD), micro-pixel/channel avalanche photodiode (MAPD), ... In the course of this paper I will use the name SiPM as a synonym of the many different types making use of basically the same principle.

3. Characteristics

In this section the most important characteristics of SiPMs (Dynamic Range, Photon Detection Efficiency, Dark Counts and Optical Crosstalk) are discussed.

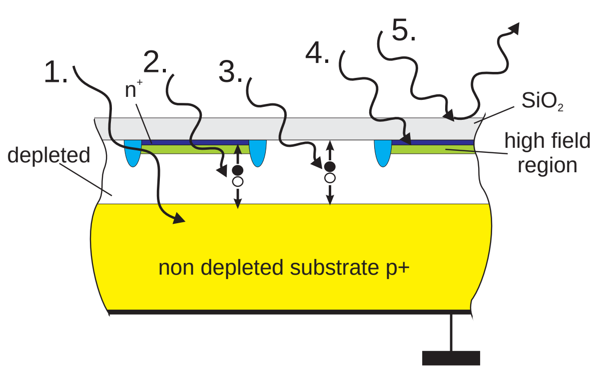

Figure 3: The drawing shows different scenarios that can occur when a photon hits a SiPM: 1. Absorption of the photon in the non depleted substrate; 2. Absorption in the depleted region and subsequent drift of the photoelectron into the high field region; 3. Absorption between two cells; 4. Absorption in the SiO_2 or non-depleted implantation below the surface; 5. Reflection on the surface

3.1. Photon Detection Efficiency

The efficiency to detect photons with a SiPM is usually characterized by quoting the overall photon detection efficiency (PDE). This is in contrast to e.g. the characterization of photomultiplier tubes, where usually the quantum efficiency of the photocathode is quoted and additional losses are neglected[1]. The PDE is a convolution of several contributions. The most important ones are shown in Figure 3 and explained in the following:

Quantum Efficiency (QE) is defined as the average number of electron–hole pairs created by conversion of one photon in the depleted layer of a semiconductor [11]. For photon energies above the band gap of the semiconductor (1.1eV in Silicon) the QE is unity and rises above unity if the energy of the photoelectron is sufficient for impact ionization (photon energies >3.6eV in Silicon). Photons with short wavelengths (<400nm) will mostly be absorbed just beneath the silicon surface within less than 100 nm. If the absorption takes place in the highly doped top implantation layer below the surface, the generated electron/hole pair is most probably lost due to the very short recombination times. The fabrication of the very shallow p^{++} (n^{++}) top layer is one of the challenges of producing blue, respectively UV sensitive photon detectors. If, on the other hand, the photon energy is too low (red, respectively IR light), the photon penetrates deeply into the silicon and is mostly absorbed in the non-depleted bulk, or traverses the detector without interaction. Therefore, red,

[1]e.g. the non perfect collection of photoelectrons onto the first dynode of the photomultiplier

respectively IR sensitive photon sensors need thick depletion layers.

Losses at the Entrance Window due to reflection and absorption. These can be minimized by proper engineering of the entrance window, e.g. by the use of optically pure materials and appropriate nonreflective structures as an intermediate Si_3N_4–layer. More than 90% transmission can be achieved.

The effective Area , i.e. the ratio of the sensitive part divided by the total area, is less than unity as the physical separation of SPAD cells introduces considerable dead space. Existing devices have effective areas ranging from 25% up to 60%. Effective areas as high as 80% seem feasible in the foreseeable future. Illumination of the device from the backside might circumvent the limitations of a small effective area (see Section 4.3).

The Breakdown Probability is the probability for a single electron of triggering a breakdown. This depends very much on the electrical field strength in the junction. As saturation of the PDE is observed with increasing voltages applied, it is commonly believed that breakdown probabilities $\sim 100\%$ can be achieved for photo-generated charge carriers generated in front of the high field region [12]. The probability of a breakdown also depends on the type of charge carrier (electron/hole) that is entering the high field region. As holes can also initiate the avalanche breakdown it is not mandatory to have e.g. a p-on.n structure for blue (UV) sensitive devices.

The Recovery Time e.g. defined as the period of time until a cell is again fully sensitive after a breakdown[2], also has an influence on the detection efficiency for the following reason. After a SPAD cell has experienced a breakdown it needs a certain time $< \mu$sec to recharge. Triggered by dark noise and background light, typically $0.1\% \ldots 1\%$ of all cells are always in a state of recovery. Therefore, the effective area of the sensor is reduced. The decrease in PDE is normally negligible for low light level applications ($\mathcal{O}\,1\%$). It should be mentioned that the recovery of individual cells is frequently misinterpreted as the recovery of the device. The situation is different in case of intense light flashes or high rate applications when the average time between consecutive events becomes comparable to the recovery time.

[2]Note that the recovery time for a SiPM is different than the recovery time for a proportional mode APD. Because of the quasi digital nature of operation the recovery of a SiPM is conveniently defined as the recovery of a single cell of the SiPM, as the time that is needed until the amplitude of a consecutive signal is at least 90% of the previous pulse.

Among all mentioned effects the biggest today's impact on the PDE is the limited effective area. This holds generally true for devices that are composed of many cells with individual quenching resistors. Electrical separation between cells requires a few micrometers dead space. The highest reported PDEs are about 40% [13]. This is slightly below the geometrical occupancy of these devices. In back-illuminated SiPMs [14] deadspace is not an issue anymore. Therefore, very high PDEs ($> 80\%$) can be hoped for.

3.2. Dark Counts

Every free charge carrier that is entering the region of high electric field in a SPAD can trigger a breakdown. Thermally generated electrons are the dominant source of dark counts of SiPMs in state of the art devices.

Typical total dark count rates of current devices at room temperature are $10^5 \ldots 10^6$ counts per second and square millimeter sensor area. As the dark counts are dominated by thermal generation it can, in most cases, be adequately suppressed by a thin active volume and by moderate cooling. For example, for application of SiPMs in air Cherenkov telescopes for ground-based astronomy one expects that cooling down to $-20°$C will reduce the intrinsic dark count rate sufficiently below the irreducible background of the night sky background [15].

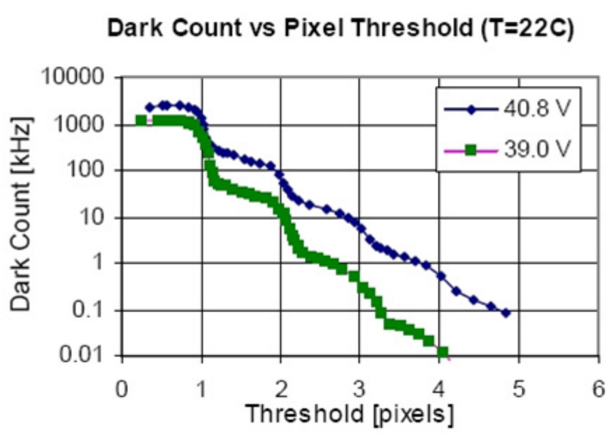

Figure 4: For two different bias voltages the dark rate versus the discriminator threshold is shown. This measurement demonstrates the strong dependence of accidental trigger rate on trigger threshold in SiPMs. Measurement from [16]

In other applications, e.g. Positron Emission Tomography, the discriminator threshold can be set comfortably above the single electron signal, and, therefore, a sufficiently low accidental trigger rate can be achieved already at room temperature. A measurement depicting the strong decrease of accidental trigger rate versus trigger threshold is shown in Figure 4.

3.3. Optical Crosstalk

A well known process in semiconductors is photon emission associated with the avalanche multiplication process. The origin of this emission is not fully understood. The situation is complicated by partially contradictory measurements e.g. [17, 18]. In [17] the authors can describe their measured emission spectrum above 1.7eV with black body radiation with an effective plasma temperature of 4000 Kelvin. The same authors have measured the efficiency of photon emission to be 3×10^{-5} photons per charge carrier crossing the junction during breakdown. In [18] the measured spectrum is steeper and the emission more intense.

In SiPMs, the hot carrier luminescence gives rise to an effect called optical crosstalk. Optical crosstalk appears when the luminescence photons can propagate unhampered within the device and might be absorbed in the sensitive volume of a different cell, thus triggering an additional breakdown.

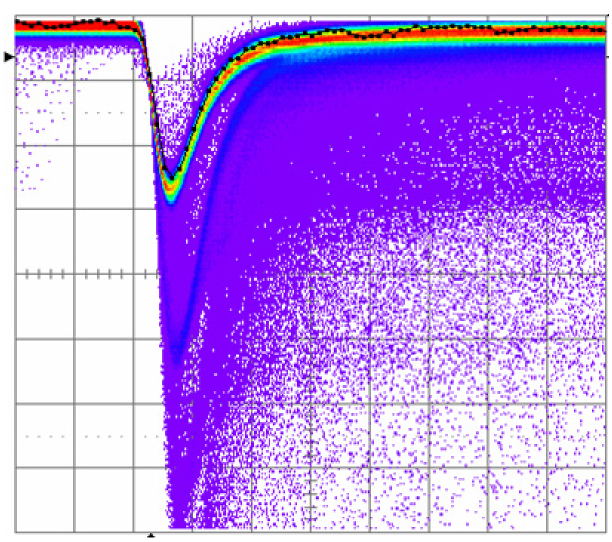

Figure 5: The picture shows, overlaid on top of each other, dark noise signals from a SiPM. Most of the time, only one cell of the SiPM gives a signal. With lower probability, 2, 3, or even more cells can fire simultaneously due to optical crosstalk.

The crosstalk effect is well demonstrated from noise count studies shown in Figure 5.

Luminescence photons can also trigger a neighboring cell if the conversion of the photon takes place in the non-depleted detector volume. In most applications this case is of minor importance, as most of the generated electron hole pairs are lost due to their too short lifetimes in the non-depleted volume. Furthermore, an additional breakdown initiated in this way can be regarded as being uncorrelated to the primary event.

3.3.1. Measures to be taken against Optical Crosstalk

One way to limit the effect of optical crosstalk is to reduce the number of charge carriers crossing the junction, i.e. to reduce the gain of the SiPM. In turn, one reduces the production of secondary photons. One obvious way to achieve this is to lower the bias voltage of the device. Although easy to do, it is unwanted because of the strong dependence of the breakdown probability on the bias voltage and, in turn, a lower PDE.

Another method is limiting the amount of charge crossing the junction by reducing all parasitic capacitances associated with the cell (pn–junction, quenching resistor,...). The reason is the linear dependence of the output signal on these capacitances. In most devices, reducing the cell capacity will result in a compromise between reduced optical crosstalk and PDE.

A third approach to avoiding direct optical crosstalk is to etch trenches between individual cells acting as optical barriers. This method has been applied previously on linear arrays of SPADs and has recently been successfully implemented in the SiPM production process at MEPhI [13].

3.4. Dynamic Range

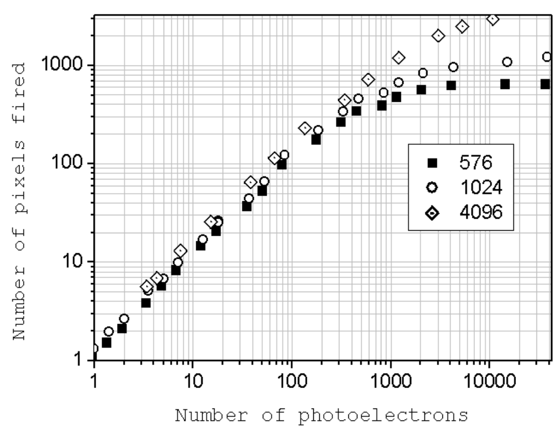

Figure 6: Response of three different SiPMs with 576, 1024 and 4096 cells as a function of generated photoelectrons (from [19])

From the device concept it follows that the output signal is not directly proportional to the number of photoelectrons but is influenced by statistical fluctuations of 2 or more photons hitting a single cell and eventually saturating at a value given by the number of available SPAD cells, as shown in Figure 6. Analytically the response can be derived by calculating for a given number of photoelectrons the average number of SPAD cells that will trigger:

$$N_{\text{fired}} = N_{\text{available}} \left[1 - e^{-\frac{N_{\text{phe}}}{N_{\text{available}}}} \right] \tag{1}$$

where N_{fired} denotes the average number of cells that trigger if on average N_{phe} photoelectrons are generated in a device with a total number of $N_{\text{available}}$ cells. From this relationship it follows that the output signal is deviating by more than 20% from linearity, if the number of photoelectrons is exceeding 50% of the available SPAD cells of the SiPM. The reason is a steadily increasing probability of multi hits of each cell. Strictly speaking, the relation only holds for very fast signals. For signals extended in time, late arriving photons can again trigger already hit but recovered cells.

At first glance, the saturation effect seems to be a disadvantage, but at second glance it can be an advantage in some applications where a large dynamic signal range is achieved by a logarithmic compression fit into a reduced dynamic range for digitization. In SiPMs, logarithmic compression is intrinsic.

4. Device Realizations

The development of SiPM is currently advancing at an incredible speed, and a lot of progress in device performance has been achieved in the past few years. Currently, several independent developments are performed at research institutes and companies e.g. SensL, HLL in collaboration with the MPI for Physics, Hamamatsu, JINR, CPTA and MEPhI. These developments aim to realize the detector concept in mainly three different ways.

4.1. Detectors based on individual Polysilicon Resistors

In this approach, followed by most designers, a high resistive epitaxial layer is grown on a low resistive substrate. In the epitaxial layer, several micrometer thick, a matrix of diodes is formed. To quench the breakdown in a cell, a dedicated miniature resistor is connecting each diode to a grid of aluminum lines. An example of such a device is shown in Figure 1, and a close-up of one of the cells in Figure 7. Some devices have a dedicated capacitor in parallel to the resistor for a better decoupling of the signal.

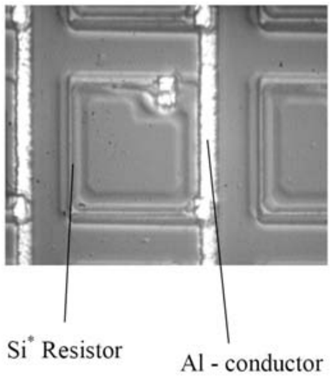

Figure 7: Close-up of one cell of a SiPM that uses individual polysilicon quenching resistors.

4.2. Detectors with buried Avalanche Regions

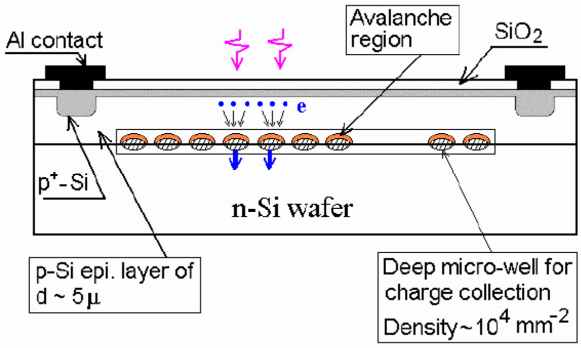

Figure 8: This sketch from [20] shows a MAPD structure. The avalanche regions are realized in a depth of a few micrometers below the surface.

The micro-pixel/channel avalanche photodiode (MAPD) that is depicted in Figure 8 has a homogenous entrance window [20]. In this device the avalanche regions are "buried" a few micrometer below the surface. The structure is self quenching due to the collection of charges at the avalanche region in so called micro-wells. An advantage of this concept is that up to 10^4 cells per mm^2 can be realized. Although the term cell might not be appropriate anymore. PDEs of 20% have been measured in recent devices [21]

4.3. Detectors with Illumination from the Backside

The main reason for the photon detection efficiencies in the devices introduced so far being lower than, naively, expected are the of dead space between cells and/or absorption losses. The problem can be solved by a full depletion of the detector volume and illuminating the device from the back side [14].

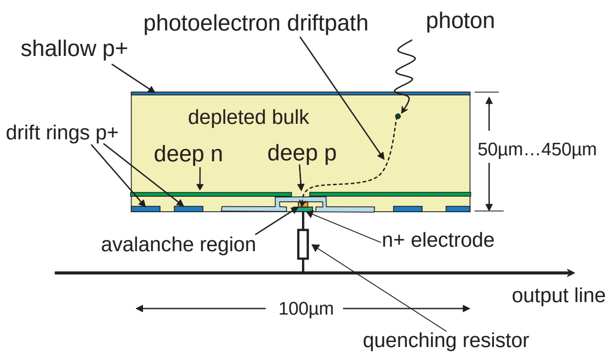

Figure 9: Blowup of one cell of the back illuminated SiPM principle. Please note that the drawing is not to scale.

Figure 9 demonstrates what a cell of such a device can look like. Photons are entering from the backside through a uniform and flat entrance window (top side in the picture). The generated photoelectron is drifting through the fully depleted semiconductor volume into a small region of a high electric field, where the multiplication takes place. A complete collection of all photoelectrons in the avalanche region is achieved by an appropriately shaped potential within the cell. This is realized by applying different potentials to the drift rings and the backside of the device. The caveat of such a concept is the high volume for crosstalk photons from the avalanche breakdown. To minimize the effect of optical crosstalk these devices have to be operated at low gain, probably with an integrated amplifier.

5. Application in Positron Emission Tomography

At present, many plans and first prototypes for many quite diversified applications e.g. CALICE [1], Si–Fiber tracker, radiation monitoring or the proposed SMART–PM [22] exist. It is beyond the scope of this paper to review many of them, and I have chosen to discuss only the use in PET detectors which are synonymous for an application in need for small, high efficient and fast photon detectors in a large number.

To make optimal use of PET good time resolution (< 1 nsec) and best possible energy resolution are required. In first studies with a 1 mm^2 device coupled to a LYSO scintillator with a surface of (2×2)mm^2, an energy resolution of 22% and a time resolution of 1.5 ns both FWHM have been obtained [23]. In a recent repetition of a very similar study, which made use of a larger device of (3×3)mm^2 and a MAPD structure (s. Section 4.2, an energy resolution of 12.7%

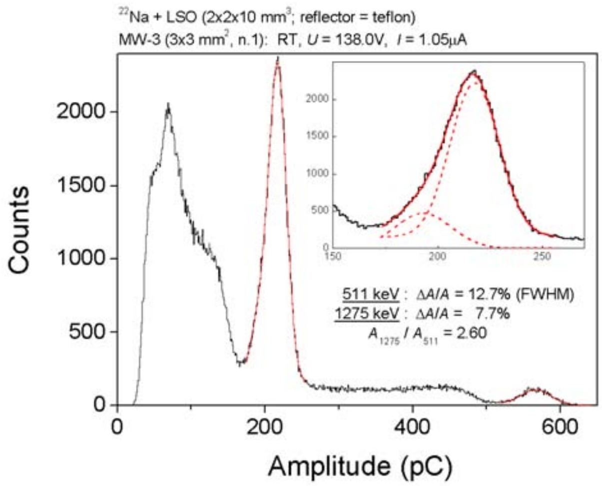

Figure 10: Emission spectrum of a source of 511 keV γ's (^{22}Na) obtained with a MAPD type detector.

(cf. Figure 10 and a time resolution of 540 psec have been obtained [24], matching measurements with high quality PMTs. Both studies have been performed at room temperature. The results show that, although still in the state of development, the novel photon detectors are outperforming proportional APDs in some applications despite their lower PDE, which was only 12% in the more recent study. An additional advantage compared to classical APDs is the high immunity against pickup, putting less stringent requirements on the amplifier and on shielding. For the same reason the preamplifier can be separated from the detector, which allows building a very compact detector system that can e.g. be placed within a MRT.

6. Summary and Discussion

The SiPM is a novel semiconductor photon detector for low light level applications. It takes advantage of the Geiger mode of operation without loosing the information on the number of photoelectrons. Advantages of the detector concept are:

- Potential of high photon detection efficiency
- Very low sensitivity against pickup because of large internal gain ($> 10^5$)
- relaxed requirements on the preamplifier compared to that needed for classical APDs
- low sensitivity against temperature and bias fluctuations compared to classical APDs
- no aging over years
- radiation hardness

- very low response to passing ionizing particles (low "nuclear counter effect", e.g. even a heavy ion would only produce a signal equivalent to one photon)
- Insensitiveness to even very strong magnetic fields
- Low operation voltage (< 100V)
- single photon response
- very fast signals for single photons
- ultra compactness
- no damage from accidental and prolonged light exposure
- low intrinsic power consumption (50μW per square millimeter sensor area)
- mechanical robustness
- production by simple mass production technology i.e. potential of low production costs
- ...

Major disadvantages are the high intrinsic single dark counting rate, optical crosstalk and limited sensor areas.

High dark count rates are, in most cases, only a problem in applications that require low rate single photon counting. In all other applications moderate cooling to say -30°C$\ldots -50$°C should be sufficient. Often, no cooling is required as e.g. in PET where the trigger threshold can be set sufficiently high to the equivalent of several tens of photoelectrons.

Optical Crosstalk is a process that can be suppressed by lowering the gain of the device or by inter cell absorption of the crosstalk causing photons. The latter solution is currently being investigated by several groups. First prototype devices exist which show almost complete suppression of optical crosstalk. The effect of optical crosstalk is basically twofold. Firstly, it increases the accidental trigger rate for a given discriminator threshold because a single initial noise event can trigger sometimes many cells. Secondly, it worsens the energy resolution because of increased statistical fluctuations.

A major challenge in the future is the increase of photon detection efficiency beyond 50% over a large range of wavelength (300 nm. . .600 nm). Latest prototypes achieve efficiencies $\sim$40% around 500nm and therefore outperform conventional photomultiplier tubes at these wavelengths. Increasing the detection efficiency at wavelengths below 400nm seems particularly difficult due to the extreme short absorption lengths of the photons in silicon.

Summarizing one can say that the SiPM has become widely accepted as a promising photon detector for a wide range of applications. The current stage of development is sufficient for some applications but still far from optimal for applications in which sensors with larger areas paired with much higher photon detection efficiencies especially in the blue wavelength region are required.

It should be mentioned that the principle of operation allows the construction of a large variety of configurations in terms of device area, cell size, dead area separation, tuned spectral sensitivity, minimal allowed dark counts, acceptable crosstalk, operation voltage, etc. The number of possible variants will be much larger compared to that of classical APDs or PMTs. On the one hand one can "tailor" the construction well to the needed applications, but on the other hand standardization with the cost saving methods will not be so easy to achieve.

Acknowledgments

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References

[1] G. Eigen, "The Calice Analog Scintillator-Tile Hadronic Calorimeter Prototype", SNIC06, April 2006

[2] E. Lorenz, "Status of the 17m ∅ MAGIC telescope", New Astron. Rev. 48, 2004, pp. 339

[3] M. Teshima et al., "EUSO (The Extreme Universe Space Observatory)- Scientific Objective", Proceedings of ICRC 2003, pp. 1069

[4] P. Buzhan et al., "An advanced Study of Silicon Photomultiplier", ICFA, Fall 2001, http://www.slac.stanford.edu/pubs/icfa/

[5] J. Grahl et al., "Radiation hard avalanche photodiodes for CMS ECAL", NIM A 504, 2003, p. 44

[6] S. Cova et al., "Evolution and prospects for single-photon avalanche diodes and quenching circuits", Journal of Modern Optics 51, 2004, p. 1267–1288 and references therein

[7] P. Buzhan et al., "Silicon photomultiplier and its possible applications", NIM A 504, 2003, p. 48–52

[8] D. Bisello et al., "Silcon avalanche detectors with negative feedback as detectors for high energy physics", NIM A 36, 1995, p. 212–214

[9] V. Golovin et al., "Novel type of avalanche photodetector with Geiger mode operation", NIM A 518, 2004, p. 560–564
[10] D. Renker, "Geiger-mode avalanche photodiodes, history, properties and problems", NIM A, 2006, in press
[11] O. Christensen, "Quantum efficiency of the internal photoelectric effect in silicon and germanium", J. Appl. Phys. 47 No. 2, 1976, p. 689–695
[12] W. G. Oldham et al., "Triggering phenomena in avalanche diodes", IEEE TED 19 No. 9, 1972, p. 1056–1060
[13] B. Dolgoshein, Private Communication
[14] G. Lutz et al., "The Avalanche Drift Diode: A New Detector Concept for Single Photon Detection", IEEE TNS 52, No. 4, 2005, p. 1156–1159
[15] N. Otte, et al., "Prospects of using silicon photomultipliers for the astroparticle physics experiments EUSO and MAGIC", IEEE TNS 53, No. 2, 2006, p. 636–640
[16] Y. Musienko, Private Communication
[17] A. L. Lacaita et al., "On the bremsstrahlung origin of hot-carrier-induced photons in silicon devices" IEEE TED 40 No. 30, 1993, p. 577–582 and references therein
[18] J. H. Swoger, S. J. Kovacic, "Enhanced luminescence due to impact ionization in photodiodes", J. Appl. Phys. 74, 1993, p. 2565–2571
[19] B. Dolgoshein, Talk given at Light06–Large–Area Photon Detectors Workshop (2006)
[20] Z. Sadygov et al.,"Three advanced designs of micro-pixel avalanche photodiodes: Their present status, maximum possibilities and limitations", NIM A, 2006, in press
[21] D. Renker, Private Communication
[22] D. Ferenc, "The novel Light Amplifier concept", NIM A, 2006, in press
[23] A. N. Otte et al., "A test of silicon photomultipliers as readout for PET", NIM A 545, 2005, p. 705–715
[24] I. Britvitch et al., "Study of avalanche microchannel photodiodes for use in scintillation detectors", JINST 1, 2006, in press