The Digital Silicon Photomultiplier

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Additional information is available at the end of the chapter

Abstract

The Silicon Photomultipliers (SiPMs) are the new step in the development of the modern detection structures in the area of low photon flux detection with a unique capability of detection up to the single photons. The Silicon Photomultiplier intrinsically represents a digital signal source on the elementary cell level. The materials and technology of SiPMs are consistent with the modern electronics technology. We present the realization and implementation of a fully digital Silicon Photomultiplier Imager with an enclosed readout and processing on the basis of modern 3D technology.

Keywords: Silicon Photomu/ltiplier, Low photon flux, single photon detection, digital detection structures

1. Introduction

The conventional Silicon Photomultipliers (SiPMs) have a great progress and success in the past ten years[1,2]. The excellent performance of SiPMs, which is up to single photon detection capability, changed the understanding of the fundamental principle of light detection and gave the possibility to reach the limit of the detection of the photon flux. The detection of the single photons opens new methods, instrumentations, and analysis of the information, and it is important for the investigation of the most fundamental physics processes, such as the nature of the electromagnetic processes and interactions, the quantum nature of the electromagnetic processes, and the photons' nature.

Many successful applications of the conventional SiPMs could be mentioned, particularly in High Energy Physics and Medical Imaging Systems[3].

The structure and technology of the Silicon Photomultipliers are based on the modern challenges in physics and technology, which are now much richer and more flexible for the creation of the new generation intelligent photon detection structures. It is important to

mention that the sensor technology of the Silicon Photomultiplier is fully compatible with the modern semiconductor technology such as CMOS technology, and it could be produced at standard Silicon mass production technology facilities[4]. This gives a huge perspective in the creation of the new generation of SiPMs, which combines the sensors and front-end and processing electronics with a wide range of variation of the performance and compatibility to connection with the modern data processing systems.

One of the first approaches to develop the structure and technology, with implementation of the readout and processing electronics, is already done with great success through the Digital Counting Silicon Photomultiplier (dSiPM)[5]. The Digital Counting Silicon Photomultiplier solved the problems of early digitization of the breakdown avalanche microcell signal and implementation of the integrated electronics (cell signal digitalization, trigger network, time-to-digital converter (TDC), and control logic on chip). In contrast to conventional SiPMs, the Counting Digital SiPM is, therefore, an all-digital (digital-in/digital-out) device and provides the digital counting of the number of photons and precise detection time. As a result, it produces faster and more accurate photon counts with extremely well-defined timing of the first photon detection. This realization is fully functional for the medical imaging systems, particularly for the Positron Emission Tomography (PET) diagnostic systems. The use of the Counting Digital Silicon Photomultipliers gives the possibility of the implementation of novel methods such as individual readout of the small size of scintillating crystals, the method of point of interaction for the improving the spatial resolution, and the time of flight method for the reduction of the background. Finally, it significantly reduces the electronic readout chain.

The new approach of the advanced digital Silicon Photomultiplier will provide full, available information of the detected low photon flux. Generally, the SiPM structure is a fine space distributed elementary sensors structure with a single photon detection capability on the single microcell level and high time resolution. The full information that is available from the SiPM structure includes the single photon detection i.e., the number of the detected photons, space distribution of the detected photons on the detected area, and detection time. The number of photons and the space distribution of the photons over the detected area could be very important for many applications and are called digital imaging.

The next step is the development of the new generation of the digital Silicon Photomultipliers, which will cover very important areas of the Digital Imaging or Real-Time Digital Imaging for the very low photon flux of the many important areas of applications such as homeland security, medical, space and astrophysics, and others.

Another area of the application of Silicon Photomultiplier-like structures is the digital coordinate sensors for the detection and the precision tracking of the charged particles in high energy physics – Avalanche Pixel Sensor (APiX)[6]. One of the important advantages of the tracking detectors on the basis of Silicon Photomultiplier-like structures is the significant reduction of the material budget, which is currently the main fundamental limitation of the improvement in precision tracking.

In the future, the development of the advanced Digital Silicon Photomultiplier structures for different applications will rapidly grow due to complete consistency with the modern semiconductor technology.

2. Physical principles of photons detection

The basic feature of the Silicon Photomultiplier as the detection structure for the low photon flux up to a single photon is the provision of internal amplification, which allows for overcoming the noise level of the front-end electronics to recognize the extremely low charge signal and to perform the processing. The internal amplification must be quite substantial, on the level of 10^6, and can be reached in the specific conditions and mode operation. The conditions for the creation of the special type of avalanche process, which allows such internal amplification, could be reached by specific semiconductor structures. The basic physics principle is based on the creation of the breakdown avalanche process due to the intensive secondary ionization of the charged carriers of both types in the strong electric field formed in the special type of semiconductor structures.

2.1. Physics of photon detection and the internal amplification

The process of detection of the low photon flux or single photon is defined by the nature of photons, the physics of the photon interaction with matter (detection media), and the formation of the electric signal, i.e., the conversion process of the photons energy into the electric signal, which is used in the measurement systems.

The fundamental problem in the detection of the photons is that the energy of the photons (especially visible light photons) is almost the minimal possible energy value in nature. The energy of photons could be estimated, as an example for the 500 *nm* visible light photons, as 2.2 *eV*. This is one of the smallest energy values, which could be found in nature, and its detection is a great challenge under many aspects. Furthermore, the detection of a single photon within a single photon distribution is a special interesting task involving the study of the fundamental quantum nature of light.

The photoelectric effect is the main physics process of photons' interaction with matter for the visible range of light. It provides the conversion of the energy of photons to the electric signal in a particular charge. The interaction media that are most suitable for the present time are semiconductor materials such as Silicon, which gives direct conversion of the energy of the light photon to the electric charge. For the visible light and semiconductor material (as detection media), this process gives the converting ratio 1:1 – one photon correspondent energy creates one electron-hole pair, and this amount of electric charge should be transferred to and measured by the electronic system.

The basic principle of the detecting structure on the basis of semiconductor materials allows to use the result of the photoelectric interaction in creating the semiconductor structure within the depleted region (free from free charge carriers), e.g., special type of the *pn*-junction under reverse bias.

By applying the reverse bias to the structure, between two regions with different types of conductivity, the depleted area is formed with a low concentration of minor carriers and in-build electric fields.

The process of the creation of the electron-hole pairs due to the photoelectric interaction of photons in semiconductor structures and transport of the charge to the output is shown schematically in Fig. 1.

Photons with energy higher than the band gap of the semiconductor material are absorbed in the depleted area, thus creating electron-hole pairs inside. Carriers are generated during this process and are separated by in-build electric field: electrons drift to positive enhanced *n*-region and holes to negative enhanced *p*-region.

The charge carriers are then collected on the electrodes and pass through the external electric circuit generating the output electric signal. As mentioned before, for the single photon, the value of the signal created inside the detection volume is extremely low. In terms of measurement, the energy is equivalent to the charge level approximately 10^{-19} C. The registration of such signals is a very complicated task and the noise of the electronic measurement system is the main problem. The electronic noise of the measurement system could be estimated in terms of the equivalent noise charge for comparison to the charge signal convertion from the photon energy and for the modern electronic readout to be estimated at room temperature conditions as few hundreds of electrons or ~ 10^{-17} C. It means that the minimal signal that could be measured with modern electronic channels should be a few hundreds of electron hole pairs or photons higher. This is still far from the goal of measuring the signal correspondent to a single photon.
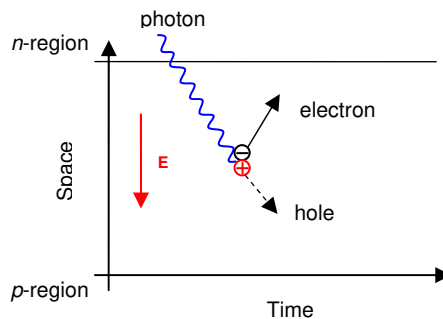

Figure 1. The creation of an electron-hole pair due to photon absorption in the semiconductor material.

The way to overcome this problem is to provide the internal amplification of the signal inside the detection media before the electronic signal processing. The value of the amplification should be at a range of 10^4-10^6. This is the main conceptual idea of detecting the low photon flux or single photon by the semiconductor structure such as Silicon Photomultipliers.

The avalanche processes in the semiconductor media due to secondary ionization processes could realize the intrinsic amplification in semiconductor structures. In the high electric field, usually higher than 10^5 V/cm^2, free carriers are accelerated and could reach energy higher than the ionization energy of valence electrons.

The minimal energy required for the impact of the ionization is called threshold ionization energy. This value is one of the main parameters of the theory of avalanche multiplication in semiconductor materials. The impact ionization parameters of the electrons and holes in the semiconductor materials are used to characterize the dynamics of the avalanche processes. They are defined as the inverse value of the average distance (along the electric field), which is necessary for electrons or holes to produce a secondary ionization and create an electron-hole pair.

The consequence of the secondary impact ionization interaction is the avalanche multiplication of the electron-hole pairs and the increase in value of the electric charge correspondent to the initial charge created by the interaction of photons.

Two types of avalanche processes could be realized in the semiconductor structures: the single carrier avalanche process and the breakdown avalanche process. These strongly depend on the value and ratio of impact ionization coefficients of the electrons and holes in Silicon. The values of the impact ionization coefficients strongly depend on the electric field. For the low electric field ~10^{-4}, shown in Fig 2 (left), the impact ionization coefficient of holes is much lower and the avalanche process is created only by one type of carrier – the electrons.
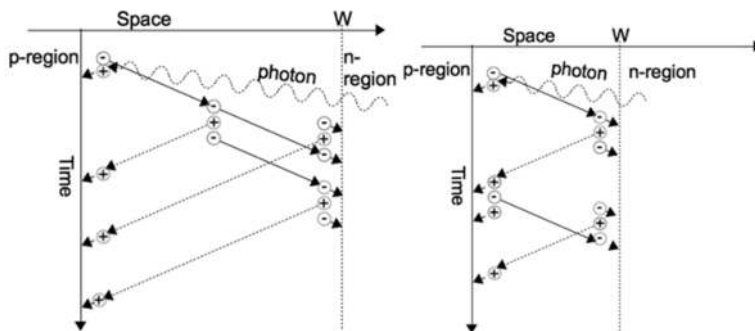

Figure 2. Two types of avalanche processes in the Silicon structures: (left) avalanche process with one type of carrier (electrons), (right) breakdown avalanche process with two types of carriers (electrons and holes)

The avalanche process, in this case, is one directional in space and self-quenched when the carriers reached the border of the depleted area in the Silicon. This type of avalanche process is used in the conventional avalanche photo detector (APD). In this case, the amplification gain is strongly dependent on the thickness of the depletion region and on the point of the inter-action of the photon inside this area.

For the high level of electric field in the Silicon structure, the process in principle is different and is shown in Fig. 2 (right). The impact ionization coefficients of electrons and holes are close to each other and both types of carriers could participate in the avalanche process. As a result, the avalanche process is self-sustaining, and the number of carriers rises exponentially with time. The avalanche process develops more in time in the thin Silicon depleted thickness, which is comparable with the ionization path of the carriers. Moreover, the amplification gain does

not depend on the point of interaction of the photons with the Silicon and practically does not depend on the thickness of the depleted region.

In the first case of the avalanche process of only one type of carriers (electrons), the gain of multiplication is limited by the thickness of depleted area. It is very important to note that the high statistical fluctuation of the amplification occurs due to dependency on the probability of the secondary ionization and the deepness of the interaction. Such conditions exclude the possibility of getting the quality of amplification necessary to resolve the single photon spectra.

In the breakdown avalanche process, which is the second case, the gain of multiplication is not limited by the depletion thickness. A thickness comparable with the secondary ionization path in the Silicon is sufficient, and the gain became infinite even on the limited depleted thickness of the Silicon. The different charge carriers undo the electric field moving in opposite directions, and the thickness of the amplification region could be just equivalent to the length of the ionization of electrons or holes under defined electric field. This gives the possibility of getting the intrinsic multiplication factor, enough for a suitable signal before the electronics detect a very small photon flux. The statistical fluctuation is much smaller because it is defined not by the statistical fluctuation of the avalanche process but by the characteristic of the quenching process.

The target of this condition is to provide a very high electric field in semiconductor-detecting structures to bring the ionization length of electrons and holes less of the depleted thickness of *pn*-junctions.

2.2. Silicon photomultiplier principle of operation

The detection principle of the Silicon Photomultiplier is based on the detection of the space- and time-distributed photons (photon flux) by the space-distributed array of the semiconductor microsensors – microcells with high intrinsic multiplication gain, allowing the detection of a single photon with high efficiency.

The output of the Silicon Photomultiplier is organized by the analog sum of the signals from the microcells. The analog sum of the signals from the microcells, which detected the photons, provides the common analog output signal proportional to the incoming photon flux.

The operational principle of the Silicon Photomultiplier is based on the use of the quenched breakdown avalanche processes in the silicon microstructure elements – micro-cells as *pn*-junctions with implemented special quenching elements. The common electrode structure connected to the microcells, in parallel, is implemented to analogs summing the signals from the microcells.

Sensor microcells are a special type of *pn*-junctions, which operate in breakdown avalanche mode, providing the intrinsic multiplication of the charges created by photons in the sensitive area of microcells by secondary ionization. Above the breakdown voltage, the *pn*-junction can be in a stable state for an infinite time, unless a single carrier is created in the depletion region as a result of photon interaction or of thermal excitation and initiates the avalanche multiplication, producing a self-sustaining flow of the charges.

The amplification gain of the breakdown avalanche process is theoretically infinite. A quench-ing mechanism is implemented in the sensitive structure to quench the breakdown avalanche process. One solution, in the case of the Silicon Photomultiplier, is the serial resistor for each sensor microcell. After the initiation of the avalanche breakdown process by the photoelectron of thermal electrons, the current rises through the structure and causes the voltage drop on the quenching resistor, and a consequent drop of the voltage is also applied to the *pn*-junction of the sensitive microcell. The quenching starts when the voltage drop on the quenching resistor lowers the voltage applied to the *pn*-junction to a value lower than the breakdown voltage, stopping the avalanche process. After the structure is quenched, a recovery time is then necessary to allow any free or stored charge to be swept from the active region of the device, followed by a recharging wherein the excess bias across the sensitive microcell is restored.

An important aspect of the described process is a significant reduction of the statistical variation of the value of the signal. For Silicon Photomultiplier structures, the amplification factor is defined not by the statistics of the avalanche processes, as in the conventional avalanche photodetectors (APD), but only by *pn*-junction characteristics and quenching circuits. The output of the microcells is identical in charge pulse for every photon detected, and the overall resolution is defined by the characteristics of the structure and the quenching element. Another very important aspect of the overall structure is the uniformity of microcells characteristics across the sensitive area of the Silicon Photomultiplier. This is provided by the modern semiconductor technology. The requirements for the uniformity define the precision of the charge pulse from the different microcells detecting the photons.

A more detailed discussion of the Silicon Photomultipliers and the study of the performances are available in [2,7].

2.3. The binary (digital) nature of the silicon photomultiplier cell signal

The Silicon Photomultiplier microcell in principle is the binary (digital) source of the signal, i.e., the signal produced by the microcell is represented by a two level of electronic signal.

Fig. 3 shows the schematic nature of the conventional Silicon Photomultiplier – the oscilloscope signal of the detection of the low photon flux and the statistical distribution of the signals, as detected by the Silicon Photomultiplier structure, with approximately 1,000 microcells at room temperature. Even with the analog summation of the signals, the well-resolved signals (peaks) of the single photon are clearly visible. It is necessary to mention that the second peak of the statistical distribution (peak of the exactly single photon detection in different microcells) is represented and that the statistical width of the single photon signal during the detection of the single photon by the randomly selected microcell from the 1,000 microcells includes the parameter of the identity of the Silicon Photomultiplier microcells. The separation of the signals with the high resolution is clearly visible and shows the high equality of the microcells over the few thousand microcells, confirming the binary (digital) nature of the signal over all the Silicon Photomultiplier structure.

The schematic nature of the single microcell of the Silicon Photomultiplier and the histogram of the Silicon Photomultiplier microcell signal during the detection of the photon (the single

microcell is capable of detecting only one photon) are presented in Fig 4. The measurements are performed at room temperature. The histogram consists of two well-separated peaks. Due to the statistical nature of the photon detection, the first peak represents the pedestal – signal level of the noise when the microcell cannot detect the photon. The second peak of the histogram represents the signal level of the photon detection i.e., electronic signal correspond-ent to the photon detection. Signals "zero" and "one" have well-separated levels and binary (digital) nature and can be well resolved by the electronics discrimination.
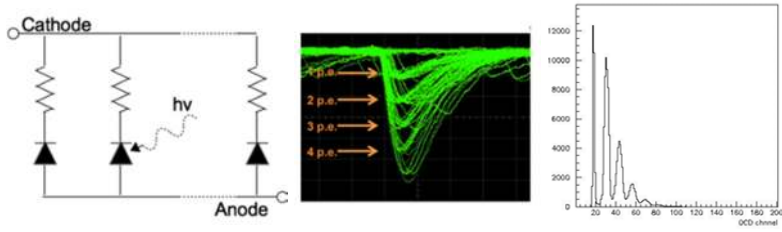

Figure 3. The signal characteristics of the conventional Silicon Photomultiplier: (left) schematic view of the array of the microcells with quenching resistors, (center) scope signal of the Silicon Photomultiplier, (right) the statistical distribu-tion of the signals during the detection of the low photon flux with the resolution of the single photon spectra.
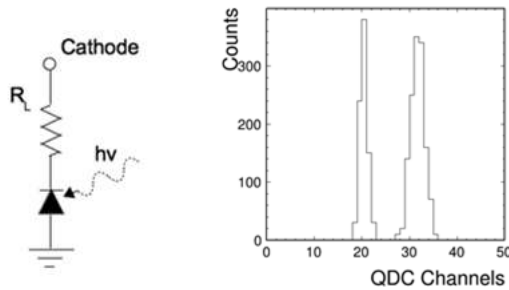

Figure 4. The signal characteristics of the single sensitive microcell, such as the microcell of the Silicon Photomultiplier, (left) schematic view of the single microcell and detection of the photon in the microcell, (right) statistical distribution of the signals of the detection of the photon by the single microcell.

The shown characteristics of the single Silicon Photomultiplier microcell and also the charac-teristics of the array of the Silicon Photomultipliers microcells – conventional Silicon Photo-multipliers – demonstrate the real performance of the processes of the photon detection. The single photon represents a source of the binary (digital) information from a single cell and cells array (the uniformity of the characteristics of the microcells, in the arrays of the microcells up to a few thousands cells, satisfies the possibility to resolve the signal of the single photon). The information consists of one bit, i.e.,. the photon detected is "one" and no-photon detected is "zero" for every individual microcell. The amplification gain of the signal, "one photon", is high enough (about 10^6) to perform the discrimination of the microcell signal to the digital

signal, without any additional analogous front-end electronics for the modern standard microelectronic components.

3. The digital counting silicon photomultiplier

The binary (digital) nature of the information provided by the Silicon Photomultiplier paves the way for the more advanced structure of the Silicon Photomultipliers, more suitable to the modern way of development in the detection systems. The information provided by the Silicon Photomultiplier cells is quite simple. It consists of a binary signal from the cell, and it is ready for the direct acceptance by the digital processing electronics.

One of the important aspects of this development is the exclusion of the analog front-end electronics, which is usually quite complicated and power consuming. One of the important application of the Silicon Photomultipliers is the medical imaging systems, which the SiPMs will bring to the new fundamental level.

It is not a surprise that the first important step to the digital Silicon Photomultiplier was done in the area of the Silicon Photomultipliers for the medical imaging systems, where the required information is more simplified, as counting of the total number of the photons and time of the detection.

3.1. The operational structure and principle of the digital counting silicon photomultiplier

The first approach to the development of the digital Silicon Photomultiplier (dSiPM) was made by the Philips Photon Counting Group for medical applications – Digital Counting Silicon Photomultiplier[8]. The necessary information for the medical imaging system applications, specifically the Positron Emission Tomography, is specific and is defined as the total number of the photons (as information of energy for the identification of the detected gamma from the annihilation process) and the precise time of the arriving of the photons (as the information for the identification of creating the two gammas at the same time from the same annihilation process). These two main parameters are required for the reconstruction and analysis.

The development of the Digital Counting Silicon Photomultiplier was the basis for those requirements. They provide the counting mode as the digital information in the form of the total number of photons detected on the area of SiPM and the arrival time related to the time of the signal.

The dSiPM solves this by the early digitization of the avalanche breakdown microcell output (cell electronics) and integrated electronics (digital summation, trigger network, time-to-digital converter (TDC), pixel controller electronics on the chip).

In contrast to conventional SiPMs, the Digital Counting SiPM is, therefore, a digital (digital-in/digital-out) device that does not use the analog signal processing. As a result, it produces faster and more accurate photon counts with extremely well-defined timing in reference to the first photon detection, both of which are important factors in applications such as medical imaging scanners and high-energy nuclear particle detectors.

Moreover, the digital SiPMs can be fabricated using a standard high-volume CMOS process technology available at the mass production Silicon technology facilities.

Another important aspect of the digital approach is the possibility to improve the noise characteristics of the Silicon Photomultiplier structures. The dark count rate is a critical point of the Silicon Photomultiplier physics and noise characterization, especially under operating at room temperature, which could disturb the low photon flux measurements. The important feature of the dark count rate sources of SiPM is that they are usually localized in the few limited regions over the full Silicon Photomultiplier area. The digital option of the realization of the Silicon Photomultiplier detection structure and the possibility of the direct access to the digital information in the microcell electronics from the processing electronics can dramatically improve this feature. The improvement could be achieved by masking of the majority of the noise microcells by the function of the processing electronics.

The general structure of the digital counting SiPM is shown in Fig. 5, which shows the microcells with active quenching and recharging, cell electronics, readout chain consisting of photon counter, and trigger network including Time Digital Converted (TDC). The output information represents the total number of photons, triggered microcells, as equivalent of energy, and time of the photon detection.
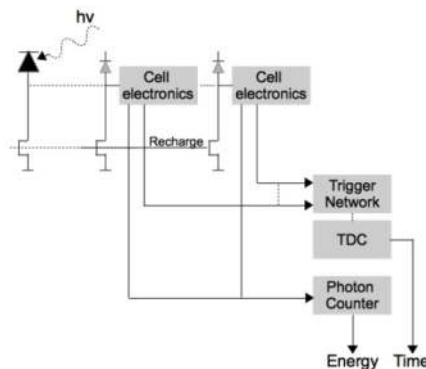

Figure 5. General structure of the Digital Counting Silicon Photomultiplier

3.2. The cell electronics

In the digital Counting SiPM, each individual microcell is equipped with its own quenching element (active), recharged element for the recovery of the sensitive state after breakdown, and one-bit on-chip analog-to-digital converter (ADC) in the form of a CMOS inverter. The quenching circuitry is added to each microcell to actively (rather than passively) quench and recharge the microcell after triggering. This active quenching/recharging in the device improves the detector's recovery time and respectively the dead time of the detection system dramatically – order of magnitude, as well as reducing its power consumption due to the exclusion of high-resistive elements from the main current line. The implementation of the

active quenching circuits solved another technological specific problem as the high-resistivity elements – quenching resistor in the CMOS technology.

Each microcell that experiences an avalanche breakdown process produces its own digital output that is captured, along with the digital outputs from all other triggered microcells, by an on-chip counter. Finally, the output information represented the number (digital form) of the photons detected in a particular time. Hence, the digitally counting SiPM converts the digital events (photon detections) directly into a digital photon count.

Another very important feature of the microcell electronics is the function of the masking. The well-known problem of the conventional Silicon Photomultiplier is the dark count rate, particularly, at room temperature. The dark count rate is the spontaneous generation of the avalanche breakdown processes due to thermally created electrons in the depleted area. The dark count rate signals are undistinguished from the signal of the detection of photons in the microcell (digital nature of the signal). Nevertheless, it is well known that the dark count rate is generated not uniformly around the full sensitive area of the Silicon Photomultiplier and is localized in particular microcells, as the dark count rate map of the digital SiPM shown in Fig. 7. To overcome the dark count rate problem associated with conventional SiPMs, each avalanche breakdown microcell in the Digital Counting SiPMs is also equipped with an addressable static memory cell that can be used to disable or enable the microcell signal transmitting to the output net (masking). The avalanche breakdown microcells that show high dark count rate levels prevented from contributing false counts to the digital Counting SiPMs output. This facility allows the Digital Counting SiPM to achieve better signal-to-noise ratios than conventional devices. As the defective microcells in the array can be disabled, the production yield is also improved.
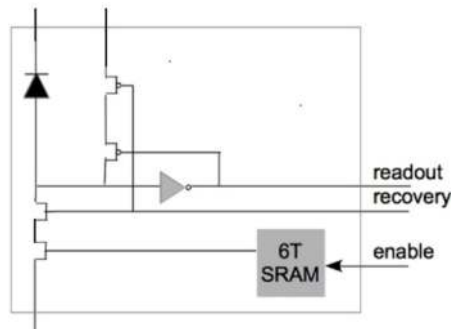

Figure 6. General structure of the avalanche breakdown microcell electronics of the Digital Counting Silicon Photomultiplier

3.3. The processing circuits

In contrast to conventional analog SiPMs, all microcells in the Digital Counting SiPM 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, thus preserving the excellent intrinsic timing performance of the avalanche breakdown microcells of the Silicon Photomultiplier. In implementing this new Digital Counting SiPM technology, the challenge was to integrate the relatively high-voltage avalanche breakdown microcell, which must be reverse-biased to around 30 V, alongside the low-voltage CMOS logic circuits on the same silicon chip, while maintaining the dark count and photon-sensitivity performance.

As an example, one of the realizations has a fully integrated 64 pixel sensor, with a sensing surface greater than 10 cm^2 and power consumption less than 15 mW/cm^2, using 180 nm CMOS technology on 8-inch Silicon wafers. The device's photon-detection efficiency is 30% at 450 nm; it has an optical crosstalk of 8% and a dark-count rate of 100 kHz/mm^2 at 20°C and 900 Hz/mm2 at -40°C.

The implemented processing electronics could be much more intelligent and provide many additional functions.

The Digital Counting Silicon Photomultiplier is an extremely important step for the development of the advanced Silicon Photomultiplier Structures, which used the digital nature of the sensor microcells and possibly processed the sensor microcell signals directly in digital form. This gives the most important evidence that could exclude the most complicated and power consumed analogs front-end electronics and processing of the analogous signals to digital forms.

The missing part of the signal processing fixes the coordinate information of each photon in the photon flux.
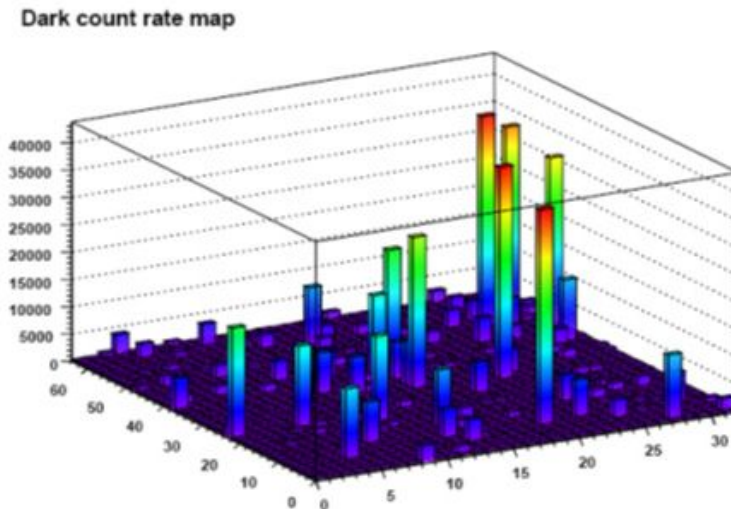

Figure 7. The dark count rate map of the non-masked Digital Counting Silicon Photomultiplier

4. The digital silicon photomultiplier (Imager)

The other area of the application of the Digital Silicon Photomultiplier is the development of the detecting structures that does not restrict the information to the number of the photons detected in the particular time interval, which is the most important information for the medical imaging system applications. The full information that the Digital Silicon Photomultiplier could provide includes the space distribution of the detected photons in the detection area, i.e., the function of the Digital Imaging of the photon flux[9]. The Digital Silicon Photomultiplier Imager could be referred to the CMOS Image Sensors and covers especially the very important areas for the digitalization of the images with extremely low photon flux such as space, military, homeland security, medical imaging systems, and other scientific applications[10]. The extremely high sensitivity of the Silicon Photomultiplier up to a single photon is very attractive for the many special applications wherein the photon flux is very low.In Fig. 8, a progress is shown in the astrophysics space application[11], where the photon flux from the far astronomical objects can be extremely low and the resolution plays a very important role.
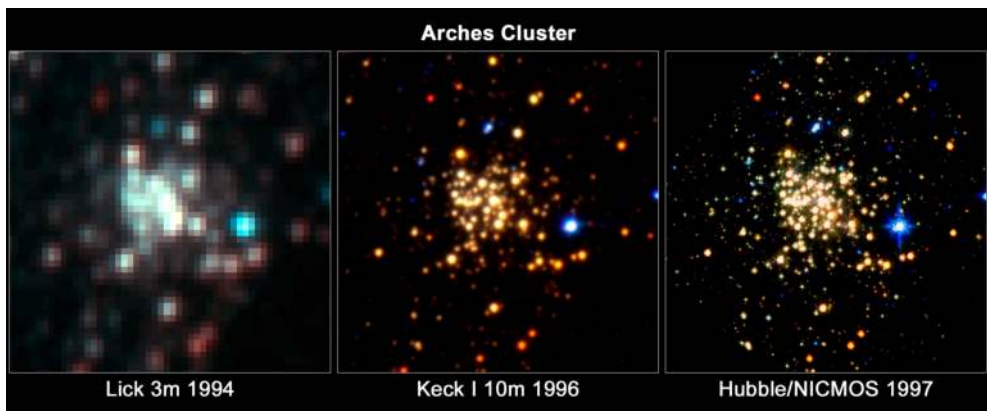

Figure 8. Progress in the astrophysics digital imaging performance

The picture shows the progress in the images taken by a "Hubble" telescope after the upgrade of the detection system. It shows the importance of space resolution detection and also the high sensitivity to the light flux, which in the astrophysical study could be extremely low on long distances.

The necessity of the detection of extremely low photon flux images is the main goal for the development of the advanced structures of the Digital Silicon Photomultiplier Imagers of the photon detection device. This will provide full information about the low photon flux such as distribution of the photons in space and time, i.e., the number of photons (the detection of the photons with different energies can be included – i.e., provide the color images), their position in space, and arrival time of the photons at detection plane.

The Digital Silicon Photomultiplier detection system could also provide the color information by the combination of the microcells with different spectral sensitivity.

The fully digital devices (Digital Silicon Photomultiplier Imagers) for the detection of the low-light photon flux provides full information that is carried by the low photon flux - the number of the photons, space distribution of the photons, and time information of the photons arriving, (color information) and will provide this information directly in digital form on the level of each single photon in the low photon flux.

The goal is to develop the fully Digital Silicon Photomultiplier Imager.

4.1. The general structure of the digital silicon photomultiplier imager

As mentioned above, the great advantage of the technology of Silicon Photomultipliers, particularly the sensor technology, is the full compatibility with the CMOS technology, which was mainly developed for the microelectronics, i.e., technology gives the possibility of the implementation of the sensors with the same structure and same technology as the electronic elements.

The second argument is the intrinsically binary (digital) nature of the SiPMs microcell signals. As mentioned before, the SiPM cell explicitly detects the single photon. The signal has a two-level feature, which is not significantly disturbed by the electronic noise and does not require the analog processing. This gives the possibility to create the elegant fully digital detection structure with individual microcell addressing. The readout signal can be associated with the coordination of microcells with the detected photon, i.e., it is possible to create the fully functional pixel structure or pixel imager structure.

The first attempt to describe the fully digital Silicon Photomultiplier was taken from the US patent "Quantum Detector Array"[12]. An advanced Digital Silicon Photomultiplier includes a semiconductor substrate, a binary breakdown avalanche sensor element situated on the semiconductor substrate, the binary breakdown avalanche sensor element having a radiation-sensitive area comprising a drift region and amplification region for detecting radiation from a radiation-emission source, particularly electromagnetic photons, and a logic electronics electrically interconnected to the binary avalanche breakdown sensor element for quenching and resetting. Preferably, the logic schematic elements are positioned, at least, partially outside of the radiation-sensitive area to leave at least a portion of the radiation-sensitive area available to detect radiation without an obstruction from the logic schematic elements (geometrical factor of the detection efficiency). This statement is important for the traditional CMOS technology. The modern 3D integration technology gives a possibility to create the advanced Silicon Photomultiplier structures with enhanced geometrical factor, which will be discussed below.

The required characteristics of the sensors signal are (1) the binary avalanche breakdown sensor should provide a signal with the characteristics and (2) provide the efficient function of the integrated logic electronics, i.e., the binary form of the signals correspondent to the modern microelectronics development and the possibility of the integration of the sensor/electronics technology, which is available in modern technology processing CMOS technology.

Referring to the description, a binary avalanche breakdown sensor array, according to a preferred embodiment of the invention, is described. As shown, the binary avalanche break-down sensors array features a sensitive area, which in a preferred embodiment comprises an epitaxial layer and a common substrate, both preferably made of silicon, although other semiconductor materials may be selected such as gallium arsenide, silicon-germanium, etc.

A binary avalanche breakdown sensor array includes a plurality of sensor elements, which may have submicron dimensions. The sensor elements comprise an n$^+$-type region or layer and a p-type region or layer, which is immediately adjacent to the n$^+$-type region to establish a pn junction as an amplification region and a p-type region as a drift region (The terms "layer" and "region" are used interchangeably herein.) Creation of an n$^+$-type region and a p-type region may be accomplished, for example, using standard doping techniques. The preferable processing of the production is integrated sensor/logic electronics elements technology based on standard CMOS technology.

The sensor elements are separated from one another by trenches formed in the epitaxial layer. Logic electronics elements on the same substrate are preferably positioned in the area of trenches between the sensor elements, outside of the radiation-sensitive area, to leave an entirety of the area available to detect the radiation without obstruction from the logic element. This method provided the suppression of the optical crosstalk in the neighborhood binary avalanche breakdown sensors from the sensor that detected the photon and prevented the decreasing detection efficiency of the low photons flux, especially on the single photon level.

A reverse structure and bias operate the binary quantum sensor element in a breakdown mode, which provides the possibility to have the sensitivity for the different areas of visible light.

Sensor elements, arrays, pixels, meta-arrays, and readout components and systems useful with this invention are described in the U.S. patent application Serial No. 11/783,613 entitled "Quantum Photodetectors, Imaging Apparatus and Systems, and Related Methods"[13].

As this invention has been described as having a preferred design, it is understood that it is capable of further modifications, uses, and/or adaptations of the invention, generally following the principle of the invention and including such departures from the present disclosure within known or customary practice in the arts to which the invention pertains and as may be applied to the central features herein before set.

The present approach to the development of the advanced Digital Silicon Photomultipliers is in pixelated structures that are more suitable to the photodetector structure including the sensor (SiPM microcell), front-end electronics, and control electronics. Also, the structure of the advanced Digital Photomultiplier will include the readout processing electronics (multi-plexer) and digital output.

One of the very important areas of application covered by this approach is the digital imager for the extremely low photon flux detection.

General processing of the advanced digital SiPMs will provide the following general functions after the sensor signal: hit decision, noise suppression, hits storage, addressing of the individ-

ual pixels, and readout chain with flexible architecture for the processing of the digital signals on the same substrate with sensors.

The choice of the certain readout architecture for the pixel structures is strongly influenced by the purposes of the applications, photons rate, trigger latency, and trigger selectivity which in turn define the readout rate. If the main particular readout functions are performed locally in the pixels, then, the data volume to be read out should be defined by the application and usually have to be strongly reduced.

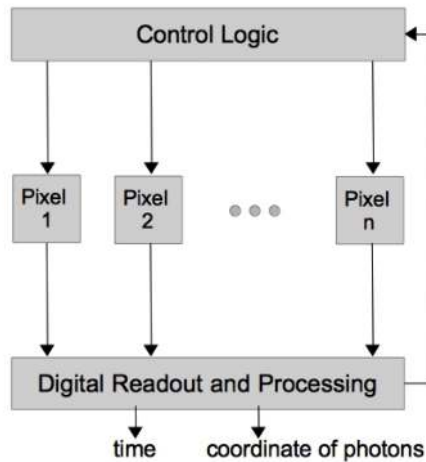Schematically, the general structure of the advanced digital SiPM is shown in Fig. 9.

Figure 9. General structure of the Digital Silicon Photomultiplier Imager

The main elements are avalanche breakdown micro-cells, quenching elements (generally passive or could be active), logical element (one-bit digital memory) with ideally individual addressing of the each micro cell, and readout and processing net, including the flexible readout and buffers for store the information.

Architecture of microcells readout and processing could be organized in different ways correspondent to the applications.

Although photon counting is by definition a digital task, conventional SiPMs combine the electrical pulses generated by multiple photon detections into a single analog output signal. As previously mentioned, this signal has to be processed by expensive analog power-consuming electronics to recover the photon count (digital form).

By integrating low-power CMOS electronics into the SiPM chip, a digital SiPM developed in which each photon detected is converted directly into an ultrahigh-speed digital pulse that can be directly used by on-chip intelligent processing circuits. In contrast to conventional SiPMs, the digital counting SiPM is, therefore, an all-digital (digital-in/digital-out) device. As

a result, it produces faster and more accurate photon counts with extremely well-defined timing of the first photon detection and digital information of addressing the triggered micro-cells individually.

This digital design provides several advantages, such as the pixel and the pixel controller being highly configurable, for the application of SiPM sensors. The individual breakdown avalanche micro cells can be switched on or off, depending on their dark count performance, validation, and integration times. Readout schemes can as well be set according to the application needs. In addition, the digital nature and independence from analog effects, such as gain or amplification, reduces the temperature sensitivity of the device. As only digital signals (photon count and time) are provided, subsequent processing electronics are greatly simplified.

4.2. The pixel electronics

Principally, the sensor of the Digital Silicon Photomultiplier is extremely simple and robust. The information is just binary (one-bit/cell), and a very high intrinsic gain allowed to use the output signal directly to the CMOS logic circuits (not necessarily the analog electronics), which simplified the cell electronic chain to a minimum. The advanced Digital Silicon Photomultiplier structure includes the breakdown avalanche microcell with a quenching element (passive or active) and a one-bit digital memory on-chip for storing the hits and addressing and reading out of the net.

An important part of the cell electronics is the circuit for the dark rate suppression.

The general cell electronics is shown in Fig. 10. Each microcell that experiences avalanche breakdown, therefore, produces its own digital output that is captured, along with the digital outputs from all other triggered microcells, and can be readout by a microcell on-chip readout net. Hence, the advanced digital SiPM converts digital events (photon detections) directly into a digital photon count and coordinates the position of each photon count and the time of arrival.

With the same very effective function of the dark rate suppression, each micro-cell in the advanced digital counting SiPM is equipped with an addressable access to the microcell memory that can be used to disable or enable the microcell. Microcells that show high dark count levels can thus be prevented from contributing false hits to the advanced digital SiPMs output.

The advanced digital SiPM equips each individual microcell with its own one-bit on-chip digital memory. Each microcell that experiences avalanche breakdown therefore produces its own digital output that is captured, along with the digital outputs from all other triggered microcells, and can be readout by an on-chip multiplexer. Hence, the advanced digital SiPM converts digital events (photon detections) directly into a digital photon count and coordinate the position of each photon count.

To overcome the dark count problem associated with conventional SiPMs, each microcell in the digital counting SiPM is also equipped with an addressable static memory cell that can be used to disable or enable the microcell. Microcells that show high dark count levels can thus

be prevented from contributing false counts to the SiPMs output. This facility allows the digital SiPM to achieve better signal-to-noise ratios than conventional devices. As defective microcells in the array can be disabled, they also help to improve production yield. Additional circuitry is added to each microcell to actively (rather than passively) quench and recharge the microcell after triggering. This active quenching/recharging in the device improves the detector's recovery time, as well as, reduces its power consumption.

4.3. The processing electronics

The main feature of the advanced digital Silicon Photomultipliers and Digital Silicon Photomultiplier Imager is the realization of the usage of the digital nature of microcell signal and the two-dimensional space distributed structure of the microcells for the coordinate detection of the signals.

The readout chain of the signals from the two-dimensional one-bit memory in this case, could be realized by a number of flexible readout architecture: counting mode, arrival time mode, and individual cell readout depending on the applications.

From the readout point of view, the pixel structure (cells with cell electronics) represents the two-dimensional one-bit memory elements. The amount of the information is not extremely high.
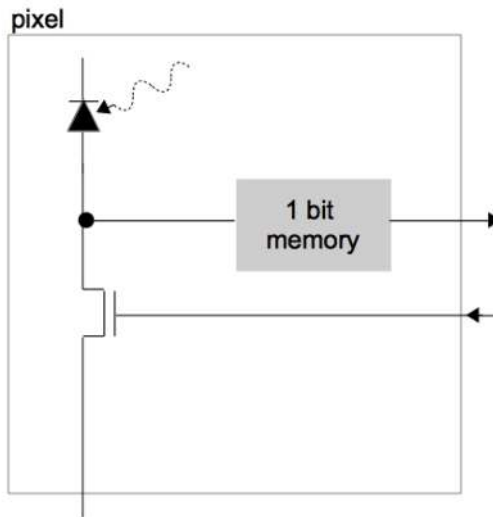
Figure 10. General structure of the Digital Silicon Photomultiplier Imager pixel

The organization of the readout could be realized in different ways depending on the performance and applications, and is not covered by this publication. It is referred to many detailed reviews, practical principles, and schematics of the pixel sensors readout.

An important comment follows about the timed performance of the Digital Silicon Photomultipliers Imager, which could be very high and used for the High Speed Imaging applications. As an example, the area of the Digital Silicon Photomultiplier Imager with 10x10 microns pixels with the total digital information is 10000 bits. The readout of this amount of information could be performed extremely fast, even with many methods of the access readout of all pixels.

5. The 3D structures of the digital silicon photomultiplier imager

The new developments in the semiconductor technology open new perspectives in the development of the advanced photon-detection structures, with improved detection efficiency and powerful processing electronics up to final information analysis. An extremely important factor is the progress in the three-dimensional (3D) integration technology proposed by a few standard CMOS technology facilities [14].

The main stream is the change in position of the functional elements from the planar view 2D to 3D structure as illustrated in Fig. 11.
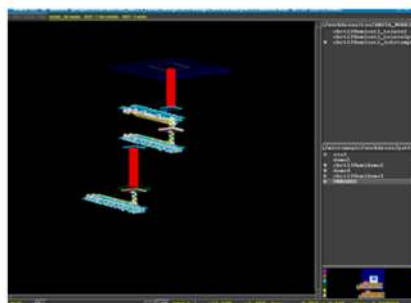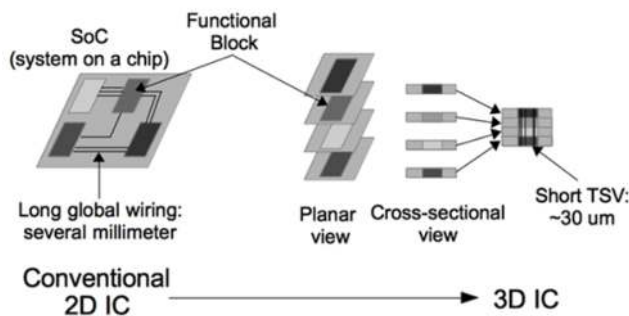

Figure 11. General structure of the 3D Integration Technology and details of the 3D integration technology design

One of the modern directions was proposed by the Tezzaron research group. The root of Tezzaron's® technology proposition is delivering the highest vertical interconnect density in

the industry. Tezzaron can stack more *wires* vertically through a stack of die in lesser space than any other industry. This allows for contact with more and smaller sensor elements and to put more memory and processing power behind them. The sensors can start processing data right away before they send it off for further processing. Those sensor arrays may *see* anything – from visible light to cosmic rays. They may even *see* the molecules that represent a specific smell, virus, or DNA sequence. Hence, they can *see* not just images, instead, they *see* just about any tiny thing needed to detect.

5.1. The general structure

Such modern 3D technology is very important and fully applicable to the sensor technology of Silicon Photomultipliers.

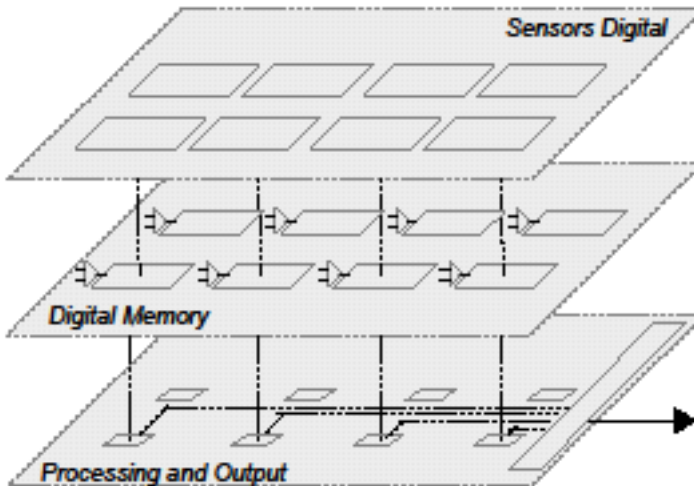The general structure is shown in Fig. 12.

Figure 12. General structure of the 3D Structure of the Digital Silicon Photomultiplier Imager

Sensor arrays fully occupy the top layer of the 3D Digital Silicon Photomultiplier Imager structure. This significantly improves the detection efficiency and in the first view, the geometrical factor, which is one of the general problems of the planar pixel sensor structures.

The second layer is dedicated to the distributed memory. One-bit memory corresponds to the pixel and is directly connected with vertical interconnections to the sensor layer. The organization of the memory will include the readout chain and the control circuit, which controls the digital representation of the pixel signal and, for example, the dark rate suppression.

The third layer is dedicated to the processing electronics and communication input /output functions, which could be highly intelligent and may even include the processors for a detailed analysis of the information.

6. Conclusion

The fully Digital Silicon Photomultiplier Structures are Digital Imagers for the detection of the low-light photon flux, providing full information, which is carried by the low photon flux – the number of the photons, space distribution of the photons, and the time information of the photons arriving. This detector will provide this information in a digital form on the level of each single photon in the low photon flux. The development of the fully Digital Silicon Photomultiplier Imager is very perspective of the many important applications.

The novel semiconductor technology, such as 3D integration CMOS technology, gives the fundamental improvement of the overall characteristics of the Digital Silicon Photomultiplier Imager with powerful digital information processing and analysis.

Acknowledgements

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