14

Silicon Photomultiplier - New Era of Photon Detection

Valeri Saveliev,
National Research Nuclear University
Russia

1. Introduction

More then 50 years Photomultiplier Tubes (PMT's) fills the area of low photon flux detection practically without alternative (Hammamatsu Photonics K.K., 2006), despite the fact that is very well known many disadvantages of this devices.
Concerning modern semiconductor structures for the photon detection, few options were investigated for the detecting of the low photon flux, but main critical problem to develop the semiconductor device was the relative high level of thermal noise of semiconductor detector structure and associated frontend electronics. One of the solutions, overcome this problem is Visible Light Photon Counter (VLPC) (Atac, 1993). This device is semiconductor avalanche structure operated at the temperature of 4K, for the suppression of thermal noise. The results was successful - possibility to detect low photon flux up to single photon, but operational conditions are to complicated to be acceptable for wide area application, cryostat for the 4K temperature up to now is challenge even in the laboratory conditions.
Development of the modern detection structures for the low photon flux Si was initiated at the beginning of 90'th from studies of Silicon Metal Oxide Semiconductor (MOS) structures with avalanche breakdown mode operation for the detecting of single visible light photons [Gasanov et al., 1989]. The results were positive, but strong limitation was the necessity to include external recharge circuits for the discharge the detector structure after charging the MOS structure during the photons detection. Next step was implementation of special resistive layer instead oxide layers, Metal Resistive Semiconductor (MRS) structures, which gives the possibility to recharge the structure after photon detection and in addition to control the breakdown avalanche process by quenching. Such structures had very high and stable amplification characteristics for photons detection, in comparison to conventional avalanche photodetector structures, but limited sensitive area. The idea of Silicon Photomultiplier or more precisely Silicon Photoelectron Multipliers was created for overcoming problem of above mentioned structures as small sensitive area due to nonstability of amplification over large area, low dynamic range, improving the resolution. It was decided create the fine metal resistor semiconductor structure with local space distributed *pn*-junctions (micro-cells) and common output. The result was fascinated, first time clear single photon spectra was detected on the semiconductor structure at room temperature.
Results of study such structures was presented on the 9th European semiconductor conference in 1995 (Saveliev, 1995).

Source: Advances in Optical and Photonic Devices, Book edited by: Ki Young Kim,
ISBN 978-953-7619-76-3, pp. 352, January 2010, INTECH, Croatia, downloaded from SCIYO.COM

And the first concept of Silicon Photomultiplier was proposed fine silicon structure of avalanche breakdown mode micro-cells with common resistive layer quenching element and common electrodes. Results of this development were presented on the conference Beaune 1999 (Saveliev & Golovin, 2000; Bondarenko et al., 2000).

The goals of next steps were the optimization of the detection structures in particular increasing so called geometrical efficiency – ratio of area sensitive to photons to the total area of the silicon photomultiplier i.e. getting as much as detection efficiency and tuning the optimal operation condition in term of bias and time performance, and generally improve the technological processes. With advanced technology, what became available in the middle of 90^{th}, the micro-cells are positioned as close as possible to each other, the common resistive layer as quenching element was substituted by individual integrated resistors coupled to the individual micro-cells with optimization of position and size. And the modern silicon photomultiplier structures start to be available for the applications (Golovin V. & Saveliev V., 2004).

New problem for optimized structures of silicon photomultipliers was the problem of optical crosstalk in fine detection structure due to light emission during the avalanche breakdown processes in Silicon. The phenomena of light emission from avalanche breakdown process is well known (A.G.Chynoweth & K.G.McKay, 1956). For the Silicon Photomultipliers with tiny space structure of microcells, the probability of detection secondary photons by neighborhood microcells is quite high and should be taking to account. Mainly this problem is affected of area of very low photon flux where the optics crosstalk could significantly change the results of measurement. The solution of this problem was achieved by implementation of modern technology process, physically optical isolation of the micro-cells on the integrated structure level. For the suppression of the optical crosstalk between the micro-cells, the trench structure was implemented around micro-cells as optic isolating elements and filled by optic non transparent material. The latest development in this area brings the very high performance for very low photon flux and created special type of silicon photomultiplier - quantum photo detectors (QPD) (Saveliev et al., 2008).

Silicon Photomultiplier is first semiconductor detector which could not only compete with photomultiplier tubes in term of detecting of low photon flux, but has a great advantages in performance and operation conditions and has great future in many areas of applications such as experimental physics, nuclear medicine, homeland security, military applications and other. Silicon Photomultipliers shows the excellent performance including the single photon response at room temperature (intrinsic gain of multiplication is 10^6), high detection efficiency ~25-60% for the visible range of light, fast timing response ~30 ps. Operational condition are suitable for many applications: operation bias 20-60 V, operated at room temperature as well in cooling conditions, not sensitive to electromagnetic fields. Production on base modern semiconductor technology, compatible with mass production semiconductor technology, compact, typical size of few mm^2 and flexible for assembling of the arrays. In this publication is impossible to eliminate all aspects of the silicon photomultiplier discovery and mainly will emphasise to more common feature to silicon photomultiplier development.

2. Conceptual idea

The main problem of detection of low photon flux or single photon is defined by nature of photons, physics of the photon interaction with matter and processes of converting the results

of interaction to the electric signal, i.e. in mechanism of converting the energy of photons in to the electric signals which is used for utilize by measurement and application systems.
The energy of photons could be estimated by standard expression:

$$E = h\nu = hc / \lambda \quad (1)$$

where: h – Plank constant,
v – frequency,
c – speed of light,
λ - wavelength.

This equation gives as example for the 500 *nm* visible light photons energy of 2.2 *eV*, it is one of the smallest quant of energy which could be found in nature and detection this quantity or single photon is challenge in many aspects. Moreover, the detection of single photon is interesting as fundamental physics task - study of fundamental quantum nature of light and their characteristics.
The basic principle of the silicon photomultiplier photon detection structure based on the quantum feature of light photon flux as space distributed quanta flux and space distributed array of micro sensors with capability to detect single quant of light – photon by every micro sensor. Main physics process of photons interaction with matter or process converting energy of photons to the other form, in particular charge in semiconductor material is photoelectric effect for the visible range of light. For considering range of light and semiconductor material, this process gives the converting ratio one to one – one photon correspondent energy create one electron-hole pair and this amount of electric charge should be transferred to and measured by electronic system. The basic principle of the photon detecting structure on base semiconductor materials micro sensor, allows utilize the result of photoelectric interaction, is creating the semiconductor structure with possibility of creating region free from charge carriers, depletion area and method of transport the created charge to outside, as example special geometry *pn*-junction (Saveliev&Golovin, 2004). By applying the reverse bias to the structure, between two regions with different type of conductivity forms the depleted area with low concentration of minor carriers and in-build electric field. Process of creating the electron-hole pair due to photoelectric interaction of photon in semiconductor structure and transport of the charges to the output shown schematically on Fig. 1.

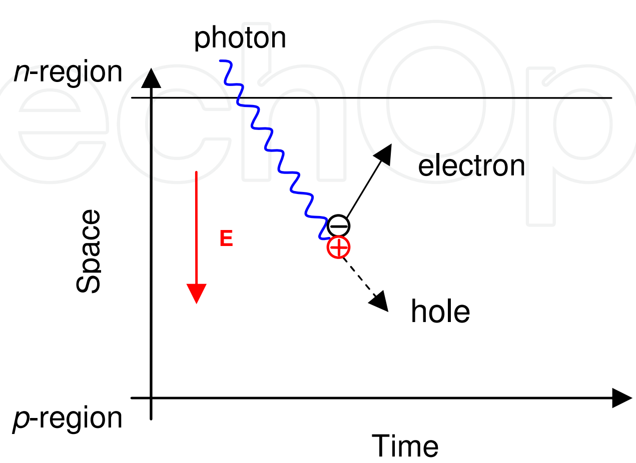


Fig. 1. Process of creating the electron hole pair due to photon absorption in semiconductor materials.

Photon with energy higher than band gap of semiconductor material is absorbed in depleted area with creating of electron-hole pair inside. Carriers, generated by photon, are separated by in-build electric field: electrons drifts to positive enhanced region *n*-region, holes to negative enhanced region *p*-region. Then the carriers are passing though external electric circuit generating the current as measurement signal. As mentioned before for the single photon the value of signal created inside detection volume is extremely low. In terms of measurement electronic system this is equivalent of charge level ~ 10^{-19} C. Registration of such signals is subject of extremely low value of charge as signal, statistical fluctuations of noise of detecting structure itself and and electronic noise generated by the electronic measurement system and is very complicated task.
Electronic noise of measurement system could be characterized in terms of equivalent noise charge for comparison to the charge signal from photon energy converting and represent the equivalent charge generated by the electronic channel in connection to the detection structure. Example of the equivalent noise charge as function of shaping time of discrete high quality frontend electronics system at room temperature presented on the Fig. 2. (Alvares-Gaume L. et al., 2008).
This value of the equivalent noise charge is calculated for discrete high quality frontend electronics. Optimal conditions gives the electronic noise on the level ~10^3 electrons (or elementary charges), it means that the minimal signal which could measured with discrete electronic channel should be higher ~3000 electrons or in term of the photons it is higher ~3000 photons with the 100% detection efficiency of photons.

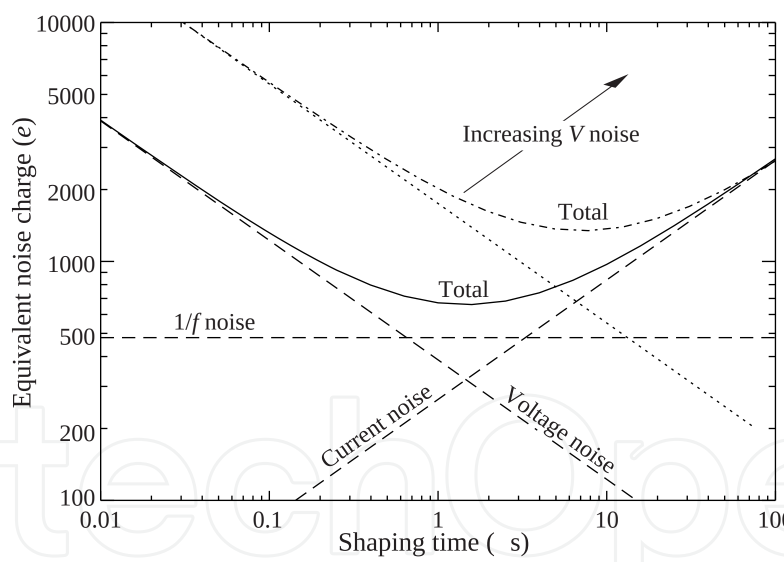


Fig. 2. Equivalent noise charge as function of shape time for discrete frontend electronic

The modern technology of integrated electronics could bring this condition on the level of equivalent noise charge around ~100 electrons at 20 ns shaping time, or equivalent of detection of ~300 photons, but not so many sensors technologies are compatible with integrated electronics on chip. And it is still far from our goal to measure signals range 1 e, which correspondent to single photon.
The way to overcome this problem is provide the internal amplification inside detection structure before transferring the signal to electronic system. The value of the amplification gain should be on range 10^4-10^6, what actually could not be achieved in conventional avalanche photodetection structures due to non stable working point in this region. This is

main conceptual idea of the detecting the low photon flux or single photon by the semiconductor strictures, like silicon photomultipliers. Nevertheless to rich the value of intrinsic gain of level 10^6 or more in semiconductor structures is not trivial task in development of silicon photomultipliers.
For remaining, the principle of internal gain of multiplication was realized in the Photomultiplier Tubes – electro vacuum devices, where the electron, created from conversion process of the photon on the photocathode, accelerated by high electric field and multiplied by few stages on the dynode system, due to secondary emission [Hammamatsu Photonics K.K., 2006). The value of the amplification gain is ~10^6, what did the Photomultiplier Tubes as unique device for the detection of very low photon flux. But the high level of statistical fluctuation of multiplication process in photomultiplier tubes don't allowed get the good resolution for the single photon detection.
The amplification in semiconductor structures based on different physical principle. The intrinsic gain in semiconductor structures could be getting by the avalanche processes due to secondary impact ionisation processes (Tsang, 1985). In the high electric field, usually of order 10^5 $V \cdot cm^{-1}$ and higher free carriers in the semiconductors are accelerated and could rich the energy higher then ionization energy of valent electrons. Minimal energy which required for the impact ionisation called threshold ionisation energy. This value is one of the main parameter of the theory of avalanche multiplication in semiconductor materials. To characterise the dynamic of the avalanche processes is used the impact ionisation parameters of the electrons and holes in the semiconductor materials: α - for electrons and β for holes. Those parameters are defined as inverse value of average distance (along the electric field), which is necessary for electrons or holes to produce a secondary ionization and create secondary electron-hole pair. The consequence of secondary impact ionisation interaction gives the avalanche multiplication of the electron-hole pairs and increasing the value of the electric charge correspondent to initial charge created by interaction of photons.
Values of α, β, width of high electric field area and carriers injection conditions defined the avalanche multiplication processes in semiconductor photon detection structures. Two types of the avalanche processes could be realized in semiconductor structures. This is strongly depends on value and ratio of impact ionisation coefficients α and β in silicon and on the value of electric field. For the low electric field ~10^{-4}, shown on Fig 3. a, impact ionisation coefficient of holes is much lower and avalanche process created practically by one type of carries – electrons. Avalanche process is one directional and self quenched when carriers is reached the border of depleted area in silicon. This type of avalanche process is usually used

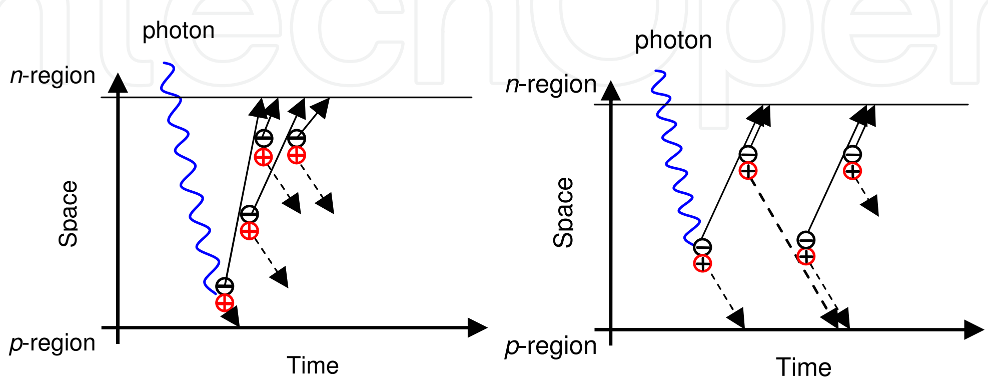


Fig. 3. Two type of avalanche processes in the Si structures, a. –self quenching avalanche process, b. – self sustaining avalanche breakdown process.

in conventional avalanche photo detectors. For high level of electric field in the silicon structure, process shown on Fig. 3.b, impact ionization coefficients coming close to each other and both type of carriers electrons and holes could participate in the avalanche process and create self-sustaining avalanche process, so the curriers rises exponentially with time and reach the breakdown conditions.
In first case the gain of multiplication is limited by thickness of depleted area, second case the gain of multiplication is not limited by the depletion thickness and became infinity even on the limited depleted thickness of silicon, because the different charge carriers undo electric field moving in opposite direction and thickness of amplification region could be just equivalent of length of ionization of electrons or holes under defined electric field. This is gives the possibility to getting the intrinsic multiplication factor enough to get the suitable signal before electronics to detect very small photon flux, up to single photon at room temperature. But avalanche breakdown mode of operation is required special effort for the quenching the avalanche process after initiation by absorbed photon or temperature created electron hole pair inside semiconductor.
The task of getting controlled avalanche breakdown process consist of providing the very high electric field in limited thickness of semiconductor detecting structure to bring the ionization length of electrons and holes less then the depleted thickness of *pn*-junctions, and getting required amplification gain with possibility of control by quenching maechanism.

3. Principle of operation, structure and technology

3.1 Silicon photomultiplier operation principle

Principle of silicon photomultiplier operation is based on quantum nature of light, detecting the space and time distributed photons (photon flux) by the space distributed array of the semiconductor micro sensors - micro-cells, operated in avalanche breakdown mode. Micro-cells are principally designed for detecting single quant of light (photon) with high efficiency. The array of space distributed micro-cells is designed for detecting of the space distributed quanta of light (flux) and sum of the signals from array provide the output signal proportional to the number of incoming photons – measurement of flux. In digital terms – number of micro-cells with avalanche breakdown process gives the number of incoming photons taking to account the detection efficiency.
Operational principle of silicon photomultiplier is based on the controlled avalanche breakdown processes in the silicon microstructure elements – avalanche breakdown micro-cells. Sensor avalanche breakdown micro-cells are special type of planar *pn*-junctions, operated in avalanche breakdown mode, providing the intrinsic multiplication of photoelectrons created by photons, absorbed in the sensitive area of micro-cell.
Above the breakdown voltage the *pn*-junction can be in stable state for a finite length of time, were it does not undergo avalanche breakdown. In this state a single carrier entering the depletion region is enough to initiate avalanche multiplication process and produce a self-sustaining current. The initiation could be as result of incoming photon interaction or termal created carrier inside depleted area. For the stopping of the avalanche breakdown process, the quenching elements are implemented in the silicon photomultiplier for each micro-cell. In case of silicon photomultiplier, the serial resistor for the each sensor micro-cell provides this function. The quenching element acting following way, after the initiation of the avalanche breakdown process by photoelectron or thermal electrons the current is rising in the external circuit and caused the drop voltage drop on the quenching resistor and accordantly of the voltage applied to the *pn*-junction. The process quenching is started when

the dropping the voltage on the quenching resistor bringing the voltage applied to the *pn*-junction to value lower then breakdown voltage, and quench the avalanche process. After the micro-cell is quenched, a hold-off 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 where the excess bias across the micro-cell is restored.

Important aspect of described process is significant reduction of statistical fluctuation of signal. For silicon photomultiplier structures the amplification factor is defined not by statistic of avalanche processes as in the conventional avalanche photodetectors, but only by *pn*-junction characteristics and quenching circuits. As result, the concept of multiplication noise or access noise is not relevant to the silicon photomultiplier and performance in particular fluctuation of signal is much lower. Output of the micro-cell in process of photon detection is identical charge pulse and overall resolution is defined by identity of characteristics of micro-cell and quenching element. According to this, very important aspect of providing the high performance of silicon photomultiplier is the uniformity of micro-cells characteristics across the sensitive area. This is provided by the modern semiconductor technology, the requirements for the uniformity correspondent to the precision of the charge pulse from different micro-cells detecting the photons across sensitive area and define the single photon detection resolution.

Finally intrinsically the silicon photomultiplier is completely digital device, which produce the number of equivalent charge pulse caused by photon interaction in the space distributed structure of equivalent micro-cells and integrated on the output and correspondent to the number of incoming photons. Future of such devices is providing completely digital signal analysis already inside structure of silicon photomultipliers.

3.2 Silicon photomultiplier structure and technology

Silicon photomultiplier is silicon microstructure consists of:

- large numbers of elementary sensors – array of micro-cells, operated in the avalanche breakdown mode, space distributed with high density on the common substrate, typical size of a few mm^2,
- implemented quenching elements for each micro-cell (in present time passive quenching elements - resistor),
- common electrode system, connected individual micro-cells to the common output of silicon photomultiplier.

Schematic view of geometry of silicon photomultiplier and equivalent electric schematics are presented on the Fig. 4, a,b.

On Fig. 4.a, is presented the schematic view of modern silicon photomultiplier with process of photon. The area of detection is divided on the fine space distributed micro cells (light gray square) and consist of the *pn*-junctions (marked as # micro-cells), every micro-cell has the quenching element, located close to the *pn*-junction (dark gray and marked as # Q. elements), the common electrode did't shown on this picture, which connected all quenching resistors to common output electrode, other electrode is on the back side of wafer. On the picture shown also space distributed photons (photon flux) and interaction in the silicon structure – three photons interact in the three micro-cells and initiated the avalanche breakdown processes. On Fig 4, b is presented correspondent electronic schematic of the silicon photomultiplier, shows the *pn*-junctions as array of diodes and quenching elements as serial resistors to the individual diodes. The process of interaction is shown as photons propagation and triggered the correspondent diodes. The electrical connection

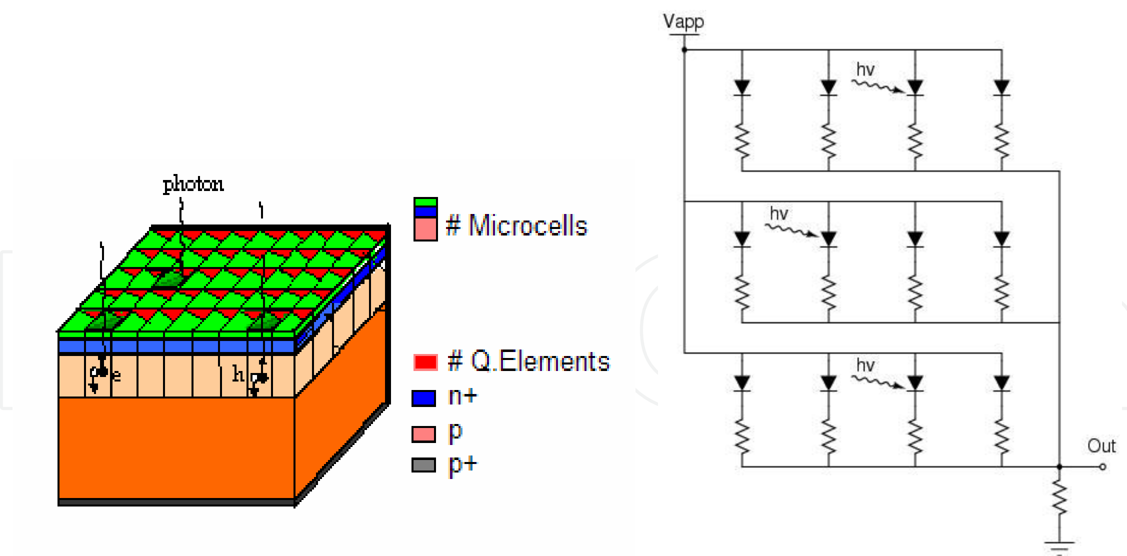


Fig. 4. a) Equivalent schematic of structure of silicon photomultiplier and b) equivalent electronic schematics of silicon photomultiplier

of the micro-cells formed two common electrodes – one for bias and second as signal output connected to the load resistor.

Structure of silicon avalanche breakdown micro-cell, based on the shallow *pn*-junction with so called virtual guard ring is shown on Fig. 5.

Structure of the avalanche breakdown micro-cell consist of silicon substrate (Substrate) with epitaxial layer *p*-type (epi). Avalanche breakdown structure represented by shallow *pn*-junction (n^+p) in silicon epitaxial layer with so called virtual guard ring to prevent peripheral avalanche breakdown processes (the virtual guard ring is formed by special geometry overlapping the n^+-and *p*-type area. To provide possibility to getting high electric field allowed realise the avalanche breakdown mode on the relative thin depletion region is chosen low resistive silicon (epitaxial layer) and additional implantation process to form *p* and n^+ region of *pn*-junction. Heavily doped n+ region connected to electrode an serial quenching resistor. Second electrode is formed on the back side of substrate.

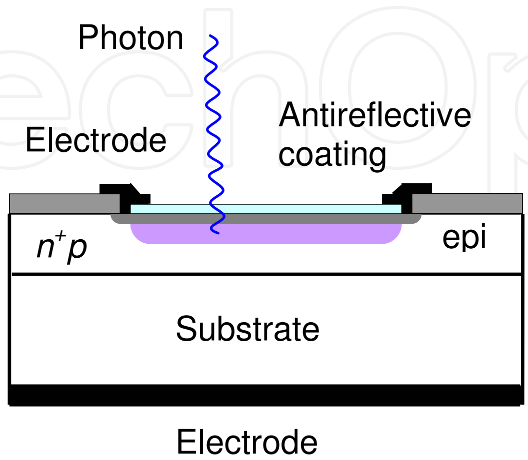


Fig. 5. Schematic schematic of avalanche breakdown micro-cell of silicon photomultiplier *n* on *p* type with virtual guard ring

Other type of avalanche breakdown micro-cell, often used for silicon photomultiplier fabrication is *pn*-junction with physical guard ring, implanted on the periphery of n^+- area. This technology more compatible with standard CMOS technology.
The guard ring in the silicon photomultiplier is important feature of structure, necessary to prevent the intensive breakdown processes in the areas with high electric field and high gradient of electric field caused earlier breakdown in the region of peripheral border of sensitive area and provide more uniform area of avalanche breakdown inside guard ring.
Such type of silicon photomultiplier micro-cell *pn*-junction is called "*n* on *p*" structures. The inverse structure of *pn*-junction, called "*p* on *n*", also is using for the manufacturing of the silicon photomultipliers. Advantage of inverse structures is possibility to increase the short wavelength light sensitivity of silicon photomultiplier (Hamamatsu, 2009)
The quenching elements – passive resistors on base poly-silicon planar technology, doped by implantation to get the correct high resistor value ~ 0.1 – 1 *MOhm* resistors on the limited area (length) of tens of microns. Forming of such elements required high precision because the geometrical characteristic significantly effected to performance of silicon photomultiplier in particular on photon detection efficiency.
The overall topology of silicon photomultiplier is presented on Fig. 6.a,b developed by Kotura Inc. (Kotura, 2009). On Fig. 6, a, is presented the top view of 1 mm² silicon photomultiplier with micro-cells size ~30x30 microns. Total number of micro-cells is ~1000 on 1 mm² silicon photomultiplier. The typical size of silicon photomultipliers are 1x1 mm² up to 5x5 mm² without significant changes in performances.

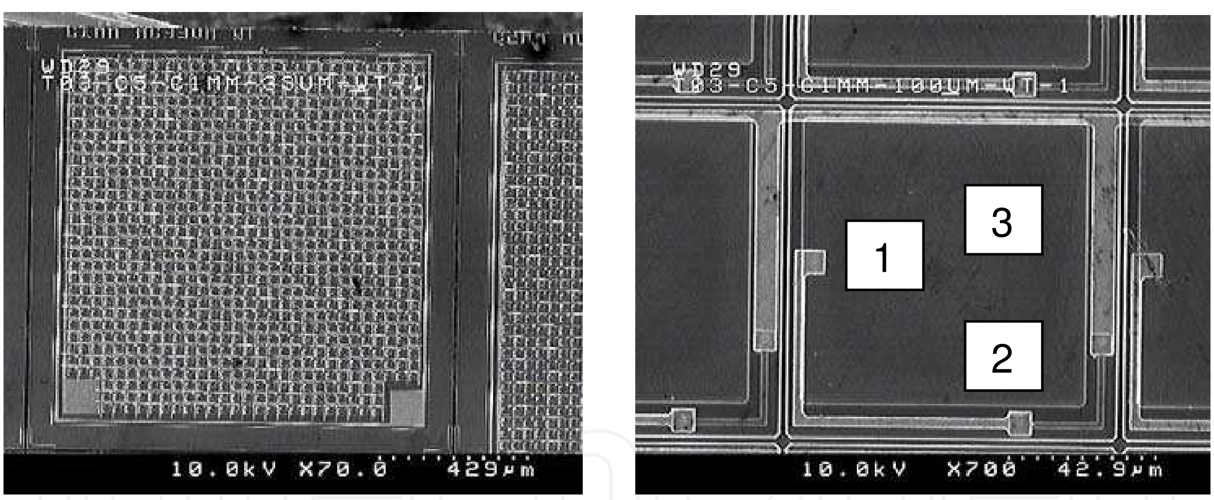


Fig. 6. a,b Micro image of modern silicon photomultiplier , a – overall view 1x1 mm², b – detailed view of micro-cell area.

On Fig.6,b is presented microscopic view of single avalanche breakdown micro-cell size ~30x30 microns with visible main elements of structure:
1. sensitive area,
2. quenching element – resistor,
3. part of the common electrode system,
4. optical isolation elements - trenches.

As mentioned before the important feature of the used material, comparison to the conventional silicon avalanche photo detectors is that for the silicon photomultiplier used low resistive silicon material and technologies compatible to the main mass production technology processes as CMOS technology and more important aspect that materials and technology allowed produce the integral device including the sensors and readout electronics on the same substrate. In future the integrated silicon photomultiplier with readout electronics on the chip will dominated on the design and gives unprecedented advantages of such devices.

3.3 Electric characteristics

Fig. 7 shows the typical reverse bias current-voltage (*CV*) characteristics for silicon photomultiplier with sensitive area of 1 mm² (Stewart A.G. et al., 2008). The plots shows the current-voltage characteristic in the range of avalanche breakdown at 293 K (room temperature) and at 253K (-20°C).

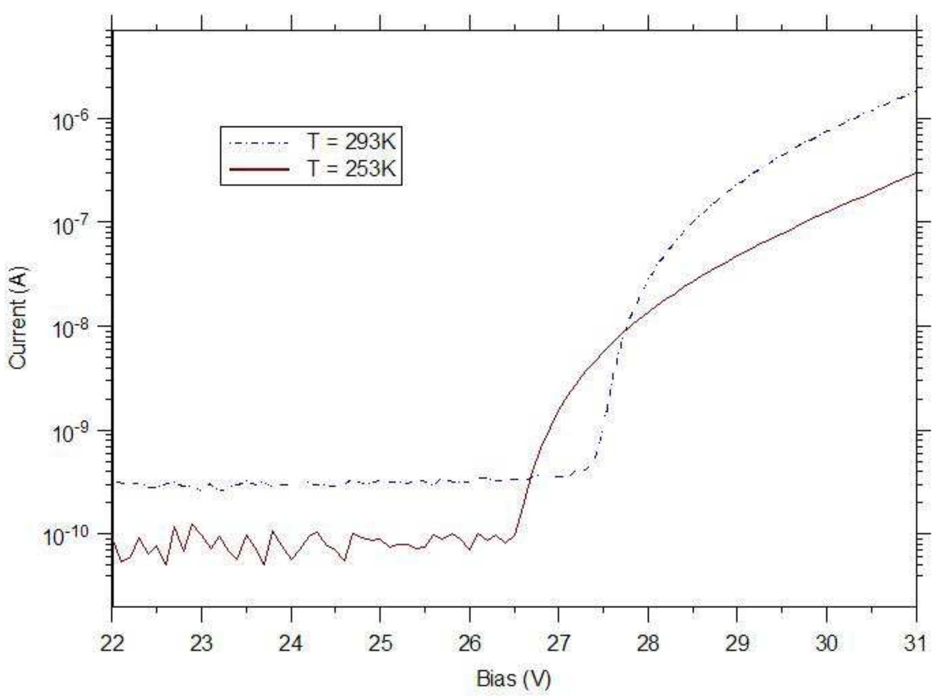


Fig. 7. Current-voltage characteristics of silicon photomultiplier at different temperatures 293 K and 253 K.

Before 26 V the current correspond non avalanche mode of *pn*-junction. At range 27.5 and 26.5 V the currents increase sharply due to avalanche multiplication process. Above avalanche processes started, the current increases by several orders of magnitude and reach the avalanche breakdown conditions, where the current is practically does not depend on the *pn*-junction state and curves follows the resistor behavior of silicon photomultiplier, mainly defined by the resistivity of quenching elements.

The silicon photomultiplier reverse bias current-voltage characteristic is used to determine the breakdown voltage and working point which is expressed in term of overvoltage. As seen from the plot, the breakdown voltage is a function of temperature and has a temperature coefficient of 23mV/°C.

4. Silicon photomultiplier performance

4.1 Single photon detection performance

Single photon detection performance at room temperature is one of the fascination characteristic of the silicon photomultipliers, shows the silicon photomultiplier as an ultimate instrument allowed detection of single photon - single quant of light in detail, that why the special type of silicon photomultipliers has name quantum photo detectors (Saveliev V., 2008). Fig.8.a,b presents the scope signals of the detecting the low photon flux by silicon photomultiplier at room temperature. The both picture shows two signals: top is the signal from silicon photomultiplier and bottom is synchronization signal of special low photon flux light source.

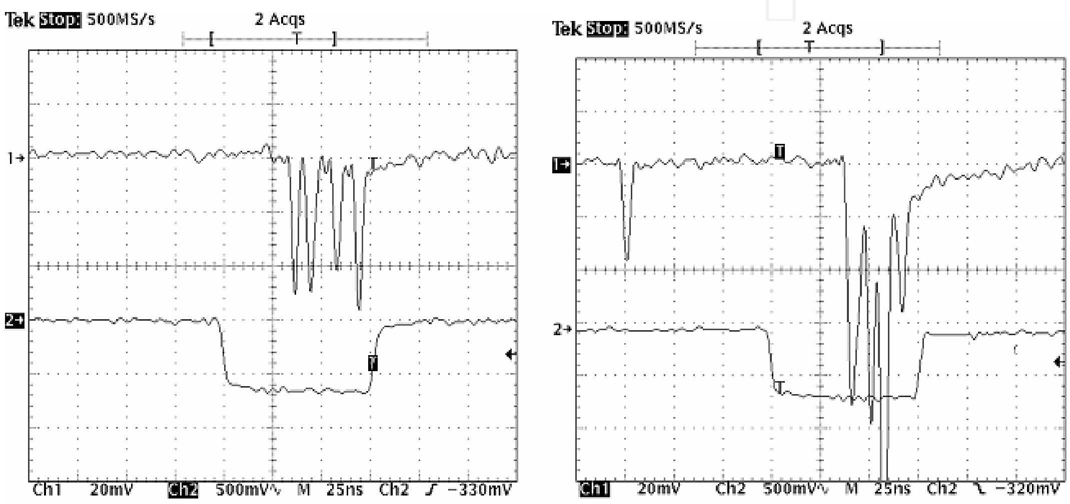


Fig. 8. Single photon detection signals: a) single photon signal, shows the signals from different micro-cells during the light pulse and collected on the output, b) signal with higher intensity of photons which not overlapping in space (signals from different micro-cells) but start overlapping in time and overlapping the electric signal on output of silicon photomultiplier during the photons detection.

On Fig. 8. a. clear visible the four signals each correspondent single photon detection distributed in time from laser diode. Signals are coming from different micro-cells of silicon photomultiplier and summed on the output. The laser diode is flushed in the gate shown on the second signal line. Fig. 8.b shows the signal with higher intensity of photon flux. Signals from different micro-cells started overlapping in time and gives on the output signal amplitudes which correspondent sum of two and more single photon signal, but steel clear seen of formation output signal from the signals of the single photons detected by the different micro-cells.

On the Fig. 9. is presented the signal distribution of the detecting the low photon flux by silicon photomultiplier at room temperature (Stewart A. G. et al., 2008). The signal distribution presented a statistical distributions of detected signals during registrations of low photon flux. Axis are represented correspondently: horizontal - the amplitudes of the signals from phtomultiplier and vertical – statistics of event with particular amplitudes. Clear seen the statistically resolved peaks of particular amplitudes. The resolution of the silicon photomultiplier is enough to distinguish the signals with discrete numbers of photons, which shows the quantum nature of the light, as a collection of discrete quanta with particular energy. The resolution of silicon photomultiplier allowed very precise analysis of the detecting photon flux up to single photon. First peak correspondent to amplitude of noise of electronic channel (pedestal), second peak correspond the amplitude of detecting one single photon, third peak correspond the amplitude of signal of detecting two photons in the same time by different avalanche breakdown micro-cells. Interesting mentioned that second peak is represented the amplitude of single photon detection collected from different avalanche breakdown micro-cells of silicon photomultiplier, - it shows also the high uniformity of characteristics of avalanche breakdown micro-cells around sensitive area of silicon photomultiplier. Clear seen the statistical behavior of the photon flux – Poisson distribution of the overall spectra of detected low photon flux.

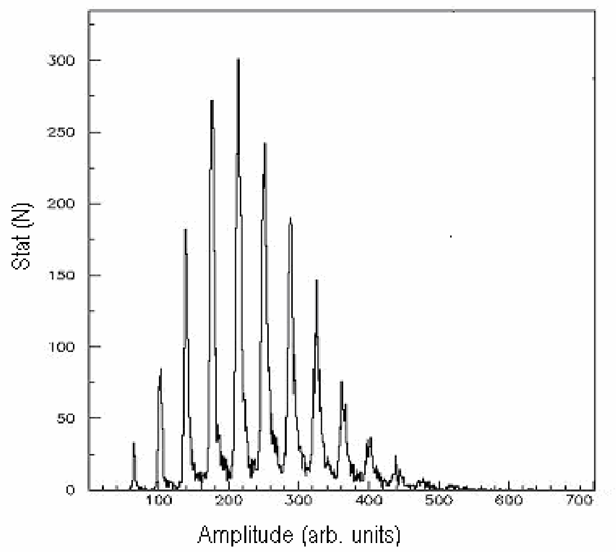


Fig. 9. Signal distribution of low photon flux signal (Poisson statistic of photon flux and peaks correspondent discrete numbers of detecting photons)

4.2 Photon detection efficiency of silicon photomultiplier

Detection efficiency of the silicon photomultiplier is a product of few main factors: quantum efficiency, efficiency of the avalanche process triggering and geometrical efficiency (geometrical filling factor).

(a) Quantum efficiency

The quantum efficiency of silicon photomultiplier is most general characteristic and consistent to general definition of the quantum efficiency of semiconductor detecting structures. Photons illuminated the silicon photomultiplier sensors with energy higher than bandgap are absorbed by the silicon crystal structure of depleted area and created the electron-hole pair, which could be detected as the signal. In some publications the quantum efficiency of semiconductor detectors is defined as number of measured electrons at the output of detector structures to the input flux, but in case photomultipliers more sufficient use the definition from [Tshang W.T (Ed), 1985], the quantum efficiency is the ratio of created electron-hole pairs to the incoming photon flux.

In real detecting structures as silicon photomultipliers part of the photon flux is affected by the reflection on the border of air/sensitive area of detection structure. For the silicon, reflection index on the border air/semiconductor is ~3.5 and correspondent Frenell coefficient for the normal incident photons R=0.3. i.e. losses on the reflection could reach ~30%. This loss could

be efficiently reduced by implementation of the antireflection coating and will be included in the quantum efficiency of silicon photo multipliers (Tsang W.A., 1985).
Main factor which define the quantum efficiency is characteristics of absorption process of photons in the depleted area of detecting structure. A photon flux of intensity $I(\lambda,z)$ will absorbed in silicon according to the Beer-Lambert law given in equation (2), creating an equivalent number of electron/hole pairs.

$$I(\lambda, z) = I(\lambda)e^{-\alpha(\lambda)z} \quad (2)$$

where:

$I(\lambda)$ – initial photon flux,
$I(\lambda,z)$ – photon flux on the distance z fron silicon photomultiplier face
$\alpha(\lambda)$ – optical absorption coefficient,
z – penetrated thickness of silicon.

This process, defined photon attenuation, is a fundamental property of all silicon detectors. I.e. photons entering a silicon layer travel a characteristic distance before giving up their energy to create a photoelectron. This distance is a function of the absorption coefficient, which is defined as the inverse of the distance a photon flux travels in a material before being attenuated by a factor of *e*. It is important parameter for the development of the silicon photomultiplier, because the thickness of depletion layer is relatively thin.
Other aspect of this consideration is that optical absorption coefficients is strong function of wavelength (or energy) of photons for particular semiconductor material, and defined the sensitivity dependency of quantum efficiency to wavelength of detecting photons. Fig. 10. shows the absorption coefficient as function of wavelength of photons in silicon (Tsang W.T., 1985).

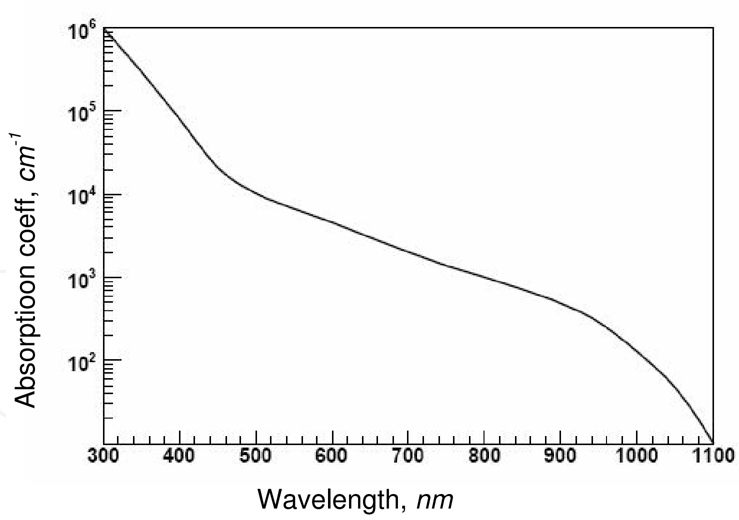


Fig. 10. Absorption coefficient of photons in silicon as function of wavelength.

Cut off at long wavelengths is fundamental limitation and occurs for a silicon photodiode at a wavelength of 1.1 µm where the photon energy is just sufficient to transfer an electron across the silicon band gap. As this wavelength is approached the probability of photon absorption decreases rapidly with increasing wavelength. It will be noted that the absorption coefficient increases with increasing temperature leading to an increase in long wavelength responsivity with temperature. Cut off at short wavelength occurs in silicon photomultiplier through structure feature of micro-cells. The top layer of a micro-cells is formed by an implantation or diffusion process that defines the edge of the depletion layer. Photons absorbed in this layer will not contribute to charge collection process and this effect causes a strong reduction of the sensitivity of photodiodes for photons with a short wavelength which are absorbed close to the surface.

Generally the quantum efficiency of silicon photomultiplier - $\eta(\lambda)$ could be calculated as:

$$\eta(\lambda) = (1 - R)(1 - e^{-\alpha(\lambda)L_d}) \tag{3}$$

where:

R – reflection Frenell coefficient,

$\alpha(\lambda)$ – optical absorption coefficient,

L_d - thickness of depleted area of micro-cell.

Correct design of the sensitive area of the silicon photomultiplier for the maximal quantum efficiency lead provide two main conditions for the vertical layers structure design:

- The top technological layers should be relatively thin, especially if the silicon photomultiplier is developed for the short wavelength region,
- The thickness of sensitive layer (depleted area) should agreed to the condition:

$$\alpha(\lambda)L_d >> 1 \tag{4}$$

where:

a(l) – optical absorption coefficient, which gives the distance over which the photon flux is reduced by a factor *e* ,

L_d – thickness of the depleted area.

In silicon the absorption coefficient for the visible range of light (as example, green light) is ~ 10^4 cm $^{-1}$, and for effective absorption the thickness of the sensitive area of silicon photomultiplier should be order of few microns, this is lead to possibility use the low resistivity silicon material as a basic material of silicon photomultilier structures.

Actually photons could absorbed in other technological layers of the detecting structure and contribute to the charge collection and quantum efficiency, but this effect is second order and will not discussed here (Tsang W. T., 1985).

(b) Efficiency of avalanche process triggering

Not all primary electron-hole pairs succeed in initiating a avalanche breakdown. Although conditions are such that, on the average, the number of carriers in the multiplying region increases exponentially with time, some just start a chain of ionizations that terminates, because of a fluctuation to zero carriers, before it really gets multiplication. The probability that the process of ionizations continues to increase until the whole *pn*-junction is discharged is called the avalanche breakdown probability (P_b). Generally avalanche breakdown probability is function of electric-field profile and the electron-hole ionization coefficients and could be calculated provided the electric field profile and electron, hole ionization coefficient are known [McIntyre, R.J.,1973]. Nevertheless study of silicon photomultiplier detecting efficiency shows that the avalanche breakdown probability in the silicon photomultiplier structures is significantly higher and probably needed to be addition investigation.

(c) The geometrical efficiency (filling factor)

The geometrical filling factor (F) is the proportion of surface area capable of detection single photons to the total area of silicon photomultiplier including technological border. Geometrical filling factor follows from the need to form independent micro-cells, quenching element and electrodes. Some affecting factor on the filling factor is optic crosstalk, which is function of the distance between the micro-cells. Special technology is used to overcome this problem, which will be discussed later.
Finally the photon detection efficiency (PDE) of the silicon photomultiplier could be defined as:

$$PDE = \eta(\lambda) \cdot P_b(V) \cdot F \quad (5)$$

where:

$\eta(\lambda)$ − quantum efficiency of silicon microcell structure,

$Pb(V)$ – probability of avalanche breakdown in silecon microcell structure,

F – geometry filling factor.

Experimental study of photon detection efficiency of silicon photomultipliers is very complicated task, especially in the low photon flux region. To simplify this problem, the experimental photon detection efficiency could be determined by measuring the photon detection probability of individual avalanche breakdown mode micro-cell, identical to those contained within the silicon photomultiplier. The photon detection probability is defined as the quantum efficiency times the avalanche breakdown probability. The photon detection efficiency of silicon photomultiplier is then determined by scaling the photon detection probability with the geometrical efficiency. The micro-cell photon detection probability was measured relative to a calibrated photo detector with monochromator light source. Fig. 11. shows the measured photon detection probability as a function of wavelength at 2 and 4V above the breakdown voltage together with the predicted wavelength response (Stewart A. G. et all, 2008).

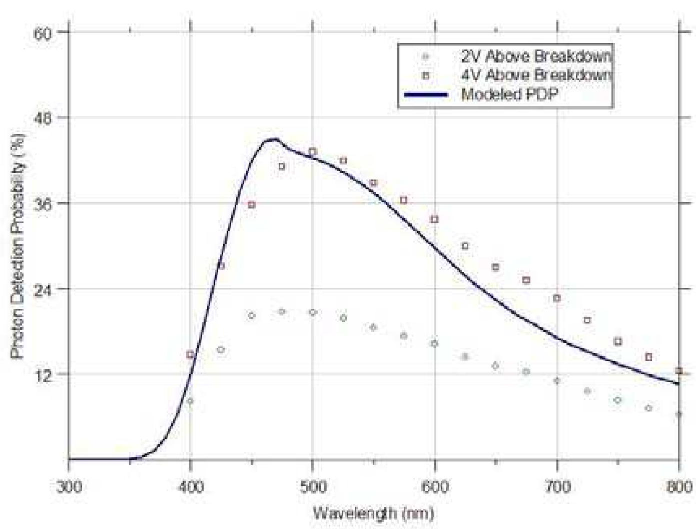


Fig. 11. Photon detection efficiency of silicon photomultiplier as function of wavelength (o – experimental measurements at $2V$ above breakdown, □ - experimental measurement at $4\ V$ above breakdown, solid line – modeling data)

At 4*V* above breakdown the peak of photon detection probability is 43% and occurs at 500 *nm* wavelength of light. At 2*V* above breakdown the peak of photon detection probability shifts to a slightly lower wavelength and has a peak value of 21%. On the Fig. 11. is presented also the curve of modeled photon detection probability. Model is using the absorption coefficient of silicon and the probability that a photon will be absorbed in the depletion region together with a model of the transmittance of the anti-reflection coating. The depletion layer absorption and anti-reflection coating determine the spectral profile of the photon detection efficiency which is then scaled to fit to the experimental photon detection probability data by using the avalanche breakdown probability as a fitting parameter.
Scaling the micro-cell photon detection probability values with the silicon photomultiplier fill factor gives the photon detection efficiency of silicon photomultiplier. For modern technology the filling factor rich value of 0.6-0.8.

4.3 Multiplication factor

Multiplication factor of silicon photomultiplier is defined by the avalanche process and the characteristic of quenching element. The value of multiplication factor could be precisely calculated from single photon spectra, as mentioned before, the signal is represented the charge generated by the avalanche breakdown process and peaks correspondent to the number of detected photons or photoelectrons. In silicon photomultiplier is possible to get the absolute calibration of the multiplication factor using the position of the single photon peak in the spectra (correspondent value in charge), because this position is exactly correspondent of creating of one electron-hole pair in micro-cell. The multiplication factor is a function of detector bias and temperature. Fig. 12 shows the multiplication factor of silicon photomultiplier increases linearly with over breakdown voltage and is greater than 1×10^6 at 0.7V above the breakdown voltage (Stewart A. G. et all, 2008) .

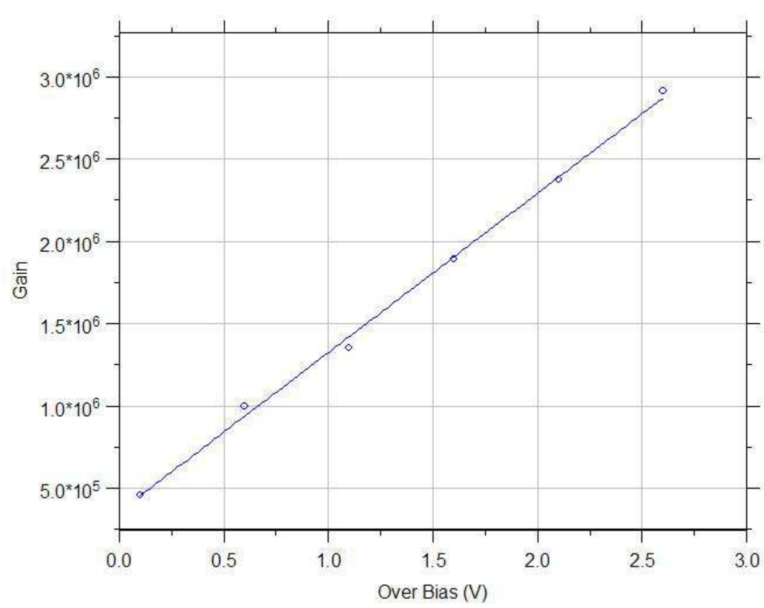


Fig. 12. Multiplication factor of silicon photomultiplier as function of voltage above the breakdown voltage.

The intra and inter micro-cell multiplication factor variation or uniformity of silicon photomultiplier can be determined from the width of the photoelectron peaks on the single photon spectra. The width of single photon peak is defined as combination of the variation of the charge produced by controlled avalanche breakdown process and uniformity of the characteristic of the micro-cells around the total area of silicon photomultiplier, because the single photon peak is collected signals statistically from different micro-cells during photon detection.

4.4 Dynamic range and linearity

The detection of photons by a silicon photomultiplier is a statistical process based on the probability of detecting randomly distributed photons by the limited number of sensitive elements micro-cells. The photon detection efficiency and the total number of micro-cells determine the dynamic range of the silicon photomultiplier. The number of detected photons n_{dph} (number of micro-cells with signal) as function of the number of incident photons can be approximated by the following expression,

$$n_{dph} = N_{mc}\left(1 - \exp\left(-\frac{PDE \cdot N_{ph}}{N_{mc}}\right)\right) \quad (7)$$

where:

N_{mc} – total number of micro-cells of silicon photomultiplier,
PDE – photon detection efficiency,
N_{ph} - number of incident photons.

Fig. 13. shows the silicon photomultiplier response (number of pixels with signals) as a function of the number of instantaneous incident photons for an silicon photomultiplier with 620 micro-cells and with a photon detection efficiency of 5% and 10% (Stewart A. G. et all, 2008).

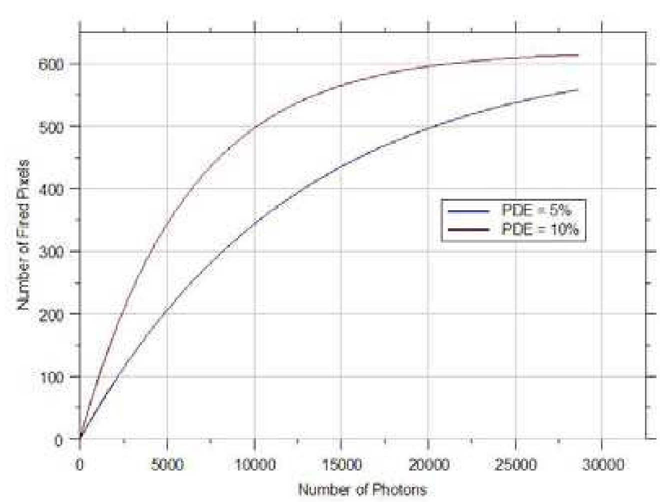


Fig. 13. Dynamic range of silicon photomultiplier – the number of fired micro-cells as function of number of incident photons

The silicon photomultiplier response is linear when the number of incident photons is much less than the total number of micro-cells. The silicon photomultiplier response begins to saturate when the number of pixels fired reaches approximately a quarter of the total number of micro-cells. The figure also shows how the silicon photomultiplier dynamic range and linearity can be extended to handle higher photon fluxes by lowering the operating bias and hence reducing the photon detection efficiency of silicon photomultiplier, in this example, from 10 to 5%. The statistical behaviour of the linearity and dynamic range curves gives the possibility to calibrate this curve to improve the characteristic of silicon photomultipliers. Nevertheless the main way to improve the linearity and increase the dynamics range of silicon photomultipliers is increasing the number of micro-cells.

4.5 Time performance

The time performance of silicon photomultipliers is defined by two parameters: the rising time of the avalanche breakdown signal and the recovery time, which defined by the process of reconstruction the *pn*-junction state after quenching the avalanche breakdown process and recharging through the quenching resistor.

The rising time is defined by the time of creating the avalanche breakdown process and characterized by drift time of carriers under the high electric field. Drift velocity carriers under electric field $\sim 10^5$ is limited by scattering and in silicon structures is approximately $\sim 10^7\ cms^{-1}$, this gives the estimation of the rising time, as example for the thickness of depleted area of 4 microns the rising time is $\sim 30\ ps$.

The timing jitter spectrum, characterized the rising time of the silicon photomultiplier shown in Fig. 14. The jitter histogram is fitted with a Gaussian curve and has a full width on half maximum of 65ps, including the response of measurement system (Stewart A. G. et al, 2008).

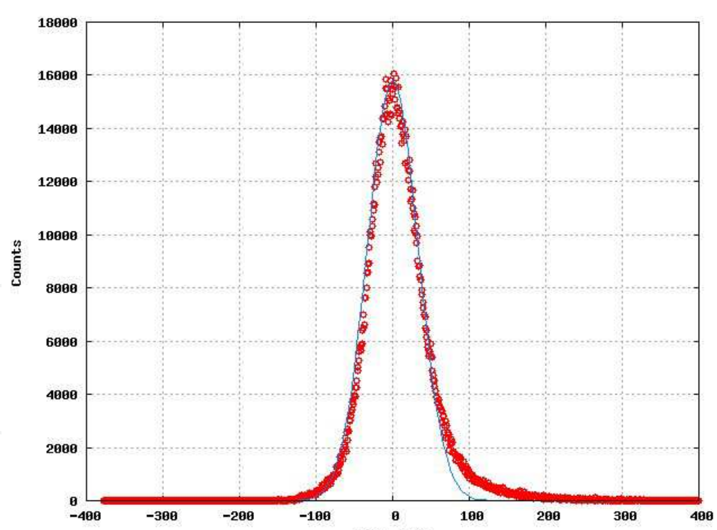


Fig. 14. Time response of silicon photomultiplier (o – experimental measurements, solid line – fit).

The recovery time is defined mainly by recharge process and could be estimated from values of RC - combination of the quenching resistor, diode capacitance and external circuit. The quenching resistor could be tuned in relatively wide range and define the recovery time of silicon photomultiplier in range $\sim 1 - 100\ ns$.

4.6 Noise consideration (dark rate)

One of the main factors limiting the performance and size of the silicon photomultiplier is the dark rate – frequency of the signals with amplitude equivalent of single photon signal, initiated by the thermal electron-hole pair created in sensitive area of silicon photomultiplier. Usually conventional photodetectors is characterized in term of noise by the dark current. In case silicon photomultiplier the very high gain is practically neglected the contribution of the dark current or leakage currents of silicon structure to the output signal, because the leakage current carriers is not affected by the amplification process. Significant for the noise consideration became the processes which included in the processes of multiplication. The thermally generated carriers in the depleted area could also initiate a avalanche breakdown and results in a current pulse that is indistinguishable from a pulse produced by the detection of a single photon. This is particularly important for room temperature operation. The silicon photomultiplier dark rate is the average frequency of the thermally generated avalanches breakdown processes from all micro-cells of silicon photomultiplier. Typical value of dark rate for the modern silicon photomultipliers is in range ~0.1-1 MHz per mm^2.

The results of experimental study of silicon photomultiplier dark rate are shown on the Fig. 15. and Fig. 16., the dark rate signals measured on the threshold correspondent to half of the single photon pulses. Fig. 15. shows the dark rate as a function of over-bias for two types of silicon photomultipliers size 1 mm^2 at room temperature and at temperature -20^{o}C (Stewart A. G. et all, 2008).

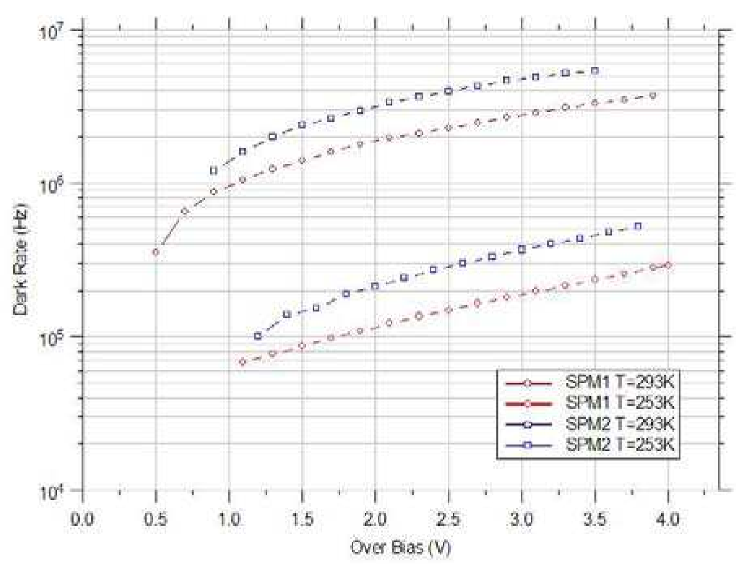


Fig. 15. Dark rate of two silicon photomultipliers as function of voltage over breakdown voltage for two temperatures.

At room temperature the dark rate increases linearly at a rate of 0.95MHz/V for one type and 1.67MHz/V for the another design.

As the dark is thermally activated it is a strong function of temperature. Fig. 16. shows the dark rate of silicon photomultiplier size 1 mm^2 at 2 and 3V above the breakdown voltage (Stewart A. G. et al, 2008).

The plot gives the dark rate thermal activation energy of 433 meV at $2V$ above breakdown and 388 meV at $3V$ above breakdown. These activation energies are close to half the bandgap of silicon (560 meV) and are indicative of thermal generation from a single trap level in the depletion region.
It should be mentioned that the amplitude of the dark rate pulses is equivalent of the single photon signal amplitude, that for many application deal with tens-hundreds photons it could be neglected. For applications with very low photon flux the average dark rate can be measured and subtracted. However, the statistical variation in the dark rate cannot be subtracted and constitutes a noise source that determines the minimum detectable signal.
Dark rate of the silicon photomultiplier is scales as its area, so in practice, the "acceptable" noise dark rate ~ 10^6 limits the maximum designable area around few mm^2.

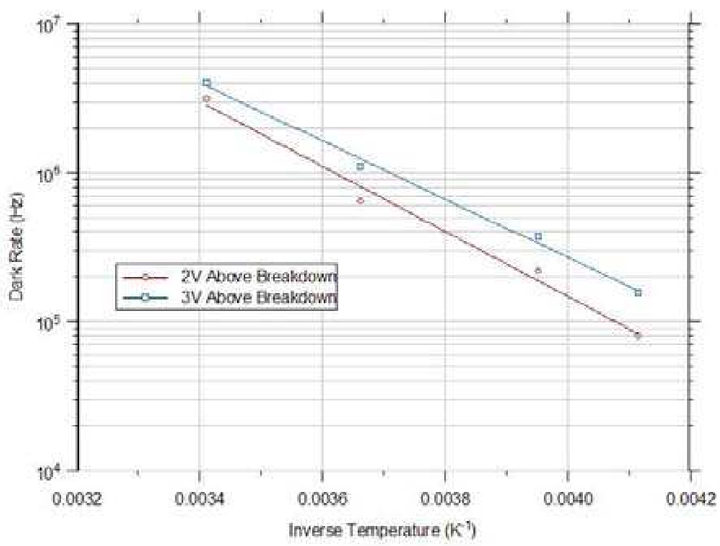


Fig. 16. Dark rate of photomultiplier as function of temperature for two value of voltage over breakdown voltage.

4.7 Optical crosstalk

Generation of the light photons during the avalanche breakdown processes in silicon is well known phenomena (Chynoweth A.G & McKay K.G., 1956). This phenomena becomes very critical in the silicon photomultiplier structures due to very tiny geometrical pattern which allowed the photons created by avalanche breakdown process during the detecting the photon in one micro-cell rich an another micro-cells and give the signal which is not distinguishing from signal of detected outside source photon. The ratio of number of secondary created photons, detected in the silicon photomultiplier to number of detected incoming photons is determinate as optical crosstalk of silicon photomultiplier.
As example the light generation in the silicon photomultiplier is illustrate on the Fig. 17., where shown single micro-cell of photomultiplier under reverse bias (actually the reverse bias is in the high value over breakdown to show the phenomena) (Kotura, Inc, 2009).
The light spots are clear visible in the corner of the avalanche breakdown micro-cell indicate the critical areas of the silicon photomultiplier structures, corners have the two dimensional curvature.

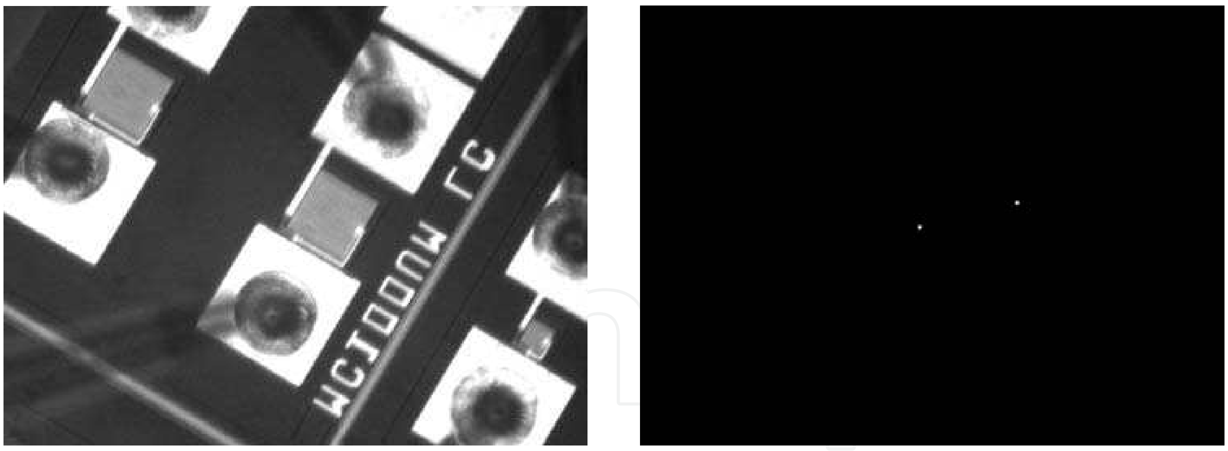


Fig. 17. a,b. Light generation in the silicon photomultiplier micro-cell in regions with high gradient of electric field, a – the micro-cell in external light, b – same micro-cell without external light.

Optical crosstalk of silicon photomultiplier scales as the product of optical generation inside the triggered micro-cell during the avalanche breakdown process, the total geometric cross section for the interaction between two micro-cells and the single photon sensitivity of micro-cells. The optical crosstalk probability is a function of silicon photomultiplier bias voltage and the distance between neighbourhood pixels.

The optical crosstalk probability preliminary can be estimated by the ratio of the count rate at the second photoelectron level to the count rate at the single photoelectron level. The count rate at the single photoelectron level is measured by setting the threshold at half the single photon peak while the rate at the second photoelectron level is measured by setting the threshold at 1.5 times single photon peak height. The measurements were taken at 253K to reduce the primary dark rate. At room temperature were the dark rates are of the order of MHz, there is a higher probability that two uncorrelated dark pulses or a dark pulse and an afterpulse event might coincide to produce a pulse with amplitude greater than the threshold setting for the second photoelectron level. At 253K the primary dark rate is of the order of a few 100kHz and the probability of uncorrelated events occurring simultaneously is minimized.

Fig. 18. a,b. shows the optic crosstalk probability, measured at 253K, for two silicon photomultiplier as a function of voltage over breakdown voltage (left) and the frequency of dark rate as a function of threshold (right) (Stewart A. G. et al., 2008).

The crosstalk probability increases linearly with over-bias and as expected the silicon photomultiplier 2 (SPM2) design has a higher crosstalk probability as the pixel pitch in this design is smaller. Plotting the pulse frequency as a function of threshold position produces a step-like curve. The flat regions of the curve correspond to the frequency of pulses at the single, double, triple photoelectron level. In the example shown the pulse frequency was measured at 253K and at 3V over-bias. At a low threshold the frequency corresponds to the single photoelectron level rate or dark rate of the silicon photomultiplier. As the threshold increases above the peak height of the single Geiger pulses, the rate falls as only pulses at the second photoelectron level, i.e. optic crosstalk, will now be measured. The rate then remains constant until the threshold increases above the peak height of two coincident pulses and then falls to the rate of the third photoelectron level. Pulses at the third photoelectron level are also mostly due to crosstalk.

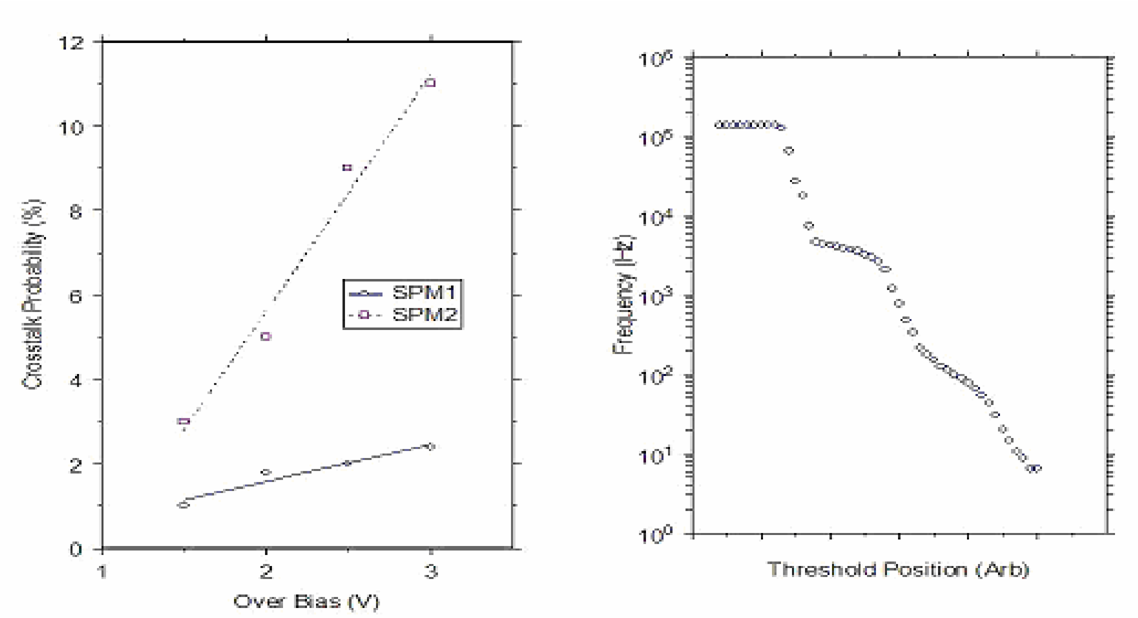


Fig. 18. Optic crosstalk probability of two photomultiplier as function of voltage over breakdown voltage and frequency of dark rate of two photomultipliers as function of threshold.

The optical crosstalk probability is a function of silicon photomultiplier bias voltage and the distance between neighboring pixels. However, the optic crosstalk can be significantly reduced by optically isolating the pixels from each other. This can be achieved by etching a trench between the pixels and filling it with an optically opaque material.

Fig. 19. a,b. shows specific element of the optic isolation, implemented for the quantum photo detector, by the high precision trench technology (Kotura Inc, 2009).

Implementation of trenches in the structure of silicon photomultipliers significantly reducing more then order of magnitude the optical crosstalk, bring on the level less 1% and create new high performance quantum photodetectors for the very low photon flux measurement (Saveliev, V et all, 2008).

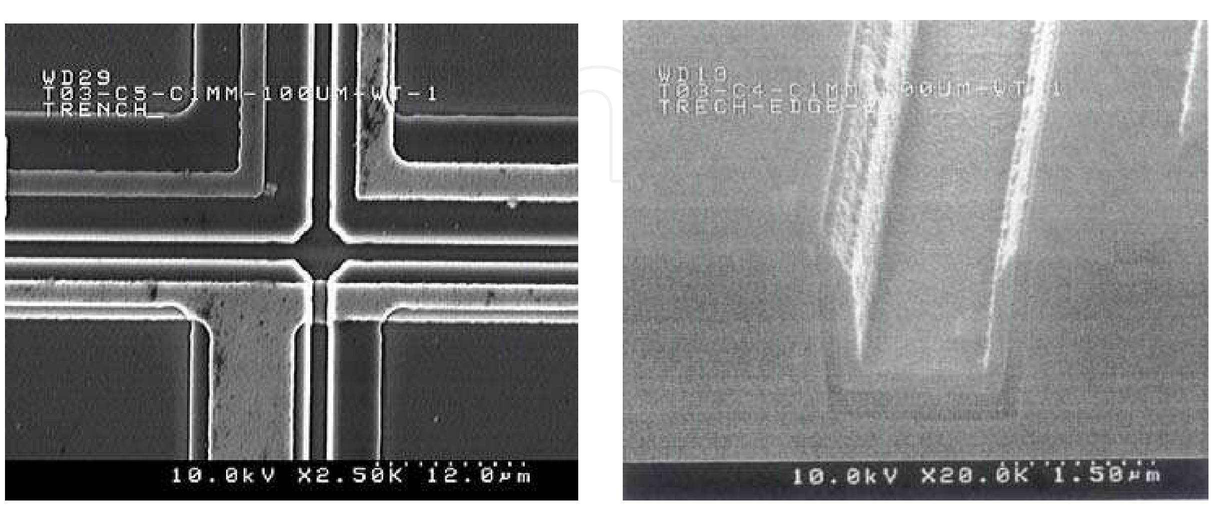


Fig. 19. a,b. micrograf of a -the trench pattern of silicon photomultiplier and b- profile of the trench of silicon photomultiplier

4.8 Afterpulsing

Afterpulsing processes of the silicon photomultiplier are breakdown processes occurs due to release of carriers captured by traps during a previewed breakdown avalanche process. During a breakdown processes a large number of carriers cross the pn-junction and finite probability that a carrier may become trapped by a bandgap state. The carrier may then be released at some time and trigger a new breakdown avalanche event.

Afterpulsing is described in term of probability. The afterpulsing probability is the probability that any gives pulse in followed by a false count or afterpulse. The afterpulsing probability is a function of the mean lifetime of the carrier in the trap. The trap lifetime depends on the trap prpperties, the type of carrier trapped and the temperature. Short trap lifetime result in a low afterpulsing probability since the carriers are likely to be emmited before the diode has fully recovered and the carrier avalanche initiation probabilities are low, Afterpulsing occurring before the diode has fully recovered will also have a lower gain since the diode will not have fully recharged. Preliminary study this effect in silicon photomultipliers shows not so dramatic effect on the performance of silicon photomultipliers.

5. Conclusion

Silicon photomultipliers is novel type of the semiconductor photodetector for the detecting of low photon flux. Already now the technology is developed and suitable for many critical application as medical imaging, and biology, homeland security, optic communications, experimental physics and military applications. Few world well known companies Hamamatsu, Sensl, Kotura are already producing or close to production of silicon photomultiplier type sensors. Near future of silicon photomultiplier development is create the completely digital quantum detector with implemented readout electronics on same substrate. Such solution will be another one step to the new era of quantum detection and will open possibility for many new applications.

6. References

Alvares-Gaume L. et al. (2008). Review of Particle Physics, Particle Detectors. *Physics Letters,* Vol. 667, No. 1-5, 2008 , 281-370, ISSN

Atac, M. (1993). Visible Light Photon Counters for Detecting Very Low Level Light. *ICFA Instrumentation Bulletin,* No 10, 1993 9-11

Bondarenko, G. et all. (2000). Limited Geiger Mode Microcell Photodiode: new results. *Nuclear Instruments and Methods,* A442, 2000 187-192

Chynoweth, A.G. & McKay K.G. Photon Emission from Avalanche Breakdown in Silicon. *Phys Review*, v 102, n2, 1956, 369-376

Gasanov, A. G. et all. (1988). *Soviet Technical. Physics Letters* Sov. 14, 313 (1988)

Golovin, V. & Saveliev V. (2004). Novel Type of Avalanche Photodetector with Geiger Mode Operation. *Nuclear Instruments and Methods,* A518, 2004, 560-564

Hammamatsu Photonics K.K. Photomultipliers Tubes, Basics and Applications, Toshikaza Hakamata et all. (Ed), 2006, 1-309, Hammamatsu Photonics K.K., Electron Tube Division, ISBN, Japan

Kotura (2009) Kotura, Inc., http://www.kotura.com

McIntyre R.J. On the Avalanche Initiation Probability of Avalanche Diodes above the Breakdown Voltage E.D., IEEE Transaction V 20, 7.,1973, 673-641

Saveliev, V. (1995). Avalanche Photodiode on Base of "Needle" Metal Resistor Semiconductor Structures, *Proceedings of New Development on Radiation Detectors, 7th European Symposium on Semiconductor Detectors*, Schloss Elmau, Germany, May 1995

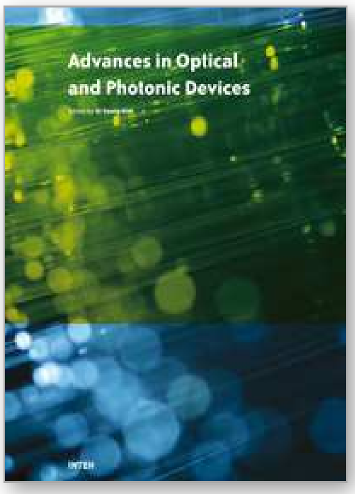
Saveliev, V. & Golovin V. (2000). Silicon Avalanche Photodiodes on base Metal Resistor Semiconductor (MRS) Structures. *Nuclear Instruments and Methods,* A442, 2000 223-229

Saveliev, V. et all (2008). Quantum Photo Detectors with Optical Crosstalk Suppression, *Proceedings of 2008Nuclear Science Simposium, Medical Imaging Conference and 16th Room Temperature Semiconductor Detector Workshop*, Dresden, Germany, October 2008

Sensl (2009). Sensl Technologies Ltd, http://www.sensl.com

Stewart A. V. et all (2008). Performance of 1-mm^2 Silicon Photomultiplier. *IEEE Journal of Quantum Electronics,* Vol. 44, No. 2, 2008, 157-164

Tsang W.T. (Ed) (1985)., *Semiconductors and Semimetals: Lightwave Communication Technology, Part D, Photodetectors,* Tsang W. T. (Ed), 1-309, Academic Press Inc., ISBN :978-0-12-752153-4



Advances in Optical and Photonic Devices
Edited by Ki Young Kim

ISBN 978-953-7619-76-3
Hard cover, 352 pages
Publisher InTech
Published online 01, January, 2010
Published in print edition January, 2010

The title of this book, Advances in Optical and Photonic Devices, encompasses a broad range of theory and applications which are of interest for diverse classes of optical and photonic devices. Unquestionably, recent successful achievements in modern optical communications and multifunctional systems have been accomplished based on composing “building blocks” of a variety of optical and photonic devices. Thus, the grasp of current trends and needs in device technology would be useful for further development of such a range of relative applications. The book is going to be a collection of contemporary researches and developments of various devices and structures in the area of optics and photonics. It is composed of 17 excellent chapters covering fundamental theory, physical operation mechanisms, fabrication and measurement techniques, and application examples. Besides, it contains comprehensive reviews of recent trends and advancements in the field. First six chapters are especially focused on diverse aspects of recent developments of lasers and related technologies, while the later chapters deal with various optical and photonic devices including waveguides, filters, oscillators, isolators, photodiodes, photomultipliers, microcavities, and so on. Although the book is a collected edition of specific technological issues, I strongly believe that the readers can obtain generous and overall ideas and knowledge of the state-of-the-art technologies in optical and photonic devices. Lastly, special words of thanks should go to all the scientists and engineers who have devoted a great deal of time to writing excellent chapters in this book.

How to reference

In order to correctly reference this scholarly work, feel free to copy and paste the following:

Valeri Saveliev (2010). Silicon Photomultiplier - New Era of Photon Detection, Advances in Optical and Photonic Devices, Ki Young Kim (Ed.), ISBN: 978-953-7619-76-3, InTech, Available from: http://www.intechopen.com/books/advances-in-optical-and-photonic-devices/silicon-photomultiplier-new-era-of-photon-detection

InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820

www.intechopen.com

Fax: +385 (51) 686 166
www.intechopen.com

Fax: +86-21-62489821