INVESTIGATION OF THE INFLUENCE THE ANGLE OF INCIDENCE OF OPTICAL RADIATION ON A PHOTO-SENSITIVE SURFACE OF THE CHARACTERISTICS OF A SILICON MATRIX AVALANCHE PHOTODETECTOR

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Annotation: The effect of supply voltage and energy exposure on the photo signal value and signal-to-noise ratio is studied when the angle of incidence of optical radiation on the photosensitive surface of Ketek RM 3325, ON Semi FC 30035 and KOF5-1035 silicon matrix avalanche photodetectors are studied. A scheme of the installation and a research technique is given. The magnitude of the photo signal of the studied photodetectors were measured as a function of the magnitude of the overvoltage and the energy exposure of optical radiation, and the signal-to-noise ratios were determined. It has been established that the flat angle of view of silicon photomultipliers depends on the supply voltage of the photodetector and doesn't depend on the energy exposure of optical radiation. Diagrams of the change in the magnitude of the photo signal from the angles of incidence of optical radiation on the photosensitive surface of photodetectors are presented as well. It has been found that at supply voltages exceeding the breakdown voltage by no more than 1 V, the maximum deviation of the angle of incidence of optical radiation on the photosensitive surface of silicon photomultipliers within the flat angle of view leads to a decrease in the signal-to-noise ratio to a component value of at least 60% of the maximum value for KOF5-1035 and at least 80% for Ketek RM 3325 and ON Semi FC 30035. The dependences of the signal-to-noise ratio on the angle of incidence of optical radiation on a photosensitive surface are given for various over voltages and energy exposures. The results of this article can be used in the development and design of instruments and devices for detecting optical radiation based on silicon photomultipliers.

Keywords: silicon matrix avalanche photodetector, photosignal, angle of incidenceof optical radiation, flat angle of view, signal-to-noise ratio.

Introduction: Currently, various types of devices based on photodetectors are widely used in science and technology: open optical communication systems for data transmission, lidars for monitoring air and water pollution, optical devices for recording signals from various kinds of astronomical objects [1 -3]. One of the most promising photodetectors for use in such systems and devices are silicon matrix avalanche photodetectors - silicon photomultipliers (SiPM) [4-6]. This is due to the fact that SiPMs have a number of advantages over other types of photodetectors used in these systems and devices: electrovacuum photomultipliers and single-element avalanche photodiodes. So, when compared with electrovacuum photomultipliers, SiPMs are more compact and insensitive to magnetic fields, have lower supply voltages, good time resolution, higher mechanical strength and better sensitivity in the visible region of the spectrum. Compared to single-element avalanche photodiodes, SiPMs have a higher gain, low sensitivity of the gain to changes in temperature and supply voltage, and large areas of the photosensitive surface.

One of the significant characteristics of photodetectors used in the above systems and devices is a flat angle of view - the angle between the normal plane to the photosensitive surface of the photodetector and the direction of incidence of a parallel optical radiation beam, at which the photo signal decreases to a predetermined level [9]. Knowing this parameter is important for optical systems in which optical radiation can arrive at the photodetector not only normally to its photosensitive surface, but also at different angles. However, the value of the flat angle of view for commercially available SiPMs is not determined. It has also not been established how the angle of incidence of optical radiation on the photosensitive surface of the SiPM affects the signal-to-noise ratio at the output of this photodetector. All this determined as the purpose of the work.

Experimental setup and measurement technique

Commercially available SiPM KOF5-1035, Ketek RM 3325, and ON Semi FC 30035 were chosen as objects of study, since they have a similar structure and parameters.

On fig. 1 shows a block diagram of the experimental setup for research.

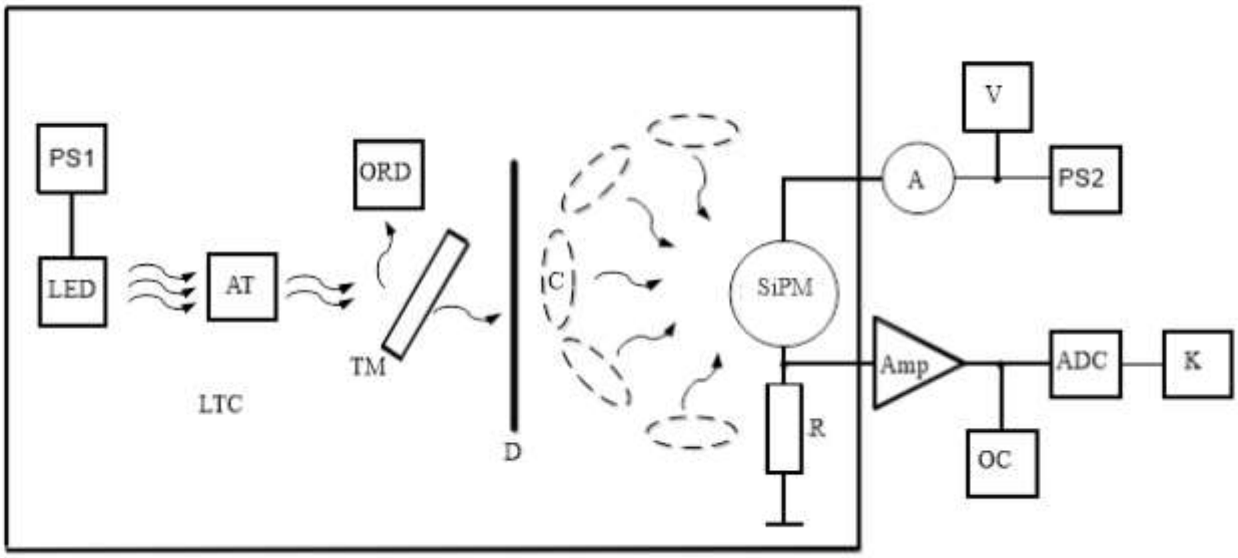

Fig.1. Block diagram of the experimental setup

PS1 and PS2 – power supply of the optical system and photodetector; S – optical system; M – modulator; AT – attenuator; A – ammeter; V - voltmeter; SiPM – silicon photomultiplier; ORD – optical radiation dosimeter; TM– translucent mirror; Amp– amplifier; D – diaphragm; R – load resistance; ADC – analog-to-digital converter; K – computer; OS – oscilloscope; LTC – light-tight camera, LED – light-emitting diode.

As a source of optical radiation, an LED with a wavelength λ = 470 nm, corresponding to the maximum sensitivity of the SiPM [10]. The LED is powered by a generator of rectangular electric pulses IP1, the duration of which is 1 μs, and the repetition rate is 104 Hz. With such a pulse repetition rate, it is possible to avoid the influence of phenomena that occur in SiPM after the end of registration of one optical pulse on the process of registration of the optical pulse following it.

From the output of the attenuator, the radiation is fed to a semitransparent mirror Z, which transmits 50% of the radiation that enters the SiPM through the diaphragm, and the mirror reflects 50% of the radiation to the laser dosimeter LD, which measures the energy exposure of optical radiation. The supply voltage Upit is supplied to the SiPM from the power supply PS2, which is controlled by a voltmeter V. A load resistor Rl is connected in series with the SiPM. When optical radiation pulses are detected, the electric current flowing through the SiPM changes, as a result of which voltage pulses are formed on the load resistor.

These pulses are amplified by the amplifier U and digitized by the analog-to-digital converter ADC, and the data are transmitted to the computer K. The form of these pulses at the output of the amplifier is controlled by the OS oscilloscope. To calculate the average amplitude of voltage pulses <Up> and their standard deviation σ, software is used. The average amplitude of voltage pulses <Up> is the value of the photo signal. When the aperture D is closed, the supply of optical radiation pulses to the photodetector stops. The SNK lightproof chamber protects the SiPM from external optical radiation.

The optical system C makes it possible to direct radiation at different angles α relative to the normal plane to the photosensitive surface of the SiPM. The angle α can be changed from 900 to –900. System C forms such a diameter of the optical radiation beam at which the optical radiation spot completely covers the square photosensitive surfaces of the studied SiPMs.

The flat viewing angle β is defined as the sum of two angles and, lying in the normal plane to the photosensitive surface of the SiPM and plotted respectively on the right and left sides of the axis drawn at an angle α = 00 to such a plane. Angles and correspond to the direction of optical radiation beams at which the photo signal becomes zero.

The geometry of the arrangement of the SiPM in the experiment is such that the distance l from the output of the optical system C to its photosensitive surface satisfies the condition [11]:

$$\frac{A}{l} \leq 0{,}01 \tag{1}$$

where A is the length of the side of the square of the photosensitive surface.

The signal-to-noise ratio at the SiPM output was determined by the following formula [12]:

$$\rho = \frac{U_{\text{п}}^2}{2\sigma^2}. \tag{2}$$

Since the studied SiPMs have different breakdown voltages Upr, then to compare their characteristics, an overvoltage is used, defined as ΔU = Upit - Upr. The breakdown voltage of the studied photodetectors was Upr = 24.7; 27.0 and 30.0 V for ON Semi FC 30035, Ketek RM 3325 and KOF5-1035 respectively. The breakdown voltage is determined from the current-voltage characteristic of the SiPM with a closed aperture according to the method described in [8].

All measurements were carried out at room temperature T = 293 K in the overvoltage range ΔU = – 0.5 – 1 V. The range of over voltages under study was limited by low gains on the one hand and high values of dark currents on the other. Also, when measuring the flat angle of view, all the requirements for the divergence of the optical beam and the measurement errors specified by the standard [11] were satisfied.

Measurement results and discussion

Based on the results of measurements, diagrams of the change in the magnitude of the photo signal from the angles α for the studied SiPMs are plotted, shown in Figs. 2. Note that along the polar axis in Fig. 2 shows the value of the photo signal Up in mV. Measurements were made at ΔU = 0.0 V and energy exposure H = 1 10-9; 1.7 10-9; 3 10-9 J/m2 for Ketek RM 3325, ON Semi FC 30035 and KOF5-1035. At supply voltages equal to the breakdown voltage or ΔU = 0.0 V, the signal-to-noise ratio of the studied photodetectors takes on a maximum value [12, 13]. The selected values of the energy exposure correspond to the upper limits of the dynamic range for all the studied photodetectors [14].

As can be seen from fig. 2, the maximum value of the photo signal voltage Umax corresponds to the angle α = 00. Note that the obtained values were symmetrical on the right and left with respect to the axis drawn at an angle α = 00 in the horizontal and vertical measurement planes. As the deviation of the angle of incidence of optical radiation from α = 00 increases, the value of the photo signal voltage decreases.

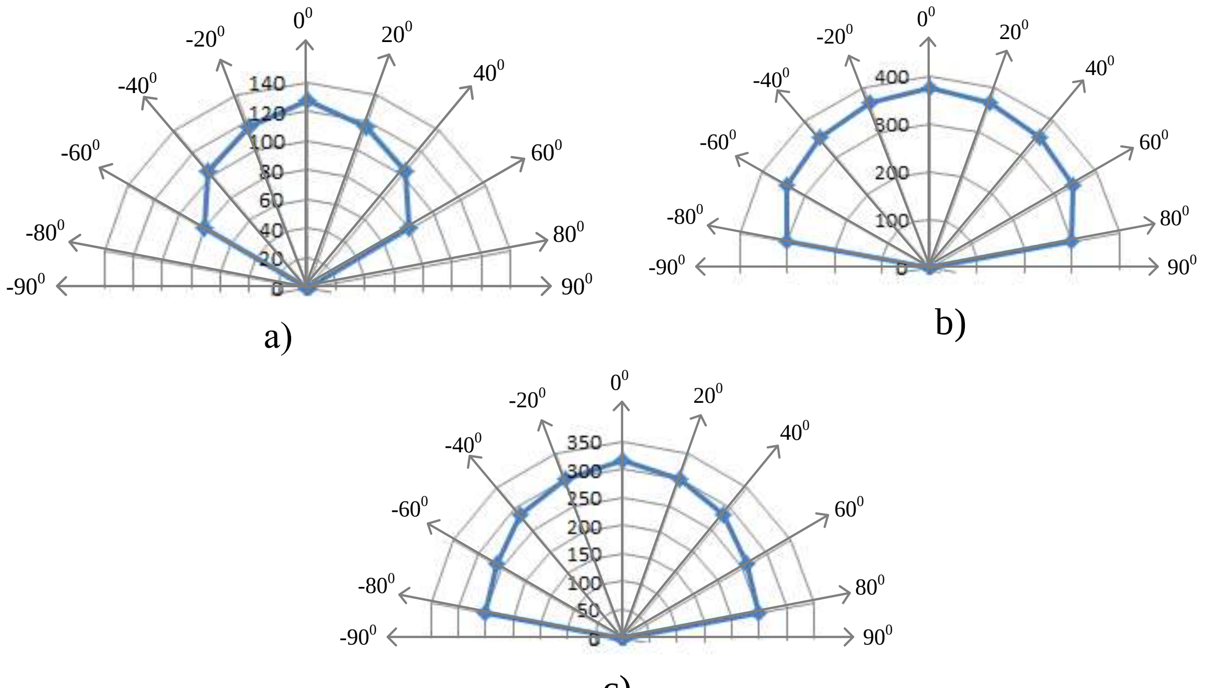

Figure 2 - Diagrams of changes in the magnitude of the photo signal from the angles α:
a) -KOF5-1035; b) - Ketek RM 3325; c) - ON Semi FC 30035.

At angles in the range α = ± 600, the photo signal voltage of the KOF5-1035 photomultiplier decreases to Up = 0.61 Umax. For angles α in the intervals from

600 to 900 and from –600 to –900, the value of Up was approximately equal to zero (Fig. 2a).

At values corresponding to the interval of angles α = ±800, the photo signal voltage of the SiPM Ketek RM 3325 decreases to Up = 0.80 Umax, and for ON Semi FC 30035 to Up = 0.82 Umax. For angles α in the ranges from 800 to 900 and from –800 to –900, the value of Up was approximately equal to zero for both photodetectors (Fig. 2b, c).

Such a difference in the angles α, at which SiPMs were sensitive to optical radiation incident on them, is due to the fact that materials with different refractive indices at the air-photosensitive surface interface were used to manufacture SiPMs. Therefore, optical radiation incident on a photosensitive surface at different angles α has different values of the Fresnel reflection coefficient. Also, the value of these angles depends on the design of the SiPM housing. Note that the housing design of the Ketek RM 3325 and ON Semi FC 30035 SiPMs was similar, so these photodetectors have the same angles for which the SiPMs were sensitive to the optical radiation arriving at them. The design of the KOF5-1035 housing differs significantly from the design of the housings of other studied SiPMs. In this regard, the value of such angles for KOF5-1035 was different compared to Ketek RM 3325 and ON Semi FC 30035.

As a result of the research, the values of the flat angle of view β of the studied SiPMs were determined for various over voltages and for the same values of energy exposure corresponding to the dynamic range of photodetectors. The dependence β(ΔU) is obtained, which is shown in fig. 3. An increase in the overvoltage led to an increase in the angle β. At ΔU = – 0.5 V, the smallest value from the studied overvoltage interval, the photo signal value took the following values: Up = 0.61 Umax for KOF5-1035 with = 400 and = – 400; Up = 0.4 Umax for Ketek RM 3325 prii = 600 and = - 600; Up = 0.46 Umax for ON Semi FC 30035 at = 600 and = - 600. In this case, the value of the flat viewing angle is β = 800; 1200 and 1200 for KOF5-1035; Ketek PM 3325 and ON Semi FC 30035 respectively.

At the highest value of ΔU = 1.0 V from the studied overvoltage interval, the photo signal value was: Up = 0.64 Umax for KOF5-1035 at = 650 and = - 650,

Up = 0.9 Umax for Ketek RM 3325 at = 850 and = – 850 and Up = 0.97 Umax for ON Semi FC 30035 at = 850 and = – 850. In this case, the flat angle of view is β = 1300; 1700 and 1700 for KOF5-1035; Ketek PM 3325 and ON Semi FC 30035 respectively.

In the range ΔU = –0.5 – 0.0 V, the dependence of β on ΔU increases linearly, and at ΔU = 0.0 - 1.0 V, saturation of this dependence is observed. This behavior of the dependence β(ΔU) is observed for all studied SiPMs. To estimate the dependences β(ΔU) in the range ΔU = –0.5 – 0.0 V, we use the value Δβ/ΔUpp, where Δβ is the change in the flat angle of view with a change in the overvoltage ΔUpp. Such an estimate shows that the value of Δβ/ΔUpp is approximately the same for all studied SiPMs and is 800/V.

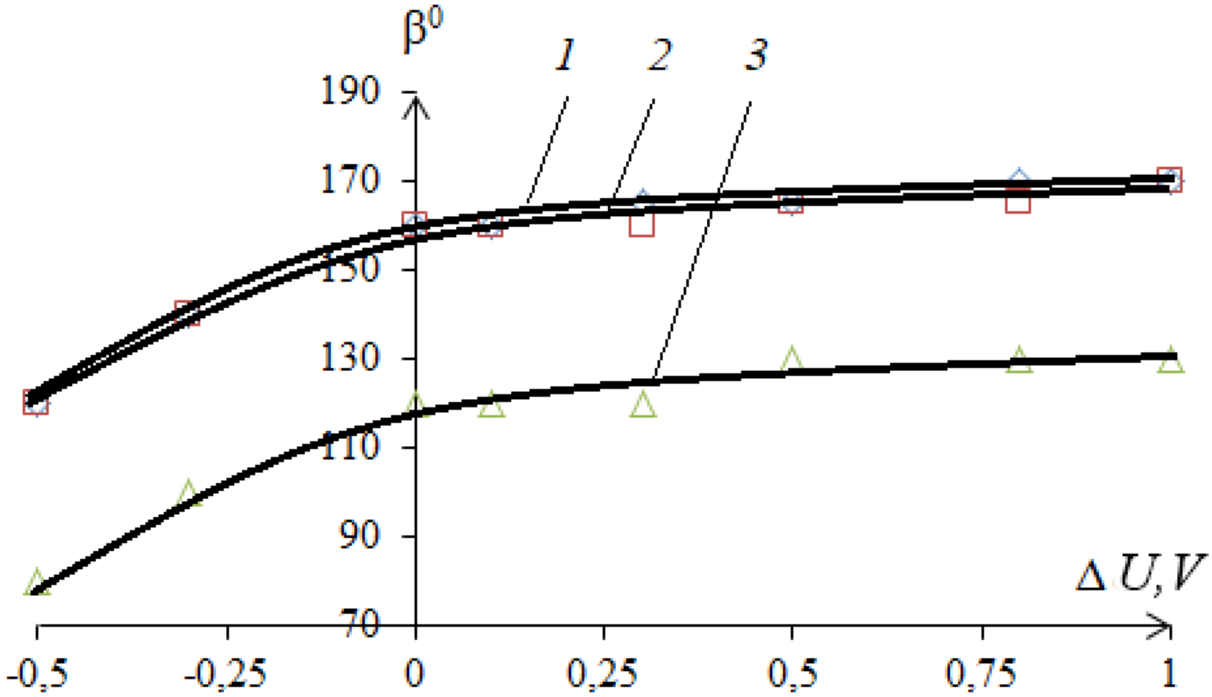

Fig.3. Dependence of the flat angle of view on the magnitude of the overvoltage:
1 - Ketek RM 3325; 2 - ON Semi FC 30035; 3 - KOF5-1035.

The dependence of the flat viewing angle on the overvoltage is due to the increase in the sensitivity of the studied photodetectors with an increase in the overvoltage. An increase in sensitivity leads to the fact that for those angles α at which the part of the optical radiation that was not reflected from the photosensitive surface, but absorbed by it, was not recorded at small over voltages, with an increase in ΔU, it begins to be recorded. For over voltages in the range ΔU = 0.0 – 1.0 V, the sensitivity of the studied SiPMs changed insignificantly. Therefore, saturation of the dependence of β on ΔU was observed for these over voltages. The dependence of the signal-to-noise ratio on the angle α was studied for different values of over voltages and for the same values of energy exposure for all the studied photodetectors. The dependences obtained were in many respects similar to the dependences of the photo signal voltage Up on the angle α. The maximum value of the signal-to-noise ratio of this dependence was at the value α = 00. The obtained values of the signal-to-noise ratio were symmetrical on the right and left with respect to the axis drawn at an angle α = 00; therefore, in Fig. 4

shows only the dependences of the signal-to-noise ratio on the angle α, which is in the range from 00 to 900 for various over voltages. On fig. Figure 4 shows the dependences for SiPM KOF5-1035 as the most typical. For other studied SiPMs, the behavior of these dependences was similar within the angles and. As can be seen from the dependences obtained, with an increase in the deviation of the angle of incidence of optical radiation from α = 00, a decrease in the signal-to-noise ratio occurs. At angles and ≤ α ≤ the value of the signal-to-noise ratio was greater than one.

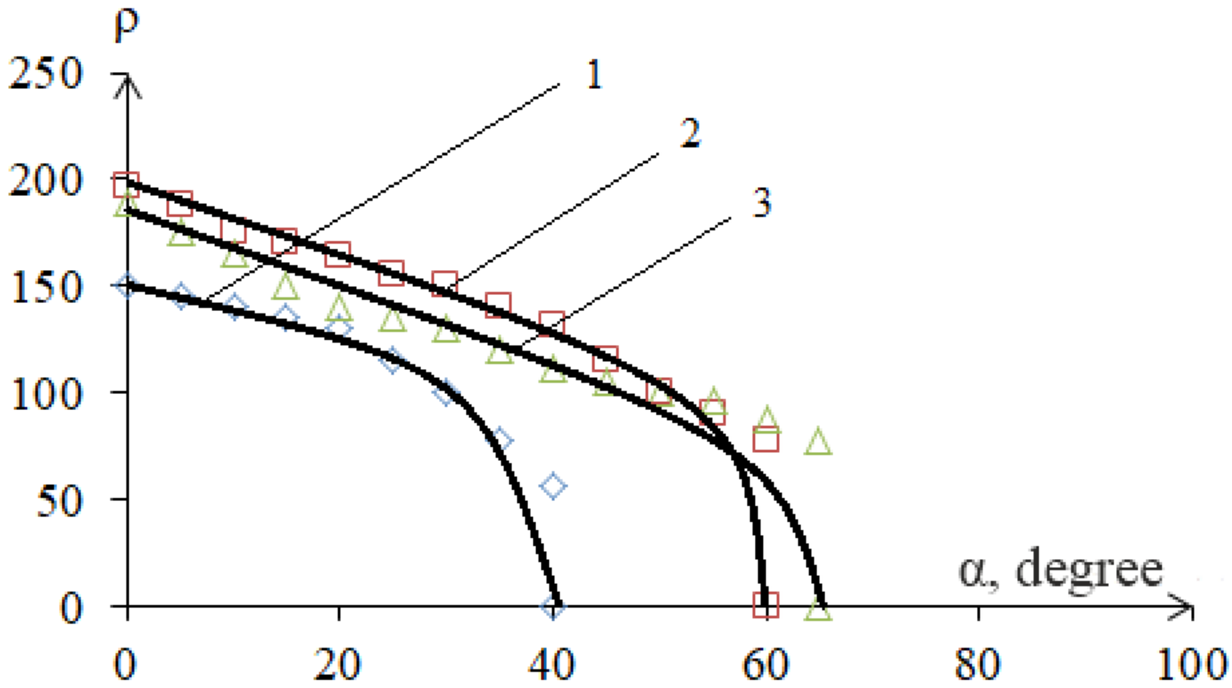

Fig.4. Typical dependences of the signal-to-noise ratio on the angle of incidence of optical radiation on the photosensitive surface of SiPM:
1 – ΔU = - 0.5 V; 2 – ΔU = 0.0 V; 3 – ΔU = 1.0 V.

The highest value of ρ in the range of angles from to for all photodetectors is observed for ΔU = 0.0 V. This is due to the fact that at ΔU < 0.0 V the sensitivity of the studied photodetectors is low. At ΔU > 0.0 V, the standard deviation σ increases significantly due to the growth of the dark current and fluctuations in the SiPM photocurrent gain. In this case, the voltage Upp practically did not increase, since the sensitivity of the studied SiPMs changed insignificantly.

In this regard, the dependences of the signal-to-noise ratio on the angle α were compared at ΔU = 0.0 V and a constant value of the energy exposure. The obtained dependencies ρ (α) are shown in Figs. 5. The largest value of the signal-to-noise ratio for all values of angles α within the flat angle of view was obtained for Ketek RM 3325, and the smallest for KOF5-1035. As can be seen from fig. 5, the dependence ρ(α) has two segments. For Ketek PM 3325 and ON Semi FC

30035 with α = 00 – 800 and for KOF5-1035 at α = 00 – 600 this dependence is linear, and then rapidly decreases to zero.

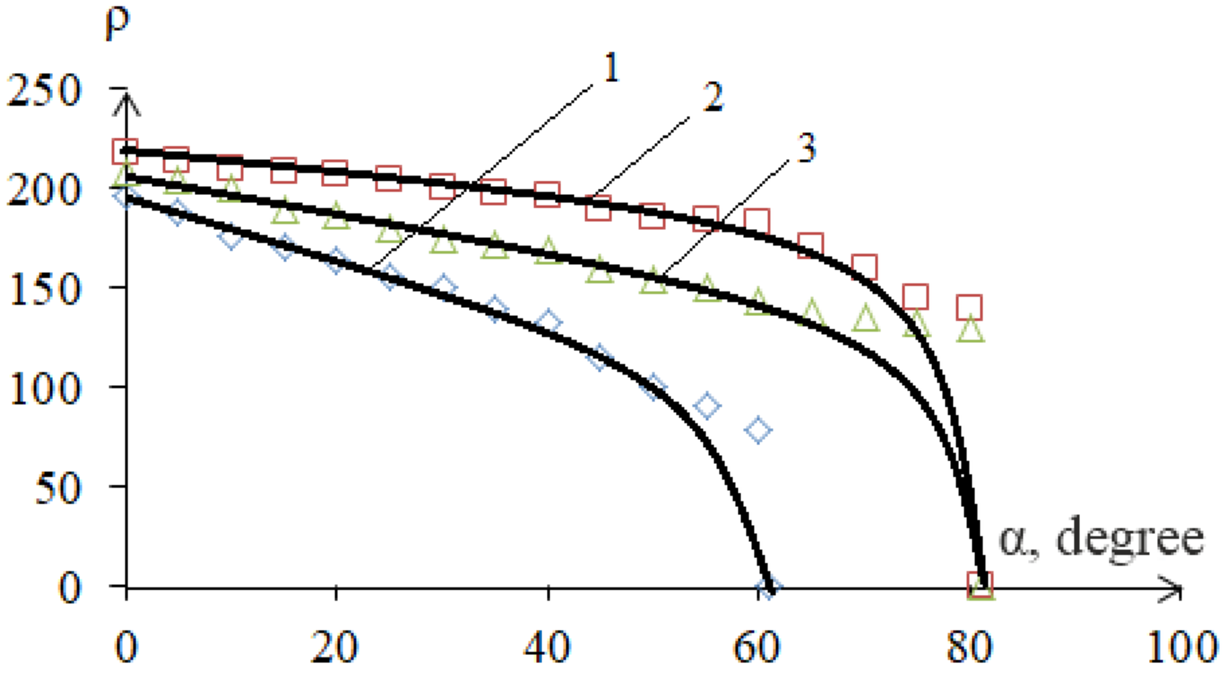

Fig.5. Dependence of the signal-to-noise ratio on the angle of incidence of optical radiation on the photosensitive surface of the SiPM:
1 – KOF5-1035; 2 – ON Semi FC 30035; 3 – Ketek RM 3325

Conclusion

It has been established that the flat angle of view of silicon photomultipliers depends on the supply voltage and does not depend on the energy exposure of optical radiation.

It is shown that the maximum signal-to-noise ratio corresponds to the breakdown voltage of the silicon photomultiplier. Ketek PM 3325 silicon photomultipliers had the highest signal-to-noise ratio within a flat viewing angle.

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