INVESTIGATION OF SILICON PHOTOMULTIPLIER AT LOW TEMPERATURE

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The physical properties of silicon-based MSFD-3NK photomultiplier was developed under the MAPD Collaboration were investigated at low temperatures. The value of temperature cofficent of breakdown voltage is typically 58±3mV/°C for MSFD-3NK photodiodes. The dark count of a single electron decreased by 169 times when the temperature difference was -81°C. It was obtained that afterpulsing played a significant role in the generation of dark count in low temperature. Amplitude resolution of single photoelectron reduced and it reached 32% when temperature difference was -93°C. Thus, the possibility of applying these photodiodes to low temperature detectors has been confirmed.

Keywords: Micro pixel avalanche photodiode; MAPD; liquid nitrogen; dark matter; inert gases.
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1. INTRODUCTION

One of the main problems of modern astrophysics and particle physics is the registration of light particles forming dark matter. Although, despite the fact that dark matter particles make up 27% of the total weight of the Universe, the probability of their registration is very low [1]. The interaction of these particles with the environment is based on a weak interaction mechanism. In this case, the probability of their registration is sharply reduced. Inert gases of high pressure as well as xenon and argon gases are used to detect these particles. The detectors used in these experiments operate at low temperatures. The particles transfer a small part of their energy to the xenon and argon atoms in an elastic interaction condition. In this case, atoms that receive very little energy from particles generate a very small amount of scintillation photons [2, 3-5]. The accurate registration of these scintillation photons is very important for correctly determining the parameters of dark matter particles incident on the detector. Currently, for register scintillation photons produced in xenon and argon detectors, using photomultiplier tubes [1]. However, the main disadvantage of these detectors is that they have photon detection efficiency of less than 20%, high operation voltage, sensitivity to a magnetic field and are radiation contaminated [6, 7]. These shortcomings cast doubt on the reliability of the results of the events mentioned in most experiments. For this reason, when preparing such detectors, the use of low-temperature and radioactively uncontaminated photo detectors is highly relevant. One of the possible candidates as photo detectors is also silicon micro pixel avalanche photodiodes (MAPD). Photodiodes of the MAPD-3NK type, prepared by the MAPD collaboration in 2014, have 40% photon detection efficiency, low operating voltage, and do not have radioactive contamination and are used as photo detectors in various experiments [8]. However, the fact that photodiodes of the MAPD-3NK type have not been studied at low temperatures does not allow their use in low-temperature detectors. Therefore, it is important to investigate the parameters of MAPD-3NK photodiodes at low temperatures. The work was devoted to the study of changes in the parameters of photodiodes MAPD-3NK in the temperature range from -108 ° C to -20 ° C.

2. EXPERIMENTAL SETUP AND RESULTS

In the work were applied MAPD-3NK photodiodes, developed in frame of MAPD collaboration. The experiments were conducted at the Joint Institute for Nuclear Research in Russia. The selected samples had the following parameters: a pixel density of 10,000 pixels / mm^2, a working voltage of 90 V, a capacity of 180 pF, a photon detection efficiency of 40%, and size 3.7 * 3.7 mm^2. To ensure a low temperature, liquid nitrogen was used and the temperature was varied by adjusting the depth of the sample location. During the measurements, the temperature change was 1%. The prepared experimental circuit is shown in fig. 1. The experimental setup included amplifiers (G1 and G2), a light diode (LED), a Keithley-6487 voltage source, CAEN-5720-analog-digital converter, pulse generator, and a resistor which measured the temperature. The amplifier (G1) located in nitrogen and has a gain of 50, the gain of second amplifier (G2) outside the cryostat was 38. When studying the properties of the MAPD-3NK photodiode, a 1 mm fiber optic cable was used to transmit light to the photodiode. Thus, the influence of the LED on the temperature changes of the photodiode was excluded. Silica gel was also used to prevent the formation of liquid vapors on the surface of the photodiode at low temperatures. Further, the received signal was processed by an analog- digital converter CAEN-5720 and stored on a computer. In signal processing, algorithms written in the C ++ programming language were applied.

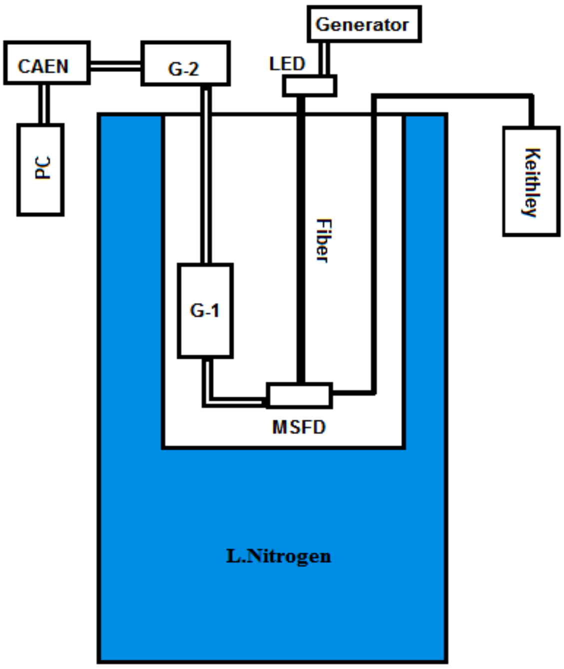

Fig. 1. Experimental setup

The following parameters of the MAPD-3NK photodiodes were investigated: the breakdown voltage, the dependence of the dark count (DC), and the amplitude resolution corresponding to the first photopeak of the amplitude on temperature. Pulse generator, CAEN-5720 ADC and amplifiers were used during the measurement of the breakdown voltage and the registration of a low photon flux. The total signal gain (G1*G2) was 1900. When recruiting the spectrum, CAEN connected to a synchronized generator output, and minimal integration limits were chosen. First of all, the temperature dependence of the parameters of the amplifier (G1) used at low temperatures was investigated. It was found that the gain of the applied amplifier varies according to the law depending on the temperature: G = 483.2+0.1212×T- 0,0109 ×T2. At the temperature -100°C, the gain reduction was below 23%. These changes were taken into account during the measurement. In determining the dependence of the photodiode gain on the temperature, a short negative pulse with a frequency of 1 kHz, duration of 30 ns and amplitude of 3.34V was applied from the pulse generator to the LED (a wavelength of 450 nm). Fig. 2a shows the dependence of the charge corresponding to the first photopeak on the voltage at -20°C of the sample MAPD -3NK.

Additionally, a voltage of 2V was applied to the operating voltage of the photodiode at each temperature. As the point of breakdown voltage, the point corresponding to the intersection line of the dependence (Q-V) is selected when Q=0 with the voltage line. As can be seen from fig. 2, the breakdown voltage of the MAPD -3 NK photodiode at -20°C was 85.7 V. In the range of applied voltage, the gain of the MAPD -3NK photodiodes varied from 3.3 to 7.4×10^4.

In fig. 2b. shows the dependence of the breakdown voltage MAPD-3NK on temperature. It is revealed that the breakdown voltage of MAPD-3NK varies linearly with temperature:Ubr =86.64+0.058×T. Here, T is the ambient temperature, expressed in Celsius. The data obtained show that the temperature coefficient influence to breakdown voltage of MAPD-3NK was 58±3 mV/°C. In other words, under constant overvoltage conditions, as the temperature increases, the gain decreases and vice versa. In such high field, as the temperature decreases, the gain of the photodiode increases due to an increase in the average length of tracking of charge carriers before the emission of optical phonons. In this case, the charge carriers get more energy between two collisions and therefore the ionization energy (3.6 *eV*) is reached faster. This allows to reduce the breakdown voltage in the area of low voltages. However, increasing the temperature leads to a decrease in the gain and increase the breakdown voltage, because of an increased likelihood of energy transfer charge carriers into the optical phonons.To increase the gain, it is necessary to increase the electric field in the avalanche region, which is possible with increasing voltage. For this reason, the breakdown voltage of MAPD increases with increasing temperature. However, another quantitative characteristic of ionization is the width of the forbidden band, which varies with temperature. Despite the fact that the temperature range was -90°C, the change in the width of the forbidden zone was about 2%.

To determine the pixel capacity of MAPD-3NK, the difference dQ /dU was calculated and the capacitance $C_{pix} \sim 4.8\times10^{-15}$ F =4.8 fF was obtained.

In determining the dark current MAPD-3NK no LEDs were appled. Similarly, the CAEN analog - digital converter was used with two amplifiers. In removing the signal, a trigger from the signal itself was used. It is known that the dark count formed by two components: thermal charge carriers in the avalanche region and afterpulses. The concentration of heat carriers depends on the number of generating centers and temperature. However, when the overvoltage applied to the MAPD photodiodes increases, the charge carriers from the generation center to the conduction band increases due to the field, which, in turn, causes the DC change. Therefore, the measurements were carried out at different temperatures and different gains. Fig. 3a shows the distribution of the amplitude corresponding to dark electrons. The measurement temperature was -27°C. The reason for this is that the distribution of the amplitude of a single electron cannot be observed due to the high level of the DC as a result of high temperatures. Amplitudes corresponding to dark electrons were within a few millivolts. Then, the change in the dark count corresponding to the threshold level value of 5 mV was investigated, depending on temperature with the same gain. The choice of the same gain, made it possible to study the effect of temperature on the change of DC. As can be seen from fig. 3b, the DC varies exponentially with temperature, and the DC drops by about 169 times, when the temperature difference is -81°C.

In addition, the dependence of the dark count corresponding to the first dark electron on the gain was also considered (fig. 4). In this case, the effect of the gain on the DC was studied. The increase in DC was close to 28%, with an increase in the gain by 36% and a temperature of -27°C. This is due to the increase in dark electrons and the high probability of an avalanche beginning by charge carriers. However, when the temperature was -108°C and the gain increased by 36%, the decrease in DC was about 75%. These changes began to be observed only at temperatures below -70°C. It can be explained only with an increased probability of the occurrence of afterpulses. It is known, that charge carriers, at higher temperatures, have a small probability of being captured by capture centers, which, after releasing them, over a short period of time. However, the time of release of charge carriers from centers at low temperatures varies according to the law $\tau i = \tau 0 \times \exp(Ei/kT)$ [4]. Where $\tau 0$ depends on the type of carriers and the band structure, Ei of the activation energy of the capture center, k is the Boltzmann constant and T is the temperature.

At low temperatures, the probability of carrier delays by capture centers inavalanche process increases dramatically. In these centers, carriers can remain for a long time and be released at different times. However, at low temperatures, various capture centers release carriers for a certain period of time and trigger the avalanche process in many pixels. As a result, the released carriers shift the amplitude of the signal to the upper energy region. As the gain increases, the amplitude and number of these events increase dramatically. The results show that afterpulses play a key role in the formation of DC at low temperatures, which leads to increase the amplitude. It was also found that the corresponding amplitude increases linearly with increasing gain. Increasing the gain causes an increase in registration efficiency. Therefore, it is very important to choose the same gain in order to investigate the amplitude variation as a function of temperature. In this case, the ratio of the peak corresponding to the first dark electron to the amplitude is established from the spectrum (fig. 5).

With the same gains, the peak corresponding to the first dark electron has an amplitude resolution of 64.7% at -30°C, 64% at -40°C, 52% at -86°C, at -123°C, 43.5%, respectively. In other words, the amplitude decreases with decreasing temperatures, and with a difference of -93°C, the reduction of resolution is 32%.Amplitude resolution corresponding to single photoelectron depending on temperature was described by a linear dependence (R=72.5+0.2357*T). The obtained results showed once again that MAPD-3 NK photodiodes can be successfully used for low-temperature detectors.

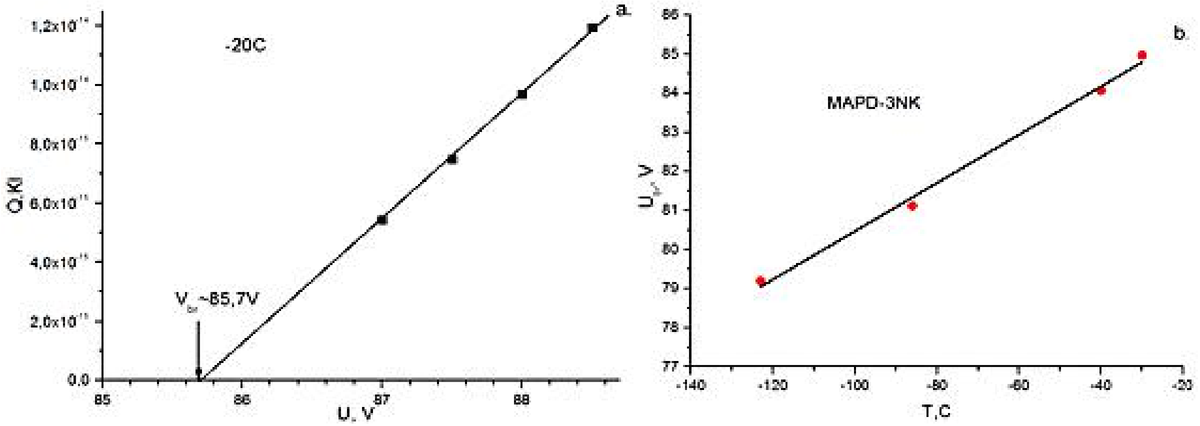

Fig. 2. Dependence of the charge corresponding to a single-electron peak on voltage (a.) and breakdown voltage on temperature (b.) for a MAPD-3NK photodiode

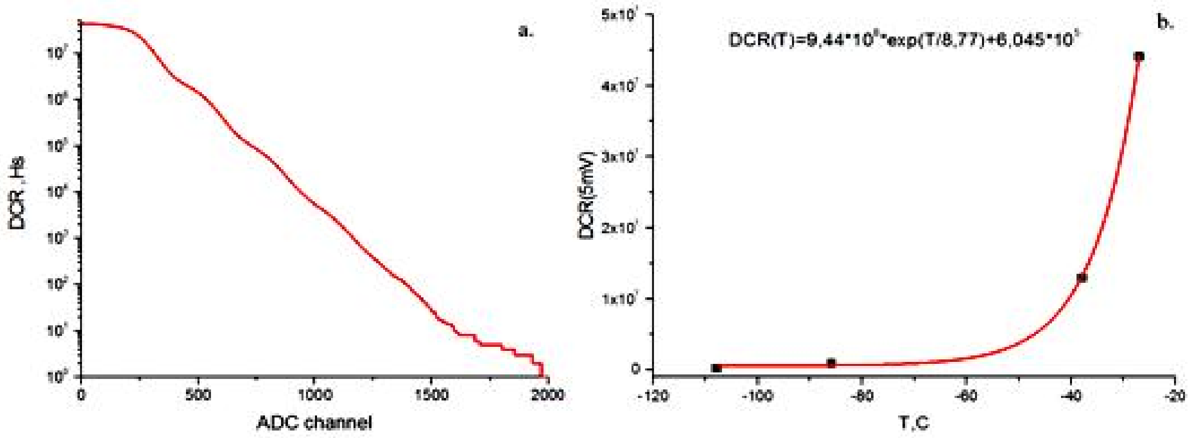

Fig. 3. Dependence of the dark count of MAPD-3NK (a) and the dark count in the threshold level by 5mV (b) on temperature.

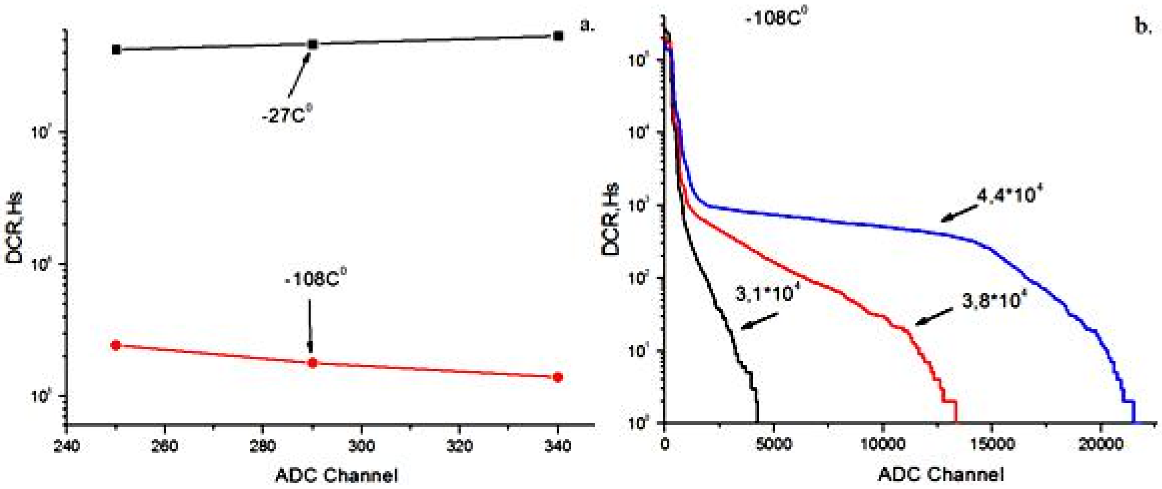

Fig. 4. The dependence of the dark count of MAPD-3NK on the gain.

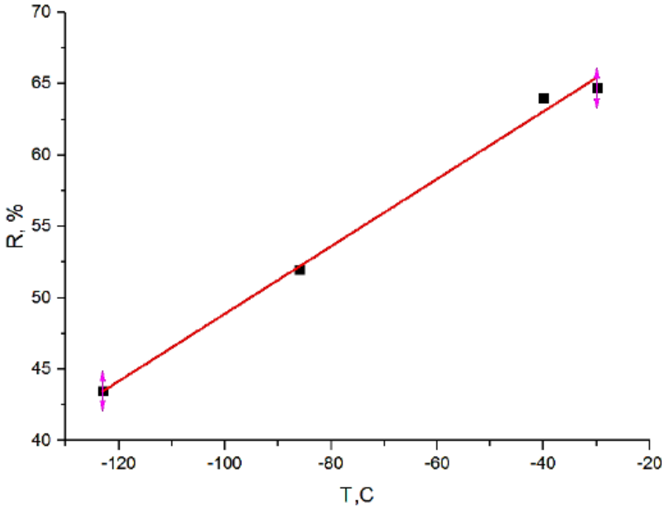

Fig. 5. The dependence of the amplitude resolution on temperature.

3. RESULTS

It was experimentally determined that the breakdown voltage of photodiodes MAPD-3NK has a dependence of 58±3mV/°C and decreases linearly with decreasing temperature. DC in photodiodes with a temperature difference of -81°C, improves 169 times. At low temperatures (-70°C and below), the appearance of dark count is mainly due to the effect of afterpulses. It was also shown that the difference between the amplitude resolution corresponding to single photoelectron improves to 32%, with a temperature difference of -93°C. In other words, the results show that MAPD-3NK photodiodes can be successfully used in low-temperature experiments.

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