PERFORMANCE OF NEW MAPD PHOTODIODES

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The article presents the results of the study of optical characteristics and the calculation of the internal gain of a new micropixel avalanche photodiode (MAPD). The calculation procedure is described, the experimental setup of the performed studies, and the results of the study of parameters at low light fluxes, up to single photons, are also presented. It was revealed that avalanche photodiodes with a micropixel structure can be silicon analogs of widely used vacuum photomultiplier tubes.

Keywords*:* Photodiode; MAPD; APD; photodetector.
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INTRODUCTION

Modern photomultiplier tubes (PMTs) have a high gain (10^6-10^7). This allows them to be used without an additional signal amplifier. Also, the photomultiplier tube can be used as a low intensity light detector. The advent of avalanche photodiodes with negative bias voltage, which quenches the avalanche process, made it possible to create an avalanche photodiode (APDg) operating in the "Geiger" mode. This APDg has a high gain (10^5-10). However, in this case, the dead time of the device becomes large (on the order of microseconds).

In order to solve the problem of recording the intensity light flux in recent years, a new type of photodetector has been developed - a silicon micropixel avalanche photodiode (MAPD), which is a photodetector based on an ordered set (matrix) of pixels (approximately 10^3 mm^{-2}) made on a common substrate. Each pixel is an APD photodiode operating in the Geiger mode with a multiplication factor of about 10^6, but the entire MAPD is an analog detector, since the MAPD output signal is the sum of signals from all pixels triggered when they absorb the photons [1].

Note that when the intensity of the incident light flux is high, i.e., the probability of the production of several photoelectrons in one pixel is significant, or all cells are triggered, the output signal from the MAPD becomes saturated. Thus, there is an upper limit on spectrometric recording of light intensity.

EXPERIMENTAL SAMPLE

MAPD is a device of a new type for detecting light flashes of low intensity (at the level of single photons) and duration of the order of units - hundreds of nanoseconds [1, 2]. Similar to vacuum PMTs, MAPD can become a device of wide application due to the following qualities:

- High internal gain of about 10^6, which significantly reduces the requirements for electronics;
- Small spread in the gain (about 10%) and, as a result, low noise factor;
- The efficiency of registration of visible light at the level of vacuum photomultipliers;
- The ability to register nanosecond light flashes without distorting the shape of the detected signal;
- The ability to work both in the pulse counting mode and in the spectrometric mode;
- Good temporal resolution (tens of picoseconds);
- Low supply voltage (50-90 V, depend on design);
- Insensitivity to the magnetic field; compactness (crystal dimensions of the order of ~3 x 3 x 0.3 mm^3).

In fig. 1 schematically shows the principle of a MAPD device, which consists of independent pixels with dimensions of the order of 30x30 μm. By means of aluminum buses, all pixels are combined, and the same bias voltage (U_{bias}) is applied to them, exceeding the breakdown voltage ($U_{breakdown}$) by 10-15% [3], which ensures operation in "Geiger" mode. When a quantum of light enters the active region of the pixel, a self-extinguishing "Geiger" discharge develops in it. Quenching, i.e. termination of the discharge, occurs due to a voltage drop at the p-n-junction below the breakdown due to the presence of a current-limiting resistor in each pixel (R_{lim} = 400 kΩ). The current signals from the triggered pixels are added to the total load. The amplification of each pixel is about 10^6, so the detector can be operated on a cable without pre-amplification.

Since all MAPD pixels are independent microcounters, and the signal from each pixel is determined by the charge accumulated at each pixel, the MAPD gain (M) is determined only by the charge (Q_{pixel}) of the pixel capacitance C_{pixel} [3]:

$$M = Q_{pixel}/e \qquad (1)$$

where, $Q_{pixel} = C_{pixel} \cdot \Delta U = C_{pixel} \cdot (U_{bias} - U_{breakdown})$, and e=1.6*$10^{-19}$ C – electron charge.

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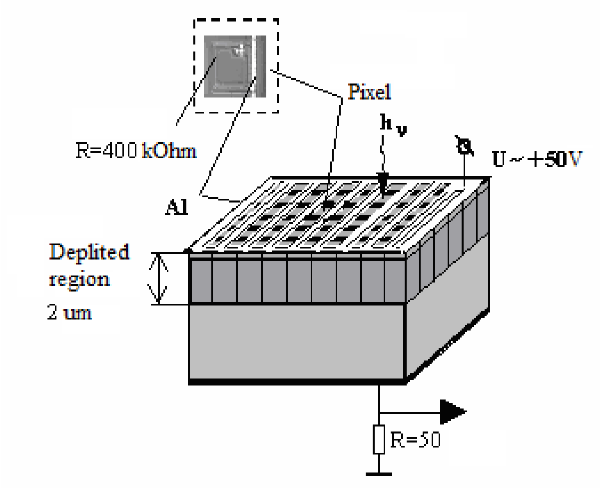

Fig. 1. Schematic view of MAPD photodiode.

The spread in the gain is determined by the technological spread in the elementary capacitance and the pixel breakdown voltage and is less than 10%. Since all pixels are the same, the detector's response to weak light flashes is proportional to their intensity [4].

EXPERIMENTAL SETUP

Figure 2 shows a diagram of the elements and blocks that make up the experimental setup, with which measurements were made.

A blue LED NSPB310A was used as a light source. The LED is powered from a waiting pulse generator (Led supply) with a frequency of 1000 Hz and duration of 15 ns. The amplitude of the pulses is adjustable in the range of 0-7 V, which allows changing the intensity of the light emitted by the LED. The waiting pulse generator is started by the trigger pulse generator (Tektronix AFG3100).

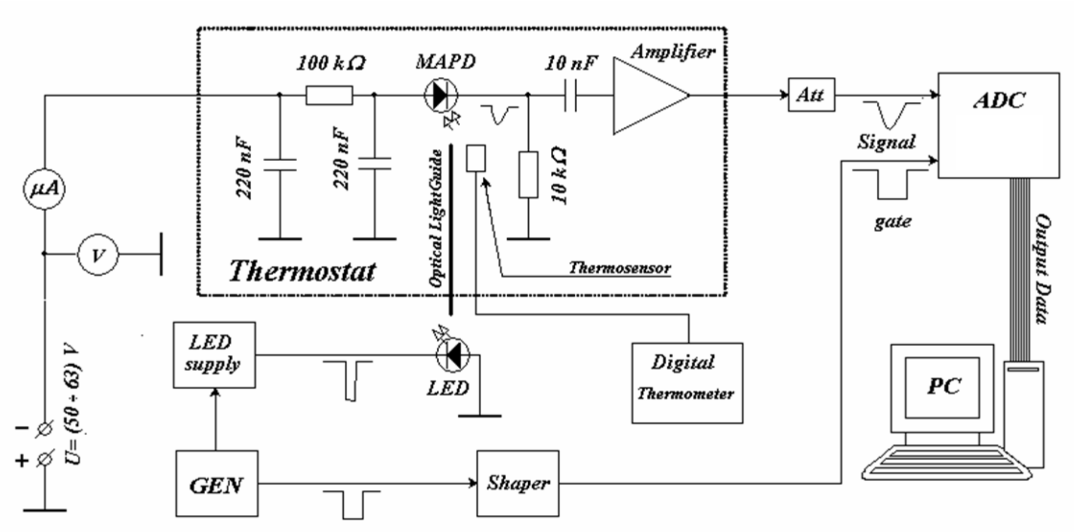

Fig. 2. Experimental setup.

The LED is located outside the Thermostat. This is necessary in order to exclude possible fluctuations of its characteristics from temperature. The light emitted from the LED is transported to the thermostat by an optical light guide to the photodiode (MAPD). The photodiode is powered by an external regulated voltage source (U = 50-63 V). To suppress ripple from the power source, as well as external high-frequency interference (which can occur in the electrical circuit through external electromagnetic radiation), C-R-C is included in the power supply circuit of the photodiode. (U-shaped) filter (here capacitance C=220nF, resistance R=100kΩ). A voltmeter measures the voltage applied to the MAPD, which is calculated:

$$U_{bias} = U - I * R, \quad (2)$$

where *I* is avalanche current, *R* is quenching resistor. As a result of the light pulse hitting the surface of the photodiode, a current pulse arises, which is amplified by a low-noise hybrid high-speed linear amplifier. The capacitance (10 nF), included at the amplifier input, to break the galvanic connection between the MAPD load (R = 10 kΩ) and the amplifier input is designed to prevent disruption of the DC input stage of the amplifier.

The installation uses a high-speed analog-to-digital converter (ADC) CAEN. The output signal from the amplifier is fed to the ADC, which digitizes the signal area (charge) in the presence of a gate pulse. The attenuator (Att) is designed to increase the dynamic range of the measured signals with MAPD. The strobe pulse is created by the trigger generator and has a duration of 60 ns, which is set by the shaper. The synchronization of the strobe pulse and the signal makes it possible to register the pulse arising from the photodiode under the action of the initiating light against the background of dark (noise) pulses. However, noise signals are recorded during the duration of the strobe pulse. The number of recorded noise pulses is determined by the formula:

$$N_c = N_n \nu \tau, \tag{3}$$

where N_c is the counting rate of random coincidences, N_n is the counting rate of noise pulses, respectively, □ is the trigger pulse repetition rate, τ is the strobe pulse duration.

The data (output data) from the ADC is read by a computer (PC) by means of a controller; a computer.

METHODOLOGY

The measurement technique is based on the use of low-intensity light flashes. The incident photon flux onto the photodetector produces photoelectrons through the photoelectric effect. Under real conditions, the number of photons hitting the photodetector is not constant, but obeys the Poisson distribution. Photo conversion is a binary process. Convolution of a Poisson process with a binary process gives again the Poisson distribution. Therefore, the formation of photoelectrons also obeys the Poisson distribution:

$$P(n;\mu) = \frac{\mu^n * e^{-\mu}}{n!} \tag{4}$$

where, μ –is the average number of photoelectrons resulting from photo effect, $P(n;\mu)$ – the probability that n photoelectrons will be observed at the output of the photodetector, with their average equal to μ.

Data from ADC are analyzed by a personal computer and presented in the form of a histogram channel number (charge) - the number of events that hit the channel (Fig. 3). The ADC channel unit is 0.25 pC. In what follows, all values (if not specified) are indicated in channel units.

To determine the average number of photoelectrons, we use the fact that at small they are distributed according to the Poisson distribution. The probability that we will not register any photoelectrons is equal to:

$$P(0;\mu) = \frac{\mu^0 * e^{-\mu}}{0!} = e^{-\mu} \tag{5}$$

hence the average number of photoelectrons hitting the photo detector:

$$\mu = -lnP(0;\mu) \tag{6}$$

The signal corresponding to the fact that no photoelectron was formed on the photo detector enters the ADC pedestal (Fig. 3). Thus, the probability of the absence of a photoelectron is:

$$P(0;\mu) = N_{ped}/N \tag{7}$$

where N_{ped} is the number of events in the pedestal, N is the total number of events.

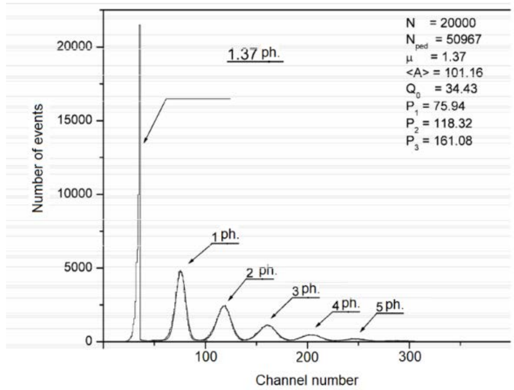

Fig. 3. MAPD spectrum (at fixed T and U_{bias}). Designations: N, N_{ped} - respectively the total number of events and the number of events in the pedestal; μ is the average number of photoelectrons; <A> - average value of the histogram; Q_0 is the position of the pedestal, P1, P2, P3 are the positions of the peaks of the 1st, 2nd and 3rd photoelectrons, respectively.

The average signal S is defined as the average of the histogram <A> minus the position of the pedestal Q_0:

$$S = < A > - Q_0 \tag{8}$$

The uncertainty that occurs when determining the signal is associated with a statistical uncertainty in determining the position of the pedestal and a statistical uncertainty in determining the average amplitude of the histogram and does not exceed 1%.

The gain fluctuates around the statistical mean and is determined by the probability distribution with the mean M [13]. The response of a photodetector (output charge) to a single photoelectron is the gain and can be described by a Gaussian distribution (similar PMT):

$$M(x) = \frac{1}{\sigma_{1\sqrt{2\pi}}} \exp(-\frac{(x-Q_1)^2}{2\sigma_1^2}) \tag{9}$$

where x is a variable (charge),$Q_1=M_e(e=1.6*10^{-19}C)$ - average charge on the output of the photodetector, when one photoelectron was generated as a result of photoconversion, σ_1 - respectively, the standard deviation of the charge distribution [5]. Thus, the position of the peak of the Gaussian distribution (Q_1) determines the gain of the photodetector and is calculated as:

$$Q_1 = P_1 - Q_0 \tag{10}$$

from where:

$$M = \frac{Q_1}{e} \tag{11}$$

It should be noted that in our case the output signal from the photodetector passes through the amplifier-attenuator system amplifying the signal by a factor of K (in our case, K = 36) times, therefore, the gain of the photodetector is:

$$M = \frac{Q_1}{K{*}e} \tag{12}$$

From the data shown in Fig. 3 MAPD gain in absolute units, based on the position of the peak (P_1) of one photoelectron (channel unit $0.25{*}10^{-12}$C):

$$M = \frac{41.51{*}0.25{*}10^{-12}C}{36{*}1.602{*}10^{-19}\,C} = 1.80 * 10^6 \tag{13}$$

The gain can be determined using the peak position of N photoelectrons (P_N) as:

$$M = \frac{(P_N - Q_0)}{N{*}K{*}e} - \frac{Q_N}{K{*}e} \tag{14}$$

The dispersion of N-electron Gaussian distributions is associated with the inhomogeneity of the photosensitivity of the photodetector surface, the technological spread and fluctuations in the number of electrons in the avalanche, as well as the noise of MAPD and recording electronics.

At low light intensities (Fig. 4, a, b), when the registration inefficiency (the relative number of events in the pedestal) is large enough, which makes it possible to determine the average number of photoelectrons (relative light intensity) with good accuracy.

If the intensity of the light flash is increased (Fig. 4,c), the registration inefficiency decreases exponentially, which worsens the ability to measure μ. At high light intensities, the registration efficiency is high, which corresponds to the absence of events in the pedestal (Fig. 4, d). It can be seen from the spectrum in Fig. 11, d that the formation of single photoelectrons is strongly suppressed. For example, the probability of the formation of first photoelectron is $P(1,16.5)=1.1{*}10^{-6}$, and second is $P(2,16.5)=1.0{*}10^{-5}$.

When registering high light intensities, the average number of photoelectrons is determined as:

$$\mu = \frac{S}{M} \tag{15}$$

where S is the average signal amplitude, M is the gain of the photodetector, which can be determined at low light intensities using the above technique, as was done to determine the light intensity in the spectrum shown in Fig. 4, d.

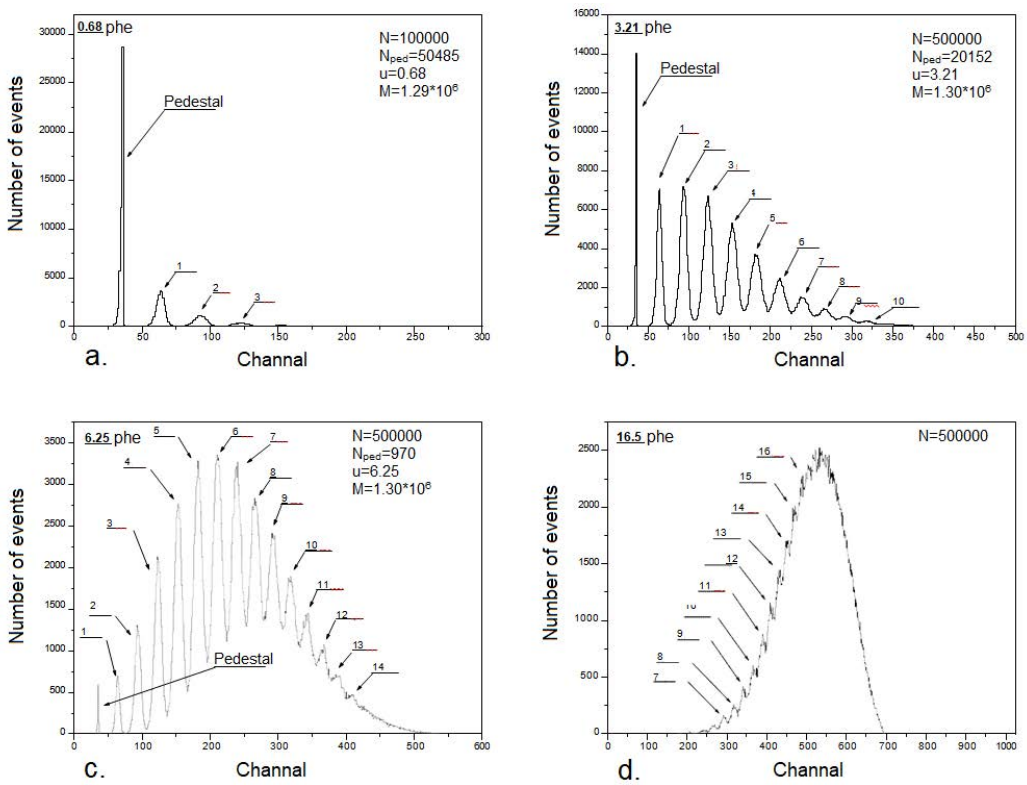

Fig. 4. Spectra obtained with MAPD (T = 220C, U_{bias} = 60V). Designations: N - total number of events, bold and underlined numbers, μ - average number of photoelectrons, M - gain determined from the peak of the first photoelectron.

RESULTS

The results of optical studies of a silicon-based micro pixel avalanche photodiode are obtained. The research method and calculations are shown, as well as the preparation of the experimental stand.

It was revealed that the photodiode of the MAPD type is a successful device for counting single photons, as well as for spectrometric measurements.

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