INVESTIGATION OF PARAMETERS OF SILICON PHOTOMULTIPLIERS

A. MAMMADLI[1], B. IBRAHIMOV[3], Y. BACHERIKOV[2], Z. AHMADOV[1]
[1]Institute of Radiation Problems, Baku, Azerbaijan
[2] V.Lashkaryov Institute of Semiconductor Physics, Kyiv, Ukraine
[3]Institute of Physics, Baku, Azerbaijan
e-mail: arzu_memmedli_92@mail.ru.

The paper presents the results of studying the parameters of silicon photomultipliers of the MAPD-3NK, MAPD-3NM-I and MAPD-3NM-II types with deeply buried pixels. These photodetectors are manufactured in cooperation with the company ZECOTEK. Parameters such as current-voltage characteristics, gain, operating voltage and breakdown voltage were investigated. As a result of the experiments, it was determined that the gain of the MAPD -3NM-II photodiode is 4.5 times higher than that of the MAPD-3NK photodiode, and 2.3 times higher than the gain of the MAPD -3NM-I photodiode. The breakdown voltage of the MAPD -3NM-II photodiode was 52.4*V*, the breakdown voltage of the MAPD -3NK photodiode was 89 *V*, the breakdown voltage of the MAPD -3NM-I was 72*V*. At the same gain value (4.4 *104), the dark current photodiode MAPD -3NM-II was reduced 15 times compared with photodiode MAPD-3NK and 3 times compared with photodiode MAPD-3NM-I.

Keywords: Micropixel Avalanche Photodiode; MAPD; MAPD-3NK; MAPD-3NM-I; MAPD-3NM-II
PACS: 85.30.−z; 85.60.Dw

INTRODUCTION

Silicon-based micropixel avalanche photodiodes (MAPDs) have outperformed photomultiplier tubes (PMTs), PIN diodes, APDs and other analogs in their field of application since 2006 [1-10]. Micropixel avalanche photodiodes have evolved from detecting large numbers of photons to detecting single photons at room temperature. These photodetectors have a wide range of linearity at voltages above the breakdown voltage (or in the Geiger mode) [8-15]. In this regard, the use of silicon photodetectors is of particular importance in studying the parameters of ionizing particles and determining their energy [16-20]. Micropixel avalanche photodiodes are used in high-energy physics, space research and medicine because of their high efficiency, which lies in their structure and operating parameters [2, 8-15]. The performance of MSFD devices is characterized by such parameters as breakdown voltage - *Ub*, dark current - *Ig*, gain - *M*, etc., and their study and improvement is the main task of researchers in this area [20].

One of the main parameters characterizing micropixel avalanche photodiodes is the breakdown voltage. The breakdown voltage in MAPD photodiodes varies depending on internal structural factors: the concentration of additive atoms, the structure (spherical or flat) of the photodiode pixels, and temperature as an external factor. When the same extreme voltage is applied to the MAPD photodiodes, the breakdown voltage and gain change with temperature. At low temperatures, the breakdown voltage decreases and the gain increases. In other words, carriers use a very small part of the energy they receive between two collisions to form optical fanons (the fraction increases with increasing temperature), and the main part to create a new pair of electron holes. Thus, the breakdown voltage decreases and, as a consequence, the gain increases [5]. In addition, the high breakdown voltage (Uop.> 100 V) of silicon photodetectors requires the assembly of multistage DC-voltage converters, which is not considered financially feasible. Low breakdown voltage in MAPD photodiodes leads to a weaker temperature dependence of photodiode parameters [5].

One of the characteristics of micropixel avalanche photodiodes is dark current. Dark current is one of the quantities that determine the signal-to-noise ratio in these photo recorders. The dark current of photodiodes is formed in photodiodes due to surface and volume currents. In MAPD photodiodes, the bulk current is formed by a temporary path due to defects and intrinsic conductivity [1]. When the applied voltage is greater than the breakdown voltage, a self-regulating process occurs and the bulk current is amplified. Thus, the dark current of the MAPD photodiode is determined as follows:

$$I=I_{surf}+I_{space}=I_{surf}+M\times I_{vol} \qquad (1)$$

Here I_{surf} is the surface current, I_{vol} is the volume current, and M is the gain. In MAPD photodiodes, it is possible to reduce the dark current by improving the photodiode fabrication technology and reducing the thickness of the active volume region. The low dark current in MAPD photodiodes determines the minimum energy limit detected in radiation detectors based on these photodiodes.

One of the main parameters characterizing MAPD photodiodes is the gain. The gain characterizes the ionization process that occurs in the avalanche region in MAPD photodiodes [2, 8, 11]. The gain depends on the photodiode capacitance and overvoltage. In MAPD, in the case of a single photoelectron distribution, each pixel has the same gain and is expressed as:

$$M=2*C_{pik}(V_{ap}-V_b)/e \qquad (2)$$

131, H.Javid ave, AZ-1143, Baku
ANAS, Institute of Physics
E-mail: jophphysics@gmail.com

Here C_{pix}–pixel capacitance, V_{ap}–voltage applied to the photodiode, V_b – breakdown voltage and e-electron charge.

In MAPD photodiodes (when the gain is small and the dark current is large), it is impossible to apply a uniform distribution of photoelectrons to determine the gain (at room temperature). In this case, the method of measuring the photocurrent due to the change in frequency with respect to the amplitude is used to determine the gain. In this case, to determine the value of the intrinsic photocurrent, the difference between the total current and the dark current is found and determined as follows.

$$I_{ph} = I_{tot} - I_{dc} \tag{3}$$

Here, I_{tot} – total current, I_{dc}– dark current, I_{ph} – photocurrent. The following expression is used to find the average value of the photocurrent at a given frequency:

$$A(M) = \frac{I_{av.ph}}{e * \nu_M} = \frac{I_{ph} * M}{e * \nu_M}, \quad M = \frac{A(M)}{A(M \sim 1)} \times \frac{\nu_M}{\nu_1} \tag{4}$$

Here, e–electron charge, $I_{av.ph.}$–avalanche photocurrent, I_{ph} –photocurrent, M amplification coefficient, ν_1, $A(M)$, ν_M, $A(M\rightarrow 1)$ the average values of the photocurrent and the frequency of the corresponding pulse. The high gain of MAPD photodiodes improves the parameters of radiation detectors based on them, and in most cases there is no need to use additional signal amplifiers.

In the presented work, the values characterizing MAPD photodiodes were studied: gain, operating voltage, detection voltage, and dark current. A comparative study of the parameters of photodiodes MAPD-3NK (2013), MAPD-3NM (2019) and a new development MAPD-3NM (2020) is presented. Correct determination of these parameters is very important for determining the performance of MAPD photodiode devices.

EXPERIMENT

The investigated photodiodes MAPD-3NK, MAPD -3NM-I and MAPD-3NM-II, were produced by Zecotek Photonis at factories in NANOFAB (MAPD-3NK) in South Korea (2013) and MIMOS (MAPD-3NM-I, MAPD-3NM-II) - in Malaysia (2019, 2020).

In the MAPD-3NK and 3NM-I photodiodes, the pixel diameter was $7\mu m$, and the pixel density with a $10\mu m$ step was *10,000 pixels/mm2* [8]. In MAPD -3NM-II photodiodes, the pixel diameter was $12\mu m$, and the pixel density with a $15\mu m$ step was 4450 *pixels/mm2* [3, 5-7, 9-11].

A Keithley 6487 instrument was used to determine the current-voltage characteristics of the photodiodes. A light emitting diode with a wavelength of 450 nm with a low luminous flux was used to determine the gain of avalanche photodiodes. In fig. 2 shows the current-voltage characteristics of the MAPD-3NK, MAPD-3NM-I, and MAPD-3NM-II photodiodes.

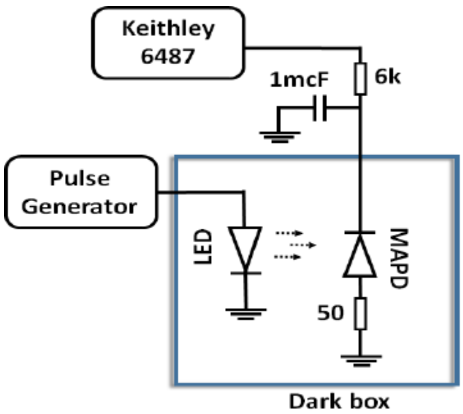

Fig. 1. Schematic of signal readout on MAPD photodiodes.

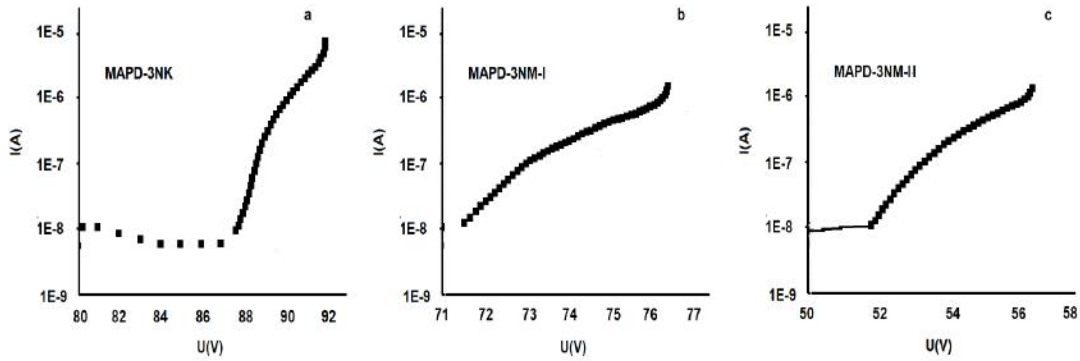

Fig. 2. Current-voltage characteristic of photodiodes MAPD-3NK, MAPD-3NM-I and MAPD-3NM-II (riverse bias).

In fig. 3 shows the dependence of the inverse differential ratio *dI/(I×dU)* of the MAPD-3NK, MAPD-3M-I, and MAPD-3NM-II photodiodes on the applied voltage [6, 13].

It was found that the dark current gradually changes sharply depending on the applied voltage. In the MAPD-3NK photodiode, the voltage $U_b=89V$ MAPD-3NM-I, and in the MAPD-3NM-II photodiodes $U_b=72V$ and $U_b=52.4V$, the dark current increases sharply, and at subsequent voltage values, the process is extinguished by a quenching resistor, and the rate of change dark current slows down to saturation. In this case, the gain of the photodiode is optimal. It was revealed that in the MAPD-3NK photodiode $U_{optimal}=91V$ voltage the dark current is 1609*nA*, in the MAPD-3NM-I photodiode the optimal voltage is $U_{optimal}=75.4V$ the dark current is 655*nA* and in the MAPD-3NM-II photodiode the operating voltage is $U_{optimal}=55.6V$ and the dark current is 815*nA*.

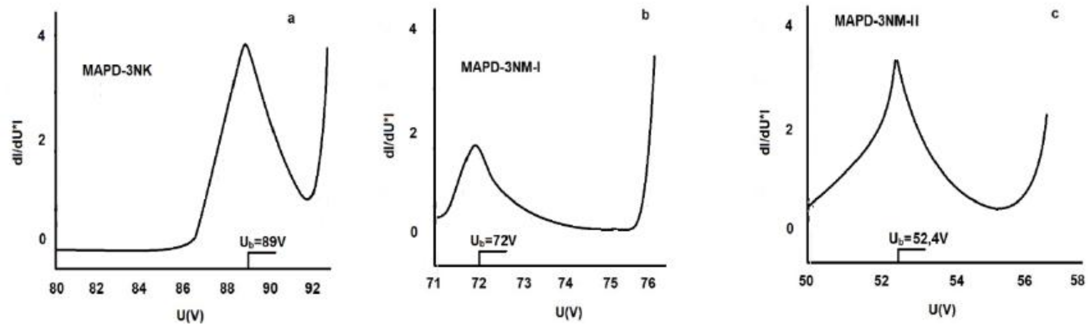

Fig. 3. Dependence of the differential ratio *dI/(I×dU)* of the MAPD-3NK, MAPD-3NM-I and MAPD-3NM-II photodiodes on the applied voltage.

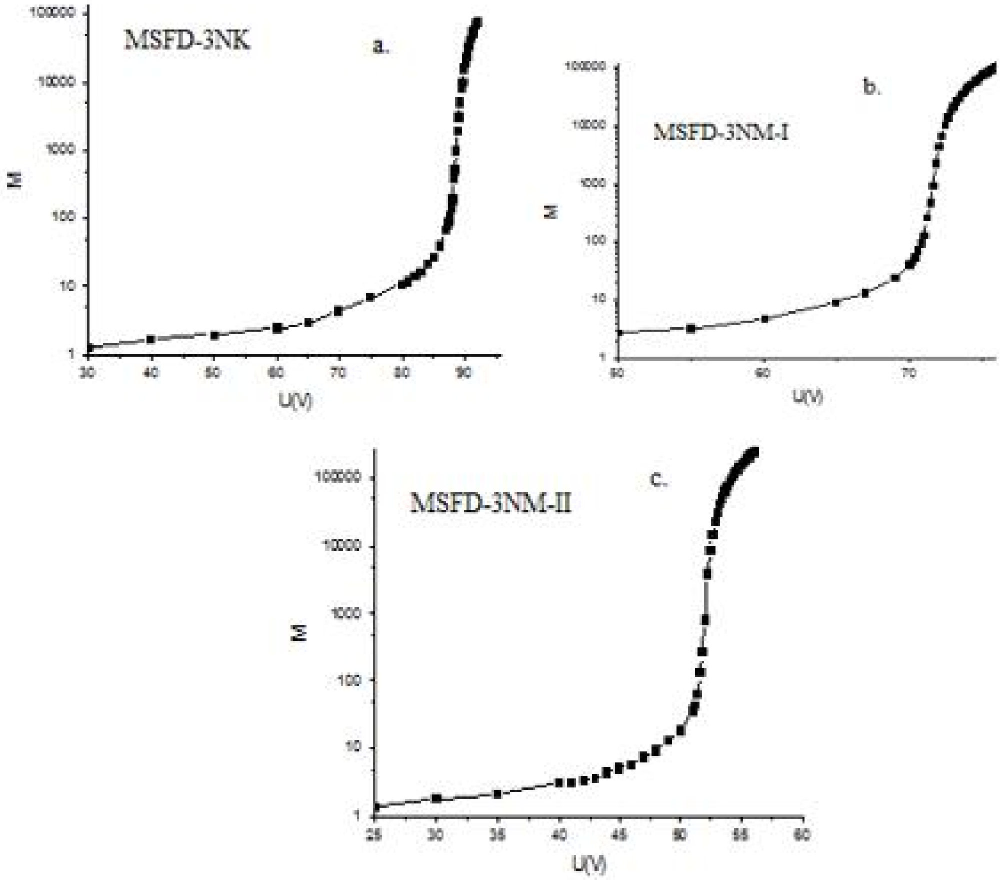

Fig. 4. Dependence of the gain on the voltage of MAPD-3NK, MAPD-3NM-I and MAPD-3NM-II.

In fig. 4 shows the voltage dependence of the gain of the MAPD-3NK, MAPD-3NM-I, and MAPD-3NM-II photodiodes.

Light with a wavelength of 450*nm* was used from a generator to determine the gain of all three photodiodes. Negative rectangular pulses with an amplitude of 2.5*V* and a width of 50*ns* were applied, varying in frequency from 1*kHz* to 1*MHz*. At low values of the gain, the frequency of a rectangular pulse applied to the LED to determine the photocurrent flowing through the photodiode varied in the range from 50*kHz* to 1*MHz*, and at high values, the pulse frequency varied between 1*kHz*-10*kHz* to ensure normal operation of the photodiodes. In practice, the total and dark current flowing through the avalanche photodiode was measured with a Keithley-6487 picoammeter to determine the gain. The LED pulse from the generator was not applied during the dark current detection.

The voltage applied to all three photodiodes starts at 20*V* and increases from the breakdown voltage to the maximum value. At 20*V*, the gain is *M=1*, this mode is called the PIN diode mode and is not subject to photocurrent amplification. As the voltage increases, the gain also begins to increase and is determined by the ratio of the average value of the photocurrent when the gain is greater than unity (*M >>1*) to the average value of the photocurrent when the gain is equal to unity (*M~1*), the result is multiplied by the frequency ratio: $M = \frac{A(M)}{A(M\sim 1)} \times \frac{\nu_M}{\nu_1}$. Thus, the gain at an optimal voltage of 91*V* for the MAPD-3NK photodiode was set at $\sim 4.4*10^4 (25°C)$. In the MAPD-3NM-I photodiode, the gain at 75.4*V* was $8.6*10^4$, and in the MAPD-3NM-II photodiode, the 55.6*V* gain was $2*10^5$ *(25°C)*.

In fig. 5 shows the dependence of the gain on the optimal voltage on the MAPD-3NK, MAPD-3NM-I and MAPD-3NM-II photodiodes.

In the optimal case, the gain of the MAPD-3NM-II photodiode was 4.5 times higher than that of the MAPD-3NK photodiode, and 2.3 times higher than the gain of the MAPD-3NM-I photodiode.

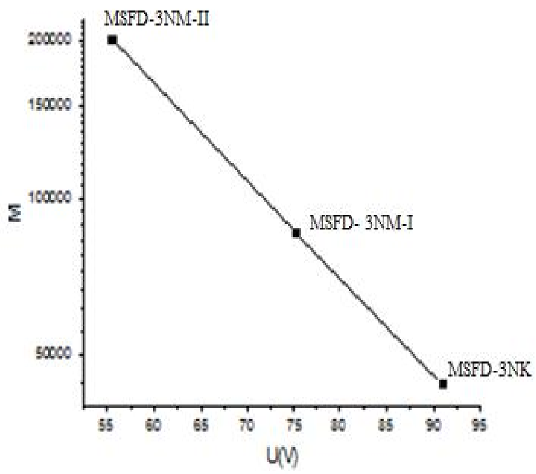

Fig. 5. Dependence of the gain on the optimal voltage on the MAPD-3NK, MAPD-3NM-I and MAPD-3NM-II photodiodes.

In fig. 6 shows the dependence of the dark current on the voltage at the same value of the gain for the MAPD-3NK, MAPD-3NM-I and MAPD-3NM-II photodiodes.

Thus, with the same value of the gain (*M=4.4*104*), the dark current of the MAPD-3NM-II photodiode is reduced 15 times compared to the MAPD-3NK photodiode and 3 times compared to the MAPD-3NM-I photodiode.

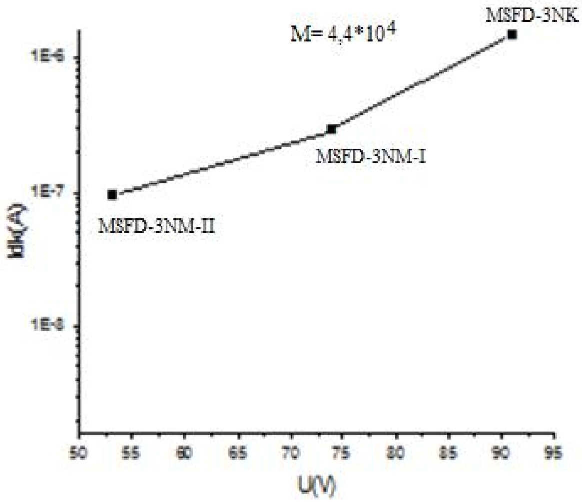

Fig. 6. Dependence of the dark current on the voltage at a constant value of the gain in the MAPD-3NK, MAPD-3NM-I and MAPD-3NM-IIphotodiodes.

RESULTS

As a result of the experiments, the parameters characterizing the MAPD photodiodes were determined. The breakdown voltage of the MAPD-3NK photodiode at 25°*C* was *201*, the optimal voltage $U_{optimal}=91V$, the gain $M=4.4*10^4$, the gain of the MAPD -3NM-IM photodiode $=8.6*10^4$, the optimal voltage $U_{optimal}=75.4V$, breakdown voltage $U_b=72V$. In the MAPD-3NM-II photodiode $U_b=52.4V$, $U_{optimal}=55.6V$, and the gain $M=2*10^5$. The dark current of the MAPD -3NM-II photodiode $I_{dk}=815nA$, the dark current of the MAPD-3NK photodiode $I_{dk}=1609nA$, photodiode MAPD-3NM-I $I_{dk}=655nA$.

It was determined that, in the optimal case, the gain of the MSFD-3NM-II photodiode was 4.5 times higher than that of the MSFD-3NK photodiode, and 2.3 times higher than the gain of the MSFD-3NM-I photodiode. With the same value of the amplification factor (*M=4.4*104*), the dark current of the MSFD-3NM-II photodiode is reduced 15 times compared to the MSFD-3NK photodiode and 3 times compared to the MSFD-3NM photodiode -I.

The results showed that the newly developed MAPD-3NM-II photodiode outperforms the MAPD-3NK and MAPD-3NM-I photodiodes in most parameters, and the development of spectrometers based on the new MAPD-3NM-II photodiodes to be more appropriate and optimal.

ACKNOWLEGMENT

This work was supported by the Scientific Fundation of SOCAR.

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Received: 12.09.2022