JOINT INSTITUTE FOR NUCLEAR RESEARCH

Frank Laboratory of Neutron Physics

FINAL REPORT ON THE START PROGRAMME

Investigation of physical parameters of silicon photomultipliers with different structures

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Abstract

Advances in the physics and technology of semiconductor devices have led to significant advancements in the development of silicon photomultipliers (SiPMs). These advancements have enabled SiPMs to replace vacuum photomultiplier tubes (PMT) in numerous experiments, making the study of SiPMs highly relevant. Two different types of SiPMs were selected to study: deeply-buried and surface pixel structure. We aim to provide a comprehensive understanding of their performance and behavior in different operating conditions. In this report, we study the key characteristics of SiPMs, including breakdown and operating voltages, capacitance, and the temperature dependence of the breakdown voltage. Two methods were used for determining the breakdown voltage of SiPMs.

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1. Introduction

PMTs were widely used as light readout devices for a long time. However, the development of semiconductor technology has led to the emergence of various devices, with silicon photomultipliers (SiPMs) representing the pinnacle of this evolution. Nowadays, there are a lot of vendors, which produce SiPMs with different structures and they called their products with different name. SiPMs possess key parameters that make them highly attractive for a wide range of applications in different fields. These parameters include high photon detection efficiency (PDE), gain, linearity, low operating voltages, and compactness. Consequently, SiPMs find extensive usage in experiments in the field of high-energy physics, such as at the LHC, NICA, JUNO, and other physics experiments. Morover, SiPMs have already find wide application field in medicine, industry, cosmology, security etc.

New and improved versions of SiPMs are regularly developed, leveraging changes in alloying parameters, the use of novel materials, and advancements in technological processes. These upgrades result in enhanced characteristics and performance.

The objective of this study is to investigate and compare the parameters of two different photodiodes that vary in structure. The following photodiodes were sudied in this research:

The following photodiodes are investigated in the work:

- MAPD-3NM-2LOT (deeply-buried pixel structure);
- HAMAMATSU MPPC S12572-010P (surface pixel structure).

The study aimed to gain insights into their performance characteristics and behavior under different conditions.

2. Silicon photomultipliers (SiPM)

The operating principle of all silicon photomultipliers involves the avalanche multiplication of electrons. This multiplication occurs when an external voltage is applied, and it originates from the creation of an electron-hole pair through light exposure. Variations arise in the specific technical design of these devices, which is aimed at addressing some of the shortcomings found in their predecessors.

Micropixel avalanche photodiodes are devices that consist of small pixels capable of independently detecting incoming photons. Currently, the two most intriguing types of SiPMs are those with surface and deeply-buried pixel structure [1]. Their primary distinction lies in how is an avalanche process stopped. In SiPMs with surface pixel structure, the avalanche is halted by employing a microresistor on the surface. This resistor changes the distribution of the applied voltage between the resistor and the pixel, thereby extinguishing the avalanche. In SiPMs with deeply-buried pixels, quenching is achieved by reducing the electric field in the region where electron multiplication occurs. This reduction is facilitated when electrons accumulate within a potential well.

2.1. Parameters SiPM

The following main parameters are distinguished from SiPM:

- breakdown voltage;
- PDE (photon detection efficiency);
- gain;
- dark current;
- temperature coefficient of breakdown voltage.

The breakdown voltage U_{br} of a silicon photomultiplier (SiPM) is the threshold voltage at is the voltage at which the detector switches to Geiger mode of operation (the current increases sharply with an increase in the applied reverse voltage) [2].

PDE – the value characterizing the efficiency of the detector is expressed as a percentage. For SiPM, it is defined as the ratio of the number of registered photoelectrons (the number of primary triggered pixels) per pulse (μ) to the number of incident photons at low illumination intensity (N_{ph}) [3]:

$$PDE = \frac{\mu}{N_{ph}} \cdot 100\%. \tag{1}$$

The gain shows how many times a photoelectron can be multiplied when the detector is operating in Geiger mode. It is defined as the ratio of the charge accumulated on the elementary capacity of a pixel during the development of a Geiger discharge (Q), to the electron charge (q) [3]:

$$M = \frac{Q}{q}. \tag{2}$$

The dark current is associated with the generation of electron-hole pair carriers without the influence of photons (mainly thermal generation and tunneling from the valence band to the conduction band) [4]. Getting into the conduction band, under Geiger regime conditions, these electrons create avalanches that are no different from those that are "triggered" by a photoelectron. This effect must be taken into account in order to distinguish a useful signal at the output from noise.

The temperature coefficient of the breakdown voltage shows the change in the breakdown voltage when the temperature changes by 1 degree [5]. It is defined as the ratio of the breakdown voltage change ΔU_{br} to the corresponding temperature change ΔT:

$$k = \frac{\Delta U_{br}}{\Delta T}. \tag{3}$$

SIPM pixels have some characteristic capacities, due to the presence of p-n junctions there. There are two types of capacitance: pixel capacitance or the sum of capacitance of pixels and thermal capacitance. The first characterizes the pixel when operating in avalanche mode, and the second – when the device is operating before the breakdown. The latter is most often used when talking about the capacitance of the photodiode.

2.2. Temperature dependence of parameters

The breakdown voltage value strongly depends on the temperature U_{br} [6]. At the same time, the dependence $U_{br}(T)$ has a linear form, which has been shown in many works. At the same time, the dependency has the form

$$U_{br} = k \cdot T + U_{br0}, \tag{4}$$

where k – temperature coefficient of breakdown voltage, T – temperature in degrees Celsius, U_{br0} – breakdown voltage at $0°C$.

The second parameter that has a temperature dependence is PDE. Unfortunately, with all the importance of this parameter, at the moment, the dependence $PDE(T)$ in general, it is poorly studied and therefore there is no data on the general appearance of this dependence [6].

The gain has a dependence on the magnitude $U_{ov} = U_{op} - U_{br}$, in this case, the breakdown voltage linearly depends on the temperature. If, when the temperature of the medium in which the photodiode operates changes, this change is leveled by adjusting the operating voltage to maintain a constant overvoltage, the gain values will remain stable.

Due to the increased mobility of charge carriers, an increase in the dark current will also occur with an increase in temperature. The capacity of pixels in SIPM will not change. A general view of the volt-farad characteristic will be observed, but it will consist in the fact that it reaches saturation faster at high temperatures.

3. Measurement setups

Figure 1 shows a diagram of a measurement setup for measuring the current–voltage characteristics (I–V curves) of photodiodes. During the measurement, a negative voltage is applied to the test diode (SiPM), located in a light-tight box. For applying bias voltage it is used a picoammeter, which is capable of both measuring the current flowing through the diode and applying a constant voltage. An oscilloscope is used to monitor the signals that occur when approaching a thermal breakdown. 50 Ω resistor is connected to it in parallel in order to reduce its input resistance (1 MΩ).

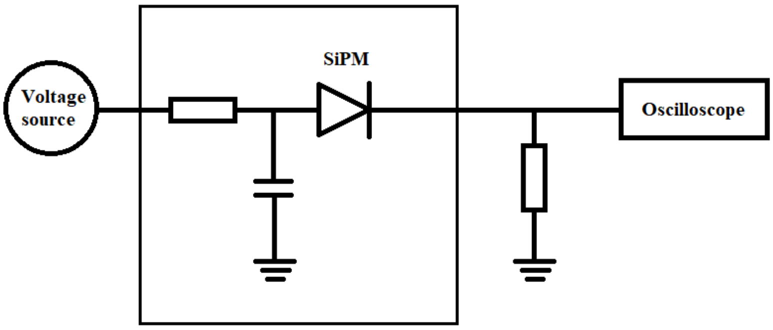


Figure 1. A block diagram of the measurement setup for I–V characteristics

Figure 2 shows a block diagram for measuring the capacitance–voltage (C–V) characteristics and determining its thermal capacitance. At low voltages, the calculated capacitance is large, and with a gradual increase in the reverse voltage, it tends to the value of the thermal capacitance, where the C–V curve goes about to a constant. The nominal value of the resistor R_n is selected so that the voltage drop on the resistor is as small as possible (it should be significantly less than the voltage applied from the generator). The connectors designated as contacts are connected to a reference capacitance (most often with a nominal value of 200 pF) at zero apply voltage. After that, a sinusoidal signal is applied to it and the amplitude A_{et} of voltage fluctuations on the reference is measured. Then, instead of the capacitance, the investigated photodiode is connected and the amplitudes of the voltage on it A_d are recorded at different values of the applied reverse voltage U. After that, the calculation was done according to the following formula

$$C(U) = \frac{A_d(U)}{A_{et}} \cdot C_{et}. \tag{5}$$

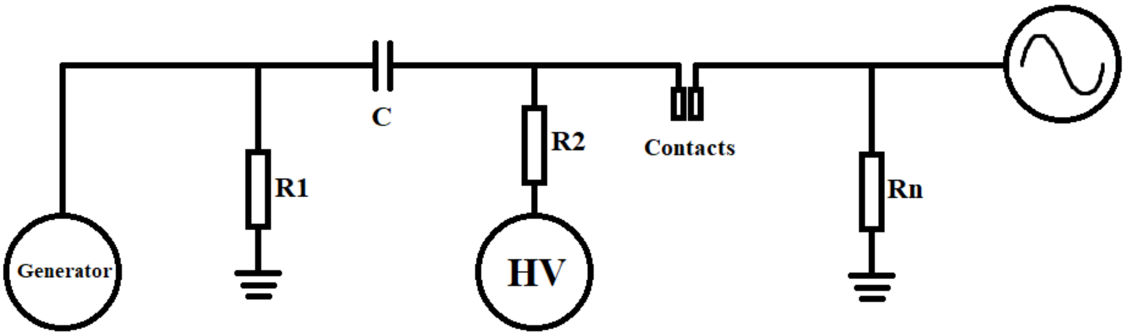


Figure 2. A block diagram of measurement setup for C-V characteristics

A block diagram of the measurement setup for measuring gain is shown in Figure 3. In the experiment, a light emission diode (LED) is controlled by a pulse generator. Since the amplitude of these signals is small, an amplifier (AM) was used to amplifier the output signal of the photodiode. the signal from the output of the amplifier is fed to the input of the analog-to-digital converter. The already digitized signal is fed to the computer. The results after analysing waveforms are presented in the form of a single-photoelectron spectrum.

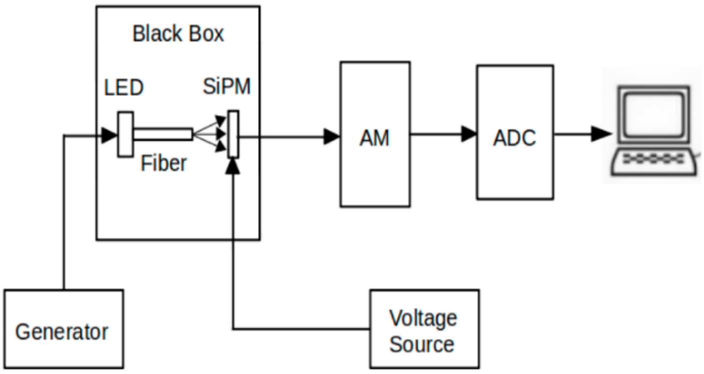
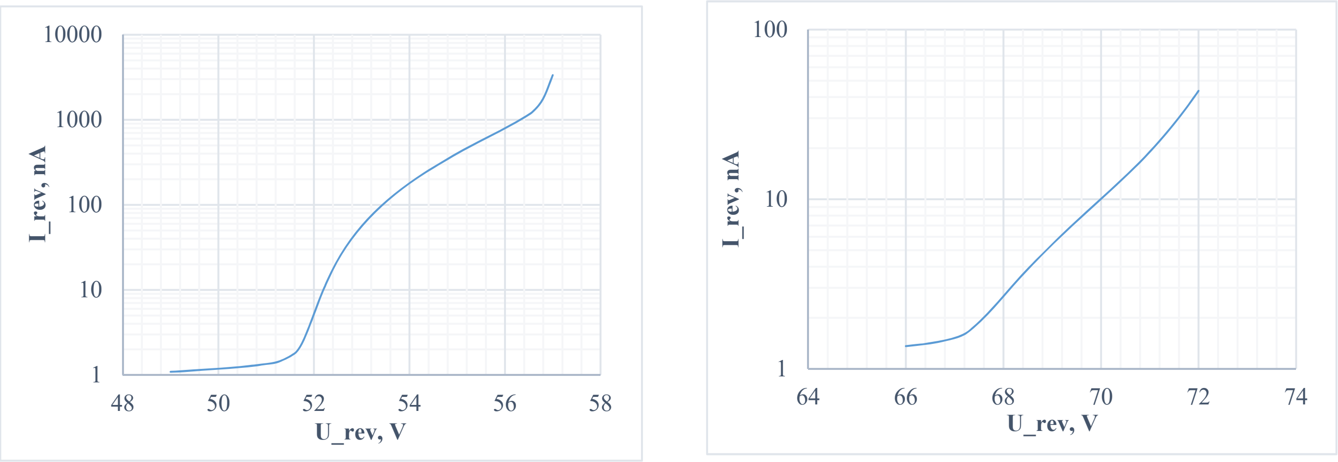


Figure 3. A block diagram of the measurement setup for measuring the single-photoelectron spectrum

4. Experimental results

4.1. I-V characteristics

One of the key characteristics of any semiconductor diode is its I-V characteristics (I-V curve). It shows the dependence of the current flowing through it on the applied voltage. Figure 4 shows the I-V curve at temperature $23°C$ for the photodiodes.



MAPD-3NM-2LOT HAMAMATSU MPPC S12572-010P

Figure 4. I-V curve the studied photodiodes at $T = 23°C$

4.2. C-V characteristics

The capacitance of the photodiode is determined using a nominal value of the reference capacitance, the amplitudes of voltage fluctuations on the photodiode and the reference capacitor. The C-V characteristics obtained at temperature $23°C$ shown in the figure 5. Thermal capacity values C_d for the studied photodiodes are shown in Table 1.

Table 1. Measurement results of photodiode capacitances

Photodiode	C_d, pF
MAPD-3NM-2LOT	147
HAMAMATSU MPPC S12572-010P	294

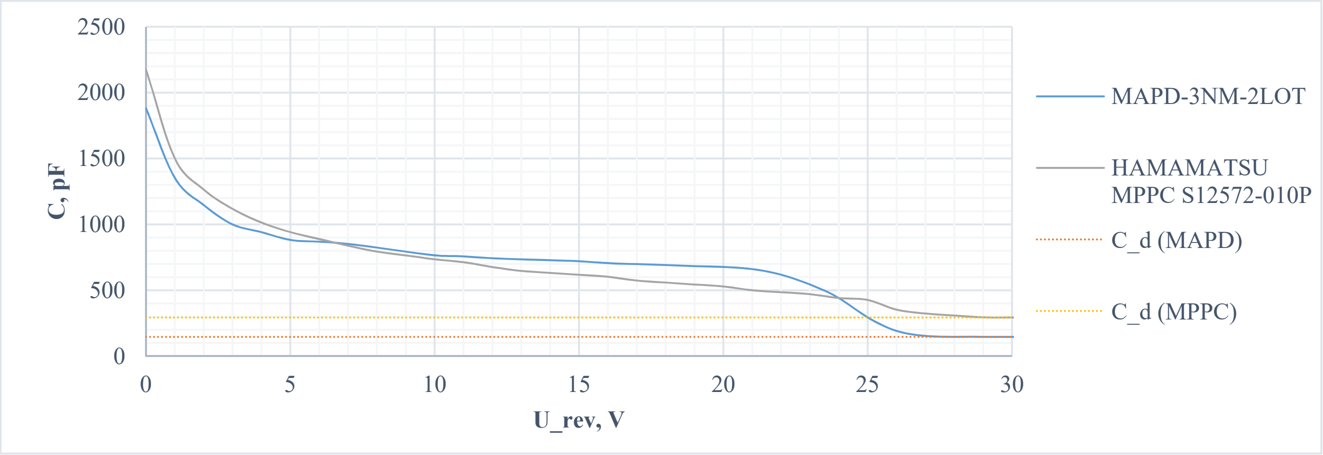


Figure 5. C–V characteristics for the studied photodiodes at $T = 23°C$

4.3. Determination of the breakdown voltage by dark current differentiation method

The breakdown voltage is determined from the volt-ampere characteristics obtained in paragraph 4.1. The following differentiated formula is used

$$F(U)=\frac{d\ln(I(U))}{dU}=\frac{1}{I(U)}\frac{dI(U)}{dU}. \tag{6}$$

Technically, we went from a higher voltage to a lower one in order to process our obtained data array and we obtain the following formula

$$F(U_i)=\frac{2}{(I_i+I_{i+1})}\frac{(I_i-I_{i+1})}{(U_i-U_{i+1})}. \tag{7}$$

The function $F(U)$ (Fig. 6, right) has two extremes, at the same time, an extremum with a maximum is observed at the breakdown voltage U_{br} and a minimum at the optimal operating voltage U_{op}.

The results of the breakdown voltage measurement for the studied photodiodes are shown in Table 2.

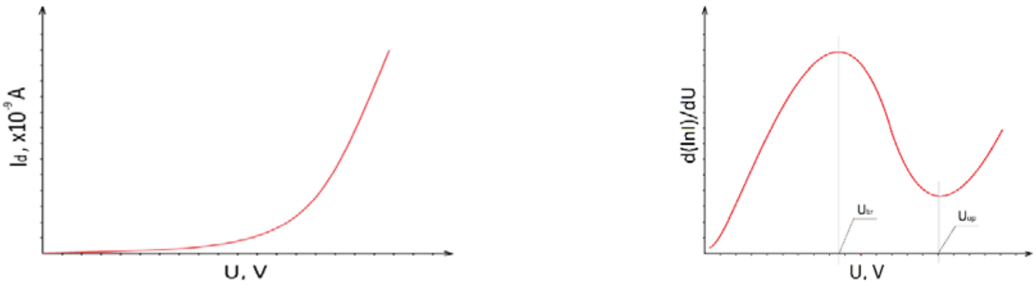


Figure 6. The inverse branch of the SiPM I–V curve (left) for the dark current; the curve of the logarithmic derivative of the function $I(U)$ (right)

4.4. Determination of the breakdown voltage by measuring the gain of the SiPM

This method of determining the breakdown voltage is based on the approximation of the linear dependence of the pixel gain M on the applied voltage.

We can find the gain from the following formula

$$M=\frac{x_{pix}\cdot K_{QDC}}{K_{ampl}\cdot q}, \tag{8}$$

where x_{pix} – the distance between neighboring peaks along the abscissa axis (in general, the distance between neighboring peaks should be the same), K_{QDC} – the resolution of one channel of the analog-to-digital converter, K_{ampl} – amplifier gain, q – electron charge.

Then, for each studied value of the reverse voltage, the gain is calculated and plotted on a graph. This dependence should be linear. Then, according to the obtained data, the dependence is approximated by a linear function $M(U_{обр})$. The breakdown voltage U_{br} is determined from the intercept of a linear fit to the abscissa axis.

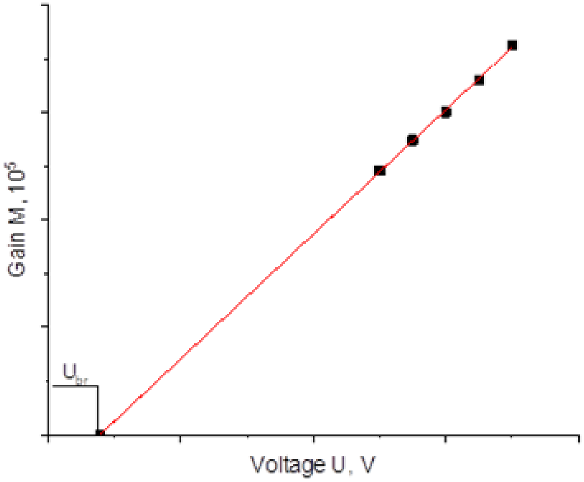


Figure 7. The dependence of the gain on the reverse voltage

For calculating the gain according to formula (8) the following ADC and gain parameters were used:

$$K_{QDC} = 4 \cdot 10^{-14}\ C,\ K_{ampl} = 80.$$

The calculation results are shown in Table 2.

Table 2. Results of finding breakdown voltages by two methods

Photodiode	U_{br}, V (Using the gain)	U_{br}, V (Using differented dark current)	U_{op}, V
MAPD-3NM-2LOT	52.3	52.025	56
HAMAMATSU MPPC S12572-010P	67.92	68.06	70.38

4.5. Breakdown voltage dependence on temperature

To determine the temperature coefficient of the breakdown voltage and determine the nature of the breakdown voltage dependence on temperature, the volt-ampere characteristics of the studied diodes in the temperature range were measured $[27°C \div 47°C]$ with step $5°C$. Then, breakdown voltage values were found for all diodes at all points and dependencies $U_{br}(T)$ were constructed. They were approximated by a linear function using the formula (4).

Approximation results:

- MAPD-3NM-2LOT

$$U_{br} = 0.0515 \cdot T + 50.803;$$

- HAMAMATSU MPPC S12572-010P

$$U_{br} = 0.057 \cdot T + 66.611.$$

The measured I–V curve and the breakdown voltage dependence on temperature are shown in Figures 8, 9. The values of the breakdown voltage temperature coefficient are given in Table 3.

Table 3. Values of the breakdown voltage temperature coefficient

Photodiode	$k,\ mV/°C$
MAPD-3NM-2LOT	51,4
HAMAMATSU MPPC S12572-010P	57

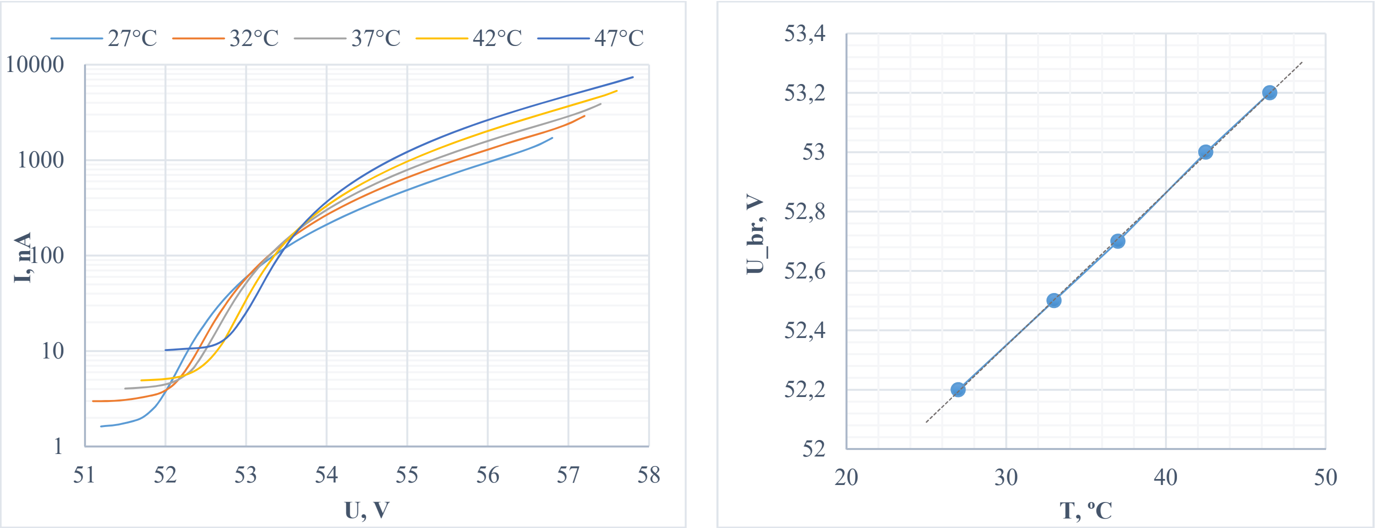


Figure 8. MAPD-3NM-2LOT: I–V curve at the studied temperatures (left); temperature dependence of the breakdown voltage

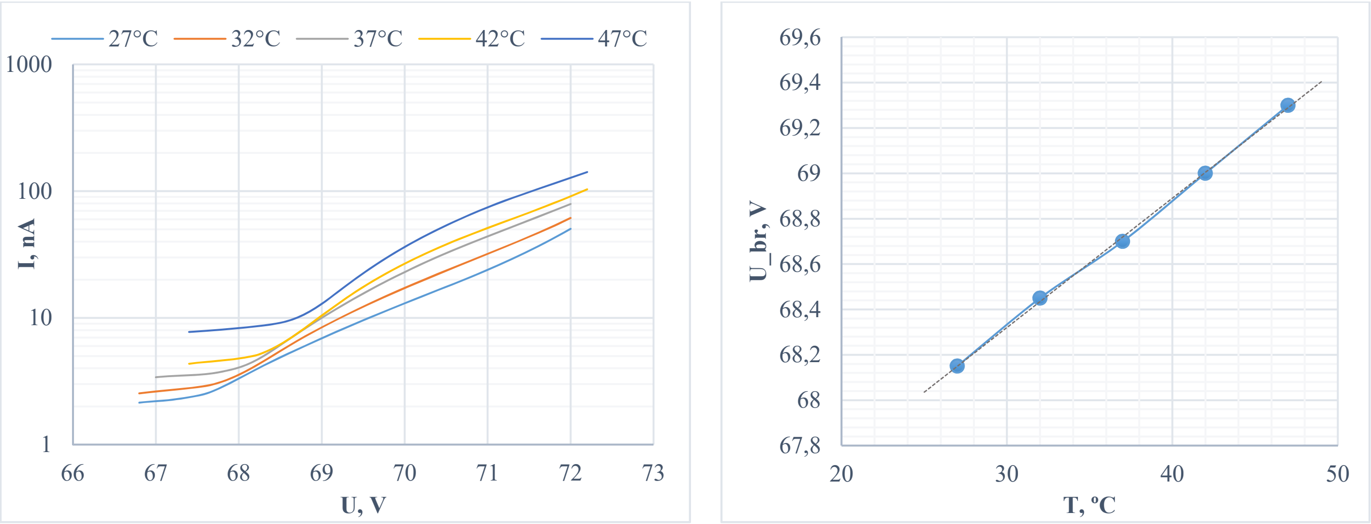


Figure 9. HAMAMATSU MPPC S12572-010P: I–V curve at the studied temperatures (left); temperature dependence of the breakdown voltage

Conclusions

In these studies, I was familiar with different types of SiPM, their operation principles and characteristics. The methods of measuring the key characteristics of SiPMs were mastered:

- measurement of current–voltage and capacitance–voltage characteristics;
- determination of breakdown voltage by (6);
- determination of the breakdown voltage by measuring the gain of the SiPM;
- determination of the temperature coefficient of the breakdown voltage.

During the measurements, I–V and C–V curves were obtained at room temperature, from which the breakdown and operating voltages for the diodes, as well as their capacitance, were determined

- MAPD-3NM-2LOT: $U_{br} = 52.03\ V \pm 0.6\%$, $U_{op} = 56\ V$, $C_d = 147 pF$;
- HAMAMATSU MPPC S12572-010P: $U_{br} = 68.06\ V \pm 1.4\%$, $U_{op} = 70.38\ V$, $C_d = 294 pF$.

Breakdown voltages were determined using the dependence of the gain on the reverse voltage

- MAPD-3NM-2LOT: $U_{br} = 52.3\ V$ ± 1.13%;
- HAMAMATSU MPPC S12572-010P: $U_{br} = 67.92\ V$ ± 1.1%.

As can be seen, the values of breakdown voltages obtained by these methods are close to each other and their values lie in each other's confidence intervals.

The temperature dependence of the breakdown voltage in the temperature range of $\left[27^{\circ}C \div 47^{\circ}C\right]$ were also investigated. The linearity of the $U_{br}(T)$ dependence was confirmed and the temperature coefficients of the breakdown voltage were calculated from the obtained dependences

- MAPD-3NM-2LOT: $k = 51.5\ \frac{mV}{^{\circ}C}$ ± 9.9%;
- HAMAMATSU MPPC S12572-010P: $k = 57\ \frac{mV}{^{\circ}C}$ ± 1.75%.

The results of the study demonstrate that diodes with deeply-buried pixels exhibit more stable behavior to temperature fluctuations.

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