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Performance of silicon photomultipliers at low temperature

S. Nuruyev,[a,b,1] **G. Ahmadov,**[a,b,c] **A. Sadigov,**[a,c] **R. Akberov,**[b,c] **F. Ahmadov,**[a,c] **M. Holik**[d,e] **and Yu. Kopatch**[b]

[a] *Azerbaijan National Academy of Sciences — CSSR and IRP, Baku, Azerbaijan*
[b] *Joint Institute for Nuclear Research, Dubna, Russia*
[c] *National Nuclear Research Centre of MTCHT, Baku, Azerbaijan*
[d] *Institute of Experimental and Applied Physics, Czech Technical University in Prague, Husova D-240/5, Prague 1, 110 00, Czech Republic*
[e] *Faculty of Electrical Engineering, University of West Bohemia in Pilsen, Univerzitni 26, 301 00 Pilsen, Czech Republic*

E-mail: sebuhinuruyev@gmail.com

Abstract: The performances of silicon photomultipliers with different structures are investigated at low temperature.The first sample is a micro pixel avalanche photodiode with deep buried pixel structure from Zecotek Photonics Inc. The second and third ones are multi-pixel photo counters with a surface pixel design from Hamamatsu Photonics. The influence of temperature on the main parameters of the photodiodes such as photon detection efficiency (PDE), gain, and capacitance was studied in the temperature range from 0°C to −120°C.

Keywords: Cryogenic detectors; Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs, CMOS imagers, etc)

[1] Correpsonding author.

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1 Introduction

The recent technological improvements made the silicon photomultipliers (SiPM) attractive alternative sensors for many detector applications that would replace vacuum photomultiplier tubes (PMT). The features such as small size, low price, low power consumption and high gain, made it possible to use SiPMs in photon detection applications of many experiments in field of nuclear physics [1–4]. Recently, there are a number of experiments where low temperature stability of photo detectors is required [5–7]. Therefore, a detail study of SiPM parameters at low temperature is needed to assess the performances since the data provided by the manufacturers do not cover low temperature interval. In this work, we used pixel photodiodes with different designs. The first sample with buried pixel structure is a micro pixel avalanche photodiode (MAPD-3NK) [1] from Zecotek Photonics Inc. A photosensitive area of MAPD-3NK is 3.7×3.7 mm^2, pixel pitch 10 µm, operation voltage ~90 V, the total number of pixel — 136000 and the avalanche gain $\sim 9 \times 10^4$. Other samples with surface pixel structure are multi pixel photon counters MPPC-S13360-3025CS and MPPC S12572-010P [8, 9] from Hamamatsu Photonics. MPPC S12572-010P features following parameters: the total number of pixel — 90000 with the pixel pitch of 10 µm, a photosensitive area — 3×3 mm^2, operation voltage ~ 70 V and avalanche gain $\sim 1.3 \times 10^5$. The photosensitive area of MPPC-S13360-3025CS is 3×3 mm^2, the total number of pixel — 14400 with the pixel pitch of 25 µm, operation voltage ~50 V and the avalanche gain $\sim 6.8 \times 10^5$.

2 Experimental setup

The experimental setup is depicted on figure 1. The samples were positioned at the centre of a copper vessel. As a light source was used a light emitting diode (LED with 420 nm wavelength) with optical fiber, which is fixed at the distance of 50 mm from SiPM. There was used a collimator in order to provide a uniform illumination of the photosensitive area of the samples. The samples were powered using a Keithley 6487 Picoammeter voltage source. Signal from the SiPMs was amplified by the amplifier with a gain of 105 and bandwidth of 50 MHz. The output signal was integrated by CAEN DT5720 digitizer with 4 ns sampling and 12 bit resolution. The digitizer was triggered directly by a two channel Textronix-AFG3022B pulse generator which both channel

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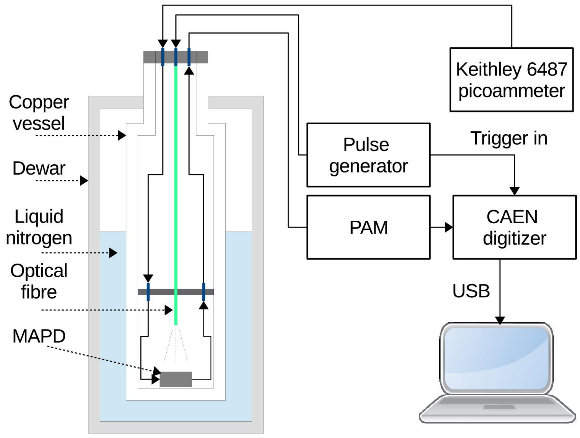

Figure 1. Experimental setup.

works in synchronization mode. The first channel of the generator was used to start the LED while the second for triggering the acquisition system. Temperature measurement with accuracy of 0.1°C was obtained by a platinum temperature sensor PT100 [10], which was fixed close to the SiPM. The copper vessel was cooled by liquid nitrogen in the range from 0°C to −120°C.

The influence of cooling on the breakdown voltage and the gain was assessed from single photoelectron distribution. This distribution was obtained by pulsing the LED with 30 ns pulses at low light level. The amount of photons was selected to 8 photons per pulse. The Integration gate of the digitizer was set to 60 nsec.

3 Experimental results

The avalanche gain (M) was determined by calculating the average distance (Q) between two peaks of single-photoelectron spectra of the samples:

$$M = \frac{Q \cdot \mathrm{ADC}}{K_{\mathrm{am}} \cdot q}, \tag{3.1}$$

where K_{am} is amplification coefficient of amplifier, ADC is corresponding channel number of the digitizer and q is electron charge.

The avalanche gain of the SiPMs as a function of applied voltage within the temperature range was depicted on figure 2 (left), figure 3 (left) and figure 4 (left). It could be seen that the avalanche gain of the three SiPMs was a linear function of the bias voltage at a fixed temperature. As shown in the figures, the dependence was well fitted by a straight line with nearly identical slopes. The identical linear slope of M as a function of the overvoltage ΔV could be explained by temperature insensitivity [7]. Linear fits of the data points allowed determining the breakdown voltage U_{br}. The breakdown voltage U_{br} of the SiPM devices were determined as the intersection point of the linear fit with the horizontal axis U_{op}. The temperature dependence of U_{br} was demonstrated on figure 2 (right), figure 3 (right) and figure 4 (right). The breakdown voltage of MPPC-S13360-3025CS was 21.4% smaller than the one of the MPPC-S12572-010P. The decreasing of U_{br} value was determined as 58 ± 3.8 mV/°C for MAPD-3NK and 51 ± 3.7 mV/°C for Hamamatsu S13360-3025CS. This

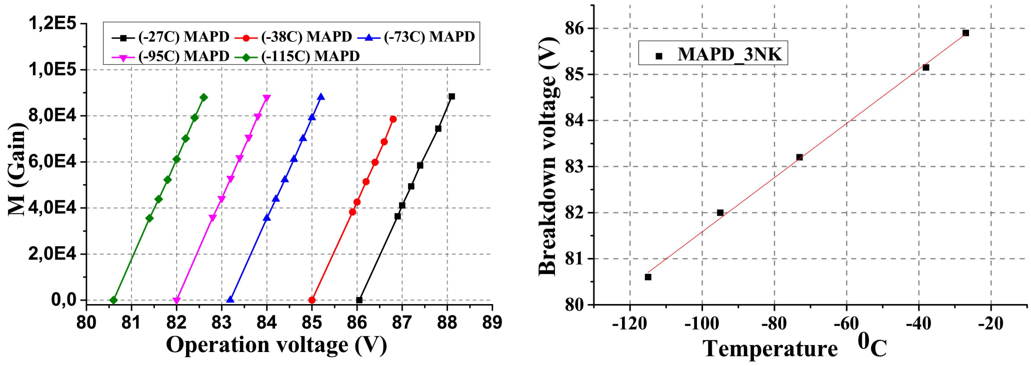

Figure 2. Avalanche gain dependence of MAPD-3NK for different bias voltages from −27°C to −115°C temperature interval (left) and temperature coefficient dependence of breakdown voltage for MAPD-3NK (right).

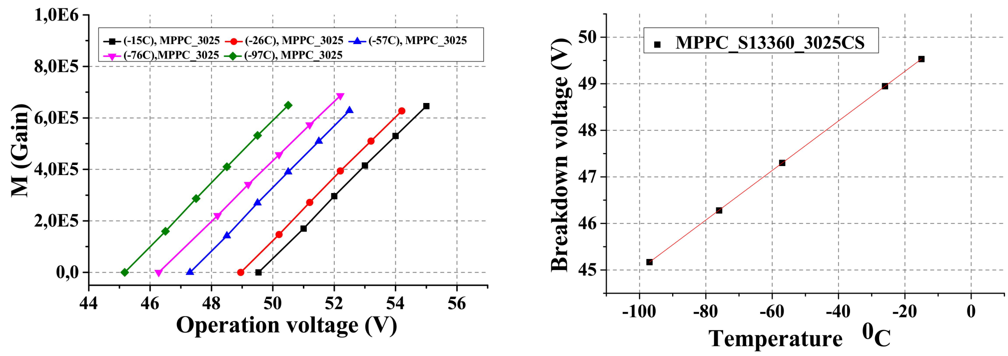

Figure 3. Avalanche gain dependence of MPPC-S13360-3025CS for different bias voltage from −6°C to −97°C temperature interval (left) and temperature coefficient dependence of breakdown voltage for MPPC-S13360-3025CS (right).

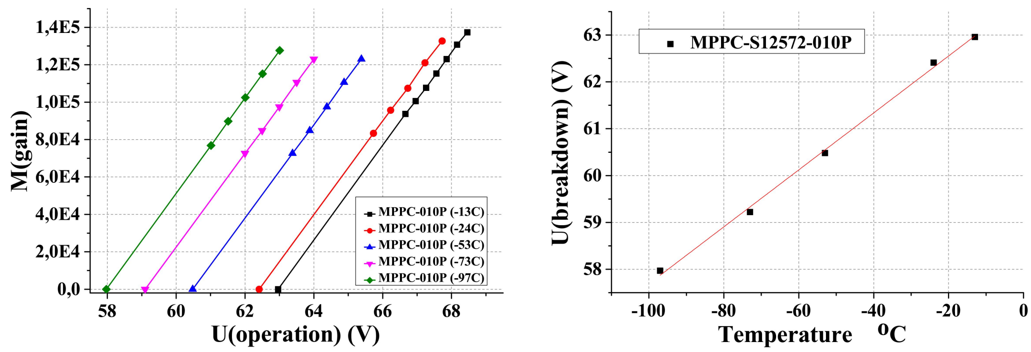

Figure 4. Avalanche gain dependence of MPPC-S12572-010P for different bias voltage from −13°C to −97°C temperature interval (left) and temperature coefficient dependence of breakdown voltage for MPPC-S12572-010P (right).

value for MPPC-S12572-010P was determined as 60 ± 3.82 mV/°C. The temperature coefficient of MPPC-S13360-3025CS was 15% smaller than MPPC-S12572-010P. This value of MAPD-3NK was 13.7% higher than the value of MPPC-S13360-3025CS and although the breakdown voltage of MAPD-3NK is 73% higher than the value of MPPC. The decreasing of breakdown voltage allowed to improve temperature stability of MPPC [9].

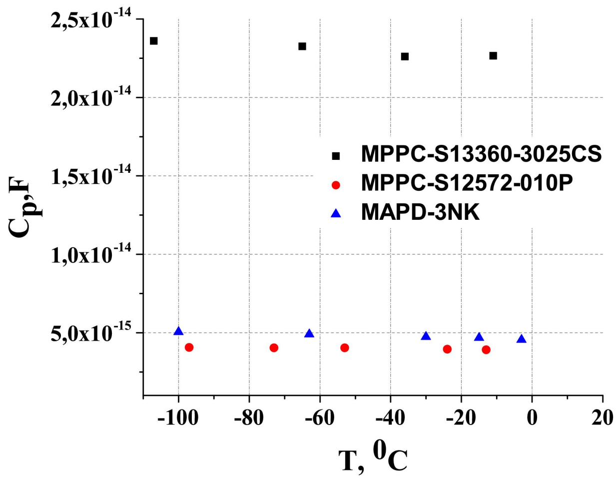

Figure 5. The effective of pixel capacitance as function of temperature for all SiPM.

The pixel capacitance was calculated using the expression $C_{\text{eff}} = \partial Q/\partial U_d$ from the Q vs. U_d dependence. The capacitance of pixel was found 24 fF for MPPC-S13360-3025CS and 3.94 fF for MPPC-S12572-010P. These values are well coincidence with data sheet values of MPPC within uncertainty of 10% [8, 9]. The capacitance of pixel was determined 4.5 fF for MAPD-3NK.

The effective pixel capacity dependence of temperature was presented in figure 5. The pixel capacity increased with decreasing temperature. The change was not higher than 5.7% for samples, when the temperature difference was about −100°C. The single photoelectron resolution did not depend on temperature for SiPMs.

The PDE of the samples was measured with the method of counting pulses of single photoelectrons in the studied temperature range. The average number of incident photons per pulse was calculated as given in equation (3.2) using a p-i-n photodiode (from Hamamatsu Photonics) with QE = 65 % for light with a wavelength of 420 ± 20 nm

$$N_{(\text{ph})} = \frac{I_{(\text{light})}}{f \cdot \text{QE} \cdot q}, \tag{3.2}$$

where f is repetition period of the light pulses, $I_{(\text{light})}$ photocurrent appeared by light, and q electron charge.

The average number of photon electrons per pulse was expressed by eq. (3.3) in case of no probability of pulse detection

$$\mu = -\frac{\ln(N_{\text{incident}} - N_{\text{detected}})}{N_{\text{incident}}}. \tag{3.3}$$

The photon detection efficiency was calculated by following equation

$$\text{PDE} = \frac{\mu}{N_{(\text{ph})}} \cdot 100\%. \tag{3.4}$$

Figure 6 and 7 show the dependence of PDE on the overvoltage value for different temperatures. The measurements showed that the PDE of the SiPMs was stable with the temperature within uncertainty of 5%, although it was sensitive to the overvoltage.

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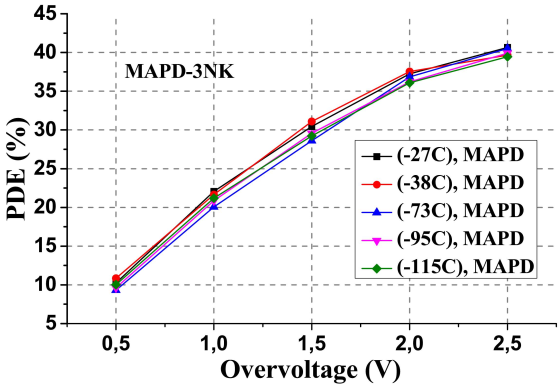

Figure 6. The PDE as a function of overvoltage for MAPD 3NK in the temperature range from −10°C to −100°C interval.

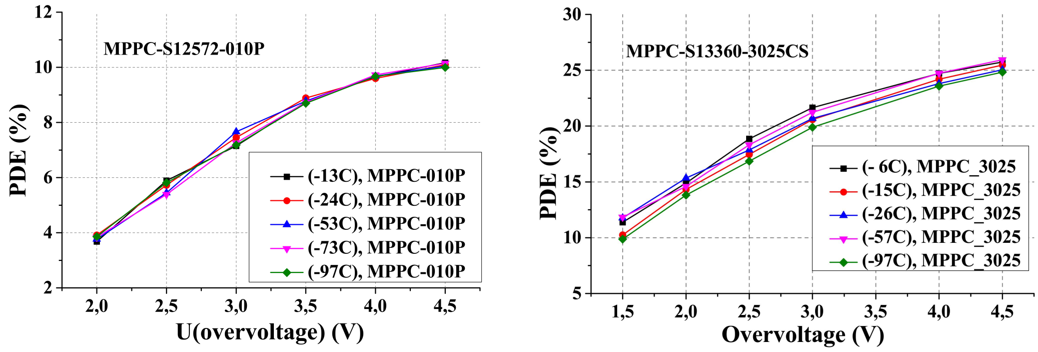

Figure 7. The PDE as a function of overvoltage for MPPC-S12572-010P (left) and MPPC-S13360-3025CS (right) in the temperature range from −10°C to −100°C interval.

The PDE was determined as 35 ± 3% for MAPD-3NK (2.5 V overvoltage), 25 ± 1.5% for MPPC-S13360-3025CS (3 V) and 10 % for MPPC-S12572-010P (4.5 V). The variation of the PDE was not higher than 10% (at fixed overvoltage) in the temperature range from −6°C to −115°C.

4 Conclusion

The basic parameters of SiPMs with different designs were studied and their operation was confirmed at the low temperature. A gain of 6.8×10^5 (3 V overvoltage) and 1.4×10^5 (4.5 V overvoltage) was obtained for MPPC-S13360-3025CS and MPPC-S12572-010P respectively. The temperature coefficient of breakdown voltage was calculated as 60 ± 3.82 mV/°C MPPC-S12572-010P and 51 ± 3.7 mV/°C for MPPC-S13360-3025CS. The gain of 9×10^4 (2 V overvoltage) was obtained for MAPD-3NK. It was determined that the breakdown voltage decreases linearly with therate of∼ 58 ± 3.8 mV/°C, although the breakdown voltage of MAPD-3NK was 73% higher than the value of MPPC-S13360-3025CS. This means that if breakdown voltage of MAPD is decreased to 70 V or 55 V, in this case temperature coefficient of breakdown voltage will be 40 mV/°C or smaller than 20 mV/°C. These results will be used to improve parameters of the new types of MAPD.

The photon detection efficiency was assessed as a function of temperature, too. The PDE was determined as 35 ± 3% for MAPD-3NK (at 2.5 V overvoltage), 25 ± 1.5% for MPPC-S13360-

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3025CS (3 V) and 10% for MPPC-S12572-010P (4.5 V). The effective capacitance of pixel increased with decreasing temperature. The changing of capacitance was about 5.7% for SiPMs within the temperature range from 0°C to −120°C. Despite of multiple thermal cycles, SiPMs consistently recovered its initial room temperature performance and no mechanical damage was observed. The obtained results showed that the all samples were well matched to light readout for low temperature experiments where temperature ranging from −0°C to −120°C.

Acknowledgments

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References

[1] Z. Sadygov, A. Olshevski and I. Chirikov, *Three advanced designs of micro-pixel avalanche photodiodes: their present status, maximum possibilities and limitations*, *Nucl. Instrum. Meth.* **A 567** (2006) 70.

[2] D. Renker and E. Lorenz, *Advances in solid state photon detectors*, 2009 *JINST* **4** P04004.

[3] F. Ahmadov et al., *New gamma detector modules based on micropixel avalanche photodiode*, 2017 *JINST* **12** C01003.

[4] F. Ahmadov et al., *Development of compact radiation detectors based on MAPD photodiodes with Lutetium Fine Silicate and stilbene scintillators*, 2015 *JINST* **10** C02041.

[5] Y. Sun et al. *Silicon photomultiplier low temperature characterization for future neutrino detectors*, *J. Phys. Conf. Ser.* **888** (2017) 012068.

[6] M. Alfonsi et al., *The XENON Dark Matter project: from XENON100 to XENON1T*, *Nucl. Part. Phys. Proc.* **273–275** (2016) 373.

[7] G. Collazuol et al., *Study of silicon photomultipliers at cryogenic temperatures*, *Nucl. Instrum. Meth.* **A 628** (2011) 389.

[8] https://www.hamamatsu.com/resources/pdf/ssd/s12572-010_etc_kapd1045e.pdf

[9] https://www.hamamatsu.com/resources/pdf/ssd/s13360_series_kapd1052e.pdf

[10] https://www.picotech.com/library/application-note/pt100-platinum-resistance-thermometers