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RESEARCH ARTICLE

Characterization of silicon photomultipliers with different structures

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Abstract

Background

Silicon Photomultipliers (SiPMs) are crucial devices in various photon-counting applications. They are mainly produced with two pixel structures, with deeply burned and surface pixel designs offering distinct advantages. This study investigates the impact of these structural differences on key parameters of two representative SiPMs: the MAPD-3NM-II (Zecotek Photonics) with a deeply burned structure and the MPPC S12572-010P (Hamamatsu Photonics) with a surface pixel structure.

Method

The performance of MAPD-3NM-II and MPPC S12572-010P was evaluated using multiple techniques. Breakdown voltage was determined using three different methods: I-V measurements, the Miller method, and the single photoelectron method. Temperature dependence was analyzed by measuring the breakdown voltage across a temperature range of 23°C to 43°C. Finally capacitance measurements were performed using a sinusoidal signal with

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constant amplitude and frequency, where determined using reference capacitance.

Results

The results from all three methods were consistent, yielding a breakdown voltage of 52.22±0.07 V for the MAPD-3NM-II and 68.08±0.10 V for the MPPC S12572-010P, within experimental uncertainties. The optimal operating voltage was determined as Ubr+4 V for the MAPD-3NM-II and Ubr+4.5 V for the MPPC S12572-010P. The temperature dependence of breakdown voltage was also investigated, revealing that the MAPD-3NM-II exhibited a lower temperature coefficient (51.32±0.44 mV/°C) compared to the MPPC S12572-010P (57.01±0.56 mV/°C). This indicates that the MAPD-3NM-II is more thermally stable. Capacitance measurements demonstrated that the MAPD-3NM-II exhibited significantly lower capacitance (155±12 pF) than the MPPC S12572-010P (294±26 pF).

Conclusions

This study provides a comparative analysis of two SiPMs with different pixel structures. The findings highlight the potential advantages of deeply burned pixel structures in terms of reduced capacitance and improved thermal stability. The lower capacitance of the MAPD-3NM-II suggests its suitability for large-area detector implementations. The results show that MAPD type photodiodes can be used in radiation detectors used in medicine and radiation monitoring systems.

Plain Language Summary

This study investigate two silicon photomultipliers (SiPMs), MAPD-3NM-II and MPPC S12572-010P, which are highly sensitive light detectors used in various applications as alternatives to photomultiplier tubes (PMTs) and direct light sensors. The investigation focused on some key parameters, including breakdown voltage, temperature dependence, and capacitance.

Breakdown voltage was determined using multiple methods, and temperature coefficients were analyzed through I-V characteristics at different temperatures. A significant difference was observed in capacitance: the MAPD-3NM-II exhibited a lower capacitance (155±12 pF) compared to the MPPC S12572-010P (294±26 pF), making it more suitable for applications requiring large detection areas with minimal capacitance-related performance issues. Additionally, the MAPD-3NM-II showed better thermal stability (51.32±0.44 mV/°C) compared to the MPPC S12572-010P (57.01±0.56 mV/°C). However, the MPPC S12572-010P demonstrated higher gain, which is linked to its higher capacitance.

These findings contribute to a better understanding of SiPM performance and offer insights into optimizing their design for

various scientific and industrial applications, including medical imaging, particle physics, and environmental monitoring.

Keywords
Silicon photomultipliers, MAPD, MPPC, C-V characteristics, I-V characteristics, Breakdown voltage, Single photoelectron, Miller method, capacitance



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1. Introduction

For decades, photomultiplier tubes (PMTs) were the primary choice for light detection in various applications. However, advancements in semiconductor technology have given rise to silicon photomultipliers (SiPMs), which have transformed the landscape of photodetector technology. Since their inception in the 1990s, SiPMs give the possibility as a photon detector, displacing PMTs in many experiments due to their photon detection capabilities. SiPMs possess several advantages, including high photon detection efficiency (PDE), gain, linearity, compact size, low operating voltage, and insensitivity to magnetic fields[1–5]. These attributes have made them highly attractive for applications spanning nuclear physics, detector physics, medicine, industry, and cosmology[4–9]. Initially, their small sensitive area limited their applications to compact detectors or systems requiring fine-grain scintillators and fiber readouts. However, recent developments have expanded their sensitive area using single element arrays and produce large area devices (limited up to 36 mm^2), enabling the use of SiPMs as replacements for PMTs, particularly in spectroscopy applications where large sensitive areas are required. Despite their advantages, large-area SiPMs face challenges, such as higher dark count rates (DCR), increased readout complexity, slower response times, and higher optical crosstalk (OCT). Moreover, a critical limitation is the increase in capacitance with the sensitive area, which affects detector performance. The capacitance of SiPMs directly affects their recovery time, gain, and noise characteristics. Larger SiPMs exhibit higher capacitance, which slows signal recovery, reduces gain stability, and increases noise levels. Additionally, at constant bias voltage large pixel capacitance worsens temperature dependence, making the detectors more sensitive to temperature variations[10,11]. Addressing this issue is essential for the development of large-area SiPMs, especially for applications requiring high performance and reliability.

SiPMs are mainly categorized into two main structural types: deeply buried and surface pixel structured photodiodes[1,12]. By comprehensively characterizing and comparing these two designs, this study aims to show the role of capacitance in SiPM development.

Furthermore, this work provides valuable insights into optimizing SiPM performance for diverse applications. Through a series of experimental studies, we demonstrate that the deeply buried pixel structure presents a promising solution to the capacitance challenge, paving the way for the development of next-generation SiPMs with enhanced performance.

2. Methods

This section describes the methodologies employed to evaluate the key parameters of SiPMs under investigation. The methods include breakdown voltage determination using three distinct techniques-current-voltage (I-V) characteristics, the Miller method, and the single photoelectron method-as well as capacitance-voltage (C-V) measurements and temperature dependence analysis of breakdown voltage.

2.1. I-V characteristics

The breakdown voltage (U_{bd}) is a key parameter for SiPM operation and must be accurately defined. This was achieved by calculating the derivative of the current with respect to voltage, normalized by the current itself, as expressed by the following expression $\frac{1}{J(U)}\frac{dJ(U)}{dU}$ 13–16. The breakdown voltage was defined as the voltage corresponding to the maximum value of the rate of change of the current.

The effect of temperature on the breakdown voltage was also investigated by these characteristics in a temperature range of 23°C to 43°C.

2.2. Miller method

The Miller method provides an alternative approach for determining the breakdown voltage. The Miller method involves measuring the luminous flux and subsequently determining the breakdown voltage by extrapolating the linear section of the inverse photocurrent versus voltage plot to the abscissa axis. The following formula was used for determining U_{br}:

$$\frac{1}{J_t} = \frac{k}{J_{ph}} + \frac{k}{U_{br} * J_{ph}} * U \quad (1)$$

Here, U_{br} is the breakdown voltage, J_t is total current, J_{ph} is photocurrent, k is an empirical parameter that depends on the structure of the device and the wavelength of the light. The light currents were calculated from the difference between the total current and the dark currents.

2.3. Single photoelectron method

In this approach, the breakdown voltage is determined by measuring the dependence of pixel gain on overvoltage. The gain of a SiPM (M) is proportional to the applied overvoltage and it was determined by following equation[17]:

$$M = \frac{m * C_{pixel} * (U_{oper.v} - U_{break.v})}{q} = \frac{A_{average} * 40\,fc}{K_{am} * q} \quad (2)$$

where Cpixel - pixel capacitance, Uapp.v - the applied voltage (Uapp.v⩾Ubreak.v), Ubreak.v - the breakdown voltage, m - coefficient which may change from 1 to 2 depending on the values of resistance of the depletion layer and the capacitance of the pixel, Kam - the amplification coefficient of the amplifier or preamplifier, q - electron charge and Aaverage- the corresponding ADC channel number to the amplitude of a single photoelectron.

The breakdown voltage is determined by applying a linear approximation to this relationship.

2.4. A method for measuring capacitance

Capacitance measurements were performed using an alternating sinusoidal signal with a constant amplitude and frequency. The SiPM capacitance was analyzed through a comparative

assessment of the output signal amplitudes from the SiPM and a calibrated reference capacitance. The capacitance of the SiPMs was determined by comparing the output signal amplitudes from the SiPMs and the reference capacitor[18]. The measurements were conducted under reverse bias conditions, and the capacitance was calculated using the ratio of the sinusoidal signal amplitudes. The capacitance values of the SiPMs were defined by the following equation:

$$C_d = \frac{A_d(U)}{A_{et}} * C_{et} \quad (3)$$

where A_d is the amplitude of the sinusoidal on SiPM, A_{et} is the amplitude of the sinusoidal on reference capacity and C_{et} is the nominal of the reference capacitance.

3. Experiment

This section details the experimental procedures employed to evaluate key parameters of SiPM devices. The following subsections describe information about studied samples, the experimental setups for each method and present the obtained results.

3.1. Samples

In this study, we investigate two SiPM designs: a deeply buried pixel structure (MAPD-3NM-II by Zecotek Photonics) and a surface pixel structure (MPPC S12572-010P by Hamamatsu Photonics). The first sample is a MAPD-3NM-II with deeply buried pixel structure from Zecotek Photonics. Its photosensitive area is 3.7×3.7 mm^2, pixel pitch 15 μm, the total number of pixels – 66500[19–22]. The second sample was MPPC S12572-010P with surface pixel structure. Its photosensitive area is 3×3 mm2, pixel pitch 10 μm, the total number of pixels – 90000[23,24]. Figure 1 presents schematic drawings of both structure.

Incident photons are absorbed in the epi layer or substrate, generating electron-hole pairs. In the reverse-biased p-n junctions, the high electric field accelerates carriers, triggering an avalanche process, resulting in a detectable current pulse. The quenching resistor stops the avalanche by reducing the local voltage across the microcell, allowing it to reset for the next photon detection. Quenching resistors (micro-resistors) in surface-structured SiPMs regulate the avalanche process, whereas in deeply burned structures, this control is achieved through the charge accumulated in the micro-wells[12].

3.2. Breakdown voltage determination by I-V characteristics

Figure 2 presents a schematic diagram of experimental setup for I-V measurement. To minimize the influence of ambient light, the samples were placed in a light isolated box and additionally insulated with a black dense material. The samples were biased by a Keithley 6487 picoammeter voltage source (Keithley Instruments, USA)[25]. Temperature monitoring of the samples was performed using a highly sensitive platinum temperature sensor (PT100) capable of measuring with an accuracy of ±0.1 °C, ensuring precise thermal readings throughout the experiment[26]. In addition, Mastech MY62 multimeter (Mastech, Taiwan) was employed to monitor the internal temperature of the box. The Hantek DSO5202P oscilloscope (Hantek, China) with a 50 Ω input was used to visualize any potential changes in the setup. Its 50 Ω input was used as a ground.

Figure 3 shows reversed I-V characteristics on a logarithmic scale for both samples at room temperature. By analyzing the current-voltage (I–V) characteristics, using indicated expression in the subsection 2.1., the operating voltage and breakdown voltage of the photodiodes were determined as shown in Figure 4.

U_{br} was determined to be 52.16±0.07 V for the MAPD-3NM-II and 68.17±0.11 V for the MPPC S12572-010P at room temperature using the differentiation method. The optimal operating voltage for the MAPD-3NM-II was determined to be U_{br}+4 V, while it was found to be U_{br}+4.5 V for the MPPC S12572-010P.

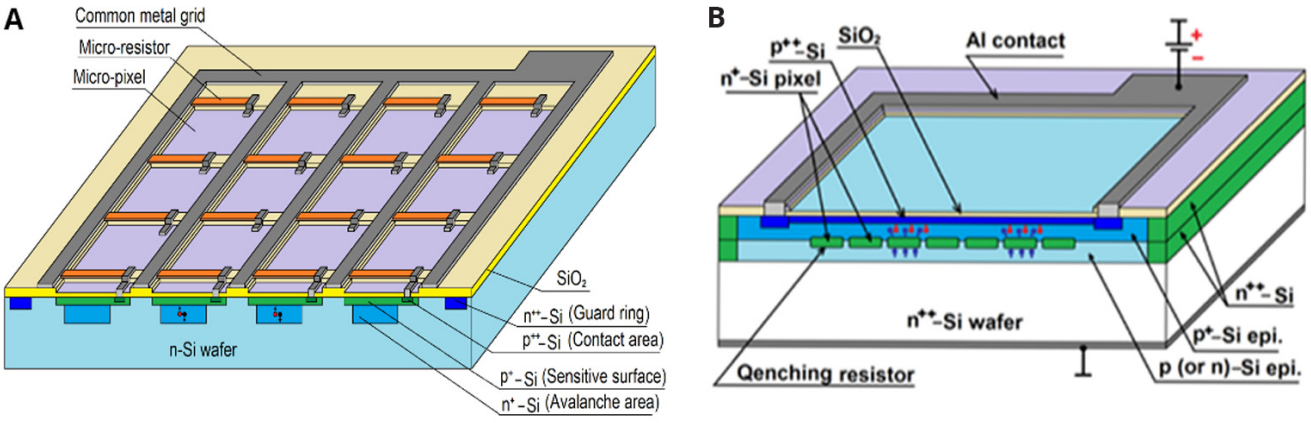


Figure 1. Schematic drawings of surface (**a**) and deeply burned (**b**) SiPM. This pictures has been reproduced with permission from 12.

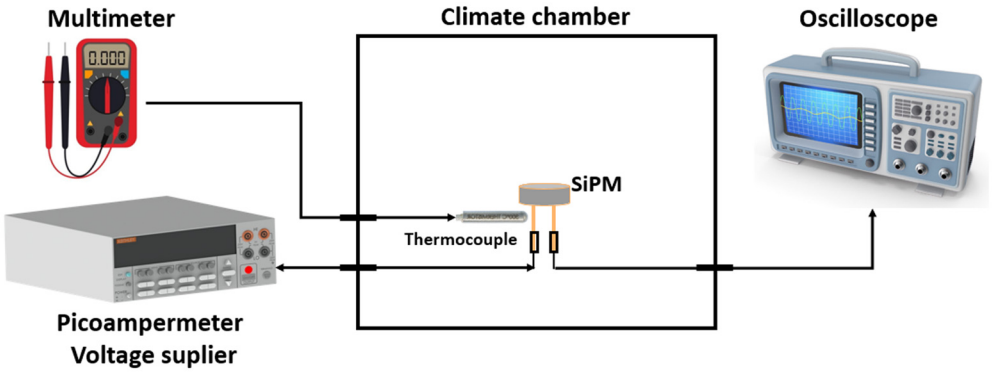


Figure 2. Schematic diagram of the experimental setup for measuring I–V characteristics at different temperatures.

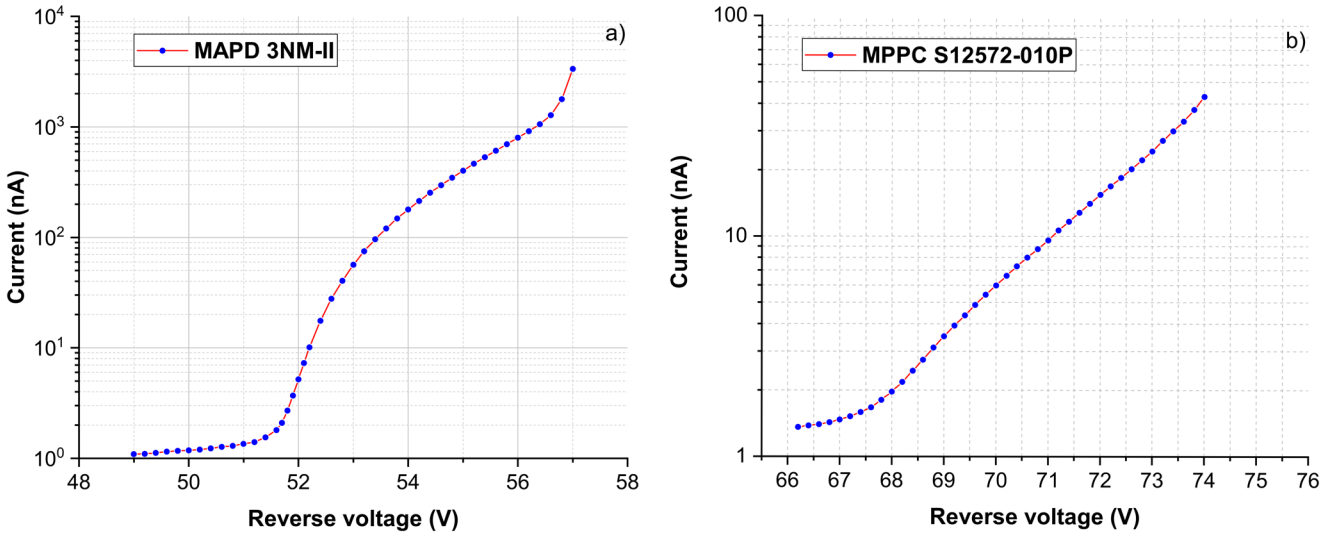


Figure 3. I-V curves for SiPMs at room temperature (T=23 °C). MAPD 3NM-II (**a**) and MPPC-S12572-010P (**b**).

3.3. Breakdown voltage determination by Miller method

Schematic diagram of the experimental setup for Miller method was shown in Figure 5. The light power was chosen in such a way that the light current was equal to 20–50% of the dark current of the photodiode at a low voltage across it (5–10 volts). In our case, the pulse with a frequency of 10 kHz and a pulse length of 30 ns was supplied from the Tektronix AFG3101 generator (Tektronix Inc., USA) to the LED, which emits photons with 450 nm wavelength. The amplitude of the supplied signal was different and depended on the type of sample being studied since each of them had a different dark current.

The reverse photocurrent I/J_{ph} dependence on the applied voltage was plotted in Figure 6 for each sample.

The approximation of the linear sections (before the inflection) was the point of intersection of the line with the abscissa axis and matches with the breakdown voltage in Figure 6. Using Miller method, breakdown voltages for MAPD-3NM-II and MPPC were determined to be 52.25±0.11 V and 68.09±0.13 V, respectively.

3.4. Breakdown voltage determination by the single photoelectron method

The experimental scheme is shown in Figure 7. Since the output amplitude of the registered photons from a photomultiplier is small, a preamplifier was used to amplify the signal. The signal from the output of the preamplifier (a preamplifier with a gain of 40) is directed to the input of an analog-to-digital

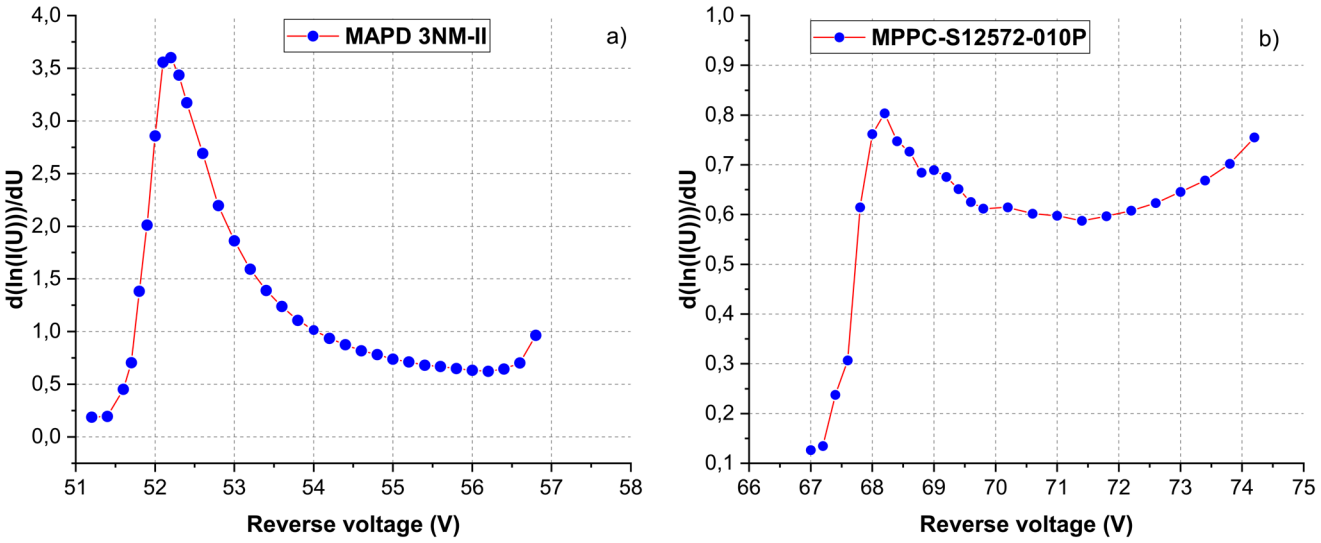


Figure 4. Determination of breakdown voltages from I–V characteristics at T=23 °C using the differentiation method.

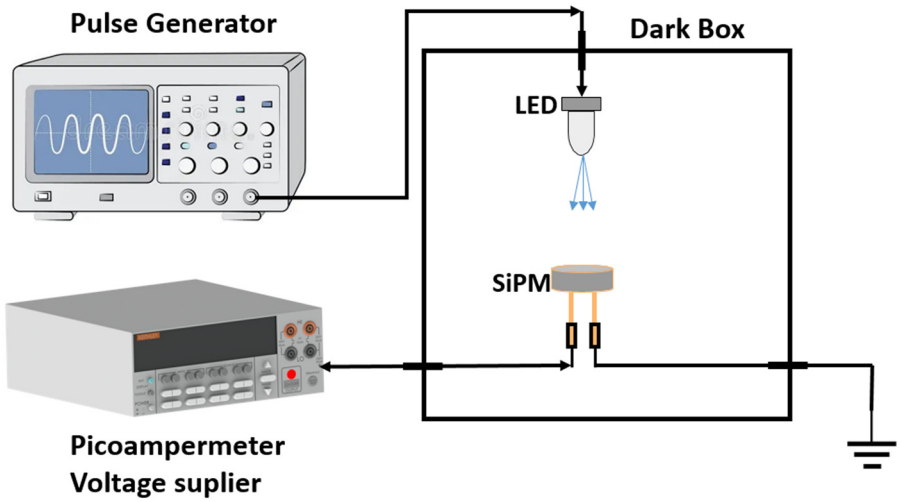


Figure 5. Schematic diagram of the experimental setups for measuring breakdown voltage using Miller method.

converter (ADC) CAEN DT5720 (12 bit 250 MS/s) (CAEN, Italy). Same pulse generator and picoammeter voltage source indicated above was used in this setup. Simultaneously, the digitizer was synchronized with the pulse generator to minimize noise.

Figure 8 provides a detailed single photoelectron spectrum for the MAPD-3NM-II. The presence of distinct peaks confirms the successful detection and amplification of single-photon events. The separation between peaks allows for precise measurement of SiPM gain and, ultimately, the determination of the breakdown voltage.

The internal gain (M) at different reverse voltage was calculated considering related parameters (K_{am}=40, q=1.602*10^{-19} C, the charge per channel of the CAEN digitizer = 40 fC) in Equation 2. For both sample, the internal gain dependence on voltage was presented in Figure 9. Notably, the internal gain exhibits a linear dependence on the operating voltage. As the voltage increases, the internal gain proportionally grows up, and the intersection of the approximation of the experimentally obtained points, where equal approximately to zero, was taken as a breakdown voltage ($U_{app.v} \approx U_{break.v}$). The values obtained using gain are very close: 52.29±0.06 V for MAPD-3NM-II and 67.98±0.09 V for MPPC S12572-010P.

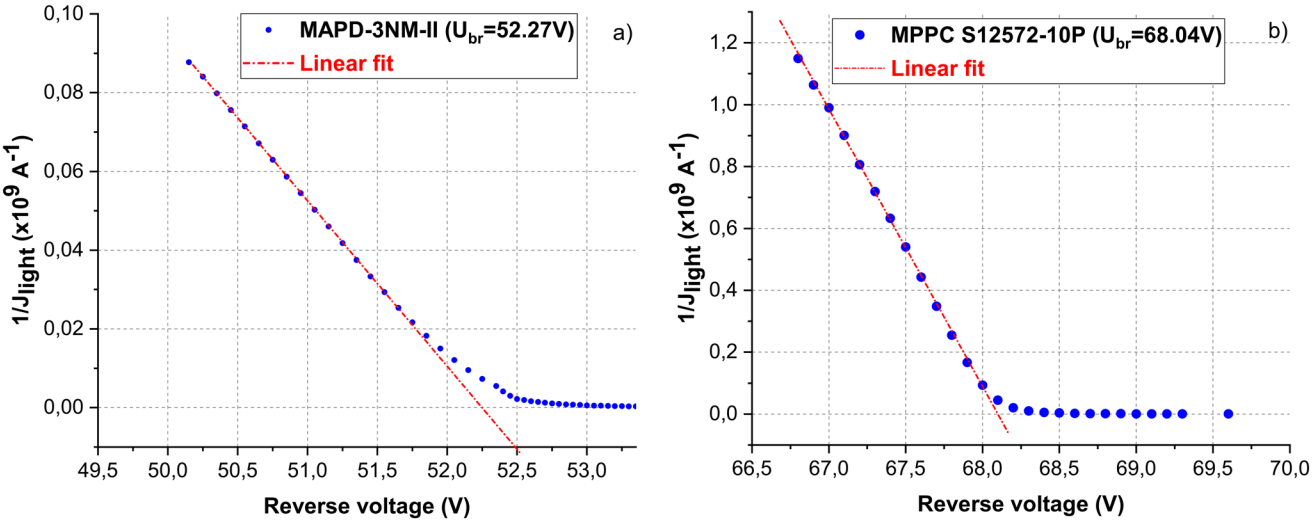


Figure 6. The dependence of the inverse value of the photocurrent on the reverse voltage for MAPD-3NM-II (left) and MPPC S12572-010P (right).

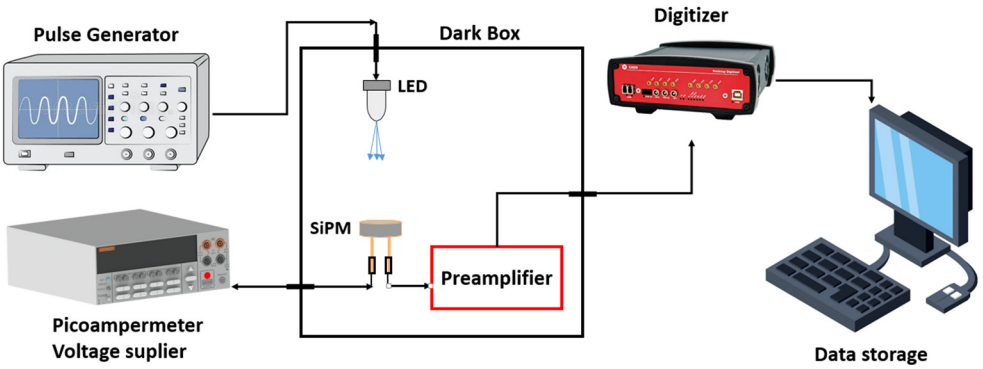


Figure 7. Schematic diagram of the experimental setup for measuring the single-photoelectron spectrum.

The IV breakdown determination gives in general slightly larger values of maximum 0.5 V higher as compared to the method determining the breakdown by extrapolating the gain to zero. The IV method is more correct, because in reality the gain at V_{bd} is not really zero since the SiPM already has a small avalanche gain before the Geiger mode starts (avalanche photodiode regime). An additional advantage of the IV method is that it can be easily obtained, and in general, measurement of the I-V characteristic is fast and applicable for device monitoring.

3.5. Dependence of breakdown voltage on temperature

To determine the temperature coefficient of the breakdown voltage and investigate its temperature dependence, I-V characteristics were measured using the experimental setup shown in Figure 2 in the a temperature range of 23°C to 43°C, with increments of 5°C. The temperature of the samples was monitored using a highly sensitive platinum temperature sensor (PT100), which provides an accuracy of ±0.1°C, ensuring precise thermal readings throughout the experiment. The results in Figure 10 (a) (MAPD-3NM-II) and Figure 11(a) (MPPC-S12572-010P) show the breakdown voltages measured at different temperatures for both devices. These data were used to plot the dependence shown in Figure 10 (b) and Figure 11 (b), which presents the determination of the temperature coefficient of the breakdown voltage.

The breakdown voltage U_{br} as a function of temperature can be approximated using a linear fit, represented by Equation (4). This approach allows for the determination of the temperature

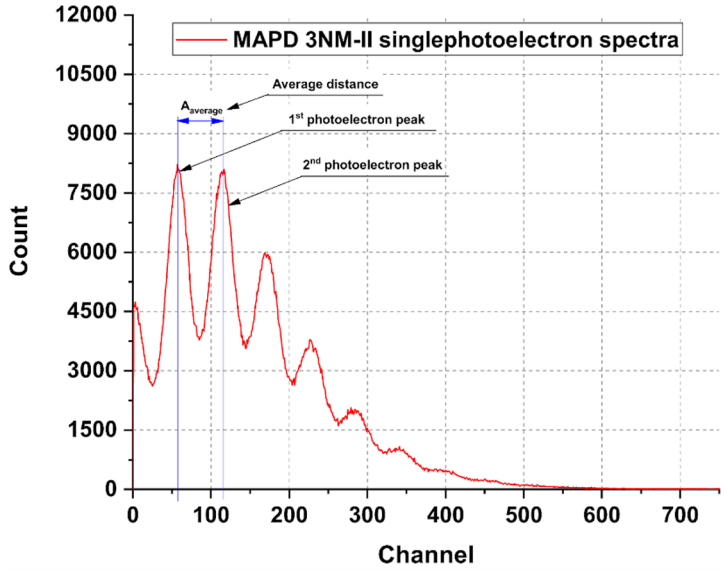


Figure 8. **Single photoelectron spectrum for MAPD-3NM-II.**

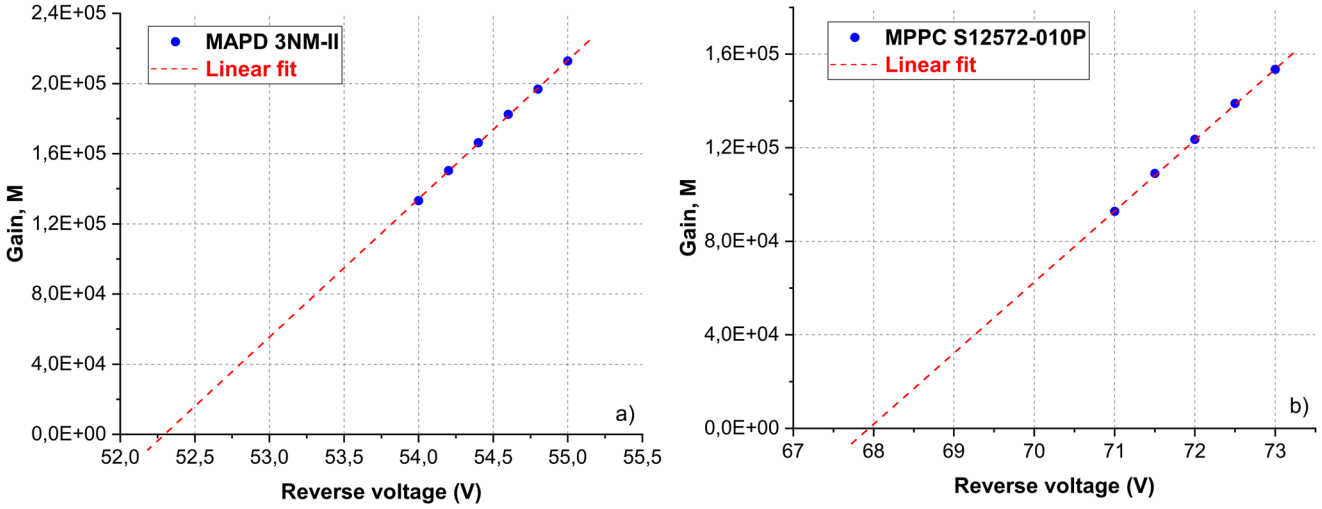


Figure 9. **The dependence of the gain on the applied voltage for MAPD 3NM-II (left) and MPPC-S12572-010P (right) at T=23 °C.**

coefficient, denoted as a, which characterizes the rate of change of the breakdown voltage with respect to temperature:

$$U_{br}(T) = a * T + U_{br} \quad (4)$$

where U_{br} is breakdown voltage at fixed temperature. The linear fit results for MAPD-3NM-II and MPPC S12572-010P are presented below:

$$U_{br}(T) = 0.0515 * T + 50.803 \quad (5)$$

$$U_{br}(T) = 0.057 * T + 66.611 \quad (6)$$

As shown in Equation (5) and Equation (6), the temperature coefficients of the breakdown voltage were determined to be 57.01±0.56 mV/°C for the MPPC S12572-010P and 51.32±0.44 mV/°C for the MAPD-3NM-II[27]. The increase in breakdown voltage with temperature can be attributed to phonon scattering. As temperature increases, lattice vibrations intensify, scattering carriers more frequently and reducing their mean free path. This makes it harder for carriers to gain enough energy for impact ionization, leading to a higher voltage requirement for breakdown. This temperature dependence can be reduced by increasing the doping concentration in the low-doped region of the photodiode. However, this approach also leads to a decrease in the breakdown voltage itself.

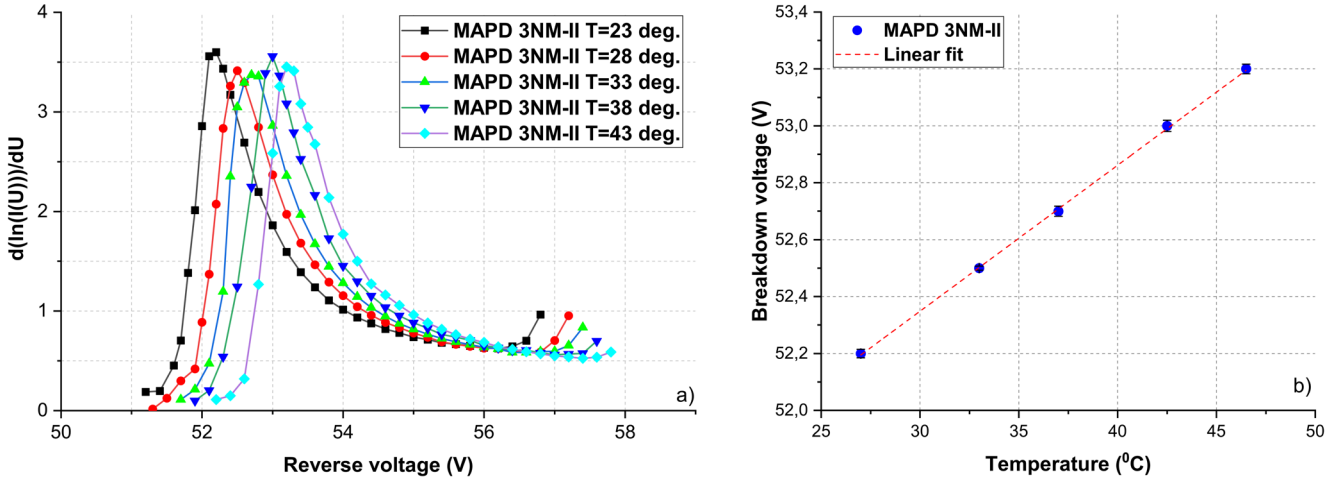


Figure 10. **Temperature dependence of the breakdown voltage for MAPD-3NM-II within the 23°C÷43°C range.**

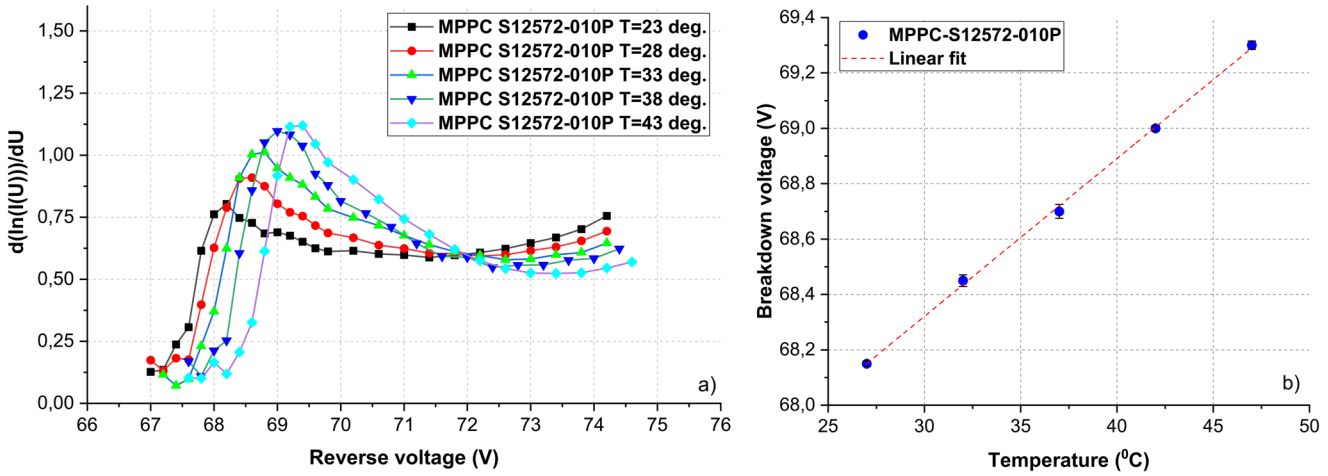


Figure 11. **Temperature dependence of the breakdown voltage for MPPC-S12572-010P within the 27°C÷47°C range.**

3.6. Capacitance determination by C-V characteristics

Figure 12 shows a setup for measuring C–V characteristics. The capacitance measurement was carried out through a comparative analysis of the output signal amplitudes derived from SiPM and the reference capacitance. In this experimental setup, the capacitor with a capacitance of 200 pF with 5% error is used as a reference. A reversed-bias voltage is applied to the common contacts (located in a dark box) from the voltage source.

At the same time, a sinusoidal input signal with an amplitude of 500 mV and a frequency of 1 MHz is supplied from the generator to the SiPM contact (either anode or cathode, depending on the source polarity). The output signal is captured using the oscilloscope. Subsequently, the capacitance values of the reference are recalculated to determine the capacitance of the SiPM. The ratio of sinusoidal signal amplitudes leads to obtaining the ratio of the capacitances of the reference and our samples. The capacitance values of the SiPMs were defined by Equation 3. C-V characteristics measured at 23°C are presented in Figure 13.

As the potential difference across the photodiode increases, the p-n junction becomes depleted and when the applied voltage equals 28 V, the active volume of SiPM is fully depleted. The subsequent increase in voltage causes only an increase in the electric field in the active volume and in this case, the capacitance of SiPM is constant[28]. The capacitance of the MAPD-3NM-II was determined to be 155±12 pF, while the MPPC S12572-010P exhibited a significantly higher capacitance of 294±26 pF - nearly twice that of the MAPD-3NM-II[18].

3. Conclusion

In this study, the performance of MAPD-3NM-II and MPPC S12572-010P silicon photomultipliers was investigated, focusing on key parameters such as breakdown voltage, capacitance,

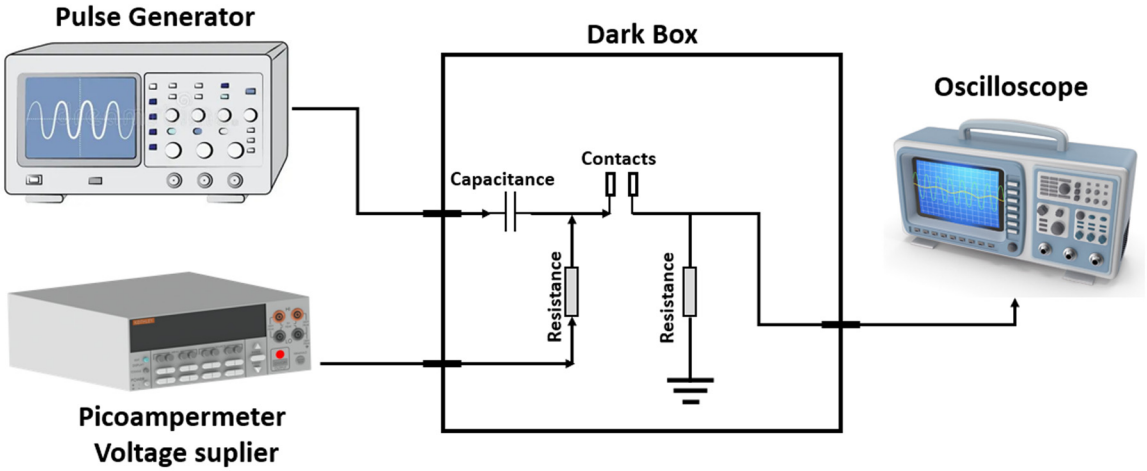


Figure 12. **Schematic diagram of the experimental setup for measuring C–V characteristics.**

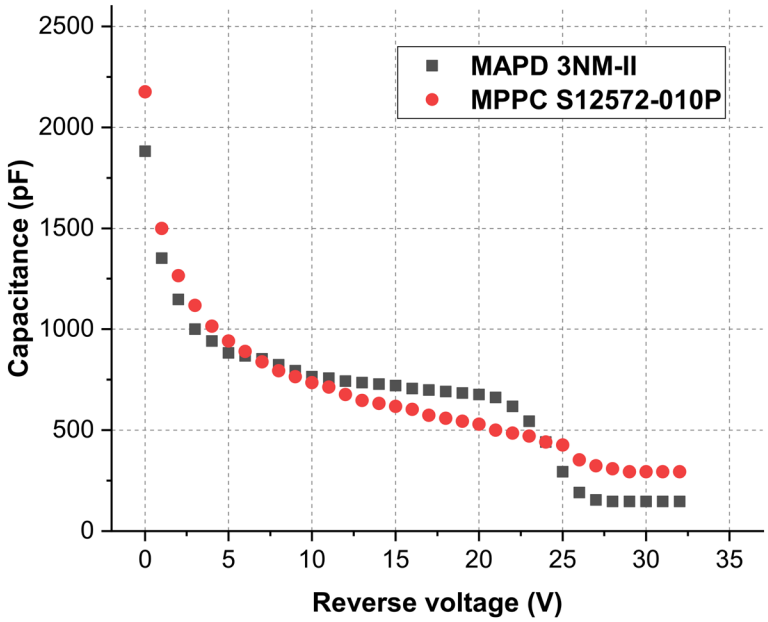


Figure 13. **C-V characteristics at T=23°C.**

internal gain, and temperature dependence. Breakdown voltage was determined using three distinct methods: the I-V characteristics method, the Miller method, and the single photoelectron method. The results from all three methods were consistent, yielding a breakdown voltage of 52.22±0.07 V for MAPD-3NM-II and 68.08±0.10 V for MPPC S12572-010P, within experimental errors. The overvoltage for the two diodes was determined to be U_{br}+4 V for MAPD-3NM-II and U_{br}+4.5 V for MPPC S12572-010P.

The temperature dependence of breakdown voltage was also investigated using I-V characteristics, providing insights into the thermal stability of both devices. The study revealed a lower temperature coefficient of breakdown voltage for the MAPD-3NM-II (51.32±0.44 mV/°C) compared to the MPPC S12572-010P (57.01±0.56 mV/°C). Capacitance measurements were performed using a sinusoidal signal with constant amplitude and frequency, with reference capacitance utilized for calibration. The MAPD-3NM-II exhibited a capacitance of 155±12 pF, significantly lower than 294±26 pF observed for MPPC S12572-010P, highlighting the advantage of the deeply buried pixel structure in reducing capacitance. The obtained results contribute to a better understanding of SiPM performance and offer insights into optimizing their design for various scientific and industrial applications, including medical imaging, particle physics, and environmental monitoring.

Data availability

Open Science Framework: **Characterization of silicon photomultipliers with different structures.**

https://doi.org/10.17605/OSF.IO/VDA5G[29]

This project contains the following data:

- **Fig 3a vs 3b.xlsx** (Current - Voltage curves for MAPD-3NM-II and MPPC-S12572.)
- **Fig 4a vs 4b.xlsx** (Determination of breakdown voltages from I–V characteristics using the differentiation method.)
- **Fig 6a.xlsx** (The dependence of the inverse value of the photocurrent on the reverse voltage for MAPD-3NM-II)
- **Fig 6bxlsx** (The dependence of the inverse value of the photocurrent on the reverse voltage for MPPC S12572-010P.)
- **Fig 8.xlsx** (Single photoelectron spectrum)
- **Fig 9a vs 9bxlsx** (The dependence of the gain on the applied voltage for MAPD 3NM-II and MPPC-S12572-010P.)
- **Fig 10a.xlsx** (Temperature dependence of the breakdown voltage for MAPD-3NM-II within the 23ºC÷43ºC range).
- **Fig 10b_vs_ Fig11b.xlsx** (determination of the temperature coefficient of the breakdown voltage)
- **Fig 11a.xlsx** (Temperature dependence of the breakdown voltage for MPPC-S12572-010P within the 23ºC÷43ºC range)
- **Fig 13.xlsx** (Capacitance-Voltage characteristics)

Data are available under the terms of the Creative Commons Zero "No rights reserved" data waiver (CC0 1.0 Public domain dedication).

Extended data

Open Science Framework: **Characterization of silicon photomultipliers with different structures.**

https://doi.org/10.17605/OSF.IO/VDA5G[29]

This project contains the following data:

- **Figure 1a.tiff** (Schematic drawings of surface pixel structure)
- **Figure 1b.tiff** (Schematic drawings of deeply buried pixel structure)
- **Figure 2** (Schematic diagram of the experimental setup for measuring I–V characteristics at different temperatures.)
- **Figure 3a.tiff** (I-V curves for MAPD 3NM-II)
- **Figure 3b.tiff** (I-V curves for MPPC-S12572-010P)
- **Figure 4a.tiff** (Determination of breakdown voltages from I–V characteristics for MAPD-3NM-II)
- **Figure 4b.tiff** (Determination of breakdown voltages from I–V characteristics for MPPC-S12572-010P)
- **Figure 5.tiff** (Schematic diagram of the experimental setups for measuring breakdown voltage using Miller method.)
- **Figure 6a.tiff** (The dependence of the inverse value of the photocurrent on the reverse voltage for MAPD-3NM-II)
- **Figure 6b.tiff** (The dependence of the inverse value of the photocurrent on the reverse voltage for MPPC S12572-010P).
- **Figure 7.tiff** (Schematic diagram of the experimental setup for measuring the single-photoelectron spectrum)
- **Figure 8.tiff** Single photoelectron spectrum
- **Figure 9a.tiff** (The dependence of the gain on the applied voltage for MAPD 3NM-II)
- **Figure 9b, Gain_M_MPPC_S12572.tiff** (The dependence of the gain on the applied voltage for MPPC-S12572-010P)
- **Figure 10a.tiff** (Temperature dependence of the breakdown voltage for MAPD-3NM-II within the 23ºC÷43ºC range)
- **Figure 10b.tiff** (Determination of the temperature coefficient of the breakdown voltage for MAPD-3NM-II)
- **Figure 11a.tiff** (Temperature dependence of the breakdown voltage for MPPC-S12572-010P within the 27ºC÷47ºC range)
- **Figure 11b.tiff** (Determination of the temperature coefficient of the breakdown voltage for MPPC-S12572-010P)
- **Figure 12.tiff** (Schematic diagram of the experimental setup for measuring C–V characteristics)
- **Figure 13.tiff** (C-V characteristics at T=23ºC)

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Acknowledgments

We would like to thank Zecotek Photonics Inc. for providing MAPD samples.

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http://www.doi.org/10.17605/OSF.IO/VDA5G

Open Peer Review

Current Peer Review Status: ? ? ?

Version 1

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?

Claudio Savarese
University of Washington, Washington, USA

Summary

This paper describes the characterization of two Silicon Photomultipliers (SiPMs) with distinct architectures. The first sample is a MAPD-3NM-II by Zecotek Photonics with a deeply buried pixel structure, and the second is an MPPC S12572-010P by Hamamatsu Photonics with a surface pixel construction. The authors determine the breakdown voltage of these two SiPMs as a function of temperature with three different techniques and measure the capacitance of the devices.

Detailed Report:

- *Is the work clearly and accurately presented, and does it cite the current literature?* Partly - The work is presented with some degree of accuracy, even though some useful details are omitted (more on this in the next answers). The papers cited are relevant to the content of this work. I have to add that, in some cases, the authors do not seem to be aware of new developments in the field, such as the production of large area (~100 mm^2) SiPMs, but generally the citations point to interesting papers.
- *Is the study design appropriate, and does the work have academic merit?* Partly - The measurement of the SiPMs' breakdown voltages and capacitances uses techniques widely accepted by the community. On the other hand, this work is lacking the characterization of other quantities of great relevance when comparing different SiPM technologies. For example, dark count rate, cross-talk probabilities, and after-pulsing probabilities are intrinsic noises that play an important role in selecting a SiPM for a given application. The same can be said of photon-detection efficiency and/or imperviousness to radiation damage (if relevant). In essence, the narrow choice of measured parameters might render the authors' conclusions less than robust. Finally, I would feel more confident in the presented results if the authors tested more than one (ideally ~10) SiPM per architecture.
- *Are sufficient details of methods and analysis provided to allow replication by others?* Partly - In my opinion, sections 3.2 and 3.4 are missing some details that would allow the replication of these results by others.
  Section 3.2: The text does not describe how the differentiation was done - if this was done

numerically, I'd expect the breakdown voltage to correspond to one of the samples. Since this is not the case, I think that more information should be added. For example, these are my questions: is the red curve in Fig.3 an interpolation of the I-V? How is this obtained? Is this curve then differentiated to get the breakdown voltage? Finally: how are the uncertainties calculated with this method?
Section 3.4: I would suggest adding more details on the experimental procedure. What was the time window used to perform the charge integration? How is the gain extrapolated from the photoelectron spectrum (i.e., the distance between the 1pe and 2pe peaks)? These things might be inferred by experts, but not by a reader with no deep knowledge of the involved experimental protocols.

- *If applicable, is the statistical analysis and its interpretation appropriate?* Partly - In general, the analysis seems appropriate, but in the text, there is no mention of the estimation of uncertainties.
- *Are all the source data underlying the results available to ensure full reproducibility?* Yes - all data is available for download and independent vetting.
- *Are the conclusions drawn adequately supported by the results?* Partly - The conclusions of this work would benefit from the characterization of a wider range of SiPM parameters (DCR, CT, AP, PDE). Nonetheless, both the determination of the capacitance and the temperature dependence of the breakdown voltage in these SiPMs are interesting. I would suggest normalizing the obtained capacitance per unit of surface, so that the reader might more easily compare the two results.
A final remark: both in section 3.2 and in the conclusions, there is mention of an optimal operating voltage. What considerations enter into the determination of the "optimal operating voltage"? What procedure? Is this concerning the amount of DCR and CT as a function of overvoltage? This point should be explicitly addressed in the text.
- *Additional suggestions for improving the work* - I list here the notes I took while reading that did not make it into the main body of the report.

1. Introduction: "limited up to 36 mm^2" —> please note that there are SiPMs with areas close to 100 mm^2. For example, please check this publication: 10.1088/1748-0221/17/05/P05038. Disclaimer: I am a co-author on this paper, but I want to let the authors know that there are now significantly larger SiPMs than the 36 mm^2 specified in the manuscript. I suggest rectifying the statement.
2. Samples: It would be informative to add here the microcells' fill factor for the two models tested.
3. Introduction: "Since their inception in the 1990s, SiPMs give the possibility as a photon detector, displacing PMTs in many experiments due to their photon detection capabilities." —> The meaning of "give the possibility" is unclear, please rephrase
4. Equation 2: the units of the terms in the right-hand side of the equation should be specified.
5. Figure 2: this figure shows that a thermocouple was used to monitor the SiPM temperature, but the text describing the setup talks about an RTD (PT100). Please correct either to have a coherent description.
6. Section 3.2: Please report the sampling used for both I-V (200mV/sample?).
7. Section 3.3: Could you please elaborate on the choice of light flux? Why is the photocurrent set to be ~20-50% of the dark current? More details on this choice would help the reader.
8. Figure 8: Considering the units on the x-axis, the single photoelectron spectrum in this figure shows (I believe) the maximum amplitude of each pulse, while the gain

determination was probably done by calculating the integral of each pulse. It would be good to substitute the amplitude spectrum with a charge spectrum. I would also suggest showing a sample of the SiPM's average waveforms and indicating the integration window. Also, is the single photoelectron resolution limited by electronic noise?

9. Methods: “techniques-current-voltage” —> I believe this should be “techniques - current-voltage”
10. Equation 2: U_oper.v is later referred to as U_app.v in the text —> Please make the equation and text coherent. I also suggest using subscripts (in the text) where necessary, which seems to be intentionally avoided.
11. Samples: “Figure 1 presents schematic drawings of both structure.” —> “... structures.”
12. Samples: 3x3 mm2 —> Use superscript for the 2 in the mm^2 unit
13. Section 3.4 (page 7): "For both sample” —> “For both samples"

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Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: I specialize in experimental techniques for the search of rare events, such as dark matter-nucleon scattering and neutrinoless double beta decay. Many of these techniques rely on the unambiguous detection of low-intensity light pulses from scintillation with single-photon detectors such as SiPMs.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 13 May 2025

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?

Fabrice Retiere
TRIUMF, Vancouver, Canada

This article describe a characterization of two key parameters of SiPMs the breakdown voltage and capacitance. The results are consistent with other measurement for the conventional Hamamatsu MPPC. The Zecotek SiPMs appear to perform in a similar fashion despite its completely different structure. The data quality appears ok though the different methods are not so well explained and related to one another. The main negative comment is that these two parameters are rather basic and do not define how the device may perform, i.e. the next step must be reporting on efficiency, dark noise and correlated avalanche, which are parameters that are critical to understand the device performances. Detail comments:

- UBr extraction consistency. The maximum derivative technique is commonly used yet it is not physically justified. Above breakdown the current can be written I = [R_DN(DV) + R_Phot * PDE(DV)] * C * DV with DV = U-Ubr, R_DN the dark noise rate, R_Phot the light flux, PDE the photon detection efficiency, C the single SPAD capacitance and ignoring the correlated avalanches, i.e. this works only at low DV. This has been shown to reproduce the data but it does not give Ubr at the maximum derivative. The Single Photo-electron method does if Gain = C DV. In general, Ubr from the derivative method tend to be higher than from the single photon electron method that should yield the right value if C does not depend on DV. This is the case for Hamamatsu as it is about 20mV higher but not for the MAPD.
- I am not familiar with the Miller method. Could the authors justify it? Or add a reference.
- Also, I am not sure what is “m” in section 2.3. And, I don’t know where the 40fF comes from. Using the numbers measured later and dividing by the number of pixels yields a much smaller number. Please clarify.
- Equation 4. Specify that it is in Celcius and specify that the last term is Ubr at T=0C
- Equation 5 and 6. Include Units
- Figure 13. Please describe the shape for the MAPD curve. I was under the impression that the depletion would take place in 2 steps. Does it happen?

Is the work clearly and accurately presented and does it cite the current literature?
Partly

Is the study design appropriate and does the work have academic merit?
Yes

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Yes

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Single photon detectors, SiPMs, dark matter and neutrino detectors

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Reviewer Report 10 April 2025

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Lucas Finazzi
Universidad de San Martín-CONICET, Yapeyú, Argentina

This article compares operating parameters of deeply burned and surface pixel SiPMs. Breakdown voltages, with their corresponding temperature dependencies, and their capacitance are measured and compared between the two technologies.

Is the work clearly and accurately presented and does it cite the current literature? Yes, the references cited are relevant,

Is the study design appropriate and does the work have academic merit? The work uses known methodologies for measuring SiPM parameters like breakdown voltage and capacitance and has merit in providing insight into comparisons for different SiPM technologies. However, IV method is said to be "more correct" in the text than the single photoelectron method when the result is not as expected/desired, so I'm wondering why you included it at all if this is the case.

In addition, the work might benefit from the characterization of other important operating SiPM parameters like Dark Count Rate or Crosstalk probability, for example. Without these inclusions, the work might feel incomplete, as these other parameters are of extreme importance in any experiment that utilizes SiPMs.

In addition, looking at Figure 13, I am unsure if the capacitance value was measured for SiPM operating conditions (above breakdown). Capacitance was measured up to 32.5 V, but the breakdown is around 52 V. Why is this?

Are sufficient details of methods and analysis provided to allow replication by others? The work provides all methods and analysis strategies for replication. However, to allow full reproducibility, the preamplifier model used in the single photoelectron method might be mentioned. Or if it is something you developed in-house, mention that instead.

In addition, it is unclear on how the "optimal" operating voltage was determined when calculating the breakdown voltage in different methods. The text will benefit from that explanation.

If applicable, is the statistical analysis and its interpretation appropriate? Many of the analyses look sound. However, there are some suggestions to incorporate to the manuscript to make it more statistically robust:

Add error bars to all plots which don't contain them. This is specially relevant in all figures that show the determination of the breakdown voltage with the three different methods.

In Figure 4, the error bars will be larger near the breakdown region and could influence the determination and uncertainty of the breakdown voltage. It is unclear how the correct uncertainty of the obtained breakdown voltage was obtained using this method.

In Figure 6 and 9, the error bars are very relevant as well, as a fit is performed and the breakdown is obtained by interpolation to a region where no data points were measured. Without error bars, fit parameter Variance and Covariance obtained will not be accurate. These values are needed for an error propagation to obtain the uncertainty of the breakdown voltage.

Are all the source data underlying the results available to ensure full reproducibility? Yes, all the data is available online. However, versions of the data which have measurement uncertainties should be included as supplemental material.

Are the conclusions drawn adequately supported by the results? The conclusions in the main text are supported by the work performed. However, conclusions might slightly change when suggestions about statistical handling of the data are incorporated to the work.

Also, the web version of the conclusions mention that "the results show that MAPD type photodiodes can be used in radiation detectors...", which was not studied in this work.

Additional suggestions for improving the work

1. Avoid using * symbol for multiplication in equations.
2. Use Latex for Figure axis labels that contain equations. For example, Figure 10 and Figure 11. This will improve Figure clarity.
3. Usually, units in plots go between [], not ().
4. Units are usually expressed as **(measurement ± uncertainty) unit**, rather than measurement ± uncertainty unit.
5. Experimental setup figures which are abstract might be better than figures which have

actual pictures of the instruments used.

Is the work clearly and accurately presented and does it cite the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Partly

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: My area of expertise is on Silicon Photomultipliers and their use for diverse applications. These applications include: Space operation and their instrumentation for Visual Light Communications and Quantum Optics experiments.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.