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Neutron Detection Using Silicon Photomultipliers: Performance and Applications

G.S.M. Ahmed[1]*, P. Bühler[3], J. Marton[3] and M.N.H. Comsan[2]

[1]*Physics Dept., Faculty of Science, Al-Azhar University, Cairo, Egypt*
[2]*Experimental Nuclear Physics Dept., Nuclear Research Centre, Atomic Energy Authority, Egypt*
[3]*Stefan Meyer Institut für subatomare Physik, Austrian Academy of Sciences, A-1090 Vienna, Austria*

*gsmoawad@azhar.edu.eg

Traditional neutron detection methods have limitations in terms of sensitivity, compactness, and response time. Instead of traditional PMTs, SiPMs offer high sensitivity, compact size, and fast response time. In the current study SiPM principles of operation as well as its most important characteristics have been investigated and discussed. Furthermore, we are proposing a technique for neutron detection based on a converter material placed on/in a scintillating medium where the induced light read out with SiPMs. Such a technology enables the development of low-price compact detectors developments. The detector we are going to illustrate makes use of four SiPMs devices, which were attached directly to the ends of a well-polished Organic scintillator. It allows choosing events that are strictly coincident between the two sides of the scintillator, reducing erroneous counts. Current study revealed that in order to optimize SiPM timing performance and to achieve low dark count rates, control of the temperature and or operating voltage is essentially important. The study addresses the design considerations, components, assembly method, and preliminary characterization. In this work, detector prototype was tested in lap using ^{90}Sr radioactive source where the results revealed good detection efficiency for monitoring beta radiation.

Keywords: Neutron detection, hand-held detector, silicon photomultiplier, scintillation detector, nuclear physics, homeland security.

1. Introduction

Neutron detection is crucial for various applications, including medical physics, security, and fundamental research [1, 2]. ^{3}He-based neutron detectors are the most commonly used systems. In spite of their optimal properties, these systems have limitations in terms of sensitivity, compactness, response time and most importance the severe lack and increasing cost of ^{3}He [3]. The limitation stimulated a vast program aiming at the development of new technologies for ^{3}He-neutron detectors replacement [4, 5]. At present, the most used materials for the production of radiation detectors are plastic scintillators, since they can cover large areas preserving good efficiency and reasonable cost. Organic scintillators are sensitive to gamma (γ)-rays, charged particles and respond with light emission as a result of induced excitation [6]. Since neutrons do not produce ionization in matter, their neutral nature necessitates indirect detection methods. Fast neutrons interact through elastic scattering on light atoms, mainly hydrogen, with the subsequent ionization of surrounding matter, whereas slow neutrons are absorbed by nuclei such as Boron (^{10}B) and Lithium (^{6}Li) releasing ionizing particles or a flash of γ-rays. Scintillation detectors, which convert neutron interactions into detectable light signals, play a vital role in this endeavor [7, 8]. For long time, the bulky and expensive Photomultiplier tubes (PMTs) have been the primary choice for light detection in such scenarios [9]. However, PMTs come with limitations, the large size and weight, makes them impractical for field use and rapid deployment. The high operating voltage, requirements increases complexity and limits portability, while its sensitivity to the magnetic field can hinder operation in certain environments. On the recent years, Silicon Photomultipliers (SiPMs) has established itself as a viable alternative to the traditional vacuum PMTs in many applications [10, 12]. SiPMs are a solid-state photodetectors composed of many array of micro-cells operating in Geiger-mode avalanche breakdown. The compact size and lightweight, enabling the development of portable and hand-held detector design. The low operating voltage simplifies power supply and reduces detector complexity. The insensitivity to the magnetic field allows an operation in environments with varying magnetic field conditions. In addition, the fast response time, enabling efficient discrimination between neutrons and other particles based on their interaction times with the detector material [13, 14]. Currently, SiPMs are an already established photodetectors having entered many fields from basic scientific research to social and medical applications [15, 16]. However, SiPM still a device with plenty of room for further developments. In order to get a deep understanding of its working principles, we are presenting a comprehensive study of its most important characterization like, dark current, operating voltage, and time resolution at different operating conditions. For the possible application in neutron detection the use of the suitable neutron-converting materials are explored. Finally, neutron based SiPM-detector design considerations, including components, assembly process and the preliminary performance results were presented.

2. SiPMs Characterization

SiPMs are a two-dimensional array of microscopic cells of avalanche photodiodes (APDs). These cells are connected via small polysilicon resistors to the common aluminum grid, serves as readout for all fired APDs [13]. The basic principle of operation relies on the Geiger-mode avalanche process within each APD. When a photon is absorbed in the depletion region, it generates electron-hole pairs. The electric field within the device causes these charge carriers to accelerate, leading to further ionization through collisions. This process creates an avalanche of charge carriers, which is amplified and collected by the detector's electrodes where the resulting charge is collected and converted into a measurable electrical signal [14, 18]. The growing variety of the available SiPM devices requires the possibility to test and to characterize them in order to support the selection procedure and finding the optimum operating conditions for given applications. Different SiPMs that were used in this work were produced by Hamamatsu-Japan. They are sold under the name Multi Pixel Photon Counter (MPPC) [19]. There were also the Multipixel Avalanche PhotoDiode (MAPD) samples available made by Zecotek Photonics Singapore, [20, 21]. Table 1 provides more information about their technical parameters. The pixel size of each different types differ which leads to differences in their characteristics e.g. operating voltage, gain, dark count rate, and time resolution. In Labe, a complicated setup was used to characterize those differences, where a blue laser has been used as the light source. The level of the laser light could be attenuated with light attenuation filters. Where SiPM was placed inside of a light and vacuum tight aluminum box, and is thermally coupled to water-cooled Peltier element, which allows cooling and stabilizing the photo sensor operating temperature during the measurements. SiPMs output signal were attached directly to preamplifiers from Photonique SA (AMP 0611) and the amplified signal was connected either to an oscilloscope or to a data acquisition-system (DAQ) depending on the requirements of the experiment.

Table 1: Tested SiPMs technical parameter information's [19− 21].

Name Part Number Producers	MPPC (S10362-11-50U) Hamamatsu	MAPD (MAPD-1) Zecotek	MPPC (S10362-11-100U) Hamamatsu	MPPC (S10362-33-100C) Hamamatsu	MPPC (S10931-100P) Hamamatsu
Active Area	1×1 mm^2	1×1 mm^2	1×1 mm^2	3×3 mm^2	3×3 mm^2
Pixels number	400	576	100	900	900
Pixel size	50×50 μm^2	42×42 μm^2	100×100 μm^2	100×100 um^2	100×100 um^2
Fill factor	78.5 %	70 %	78.5 %	78.5 %	78.5 %
PDE (%)	65@440 nm	30@480 nm	65@440 nm	55@440 nm	50@440 nm
Bias range	70 ± 2	32 ± 1	70 ± 3 V	70 ± 3 V	70 ± 3 V

2.1. Dark Current (DC)

The aim of these measurements was to get information about the general behavior of the devices and to obtain information about the breakdown voltage, by studying current-voltage (I-V) characteristic curves. Figure 1 shows the dark current characteristic curves for two different devices, both has 1 mm^2 active area: the MPPC (S10362-11-50C) and the MAPD-1. The results show the expected characteristics curves' shapes where dark current increase with increasing the bias voltage. MPPC shows smoother I-V curves and an abrupt change can be seen at the device breakdown voltage. MAPD-1 show different behavior might indicate that some microcells are not properly working affecting the output current of the device and making it difficult to determine a well-defined breakdown points.

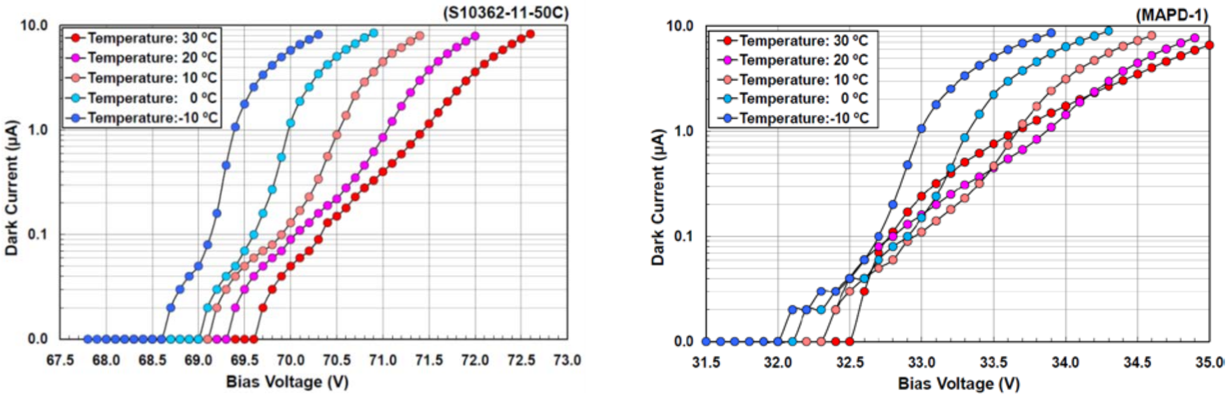

Figure 1. The dark current-voltage characteristic curves of two different types of SiPMs photo sensors. The abrupt changes refer to the breakdown voltage for each device.

2.2. Time resolution

In view of possible usage of SiPMs in timing applications such as (TOF) measurements, we started a systematic study for a set of SiPMs devices to find how the operating conditions would affect the device timing performance. The intensity of the delivered light to the SiPM, should be tuned to the intended level before the start of each measurements. With the trigger-signal a time window was selected (~ 120 ns) and the time at which the signal crossed the threshold for the first time was taken as the arrival time or the stop signal (figure 2, from the left). For each event, the timing is measured as the difference between the trigger time and the stop signal [22]. Figure 2 (from the right) shows that at fixed operating condition MPPC time resolution improves with increasing the number of fired pixels (light intensity).

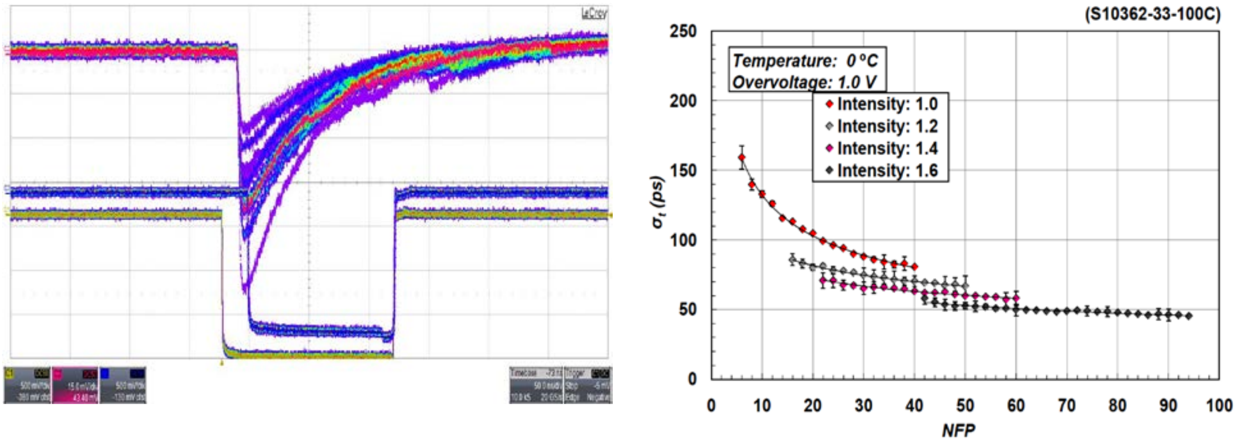

Figure 2. An oscilloscope screen shot, showing the SiPM output signal (from the left). MPPC (S10362-33-100C) time resolution as a function of the NFP at different light intensities (from the right).

3. SiPM neutron detector prototype

The assembly process of the neutron detector using a SiPM involves several crucial steps: The selected scintillator was carefully polished to ensure efficient light collection. A reflective coating, such as thin layer of aluminum or teflon was applied to the polished surfaces of the scintillator. This coating reflects internally generated light towards the SiPM effective area, maximizing light collection efficiency (figure 3, from the left). SiPM converts the incoming light into an electrical signal. The weak signal then amplified and processed by a suitable electronic, and is converted into digital format for analysis by a computer. The complete detector assembly (figure 3, from the right) undergoes a series of rigorous laboratory tests to ensure proper functionality and performance. These tests may include:

Dark count rate measurement, assesses the detector response in the absence of any external radiation source. **Energy calibration**, a calibrated radioactive source emitting well-defined energy particles like ^{90}Sr was used to calibrate the detector response and map the measured signal to the actual particle energy.

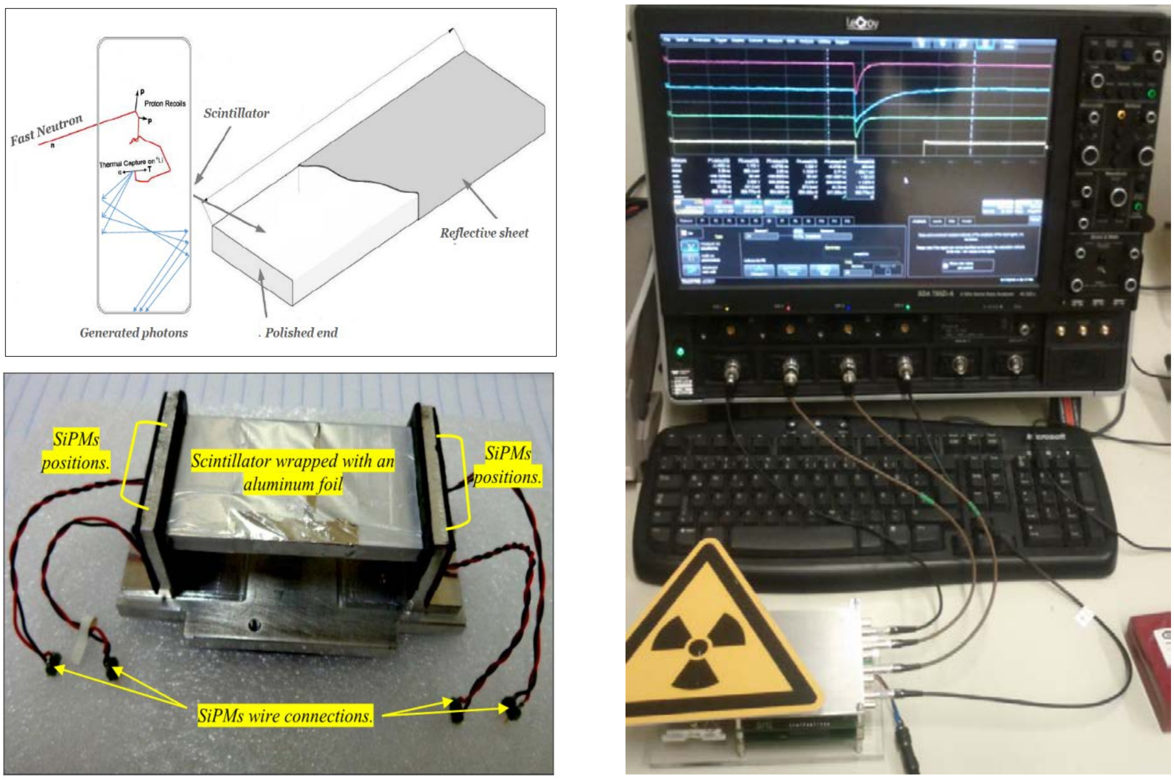

Figure 3. Schematic representation as well as picture of the detector prototype where a piece of plastic scintillator attached to set of MPPC photo sensors (from the left); laboratory test, where each MPPC signal output had been monitored using a fast oscilloscope from LeCroy (form the right).

4. Conclusion and future perspectives

SiPMs are solid-state detectors that provide high sensitivity, compact size, and fast response, making them ideal for neutron detection. To obtain best performance a careful optimization of the operation conditions is obviously required. Time resolution is best at low temperature and high overvoltage. Neutron detection using SiPMs involves the use of a scintillator to convert the charged particles produced by the nuclear reaction into light, which is then detected by the SiPM. The development and prototype of a compact radiation detection system has been successfully realized and tested in lab using β^--particles from ^{90}Sr radioactive isotope. The outcome results revealed that our detection system prototype has succeeded to monitor β^- radiation with good efficiency. The next step is the performing of neutron exposure test using the ^{241}Am/Be neutron source. This research aims to contribute to the advancement of portable neutron detection solutions for various applications. We think there is a room for further improving our detector system module especially in the electronic side part. In applications where fast neutron detection is required, such as in nuclear reactors, accelerators, or radiography systems, SiPM-based neutron detectors can offer high detection efficiency and fast response times. This combination enables the accurate and real-time monitoring of fast neutron fluxes, which is important for ensuring safety and optimizing performance in various industries.

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