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Hand-held Gamma-rays detector based on the use of silicon photomultipliers.

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ABSTRACT

A simple yet compact Gamma-rays detector prototype based on the use of Silicon PhotoMultipliers (SiPMs) as photons read-out photosensors, are presented. The proposed detector has the advantage of being used as a low cost Hand-held detector for Gamma-rays detection in several fields, especially application in Healthcare, Homeland Security & Defense. The main goal was to build a simple and cheap Gamma-rays detector prototype which should be robust, light weight with very low power consumptions used as survey meters to replace the current Gas-Filled Detectors. The detector prototype consists of a combinations of SiPMs and LYSO (Cerium-doped Lutetium Yttrium Orthosilicate) Scintillator. A Crystal of 0.4 cm thickness and 2.2 cm length was optically coupled on both sides to 3×3 mm^2 MPPCs (S10931-100P) from Hamamatsu Photonics. For testing our prototype, the device was exposed to gamma radiation using different radioactive sources (Ba-133, Co-60, and Cs-137). In response to the penetrating radiation, SiPMs pulses were digitized and processed for pulse counting using a digital technique performing numerical weighted integrations on each pulse. Basic principles of operation as well as the status and prospects of the detector are briefly reviewed.

INTRODUCTION

Many different types of radiation detectors have been developed to fit special needs of a certain application. Most of the detection systems are based on the use of photomultiplier tubes (PMTs). Only recently new types of detector based on silicon diodes working in the avalanche regime, have been developed and proved to be extremely interesting candidates to replace the existing vacuum-based systems. These are the Silicon PhotoMultipliers (SiPMs) (Claudio Piemonte, 2006). SiPMs are extremely versatile photo sensors consisting of Multi-pixel APDs working in Geiger-mode. Because of their excellent performance together with ease of operation they can be used in many fields ranging from astrophysics, particle and nuclear physics to medical imaging. Like PMTs, SiPMs are capable of measuring extremely low light levels to the point of being able to detect single photons. However, compared to PMTs, SiPMs offer the 'solid-state' advantages of ruggedness, lighter weight and lower operating voltages. SiPMs also have two key advantages over the PMT; these are insensitivity to magnetic fields (<15T) and are not damaged by exposure to high photon flux. These advantages make them excellent candidates for different applications (Gamal Ahmed *et al.*, 2012; M. Danilov, 2007; G.S.M. Ahmed *et al.*, 2011), and made SiPMs the preferred choice to fit the requirements for our gamma-rays detector prototype.

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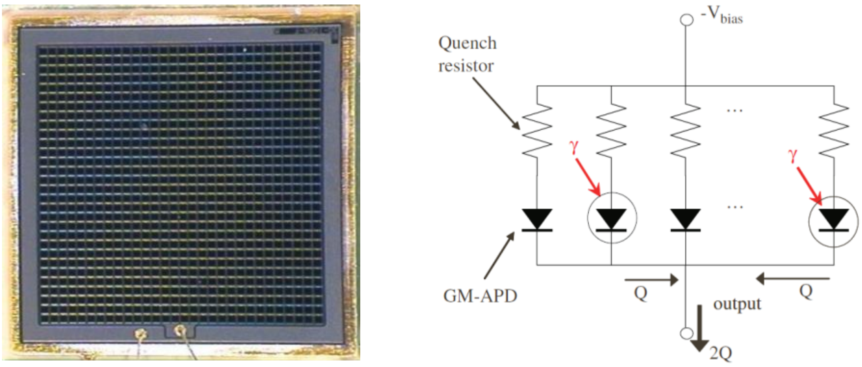
SiPM principle of operation:

The relatively inexpensive device consists of many array of small (20 – 100 µm) independent pixels arranged on a common substrate to form a macroscopic unit with 100 - 4000 pixels/mm^2 (Figure.1 a.). Each pixel is operated with a bias voltage, a few volts above breakdown voltage. In this mode a photoelectron is created in the silicon and reaching the high field region by diffusion or drift initiates a Geiger discharge confined to that pixel. The discharge is quenched by limiting the current to about 10 µA with a small polysilicon resistor in each pixel.

The independently operating pixels are connected to the same readout line; therefore the combined output signal corresponds to the sum of all fired pixels, which is a measure of the photon flux (Figure.1. b.) (Junji Haba, 2008).



(a) (b)

Fig. 1a: A captured picture of one SiPM with 3x3 mm^2 active area form a macroscopic unit with 900 pixels.
b: A Schematic illustration of SiPMs construction, each APD is connected to a quenching resistant and the output signals is the summation of all fired APDs.

Bias voltage and power consumption:

Breakdown electric field in Si is about 2.5×10^5 V/cm. Since SiPM depletion zone is typically 1 - 3 µm thin, working bias voltage is rather low (25 - 100 V). This is comfortable for the design of systems with a large number of SiPMs. For instance, a single coaxial cable is needed to supply bias voltage and provide the signal line to one SiPM. SiPM typical dark current for a 1 mm^2 is about 1 µA. Therefore, the corresponding power consumption is also very small (~ 50 µW) (P. Buzhan, *et al*., 2001; B. Dolgoshein, *et al*., 2006).

Long term stability and ageing:

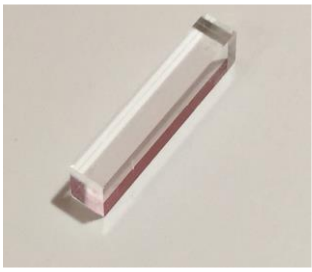
Several dedicated tests have been performed in order to study the SiPM long-term stability and ageing under different operating conditions (Bias voltage, temperature). SiPM parameters such as gain, PDE, dark noise rate and dark current were measured before the test and after 500 and 1500 h of operation. SiPM parameters did not show noticeable variation during these stability tests (B. Dolgoshein, *et al*., 2006).

LYSO Scintillator:

LYSO is a premium scintillator material, has the advantages of high light output and high density, fast response and low cost. With a specific density of 7.4 g/cm^3 that provides excellent stopping power for high energy photons. Much greater density than that of NaI(Tl) and is non-hygroscopic and safe to handle. LYSO scintillator is very durable and does not break easily, these properties make it an ideal candidate for a range of gamma-rays detection applications in nuclear physics and nuclear medicine (for more details see table 1.)

Table 1: Physical Properties of LYSO;

Density (g/cm3)	7.4
Effective Atomic Number	66
Radiation Length (cm)	1.10
Decay Constant (ns)	40-44
Peak Emission (nm)	428
Light Yield (Relative BGO=100%)	190
Index of Refraction	1.82
Peak excitation (nm)	375
Radiation Hardness (rad)	$>10^6$
Melting Point (°C)	2050



Detector Prototype:

Prototype Gamma-rays detector is displayed in figure. 2. It consists of LYSO scintillator, a slab-like radiator of 4 mm thickness and 22 mm length. Each end of the radiator has a quadratic surface of 4x4 mm^2. LYSO scintillator produces a brief flash of light when excited by Gamma radiations. The produced light is supposed to be totally reflected on the internal surfaces of the radiator and to be guided to its ends. In order to reduce the losses due to imperfect reflection the radiator was wrapped with a Teflon, and then covered with light-tight black tape. Both ends of the radiator are optically coupled to one SiPM, which are used to detect the arriving photons. For the presented prototype detector we used MPPCs from Hamamatsu Japan, series (S10931-100P). This specific SiPM photosensor consists of 900 APDs each of 100x100 µm^2, with a fill factor of 78.5%. Its nominal gain is 2.4x10^6 and it has a terminal capacitance of 320 pF. The maximum photo-detection efficiency is 65% at 440 nm. Measurements of dark current, dark count rate and timing performance of this device have been presented in elsewhere (G.S.M. Ahmed et al., 2009; Ahmed Gamal *et al*., 2011a, b).

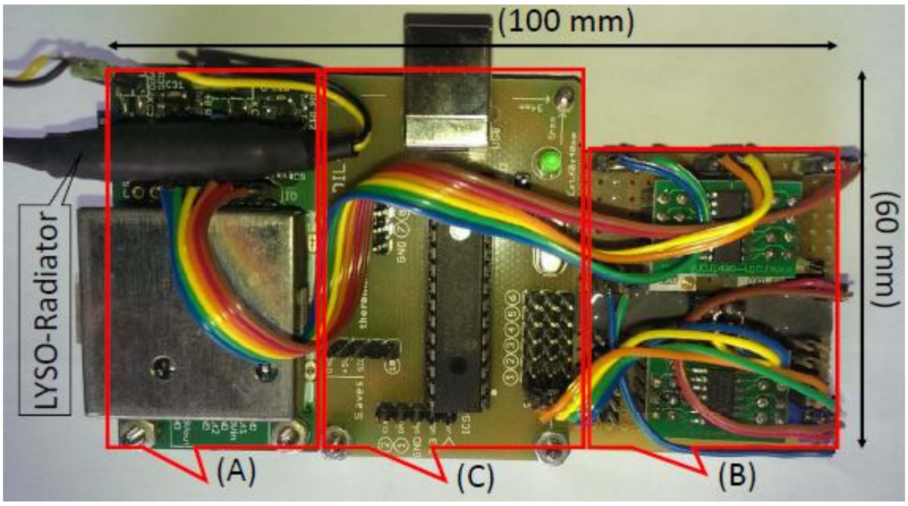


Fig. 2: A picture of the prototype Gamma-rays detector. SIPMs have been attached to LYSO scintillator ends and wrapped with a Teflon and then a black tape. (**A**); SiPMs have been attached to the preamplifier board. (**B**); Electronic CMOS inverter and coincidence board. (**C**); Theremino Master Module (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).

Laboratory tests and results:

For signal read out, SiPMs have been attached to custom electronic PCB-board (Figure.2. A.). In order to minimize the electronic connections the new PCB-board had been designed to include step-up bias voltage necessary for the SiPMs bias supply and two preamplifiers. The PCB-board has been designed and fabricated at the Stefan Meyer Institute (SMI), Vienna/Austria (Figure.3).

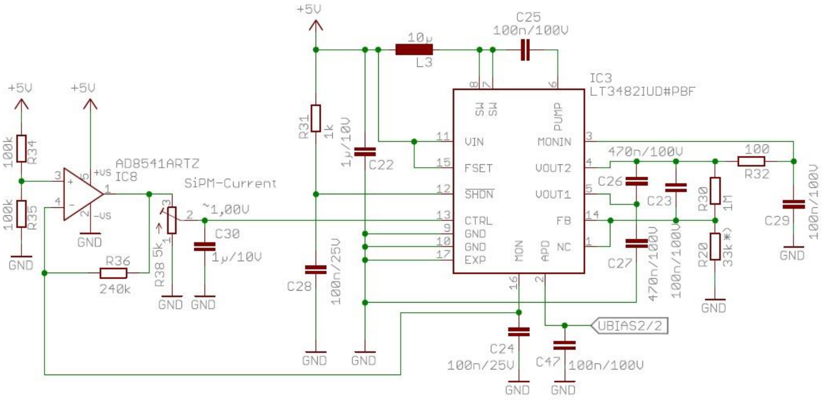


Fig. 3: Schematic diagram showing the design of SiPMs read out electronic PCB-board. PCB-board had been designed and fabricated at SMI.

Figure. 4. Shows, prototype Gamma-rays detector signals output using fast Oscilloscope from LeCroy (WavePro 735Zi 40 Gs/s). The signals output are squared by CMOS inverter. A positive CMOS signal of 3,3V with a duration of about 200 ns is obtained. The CMOS inverters have been chosen because of their high speed and because they do not need special double voltage power supply.

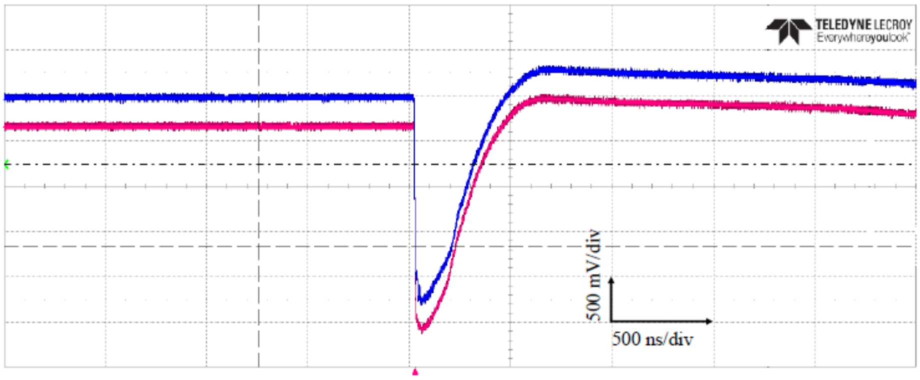


Fig. 4: Oscilloscope screen shot show, the analog output pulses from the two SiPM photosensors after the amplification stage.

In order to minimize electronic noise pick-up, the photosensors are attached directly to the preamplifier board (very short wire). The excellent timing properties of SiPMs are exploited to make precise measurements of events in coincidence by using two SiPM photosensors instead of one (see previous section), whose outputs are sent to an AND logic gate. In this way an output pulse is obtained only if both SiPMs producing a pulse at the same time (Figure.5).

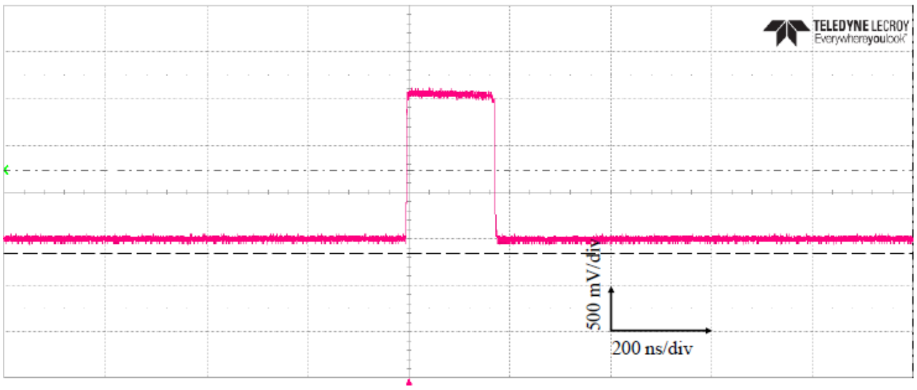


Fig. 5: Oscilloscope screen shot show coincidence measurements, the line represents a 3.3 V pulses of about 200 ns.

Counting system:

For testing our Gamma-rays detector, the prototype was exposed to gamma radiation using different radioactive sources (Ba^{133}, Co^{60}, and Cs^{137}) with different activities. In response to the penetrating radiation, SiPMs pulses were digitized and processed for pulse counting using the commercial Theremino Master Module, which can be easily connected to personal computer, laptop or even smart phone. We used the Theremino Geiger software which is generously provided free of cost (http://www.theremino.com). Theremino Geiger has to be calibrated. After calibration good results can be obtained. A little defect is that LYSO scintillators contains Lutetium (Lu176) that is slightly radioactive itself, so you have a very specific background in this material (~ 60 CPS has been recorded). Figure. 6. Shows radiation measurements for some radioactive sources as well as the LYSO background.

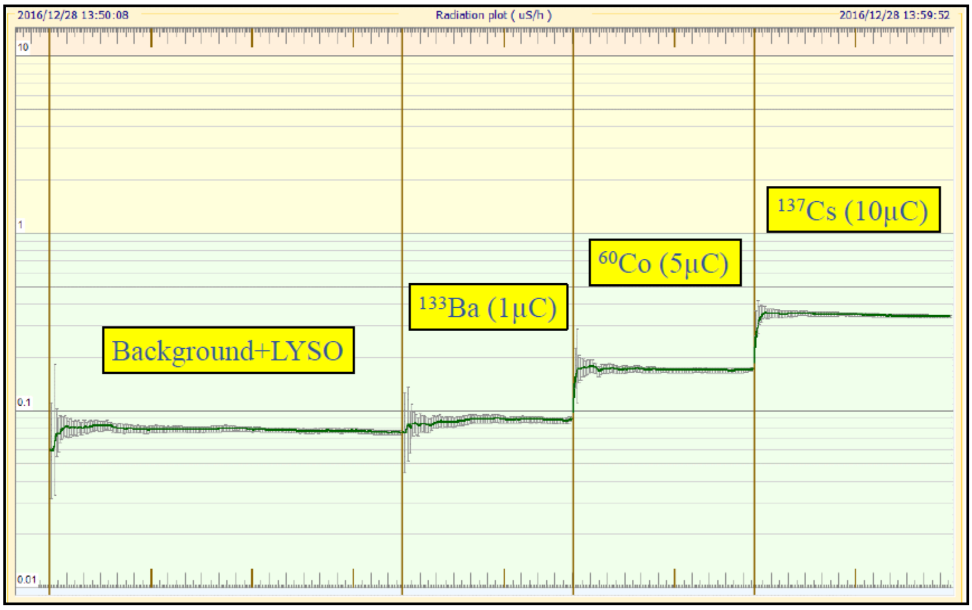


Fig. 6: Radioactivity measurements performed with Gamma rays detector prototype for different radioactive sources with different activities. Figure shows a screen shot for the radiation plot (µs/h) using the Theremino Geiger software.

Discussion and Conclusions:

Based on the use of LYSO scintillator crystal in combination with SiPMs photosensors, we have built Hand-held Gamma-ray detector prototype. Laboratory test using different gamma-rays standard radioactive sources is shown very good response to the exposed gamma radiations. The new detector has succeeded to monitor gamma radiation with very good efficiency in comparison to the standard survey meter.

The detector prototype consumes very low power (~ 40 mAh), for this reason we don’t need any external power supply and it’s enough to be connected to a laptop and our detector prototype is ready to do the measurements.

The main goal was to build a light weight (easy to handle), low power consumption (~ 50 mAh), and cheap detector which might be useful in detecting gamma-rays for many fields especially security and defense. With the proposed techniques, a single crystal can be used to make a decent detector capable of gamma spectrometry at an unbelievable price. LYSO is slightly radioactive, there is a very specific background in this material. Since the emitted energies (201.8 keV and 306.8 keV) are in a common area of interest, Lu176 makes an excellent calibration source for gamma spectrometry. When measuring low energy samples, this background can be subtracted, but is not always necessary.

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