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Optimizing the design of a silicon photomultiplier-based radiation detector

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A B S T R A C T

The silicon photomultiplier (SiPM) is a novel photo-sensor technology. This paper presents the design optimization process for implementing this technology in a scintillator-based radiation detector. The device provides the advantages of low current consumption, small dimensions, and high gain. These properties make SiPM of great interest for applications involving portable instrumentation. However, a novel approach to establish a set of parameters and their limits is required to optimize the performance of this new technology in radiation detection applications. The trade-offs and the influences of factors such as the photon detection efficiency (PDE), dynamic range (DR), various scintillation crystal characteristics, and light-reflecting materials are discussed. This study investigates the incorporation of CsI(Tl) scintillation crystals with SiPMs based on measurements and results for different photo-coupling configurations, and the obtained achievements are described. A method for evaluating the photon collection efficiency of scintillator-SiPM-based detectors is proposed.

1. Introduction

The silicon photomultiplier (SiPM) is a novel and rapidly developing solid-state optical sensor [1]. Its low power consumption, small dimensions, and high gain make SiPM of great interest for applications in portable radiation detection instrumentation based on scintillation materials. In contradistinction to its use for photon counting, the operating conditions of SiPM are of primary concern when it is used as a light sensor in radiation detection due to the gain dependence on temperature and operating voltage. The improvement and optimization of these operational considerations directly affect the critical parameters and the performance of radiation detectors. For instance, the PDE of SiPM directly influences the signal-to-noise ratio (SNR) and thus the significant parameters for isotope identification, such as the full-width at half-maximum (FWHM). Optimization of PDE can be achieved by increasing the pixel size, thereby improving the detector geometrical fill-factor (FF) and the sensitive area. Conversely, this increase in pixel size reduces the number of pixels and therefore DR.

Prior to optimization efforts, the operating conditions of SiPMs were carefully investigated, and the effects on radiation measurement performance were deduced [2,3]. The main examined parameters included the energy-equivalent noise level, the resolution for ^{137}Cs, and DR. A set of experiments was carried out to determine the influence of SiPM active area and variations in pixel size and pixel number on the tested parameters.

To finalize the optimization process, a systematic overview of different multiple design considerations was constructed, and the resulting approach is presented in this work. Using this approach, a method to determine the light collection efficiency of the whole radiation sensor is proposed for the first time.

Finally, the main achievements in improving the radiation sensor performance throughout the research are described.

2. Scintillation light detection with SiPM: parameters for consideration

Scintillation detectors are commonly used when high sensitivity is required [4]. Other configurations can maintain the gas tube (e.g., Geiger–Muller) as the radiation sensor, but they carry the drawback of low sensitivity. A scintillator is a material that converts radiation energy into pulses of light. Those pulses of light emitted by the scintillation material can be detected using a sensitive light detector. In the scintillation detector, this emitted light is collected and measured to provide an indication of the amount of incident radiation. Scintillation materials have different characteristics. They are distinguished by density, sensitivity, temperature dependence, emission light output spectra, decay time, and mechanical and optical

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properties [5]. These various characteristics can be exploited in a variety of applications by choosing the appropriate light detector. When high sensitivity and low noise level in a portable instrument are the main concerns, a crystal with a combination of good density and high light output should be selected. However, the optimal configuration for lowering the noise level and improving the resolution of the signal depends not only on the light yield of the scintillator but also on the correspondence of the emitted light spectrum (crystal wavelength emission) to the spectrum absorbed (quantum efficiency curve) by the photon sensor. Following the impingement of a γ photon in the scintillator, light photons in the visible wavelength range are produced. Both efficient detection and conversion of these light photons into an electrical signal are key to the effective radiation detection and qualitative spectral capabilities. For the proper analysis of the scintillation light detection process, it was divided into the following three main sub-processes.

2.1. Light generation

The light generation is solely dependent on the scintillation crystal properties, including its responsiveness to the penetrating radiation type and energy. Our research focused on γ radiation within the range of 30–3000 keV, which is the region of interest for ANSI N42- [6] series homeland security standards.

2.1.1. Crystal type

The scintillation crystal chosen for this work is CsI with Tl doping [7]. This, however, was not a random choice but was rather a consequence of intensive study [2]. Several scintillation crystals were considered as candidates for this research.

Eventually, the two main parameters had preponderance over all the rest: cost effectiveness and compatibility with a solid-state photo-sensor. The CsI(Tl) crystal was superior in both. Though NaI(Tl) is widely used and known as the traditional choice for scintillation radiation detectors, its wavelength compatibility is best suited for photomultiplier tubes rather than for silicon solid-state photo-detectors. While $LaBr_3(Ce)$ has an unprecedented light yield, its cost is rather high, and, moreover, its short wavelength emission (380 nm) almost eliminates the benefit of high light yield. This could be observed in the following calculations for the produced unit charge:

$$Q = E_\gamma YQEq_e \tag{1}$$

where E_γ is the incident gamma energy in units of MeV (we used the representative 0.662 MeV of the ^{137}Cs isotope), Y is the light yield in photons/MeV, QE is the quantum efficiency of the SiPM, as claimed by the manufacturer, and q_e is the electron charge (1.602×10^{-19} C).

By substituting the relevant values once for the CsI(Tl) crystal and once for the LaBr(Ce) crystal, we obtained unit charges of ~1.92 fC for the former and 1.02 fC for the latter.

However, recently, efforts have been made by different manufacturers to improve the response of SiPMs and thus the quantum efficiency for the shorter wavelengths. In spite of these efforts, the basic limitations of silicon production merely allow the response curve's effective coverage to be the whole blue region.

To conclude, the selection of a scintillator affects the light generation efficiency (light yield) process, whereas the suitability of its emission wavelength to the SiPM responsivity increases the chances of the generated light to be converted into an electrical signal. Though light collection efficiency is a principal parameter, the trade-off with the crystal cost should also be considered.

2.1.2. Crystal geometry

The surface area and volume of the crystal determine the initial geometrical efficiency and energy response of the sensor to the exposed radiation. Thus, the crystal dimensions are primarily dictated by the sensitivity requirements for the radiation detection application. These requirements are generally imposed by various standards.

After determining the crystal size, matching the coupling surface area of the scintillator against the SiPM active area will increase the performance of the radiation sensor. The dependence of the main parameters (i.e., the energy-equivalent noise level and resolution, FWHM) on crystal dimensions was examined in a series of measurements using about 10 different crystal sizes (with effective volumes between 0.4and 8 cm^3; see Fig. 1) [1].

2.2. Light transition: optical reflectors

Following in importance in the generation of scintillation light within the crystal, preventing losses in the light path and providing efficient transportation of light towards the light sensor are the main goals. These tasks are mainly achieved by applying reflecting material on the surface of the crystal. The efficiency of various reflecting materials had been evaluated in several works [8–10]. We propose an approach of simultaneously applying two different types of reflectors (specular and diffusive). Measurements to emphasize the predominance of this method are introduced in Table 1.

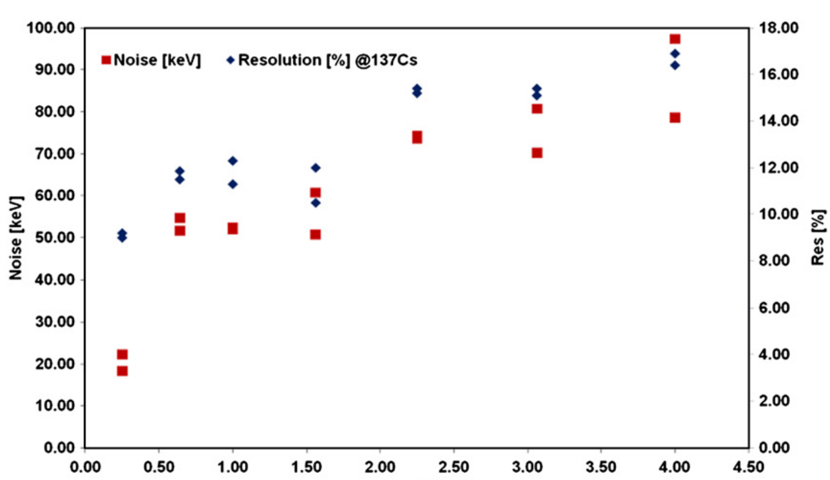

Fig. 1. Energy-equivalent noise level (left axis) and ^{137}Cs resolution (right axis) vs. crystal optically coupled surface area.

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The comparison of different types of reflecting materials was performed by evaluating the influence of the reflector on the radiation sensor performance, in terms of the energy-equivalent noise threshold (in keV) and the obtained resolution (in %) for a ^{137}Cs source. Different configurations of crystal-to-SiPM coupling were examined. A measurement with no reflector (black opaque tape) was used as a reference. Optical Poly Reflector White and a Teflon® film represented the diffusive materials, whereas Enhanced Specular Reflector (ESR) was used due to its specular light distribution properties.

The results demonstrate that improved performance is attained by a combination of diffusive and specular materials, induced by better light collection and a higher signal per energy unit (keV) of the interacting ionizing gamma-photon.

2.3. Light conversion: DR vs. PDE

One of the most important parameters influencing the light conversion efficiency is geometrical FF, which can actually be interpreted as the variation of microcell size vs. the number of microcells within the SiPM. The number of microcells determines the DR of the device in such a way that eventually more microcells will enable the differentiation of higher γ energy. Microcell size determines the PDE of the device, and thus larger microcells would result in an improved signal-to-noise ratio that would lead to improvements in the resolution (for ^{137}Cs) and energy-equivalent noise threshold of the radiation detector.

The linearity of DR is an important parameter when assessing the energy response of the whole sensor. DR is increased by increasing the number of pixels. This process is opposite to the increase in SiPM's pixel size and eventually causes a decrease in PDE. The results shown in Fig. 2 describe the energy linearity functions of diodes with different pixel sizes. All the measurements for this experiment were performed with a 1 mm × 1 mm SiPM with different pixel sizes (Fig. 3) and a 5 mm × 5 mm × 15 mm CsI(Tl) crystal. In addition, a spectrum obtained using a SiPM with a 100 μm pixel size, shown in Fig. 4, describes the distortion caused by the nonlinearity of this device. The distortion can be observed on the unusually stretched Compton region, which precedes the photopeak.

The optimization of FF is achieved by selecting the pixel size (20 μm/35 μm/50 μm/100 μm) that would satisfy the requirements for DR of the application while achieving the best possible PDE. Reverting to the choice of crystal type (Section 2.1.1), a scintillator with a longer scintillation decay time will enable the use of a SiPM with a higher PDE and a low DR. This is due to the faster recovery time of SiPM than the decay time of the scintillation. In this case, in spite of fewer pixels, SiPM is recovered fast enough to be ready to count as much as 90% of emitted light.

3. Determination of light collection efficiency

The light collection efficiency (LCE) is a comprehensive term for the number of light photons that reach the light sensor (in our case, SiPM) per light photons created due to the interaction of the irradiated γ photon with the scintillation crystal. This factor is often most important when dealing with the isotope identification capability of the radiation sensor. To distinguish between γ photons of different energies impinging the crystal, the light that reaches the photo-sensor should be proportional to the initial light

Table 1
Results from comparison of different types of reflectors for three detector configurations.

	Black opaque tape		Optical Poly Reflector White with ESR		Teflon® film		Enhanced Specular Reflector		Optical Poly Reflector White	
	Noise [keV]	Res. [%]	Noise [keV]	Res. [%]	Noise [keV]	Res. [%]	Noise [keV]	Res. [%]	Noise [keV]	Res. [%]
CsI(Tl) 10 mm × 10 mm × 20 mm coupled to SPM single 9 mm²	> 800	–	46.43	11.9	56.07	14.2	79.13	15.6	67.04	14.3
CsI(Tl) 10 mm × 10 mm × 20 mm coupled to SPM Quad 36 mm²	452.7	–	34.4	11.1	43.86	11.9	61.15	13.2	45.98	11.5
CsI(Tl) 12.5 mm × 12.5 mm × 12.5 mm coupled to SPM Plus 144 mm²	105.9	14	23.06	7	25.57	8.9	28.87	8.7	30.74	7.9

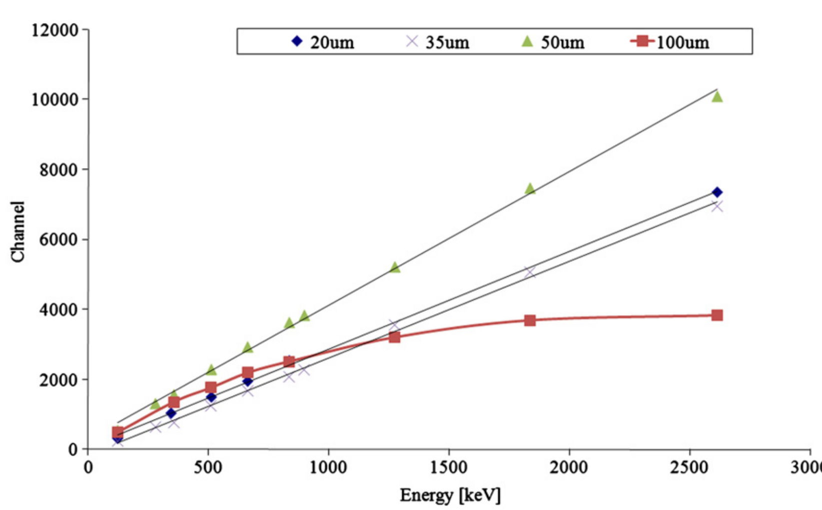

Fig. 2. Measured linearity of the energy dynamic range as a function of pixel size (20 μm/35 μm/50 μm/100 μm) in a 1 mm × 1 mm SiPM.

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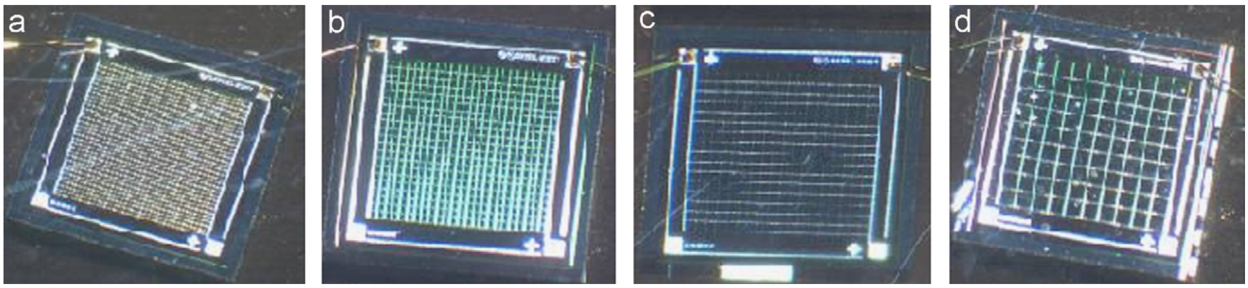

Fig. 3. Microscopic view (× 40) of the 1 mm × 1 mm silicon photomultiplier with different pixel sizes: (a) 20 μm, (b) 35 μm, (c) 50 μm, and (d) 100 μm.

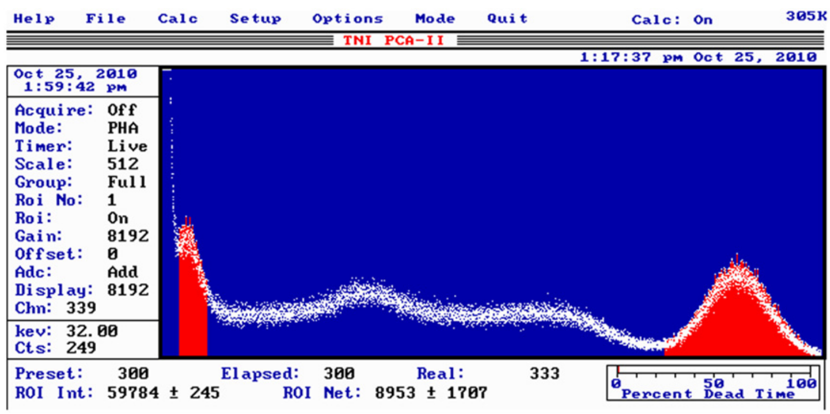

Fig. 4. Demonstration of distorted spectrum of ^{137}Cs, obtained with 14 mm × 20 mm CsI(Tl) scintillator coupled to a SiPM with 100 μm pixel size.

produced by the scintillator (the latter is usually proportional to the γ energy due to crystal properties). Only in this way will the output signal correspond to the detected radiation energy. Due to the low amount of light produced when a γ photon (within the concerned energy range) induces the scintillation crystal, there is a real concern to collect as much light as possible, i.e., "every photon counts".

The efficiency of light collection is mainly influenced by the optical characteristics of the radiation sensor assembly, which includes the scintillation crystal, the optical reflectors covering the crystal, and the medium between the crystal and the light sensor. The efficiency is also considerably influenced by the coupling technique and by the compatibility of the specified components to each other. Finally, the collected light is translated into an electrical signal by the light converter (SiPM), and thus its characteristics aid in the evaluation of LCE.

To assess LCE (denoted as η from now on), we used the manufacturer curve for SiPM efficiency for SPMMicro1100 specifications,[1] as derived from Eq. (2) [11]:

$$N_{sig} = M\left(1 - \exp\left(\frac{-PDE N_{ph}}{M}\right)\right) \tag{2}$$

where N_{sig} is the number of detected photons, M is the number of microcells, PDE is the photon detection efficiency, and N_{ph} is the number of incident photons.

Let us substitute the number of incident photons by the expression ηN_{gen}, where N_{gen} is the number of scintillation light photons produced within the crystal, proportional to the energy of the induced γ photon, e.g., for the CsI(Tl) crystal, 56,000 light photons (at the peak wavelength emission of 550 nm) are obtained per interaction of 1000 keV of γ photons.

For the calculation of η, we start by superimposing the curve that represents energy DR (Fig. 2) of the specified device (100 μm microcell) over the corresponding efficiency curve. Then, by applying analytical manipulations that consider the decay constant of the crystal and the integration time of the signal, LCE can be retrieved.

A more detailed study including both experimental and analytical investigations to evaluate LCE based on its efficiency curve is being carried out. Further optimization of the coupling between the scintillation crystal and SiPM can be performed with the help of software simulation.

LCE has a vast impact on the energy-equivalent noise threshold that can be achieved using SiPMs. Recent improvements of SiPMs, as well as coupling and coating the scintillation crystal with reflective materials, have enabled a significant improvement in the noise threshold (see Fig. 5).

4. Summary of performance

The progress in the investigation of SiPM's performance during the R&D time-line is displayed in Fig. 6. It is shown that there were improvements in two major parameters: the noise level and the resolution. These improvements were achieved by addressing and optimizing the following factors:

a. The detector housing was upgraded from metal housing to ceramics. This enabled a reduction in the distance between the crystal and the light sensor and thus enhanced light collection.
b. The pixel size (20→35→50→100 μm) was selected for the best possible PDE while maintaining the required DR.
c. The technology was improved by the manufacturer, over 2 years of the development period, by matching the wavelength emission of the crystal to the light sensor quantum efficiency curve and by reducing the crosstalk probability between pixels, thereby lowering the sensor's inherent noise.
d. Crystal light reflectors were optimized by combining diffusive and specular materials as the crystal covers for the better light collection, leading to the higher signal per energy unit (keV) of the interacting ionizing gamma-photon.

[1] SensL datasheet – 1 mm × 1 mm SiPM with 100 μm microcell size.

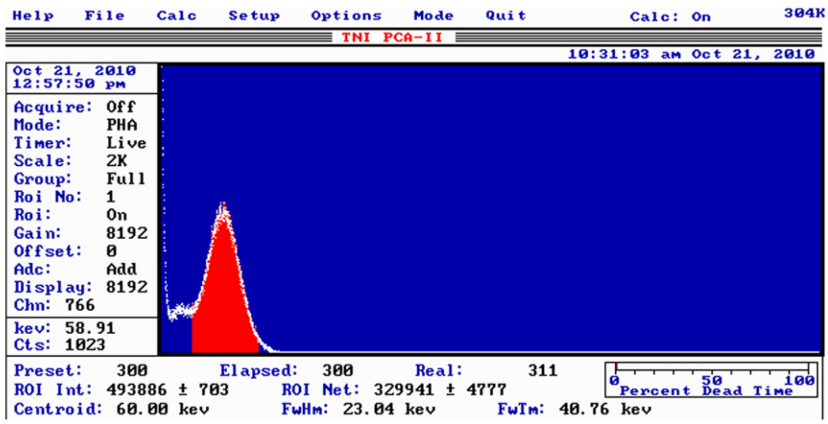

Fig. 5. Obtained spectrum of ^{241}Am using 14 mm × 20 mm CsI(Tl) cylindrical scintillator coupled to a SiPM with 50 μm pixel size. Noise level of 19 keV is measured.

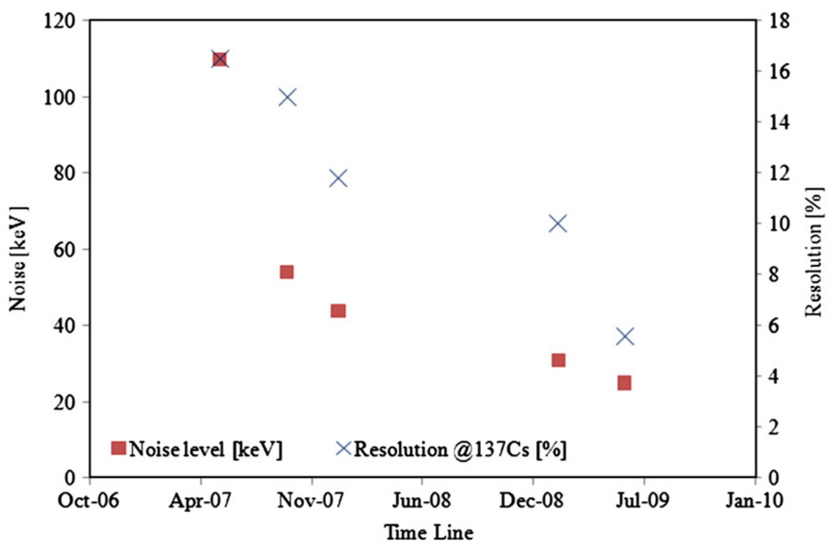

Fig. 6. Progress during the time-line; reducing the noise level from 110 keV down to 20 keV and improving the resolution from 16% to about 6%.

e. The amplifier parameters were optimized for applications of radiation detection, as opposed to the photon counting with fast rise times applicable for time-of-flight measurements. The optimization was achieved by setting the amplifier impedance according to the SiPM electrical module characteristic for reducing the noise level at the expense of the response time.

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