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NaI(Tl) scintillator read out with SiPM array for gamma spectrometer

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ABSTRACT

The NaI(Tl) scintillator is widely used in gamma spectrometer with photomultiplier tube (PMT) readout. Recently developed silicon photomultiplier (SiPM) offers gain and efficiency similar to those of PMT, but with merits such as low bias voltage, compact volume, low cost, high ruggedness and magnetic resonance compatibility. In this study, 2-in. and 1-in. NaI(Tl) scintillators were readout with SiPM arrays, which were made by tiling multiple SiPMs each with an active area of 6×6 mm^2 on a printed circuit board. The energy resolutions for 661.6 keV gamma rays, obtained with Φ2×2 in. scintillator coupled to 6×6 ch SiPM array and Φ1×1 in. scintillator coupled to 4×4 ch SiPM array were 7.6% and 7.8%, respectively, and were very close to the results obtained with traditional bialkali PMT (7.3% and 7.6%, respectively). Scintillator coupled to photodetector with smaller area was also studied by adding a light guide or using scintillator with tapered head. The latter showed better performance than using light guide. The 1-in. NaI(Tl) scintillator with tapered head coupled to 2×2 ch SiPM array achieved 7.7% energy resolution at 661.6 keV, the same as that obtained with standard Φ1×1 in. scintillator coupled to 4×4 ch SiPM array. While the 2-in. scintillator with similar geometry showed degraded energy resolution, 10.2% at 661.6 keV, but could still be used when high efficiency is preferred over energy resolution.

1. Introduction

Scintillation detectors, mainly inorganic scintillators, are the most widely used detectors in gamma spectrometers because of low cost and availability in large size. The thallium-doped sodium iodide [NaI(Tl)] scintillator is the most commonly used inorganic scintillator because of its high light yield, high density, low cost and mature manufacturing technique. Photomultiplier tubes (PMTs) are commonly used for NaI(Tl) scintillators, but they have disadvantages such as bulky, fragile, high operating voltage, sensitivity to magnetic field and complex manufacturing.

In recent years, a novel semiconductor photodetector called silicon photomultiplier (SiPM) has been developed. A single SiPM consists of several thousand or more small microcells connected in parallel. Each microcell consists of an avalanche photodiode (APD) operating in Geiger mode and a quenching resistor in series. The summed output signal is proportional to the total number of microcells that are triggered by the absorption of photon. A prominent feature of SiPM is the high gain at the level of 10^6 which makes it an alternative to PMT. SiPMs have advantages over PMTs such as low bias voltage, high ruggedness, insensitivity to magnetic fields, and mass production.

The performances of different kinds of scintillators coupled to SiPM were studied detailedly in Ref. [1–4], and results showed that energy resolution obtained with SiPM was close to that obtained with PMT (even better for some scintillators) when using small scintillator (3–6 mm) coupled to matched SiPM. But detection efficiency is very low for such small scintillator which is unpractical for gamma spectrometer. Fortunately, the compact package of SiPM makes it feasible to build an array to matched large scintillator.

As reported in Ref. [5,6], 4×4 ch and 8×8 ch SiPM arrays (3×3 mm^2 active area per channel) were used for 1-in. and 2-in. NaI(Tl) scintillators. In Ref. [7], 2-in. NaI(Tl) scintillator was coupled to a 4×4 ch SiPM array (3×3 mm^2 active area per channel) using light guide. The SiPM arrays used in Ref. [5,7] are commercial monolithic arrays, which are old designs and already out of production. The SiPM arrays (S12642 series) used in Ref. [6] are also ready-made products from Hamamatsu using the TSV (Through Silicon Via) technology. The adoption of TSV structure makes it possible to eliminate wiring on the photosensitive area side, resulting in a compact structure with little dead space (only 0.2 mm gap between adjacent channels). The newest product from Hamamatsu using TSV technology is the S13361 series, with total active area only up to 24×24 mm^2 [8].

In this work, SiPM arrays were built by tiling multiple standard SiPMs on a printed circuit board (PCB). Arrays with arbitrary number of channels can be made. SiPMs with an active area of 6×6 mm^2 are used, which is the largest size of currently available. Standard Φ1×1 in.

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Table 1
Main parameters of the used SiPM and fabricated arrays.

Manufacturer	SensL		
Model	MicroFC–60035		
Active area	6×6 mm^2		
Package dimension	7×7 mm^2		
Number of APD-cells	18,980		
APD-cell size	35×35 µm		
Microcell fill factor	64%		
Rated gain	3×10^6		
Spectral range	320–900 nm		
Maximum sensitivity	420 nm		
Capacitance	3400 pF		
Fabricated array	2×2 ch	4×4 ch	6×6 ch
Number of channels	4	16	36
Total active area (mm)	12×12	24×24	36×36
Total number of APD cells	75,920	303,680	683,280

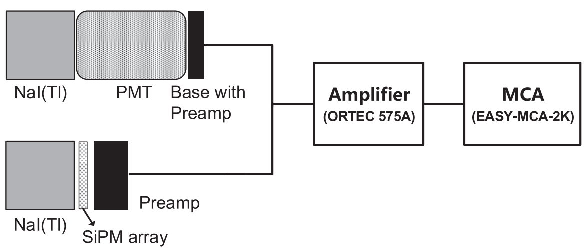

Fig. 1. Experiment setup for gamma spectrum measurements.

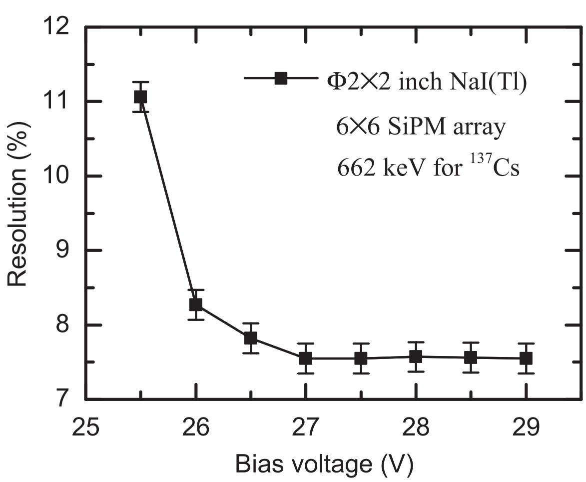

Fig. 2. Energy resolution of 661.6 keV gamma-rays versus bias voltage for the *Φ*2×2 in. NaI(Tl) scintillator coupled to 6×6 ch SiPM array.

and *Φ*2×2 in. NaI(Tl) scintillators were read out with 4×4 ch and 6×6 ch arrays, respectively, with comparison to PMT. For coupling large scintillator to small photodetector, light guides with different reflector and length were tested. According to the experiment results with light guides, an alternative approach was developed using scintillator with tapered head. The performances of both 2-in. and 1-in. scintillators with tapered head coupled to simple 2×2 ch SiPM array were evaluated.

2. Energy resolution of scintillation detector

The energy resolution of the full energy peak measured with scintillation detector can be expressed as [5]:

$$\left(\frac{\Delta E}{E}\right)^2 = (\delta_{sc})^2 + (\delta_p)^2 + (\delta_{st})^2 + (\delta_n)^2 \quad (1)$$

where δ_{sc} is the intrinsic resolution of the crystal, δ_p is the transfer resolution, δ_{st} is the statistical contribution of the photodetector and δ_n is the dark noise contribution connected with the detector's current and the noise of the electronics. The statistical uncertainty of the signal from the photodetector can be described as [5]:

$$\delta_{st} = 2.355 \times (ENF/PHE)^{1/2} \quad (2)$$

where PHE is the number of photoelectrons and ENF is the excess noise factor.

ENF for PMTs comes from variance of the electron multiplier gain and has a value of 1.1–1.2 for modern PMTs. For SiPMs, ENF is caused by crosstalk and afterpulses. PHE is proportional to the Photon Detection Efficiency (PDE). Both PDE and probability of crosstalk and afterpulses will increase with bias voltage. Thus optimum bias voltage should be determined to achieve the best energy resolution.

The number of photoelectrons (phe) was measured using pulse height resolution (PHR) method [1]. The PHR method (PHE_{phr}) is based on the calculation of the photoelectron's number from the pulse height resolution of a LED light pulse peak assuming a Gaussian curve and an ENF value of 1. A blue LED with peak wavelength at 428 nm was used, and the pulse width was set to 250 ns according to the decay time of NaI(Tl) scintillator. For uniform illumination, the LED was placed at certain distance from the SiPMs, with light attenuator and diffuser inserted in between. Besides, diffuse reflector (white paper) was added around the SiPMs. The peak position of LED pulse corresponds to the given energy of gamma rays. Assuming the ENF equal to 1, the calculated phe number using PHR method represents the lower limit of the phe number [5].

$$PHE_{phr} = (2.355/\delta_{st})^2 \quad (3)$$

The number of photoelectrons per unit energy (phe/MeV) was measured using PHR method (PHE_{phr}) for tested scintillators illuminated with the ^{137}Cs gamma source.

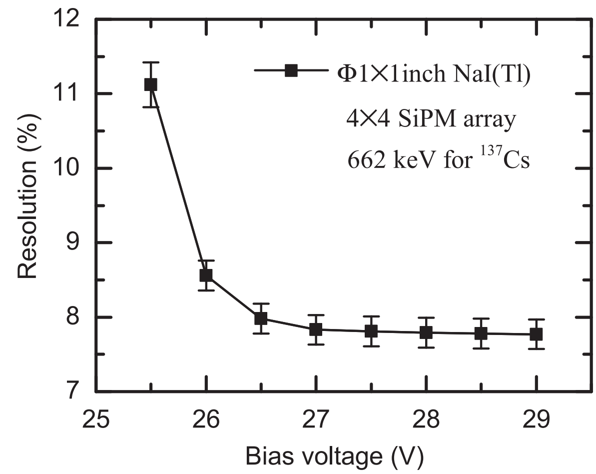

Fig. 3. Energy resolution of 661.6 keV gamma-rays versus bias voltage for the *Φ*1×1 in. NaI(Tl) scintillator coupled to 4×4 ch SiPM array.

3. Scintillator read out with SiPM array

The SiPMs used in this work are standard products from SensL Technologies Ltd. The main parameters of the SiPM and fabricated arrays are collected in Table 1. Standard *Φ*2×2 in. and *Φ*1×1 in. NaI(Tl) scintillators from Beijing Hamamatsu Photon Techniques Inc were used. A 2-in. head-on bialkali PMT (Model CR105) was used for comparison. Silicone oil was used for optical coupling between the components. The experiment setup based on NIM system is shown in Fig. 1. Shaping time of 1.5 µs was chosen for the amplifier. All the tests were carried out in an air-conditioned laboratory, at temperature of 24 °C.