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Abstract

With the development of clinical nuclear medicine imaging technology, the development of time-of-flight positron emission tomography (TOF-PET) detectors with high time resolution and high efficiency has become a current research focus. As a core component of the detector, the performance of the silicon photomultiplier (SiPM) directly affects the imaging quality of the system. In this work, the performance of an epitaxial resistor quenching silicon photomultiplier (model: NDL Optics (EQR20 11-4040D-SN)) was evaluated and compared with SiPMs of the same size. Two scintillation crystals, lutetium yttrium oxyorthosilicate (LYSO) and gadolinium aluminum gallium garnet (GAGG), were selected, with crystal sizes of $2 \times 2(\times)3$ mm3 and $2 \times 2(\times)20$ mm3, and were coupled to 4×4 mm2 SiPMs using optical adhesive. In a constant-temperature environment of 16℃, a 22Na radioactive source was used to systematically measure and analyze key performance indicators, including the signal-to-noise ratio, energy resolution, and coincidence time resolution, of the two SiPMs over different operating voltage ranges. The experimental results show that the epitaxial resistor quenching SiPM exhibited excellent overall performance under different operating voltage conditions and with crystals of different sizes. At a voltage of 32V, the energy resolution for 511 keV gamma photons measured with a $2 \times 2(\times)3$ mm3 LYSO crystal was 10.2 ± 0.6 %, and the coincidence time resolution was 105.7 ± 1.4 ps, demonstrating its promising potential for application in TOF-PET detectors and providing experimental evidence for the domestic development of related detectors.

Full Text

Study on the Performance of an Extended-Resistor-Quenching Silicon Photomultiplier for TOF-PET Detectors

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Abstract: With the development of clinical nuclear medical imaging technology, the development of high-time-resolution and high-efficiency time-of-flight positron emission tomography (TOF-PET) detectors has become a current research hotspot. As the core component of the detector, the performance of the silicon photomultiplier (SiPM) directly affects the imaging quality of the system. In this work, the performance of an extended-resistor-quenching silicon photomultiplier (model: Novel Device (EQR20 11-4040D-SN)) was evaluated and compared with SiPMs of the same size. Two scintillation crystals, lutetium yttrium oxyorthosilicate (LYSO) and gadolinium aluminum gallium garnet (GAGG), were selected, with crystal sizes of $2 \times 2(\times)3$ mm^3 and $2 \times 2(\times)20$ mm^3, and were coupled to a 4×4 mm^2 SiPM using optical adhesive. In a constant-temperature environment of 16°C, a ^{22}Na radioactive source was used, and the system measured and analyzed key performance indicators such as the signal-to-noise ratio, energy resolution, and coincidence time resolution of the two SiPMs under different operating-voltage ranges. The experimental results show that the extended-resistor-quenching SiPM exhibits excellent comprehensive performance under different operating-voltage conditions and with crystals of different sizes. At a voltage of 32 V, the measured energy resolution of the $2 \times 2(\times)3$ mm^3 LYSO crystal for 511 keV gamma photons was $10.2 \pm 0.6\%$, and the coincidence time resolution was 105.7 ± 1.4 ps, demonstrating its good potential for application in TOF-PET detectors and providing experimental evidence for the localization of related detectors.

Keywords: silicon photomultiplier; TOF-PET; coincidence time resolution

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0 Introduction

Positron emission tomography (PET) is an important molecular imaging technology and has broad applications in tumor diagnosis, neurological disease research, and functional imaging [1−5]. Developing detectors with high detection efficiency and high resolution to further improve the imaging quality of PET systems has become an important direction of related research [6, 7]. With the introduction of time-of-flight PET (TOF-PET) technology, by measuring the time difference between coincident photons arriving at the detectors, the position of the annihilation event along the line of response (LOR) can be further constrained, thereby significantly improving the signal-to-noise ratio of the image [8, 9]. At the same time, the development of multimodal molecular imaging equipment such as PET/MR has also placed higher requirements on the timing performance, system integration, and operational stability of detectors [10, 11]. Against this background, coincidence time resolution

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The coincidence time resolution (CTR) has become a key parameter for measuring the temporal performance of the system[^12,^13].

Early TOF-PET detectors usually used photomultiplier tubes (PMTs) as scintillation-light readout devices. PMTs have high gain and good time-response capability, but they are relatively large in size, require high operating voltage, and are comparatively sensitive to magnetic fields. With the development of TOF-PET detectors toward miniaturization and integration, as well as toward multimodal compatibility with PET/MR, the limitations of PMTs have gradually become apparent[^14].

Against this background, the silicon photomultiplier (SiPM), as a solid-state photodetector, offers advantages such as compact structure, high gain, high photon-detection efficiency, and fast time response. In recent years it has gradually replaced traditional photomultiplier tubes and become the mainstream photoelectric readout device for TOF-PET detectors[^15–^17]. Characteristics of SiPMs such as gain, photon-detection efficiency, dark count rate, and time response directly affect the detector' s energy resolution, signal-to-noise ratio, and coincidence time resolution[^18,^19]. At present, representative foreign SiPMs from Hamamatsu, FBK, Broadcom, and other manufacturers have been widely used in TOF-PET detectors and exhibit excellent timing performance[^20–^22].

On the basis of the continuous development of SiPM devices, researchers have optimized scintillator materials, SiPM device performance, optical coupling methods, front-end readout electronics, and time-extraction methods, thereby continuously improving the timing performance of TOF-PET detectors. For example, when the digital SiPM developed by Philips was coupled with a $2\times2(\times)20\ \mathrm{mm}^3$ LYSO crystal, a CTR of 177.9 ps was achieved[^23]; when a Hamamatsu SiPM was coupled with a $3\times3(\times)5\ \mathrm{mm}^3$ LYSO crystal, a CTR of 166.5 ± 2.5 ps was obtained[^24]. In addition, when high-density FBK SiPMs were coupled with $2\times2(\times)5\ \mathrm{mm}^3$ Ce:LYSO and Ce:GaGG crystals, CTRs of 157 ps and 260 ps were obtained, respectively[^25]. Studies have shown that, in addition to the intrinsic performance of the SiPM device, front- and back-end electronics, temperature, optical coupling methods, and the size and material properties of the scintillator also jointly affect the timing performance of TOF-PET detectors[^22,^26,^27].

However, conventional SiPMs are still constrained in microcell structural design by factors such as fill factor, effective photosensitive area, and photon-detection efficiency, which to some extent affects further improvement of their signal-output capability and timing performance. To overcome the limitations of the traditional polysilicon quenching-resistor structure in terms of fill factor and photon-detection efficiency, the epitaxial quenching resistor SiPM (EQR-SiPM) has been proposed and gradually implemented as a device[^28,^29]. This structure directly integrates the quenching resistor inside the silicon by means of an epitaxial process, replacing the traditional surface polysilicon resistor structure, thereby reducing the proportion of non-sensitive regions on the surface and increasing the microcell fill factor and effective photosensitive area. Compared with the traditional structure, the epitaxial quenching resistor SiPM has

Fig. 1 Experimental test SiPMs and scintillation crystals

Figure 1: Fig. 1 Experimental test SiPMs and scintillation crystals

potential advantages in photon-detection efficiency, dynamic range, and time-response characteristics, and is expected to improve the detector's timing resolution and signal-to-noise performance[^30]. Especially in TOF-PET applications requiring high time resolution, structural optimization may provide a new technical pathway for further improving coincidence time resolution[^31,^32].

In this study, under the same experimental conditions, the performance of a domestic Nanjing Lightsemi epitaxial quenching resistor SiPM (EQR20 11-4040D-SN) was investigated, and a Hamamatsu polysilicon quenching-resistor SiPM of the same size (S14160-4050HS) was used as a performance reference. The experiment used LYSO and GAGG scintillation crystals, and employed a NINO ASIC for fast timing-signal readout[^33], measuring and analyzing key performance parameters including signal-to-noise ratio, energy resolution, and coincidence time resolution.

1 Detector Design and Experimental Methods

1.1 Detector Design

This study used domestically produced Zhongjing Optoelectronics SiPMs and Hamamatsu Photonics SiPMs as photoelectric readout devices. The main parameters of the two SiPMs are listed in Table 1. The SiPMs and scintillation crystals used in the experiment are shown in Fig. 1. There were four scintillation crystals in total, including two types of crystals, LYSO and GAGG; for each crystal type, two sizes were used: $2 \times 2 \times 3$ mm^3 and $2 \times 2 \times 20$ mm^3. The four side surfaces of the crystals were wrapped with aluminum foil, and a barium sulfate reflective layer with a thickness of 0.1 mm was filled between the crystal and the aluminum foil to enhance the reflection efficiency of scintillation photons and improve light-collection capability. One end of the crystal was coupled to the effective photosensitive surface of the SiPM using optical adhesive, enabling effective transmission and detection of the scintillation-light signal. To ensure the comparability of the experimental results, the same packaging structure and coupling method were used under different SiPM and crystal conditions, thereby ensuring the reliability and consistency of the measurement results.

Fig. 1 Experimental test SiPMs and scintillation crystals

(a) From left to right: $2 \times 2 \times 20$ mm^3 LYSO crystal, $2 \times 2 \times 20$ mm^3 GAGG crystal, $2 \times 2 \times 3$ mm^3 LYSO crystal, and $2 \times 2 \times 3$ mm^3 GAGG crystal; (b) Hamamatsu Photonics (S14160-4050HS) SiPM; (c) Zhongjing Optoelectronics (EQR20 11-4040D-SN) SiPM.

Table 1 Detailed SiPM Parameters

Fig. 2 Experimental setup diagram. (a) Coincidence time resolution experimental setup; (b) signal-to-noise ratio experimental setup.

Figure 2: Fig. 2 Experimental setup diagram. (a) Coincidence time resolution experimental setup; (b) signal-to-noise ratio experimental setup.

Parameter name	Detector1	Detector2
SiPM Models	EQR20 11-4040D-SN	Hamamatsu S14160-4050HS
Microcell Size	20 μm	50 μm
Number of cells	40000	6331
SiPM size	4×4 mm^2	4×4 mm^2
Breakdown voltage (V_B)	26.5 ± 1 V	38 V
Recommended Operation Voltage	$V_B + 5$ V	$V_B + 5$ V
Dark current (Typ./Max.)	0.7/3 μA	1.1/3.3 μA
Gain	8×10^5	2.5×10^6
Photon detection efficiency	47.8 %	50 %

1.2 Experimental Setup and Test Methods

This study used two different experimental setups to evaluate the detector' s signal-to-noise ratio and coincidence time resolution performance. The coincidence time resolution was measured using the coincidence measurement method. The structure is shown in Fig. 2(a), and consists of the detector under test and a reference detector. The detector under test and the reference detector were placed on the two sides of a ^{22}Na point source, respectively, both at a distance of 10 mm from the point source, and arranged along the same horizontal axis. The reference detector was formed by coupling a Hamamatsu SiPM with a $2 \times 2 \times 3$ mm^3 LYSO scintillation crystal, and was used to provide the timing reference signal. The ^{22}Na point source produces two photons with an energy of 511 keV and opposite directions, which are detected by the detector under test and the reference detector, respectively, thereby forming coincidence events. After the output signals of the two detectors were processed by front-end electronics, the timing signals were extracted by the NINO ASIC readout system, while the energy signals were amplified by an AD8045 amplifier and acquired by a CAEN data acquisition card.

Fig. 2 Experimental setup diagram

(a) Coincidence time resolution experimental setup; (b) signal-to-noise ratio experimental setup.

The signal-to-noise ratio measurement used a frontal irradiation method, with the structure shown in Fig. 2(b). The distance between the ^{22}Na point source and the detector under test was set to 10 mm. During the experiment, the noise voltage amplitude output by the SiPM was first acquired using the internal random-trigger mode of the DAQ data acquisition system, in order to characterize the intrinsic noise level of the detector. The system was then switched to the external-trigger mode to acquire the voltage amplitude corresponding to the scintillation signal, so as to obtain the signal response amplitude under radiation excitation conditions. In the experiment, the SiPM bias voltage was adjusted, and relevant performance parameters were repeatedly measured under different operating-voltage conditions. All tests were carried out at a constant temperature of 16°C and in a completely light-shielded environment, in order to reduce the influence of temperature fluctuations and ambient light on the SiPM gain, noise level, and timing performance.

1.3 Data Processing and Analysis Methods

Based on the raw data collected, an offline data analysis program was used to calculate and evaluate the detector performance, mainly extracting key performance parameters such as the signal-to-noise ratio, energy resolution, and coincidence time resolution. This section mainly introduces the extraction methods and calculation formulas for each performance parameter.

The signal-to-noise ratio (Signal-to-Noise Ratio, SNR) is used to characterize the detector' s resolving capability for weak optical signals, and its magnitude directly affects the time-extraction accuracy and subsequent time-resolution performance. The noise signal was acquired using the internal random-trigger mode of the acquisition card, and its amplitude distribution was Gaussian-fitted to obtain its full width at half maximum $FWHM_{\text{noise}}$, which was used to characterize the noise level. The response signal was sampled by external triggering; the photoelectric peak in the obtained energy spectrum was Gaussian-fitted, and the photoelectric peak position was taken as the response signal V_{signal}[34]. The signal-to-noise ratio is defined as:

$$SNR = \frac{V_{signal}}{FWHM_{noise}} \qquad (1)$$

The energy resolution (Energy Resolution, ER) is obtained by analyzing the energy spectrum measured by the detector. To realize the conversion of the energy scale, the 511 keV and 1275 keV photoelectric characteristic energy points produced by the ^{22}Na radioactive source are used, and the zero-deposited energy corresponding to a zero output amplitude is taken as a constraint to establish the calibration relationship between the detector output amplitude and the γ-photon energy [35–38]. This calibration relationship reflects the overall output response of the detector unit after the scintillation crystal is coupled to the SiPM. Because the number of SiPM microcells is limited, under conditions of relatively high light output, some microcells are triggered within a short time, and the output amplitude may exhibit a saturation effect, causing the detector response to deviate from an ideal linear relationship [39]. According to the saturation-response model of the limited SiPM microcells [37], the number of triggered microcells can be expressed as:

$$N_{fired} = N_{cell} \times \left(1 - e^{-\left(\frac{N_{photon} \times PDE}{N_{cell}}\right)}\right) \qquad (2)$$

The total number of SiPM microcells is N_{cell}, the number of scintillation photons reaching the SiPM photosensitive surface is N_{photon}, and the photon detection efficiency is PDE. For a scintillation-crystal-coupled SiPM detector, under the condition that the crystal light yield and light-collection efficiency are approximately stable, the number of scintillation photons reaching the SiPM is approximately proportional to the γ-photon deposited energy E, namely:

$$N_{photon} = k \times E \qquad (3)$$

k is the proportionality coefficient between the deposited energy and the average number of scintillation photons reaching the SiPM photosensitive surface. Meanwhile, the output amplitude f measured by the detector is approximately proportional to the average number of triggered microcells N_{fired}, namely:

$$f = g \times N_{fired} \qquad (4)$$

g is an equivalent coefficient that includes the SiPM gain, front-end amplification, and data-acquisition conversion relationship. Substituting the above relationships into the triggered-microcell response model gives:

$$f = g \times N_{cell} \times \left(1 - e^{-\left(\frac{k \times PDE}{N_{cell}} \times E\right)}\right) \qquad (5)$$

Let $A = g \times N_{cell}$, $B = \dfrac{k \times PDE}{N_{cell}}$. Then the calibration relationship between the detector output amplitude and the γ-photon energy can be written as:

$$f = A \times (1 - e^{-B \times E}) \qquad (6)$$

where f denotes the measured photoelectric peak amplitude, E denotes the corresponding γ-photon energy, and A and B are nonlinear energy-calibration parameters introduced based on the saturation-response model of the limited SiPM microcells. Figure 3 shows the energy calibration curve. This energy calibration method was also comparatively validated by testing one set of data using the 202 and 307 keV energy peaks inherent to LYSO plus the ^{22}Na source; the experimental results were consistent with the method used in this paper.

Figure 3. Calibration curves. (a) Calibration curve of a $2 \times 2(\times)3$ mm^3 LYSO crystal coupled to a 32 V Beijing Zhongke Photon SiPM; (b) calibration curve of a $2 \times 2(\times)3$ mm^3 LYSO crystal coupled to a 43 V Hamamatsu Photonics SiPM.

Figure 3: Figure 3. Calibration curves. (a) Calibration curve of a $2\times2(\times)3$ mm^3 LYSO crystal coupled to a 32 V Beijing Zhongke Photon SiPM; (b) calibration curve of a $2\times2(\times)3$ mm^3 LYSO crystal coupled to a 43 V Hamamatsu Photonics SiPM.

After completing the energy calibration, the calibration parameters are applied to the original energy spectrum to realize energy-scale correction, and Gaussian fitting is performed on the 511 keV photoelectric peak to obtain the full width at half maximum $FWHM$ and the peak position E_{peak}. The energy resolution is defined according to the ratio of the photoelectric peak full width at half maximum to the peak position as:

$$ER = \frac{FWHM}{E_{peak}} \times 100\% \qquad (7)$$

Figure 3 Calibration curves

(a) Calibration curve of a $2 \times 2(\times)3$ mm^3 LYSO crystal coupled to a 32 V Beijing Zhongke Photon SiPM; (b) calibration curve of a $2 \times 2(\times)3$ mm^3 LYSO crystal coupled to a 43 V Hamamatsu Photonics SiPM.

Coincidence time resolution is a key parameter for measuring the timing performance of TOF-PET detectors. Its magnitude directly determines the time-localization accuracy of the system and affects the ability to improve the image signal-to-noise ratio. To obtain valid coincidence events, only signals triggered simultaneously by two detectors within a preset coincidence time window are selected for analysis, thereby reducing the influence of random coincidence events and intrinsic noise. By statistically analyzing the time-difference distribution between the two detectors and fitting it with a Gaussian function, the coincidence time resolution is obtained. To further improve the measurement accuracy of the time resolution, an energy-window screening condition is added during the time-difference statistics: only photopeak events with an energy range of 400-600 keV are selected for analysis, in order to reduce the influence of Compton scattering events on timing measurements. The time difference between the signals of the two detectors is defined as:

$$\Delta t = T_{test} - T_{ref} \qquad (8)$$

where T_{test} and T_{ref} denote the signal times recorded by the detector under test and the reference detector, respectively, and the standard deviation is σ_t.

Figure 4(a) Energy-resolution variation line plot

Figure 4: Figure 4(a) Energy-resolution variation line plot

Figure 4(b) Energy-resolution variation line plot

Figure 5: Figure 4(b) Energy-resolution variation line plot

The time-difference distribution is fitted with a Gaussian function, and the coincidence time resolution is defined as:

$$CTR = 2.355 \times \sigma_t \qquad (9)$$

2 Results and Analysis

2.1 Energy Resolution

To analyze the energy-response performance of the two types of SiPMs within the actual operating-voltage range, this work tested the 511 keV energy resolution after coupling Beijing Zhongke Photon SiPMs and Hamamatsu Photonics SiPMs, respectively, with LYSO and GAGG crystals of different sizes. As can be seen from Figure 4, within the measured operating-voltage range, the energy resolution of the two types of SiPMs under different crystal conditions varies only slightly with the operating voltage overall, showing relatively gentle and stable characteristics. The reason may be that, within this operating-voltage range, the SiPM gain increases as the voltage rises, which helps increase the signal amplitude; however, at the same time, factors such as dark counts, optical crosstalk, and microcell saturation also affect the energy response. Therefore, the energy

resolution did not continue to improve as the operating voltage increased. In comparison, the NDL SiPM achieved relatively good energy resolution under most crystal conditions, indicating that domestic SiPMs have good energy-resolving capability in 511 keV gamma-photon energy measurements.

Figure 4 Line plots of energy-resolution variation

(a) NDL SiPM coupled to $2 \times 2 \times 3$ mm^3 and $2 \times 2 \times 20$ mm^3 LYSO and GAGG crystals; (b) Hamamatsu SiPM coupled to $2 \times 2 \times 3$ mm^3 and $2 \times 2 \times 20$ mm^3 LYSO and GAGG crystals.

On the basis of analyzing the overall variation trend, single energy spectra under typical operating-voltage conditions were further selected for analysis; the results are shown in Figure 5. Among them, the operating voltage of the NDL SiPM was 32 V, and that of the Hamamatsu SiPM was 43 V. Both SiPMs, after being coupled to $2 \times 2 \times 3$ mm^3 LYSO crystals, were able to obtain a relatively clear 511 keV photopeak, and the Gaussian fitting results for the photopeak region agreed well with the measured energy spectra, indicating that

Figure 5(a) Energy-resolution plot

Figure 6: Figure 5(a) Energy-resolution plot

Figure 5(b) Energy-resolution plot

Figure 7: Figure 5(b) Energy-resolution plot

the fitting results could well reflect the energy-response characteristics of the detector. According to the photopeak position and standard deviation obtained from Gaussian fitting, the energy resolutions of the NDL SiPM and Hamamatsu SiPM were $10.2 \pm 0.6\%$ and $12 \pm 0.6\%$, respectively.

Figure 5 Energy-resolution plots

(a) NDL SiPM coupled to a $2 \times 2 \times 3$ mm^3 LYSO crystal; (b) Hamamatsu SiPM coupled to a $2 \times 2 \times 3$ mm^3 LYSO crystal.

2.2 Signal-to-noise ratio

To analyze the signal response and noise characteristics of the two SiPMs under actual operating-voltage conditions, the signal-to-noise ratios of the NDL SiPM and Hamamatsu SiPM when respectively coupled to $2 \times 2 \times 20$ mm^3 LYSO crystals were tested; the results are shown in Figure 6. Within the tested operating-voltage range, both SiPMs were able to obtain stable signal output. As the operating voltage increased, the SiPM gain gradually increased, the scintillation-signal amplitude increased accordingly, and the overall signal-to-noise ratio showed an upward trend, tending to stabilize or showing a slight decrease under higher operating-voltage conditions. This is mainly related to

At high operating voltage, dark count rate and optical crosstalk increase, and the rise in noise level limits further improvement of the signal-to-noise ratio. From the overall variation curves of the two SiPMs, it can be seen that the signal-to-noise ratio of the Hamamatsu Photonics SiPM is overall higher than that of the NDL SiPM, indicating better signal response and noise suppression capability. At representative operating voltages, the operating voltage of the NDL SiPM is 32 V, and the measured signal-to-noise ratio is 548.6 ± 1.4; the operating voltage of the Hamamatsu Photonics SiPM is 43 V, and the measured signal-to-noise ratio is 590.7 ± 1.5.

Figure 6. Signal-to-noise ratio plots. (a) NDL SiPM coupled to a $2 \times 2 \times 20$ mm^3 LYSO crystal; (b) Hamamatsu Photonics SiPM coupled to a $2 \times 2 \times 20$ mm^3 LYSO crystal.

Figure 8: Figure 6. Signal-to-noise ratio plots. (a) NDL SiPM coupled to a $2 \times 2 \times 20$ mm^3 LYSO crystal; (b) Hamamatsu Photonics SiPM coupled to a $2 \times 2 \times 20$ mm^3 LYSO crystal.

Figure 6 Signal-to-noise ratio plots

(a) NDL SiPM coupled to a $2 \times 2 \times 20$ mm^3 LYSO crystal; (b) Hamamatsu Photonics SiPM coupled to a $2 \times 2 \times 20$ mm^3 LYSO crystal.

To further verify the influence of the signal-to-noise-ratio calculation method on the comparison results, this paper recalculated the data of the two SiPMs at all tested operating voltages using a logarithmic signal-to-noise-ratio formula based on the ratio of the standard deviations of the signal voltage and the noise voltage, and compared the results with those obtained by the method of formula (1). The calculation results show that there is a certain difference in the absolute numerical values of the signal-to-noise ratios obtained by the two methods, but the overall trends with operating voltage and the relative performance relationship between the two SiPMs remain consistent. Table 2 lists the calculation results for the two SiPMs at representative operating voltages. The conclusions obtained using the traditional logarithmic signal-to-noise-ratio formula are consistent with the variation trends and comparison results reflected in Figure 6.

Table 2 Comparison of calculated signal-to-noise-ratio results for the two SiPMs at representative operating voltages

SiPM	Representative operating voltage/V	SNR	SNR/dB
NDL	32	548.6 ± 1.4	~ 62.2
Hamamatsu Photonics	43	590.7 ± 1.5	~ 62.9

2.3 Coincidence time resolution

To analyze the time-response performance of the two SiPMs within their actual operating-voltage ranges, this paper separately tested the coincidence time resolution of the NDL SiPM and the Hamamatsu Photonics SiPM after coupling them to LYSO and GAGG crystals of different sizes, and performed Gaussian fitting analysis on the coincidence-time-difference distributions. Figure 7 gives the variation relationship of the coincidence time resolution of the two SiPMs when coupled to different crystals within their respective operating-voltage ranges. It can be seen from the figure that, within the tested operating-voltage range, both SiPMs can obtain relatively good time-response performance under different crystal conditions, and the coincidence time resolution generally shows an improving trend as the operating voltage increases, gradually tending to stabilize at higher operating voltages. The possible reason is that, as the operating voltage increases, the SiPM gain increases, the output signal amplitude increases, and the rising edge of the signal becomes steeper, which is conducive to improving the time-pickoff precision; however, when the operating voltage continues to increase, noise factors such as dark count and optical crosstalk also become stronger, so the improvement in coincidence time resolution gradually decreases.

Figure 7(b): Coincidence time resolution versus operating voltage. The vertical axis is "Coincidence time resolution / ps," and the horizontal axis is "Operating voltage / V." Curves are labeled 20 mm GAGG, 3 mm GAGG, 20 mm LYSO, and 3 mm LYSO.

Figure 9: Figure 7(b): Coincidence time resolution versus operating voltage. The vertical axis is "Coincidence time resolution / ps," and the horizontal axis is "Operating voltage / V." Curves are labeled 20 mm GAGG, 3 mm GAGG, 20 mm LYSO, and 3 mm LYSO.

Figure 8(a): coincidence time distribution for Zhongjing Photoelectric SiPM coupled with a $2 \times 2(\times)3$ mm^3 LYSO crystal. The plot is labeled "FWHM 105.7 ± 1.4 ps." Figure 8(b): coincidence time distribution for Hamamatsu Photonics SiPM coupled with a $2 \times 2(\times)3$ mm^3 LYSO crystal. The plot is labeled "FWHM 101.9 ± 1.0 ps."

Figure 10: Figure 8(a): coincidence time distribution for Zhongjing Photoelectric SiPM coupled with a $2 \times 2(\times)3$ mm^3 LYSO crystal. The plot is labeled "FWHM 105.7 ± 1.4 ps." Figure 8(b): coincidence time distribution for Hamamatsu Photonics SiPM coupled with a $2 \times 2(\times)3$ mm^3 LYSO crystal. The plot is labeled "FWHM 101.9 ± 1.0 ps."

Figure 7 Line plots of the variation in coincidence time resolution

(a) Zhongjing Photoelectric SiPM coupled with $2 \times 2 \times 3$ mm^3 and $2 \times 2 \times 20$ mm^3 LYSO and GAGG crystals; (b) Hamamatsu Photonics SiPM coupled with $2 \times 2 \times 3$ mm^3 and $2 \times 2 \times 20$ mm^3 LYSO and GAGG crystals.

On the basis of the analysis of the overall variation trends, the coincidence time-difference distributions under typical operating-voltage conditions were further selected for analysis. The results are shown in Figure 8. Among them, the operating voltage of the Zhongjing Photoelectric SiPM was 32 V, and that of the Hamamatsu Photonics SiPM was 43 V. The coincidence time-difference distributions obtained after coupling both SiPMs with the $2 \times 2 \times 3$ mm^3 LYSO crystal were approximately Gaussian, and the Gaussian fitting results were in good agreement with the experimental data, indicating that the fitting results could well reflect the time-response characteristics of the detector. From the full width at half maximum of the time distributions obtained by Gaussian fitting, the coincidence time resolutions of the Zhongjing Photoelectric SiPM and the Hamamatsu Photonics SiPM were calculated to be 105.7 ± 1.4 ps and 101.9 ± 1 ps, respectively.

Figure 8 Coincidence time resolution plots

(a) Zhongjing Photoelectric SiPM coupled with a $2 \times 2 \times 3$ mm^3 LYSO crystal; (b) Hamamatsu Photonics SiPM coupled with a $2 \times 2 \times 3$ mm^3 LYSO crystal.

To further analyze the optimal timing performance under different combinations of SiPMs and crystals, Table 3 summarizes the best coincidence time resolutions measured for the two SiPMs under different crystal conditions. It can be observed that, under all test conditions, the LYSO crystal exhibited better timing performance than the GAGG crystal, mainly because the LYSO crystal has a higher light output and a faster decay time. Under the $2\times2\times3$ mm^3 LYSO crystal condition, the best coincidence time resolution measured with the Zhongjing Photoelectric SiPM was 103.1 ± 1 ps, whereas the coincidence time resolution measured with the Hamamatsu SiPM was 101.9 ± 1 ps; the two showed similar timing performance. The results show that the Zhongjing Photoelectric SiPM can achieve good timing performance under different crystal conditions.

Table 3 Optimal coincidence time resolution under different SiPM and crystal conditions

SiPM type	Crystal type	Crystal size (mm^3)	Operating voltage (V)	Optimal CTR (ps)
NDL	LYSO	$2 \times 2(\times)3$	31.5	103.1 ± 1
Hamamatsu Photonics	LYSO	$2 \times 2(\times)3$	43	101.9 ± 1
NDL	LYSO	$2 \times 2(\times)20$	32	165.1 ± 1.6
Hamamatsu Photonics	LYSO	$2 \times 2(\times)20$	43	155.0 ± 1.5
NDL	GAGG	$2 \times 2(\times)3$	31.5	137.3 ± 1.6
Hamamatsu Photonics	GAGG	$2 \times 2(\times)3$	42	121.8 ± 1.6
NDL	GAGG	$2 \times 2(\times)20$	32	256.7 ± 3.2
Hamamatsu Photonics	GAGG	$2 \times 2(\times)20$	42	223.0 ± 2.7

3 Summary and Outlook

This study systematically evaluated the performance of a domestically produced, low-crosstalk silicon photomultiplier in a TOF-PET detector and compared it with a Hamamatsu Photonics SiPM. Its performance was comprehensively analyzed using key indicators including energy resolution, signal-to-noise ratio, and coincidence time resolution. The experimental results show that this low-crosstalk SiPM can achieve stable signal response and good detection performance under different crystal conditions.

In terms of energy resolution, when coupled to scintillation crystals, this SiPM can clearly resolve the 511 keV photoelectric peak. The best measured energy resolution was $8.4 \pm 0.5\%$ ($2 \times 2(\times)3$ mm^3 GAGG, 30 V), indicating excellent energy-response performance. The signal-to-noise-ratio test results show that, within the measured voltage range, this SiPM has stable signal-output characteristics under different operating-voltage conditions. The signal-to-noise ratio first increases and then decreases as the operating voltage rises; the best signal-to-noise ratio was 548.6 ± 1.5 ($2 \times 2(\times)20$ mm^3 LYSO, 32.5 V), demonstrating good photoelectric conversion capability and signal stability of the device. However, compared with the Hamamatsu Photonics SiPM, its signal-to-noise ratio still shows a certain gap, which may be related to differences in device structure and photon detection efficiency.

In terms of coincidence time resolution, this low-crosstalk SiPM exhibited good time-response performance. The best measured coincidence time resolution was 103.1 ± 1 ps ($2 \times 2(\times)3$ mm^3 LYSO, 31.5 V). Although its timing performance can reach the best level close to that of the Hamamatsu Photonics SiPM, its overall timing performance remains slightly lower than that of the Hamamatsu Photonics SiPM, indicating that there is still room for further optimization of its time-response performance.

In summary, the domestically produced, low-crosstalk silicon photomultiplier can achieve excellent energy resolution and good time-response performance, while also possessing stable signal-output capability, meeting the basic application requirements of TOF-PET detectors. Compared with the Hamamatsu Photonics SiPM, the photon detection efficiency of this device is already at a relatively close level. Meanwhile, its microcell size is 20 μm, smaller than the 50 μm microcell size of the Hamamatsu Photonics device; therefore, under the same effective area, it has a larger number of pixels, exhibits higher pixel density, and has certain advantages in dynamic range. These results indicate that domestically produced low-crosstalk SiPMs already have a performance basis for further application in TOF-PET detectors.

Based on the above performance and device characteristics, domestically produced SiPMs have favorable application prospects in the field of nuclear medical imaging. For a long time, key photoelectric readout devices such as high-performance SiPMs have mainly been dominated by foreign manufacturers; domestic devices still need to make further improvements in gain consistency, noise control, and

Continuous optimization has been carried out in readout matching and other aspects. In the future, with further advances in device fabrication processes, packaging technologies, and supporting readout electronics, domestic SiPMs are expected to find broader application in high-performance TOF-PET detectors and nuclear medical imaging equipment, and to provide support for the localization and independent development of related equipment.

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Performance Investigation of an Epitaxial Quenching Resistor Silicon Photomultiplier Applied in TOF-PET Detectors

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Abstract: Time-of-flight positron emission tomography (TOF-PET) is an important molecular imaging technique in clinical nuclear medicine. The continued development of TOF-PET has imposed increasingly stringent requirements on detector timing performance and detection efficiency, making the development of detectors with high timing resolution and high detection efficiency a key research focus. As the core component of the detector, the performance of the Silicon Photomultiplier (SiPM) directly influences the imaging quality of the system. This study evaluates the performance of a SiPM with epitaxial quenching resistors (model: CGN Capital Photonics Technology (Tianjin) (EQR20 11-4040D-SN)) and compares it with a reference SiPM of the same size. Lutetium–Yttrium Oxyorthosilicate (LYSO) and Gadolinium Aluminum

Gallium Garnet (GAGG) scintillators, with crystal dimensions of 2 × 2(×)3 mm^3 and 2 × 2(×)20 mm^3, were selected for the experiment and coupled with a 4 × 4 mm^2 SiPM using optical adhesive. Under a constant temperature of 16 °C and utilizing a ^{22}Na radioactive source, key performance metrics such as signal-to-noise ratio, energy resolution, and coincidence time resolution were systematically measured and analyzed for both SiPMs across various operating voltage ranges. The experimental results demonstrate that the SiPM with epitaxial quenching resistors exhibits excellent overall performance under different operating voltages and crystal sizes. Specifically, at 32 V, the energy resolution for 511 keV annihilation photons using a 2 × 2(×)3 mm^3 LYSO crystal is 10.2 ± 0.54 %, and the coincidence time resolution is 105.7 ± 1.4 ps, highlighting its promising potential for application in TOF-PET detectors and providing experimental evidence for the localization of related detectors.

Keywords: Silicon photomultiplier (SiPM); time-of-flight positron emission tomography (TOF-PET); Coincidence time resolution (CTR)

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Note: Figure translations are in progress. See original paper for figures.