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Performance Evaluation of “XRPIX” Event-Driven SOI Pixel Detector for Cosmic MeV Gamma-ray Observation

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Cosmic MeV gamma-ray observations are important for elucidating physics in high-energy objects such as gamma-ray bursts and active galactic nuclear jet blazars, for detecting nuclear gamma-rays in supernova explosions, and for advancing multi-messenger astronomy. However, there has been no progress since the COMPTEL detector on board the CGRO satellites in the 1990s, and a satellite for MeV gamma-ray observations is essential. Compton scattering is the dominant interaction between MeV gamma-rays and matter. The minimal way to reconstruct the arrival direction of an incident gamma-ray is to utilize both the deposit energy and hit position measured in both the scatterer and absorber, giving an event circle. The circle can be reduced to an arc if the initial direction of the Compton scattered electron is measured. Thus such an electron-tracking Compton camera is expected to improve the source sensitivity by reducing background events. Therefore, our goal is to enable more accurate Compton imaging by using an event-driven SOI pixel detector “XRPIX” as a scatterer in an electron-track Compton camera. The pixel size of XRPIX is as small as 36 um square, so it is expected to capture electron trajectories for scattering of gamma-rays of several hundred keV. In this contribution, we report on the evaluation of the depletion layer thickness of XRPIX8.5, which can be fully depleted at room temperature, the sensor response when irradiated with gamma-rays such as 662 keV of Cs-137 and 511 keV of Na-22, and a method for estimating the direction of scattered electrons.

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1. Introduction

Gamma-ray bursts (GRBs) are the most powerful cosmic explosions, emitting energy equivalent to the Sun's entire lifetime within a span of a few seconds to a few hundred seconds. They are accompanied by the ejection of relativistic jets. A fraction of this energy dissipates and is radiated as gamma rays. Since their initial discovery in 1967 by the American nuclear test detection satellite ”Vela”, numerous satellites such as CGRO, Swift, and Fermi have been used for observation and research. However, many aspects of GRB physics remain unexplained, including the structure and acceleration mechanisms of the jets and the radiation mechanisms of gamma rays. Previous studies have revealed that GRB prompt emission peaks in the range of a few hundred keV to a few MeV and GRBs occur uniformly across the sky. Therefore, wide-field detectors with sensitivity to MeV gamma-rays are required for GRB observations.

Due to the dominant interaction of MeV gamma rays with matter through Compton scattering, the original energy and arrival direction of the gamma rays can be reconstructed through Compton imaging using scattering and absorption detectors, which measure the deposited energy and reaction position, respectively. In this process, the arrival direction of the original gamma ray is constrained to a circular ring. Furthermore, by detecting the track of scattered electron, the arrival direction can be further constrained to a specific azimuthal direction. This allows narrowing the circular ring to an arc, reducing background events without sacrificing the field of view. This type of device is known as an electron-tracking Compton camera. For the scattering detector of an electron-tracking Compton camera, a pixel detector with excellent position resolution, capable of accurately tracking the trajectory of electrons, is effective.

Therefore, we focused on the event-driven SOI (Silicon on Insulator) pixel detector called ”XRPIX”. XRPIX is a detector designed for X-ray astronomy, equipped with readout and trigger circuits in each pixel. It achieves high time resolution by reading out signals only from the regions where X-rays arrived, confirmed by trigger signals. This readout method is called event-driven readout and is the key feature of XRPIX. Additionally, XRPIX has a fine pixel size and a thick sensor layer, providing sufficient sensitivity to X-rays and gamma rays while maintaining a high position resolution capable of resolving the tracks of scattered electrons from Compton scattering of gamma rays with energies in the range of a few hundred keV. We aim to develop an electron-tracking Compton camera using XRPIX as the scattering detector, with the goal of achieving clearer imaging of MeV gamma-ray sources. In this study, we used XRPIX8.5 (Figure 1) with a pixel size of 36 µm and a sensor layer thickness of 300 µm, which allows a full depletion at room temperature, to detect the tracks of scattered electrons caused by gamma rays and developed the algorithm to determine their initial momentum direction.

2. Measurement of the depletion layer thickness

By applying a back bias to the electrodes of the sensor, the depletion layer sensitive to gamma rays can be expanded. If the scattered electrons enter the insensitive region, both their tracks and energies cannot be detected. Therefore, to verify a full depletion, we conducted measurements of the depletion layer thickness of XRPIX8.5. The measurements were performed at room temperature in event-driven readout mode, with the back bias varied from 10 V to 200 V. We used Am-241 as the

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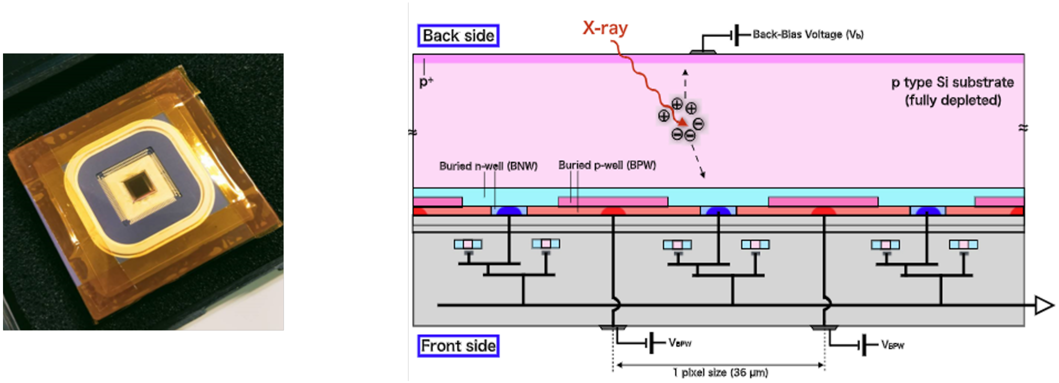

Figure 1: XRPIX8.5 (left) and its schematic drawing (right[1])

radiation source. The measurement of the depletion layer thickness can be obtained by measuring the counts of a specific peak and calculating the detection probability based on it. However, this method involves various parameters such as detector dead time and the solid angle subtended by the detector from the radiation source, making the systematic uncertainty larger. To address this, we measured the counts of two peaks and took their ratio to eliminate the parameters dependent on the experimental geometry and uncertainty of radiation source intensity. In the analysis, we first fit the peaks at 13.9 keV and 59.5 keV in the obtained energy spectrum with a Gaussian function. Then, we summed the counts within $\pm 3\sigma$ range around the peak centers for each bin. Next, we took the ratio of the summed counts for each peak and used

$$\begin{aligned}&\frac{Emission\ probability(13.9keV)}{Emission\ probability(59.5keV)} \times \frac{\exp\left(-\frac{d_{other}}{\lambda_{other}(13.9keV)}\right)}{\exp\left(-\frac{d_{other}}{\lambda_{other}(59.5keV)}\right)} \times \frac{\left[1-\exp\left(-\frac{W_{dep}}{\lambda_{Si}(13.9keV)}\right)\right]}{\left[1-\exp\left(-\frac{W_{dep}}{\lambda_{Si}(59.5keV)}\right)\right]} \\ &= \frac{Counts(13.9keV)}{Counts(59.5keV)}\end{aligned} \tag{1}$$

where d_{other} represents the thickness of the non-Si material, λ is the product of the density and the photoelectric cross-section for each energy, and W_{dep} is the depletion layer thickness being calculated. The second term of the left-hand side in Equation 1 represents the ratio of the probability of transmission through non-Si materials, such as a protective sheet or air.

The left side of Figure 2 shows the energy spectrum of Am-241. The energy is shown on the horizontal axis and the counts are shown on the vertical axis in logarithmic scale. The generated charge might not be entirely captured by a single pixel and could be collected across multiple pixels. Therefore, we created this spectrum by summing the counts of events where the number of pixels capturing charge ranged from 1 to 5. The right side of Figure 2 shows the results of the depletion layer thickness measurement. The horizontal axis represents the back bias, while the vertical axis represents the depletion layer thickness. The depletion layer thickness was determined to be 276 ± 7 (stat.) μm at a back bias of 200 V, which is close to the thickness of the sensor layer, approximately 300 μm.

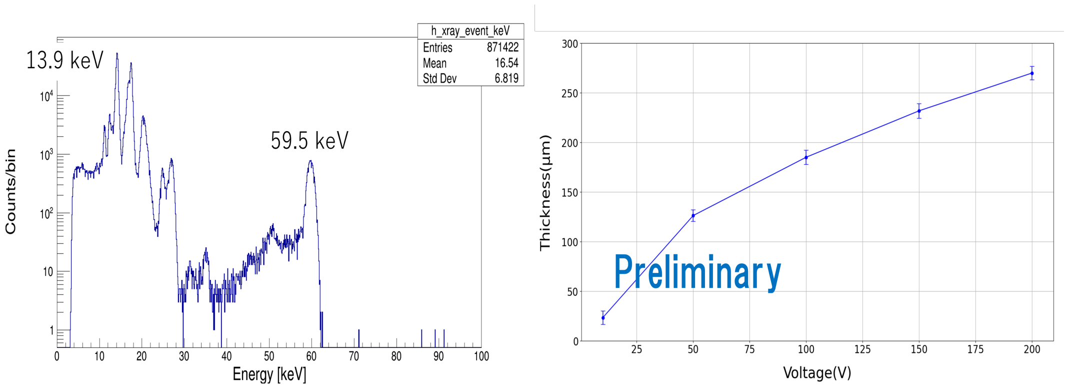

Figure 2: Energy spectrum of Am-241 and depletion layer thickness of XRPIX8.5

3. Evaluation of response to gamma rays

3.1 Energy Spectrum

The measurements of energy spectrum were conducted at room temperature, in event-driven readout mode, with a back bias of 200 V. We used three types of radioactive sources: Co-57 (122 keV, 136 keV), Na-22 (511 keV, 1275 keV), and Cs-137 (662 keV). In the event-driven readout mode of XRPIX, an 8 pixels x 8 pixels region centered around the pixels where X-rays or gamma rays hit is read out. For the analysis, within the 8x8 pixel region, the pulse height of the pixels that exceeded the threshold were summed to create an energy spectrum. The threshold was set as +10σ from the mean of pedestal distribution.

Figure 3 shows the energy spectrum for Co-57 (black), Na-22 (blue) and Cs-137 (red). First, the photoelectric absorption peak at 122 keV is observed for the Co-57 spectrum. The 136 keV peak is mostly overlapped with the 122 keV peak, but it can still be faintly observed. Second, the photoelectric absorption peaks at 511 keV (Na-22) and 662 keV (Cs-137) are not visible. Instead, a smooth distribution is observed from 100 keV to 400 keV, indicating the occurrence of Compton scattering of gamma rays in XRPIX. Figure 4 is a plot of the number of pixels that exceeded the threshold against energy. We used Cs-137 (662 keV) as the radiation source. The positive correlation indicates that as the energy increases, electrons pass over more pixels.

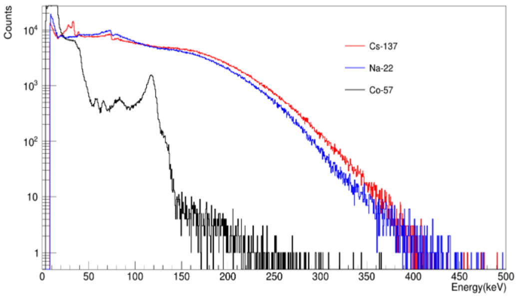

Figure 3: Energy spectrum of Co-57 (black), Na-22 (blue) and Cs-137 (red)

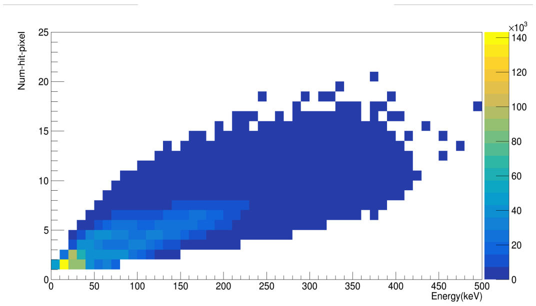

Figure 4: The number of pixels that exceeded the threshold against energy (Cs-137, 662 keV)

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3.2 Energy calibration and Energy Resolution

We evaluated the linearity of the output with respect to the irradiated gamma rays. Figure 5 shows the energy calibration line. The solid line is the calibration line for X-ray data. This is obtained by fitting the data points with a straight line up to 25 keV. The obtained straight line was extended towards the high-energy side, indicated by the dashed line. As a result, it can be observed that the three points of Am-241 at 59.5 keV, Co-57 at 122 keV, and Cs-137 at 184 keV, which is backscattering to 662 keV, are roughly on the line and the dynamic range up to 184 keV is confirmed. The deviation from the line was within 7 percent at most. Figure 6 plots the full width at half maximum (FWHM) of each peak against energy. This one was confirmed to follow the power law up to 122 keV of Co-57.

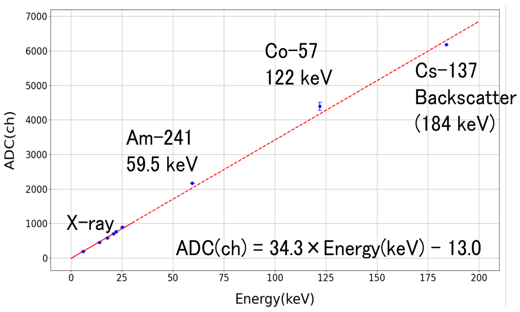

Figure 5: Energy calibration. The solid line represents the data points fitted with a straight line up to 25 keV. The dashed line is an extension of that solid line.

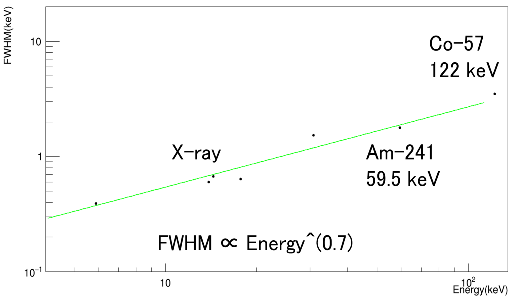

Figure 6: Energy resolution. Both axes are shown in logarithmic scale. The green line represents the data points fitted with a power law function.

3.3 Track of scattered electron

Since the tracks of scattered electron has been observed with previous versions of XRPIX ([3–5]), we also output the tracks of scattered electrons for each event with XRPIX8.5. Within the 8x8 pixels region, we plotted the coordinates of the pixels that exceeded the threshold and indicated the pulse height of each pixels on a 2D map. The threshold value used was the same as when creating the spectrum. Figure 7 shows some examples of the output results. We successfully detected the tracks of electrons with energies of approximately 300 keV and confirmed the bragg peak. The red arrows in the figure represent the estimated direction of the tracks. Since the bragg peak corresponds to the endpoint of the track, it can be used to determine the initial momentum direction of the scattered electrons.

4. Direction reconstruction algorithm for Compton-scattered electrons

4.1 Measurement

Determining the initial momentum direction of scattered electrons is essential for the realization of an electron-tracking Compton camera. To develop an algorithm for determining the initial momentum direction of electrons, we obtained samples of electron tracks using Sr-90, which

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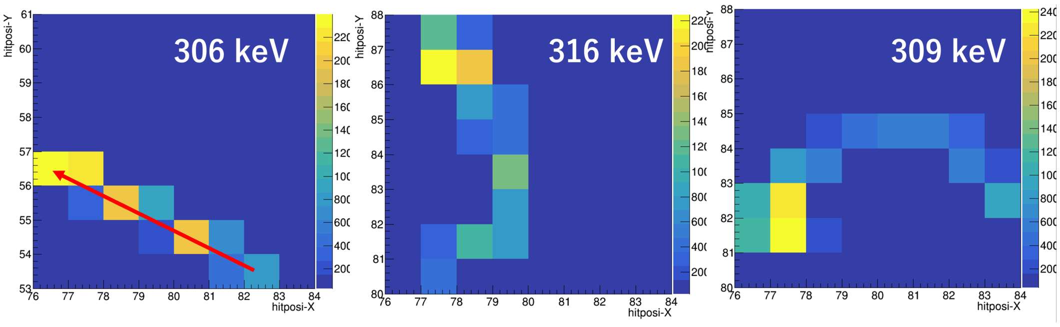

Figure 7: Tracks of Compton-scattered electrons ejected by the 662 keV gamma rays from Cs-137

emits beta particles. The measurements were conducted at room temperature in event-driven readout mode with a back bias of 200 V. Additionally, we positioned the radiation source to induce anisotropy in the beta radiation.

4.2 Algorithm

From the obtained data, we first output the electron tracks using the same method as in Section 3.3. However, if we leave it as it is, the tracks will align with the pixel arrangement, which limits the possible angles and leads to a discrete distribution in the arrival direction distribution. To address this, we applied the charge centroid method to correct the positions where the electrons passed through. Specifically, we took a weighted average of the pulse heights within a 3x3 range centered around each pixel that exceeded the threshold. The charge centroid method has already been used in other pixel detectors ([2]).

Next, we determine the starting point of the tracks. We identified the position with the maximum pulse height as the bragg peak, which we considered as the ending point. Then, we calculated the distances from the ending point to other points and selected the point with the maximum distance as the starting point. Once the starting point was determined, we measured the distances from the starting point to other points and selected three points, including the starting point, which the electron first passed through. We fitted these three points with a straight line to calculate the angle based on the slope. Through this process, we were able to determine the initial momentum direction of the electrons.

In this study, we developed an algorithm to apply this sequence, from the correction of electron positions using the charge centroid method to the fitting with a straight line, to all acquired events. Figure 8 provides an example of the obtained track and the result after applying the algorithm. By correcting the electron tracks from being aligned with the pixel arrangement to a sequence of points where the electrons passed through and performing the fitting only around the starting point of the tracks, we successfully determined the initial momentum direction for the electrons.

4.3 Incident direction distribution

Figure 9 is a histogram of the obtained angles. It is evident that there are peaks in the targeted angle of -135° and its opposite direction 45°. The algorithm developed in this study assumes the existence of a bragg peak, so there is a risk of incorrectly determining the starting and ending points of the tracks when the electron penetrates the detector. However, since gamma-ray detection targets

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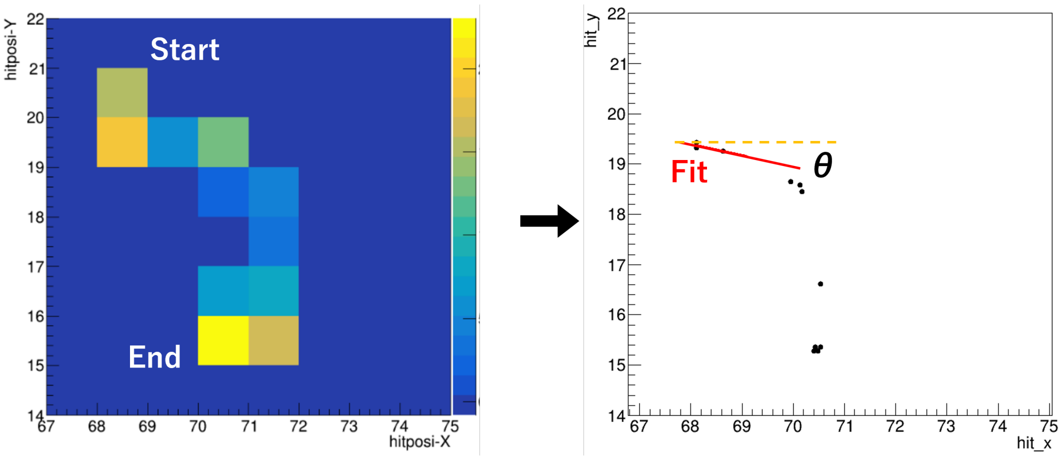

Figure 8: Original track (left) and charge weighted average points (right)

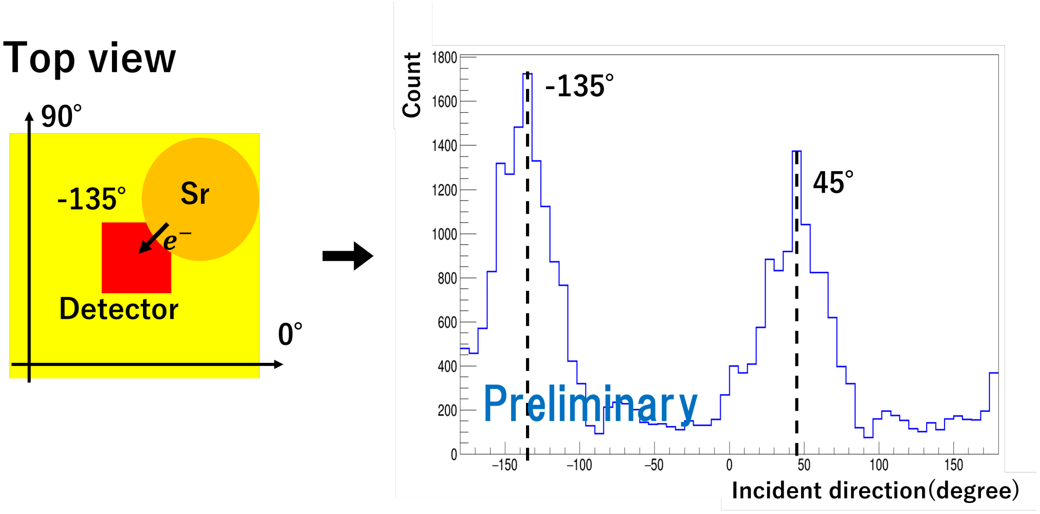

Figure 9: Experiment setup (left) and incident direction distribution (right)

energy ranges where the bragg peak is visible, the starting point of the track would be correctly determined for gamma rays. Through this experiment, we confirmed that XRPIX8.5 has sensitivity to the direction.

5. Summary

We are developing an electron track-based Compton camera using the event-driven SOI pixel detector ”XRPIX” for cosmic MeV gamma-ray observations. XRPIX combines a thick sensor layer with fine pixel size, providing sensitivity to gamma rays in the few hundred keV range while offering high position resolution to resolve the tracks of scattered electrons. In this study, we investigated the response of XRPIX, originally developed for X-ray astronomy, to gamma rays. As a result, we confirmed a dynamic range up to 184 keV and successfully detected the tracks of scattered electrons with energies of 300 keV. Furthermore, we developed an algorithm to determine the initial

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momentum direction of the obtained electron tracks. By applying this algorithm to the data obtained from electron irradiation, we were able to demonstrate the sensitivity of XRPIX to direction. Our research so far allows us to obtain the deposited energy, reaction position, and initial momentum direction of the scattered electrons for each event where gamma rays arrived. Based on these results, one can say that XRPIX is an effective scatterer for electron track-based Compton cameras. In our future work, we plan to combine the absorber with the scatterer and select Compton events using trigger signals from both detectors. Ultimately, we aim to discuss the impact of background event removal based on the direction of electron tracks on the determination of the incident direction of the gamma-rays.

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