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Development of low-noise double-sided silicon strip detector for cosmic soft gamma-ray Compton Camera

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Abstract

Double-sided silicon strip detectors (DSSD) provide a very promising technology for constructing a Compton Camera, which is expected to provide a high-sensitivity soft gamma-ray observation in the 0.1–20 MeV energy range. The merits of DSSD are the high-energy resolution, high scattering efficiency, low radio-activation in the orbit, moderate radiation hardness, smaller Doppler broadening, large size, and stable performance. A key feature for optimal performance is the low noise level of the DSSD and the attached frontend electronics. We minimized the noise by optimization of the electrode geometry of the DSSD. We have thus obtained an energy resolution of 1.3 keV (FWHM) for 60 and 122 keV at $-10\,^{\circ}\mathrm{C}$. It was found that the detection efficiency for gamma-rays was uniform over the DSSD and the signal charge split between neighboring strips was not significant. We also confirmed that the Compton imaging by two DSSDs achieved a good angular resolution close to the Doppler-broadening limit.

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Keywords: Silicon strip detector; Compton Camera; VA-chip; Gamma-ray detector

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1. Introduction

Recent soft gamma-ray observations have revealed that the universe is rich in high-energy phenomena, associated with supernova remnants, black holes, pulsars, clusters of galaxies, and gamma-ray bursts. Observations of nonthermal gamma-ray emissions is important to understand

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the physics of these phenomena. However, high-sensitivity observations in the energy range of 10 keV to 20 MeV have not been possible due to difficulties in detection, imaging, and background rejection. Recent developments of the hard X-ray telescope will improve the sensitivity below 80 keV, but the energy range between 0.1 and 20 MeV will still be unaffected. Since Compton scattering is the dominant photon–matter interaction, the Compton imaging telescope is the appropriate tool for studying this energy range. The COMPTEL onboard the Compton Gamma-Ray Observatory (CGRO) was the first instrument to use Compton imaging, and it was found to be very effective in the MeV gamma-ray observation. A more sophisticated technique for Compton imaging has become available, through the use of segmented semiconductor detectors, such as silicon strip detectors and CdTe (Cadmium Telluride) pixel detectors [1–4]. A multi-layer semiconductor detector allows good energy resolution, good angular resolution, compactness, small weight, high efficiency, and effective background rejection.

Compton imaging of gamma-rays is based on the measurement of detector records of scattered and absorbed photons. When the gamma-ray with an incident energy E_1 is scattered by the detector material, the scattering angle θ against the incident direction is constrained as

$$\cos\theta = 1 + \frac{m_e c^2}{E_1 + E_2} - \frac{m_e c^2}{E_2}$$

where E_2 and $m_e c^2$ are the energy of the scattered photon and the electron rest mass, respectively. The incident direction of one gamma-ray is constrained to a cone with the opening angle θ, and we can determine the source position by superposing the Compton cones of many events. The uncertainty of measurement of the recoil electron energy $E_1 - E_2$, that mainly determines the angular resolution, is attributed to the detector energy resolution and to the Doppler broadening of the energy of the recoil electron caused by the orbital angular momentum of electrons bound to the atoms. The limit to the angular resolution induced by Doppler broadening is $\sim 4^\circ$ and $\sim 1^\circ$ for a gamma-ray energy of 100 and 500 keV, respectively, and the contribution of the detector energy resolution δE becomes important for $\delta E > 2$ keV (FWHM). We are developing a low-noise Compton camera with the energy resolution of ~ 1.5 keV (FWHM) for the soft gamma-ray detector.

Our choice consists of a multi-layer semiconductor hybrid detector with double-sided silicon strip detectors (DSSD) and CdTe pixel detectors. The DSSD is suitable as a scattering material because it provides good position resolution, good energy resolution, high scattering efficiency and small Doppler broadening. Low radio activation by protons in the orbit also helps us to achieve a low background level. At photon energies of 0.1–0.5 MeV, Compton scattering occurs mainly in the DSSD layers and the scattered photon is absorbed by the CdTe layers. In order to capture the scattered photon, the DSSD layers are surrounded by the CdTe detectors. At higher energy, multiple scattering frequently occurs, but tracking three hits of Compton scattering is sufficient to reconstruct the energy and the direction of the incident photon [1]. In order to achieve the required energy resolution, a low-noise multi-channel readout large-scale integration (LSI) is also a key feature. A detailed introduction and early demonstration have been reported by Tajima et al. [5,6] and Mitani et al. [7]. In this paper, we shortly describe the optimization of the detector components to improve the energy resolution, and demonstrate the good performance of Compton imaging. A detailed description of the performance of the DSSD, of the DSSD in combination with the CdTe pixels, and of the polarization measurement are reported in Fukazawa et al. [10], Tanaka et al. [11], and Tajima et al. [8,9], respectively.

2. Low-noise DSSD system

The DSSD were designed with no bias resistors and AC coupling capacitances, to allow readout with DC coupled electronics. Alternatively, we used a dedicated chip (the RC chip) to provide biasing resistors and decoupling capacitances to the read-out electronics. The DSSDs and RC chips are fabricated by Hamamatsu Photonics, Japan.