Nuclear Instruments and Methods in Physics Research A 695 (2012) 179–183

Contents lists available at SciVerse ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

High-resolution Compton cameras based on Si/CdTe double-sided strip detectors

Hirokazu Odaka [a,*], Yuto Ichinohe [a,b], Shin'ichiro Takeda [a], Taro Fukuyama [a,b], Koichi Hagino [a,b], Shinya Saito [a,b], Tamotsu Sato [a,b], Goro Sato [a], Shin Watanabe [a], Motohide Kokubun [a], Tadayuki Takahashi [a,b], Mitsutaka Yamaguchi [c], Takaaki Tanaka [d], Hiroyasu Tajima [e], Kazuhiro Nakazawa [b], Yasushi Fukazawa [f]

[a] *Department of High Energy Astrophysics, Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), 3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa 252-5210, Japan*
[b] *Department of Physics, Graduate School of Science, University of Tokyo, Hongo 7-3-1, Bunkyo, Tokyo 113-0033, Japan*
[c] *Takasaki Advanced Radiation Research Institute, Japan Atomic Energy Agency (JAEA), 1233 Watanuki-machi, Takasaki, Gunma 370-1292, Japan*
[d] *Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94305, USA*
[e] *Solar-Terrestrial Environment Laboratory, Nagoya University, Furo-cho, Chikusa, Nagoya 464-8601, Japan*
[f] *Department of Physical Science, Hiroshima University, 1-3-1 Kagamiyama, Higashi-Hiroshima, Hiroshima 739-8526, Japan*

ARTICLE INFO

Available online 27 December 2011

Keywords:
Gamma-ray imaging
Compton camera
CdTe double-sided strip detector

ABSTRACT

We have developed a new Compton camera based on silicon (Si) and cadmium telluride (CdTe) semiconductor double-sided strip detectors (DSDs). The camera consists of a 500-μm-thick Si-DSD and four layers of 750-μm-thick CdTe-DSDs all of which have common electrode configuration segmented into 128 strips on each side with pitches of 250 μm. In order to realize high angular resolution and to reduce size of the detector system, a stack of DSDs with short stack pitches of 4 mm is utilized to make the camera. Taking advantage of the excellent energy and position resolutions of the semiconductor devices, the camera achieves high angular resolutions of 4.5° at 356 keV and 3.5° at 662 keV. To obtain such high resolutions together with an acceptable detection efficiency, we demonstrate data reduction methods including energy calibration using Compton scattering continuum and depth sensing in the CdTe-DSD. We also discuss imaging capability of the camera and show simultaneous multi-energy imaging.

1. Introduction

A Compton camera using high-resolution semiconductor detectors is a promising gamma-ray imaging spectrometer in the energy band from 100 keV up to 10 MeV, in which Compton scattering is dominant over other interactions of a photon with matter. In astrophysics, gamma rays in this energy band are important probes of energetic phenomena in the universe such as cosmic-ray acceleration and nucleosynthesis. In this field, the first Compton telescope in orbit, *COMPTEL* [1], provided pioneering results of the gamma-ray sky. The gamma-ray imaging technique is also useful for medical imaging, nondestructive inspection, and search for radioactive isotopes.

The authors have been developing Compton cameras based on advanced technologies of silicon (Si) and cadmium telluride (CdTe) semiconductor detectors with high energy and position resolutions [2–4]. Adoption of such devices are great advantage to the angular (spatial) resolution since it depends mainly on precision of the energy and position measurements. Si is good scatterer since it yields a large Compton-scattering probability and has a small Doppler broadening effect; this effect degrades the angular resolution due to nonzero momentum of the target electron [5]. On the other hand, CdTe is used as absorber owing to its large photoelectric-absorption cross section. Using our camera prototypes [6], we have achieved an excellent angular resolution of 2.5° at 511 keV [7], and have demonstrated high-resolution Compton imaging for diffuse emission as well as point sources, resolving a-few-millimeter scale structure at a distance of several centimeters from the detector head [8]. In addition, high-precision polarimetry was conducted using a synchrotron photon beam [9].

In this work, we have developed a new Compton camera that simultaneously realizes high angular resolution and compactness of the entire detector size. The high-density integration of the camera is essential to obtain acceptable detection efficiency for all applications and to achieve fine spatial resolution for near-source

* Corresponding author.
E-mail address: odaka@astro.isas.jaxa.jp (H. Odaka).

0168-9002/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.nima.2011.12.061

imaging such as medical applications. The camera consists of a compact multiple-layer stack of Si and CdTe double-sided strip detectors (DSDs) which have common geometrical configurations. This modular design allows us to optimize the scale (e.g. the number of the stacks) of the camera for future practical applications. In the present paper, we describe the detector design and analysis methods to obtain the high angular resolution with the ultra-compact instruments, and then show achieved performances. The detector concept is adopted as the key technology for the Hard X-ray Imager (HXI) and the Soft Gamma-ray Detector on board the *ASTRO-H* X-ray observatory, which is scheduled for launch in 2014 [10].

2. Detector design

The new Compton camera consists of a 500-μm–thick Si-DSD (collaboration with Hamamatsu Photonics) and four layers of 750-μm–thick CdTe-DSDs (collaboration with ACRORAD), as shown in Fig. 1. The CdTe detector holds aluminum (Al) electrodes on the anode (high-voltage side) and platinum (Pt) electrodes on the cathode. As we adopt a modular design to assemble the detector system, the camera is designed as a stack of "standardized" detector trays with detector-to-detector pitches of 4 mm. Fig. 2 shows the tray on which each detector is integrated with front-end readout electronics including eight signal processing ASICs (VATA 460). Each detector has the same active area of 32×32 mm^2 and the same electrode configuration that is segmented into 128 strips on each side with strip pitches of 250 μm. The readout ASIC simultaneously processes signals from 32 strips and digitizes the heights of the shaped pulses. The HXI onboard *ASTRO-H* adopts similar module, but it has different detector numbers (four Si-DSDs and one CdTe-DSD) and different readout ASICs (VATA 461).

In the experimental evaluation of the camera, these detectors were operated about $-15\,^{\circ}$C. A bias of 250 V was applied to the Si-DSD for full depletion; a bias of 250 V was applied to the

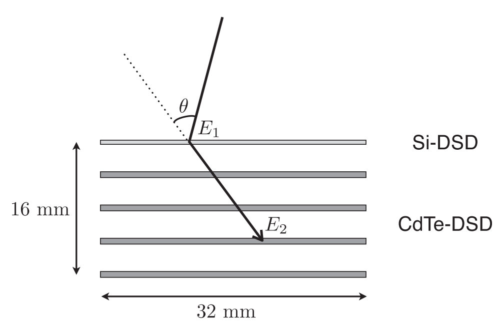

Fig. 1. Schematic drawing of the Si/CdTe Compton camera.

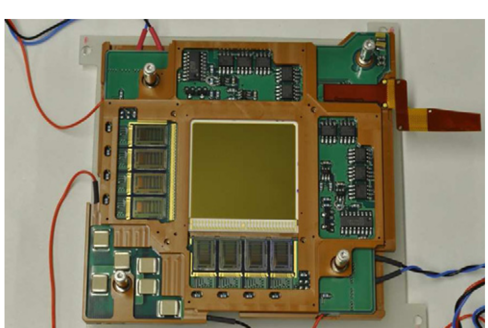

Fig. 2. Photograph of the CdTe-DSD tray.

CdTe-DSDs, balancing between increasing charge collection efficiency and suppressing leakage currents. The typical energy resolution of the Si-DSD was 2.3 keV (full width at half-maximum or FWHM) at 59.5 keV. The CdTe-DSD achieved energy resolutions of 3.8 keV (FWHM) at 81.0 keV and $\Delta E/E=3\%$ (FWHM) at 511 keV. Since VATA 460 is low-gain or high-dynamic-range type, its spectral performance is modest comparing to an energy resolution of 1.7 keV at 59.5 keV obtained by an equivalent CdTe-DSD with high-gain type VATA 461. Detailed description of CdTe-DSDs are given by Watanabe et al. and Ishikawa et al. [11,12].

3. Data reconstruction

As shown in Fig. 1, a typical Compton event consists of a scattering in Si and an absorption in CdTe. By using the energies of the recoil electron (E_1) and of the scattered photon (E_2), the scattering angle θ_K and the energy E of the incident photon are given by the Compton kinematics:

$$\cos\theta_K = 1-\frac{m_e c^2}{E_2}+\frac{m_e c^2}{E_1+E_2}, \quad E=E_1+E_2, \tag{1}$$

where m_e is the electron mass and c is the speed of light. When the scattering angle θ_G is geometrically calculated by the positions of the two interactions and the given incident direction, the difference between the scattering angles calculated in two ways, $\Delta\theta=\theta_K-\theta_G$, provides the angular resolution measure (ARM) of the Compton camera. Obviously, uncertainties of the measured energies and positions affects the performance of Compton imaging. In this section, we describe analysis methods to fulfill simultaneously high angular resolution and sufficient efficiency.

3.1. Energy calibration

Accurate gain calibration are essential to make the best use of the high-resolution semiconductor detectors. Though we usually apply gamma-ray radioactive sources to energy calibration, it is not realistic to use photoelectric peaks at high energies for this purpose. Above 150 keV, photoelectric absorption hardly occurs in Si; furthermore, absorption events would be infrequent even in CdTe when the trigger logic requires event coincidence in both the Si and CdTe detectors.

We propose a calibration method using Si–CdTe two-hit events, which are major events of the Compton camera. The following is brief description of the calibration procedure. First, a temporary gain correction function from the pulse height value to the energy is determined by using photoelectric peaks below $E_{sup}=136$ keV (^{57}Co) for every readout channel. Above E_{sup}, the functions are linearly extrapolated. At this step, we have obtained gain functions which are valid below E_{sup}. Second, by using the two-hit events that satisfy $E_1+E_2=E_{line}$ within a certain error and $E_1<E_{sup}$, we fit gain functions of the CdTe detectors represented as third-order polynomials, regarding a true value of E_2 as $E_{line}-E_1$. Here, we have applied gamma-ray lines of 356 keV (^{133}Ba), 511 keV (^{22}Na), and 662 keV (^{137}Cs). Final gain correction functions of the CdTe detectors are obtained in the second step. Third, we fit gain functions of the Si detector above E_{sup}, regarding a true value of E_1 as $E_{line}-E_2$, where the calibrated values of E_2 at the second step are used. Consequently, we have obtained well-calibrated gain functions of all the detectors in the entire energy range.

Fig. 3 shows correlations between E_1 (Si) and E_2 (CdTe) using the temporary gain functions at the first step and those at the final step for the ^{137}Cs data. After the calibration, the two-hit events are distributed along the line $E_1+E_2=E_{line}$ (662 keV). This