SLAC-PUB-11147
April 2005

Application of CdTe for the NeXT Mission

Tadayuki Takahashi[a,b,*] Kazuhiro Nakazawa[a] Shin Watanabe[a]
Goro Sato[a,b] Takefumi Mitani[a,b] Takaaki Tanaka[a,b]
Kousuke Oonuki[a,b] Ken'ichi Tamura[a,b] Hiroyasu Tajima[c]
Tuneyoshi Kamae[c] Greg Madejski[c] Masaharu Nomachi[d]
Yasushi Fukazawa[e] Kazuo Makishima[b] Motohide Kokubun[b]
Yukikatsu Terada[f] Jun Kataoka[g] Makoto Tashiro[h]

[a] *The Institute of Space and Astronautical Science*
3-1-1 Yoshinodai, Sagamihara, Kanagawa, 229-8510, Japan

[b] *University of Tokyo, 7-3-1, Hongo, Bunkyo, Tokyo 113-0033, Japan*

[c] *Stanford Linear Accelerator Center, Stanford, CA 94309-4349, USA*

[d] *Osaka University, Toyonaka, Osaka, 560-0043, Japan*

[e] *Hiroshima University, Higashi-Hiroshima, Hiroshima, 739-8526, Japan*

[f] *RIKEN, Wako, Saitama, 351-0198, Japan*

[g] *Tokyo Institute of Technology, Meguro-ku, Tokyo, 152-8551, Japan*

[h] *Saitama University, Saitama, 338-8570, Japan*

Abstract

Cadmium telluride (CdTe) and cadmium zinc telluride (CdZnTe) have been regarded as promising semiconductor materials for hard X-ray and γ-ray detection. The high atomic number of the materials (Z_{Cd} =48, Z_{Te}=52) gives a high quantum efficiency in comparison with Si. The large band-gap energy (Eg = 1.5 eV) allows to operate the detector at room temperature. Based on recent achievements in high-resolution CdTe detectors, in the technology of ASICs and in bump-bonding, we have proposed the novel hard X-ray and γ-ray detectors for the NeXT mission in Japan. The high-energy response of the super mirror onboard NeXT will enable us to perform the first sensitive imaging observations up to 80 keV. The focal plane detector, which combines a fully depleted X-ray CCD and a pixellated CdTe detector, will provide spectra and images in the wide energy range from 0.5 keV to 80 keV. In the soft gamma-ray band up to $\sim$ 1 MeV, a narrow field-of-view Compton γ-ray telescope utilizing several tens of layers of thin Si or CdTe detector will provide precise spectra with much higher sensitivity than present instruments. The continuum sensitivity will reach several $\times$ 10^{-8} photons/s/keV/cm^2 in the hard X-ray region and a few $\times$ 10^{-7} photons/s/keV/cm^2 in the soft γ-ray region.

Key words: gamma-ray astronomy, Compton telescope, CZT, CdTe

Submitted to Nucl. Instrum. Methods A

Work supported in part by the Department of Energy contract DE-AC02-76SF00515

PACS:

1 Introduction

The hard X-ray and gamma-ray bands have long been recognized as important windows for exploring the energetic universe. It is in these energy bands that non-thermal emission, primarily due to accelerated high-energy particles, becomes dominant. The Compton Gamma-ray Observatory (CGRO) satellite, which operated from 1991 to 2000, revealed that there are a variety of γ-ray sources. With its four onboard instruments, CGRO covered a wide energy range, from 20 keV to 30 GeV. This wide energy coverage, six decades in photon energy, played an important role in studying the realm of non-thermal astrophysics.

We can expect a further revolution brought by the INTEGRAL, Astro-E2, GLAST and other near-future missions. However, when compared with X-ray astronomy, hard X-ray and γ-ray astronomy are still immature. As clearly shown in Fig. 1, the sensitivity of instruments is far from the level achieved by the current X-ray missions employing focusing telescopes in the energy band below 10 keV. The situation is particularly unsatisfactory in the region between $\sim$10 keV and $\sim$100 MeV. In this "sensitivity gap", the jump at the low energy end comes from the fact that current X-ray mirrors cannot focus hard X-rays. At energies above $\sim$100 MeV, sensitivity is recovered by utilizing pair-production telescopes.

In order to study the non-thermal emission and to draw a more complete picture of the non-thermal universe, highly sensitive observations by high energy missions are important. In particular, hard X-ray and γ-ray observations to match observations at other wavelengths are indispensable. To this end, future high-energy instruments should provide much improved angular and spectral resolutions over the instruments in use today. Cadmium telluride (CdTe) and cadmium zinc telluride (CdZnTe) have been regarded as promising semiconductor materials to realize such instruments for the next generation of astronomical observations in the hard X-ray and γ-ray regions [1–3]. Here, we report recent achievements of high-resolution CdTe detectors and their application to the Japanese future high-energy mission.

*

Email address: `takahasi@astro.isas.jaxa.jp` (Tadayuki Takahashi).

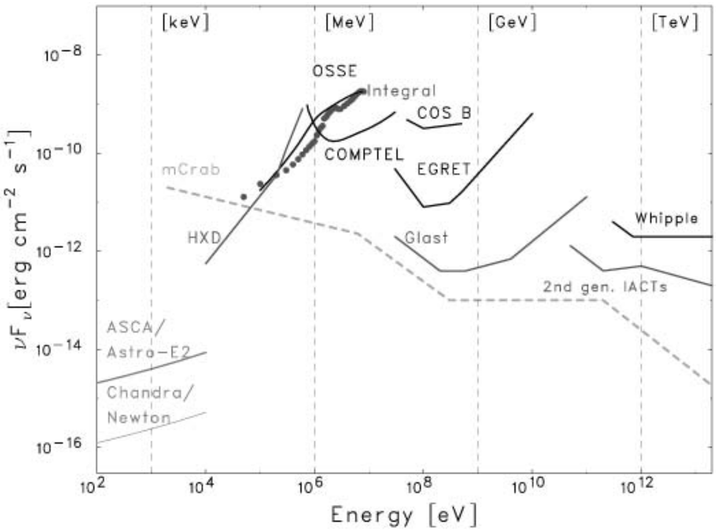

Fig. 1. Sensitivities of past and future X-ray and γ-ray missions together with the sensitivity of ground based imaging atmospheric Cherenkov telescopes (IACTs). The spectrum of 0.1 % of the Crab Nebula is shown.

2 High resolution CdTe detector

Among the range of semiconductor detectors available for γ-ray detection, CdTe and CdZnTe have a privileged position because of their high density and the high atomic number of their components, as well as a wide bandgap. In the 1990's, the remarkable progress in the technology of producing a high quality single crystal of CdTe and the emergence of CdZnTe have dramatically changed the situations of high resolution room temperature detectors based on these materials. A review of the recent progress of CdTe and CdZnTe detectors is available in Takahashi & Watanabe [4]. The performance of CdTe for the IBIS instrument onboard the INTEGRAL mission and CdZnTe for the BAT instrument on the Swift mission are described in Lebrun et al. [5] and Sato et al. [6], respectively.

For an imaging detector, the good energy resolution and ability to fabricate compact arrays expected from semiconductor detectors are very attractive features in comparison with inorganic scintillation detectors coupled to either photodiodes or photomultiplier tubes. The uniform charge transport properties of the wafer are very important, not only for fabricating large area strip or pixel detectors but also for constructing a large scale γ-ray camera consisting of many individual detectors. Recently, based on single crystal growth by the Travelling Heater Method (THM-CdTe) by ACRORAD [7], the crystal produced is large enough to obtain (1 1 1)- oriented single-crystal wafers with an area as large as 40×40 mm^2 (Fig. 2 (a)) [8]. Although the energy information can not be obtained, the fine-pitch CdTe γ-ray camera recently developed by ACRORAD already demonstrates the potential of a γ-ray imager made of

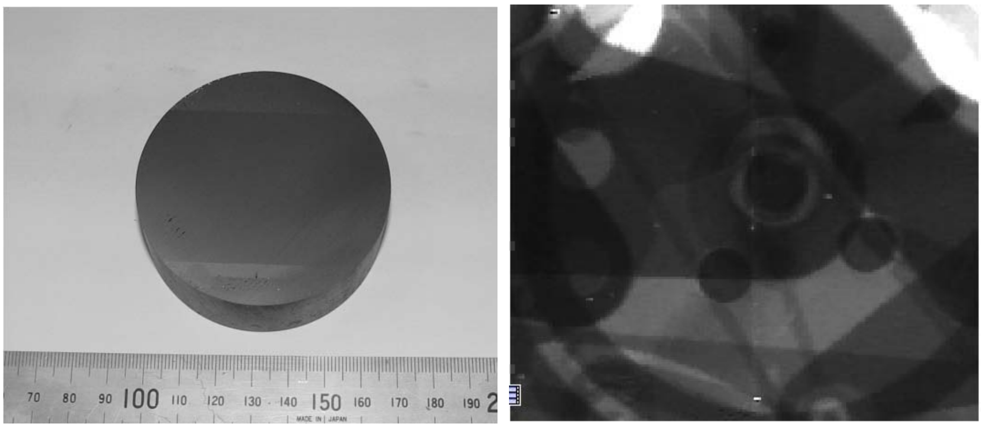

Fig. 2. (a) (left) photo of THM-CdTe wafer and (b) (right) γ-ray photo taken with the CdTe γ-ray camera with a pixel size of 200 μm (courtesy of ACRORAD Co.).

highly uniform CdTe semiconductor (Fig. 2 (b)).

Based on the THM-CdTe wafers, we have developed CdTe detectors with high energy resolution for both planar and pixel configurations [3,9–13,15]. We have demonstrated that the wafer shows good uniformity when we make a large area CdTe detector with planar electrodes [9,11]. According to measurements using a collimated γ-ray beam from an ^{241}Am source, the location of the peak in the pulse height distribution is obtained to within 0.1 % and the variation of the area of the 60 keV peak is less than 0.9 %, regardless of the position in the 21 mm $\times$ 21 mm surface. In addition to the highly uniform wafer, we have achieved a significant improvement in the spectral properties by forming the Schottky junction on the Te side of the CdTe wafer [3]. For the detector with an area of 2 mm $\times$ 2 mm and a thickness of 0.5 mm, the leakage current of the new CdTe diode is as low as 10 pA at 20 °C at a bias voltage of 800 V. As demonstrated in Fig. 3 (a) and (b), an energy resolution of 1.1 keV (FWHM) for the 122 keV line from ^{57}Co is obtained [13]. When we cool down the detector, the energy resolution is improved. A CdTe diode with an area of 3 mm $\times$ 3 mm and a thickness of 1 mm installed in the system manufactured by Amptek [14] has an energy resolution of 260 eV (FWHM) at 6.4 keV when operated at -40 °C .

3 NeXT Mission

The NeXT (Non-thermal Energy eXploration Telescope) mission proposed in Japan is a successor to the Astro-E2 mission, and is optimised to study the high-energy non-thermal universe [16,17]. NeXT will carry three hard X-ray telescopes (HXTs) for the wide band X-ray imager (WXI), one soft X-ray telescope for the soft X-ray spectrometer, and a soft γ-ray detector (SGD). The HXT is based on a depth-graded multi-layer mirror, referred to as a *super*

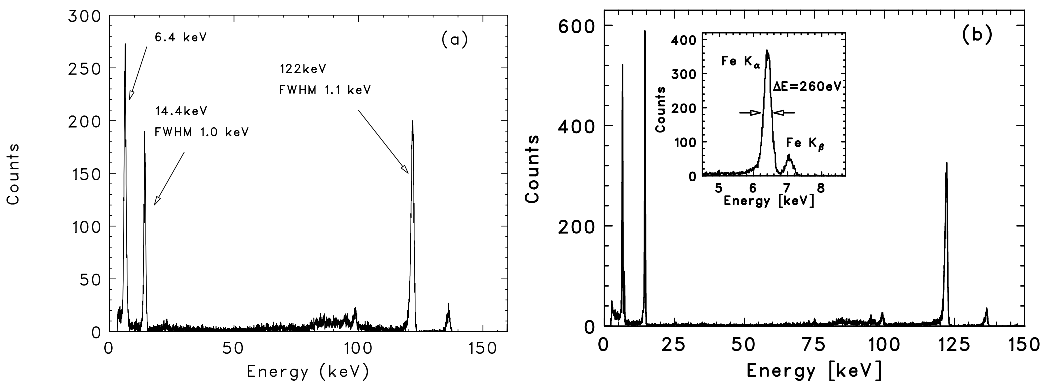

Fig. 3. (a) ^{57}Co spectrum obtained with the CdTe diode operated at 20 °C .The active area of the detector is 2×2×0.5 mm^3. The applied voltage is 800 V. (b) ^{57}Co spectrum obtained with the CdTe diode system manufactured by Amptek [14] . The detector size is 3×3×1 mm^3 and the operating temperature is −40 °C .

mirror, to enhance the hard X-ray reflectivity. With three HXT units, effective areas of 1100 cm^2 at 20 keV and 230 cm^2 at 60 keV can be achieved with a focal length of 12 m [19]. With the first imaging observations up to 80 keV, NeXT is expected to achieve two orders of magnitude improvement in the sensitivity in the hard X-ray region. The SGD utilizes a new concept of a narrow-FOV Compton telescope [18,20] to improve the sensitivity in the soft γ-ray region for matching with the sensitivity of the HXT/WXI combination. The extremely low background brought by the SGD will allow us to measure the precise γ-ray spectrum up to 1 MeV. Furthermore, as described in a separate paper [23], the SGD will be sensitive to the polarization of the incident γ-rays, and will potentially be the first hard X-ray polarimeter in orbit.

4 Hard X-ray Imager (HXI)

In order to match the energy range covered by the super mirror (0.5 − 80 keV), the focal plane detector for the HXT is required to cover a very wide energy band. To this end, we have proposed a new focal plane detector based on an idea of combining an X-ray CCD and a CdTe (Cadmium Telluride) pixel detector as the Wide-band X-ray Imager (WXI) [3,20,21]. As schematically shown in Figure 4, the WXI is composed of two sub-instruments; the hard X-ray Imager (HXI) and the soft X-ray Imager (SXI). In the WXI, soft X-rays will be absorbed in the CCD of the SXI, while hard X-rays will penetrate through the CCD and be absorbed in the CdTe pixel detector in the HXI. For the detection of soft X-rays below 10−20 keV with the high position resolution, a CCD with very thin dead layer will be used in the SXI [22].

Semiconductor detectors such as CdTe with a high mass absorption coefficient are crucial for the detection of hard X-ray photons. For CdTe, even a detector

Table 1
Specification for the HXI [16]

HXI	Energy Range	8 – 80 keV
	Energy Resolution	0.5 – 1 keV (FWHM)
	Trigger Threshold	$\sim$ 8 keV
	Pixel Size	200 $\sim$ 500 μm
	Detector Size	20 mm $\times$ (20 – 30) mm
	Timing Resolution	$<$ 100 μs
	Operating Temperature	-50 – 0 degree

with a thickness of 0.5 mm provides a good detection efficiency for the hard X-ray region up to 80 keV. The current goal for the CdTe detector in the HXI is a pixel detector with both a fine position resolution of 200$-$250 μm and a high energy resolution, better than 1 keV (FWHM), in the energy range from 5 keV to 80 keV. Signals from the individual pixel electrodes formed on the surface of the CdTe wafer are fed into the readout circuit built in the ASIC. To realize the fine pitch CdTe pixel detector for the HXI, a low noise front-end ASIC with more than several thousand independent channels will be the key technology. Specifications of the HXI are listed in Table 1.

As shown in Fig. 4, the CdTe detector mounted in the HXI is shielded by a BGO ($Bi_4Ge_3O_{12}$) scintillator. This shield is indispensable, as the non X-ray background is the dominant source of the background in the energy range of the HXI. A thickness of $\sim$2 cm for BGO will be required, not only for shielding against background photons but also for reducing the number of particles that reach the CdTe detector and give rise to activation.

With NeXT, we expect to achieve an area of about 750 cm^2 at 30 keV with a typical angular resolution of 30". Fig. 5 shows the efficiency of the WXI with a 300 μm thick X-ray CCD and a 0.5 or 1.0 mm CdTe pixel detector. In the calculation, effects of a possible dead layer in the CCD are not taken into account. By assuming a background level of 1×10^{-4} counts/s/cm^2/keV, in which a non X-ray background is dominant, the source detection limit in 100 ksec would be roughly be 10^{-14} erg cm^{-2} s^{-1} in terms of the 10–80 keV flux for a power-law spectrum with a photon index of 2. This is about two orders of magnitude better than present instrumentation.

5 Soft Gamma-ray Detector

Highly sensitive observations in the energy range above the bandpass of the hard X-ray telescope are crucial to study the spectrum of accelerated particles.

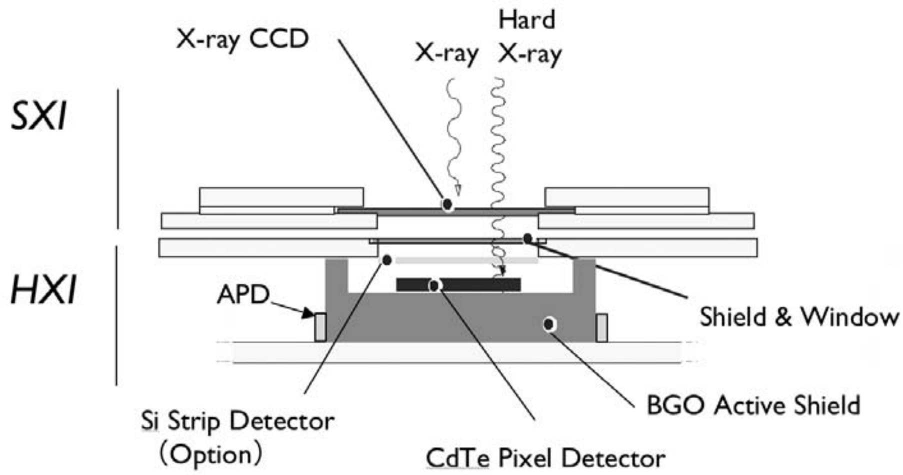

Fig. 4. Conceptual drawing of the WXI proposed for the NeXT mission. The WXI is composed of two sub-instruments: the soft X-ray Imager (SXI) and the hard X-ray Imager (HXI). The CdTe pixel detector in the HXI is placed beneath the X-ray CCD in the SXI. In the WXI, soft X-rays are absorbed in the CCD, while hard X-rays penetrate through the CCD and are absorbed in the CdTe pixel detector. The Si strip detector is considered as an option to shield fluorescence lines from CdTe [18].

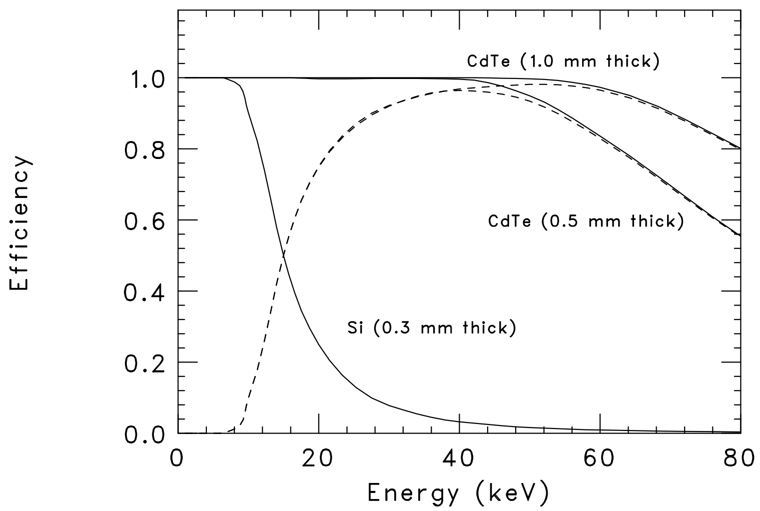

Fig. 5. Efficiency of the SXI with a 300 μm thick Si CCD and the HXI for 0.5 mm and 1.0 mm thick CdTe detector. Effects of a possible dead layer in the Si CCD are not included in the calculation.

The SGD outperforms previous soft-γ-ray instruments in background rejection capability by adopting a new concept of narrow-FOV Compton telescope [21]. In the energy range above one hundred keV (sub-MeV region), shielding against background photons becomes important yet difficult. The well-type phoswich counter, which we developed for the WELCOME balloon experiment [24] and also for the Astro-E Hard X-ray Detector (HXD) [25–27] is a

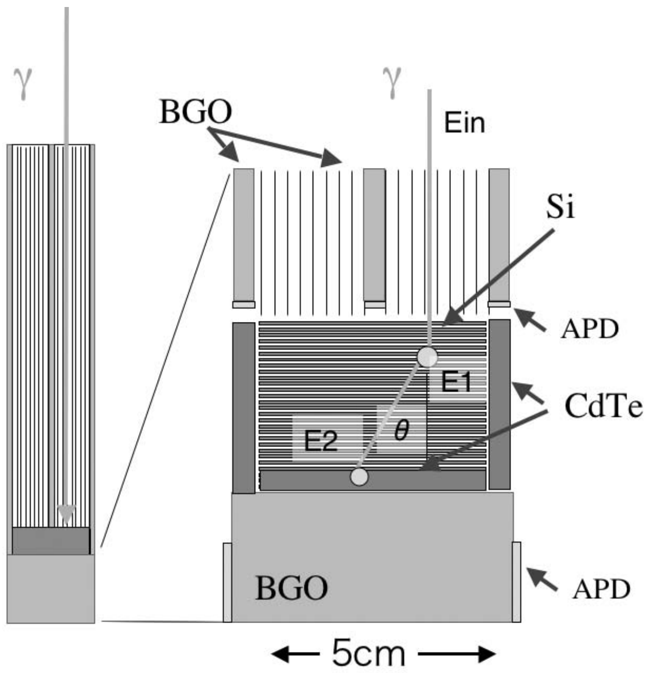

Fig. 6. Conceptual design of the SGD module [21]. A stack of 24 Si DSSDs and CdTe pixel detectors are assembled to form a semiconductor Compton Telescope. The telescope is mounted inside the bottom of a well-type active shield. The opening angle provided by the BGO shield is 4 deg at 500 keV. An additional copper collimator restricts the field of view of the telescope to 30' for low energy photons (<100 keV). With this narrow FOV, events are rejected as background if the reconstructed Compton ring does not intercept the FOV.

possible solution to achieve a very low background rate. The phoswich configuration and a tight and active "well-type" shield made of BGO scintillators is expected to reduce the background to $<10^{-4}$ counts/cm^2/s/keV, almost the limit achieved by the configuration of active shield and collimator.

In order to lower the background dramatically and thus to improve the sensitivity as compared to the HXD, we combine a stack of Si strip detectors and CdTe pixel detectors to form a Compton telescope. The telescope is then mounted inside the bottom of a well-type active shield. As shown schematically in Fig.6, the telescope consists of 24 layers of DSSDs (double-sided silicon strip detectors) and 2 layers of thin CdTe pixellated detectors surrounded by 5 mm thick CdTe pixellated detectors. The opening angle provided by the BGO shield is 4 degrees at 500 keV. As compared to the HXD, the shield part is made compact by adopting the newly developed avalanche photodiode [30,31]. An additional copper collimator restricts the field of view of the telescope to 30' for low energy photons (<100 keV) to minimize the flux due to the Cosmic X-ray Background from the FOV. These modules are then arrayed to provide the required area (Figure 9).

An important feature of the SGD is that we can require each event to interact

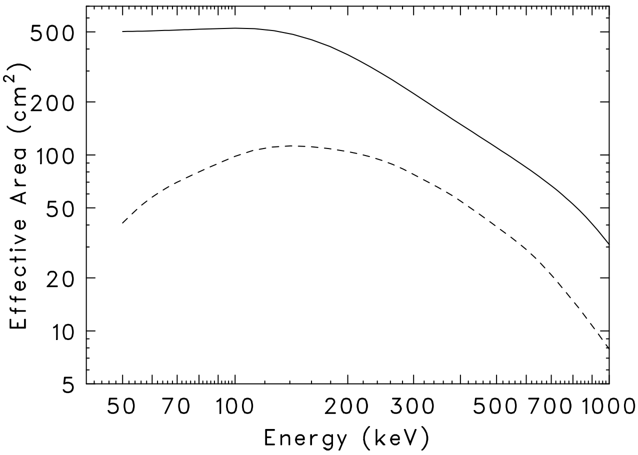

Fig. 7. Effective area of the SGD. Solid line shows the area calculated for photo absorption. Dashed line shows the area when the detector is operated as a Compton camera

twice in the stacked detector, once by Compton scattering in a stack of Si strip detectors, and then by photo-absorption in the CdTe part (Compton mode). Once the locations and energies of the two interactions are measured, the Compton kinematics allows us to calculate the energy and direction (as a cone in the sky) of the incident γ-ray by following the Compton equation,

$$E_{in} = E_1 + E_2, \tag{1}$$

$$\cos\theta = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2}\right), \tag{2}$$

where E_1 is the energy of the recoil electron, E_2 is the energy of the scattered photon and θ is the scattering angle[28,29]. As shown in the equations, incident direction of a γ-ray is calculated from the position and the energy information of interactions. The high spectral and spatial resolution of Si and CdTe semiconductor detectors allow the instrument to achieve high angular resolution. Since the major interaction of photons above 60 keV in Si is Compton scattering, the stack of DSSDs acts as an efficient scatterer especially for the low energy region below 300 keV. Regarding the uncertainty of the order of scattering in an event, we can use the relation that the energy deposition by Compton scattering is always smaller than that of the photo-absorption for energies below $E_\gamma = 255$ keV ($E_\gamma = m_e/2$). As shown in Fig. 8, this relation holds above this energy and there is only one solution, if the scattering angle θ is smaller than $\cos^{-1}(1 - \frac{1}{2}(\frac{m_e}{E_\gamma})^2)$.

The major advantage of employing a narrow FOV is that the direction of incident γ-rays is constrained inside the FOV. If the Compton ring does not intercept the FOV, we can reject the event as background. Most backgrounds can be rejected by requiring this condition (albeit with an corresponding re-

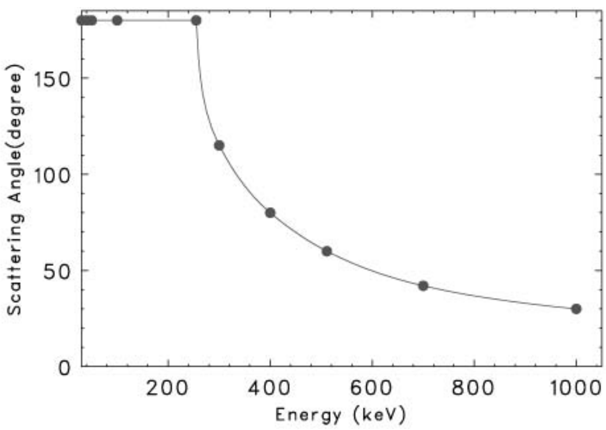

Fig. 8. The ordering of Compton scattering and photo-absorption is uniquely identified, if the scattering angle is smaller than the value shown by the solid curve. With this condition, the energy deposited by Compton scattering (first scattering) is always smaller than that of the photo-absorption.

duction in instrument effective area). Background photons from the BGO and copper collimator for which the reconstructed Compton ring intersects the FOV cannot be eliminated if there is no signal detected in the active shield, however this source of background contributes only within a limited range of scattering angle. Combining background suppression techniques available in the SGD, we expect to achieve background levels of 5×10^{-7} counts/s/cm^2/keV at $\sim$ 100 keV and 2×10^{-7} counts/s/cm^2/keV at $\sim$ 500 keV. As shown in Fig. 7, the effective area of the SGD in the Compton mode is 120 cm^2 at 200 keV and 50 cm^2 at 400 keV, if we use 25 units (total geometrical area of 625 cm^2).

The concept of a narrow FOV Compton telescope is expected to reduce drastically the background from radio-activation of the detector materials, which is a dominant background in the case of the Astro-E2 HXD [27]. The 30' FOV of the fine collimator is required to improve the sensitivity limited by source confusion below a few hundred keV. With the SGD, we can also measure polarization of incident γ-rays from the azimuthal distribution of the Compton scattered photons [12,23].

Based on our CdTe and Si detector technologies, we are working on a Si/CdTe semiconductor Compton telescope. The photo of DSSD and CdTe pixel detectors used in the prototype and spectra taken from those detectors are shown in Fig. 10 and Fig. 11. We have successfully obtained clear images and spectra in the energy range from 80 keV up to 700 keV. The performance of the prototype and results of polarization measurements are described in other publications [12,13,33,34,36]. In order to realize the Compton Camera that fits in the BGO well, we need to optimize the mechanical support structure and the readout scheme. Efforts to improve the performance of CdTe pixel detectors as thick as 5 mm are under way (Fig. 12).

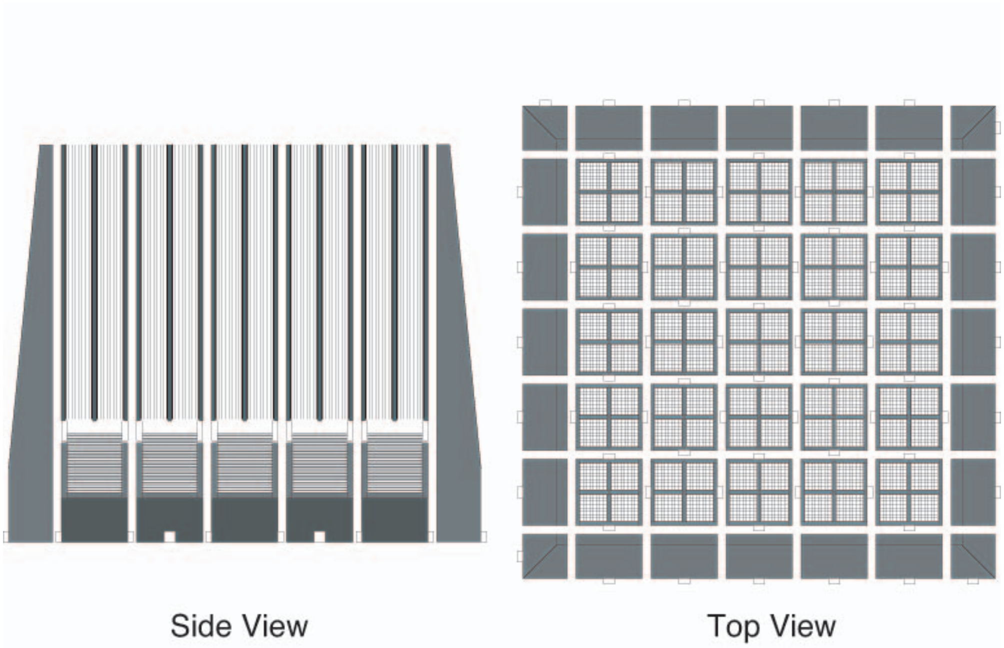

Fig. 9. A schematic drawing of the SGD. It consists of 25 units of the narrow FOV Compton telescope surrounded by 24 shield counters made of BGO. A geometrical area of 525 cm^2 is currently assumed for the sum of 25 units. If we select an event that has two hits in the detector (and no hit in the BGO shields) and if we require the proper reconstruction for the Compton kinematics, the effective area at 200 keV becomes $\sim$ 100 cm^2, including the reconstruction efficiency.

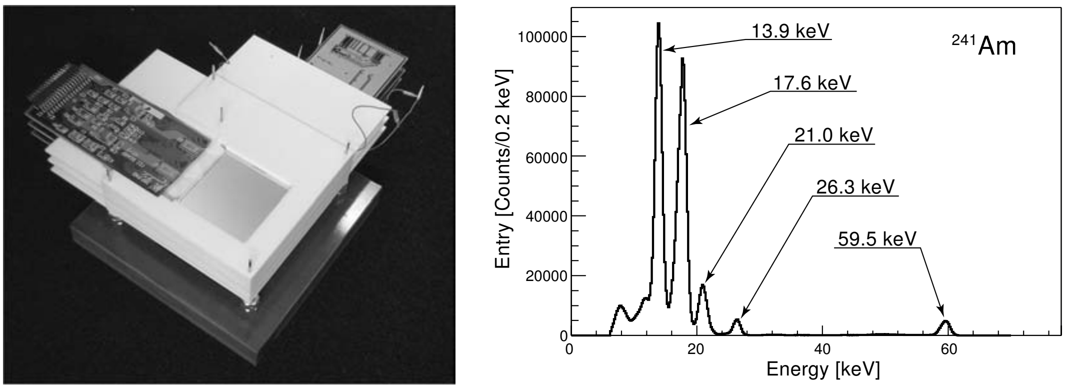

Fig. 10. (left) Photo of three layers of DSSD stack developed for the prototype Si/CdTe Compton Camera [33,34] (right) DSSD Energy spectrum from an ^{241}Am source. The signal from each strip is processed by a newly developed analog front-end ASIC developed with Ideas ASA [32,35]. An energy resolution of 1.3 keV (FWHM) for 60 keV can be achieved at 0 °C .

6 Conclusion

The continuum sensitivities of the NeXT mission could reach several $\times\ 10^{-8}$ photons/s/keV/cm^2 in the hard X-ray region and a few $\times\ 10^{-7}$ photons/s/keV/cm^2

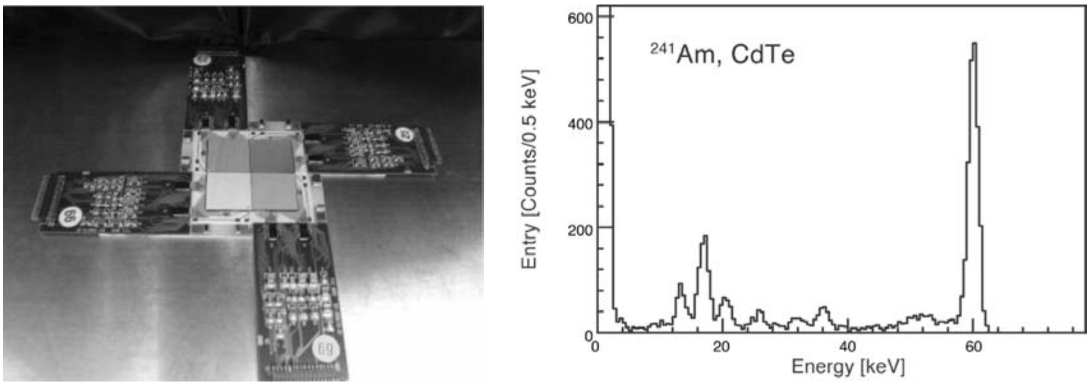

Fig. 11. (left) Photo of large area CdTe pixel detectors developed for the prototype Si/CdTe Compton Camera [12,13]. The detector has an area of 3.2 cm $\times$ 3.2 cm and a thickness of 0.5 mm. Pixel size is 2 mm $\times$ 2 mm. (right) Energy spectrum from CdTe (one pixel) with an ^{241}Am source. The energy resolution is 1.6 keV (FWHM) for 60 keV at 0 °C .

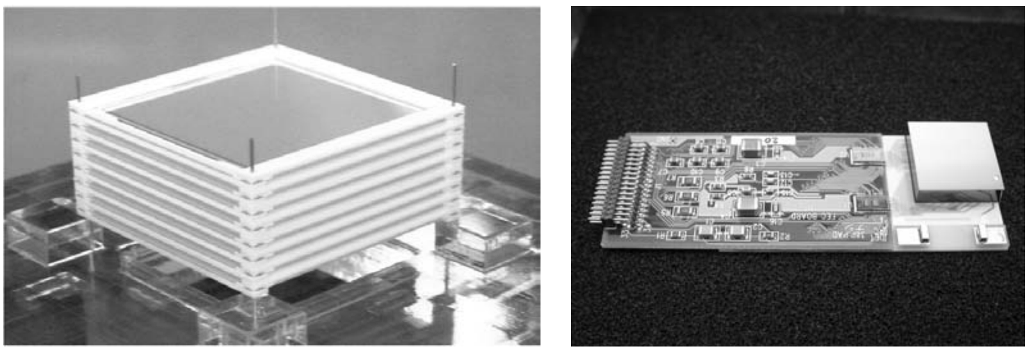

Fig. 12. (left) Photo of the mechanical model of the DSSD stack for the SGD. The signals from each strip will be extracted from the side wall of the stack and processed by front-end ASICs. (right) 5-mm thick CdTe Pixel detector with a pixel size of 2 mm $\times$ 2 mm (64 pixels).

in the soft γ-ray region [16,21]. The high-energy response of the super mirror of NeXT will enable us to perform the first sensitive imaging observations up to 80 keV. By combining an X-ray CCD and a CdTe pixel detector, the WXI is an ideal solution for the focal plane detector of the super mirror, providing fine imaging capability and high spectral resolution with almost full detection efficiency. The narrow field-of-view Compton γ-ray telescope realized by the SGD extends the bandpass to well above the cutoff for the hard X-ray telescope and allows us to study the high energy end of the particle spectrum through the sensitive observation of the γ-ray spectrum up to 1 MeV. By combining these detectors, we expect to achieve an unprecedented level of sensitivity in the hard X-ray and sub-MeV γ-ray region for both line and continuum emission.

Acknowledgement

This research was partially supported by the Ministry of Education, Science, Sports and Culture, Grant-in-Aid in Japan (13304014, 14079207).

References

[1] O. Limousing, C. Blondel, J. Cretolle, H. Dzitko, P. Laurent, F. Lebrun, J.P. Leray, et al. “The ISGRI CdTe gamma-ray camera first steps,” *Nucl. Instr. Meth.*, vol. A442, pp. 244-249, 2000.

[2] S. D. Barthelmy, “The Burst Alert Telescope (BAT) on the Swift MIDEX mission,” *SPIE*, vol. 4140, pp. 50-63, 2000.

[3] T. Takahashi, B. Paul, K. Hirose, C. Matsumoto, R. Ohno, T. Ozaki, K. Mori, Y. Tomita, “High-resolution Schottky CdTe Detectors for Hard X-ray and Gamma-ray Observations ,” *Nucl. Instr. Meth.* vol. A436 pp.111-119, 2000

[4] T. Takahashi and S. Watanabe “Recent Progress on CdTe and CdZnTe detectors,” IEEE Trans. Nucl. Sci., vol. 48, pp. 950-959, 2001

[5] F. Lebrun et al. ,”INTEGRAL: In flight behavior of ISGRI and SPI,” these proceedings, 2004

[6] G. Sato et al., “Development of a Spectral Model Based on Charge Transport for the Swift/BAT 32K CdZnTe Detector Array,”, these proceedings, 2004

[7] Acrorad Co.,Ltd., http://www.acrorad.co.jp

[8] M. Funaki, T. Ozaki, K. Satoh, and R. Ohno, “Growth and Characterization of CdTe Single Crystal for Radiation Detectors,” Nucl. Instr. Meth. , vol. A436, pp. 120-126, 1999.

[9] T. Takahashi, T. Mitani, Y. Kobayashi, M. Kouda, G. Sato, S. Watanabe, K. Nakazawa, Y. Okada, M. Funaki, R. Ohno, “High Resolution Schottky CdTe Diodes,” IEEE Trans. Nucl. Sci., vol. 49, No. 3, pp. 1297-1303, 2002.

[10] S. Watanabe, T. Takahashi, K. Nakazawa, Y. Kobayashi, Y. Kuroda, K. Genba, M. Onishi, K. Otake , “A stacked CdTe Gamma-ray Detector and its application as a range finde,” IEEE Trans. Nucl. Sci., vol. 49, No. 3, pp. 1297-1303, 2002

[11] K. Nakazawa, K. Oonuki, T. Tanaka, Y. Kobayashi, K. Tamura, T. Mitani, G. Sato, S. Watanabe, T. Takahashi, R. Ohno, A. Kitajima, Y. Kuroda and M. Onishi, “Improvement of the CdTe Diode Detectors using a Guard-ring Electrode,” IEEE Trans. Nucl. Sci, in press, 2004

[12] T. Mitani,T. Tanaka, K. Nakazawa, T. Takahashi, T. Takashima, H. Tajima, H. Nakamura, M. Nomachi, T. Nakamoto, Y. Fukazaw, “A Prototype Si/CdTe Compton Camera and the Polarization Measurement,” IEEE Trans. Nucl. Sci., vol. 5, No. 5, pp. 1-6, 2004

[13] T. Tanaka,T. Mitani, S. Watanabe, K. Nakazawa, K. Oonuki, G. Sato, T. Takahashi, K. Tamura, H. Tajima, H. Nakamura, M. Nomachi, T. Nakamoto, Y. Fukazawa ,"Development of a Si/CdTe semiconductor Compton Telescope," Proc. SPIE, vol. 5501, pp. 229-240, 2004

[14] Amptek Inc., http://www.amptek.com

[15] K. Oonuki, H. Inoue, K. Nakazawa, T. Mitani, T. Tanaka, T. Takahashi, C.M.H. Chen, W.R. Cook, F.A. Harrison, "Development of Uniform CdTe Pixel Detectors Based on Caltech ASIC," Proc. SPIE, vol. 5501, pp. 218-228, 2004

[16] NeXT Satellite Proposal,the NeXT working group, submitted to ISAS, 2003.

[17] H. Kunieda, "New X-ray Telescope Mission (NeXT)," Proc. SPIE, vol. 5488, pp. 187-196, 2004

[18] T. Takahashi, K. Nakazawa, T. Kamae, H. Tajima, Y. Fukazawa, M. Nomachi, and M. Kokubun , "High resolution CdTe detectors for the next generation multi-Compton gamma-ray telescope ," Proc. SPIE, vol. 4851, pp. 1228-1235, 2002

[19] Y. Ogasaka, K. Tamura, R. Shibata, A. Furuzawa, T. Okajima, K. Yamashita, Y. Tawara, H. Kunieda, "NeXT Hard X-ray Telescope," Proc. SPIE, vol. 5488, in press, 2004

[20] T. Takahashi, K. Makishima, F. Fukazawa, M. Kokubun, K. Nakazawa, M. Nomachi, H. Tajima, M. Tashiro, and Y. Terada, "Hard X-ray and Gamma-ray detectors for the NeXT mission,", New Astronomy Reviews, 48, pp. 309-313, 2004

[21] T. Takahashi, A. Awaki, T. Dotani, Y. Fukazawa, K. Hayashida, T. Kamae, J. Kataoka, N. Kawai, S. Kitamoto, T. Kohmura, M. Kokubun, K. Koyama, K. Makishima, H. Matsumoto, E. Miyata, T. Murakami, K. Nakazawa, M. Nomachi, M. Ozaki, H. Tajima, M. Tashiro, T. Tamagawa, Y. Terada, H. Tsunemi, T.Tsuru, K. Yamaoka, D. Yonetoku, and A.Yoshida,, "Wide band X-ray Imager (WXI) and Soft Gamma-ray Detector (SGD) for the NeXT Mission," Proc. SPIE, vol. 5488, pp.549-560, 2004

[22] T. G. Tsuru, S. Takagi, H. Matsumoto, T. Inui, K. Koyama, H. Tsunemi, K. Hayashida, E. Miyata, T. Dotani, M. Ozaki, H. Awaki, S. Kitamoto, T. Kohmura, "The Development of back supportless CCD for SXI onboard the NeXT satellite," these proceedings, 2004

[23] H. Tajima, T. Mitani, T. Tanaka, H. Nakamua, T. Nakamoto, K. Nakazawa, T. Takahashi, Y. Fukazawa, T. Kamae, M. Kokubun, G. Madejski, D. Marlow, M. Nomachi, E. do Couto e Silva, "Gamma-ray polarimetry with Compton Telescope," Proc. SPIE, vol. 5488, pp. 561-571, 2004

[24] T. Kamae et al., "Well-type Phoswich Counters for Low-Flux X-Ray/Gamma-Ray Detection ," Proc. SPIE, vol. 1734, pp.2-13, 1992

[25] T. Kamae et al., "Astro-E hard X-ray detector," Proc. SPIE, vol. 2806, pp. 314-328, 1996

[26] M. Tashiro et al. "Performance of the ASTRO-E Hard X-ray Detector," IEEE Trans. Nucl. Sci. 49, pp. 1893-1897, 2002

[27] M. Kokubun et al.,"Improvements of the Astro-E2 Hard X-ray Detector (HXD-II), " IEEE Trans. Nucl. Sci., in press, 2004

[28] V. Scoenfelder et al., "COMPTEL overview: Achievements and expectations," Astron. Astrophys. Suppl., 120. pp. 13-21, 1996

[29] G. Kanbach et al., "The MEGA project," New Astronpmy Reviews, 48, pp. 275-280, 2004

[30] J. Kataoka, T. Ikagawa, Y. Yatsu, Y. Kuramoto, T. Saito, N. Kawai, Y. Serino, J. Kotoku, Y. Ishikawa, N. Kawabata,"Performance of the most recent avalanche photodiodes for future X-ray and gamma-ray astronomy," Proc. SPIE, vol. 5501, pp. 249-260, 2004

[31] T. Nakamoto, Y. Fukazawa, T. Ohsugi, T. Kamae, and J. Kataoka, "BGO readout with photodiodes as a soft gamma-ray detector at $-30°$C," NIM A, in press, 2004

[32] H. Tajima, T. Nakamoto , T. Tanaka , S. Uno , T. Mitani , E. do Couto e Silva, Y. Fukazawa, T. Kamae, G. Madejski, D. Marlow, K. Nakazawa, M. Nomachi, Y. Oakada, T. Takahashi, "Performance of a low noise front-end ASIC for Si/CdTe detectors in Compton gamma-ray telescope," IEEE Trans. Nucl. Sci., 51, pp. 842-847, 2004.

[33] H. Tajima, T. Kamae, S. Uno, T. Nakamoto, Y. Fukazawa, T. Mitani, T. Takahashi, K. Nakazawa, Y. Okada, and M. Nomachi, "Low noise double-sided silicon strip detector for multiple-Compton gammaray telescope," Proc. SPIE, vol. 4851, pp. 875-884, 2002

[34] Y. Fukazawa, T. Nakamoto, N. Sawamoto, S. Uno, T. Ohsugi, H. Tajima, T. Takahashi, T. Mitani, T. Tanaka, K. Nakazawa, "Low-noise double-sided silicon strip detector for soft gamma-ray Compton camera," Proc. SPIE, vol. 5501, pp. 197-207, 2004

[35] Ideas ASA, http://www.ideas.no/

[36] S. Watanabe, T. Tanaka, K. Nakazawa, T. Mitani, K. Oonuki, T. Takahashi, H. Tajima, Y. Fukazawa, M. Nomachi, S. Kubo, M. Onishi, and Y. Kuroda, "Si/CdTe Semiconductor Compton Camera", in Proc. IEEE, Nuclear Science Symposium, Rome, 2004