High resolution CdTe detectors for the next generation multi-Compton gamma-ray telescope

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ABSTRACT

A multi-Compton gamma-ray telescope based on high resolution semiconductor materials (Semiconductor Multi-Compton Telescope (SMCT) or Advanced Compton Telescope (ACT)) is a promising approach to achieve high sensitivity for gamma-rays with energies from several hundred keV up to several MeV. A SMCT utilizing several tens of layers of thin CdTe (Cadmium Telluride) detector is an attractive concept to obtain higher detection efficiency in comparison with Si-based SMCT. Recently we have developed high energy-resolution CdTe diode detectors. A large-area detector with dimensions of 2.15×2.15 cm^2 with a thickness of 0.5 mm shows an energy resolution of better than 3 keV (FWHM) at 60 keV. In order to extend the application of CdTe diodes to the detection of MeV gamma-rays, we have constructed a stacked detector consisting of 40 layers of large CdTe diodes. Here we report the recent progress on the high-resolution CdTe diode and describe the conceptual design of new Multi-Compton Gamma-ray telescopes based on Monte Carlo simulation. An idea of active pair production telescope is briefly described.

Keywords: gamma-ray, Compton telescope, ACT, SMCT, CdTe, CZT

1. INTRODUCTION

The hard X-ray and gamma-ray bands are important windows for exploring the energetic universe. It is in these energy bands that non-thermal emission, mostly due to accelerated high energy particles, becomes dominant. In fact, the results from the recent X-ray observatories showed that sensitive observations in these high energy bands are necessary to constrain the continuum spectra of many classes of X-ray sources. However, the lack of sensitive instruments prevents us from further studying the non-thermal spectra. The situation is much worse in the hard X-ray and MeV gamma-ray bands, where the reduction of background is difficult. The *CGRO* satellite revealed that a variety of gamma-ray sources exist in the sky and the improved angular and spectral resolution by the *INTEGRAL* satellite will be a good advance, but 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.

In order to fully explore the dynamic universe, hard X-ray and gamma-ray instruments in the 21st century should provide much improved sensitivity for both point and extended sources over the instruments in use today.[1] Toward this goal, we are working on research and development of the next generation gamma-ray detector based on high resolution Si and CdTe imaging devices.[2] Here we focus on an application of CdTe detector. Our work for Si strip detectors is reported elsewhere in this proceedings.[3]

2. HIGH RESOLUTION CDTE DIODE DETECTOR

The high absorption of cadmium telluride (CdTe) or cadmium zinc telluride (CdZnTe), comparable with that of NaI and CsI, is a very attractive feature for the next generation of gamma-ray detectors.[4] As shown in Fig. 2, photoelectric

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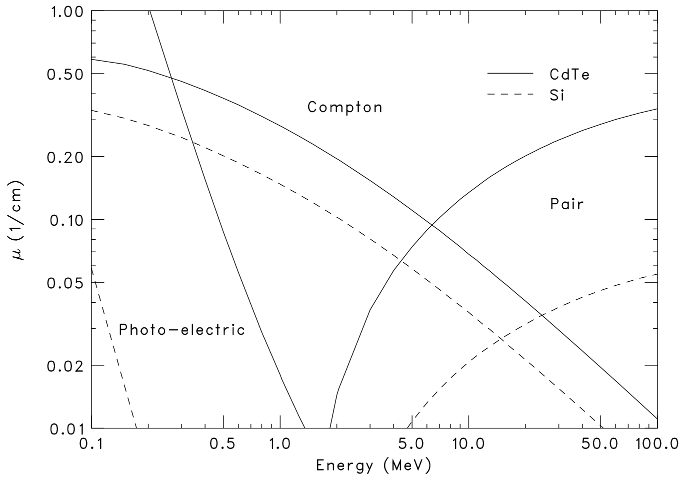

Figure 1. Linear attenuation coefficients in CdTe and Si as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\mu x)$, where x is the path length in cm.

absorption is the main process up to 300 keV for these materials, as compared to 60 keV for Si. Therefore, it is expected that CdTe and CdZnTe become efficient when the gamma-ray energy exceeds several hundred keV. However, despite long-term efforts for their improvement, it is only recently that high resolution CdTe and CdZnTe detectors, with energy resolution better than a few keV (FWHM), have become available. This was due to incomplete charge collection caused by the low mobility and short lifetime of holes, as the energy resolution does not reach the theoretical limit expected from statistical fluctuations in the number of electron-hole pairs, and the Fano factor.

Recently, we have achieved a significant improvement in the spectral properties of CdTe detectors.[5–7] By adopting the Schottky junction, the very low leakage current of the CdTe diode detector enables us to apply a high electric field to ensure complete charge collection in relatively thin (< 1 mm) devices. Dramatic improvement in both spectral resolution and stability can be obtained from a detector with a thickness of $0.5 - 1.0$ mm operated at low temperature.[8] As demonstrated in Fig. 2, an energy resolution of 530 eV (FWHM) for the 14 keV line from ^{241}Am is obtained from a detector with an area of 2 mm $\times$ 2 mm and a thickness of 1 mm, operated at -25 °C . The applied bias voltage is 300 V and the resultant leakage current was 4 pA. Under these conditions, the detector showed the same spectral performance for more than 24 hours. Another important reason for adopting thin devices is that we can apply sufficient bias voltage to collect all charges produced in the detector. When we increase the thickness of the CdTe/CdZnTe detector to improve the efficiency for high energy gamma-rays, the effects of incomplete charge collection become significant and lead to the increase of in-active region in the detector volume, especially for the region close to the anode. The 0.5 mm thick CdTe diode becomes fully active, and even holes generated near the anode face can be completely collected.

3. LARGE AREA CDTE DETECTOR FOR A STACKED DETECTOR

For the application of CdTe semiconductors to a multi-Compton telescope, we need an imaging detector capable of covering at least several cm^2. In order to verify the performance of such a large CdTe diode detector, we have developed a detector with an area of 21.5 $\times$ 21.5 mm^2 using the 0.5 mm thick device using a simple planar electrode configuration. Generally, the homogeneity of the wafer is of particular importance for imaging detectors, because defects in the wafer can deteriorate the energy resolution through positional variation of properties such as charge collection efficiency and leakage current. As reported in our previous publications,[8,9] the location of the peak in the pulse hight distribution agrees within 0.1% in the whole detector plane, when an ^{241}Am gamma-ray source irradiates the detector through a tungsten collimator with a 1mm-hole. The energy resolutions (FWHM) are almost identical and range from 2.71 keV to 2.78 keV, when operated at -20 °C and under a bias voltage of 300 V. The energy resolution of 2.73 keV was obtained when we irradiated the whole area of the detector without using a collimator. This resolution improves by dividing the electrode to lower the capacitance of the individual detector element. By dividing the 21.5 $\times$ 21.5 mm^2 electrode into four, the energy

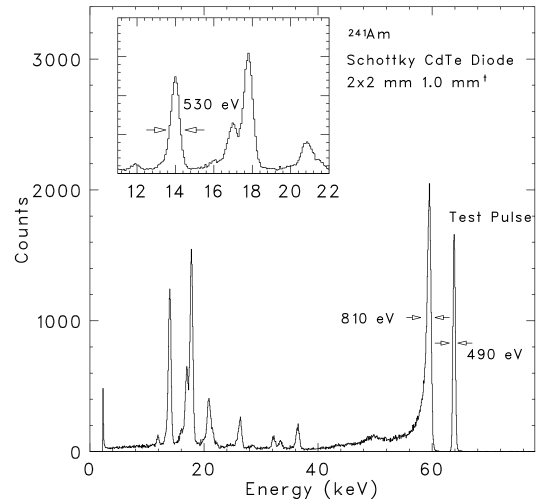

Figure 2. ^{241}Am spectra obtained with the Schottky CdTe diode.[8] The applied bias voltage is 300 V and the operating temperature is -25 °C . The energy resolution (FWHM) at 14 keV and 59 keV is 530 eV and 810 eV, respectively. The detector has a surface size of 2 mm × 2 mm and a thickness of 1.0 mm. The signal is integrated by a Charge Sensitive Amplifier (CP-5109 by Clear Pulse) and shaped by an ORTEC 571 with the time constant of 3 μs. No rise time discrimination or pulse height correction technique was used.

resolution improved to 1.8 keV.[9] For a smaller size of the pixel, the energy resolution is expected to be improved, if we can combine low noise ASICs for the readout.

In order to extend the application of CdTe diodes to the detection of MeV gamma-rays, we proposed the idea of a stacked detector, in which several thin and large CdTe diodes are stacked together and operated as a single detector.[7, 10, 11] Figure 3 shows a stacked detector consisting of 40 layers of CdTe diodes each with an area of 21.5 mm × 21.5 mm and a thickness of 0.5 mm. The gap of only 0.7 mm has been achieved by utilizing 0.5 mm thick ceramic sheet for the detector housing. The total volume of the stacked detector amounts to 9.2 cm^3, which provides an efficiency of 20 % at 500 keV and 7 % at 1 MeV. In our stacked detector, the signal from each layer is processed independently by using an individual analog chain. The gamma-ray spectrum from the detector is obtained by summing the spectra from all layers which record pulse heights above a certain threshold. With this approach, the energy resolution could be kept at the same level as that of a single layer. Although there is still room for improvements for the prototype detector, we obtain an energy resolution of 1.6–1.7 % (FWHM) for the two peaks of 1.17 MeV and 1.33 MeV in the energy spectrum of gamma-rays from ^{60}Co. The advantage over conventional scintllation counters is demonstrated in Fig. 4 (right) in which gamma-ray lines up to 6 MeV from neutron captures in Na and Cl are shown.

The stack configuration and individual readout provide informations of the interaction depth. This depth information is very useful to reduce the background in space applications, because we can expect that low energy gamma-rays interact in the upper layers and, therefore, we can reject low energy events detected in lower layers. Moreover, since the background rate is proportional to the detector volume, low energy events collected from the first few layers in the stacked detector have a high signal to background ratio, in comparison with events obtained from a monolithic detector with the same thickness as the sum of all layers.

As discussed later, good positional resolution is of great importance to realize the SMCT, in addition to the high energy resolution. Therefore, we have developed prototype pixel detectors with an array of 20×20 pixels using a 15× 15 mm^2 CdTe diode[12] and 32×32 pixel detector[13] with pixel size of 200×200 μm. The technology for gold-stud bump bonding suitable for CdTe/CdZnTe semiconductor has been developed and used to connect each pixel to the fanout board consisting of bump pads and patterns to route the signal from the pad or the ASIC itself.[12]

4. APPLICATIONS OF COMPTON SCATTERING

The sensitivity of observations with hard X-ray and gamma-ray detectors are limited by the background rate. The phoswich configuration and the narrow field of view obtained by a tight active "well-type" shield developed for the

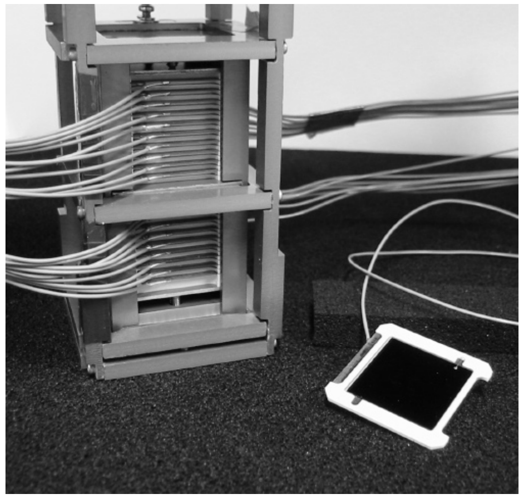

Figure 3. The 40 layer CdTe stacked detector and one of the layers from the stacked detector.[11]

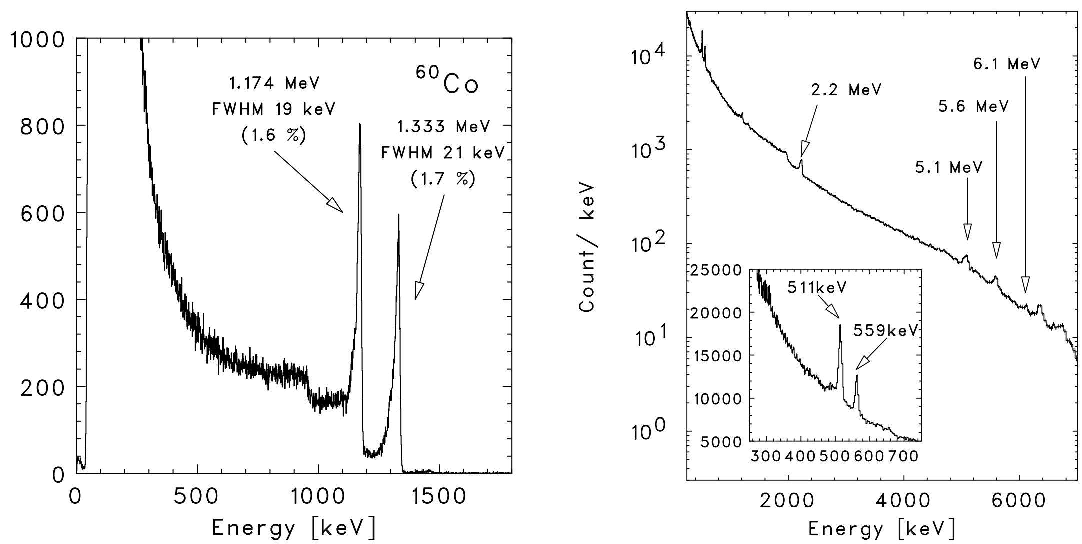

Figure 4. Spectrum of ^{60}Co obtained with the stacked detector. The energy resolutions at 1.17 MeV and 1.33 MeV are 19 keV (FWHM) and 21 keV (FWHM), respectively. The operating temperature is 0 °C (left). Spectrum of neutron capture gamma-rays (right). Neutrons from ^{252}Cf are slowed down by polyethylene and injected to NaCl. The peaks of 6.1 MeV, 5.6 MeV and 5.1 MeV correspond to gamma-rays from neutron captures in Cl nuclei, together with single and double 511 keV escapes. The peaks of 559 keV and 2.2 MeV correspond to gamma-ray produced by neutron captures of Cd and H, respectively.[11]

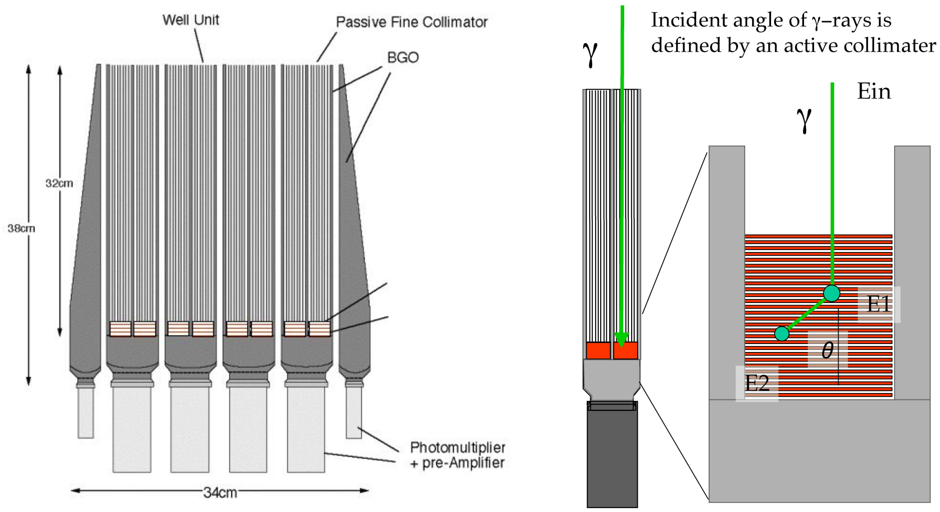

Figure 5. The conceptual design of the next generation well-type gamma-ray detector utilizing Compton kinematics. Compound eye configuration similar to the HXD-II detector on Astro-E2 mission (left). A combination of stacks composed of CdTe imaging devices are buried in the deep BGO well (right).

Astro-E2 Hard X-ray Detector (HXD-II) is the solution to achieve a very low background rate in the energy range up to several hundred keV.[14] In order to further reduce the background, we have proposed a new detector based on a stack of thin CdTe pixel or strip devices in the well-type active shield.[2] The key concept is the requirement of Compton kinematics for events which interact twice (once by Compton scattering and the other time by photo-absorption) in the stacked detector. In the well-type configuration, the detection part is surrounded in almost all directions by the active shield. Therefore, background photons which deposit some of their energy in the shield through Compton-scattering are rejected efficiently. In this low background environment, we further require that gamma-rays should come from the narrow FOV of the well-type collimator and do not escape from the CdTe part. By using the information of interaction position, we can constrain the energy of the two gamma-ray interactions from the formula of Compton scattering. If the energy recorded in the detector does not match this prediction, we can regard them as background.

Above 100 keV, thin CdTe layers can act both as scatterer and absorber. Fig. 6 shows the simulated peak efficiency of the twenty four layers of 2.2 $\times$ 2.2 cm^2 CdTe detector with a thickness of 0.5 mm. In the simulation, gamma-rays are injected uniformly on the surface of the top layer. The total efficiency, including single photo-absorption, is almost the same as that of the 5 mm thick GSO scintillator used in the HXD-II. The fraction of Compton events, which undergo single Compton scattering and subsequent photo-absorption is $\sim$12 % at 200 keV and $\sim$ 5% at 500 keV. If we successfully constrain the kinematics for these events, we can reduce the background, due to shield leakage and activities, and obtain an event set with very high signal-to-background ratio. It should be noted that we can also measure polarization of incident gamma-rays from the azimuthal distribution of Compton scattered photons.

5. NEXT GENERATION COMPTON TELESCOPE

As gamma-ray energy increases to the MeV region, the detection becomes very difficult. By utilizing the technique of the Compton telescope, the $COMPTEL$ instrument on-board the $CGRO$ satellite has achieved pioneering results in this energy region. A concept called the Multiple Compton Method, which was originally proposed by Kamae et al. (1987), is very attractive. The idea of using silicon strip detectors stimulated new proposals for the next generation Compton telescope.[17,18] In this technique, a stack of many thin scatterers is used to record the Compton scatterings. The order of the interaction sequences, hence the correct energy and direction of the incident photon, can be reconstructed by examination of the energy-momentum conservation for all possible sequences. This technique is very powerful to

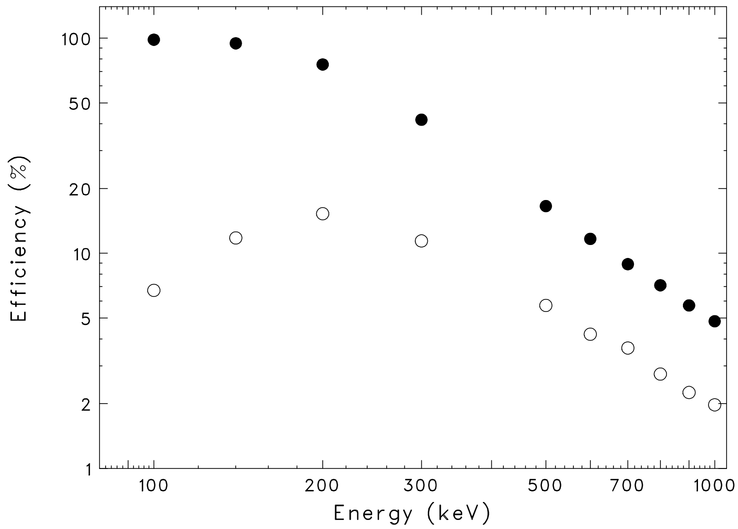

Figure 6. Peak detection efficiency of the 24-layers CdTe stack detector calculated by Monte Carlo simulation for all interactions (filled circle) and for events which interacts twice (once Compton scattering and the other time by photo-absorption) (open circle). Dimensions of each CdTe layer are 22 × 22 × 0.5 mm^2. Gamma-rays are injected uniformly on the surface of the top layer.

suppress background. Figure 7 illustrates a case with two Compton scatterings and one photoelectric absorption in the detector. In this situation, both scattering angle θ_1 and and θ_2 can be obtained from the recoil electron energies as

$$\cos\theta_1 = 1 + \frac{m_e c^2}{E_0} - \frac{m_e c^2}{E_1}, \cos\theta_2 = 1 + \frac{m_e c^2}{E_1} - \frac{m_e c^2}{E_2}$$

while θ_2 can also be reconstructed from the hit positions of the three interactions. This over-constraint provides stringent background suppression that is crucial to observe faint or diffuse gamma-ray sources. Another important point of this method is that, if the incident gamma-rays undergo at least the first three or four Compton scatterings which are sufficient to reconstruct the correct order, gamma-rays do not need to be fully absorbed by the detector and are allowed to escape.

We are working on the study of the optimum configuration of the geometry to be used in the Multi Compton telescope based on high resolution Si and/or CdTe imaging devices. Depending on the energy of interest, the number of Si and CdTe layers and their ratio should be chosen. Fig. 8 shows the peak detection efficiency of events which undergo multi Compton scattering and final photo absorption in a 80 layer detector. The efficiency for the different numbers of Si and CdTe layers are shown as a function of photon energy. The dimensions of the detector are 25 cm × 25 cm and the thickness of each layer is 0.5 mm. Gamma-rays are injected to the center of the top layer.

As clearly seen in Fig. 8, the role of the CdTe layer is important to obtain high detection efficiency for events which include final photo absorption. Replacement with Si layers for upper half 40 layers is effective to improve the efficiency for gamma-rays with the energy below 200 keV. If we surround the layer part by a block of absorber made of CdTe or heavy scintillators , then layers of only Si could maximize the scattering probability.

6. ACTIVE PAIR PRODUCTION TELESCOPE

In the energy region above 10 MeV, pair production becomes the dominant process (see Fig. 1). A stack of thin CdTe pixel or strip detectors has the potential to realize a new detector concept, an "active pair-production telescope". CdTe has a radiation length of 1.52 cm. A thickness of 0.5 mm of CdTe layer corresponds to 0.03 r.l, which is almost same as the thickness of Tantal or Tungsten sheet used in the EGRET or LAT detectors. If we prepare 80 layers of CdTe with a thickness of 0.5 mm, we will have 2.6 r.l in total. Since each layer acts both as a converter and a tracker, the detector is very efficient at detecting pair-production events, especially for energies below 100 MeV, where energy information would be lost in passive material in the conventional pair-production telescopes which used the passive material as a

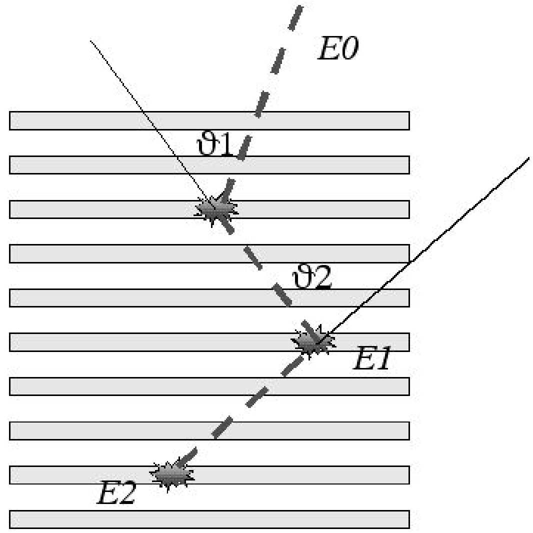

Figure 7. Concept of multi Compton technique.

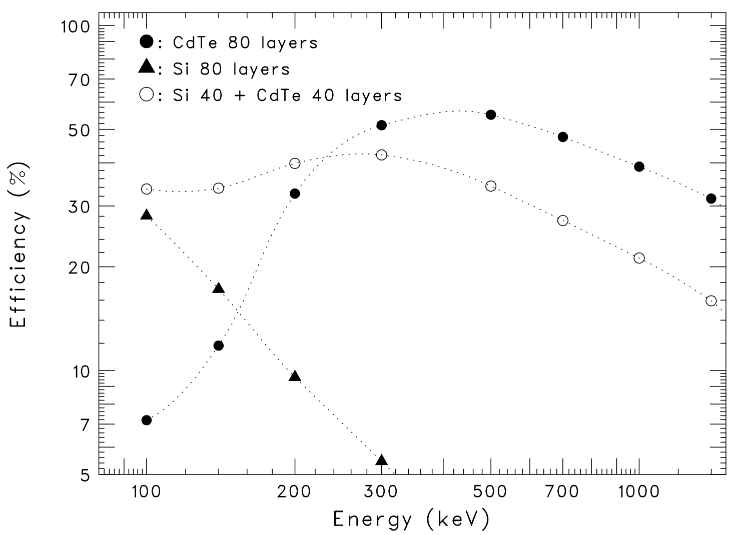

Figure 8. Simulated peak detection efficiency for events which interact more than twice in the detector volume (more than one Compton scattering and final photo-absorption). The detector consists of 80 layers of thin Si or CdTe detector. The results are shown for CdTe layers only (filled circle), Si layers only (filled rectangular) and mixture (open circle). Dimensions of each layer are 25×25 cm^2 with a thickness of 0.5 mm^2. Gamma-rays are injected at the center of the top layer.

converter. High atomic number of CdTe provides the coversion probability of 59 % at 20 MeV and 71 % at 50 MeV in the 80 layers CdTe telescope whose total thickness is 40 mm. Since high positional resolution can be easily achieved by Si strip detectors, interleaving Si strip detectors between CdTe would be more feasible to realize this "active pair-production telescope".

7. CONCLUSION

The high energy resolution of the CdTe diode is very attractive for hard X-ray and gamma-ray detection. A large CdTe diode with dimensions larger than 20×20 mm^2 has a potential to replace scintillation detecotrs due to its high stoppiong power and energy resolution. Many concepts vased on high resolution CdTe diodes are now being investigated and prototype detectors are being developed. For gamma-ray astronomy from several hundred keV to several 10 MeV region, a multi-Compton telescope and an active pair telescope which utilize the CdTe detectors are promissing approaches. For this, we have established technologies such as a stack of 40-layers CdTe detectors and the procedure of fine pitch bump bonding to realize fine pitch pixel and strip detectors.

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