High Resolution Schottky CdTe diode for Hard X-ray and Gamma-ray Astronomy

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Abstract

We report a significant improvement of the spectral properties of cadmium telluride (CdTe) detectors, fabricated in the form of a Schottky CdTe diode. With the use of high quality CdTe wafer, we formed a Schottky junction by evaporating indium on the Te-face and operated the detector as a diode. This allows us to apply much higher bias voltage than was possible with the previous CdTe detectors. A 2 $mm \times 2\ mm$ detector of thickness 0.5 mm, when operated at a temperature of 5 °C , shows leakage current of only 0.2 and 0.4 nA for an operating voltage of 400 and 800 V respectively. We found that, at a high electric field of several kV cm^{-1}, the Schottky CdTe diode has very good energy resolution and stability, suitable for astronomical applications. The broad low energy tail, often observed in CdTe detectors due to the low mobility and short lifetime of holes, was significantly reduced by the application of a higher bias voltage which improves the charge collection efficiency. We achieved very good FWHM energy resolution of 1.1% and 0.8% at energies 122 and 511 keV respectively, without any rise time discrimination or pulse height correction electronics. For the detection of hard X-rays and gamma-rays above 100 keV, we have improved the detection efficiency by stacking a number of thin CdTe diodes. Using individual readout electronics for each layer, we obtained high detection efficiency without sacrificing the energy resolution. In this paper, we report the performance of the new CdTe diode and discuss its proposed applications in future hard X-ray and gamma-ray astronomy missions.

Key words: CdTe, CdZnTe, Schottky CdTe, Hard X-ray detector, Gamma-ray detector, Gamma-ray spectroscopy

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1 Introduction

X-ray astronomy is an indispensable tool in understanding our Universe. X-ray emission from all kinds of celestial objects has been detected by previous X-ray astronomy satellites, such as $ASCA$ and $ROSAT$. However, our knowledge about the universe is very limited in the hard X-ray region, above 10 keV. It is in this hard X-ray band that the non-thermal emission, mostly due to accelerated high energy particles, becomes dominant. In fact, the results from $ASCA$ showed that sensitive observations in this energy band are necessary to constrain the continuum spectra of many classes of X-ray sources. Observations of extended sources are of particular importance, because particles are thought to be accelerated to high energy in the environment with large scale, such as SNR, galaxy and cluster of galaxies. Furthermore, the nuclear γ-ray lines from the radioactive nuclei produced by supernovae explosions are expected to appear above 10 keV. The line profile provides information on the line of sight velocity distribution of the nuclei and also that of the environment of the emitting region. There has been a lack of measurements in the hard X-ray band, mainly due to the unavailability of imaging detectors with sensitivity comparable to that achieved in the energy band below 10 keV, as well as the high energy resolution of $\Delta E/E \sim 1$ %. Cadmium Telluride (CdTe) and Cadmium Zinc Telluride (CdZnTe) solid state detectors have several promising characteristics which make them suitable instruments to be used at the focal plane of a multi-layer grazing incidence mirror or a coded mask aperture for the next generation hard X-ray and γ-ray astronomy satellites.

CdTe has been regarded as a promising semiconductor material for hard X-ray and γ-ray astronomy [1] because of such features as room temperature operation and large band-gap energy ($E_g \sim$ 1.5 eV). The high atomic number of the materials ($Z_{Cd} = 48, Z_{Te} = 52$) gives a high quantum efficiency for photons with energy below 100 keV even for a detector thickness of 0.5 mm. However, a considerable amount of charge loss in CdTe detectors produces a reduced energy resolution. This problem arises due to the low mobility and short lifetime of holes (mobility-lifetime product: $\mu_h\tau_h \sim 10^{-5}$–10^{-4} cm^2 V^{-1}) compared to that of electrons ($\mu_e\tau_e \sim 10^{-4}$–10^{-3} cm^2 V^{-1}). If the mean drift path of the charge carriers, expressed as the product of $\mu\tau$ and the applied electric field E in the device, is smaller than the detector thickness l, due to the hole trapping in the device, only a fraction of the generated signal charge is induced at the detector electrode. The fraction of the charge collected and the resultant pulse height depends on the interaction depth. With hole-trapping, the number of photons in the photopeak is reduced and a broad low energy shoulder appears in the pulse height spectrum. Although CdTe has a high resistivity of $\sim 4 \times 10^9$ Ω-cm, application of very high bias voltage to improve the charge collection increases the leakage current and electronic noise.

Efforts have been made to overcome the hole-trapping problem in CdTe detectors. Using hemispheric or coaxial detectors and compensating the pulse height based on the pulse shape information, some improvement has been achieved [2]. An alloy of CdTe and Zn (CdZnTe) has a resistivity of 10^{11} ohm-cm. Application of a grid structure has been proposed to improve the energy resolution in γ-ray energies around 500 keV [3,4].

Recently, based on the advances in the production of homogeneous and large volume CdTe crystals [5], we achieved a significant improvement in the spectral properties of CdTe detectors [6,7]. The basic idea is to utilize indium as the anode electrode for p-type CdTe semiconductor. Work function of indium is 4.1 eV and lower than that of Pt (5.65 eV) and Au (5.10 eV). A high Schottky barrier formed on the In/p-CdTe interface allows us to operate the detector as a diode (Schottky CdTe diode). This is different than the earlier use of the CdTe detectors (Pt/CdTe/Pt) as a solid ionization chamber. At 400 V, the leakage current of the In/CdTe/Pt detector with a thickness of 0.5 mm in the reversed biased condition is 2 orders of magnitude smaller than the leakage current of Pt/CdTe/Pt. The very low leakage current of the Schottky CdTe diode enables us to apply high electric field to ensure a complete charge collection in the device.

In this paper, we discuss the spectral characteristics and stability of the Schottky CdTe diodes at an operating temperature of 5 °C . We present the results obtained with a stack of CdTe diodes used for good detection efficiency of photons with energy upto 400 keV. The possible application of the new stacked CdTe pixelated detectors for high resolution imaging spectrometers for the next generation X-ray and γ-ray missions is discussed.

2 Schottky CdTe diode

The Schottky CdTe diodes used in this study were fabricated with the prescription described in Ozaki et al. [8]. We used Cl-doped CdTe single crystals grown by the traveling heater method (THM). It has p-type resistivity of $\rho = 4\times10^9$ Ω cm. We formed a Schottky junction on the B-face (Te-face) of the wafer by evaporating indium after heating the wafer to $200 - 300$ °C . On the opposite face (Cd-face), Pt was formed by electro-less plating. As shown in Fig. 2, the detectors show current-voltage characteristics typical to a diode. A significant suppression of the leakage current is obtained in the reverse bias operation of the In(anode)/CdTe/Pt(cathode) configuration [6]. The leakage current of the $2\ mm \times 2\ mm \times 0.5\ mm$ detector was 0.7 nA with a bias voltage of 400 V at (20 °C). When cooled to 5 °C , the leakage current was measured to be 0.4 nA even with a bias voltage of 800 V corresponding to an internal electric field of 16 kV cm^{-1}.

The barrier height of the Schottky junction is one of the most important parameters for the Schottky CdTe diodes. We measured the barrier height directly by X-ray Photoelectron Spectroscopy (XPS) from a VG ESACALAB 220i_XL spectrometer.

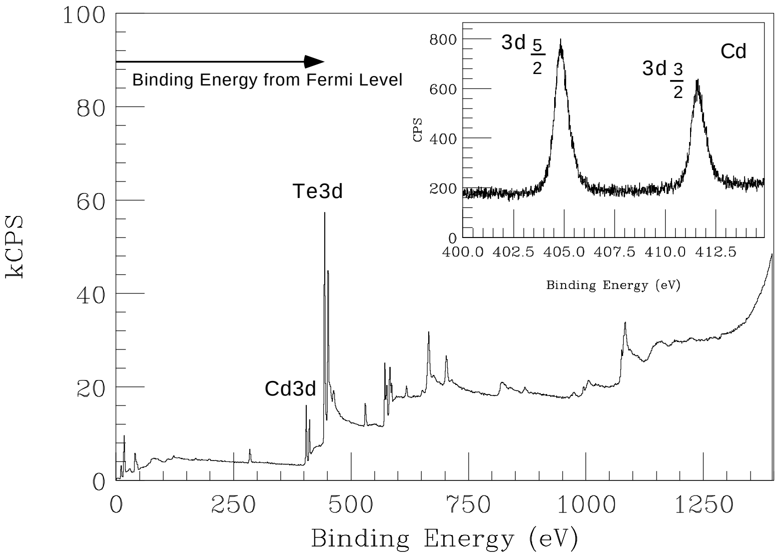

Fig. 1. Electron binding energy spectrum of CdTe obtained by illuminating it with Al K_α X-rays of energy 1486.6 eV. The inset shows the spectrum in the regions of Cd 3d.

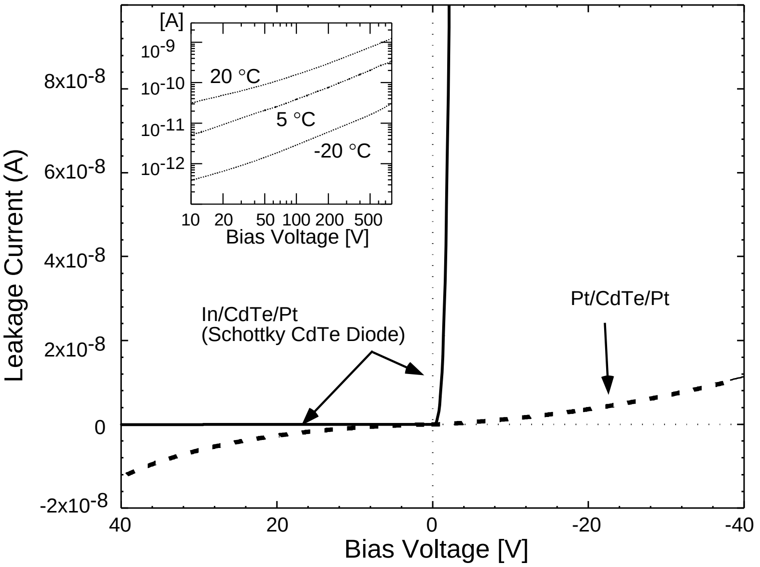

Fig. 2. Current-voltage (I-V) characteristics at room temperature of the Pt/CdTe/Pt and In/CdTe/Pt with dimensions of 2×2 mm^2 and a 0.5 mm thickness. For the latter electrode configuration, a positive bias is applied on the In electrode. The insert shows the reverse current of the In/CdTe/Pt at different operating temperatures

We used the polished CdTe wafers of dimensions 1 $cm \times 1$ cm and a thickness of 0.5 mm. After cleaning by ethyl alcohol, indium was evaporated on the B-face of CdTe to form $\sim$20 atomic layers (26.8 Å) in the ultra-high vacuum condition of $\sim 10^{-10}$ torr. Figure 1 shows a electron binding energy spectrum obtained with a wide XPS scan. Several lines including Cd 3d and Te 3d are clearly seen in the energy spectrum. An energy calibration is obtained by using the indium 3d $\frac{5}{2}$ peak which has a binding energy of 443.8 eV.

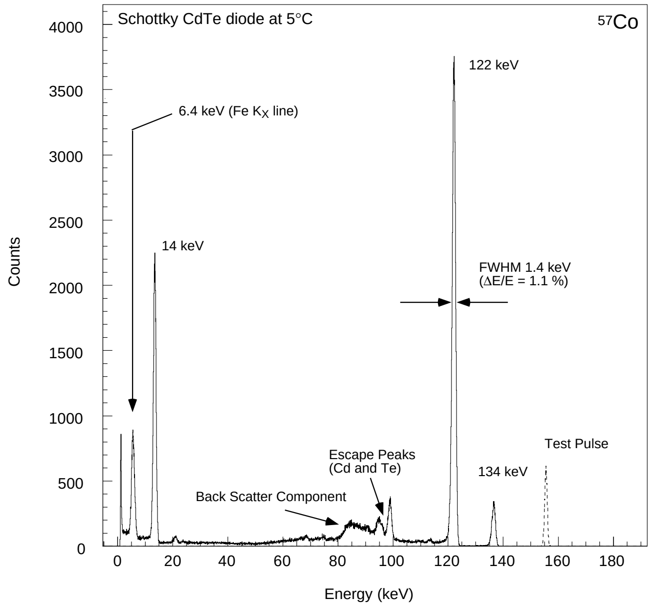

Fig. 3. ^{57}Co spectrum obtained with the $2\,mm \times 2\,mm$ Schottky CdTe detector of thickness 0.5 mm. It was operated at 5 °C and a bias voltage of 800 V was applied. The time constant of a shaping amplifier was set at 1 μs.

As shown in the inset of figure 1, a fine scan around Cd 3d peak measured the binding energy of Cd 3d $\frac{5}{2}$ to be 404.81 eV. The measured binding energy corresponds to the difference between the Fermi level of CdTe at the In/p-CdTe interface and the CdTe 3d $\frac{5}{2}$ core level. By subtracting 404.06 eV, which is the Cd 3d $\frac{5}{2}$ level with respect to the valence band maximum [9], from 404.81 eV (the binding energy of Cd 3d $\frac{5}{2}$), a barrier height of 0.75 eV is obtained for the indium junction. Our measurement shows that the Schottky barrier at the anode is high enough to prevent injection of holes into the CdTe detector, which is the major carrier in the p-type semiconductor. The barrier height obtained here is lower than the value estimated for the In/n-CdTe [10,11,6]. The difference is probably due to the presence of an oxidized layer on the surface. Existence of an oxidized layer is also inferred from a double peaked nature of the Te 3d line.

3 Spectral performance and stability

The signal from the detector was extracted from the cathode side and directly fed into a Charge Sensitive Amplifier (CSA). Since the Schottky CdTe diode has very low leakage current, we do not need to use a de-coupling capacitor to maximize the charge to be integrated and to minimize the electronic noise. For this experiment, we developed a new CSA (CP-5109LS). In the CSA, special care was taken to select FETs with low gate leakage current. The feedback network consists of 0.5 pF capacitance and 10 GΩ resistance. The charge signal is integrated in the CSA and shaped by an ORTEC 571 amplifier. With 1 μsec shaping time, the equivalent

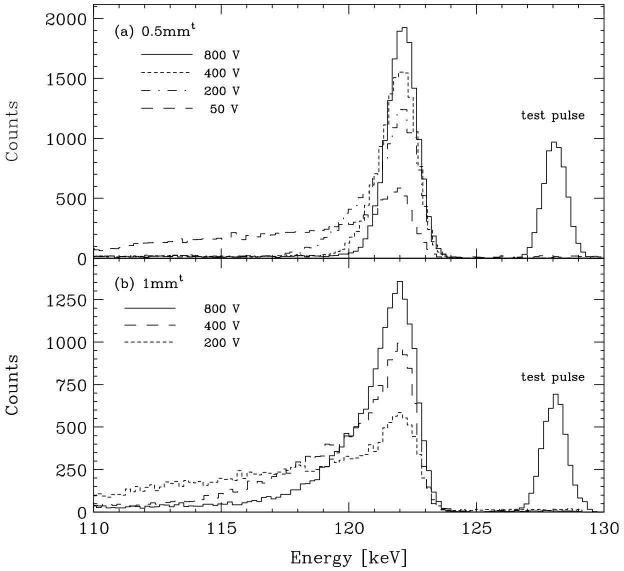

Fig. 4. Spectra of the 122 keV line of ^{57}Co obtained with different bias voltages. The Schottky CdTe detectors have identical surface area of $2\ mm \times 2\ mm$ and thickness of (a) 0.5 mm and (b) 1 mm. The spectra are normalized according to the intensity of the 14 keV line. The operating temperature was 5 °C for both the detectors.

RMS noise charge was $\sim$60 electrons at C_{in} = 0 pF and $\sim$270 electrons at C_{in} = 100 pF, respectively. We mounted the detector and the CSA into the thermostatic chamber with the temperature controlled at 5 °C .

Figure 3 shows the energy spectrum of γ-rays from ^{57}Co obtained with the same diode. A bias voltage of 800 V was applied and the operating temperature was 5 °C . The 6.4 keV (Fe K_α) line of iron is clearly detected. The FWHM of the 122 keV line is 1.4 keV corresponding to an energy resolution ($\Delta E/E$) of 1.1 %. This is close to the energy resolution of HP-Ge detectors cooled at liquid nitrogen temperature. Though a better performance of the CdTe detectors was achieved at lower temperature (i.e. lower leakage current), we chose 5 °C as the operating temperature throughout this experiment. Operation at 5 °C requires a simple cooling system, which is important for future large-scale detectors. The performance of the Schottky CdTe diodes at room temperature and lower temperatures of –20 °C and –70 °C were reported earlier [6,7].

We studied how the high bias voltage improves the charge collection efficiency for detector thickness of 0.5 and 1 mm. Spectra of the 122 keV line from ^{57}Co taken at different bias voltages are shown in figure 4. A broad shoulder or low energy tail due to incomplete of charge collection is apparent in the spectra obtained with bias voltages below 400 V. At 800 V, the FWHM of the 122 keV line spectrum approaches the one obtained with a constant voltage test pulse. In order to fully collect charges produced by the transit of carriers, the transit time must be shorter than the carrier life time. Since the transit time is calculated from the velocity, which is proportional to the internal electric field and the thickness, the bias voltage

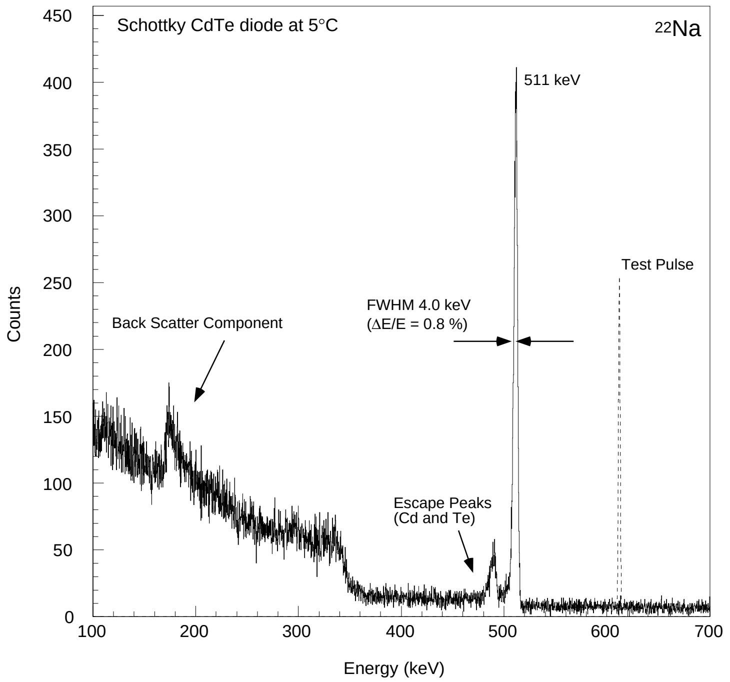

Fig. 5. Spectrum obtained by irradiating the Schottky CdTe detector with 511 keV line from ^{22}Na . Operating temperature was 5 °C and a bias voltage of 800 V was applied. The time constant of the shaping amplifier was set to 1 μs. Compton edge and X-ray escape peaks of Cd and Te are clearly seen below the 511 keV line. No rise time discrimination or pulse height correction technique was used.

required for any given transit time is proportional to the second power of thickness. This relation is clearly seen when the spectra obtained with the 0.5 mm and 1 mm thick detectors at different bias voltages are compared (figure 4). The spectrum obtained with the 1 mm thick detector at bias voltage of 800 V is very similar to that obtained with the 0.5 mm thick detector at 200 V.

We also have studied the spectral performance of the 0.5 mm thick detector at the electron-positron annihilation line energy of 511 keV by irradiating it with positrons from ^{22}Na under the same operating conditions. The resultant spectrum is shown in figure 5. At 511 keV, a FWHM energy resolution of 4.0 keV ($\Delta E/E$ of 0.8 %) was achieved. Absence of a broad low-energy tail often seen in ordinary CdTe or CdZnTe detectors [1,12,13] is the most important feature of the Schottky CdTe diodes. In the figure, Compton edge and X-ray escape peaks of Cd and Te are clearly seen below the 511 keV line, implying the superior energy resolution of the Schottky CdTe diode. It should be noted that we have not used any rise time discrimination or pulse height correction technique.

Although the improvement of the energy resolution by adopting the Schottky junction is drastic, we found that when operated with a low bias voltage (below 200 V for 0.5 mm thick detector) at room temperature, the time dependent drift of the pulse height is significant. The peak channel of the γ-ray line started to drift after a stable period. This phenomenon is similar to the “Polarization” effect observed in semiconductor detectors [14–16]. It should be noted that that the spectral performance recovers after the bias voltage is re-applied. Through the test of the Schottky CdTe diode at different operating conditions, we have found that a high internal electric field of several kV cm^{-1} and low operating temperature are important to obtain long term stability [6,7]. For a detector with dimentions of 2×2 mm^2 and a thickness of 0.5 mm, the drift stated 5 minutes after the bias voltage of 40 V was applied. At 200 V, it started 4 hours after the bias was applied. The degradation of the spectrum started later for higher bias voltage. The operating temperature is another important factor for the long term stability. Similar behavior observed with respect to an operating temperature is seen. At 30 °C , the drift started after 20 min. By lowering the operating temperature, degradation of the spectrum started later. At 0 °C , the peak stayed at the same pulse height for 10 hours. It is noted that a distortion of the spectrum was seen after 8 hours after the bias voltage was applied. When we cooled the detector down to -20 °C , the detector performed consistently for more than several days at the bias voltage of 400 V without distortion of the spectrum. When we applied 800 V to the 0.5 mm Schottky CdTe detector at 5 °C , the peak position of 122 keV remained unchanged for 12 hours.

According to Yao et al., the polarization effect can be explained by the non-uniform electric field due to the charge accumulation [17]. The polarization effect starts to appear when the internal electric field by the accumulated charge becomes comparable to the electric field generated by the external bias. Therefore, the high electric field is the key to obtain the long term stability. A low temperature operation of the detector delays the degradation of the spectrum. One possible reason is the time required for the charge build-up is longer with lower leakage current.

4 A stacked CdTe detector

Energy resolution of $\leq 1\%$ at high photon energy of several hundred keV under moderate operating condition is very attractive in high energy astrophysics. However, good energy resolution with a thick Schottky CdTe diode will be difficult to achieve as the bias voltage required for complete charge collection scales with the second power of the detector thickness. For a detector with 5 mm thickness, the voltage required for full charge collection would be $\sim$ 80 kV. We, therefore, adopted the idea of a stacked detector, in which several thin CdTe diode are stacked together and operated as a single detector.

For photon energy upto several hundred keV, adequate detection efficiency can be achieved by stacking 0.5 mm thick detectors with 10 to 20 layers. Instead of combining the signal from all the layers, we used an individual readout electronic system for each layer. With this approach, we are able to select events in which energy deposition is in a single layer as expected from interaction via photon absorption. Adding spectrum from all the layers, very good spectral performance and quantum efficiency is achieved. One additional feature of the stacked detector is that Compton down-scattering of high energy γ-rays, which increases the detector background, can be reduced by demanding anti-coincidence between signals from different layers. If the stacked detector has sufficient volume, it can also act as a multi-layer Compton detector.

We made a prototype stacked detector (figure 6) with 12 Schottky CdTe diodes, each with a surface area of $5\ mm \times 5\ mm$ and thickness 0.5 mm. A bias voltage of 400 V was applied to all the diodes and the operational temperature was fixed to 5 °C . The signal from each layer was integrated using a CSA hybrid CS515-2 (the equivalent RMS noise charge was 83 electrons at C_{in} = 0 pF and 225 electrons at C_{in} = 100 pF, respectively) by Clear Pulse to reduce the size of the front readout system. The signal from each channels was then shaped by an ORTEC 571 amplifier. Threshold discrimination was applied to the output from each shaping amplifier and the resultant signals were OR-ed and used to trigger the data acquisition. A mutual anti-coincidence was applied between the layers to select the events which occured in only one layer. The energy spectrum from different layers were accumulated separately.

Figures 7 (a)-(c) show energy spectra of ^{133}Ba γ-rays obtained from layer 1, layer 2 and layer 6. The stacked detector provides information of the interaction depth with a resolution of the thickness of the individual elements (0.5 mm for this detector). It is easily noticed that the low energy peak at 30 keV is prominent in the first layer, while high energy peaks are prominent in the subsequent layers. As expected, the ratio of the amplitudes of high energy lines to low energy lines increases in the deeper layers. The sum of the spectra from the first 8 layers are shown in figure 6(d) in a logarithmic scale along with the spectrum from layer 1. A FWHM resolution of the summed spectrum is 3 keV at 81 keV and 7.5 keV at 356 keV. There was no degradation of energy resolution in the summed spectrum which has higher quantum efficiency in a wide energy band . An asymmetry is noticed in the line shape for energies above 250 keV. This is due to the fact that a bias voltage of 400 V was applied to the 0.5 mm thick diodes, which is not sufficient for full charge collection.

5 Application to future hard X-ray astronomy missions

The discipline of X-ray astronomy has become mature, and future X-ray observatories need to be highly specialized. High-resolution spectroscopic imaging at energies above 2 keV, systematically exploited by the Japanese X-ray astronomy satellite $ASCA$, has led to many new astrophysical discoveries. Very high spectral resolution in the 0.5–12 keV band and a wide energy band extending upto 700 keV are the important features of the successor to $ASCA$, the $Astro-E$ [18,19]. For

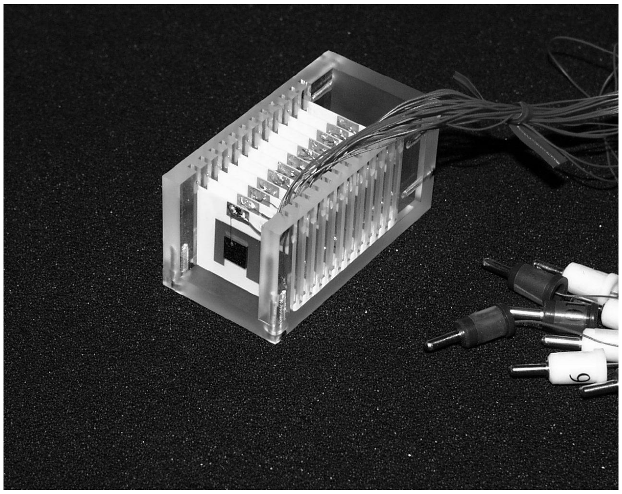

Fig. 6. The stacked Schottky CdTe detector. 12 Schottky CdTe diodes of surface area $5\ mm \times 5\ mm$ and thickness 0.5 mm are stacked together. The detector was operated at a temperature of 5 °C and a positive bias of 400 V was applied to the indium electrodes. The output from each diode was fed into an individual readout electronics system, which were operated in anti-coincidence.

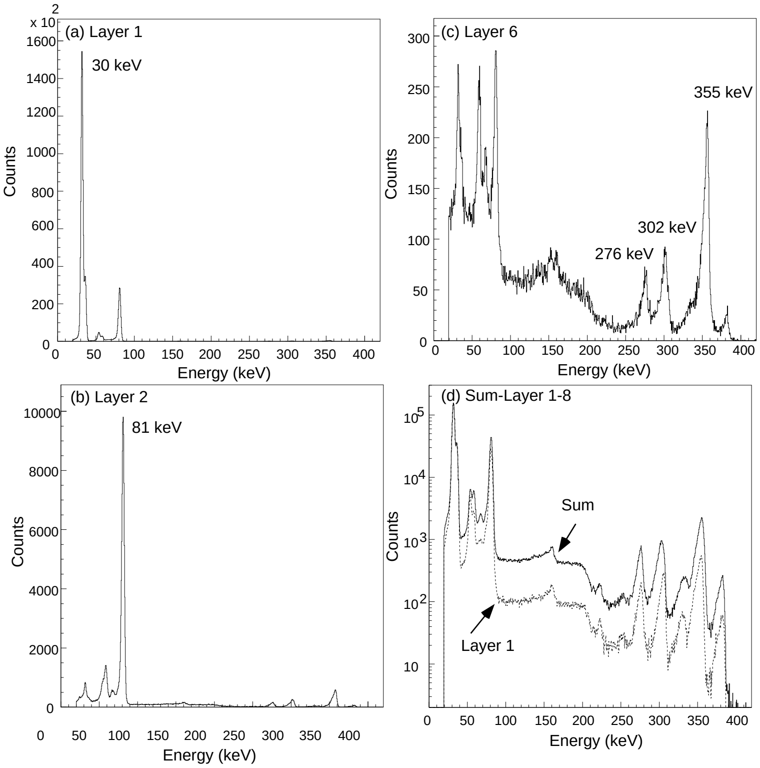

Fig. 7. ^{133}Ba spectrum measure using the stacked CdTe detector at 5 °C under a bias voltage of 400 V. Energy spectrum obtained from (a) first layer, (b) second layer, and (c) 6th layer. Added spectrum from the top 8 layers is shown in (d) together with the spectrum of the 1st layer. γ-ray events that deposit energy in only one layer were selected.

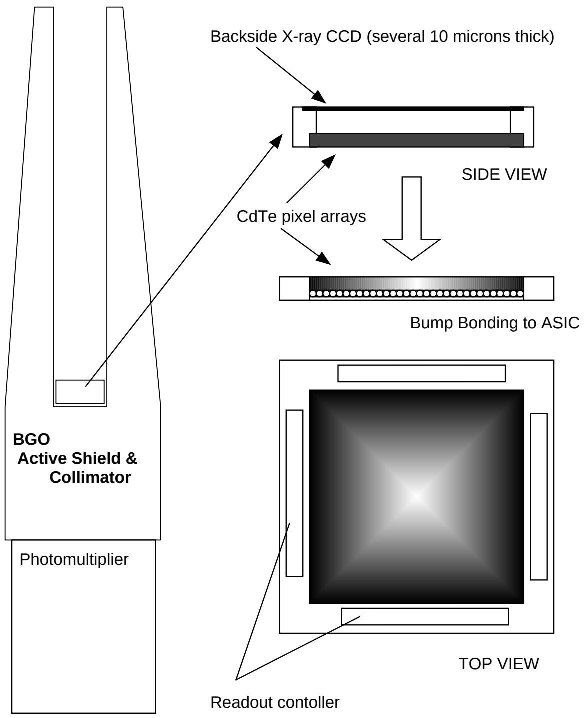

Fig. 8. A schematic diagram of a wide band imaging spectrometer detector to be used at the focal plane of a super mirror for the Japanese next generation X-ray satellite. The detector is a combination of back-illuminated X-ray CCD and the pixelated CdTe detector covering 0.1 - 60 keV.

the future X-ray astronomy missions in Japan, one of the main objectives is a very high sensitivity in the 10–50 keV band. This could be achieved by employing a multi-layer, grazing incident hard X-ray telescope (“super mirror”) in conjunction with a hard X-ray imaging detector. According to the analysis based on laboratory experiments [20], with six mirrors of 7 m focal length and 60 cm aperture, we will be able to have an affective area of 400 cm^2 in the 10–40 keV range. With this telescope, sources with an intensity of the order of 10^{-5} to 10^{-6} times the Crab intensity could be detected in an observation lasting one day.

Since the super mirror is able to cover the energy range from $\sim$ 0.5 keV up to 40-60 keV, the focal plane detector is required to cover a very wide energy band. Development of such a detector is now underway at ISAS. One idea is to combine a back-illuminated X-ray CCD and a pixelated CdTe detector, bump-bonded to the readout electronics chip. Soft X-rays will be absorbed in the X-ray CCD, and hard X-rays will penetrate the CCD and be absorbed in the CdTe pixelated array. High background is a major concern in hard X-ray astronomy, and we plan to use a tight active “well-type” shield developed for the Astro-E Hard X-ray detectors. As shown in figure 8, the active volume will be surrounded in almost all directions by the active shields. With this configuration, we expect that the detector background, which limits the sensitivity of the detectors in hard X-ray energy range, will be reduced significantly.

6 Conclusion

With a Schottky junction developed on the Te face of the p type CdTe semiconductor by evaporating indium, we have been able to reduce the leakage current considerably. This allows us to use a higher bias voltage which results into complete charge collection. One additional advantage of this detector is the moderate cooling requirement. At 5 °C , we obtained a very good energy resolution (FWHM) of $\sim$ 1.1 % at 122 keV and 0.8 % at 511 keV, for a 2 mm × 2 mm detector of thickness 0.5 mm, is achieved without any rise time discrimination or pulse height correction electronics. We have also found that long time stability of the gain and resolution can be achieved by applying higher bias voltage and lower temperature. For application of the CdTe detectors in the soft γ-ray region, we developed a stacked CdTe detector which has high detection efficiency for photons upto about 400 keV. A pixelated imaging detector made with Schottky CdTe diodes with high energy resolution and quantum efficiency is a very attractive device for the future hard X-ray astronomy missions. A stacked CdTe detector that is efficient at energies upto a few hundred keV and has good energy resolution can be used with a coded mask aperture in imaging mode and also for detection of γ-ray line features from astrophysical sources.

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