# Performance of a New Schottky CdTe Detector for Hard X-ray Spectroscopy

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## ABSTRACT

We report a significant improvement of the spectral properties of a cadmium telluride (CdTe) detector. With the use of a high quality CdTe crystal, we formed a high Schottky barrier for the holes on a CdTe surface using a low work-function metal, indium. For a 2×2 mm$^2$ detector with a thickness of 0.5 mm the leakage current was measured to be 0.7 nA at room temperature (20 °C ) and 10 pA at $-20$ °C for a 400 V bias voltage. The low-leakage current of the detector allows us to operate the detector at a higher bias voltage than previous CdTe detectors. The improved charge collection efficiency and the low-leakage current leads to an energy resolution of 1.1–2.5 keV FWHM in the energy range 2 keV to 150 keV at 20 °C without charge loss correction electronics. We confirmed that once a high electric field of several kV/cm is applied, the Schottky CdTe has a very good energy resolution as well as sufficient stability to be used for practical applications.

**Keywords:** CdTe, CdZnTe, Schottky CdTe, Hard X-ray detector, Gamma-ray detector, Gamma-ray spectrometry

## 1. INTRODUCTION

Cadmium telluride (CdTe) has been regarded as a promising semiconductor material for X-ray and $\gamma$-ray detectors operated at room temperature, because of features such as a high atomic number ($Z_{Cd} = 48, Z_{Te} = 52$) and a large band-gap energy ($E_g \sim 1.5$ eV).[1] However a considerable amount of charge loss in CdTe results in a limited capability when such detectors are used as high resolution spectrometers in X-ray and $\gamma$-ray astronomy, such as the next generation Japanese X-ray satellite. This problem is due mainly to the low mobility and short lifetime of holes (mobility-lifetime product: $\mu_h\tau_h \sim 10^{-5}$–$10^{-4}$ cm$^2$/V) compared to that of electrons ($\mu_e\tau_e \sim 10^{-4}$–$10^{-3}$ cm$^2$/V).

Full-charge collection of electrons and holes is required to achieve high spectral resolution in a semiconductor detector. The mean drift path of the charge carrier is expressed as the product of $\mu\tau$ and $E$, where $E$ is the applied electric field in the device. When a detector with a thickness $l > \mu_h\tau_h E$ is used, only a fraction of the generated signal charge is induced at the detector electrode due to the hole trapping in the device. The fraction and the resultant pulse height depend on the interaction depth. This position dependency produces a shoulder (tailing) in the peaks of $\gamma$-ray lines towards the low energy region, which leads to a distortion of the spectrum.

Great efforts have been made to overcome the hole-trapping problem. These efforts include electronic signal processing which compensates for the pulse height based on its pulse shape information and designing various detector shapes such as hemispheric and coaxial.[2] The application of a grid structure has been proposed to improve energy resolution in $\gamma$-ray energies around 500 keV.[3,4] Recently, the application of a p-i-n structure with a moderate cooling system in conjunction with a miniature Peltier cooler and the rise time discrimination electronics has been reported.[7]

Previous studies by our group have shown that once a Schottky junction is formed on the metal/p-CdTe interface, the leakage current is reduced significantly.[5,6] Since the charge-sensitive amplifier integrates the charge in the crystal and converts it to a voltage pulse, the magnitude of the electronic noise strongly depends on the leakage current. The

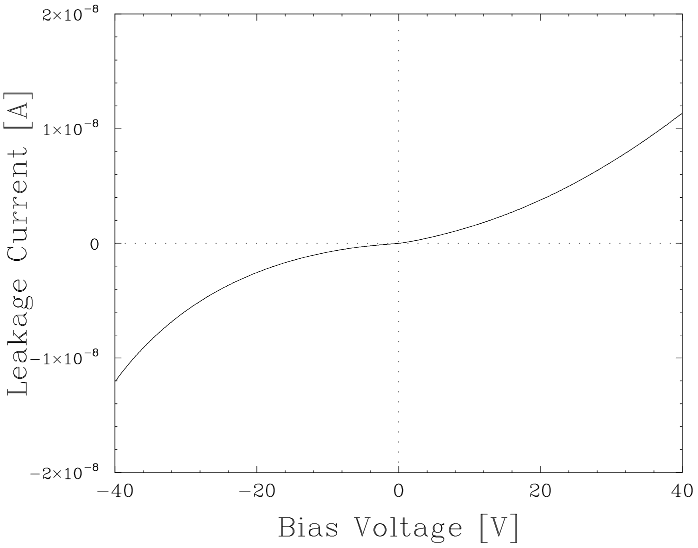

**Figure 1.** Current−voltage (I-V) characteristics at room temperature of the Pt/CdTe/Pt with dimensions of $2 \times 2$ mm$^2$ and a 0.5 mm thickness. For the Pt/CdTe/Pt, the electrode formed on the Cd face was connected to the ground level. The applied voltage was swept over the electrode on the Te face.

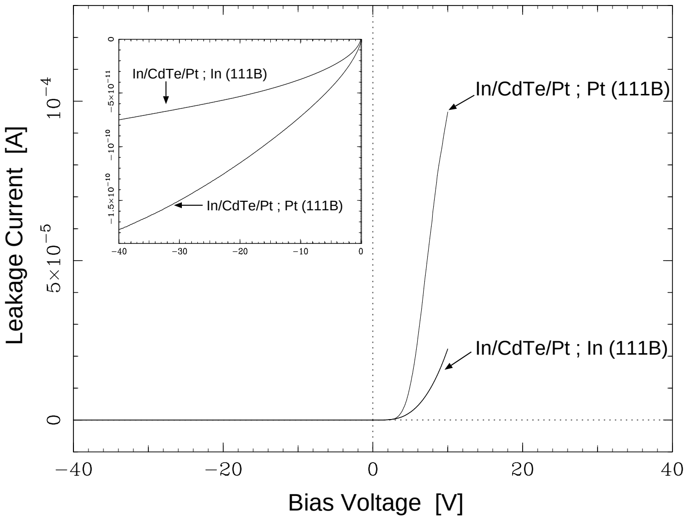

**Figure 2.** I-V characteristics at room temperature of the In/CdTe/Pt with dimensions of $2 \times 2$ mm$^2$ and a 0.5 mm thickness. The In electrode was connected to the ground level. The insert shows the reverse current.

Schottky CdTe detector (In/CdTe/Pt) enables us to apply a bias voltage of more than 400 V for the 0.5mm-thick detector at room temperature without a loss of resolution. This high bias voltage, which corresponds to several thousand kV electric field, is sufficient to collect the full charge generated in the device.[6] The polarization effect is found to be suppressed with a high bias voltage and/or low temperature operation. In this presentation, we focus on the performance of a new Schottky CdTe detector.

## 2. SCHOTTKY CDTE DETECTOR

The Schottky CdTe detectors used in this study were fabricated with the prescription described in Ozaki et al.[5] We used *Cl*-doped CdTe single crystal with p-type resistivity grown by the traveling heater method (THM). The $\mu\tau$ products are $\sim 10^{-4}$ cm$^2$/V and $\sim 3 \times 10^{-3}$ cm$^2$/V for holes and electrons, respectively. Polished wafers with (1,1,1)

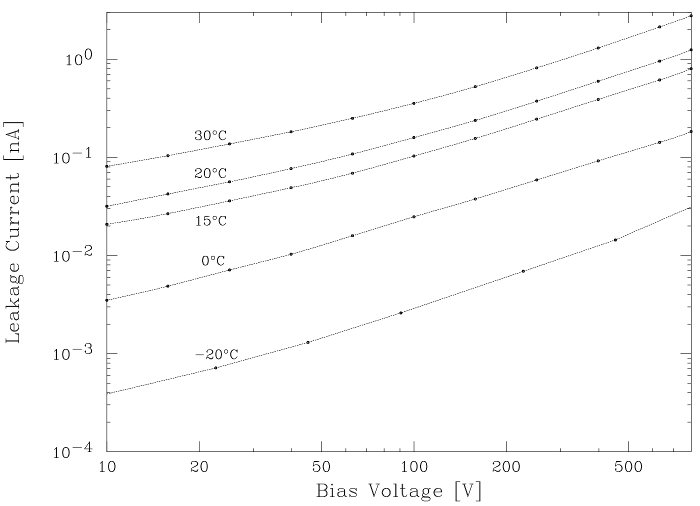

**Figure 3.** I-V characteristics of the Schottky CdTe at different operating temperatures. The detector has dimensions of 2×2 $\mathrm{mm}^2$ and a 0.5 mm thickness. A positive bias was applied on the In electrode.

orientation were used. We prepared three kinds of detectors: (1) Indium on the B-face (Te-face) and Pt on the A-face (Cd-face) (In/CdTe/Pt; In(111)B), (2) Pt on the B-face and In on the A-face (In/CdTe/Pt; Pt(111B)) , and (3) Pt on the both sides (hereafter referred to as Pt/CdTe/Pt). The In electrode was formed by vacuum evaporation after heating the crystal to 200–300 °C.[5] This thermal process is thought to remove an amorphous Te-rich layer and recover the stoichiometry. The Pt electrode was formed by electroless plating. The wafers were then cut into detectors and mounted on Alumina backing.

The current-voltage characteristics of the Pt/CdTe/Pt and the In/CdTe/Pt are shown in Fig. 1 and Fig. 2, respectively. Each detector has dimensions of 2×2 $\mathrm{mm}^2$ and a 0.5 mm thickness. The I-V curve of the Pt/CdTe/Pt is symmetric with respect to the polarity of the applied bias voltage and the leakage current is $3-4\times10^{-9}$ A at 20 V. Differential resistivity of the Pt/CdTe/Pt is calculated to be $3-4\times10^{9}\Omega$cm at 20 V. On the other hand, the diode characteristic in the I-V curve of the two configurations of the In/CdTe/Pt is clearly seen in Fig. 2. As pointed out in Ozaki et al,[5] the lower leakage current was obtained when the In-electrode was formed on the B-face (Te-face) (Fig. 2). The reverse current of the In/CdTe/Pt is much more reduced than the leakage current of Pt/CdTe/Pt (more than 2 orders of magnitude at 40 V). Even at room temperature (20 °C ), the leakage current was suppressed to 0.7 nA at a bias voltage of 400 V. By cooling to −20 °C , the leakage current decreased to 10 pA.

The metal contact on the surface of semiconductor is known to play an important role,[9,10] because the Schottky barrier formed on the interface between metal and semiconductor significantly influence on the flow of electrons and holes. Using measurements at the metal/n-CdTe interface,[8,11] the Schottky barrier heights at In/p-CdTe and Pt/p-CdTe are calculated to be 1.38 eV and 0.53 eV, respectively. The difference of these barriers can explain the current-voltage characteristics of the Pt/CdTe/Pt and the In/CdTe/Pt. According to Iwase et al.,[8] the leakage current of the Pt/CdTe/Pt is explained by the hole injection from the positive electrode (anode). In the I-V curve of the Pt/CdTe/Pt, the deviation from the linear relation, which is expected from the ohmic contact, implies that the Schottky barrier is formed on the Pt/p-CdTe surface. However, the Schottky barrier height at the Pt/p-CdTe is still low and results in a relatively large leakage current. On the other hand, by using a low work-function metal Indium, as an anode, a significant suppression of the leakage current is obtained in the reverse bias operation of the In(anode)/CdTe/Pt(cathode). The high Schottky barrier of In/p-CdTe at the anode surface prevents the injection of holes into CdTe. In the forward bias operation, the electron injection becomes the dominant source of the leakage current, because the barrier height of In for electrons is much lower than that obtained by Pt.[11]

The large leakage current of the In/CdTe/Pt;Pt(111B) compared with that of the In/CdTe/Pt;In(111B) implies that its Schottky barrier is lower in the In/Cd-face than that in the In/Te-face, and suggests that the surface Fermi level is lower for the Cd-face. It is reported that an acceptor level of 0.2 eV is yielded when the wafer is in the situation of Te-excess.[12] If the acceptor level is the origin of the interface states then the excess of Te on the Cd face of the Br-MeOH etched CdTe wafer may be the reason of the larger leakage current of In/CdTe/Pt;Pt(111B).

Since the Schottky junction on In/p-CdTe (anode) and Pt/p-CdTe (cathode) determines important characteristics of the detector, hereafter we refer to the In/CdTe/Pt;In(111B) electrode system as the Schottky CdTe detector.

## 3. SPECTRAL PERFORMANCE AND STABILITY

Figure 4 shows the energy spectrum of $\gamma$-rays obtained from $^{241}$Am at 20 °C with the Pt/CdTe/Pt. Figure 5 shows that for the Schottky CdTe detector. We tried to apply a highest bias voltage possible to obtain a high electric field in the device for the efficient charge collection under the condition that the low-energy threshold of several keV was obtained. This criterion corresponds to the bias voltage of 40 V for the Pt/CdTe/Pt and 400 V for the Schottky CdTe. In the measurement, the charge signal is integrated in the Clear Pulse CP-5102 charge sensitive pre-amplifier and shaped by an ORTEC 571 amplifier. The time constant of a shaping amplifier was set at 0.5 $\mu$s for both detectors. In order to minimize the effect of the incompleteness of the hole collection, we irradiated $\gamma$-rays from radioactive sources on the negative electrode (cathode).

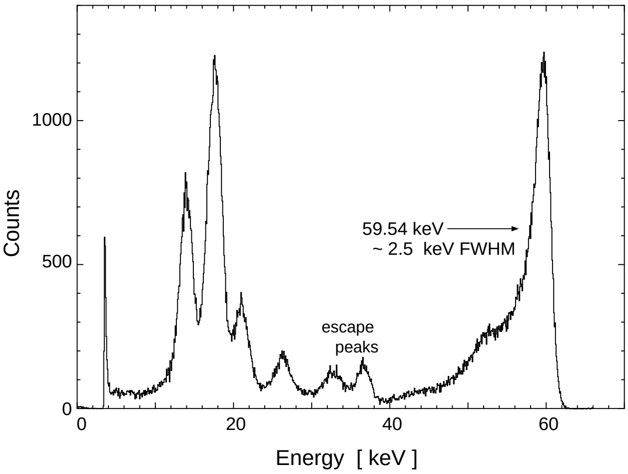

**Figure 4.** $^{241}$Am spectrum by a 2× 2 mm$^2$ Pt/CdTe/Pt detector with 0.5 mm thickness at 20 °C under a bias voltage of 40 V. The low energy tail because of incomplete charge loss due to trapping is clearly seen.

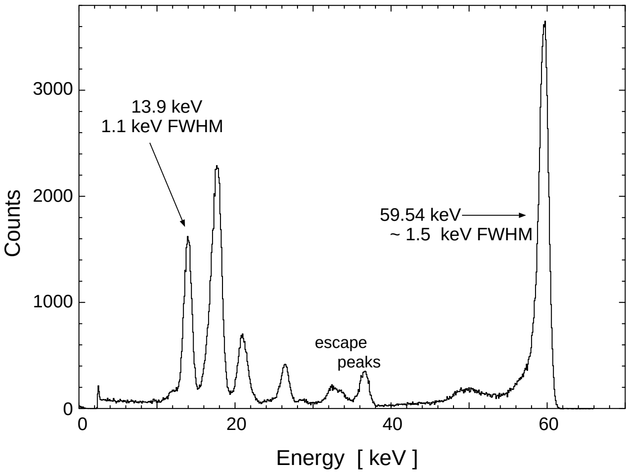

**Figure 5.** $^{241}$Am spectrum obtained by a 2× 2 mm$^2$ Schottky CdTe detector with 0.5 mm thickness at 20 °C . A positive bias of 400 V was applied on the In electrode (anode). No rise time discrimination or pulse height correction electronics were used.

The improvement of the energy resolution is clearly seen by comparing the two spectra. The lower leakage current leads to a sharp increase in the peak amplitude and photo-peak efficiency of the Schottky CdTe detector compared to Pt/CdTe/Pt. The improvement at 60 keV is also due to the improved charge collection efficiency, because the 40 V bias for the Pt/CdTe/Pt is far from sufficient for the full charge collection for 60 keV $\gamma$-rays.

Although the improvement of the energy resolution by adopting the Schottky junction is drastic, we found that the time dependent drift of the pulse height is significant for the Schottky CdTe detector operated with a low bias voltage and at room temperature. It should be noted that the leakage current did not change during the operation and the spectral performance recovered after the bias voltage was re-applied. These phenomena are similar for those reported as “Polarization” in the literature.[13–15] On the contrary, the Pt/CdTe/Pt shows very stable operation for several days, without changing its spectral performance. Fig. 6 shows the change of the spectrum obtained by one of the Schottky CdTe detectors under different bias voltages. As shown in the figure, the situation improved when we applied a high bias voltage of a few hundred volts. At 400 V, the spectral performance for $^{241}$Am was stable for about 6 hours.

Figure 7 (a) shows the relative change of the peak channel of the 60 keV line of $^{241}$Am at different bias voltages. It is intriguing that the peak started to drift after a stable period. At 40 V, the drift stated 5 minutes after the

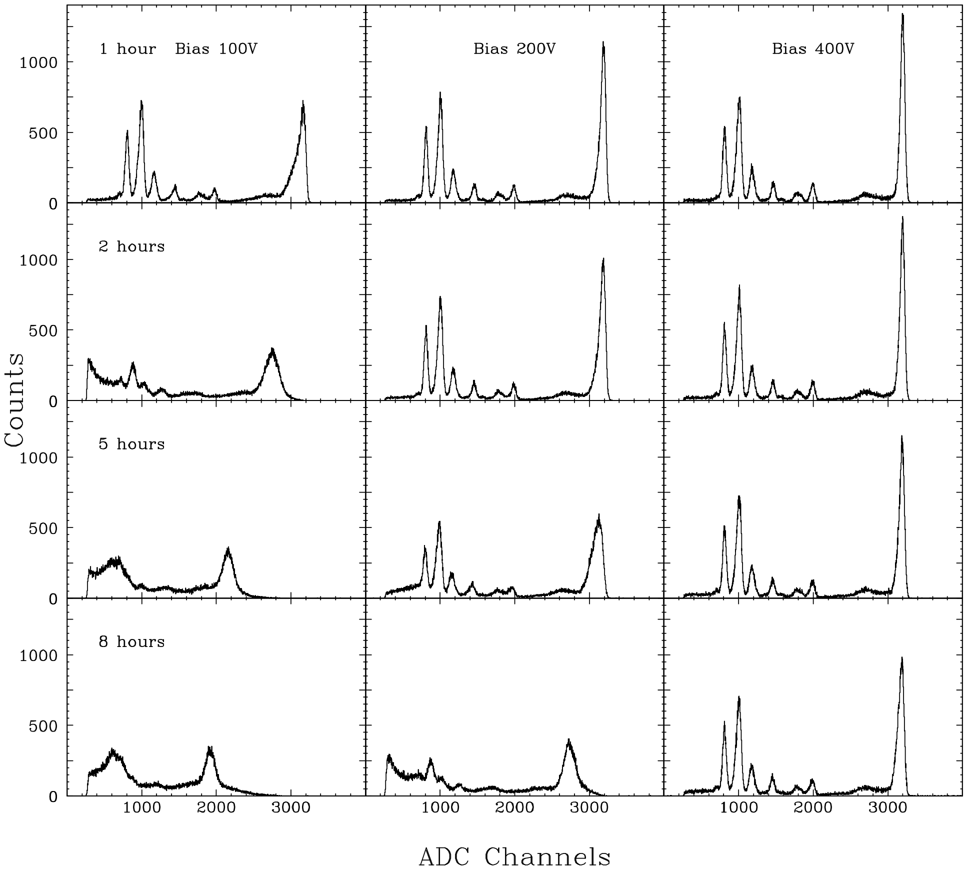

**Figure 6.** Change of the $^{241}$Am spectrum of the Schottky CdTe detector (dimensions of 2×2 mm$^2$ and a thickness of 0.5 mm) at bias voltages of 100 V, 200 V and 400 V (from left to right). The spectra obtained after 1 hour, 2 hours, 5 hours, and 8 hours are shown from top to bottom. Operating temperature was 20 °C . Each spectrum was accumulated in 10 min.

bias voltage 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. We mounted the detector and the CSA into the thermostatic chamber with the temperature controlled from 30 °C to -20 °C . Fig. 7 (b) shows the relative change of the peak channel of the 60 keV line with respect to the change of the temperature at a bias voltage of 100 V. Similar behavior observed with respect to a bias voltage (Fig. 7 (a)) is seen in the figure. 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.[6]

## 4. SCHOTTKY CDTE DETECTOR WITH THERMOELECTRIC COOLING

The long term stability and the good spectral resolution of the Schottky CdTe detector operating at a low temperature is very attractive for practical uses. The decrease in the leakage current introduces improvements on the spectrum when we cool the detector. The low leakage current of the detector enables us to apply a higher bias voltage so that we can collect the full charge generated in the detector.

In order to obtain a low temperature environment, we mounted a Schottky CdTe detector with dimensions of 2×2 mm$^2$ and a 0.5 mm thickness in a small metal can (Fig. 8). The detector was cooled by a low-noise two-stage

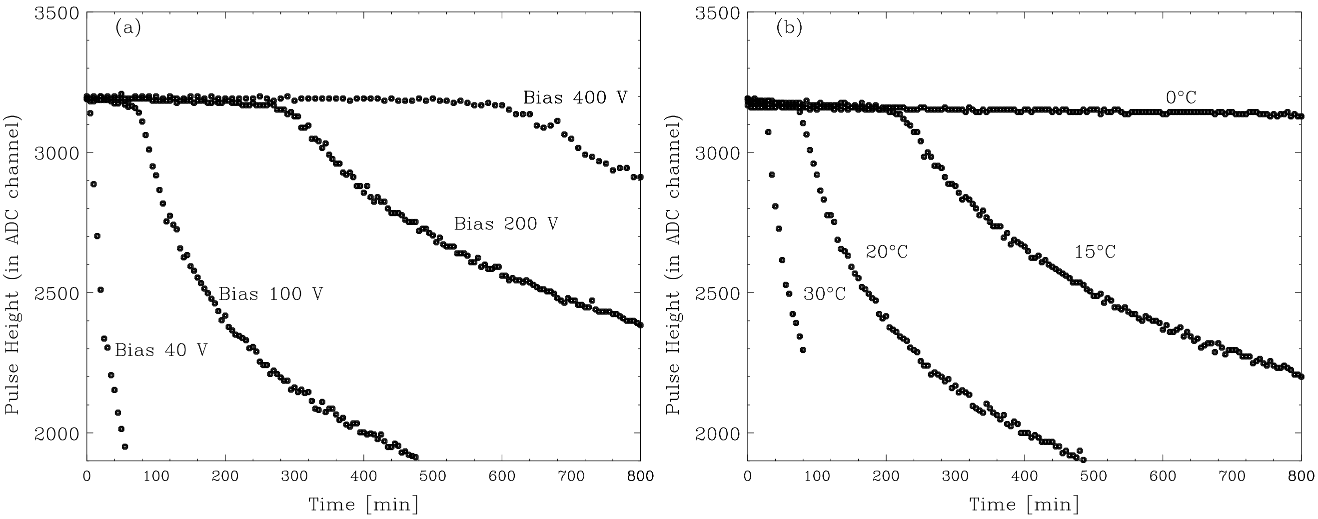

**Figure 7.** (a) Drift of the pulse height taken with the Schottky CdTe detector at 20 °C with respect to different bias voltages. (b) Drift of the pulse height taken with the Schottky CdTe detector at different temperatures with a bias voltage of 100 V. The horizontal axis shows the time in minutes after the bias was applied to the detector. The vertical axis shows the change of the peak channel of the 60 keV line from $^{241}$Am .

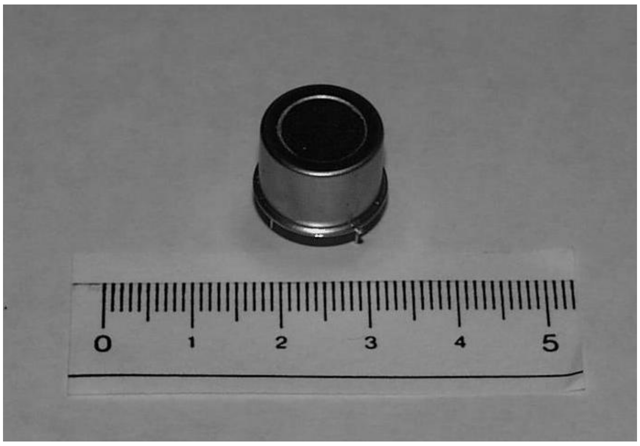

**Figure 8.** The Schottky CdTe detector with a thermo-electric Peltier cooler, manufactured by Hamamatsu Photonics.

thermoelectric Peltier cooler. Dry nitrogen gas was used to avoid humidity inside the can. The detector temperature was controlled by monitoring the resistivity of a miniaturized thermistor mounted in the can. By using the Peltier cooler and operating at room temperature, we were able to cool the detector to −20 °C with 0.3 W of electric power. The detector was manufactured by Hamamatsu Photonics. The signal from the can was fed into the electronic system described in §3.

Using the thermo-cooler detector, we studied how the high bias voltages improve the energy resolution. Fig. 9 shows the spectra of the 122 keV line from $^{57}$Co at different bias voltages. The best energy resolution was obtained at $3\mu$s shaping time. Each spectrum in the figure is normalized so that the intensity of 14 keV line is the same. This is because most of 14 keV photons interact near the cathode and the induced signal is mostly caused by the traversal of electrons, and the intensity of 14 keV lines is less affected by the hole trapping. The effect of high bias voltage is clearly shown in the figure. When we apply a low bias voltage, the shoulder due to the incompleteness of charge is very clear. For full charge collection in the detector, the required bias voltage is calculated to be 500 V for the 0.5 mm thickness from the $\mu\tau$ product of holes. The leakage current of the Schottky CdTe is measured to

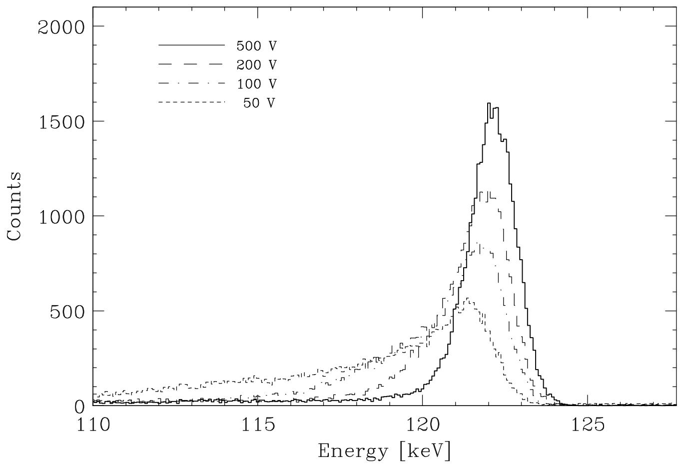

**Figure 9.** Change of the shape of 122 keV line from $^{57}$Co with respect to a bias voltage, obtained by the Schottky CdTe detector with a thermo electric cooling. Each spectrum is normalized so that the intensity of 14 keV line is the same

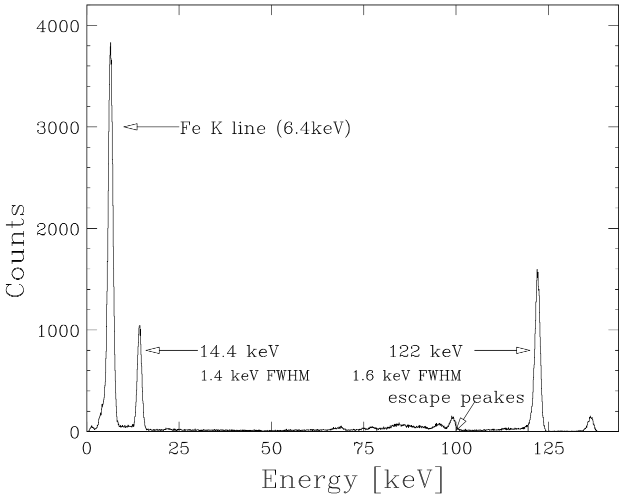

**Figure 10.** $^{57}$Co spectrum obtained by the Schottky CdTe detector with the thermoelectric cooler. The detector has dimensions of 2×2 mm$^2$ and a 0.5 mm thickness. Bias voltage of 500 V was applied. Temperature was controlled to be $-20$ °C . The time constant of a shaping amplifier was set at 3 $\mu$s.

be 10 pA at $-20$ °C and 500 V and the energy resolution of the 122 keV line is 1.6 keV (FWHM) which is close to that obtained from the pulsar (1.3 keV) (Fig. 10). The symmetric shape for the 122 keV line indicates that the full charge collection is almost complete with the 500 V bias (10 kV/cm) operation.

The change of the spectrum obtained by the Schottky CdTe detector with the thermoelectric cooler is shown in Fig. 11. The detector showed a stable performance for two weeks without distortion of the spectrum.

As shown in Fig.12, the energy resolution of 4.7 keV FWHM is obtained for the 511 keV line for $^{22}$Na . In the figure, X-ray escape peaks of Cd and Te are clearly seen below the 511 keV line. In the previous experiments, measurements of energy of $\gamma$-rays above 500 keV were usually obtained with the help of electronics, which correct the charge loss by means of the rise time information or select events with fast rise time.[2] The Schottky CdTe, with a thickness of 0.5 mm and under high bias voltage, does not require such electronics. However to extend this idea to thicker detectors may not be practical. Because, a very high bias voltage of 50 kV is necessary, if we want to collect full charge from a detector with 5 mm thickness within the limited lifetime of holes. This, however, immediately

**Figure 11.** Change of the $^{57}$Co spectrum obtained with the Schottky CdTe detector with a thermoelectric cooler. The spectra after 1 hour, 6 hours, 12 hours, 24 hours, 7 days, and 14 days are shown. Each spectrum was accumulated in 30 min.

leads to the idea of a stacked detector. Although, a 0.5mm thick CdTe might be only attractive for photons up to 100 keV, a high efficiency can be achieved by stacking 0.5 mm thick detectors with 10 to 20 layers or more. Using individual readout electronic systems for each layer, it is possible to make a detector with sufficient thickness without a loss of resolution. The construction and evaluation of the stacked detector is underway and will be presented in a separate paper.

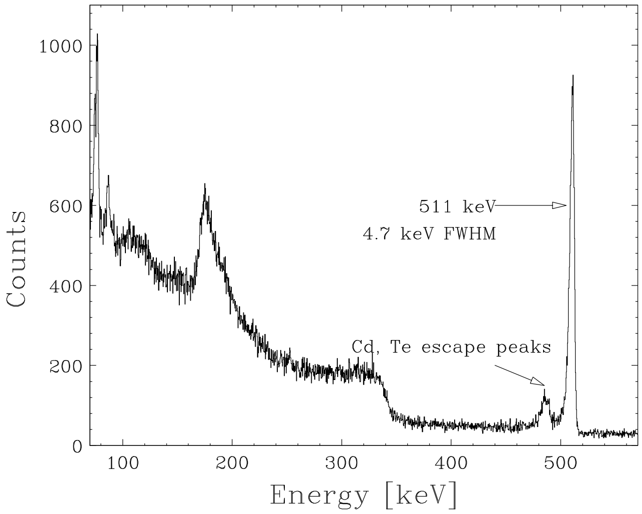

**Figure 12.** $^{22}$Na spectrum obtained by the Schottky CdTe detector with the thermoelectric cooler. Bias voltage of 500 V was applied. Temperature was controlled to be $-20$ °C . The time constant of a shaping amplifier was set at 3 $\mu$s. X-ray escape peaks of Cd and Te are clearly seen below the 511 keV line.

## 5. CONCLUSION

We investigated the Schottky CdTe detector with the In/CdTe/Pt electrode system using a high quality CdTe crystal manufactured by ACROTEC. Good performance was obtained at room temperature operation. We achieved an energy resolution of 1.1–2.5 keV FWHM at 20 °C in the energy range from $\sim$2 keV up to $\sim$150 keV without any charge loss correction or rise time discrimination electronics. We confirmed that, once a high electric field of several kV/cm is applied, the Schottky CdTe has a very good energy resolution and stability, allowing it to be used for practical applications. The moderate cooling system with a miniature Peltier cooling shows a stable performance for more than several days without a loss of resolution.

## 6. ACKNOWLEDGMENTS

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