Recent achievements of the high resolution Schottky CdTe diode for gamma-ray detectors

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Abstract

We describe the recent progress on the use of Schottky CdTe diode detectors for gamma-ray spectroscopy. The extremely low leakage current of the newly developed CdTe diode allows us to apply a much higher bias voltage in comparison with the previous CdTe detectors. Both the improved charge-collection efficiency and the low leakage current lead to a good energy resolution even at room temperature. Large-area CdTe diode detectors with dimensions of 21.5 × 21.5 mm^2 are now available. By stacking 40 layers of these large-area devices, we have achieved a good energy resolution of several keV (FWHM) for MeV gamma-rays.

Key words: Cadmium telluride (CdTe), CdTe diode detector, gamma-ray, X-ray
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1 Introduction

Cadmium telluride (CdTe) and cadmium zinc telluride (CdZnTe) have been regarded as promising semiconductor materials for hard X-ray and gamma-ray detection. The high atomic number of the materials (Z_{Cd} =48, Z_{Te}=52) gives a high absorption efficiency in comparison with Si and Ge. The large band-gap energy (Eg $\sim$ 1.5 eV) allows us to operate the detector at room temperature. However, it is only recently that a high quality material has become available. The first space instrument which utilizes a large number of CdTe detectors is

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the IBIS on the INTEGRAL (launched in 2002). It uses 16384 CdTe detectors for the observation of gamma-rays from 10 keV to $\sim$ 300 keV. More missions are expected to follow.

Despite the recent advances, it is still pointed out that the considerable amount of charge loss in CdTe and CdZnTe limits their capability as high resolution spectrometers (e.g. Takahashi and Watanabe , 2001). This is due mainly to the poor charge transport properties, especially for holes. The charge loss (or incomplete charge collection) in the device limit the thickness and, thus, the volume of detectors which in turn limits the usefulness of the detector. Resultant loss of the peak detection efficiency becomes much more significant when we use a detector thicker than 5 mm for the detection of gamma-rays above $\sim$ 500 keV

We have achieved a significant improvement in the spectral properties of CdTe detectors by adopting the configuration of Schottky diode (CdTe diode) (Takahashi et al. , 2002). In this paper, we report the recent improvements made on the CdTe diode detectors by means of the guard ring structure. The application to the detection of MeV gamma-rays based on the idea of "stacked detector" is also presented.

2 Development of high resolution CdTe diode

The CdTe diode detector is based on the high quality single crystal of CdTe manufactured by ACRORAD, Japan. With the use of indium (In) for the anode electrode and platinum (Pt) for the cathode electrode, we can operate the detector as a diode. Because, a high Schottky barrier is formed at the interface between In and CdTe. The low leakage current of the CdTe diode allows us to apply a much higher bias voltage than was possible with the previous CdTe detectors. For a relatively thin detector of $0.5-1$ mm thick, the high bias voltage results in a high electric field in the device. Both the improved charge collection efficiency and the low-leakage current lead to an energy resolution of better than 600 eV FWHM at 60 keV for a 2×2 mm^2 device at -20 °C without any charge-loss correction electronics. With the thickness of 0.5 mm, the whole volume of the detector is verified to be sensitive to the peak detection.

A large CdTe diode with an area of 21.5×21.5 mm^2 using the 0.5 mm thick device has been developed using a simple planar electrode configuration. As reported in our previous publications, the detector shows very high uniformity for all over the detector plane (Takahashi et al. , 2002; Nakazawa et al. , 2003). The location of the peak in the pulse hight distribution agrees within 0.1% in the whole detector plane. In view of practical space application of

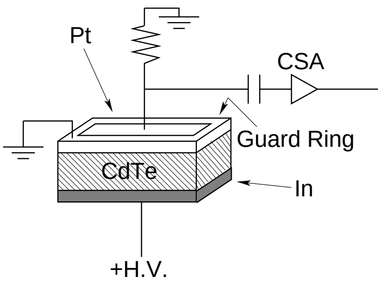

Fig. 1. Conceptual design of a new CdTe diode with a guard ring. The cathode face (Pt) is devided into the guard ring and the central plane (active area).

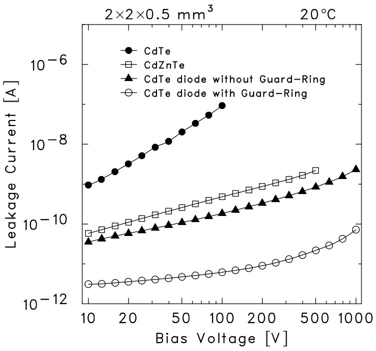

Fig. 2. Current-volatage (I–V) characteristics of CdZnTe and CdTe detectors with dimensions of $2 \times 2 \times 0.5$ mm^3 measured at 20 °C. For the guard ring device, the central active area is 2×2 mm^2 and the width of the guard ring around it is 500 μm. The gap between the active area and the guard ring is 50 μm.

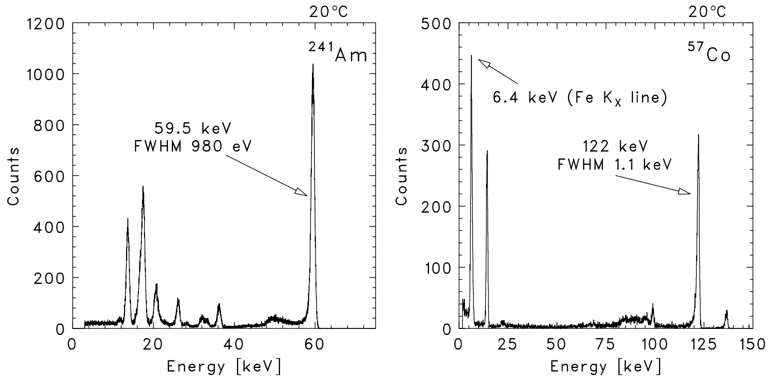

Fig. 3. ^{241}Am and ^{57}Co spectra obtained with the CdTe diode operated at 20 °C. 500 μm-wide guard ring on the cathode face surrounds the active area of $2 \times 2 \times 0.5$ mm^3. The applied bias voltage is 800 V.

the CdTe diode, we performed a series of extensive tests. They include the mechanical environment tests, long-run and vacuum run, as well as a proton beam experiment to the large area planar detector (Nakazawa et al. , 2003; Murakami et al. , 2003).

Recently we have found that the leakage current of the CdTe diode increase with the square root of the area of the detector. It implies that the surface

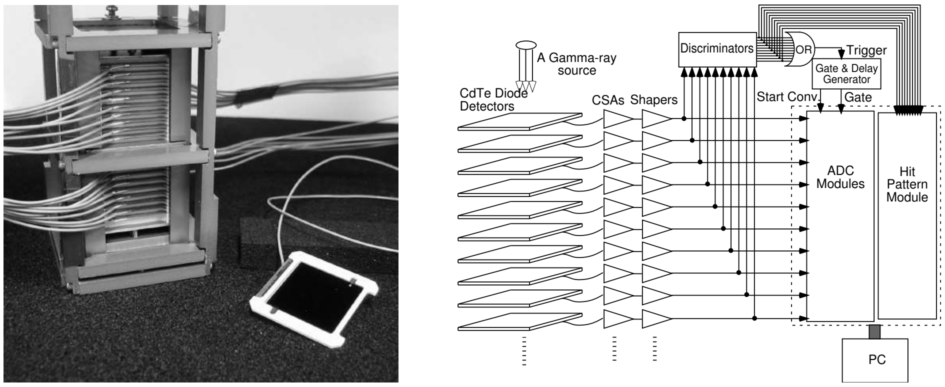

Fig. 4. Picture of our 40 layer CdTe stacked detector (left) and the schematic diagram of its readout (right). Each detector has the dimensions $21.5 \times 21.5 \times 0.5$ mm^3 and the gap between each layer is only 0.7 mm to prevent escapes of Compton recoiled photons and positron-electron pairs from the detector.

leakage through the side edge dominates over the bulk current. In order to verify this, we made a detector with a guard ring that surrounds the cathode. Fig. 2 shows the comparison for the current-voltage (I–V) characteristics of various configuration of CdTe and CdZnTe detectors. As shown in Fig. 2, 90% of the leakage current is reduced by adopting the guard ring. For the detector with an active area of $2 \times 2 \times 0.5$ mm^3, the leakage current of the new CdTe diode is as low as 10 pA at 20 °C at a bias voltage of 500 V. In order to find the optimum design, we changed the width of the guard ring. The leakage current starts to increase when we reduce the width below 500 μm. Fig. 3 demonstrates the spectra of gamma-rays from ^{241}Am and ^{57}Co obtained with the CdTe diode with a guard ring.

3 MeV gamma-ray detection with stacked detector

An energy resolution of a few keV at a high photon energy of several hundred keV under moderate operating conditions is very attractive in high energy astrophysics. 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 (Watanabe et al. , 2003). Fig. 4 shows the first prototype of 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. For this prototype, we did not use the detector with guard ring. 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.

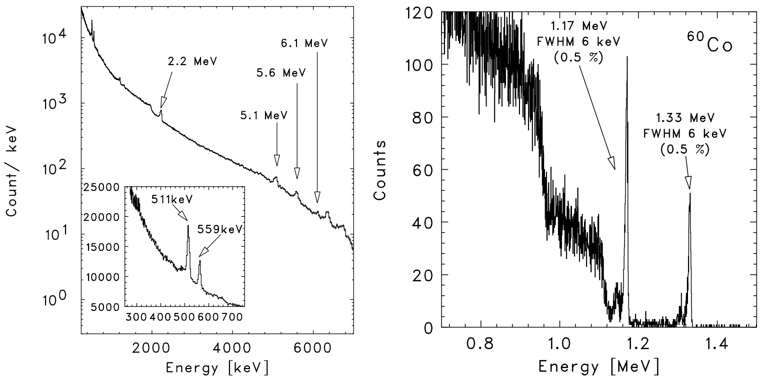

Fig. 5. (left) A spectrum of neutron capture gamma-rays obtained from the 40-layer stacked detector at 0 °C. Neutrons from ^{252}Cf are slowed down by polyethylene and injected to NaCl. The peaks of 6.1 MeV, 5.6 MeV and 5.1 MeV correspond to gamma-rays from neutron captures in Cl nuclei, together with single and double 511 keV escapes. The peaks of 559 keV and 2.2 MeV correspond to gamma-rays produced by neutron captures of Cd and H, respectively. (right) A spectrum of gamma-rays from ^{60}Co obtained by the large CdTe diode with four-segmented cathode operated at 0 °C. The width of the guard ring is 1 mm. Applied bias voltage is 1000 V.

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. The spectrum from the detecter is obtained by summing up spectra from the layers with output signals above a certain threshold level. For gamma-ray photons with an energy of 1 MeV, about 90 % of interacted events records the energy deposit from one to three layers, therefore, the energy resolution of summed spectra is $\sim \sqrt{3}\ \Delta E$ at most, where ΔE is the energy resolution of each layer. The advantage over conventional scintillation counters is demonstrated in Fig. 5 (left), in which gamma-ray lines up to 6 MeV from neutron captures in Na and Cl are shown (Watanabe et al. , 2003). Both spectra were obtained with a 350 V bias voltage for each layer and at a temperature of 0 °C . The achieved energy resolutions are 19 keV, 21 keV and 47 keV at 1.17 MeV, 1.33 MeV and 2.22 MeV, respectively. We are now working on the improvement of the stacked detector in terms of the energy resolution. Fig. 5 (right) shows the energy spectrum obtained with a new CdTe diode for the second prototype. Four segmented electrodes with dimensions of 1×1 cm^2 are formed at the cathode face in addition to a guard ring. The smaller capacitance of the detector and the lower leakage current brought by the guard ring in comparison with the first prototype , we obtain an energy resolution of 6 keV (FWHM) for 1 MeV gamma-rays from the single layer.

4 Conclusion

The high energy resolution of the CdTe diode is very attractive for hard X-ray and gamma-ray detection. We have developed a new CdTe diode device which shows good energy resolution (~ 1 keV(FWHM)) and achieved high stability for long term operation at room temperature. Based on the high resolution CdTe diode, we have developed a large-area detector with very high uniformity. The large CdTe diode with dimensions larger than 20×20 mm^2 has a potential to replace scintillation detectors due to its high stoppiong power and energy resolution. Many concepts based on the high resolution CdTe diodes are now being investigated and prototype detectors are being developed (Takahashi et al. , 2003; Mitani et al. , 2003). For gamma-ray astronomy from several hundred keV to several 10 MeV region, a semiconductor Compton telescope and an active pair telescope which utilize the CdTe detectors are promissing approaches (Takahashi et al. , 2003). For this, we have established technologies such as a stack of 40-layers CdTe detectors

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