A Stacked CdTe Gamma-ray Detector and its application as a range finder

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Stacking several tens of thin CdTe devices is a new concept for a gamma-ray detector, featuring both good energy resolution and high efficiency. We have developed prototype models of the CdTe stacked detector which consists of 10 layers and 40 layers based on a newly-developed large CdTe diode. The energy resolution of the detector is measured to be 1–2 % (FWHM) from 500 keV to 6 MeV. In addition to the gamma-ray spectroscopy, we propose to use the stack detector as a new type of range finder for gamma-ray sources below a few hundred keV. We demonstrate that the distance of a ^{57}Co radio active source, which is located 5 cm from the detector surface, is measured with an accuracy of 1–2 mm.

1. Introduction

The high absorption of cadmium telluride (CdTe) or cadmium zinc telluride (CdZnTe), comparable with that of NaI and CsI, is very attractive feature for the next generation of gamma-ray detectors [1]. However, when we increase the thickness of the CdTe/CdZnTe detector to improve the efficiency for high energy gamma-rays, the effect of the incomplete charge collection becomes significant. It introduces a low energy tail which degrades the energy resolution and, more importantly, lowers the effective peak detection efficiency. This effect becomes much more significant when we use a detector thicker than 5 mm for the detection of gamma-rays above $\sim$ 500 keV [2].

We, therefore, proposed the idea of a stacked detector, in which thin CdTe diodes are stacked together and operated as a single detector [2,3]. The very low leakage current of the CdTe diode enables us to apply a high electric field to ensure complete charge collection in relatively thin (<1 mm) devices [4]. By utilizing thin CdTe diodes, the stacked detector in which several tens of layers are stacked together realizes a good energy resolution and a high detection efficiency for gamma-rays at the same time. In this paper, we present the performance of our 10 layers and 40 layers prototype detectors.

2. Stacked CdTe detector and its readout

Figure 1 shows a schematic diagram of the readout electronics for the stacked detector. In our stacked detector, the signal from each layer is processed independently 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. Also, the hitpattern information from discriminators attached to each layer is useful for applying various kinds of data reduction.

The first results obtained from a prototype de-

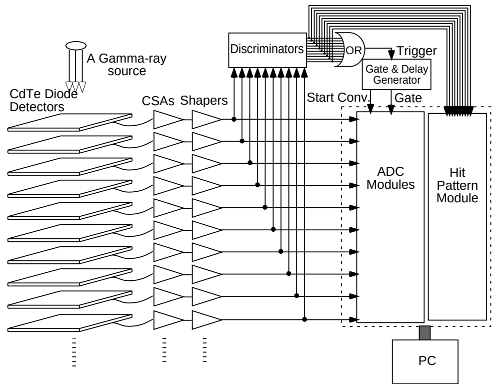

Figure 1. Schematic diagram of the stacked CdTe detector and its readout.

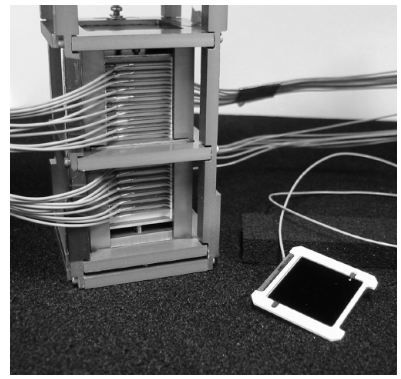

Figure 2. The 40 layer CdTe stacked detector (Left) and one of the layers from the stacked detector (Right).

tector consisting of ten layers of large CdTe diodes were reported in our previous publication [2]. The diode has an area of 21.5 mm × 21.5 mm and a thickness of 0.5 mm. The gap between layers is 4.5 mm. Energy resolutions (FWHM) of 5.3 keV at 356 keV and 7.9 keV at 662 keV are obtained at an operating temperature of −20 °C , when we apply a bias voltage of 300 V.

3. A stacked detector for MeV gamma-ray detection

In order to improve the efficiency for gamma-rays of several MeV, we need to increase the number of layers in the CdTe stacked detector. At the same time, we should minimize the gap between layers to prevent the escape of Compton recoil photons and electron-positron pairs from the detector, because Compton scattering and the pair creation become important processes in this energy region.

Along these lines, we have developed a second prototype detector (Figure 2). It consists 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 with a new housing for the CdTe diode by utilizing thin ceramic sheets. The total volume of the stacked detector amounts to 9.2 cm^3. The detector is operated with the same readout system shown in Figure 1. In the experiment, an active shield made of CsI(Tl) scintillator surrounds the stacked detector to detect escape photons.

Figure 3 shows the peak detection efficiency calculated by Monte Carlo simulations based on the Geant4 library [5]. In order to take various types of event into account, the exact geometry of the detector is implemented in the code. Gamma-rays irradiate the top surface of the detector uniformly. The peak detection efficiency is calculated from the count that falls on the energy equal to the incident gamma ray, before smearing by the energy resolution of the detector. For energies above 1022 keV, double and single escape peaks of 511 keV lines due to positron annihilation are included in the efficiency. The efficiencies are 20 %, 7 %, and about 5 % at 500 keV, 1 MeV and 2–6 MeV, respectively. As shown in Figure 3, the efficiency of the CdTe stacked detector for MeV gamma-rays is comparable with that of NaI and about two times higher than that of Ge detector with the same dimension.

The energy resolution of each CdTe diode ranges from 3.5 keV to 6 keV (FWHM) for 122 keV gamma-rays when operated at 5 °C and with a bias voltage of 300 V. With a capacitance

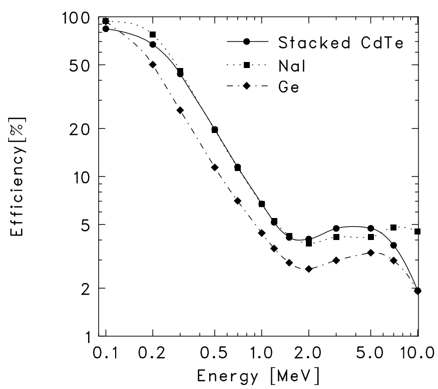

Figure 3. Peak detection efficiency of the 40-layers CdTe stacked detector calculated by Monte Carlo simulations. The results for a NaI scintillator (dotted line) and Ge detector (dashed line) with the same volume are also shown.

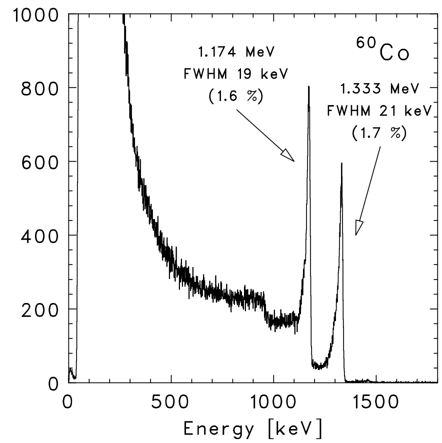

Figure 4. Spectrum of ^{60}Co obtained with the stacked detector. The energy resolutions at 1.17 MeV and 1.33 MeV are 19 keV (FWHM) and 21 keV (FWHM), respectively. The operating temperature is 0 °C .

of $\sim$ 100 pF and leakage currents of 2–3 nA at this operating temperature, the time constant of the shaping amplifiers is chosen to be 6 μs. The dynamic range of each layer is set from 40 keV to 4 MeV.

Although there is still room for improvements for the prototype detector, the energy resolution of several keV is very attractive. Figure 4 shows the energy spectrum of gamma-rays from ^{60}Co. With the energy resolution of 1.6–1.7 % (FWHM), the two peaks at 1.17 MeV and 1.33 MeV are clearly resolved. The advantage over conventional scintillation counters is demonstrated in Figure 5, in which gamma-ray lines up to 6 MeV from neutron captures in Na and Cl are shown. 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.

4. Application as a range finder

For photons with energy up to several hundred keV, a large fraction of events have the energy deposition in a single layer via photon absorption. In this circumstance, we can apply the stacked detector for measuring the distance from a gamma-ray source. When a source located at a distance of x from the top layer emits mono-energetic gamma-rays homogeneously, the photo peak counts detected in the ith layer (N_i) of the stacked detector is given as

$$N_i \propto \exp\left(-\mu\,(i-1)\,t\right) \times \left(\frac{x}{x+(i-1)\,d}\right)^2 , \quad (1)$$

where μ is the total photon cross section of the detector material, t is the thickness of each layer and d is the gap between layers. The first term corresponds to the effect of the blocking by the front layers, and the second term is introduced by different distances from the source for each layer. Due to the second term, the ratio of the photo peak counts in each layer to the sum from all layers changes with respect to the distance from the source. Therefore, if the ratio for each layer is measured, the distance from the source can be calculated by χ^2 fitting based on the function

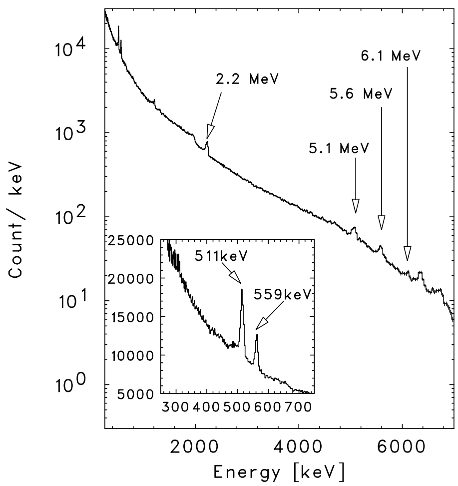

Figure 5. A spectrum of neutron capture gamma-rays obtained with the stacked detector. Neutrons from ^{252}Cf are slowed down by polyethylene and injected to NaCl. The peaks of 6.1 MeV, 5.6 MeV and 5.1 MeV correspond to gamma-rays from neutron captures in Cl nuclei, together with single and double 511 keV escapes. The peaks of 559 keV and 2.2 MeV correspond to gamma-rays produced by neutron captures of Cd and H, respectively.

shown in Eq. (1).

We verified this method with the 10-layer detector described in Section 2. We used 122 keV gamma-rays from a ^{57}Co radio active source for the experiment. As shown in Figure 6, we can measure the distance to the gamma-ray source with good accuracy. In order to estimate the systematic uncertainties of the method, we repeated 50 measurements with the same experimental setup and the source located at the distance of 5 cm. For 200,000 events for each measurement, the RMS deviation of the distances is 1.3 mm. It should be noted that the applicable range of distance is determined by the gap and the size of the detector.

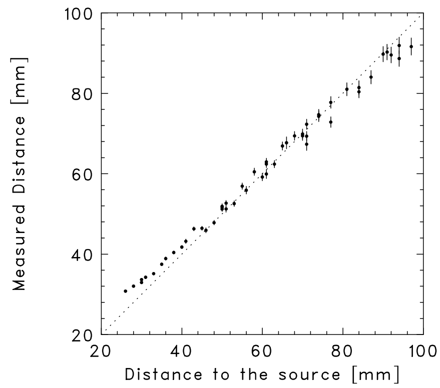

Figure 6. The relation between the distance to the source and the measured distance.

5. Conclusion

We constructed a CdTe stacked detector with 40 layers of thin and large CdTe diodes, each with an area of 21.5 mm × 21.5 mm and a thickness of 0.5 mm. We have succeeded to measure gamma-ray lines from neutron capture in nuclei in the energy region from 500 keV up to 6 MeV. The achieved energy resolution is about 20 keV (FWHM) at 1.17 MeV or 1.33 MeV. By utilizing count rate information obtained from each layer of the stacked detector, we demonstrate a new method to measure a distance to a gamma-ray source. With the 10-layer detector, the distance of a ^{57}Co radio active source, which is located 5 cm from the detector surface, is measured with an accuracy of 1–2 mm.

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