High Resolution CdTe Detector and Applications to Imaging Devices

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Abstract—

Using a high quality Cadmium Telluride (CdTe) wafer, we formed a Schottky junction and operated the detector as a diode (CdTe diode). 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 $\sim$ 0.5 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 1.1 keV FWHM at 60 keV for a 2×2 mm^2 device and 2 keV for a 10×10 mm^2 device at 5 °C without any charge-loss correction electronics. For astrophysical applications, we have developed an initial prototype CdTe pixel detector based on the CdTe diode. The detector has 400 pixels with a pixel size of 625×625 μm^2. Each pixel is gold-stud bonded to a fanout board and routed to a front end ASIC to measure pulse height information for each γ-ray photon.

Keywords—**CdTe, CdZnTe, Pixel Detector.**

I. INTRODUCTION

CADMIUM Telluride (CdTe) and Cadmium Zinc Telluride (CdZnTe) have been regarded as promising semiconductor materials for hard X-ray and γ-ray detection [1], [2], [3], [4]. The high atomic number of the materials (Z_{Cd}=48, Z_{Te}=52) gives a high quantum efficiency suitable for a detector operating typically in the $10-500$ keV range. However, due to incomplete charge collection caused by the low mobility and short lifetime of holes, 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 achieved a significant improvement in the spectral properties of CdTe detectors[5], [6], [7]. Our detector is based on the advances made in the production of high quality CdTe monocrystals by ACRORAD, Japan[8]. The basic idea is to utilize indium as the anode electrode on the Te-face of the p-type CdTe wafer with (1,1,1) orientation[9]. A high Schottky barrier formed on the In/p-CdTe interface allows us to operate the detector as a Schottky diode (CdTe diode). This is different from the earlier use of CdTe detectors with the Pt/CdTe/Pt electrode configuration operated as a solid ionization chamber. A 2

mm $\times$ 2mm detector of thickness 0.5 mm, when operated at a temperature of 5 °C , shows leakage currents of only 0.2 and 0.4 nA for operating voltages of 400 and 800 V respectively. The very low leakage current of the CdTe diode enables us to apply a high electric field to ensure complete charge collection in the device.

A problem with the stability of the detector, probably due to the non-uniform electric field caused by the charge accumulation, has often been reported for CdTe detectors (*polarization*). The CdTe wafer from ACRORAD is free from this problem when the Pt/CdTe/Pt electrode configuration is used. However once the diode was formed, we experienced degradation of gain and resolution with time. We found that, both a high electric field of several kV cm^{-1} and a low operating temperature (below several °C) ensure stability on time scales longer than weeks[5].

For future X-ray astronomy missions, one of the main objectives is observation with a very high sensitivity in the 10–100 keV band, where non-thermal emission becomes dominant over thermal emission[7]. This could be achieved by employing a multi-layer, grazing incidence hard X-ray telescope ("super mirror") in conjunction with a hard X-ray imaging detector as a focal plane detector. Our aim is to develop a CdTe (or CdZnTe) pixel detector with both a fine position resolution of a few 100 μm and a high energy resolution better than 1 keV (FWHM) in this energy range.

II. ENERGY RESOLUTION

For energies below 100 keV, a detector thickness of 0.5 mm provides a good detection efficiency with CdTe. The efficiency is 90 % at 40 keV and 30 % at 100 keV, respectively. For use as a high resolution detector in the hard X-ray band, the thin CdTe device has an advantage over the thick one because sufficient bias voltage for full charge collection can be easily applied. Collecting full information due to the transit of both electrons and holes is important for obtaining the ultimate energy resolution from the device. For this, the transit time must be shorter than the carrier lifetime. The mean drift path of the charge carrier is expressed as the product of $\mu\tau$ and E, where $\mu\tau$ is mobility-lifetime product and E is the applied electric field in the device. Due to the slow mobility and short lifetime of holes, the thickness of the detector should be smaller than $\mu_h \tau_h E$, where μ_h and τ_h are the mobility and lifetime of holes. Our previous measurement showed that at least $400 - 800$ V is required to suppress the broad low energy tail of the 122 keV line and obtain the energy resolution (FWHM) of $\sim$ 1 keV for a detector with a thickness of 0.5 mm, if all charge carriers are to be collected. It would be difficult to apply this approach to a thicker
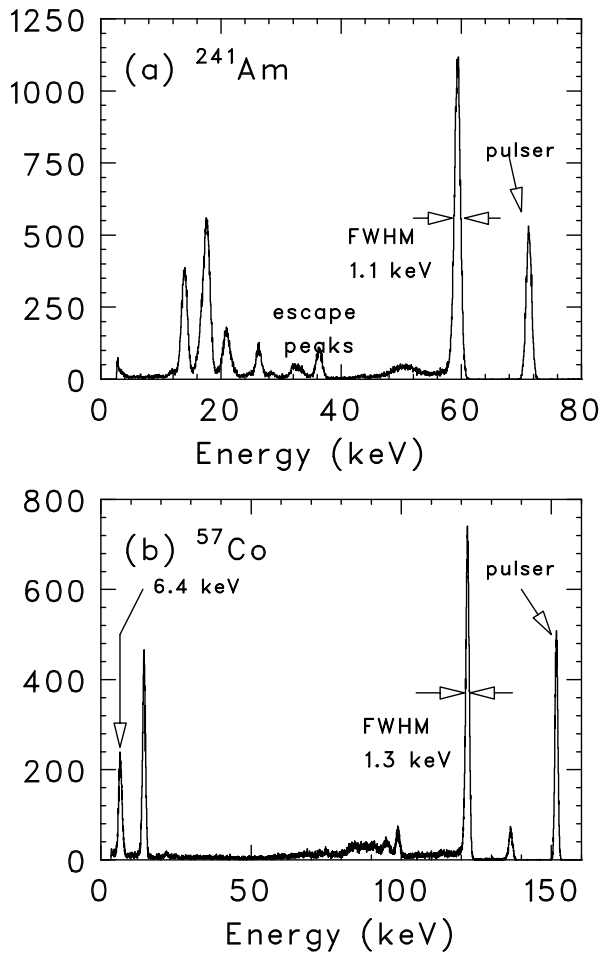
Fig. 1. Spectra of (a) ^{241}Am and (b) ^{57}Co obtained with a 2 mm × 2 mm CdTe diode of thickness 0.5 mm. The spectra are taken without any charge-loss correction or rise time discrimination electronics. The diode was operated at 5 °C . The applied bias voltage is 600 V for ^{241}Am and 800 V for ^{57}Co . The time constant of the shaping amplifier was set at 0.5 μs.

CdTe detector, as the bias voltage required to achieve a certain level of charge collection scales as the square of the detector thickness.

Figs. 1(a) and 1(b) show the energy spectra of γ-rays from ^{241}Am and ^{57}Co obtained with the CdTe diode. The detector has a surface area of 2 mm × 2 mm and a thickness of 0.5 mm. In the measurement, the charge signal is integrated in the Clear Pulse CP-5102 charge sensitive pre-amplifier (CSA) and shaped by an ORTEC 571 amplifier. In order to reduce the leakage current and to obtain long-term stability of the CdTe diode, we mounted the detector and the CSA in a thermostatic chamber with the temperature controlled at 5 °C .

The 6.4 keV (Fe K_α) line of iron is clearly detected in the ^{57}Co spectrum, demonstrating the high performance of the CdTe diode in terms of the energy resolution. The photopeak resolution (FWHM) is 1.1 keV at 60 keV and 1.3 keV at 122 keV at 5 °C without any charge loss correction or rise time discrimination electronics. Significant reduction of the broad low energy tail is a very important characteristic of the detector for spectroscopy, because it simplifies the energy response considerably.

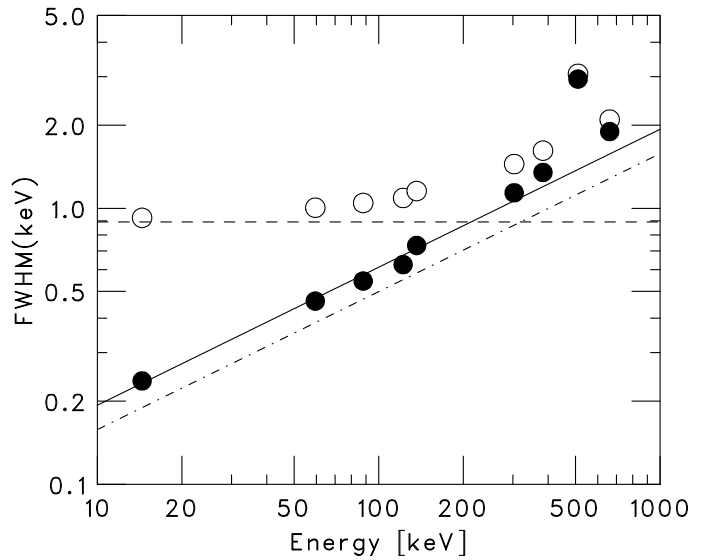When the detector is cooled down, the decrease in the leak-

Fig. 2. Spectral resolution as a function of energy for a 2 mm × 2 mm CdTe diode of thickness 0.5 mm. The detector was operated at -40 °C and under a bias voltage of 1400 V. The time constant of the shaping amplifier was set at 1.0 μ s. The open circles are the measured resolution and the closed circles are calculated by subtracting the noise in quadrature. The solid and dot-dashed lines are predictions from F=0.15 and F=0.10, respectively. The dashed line is measured electronic noise from a test pulse.

age current enables us to apply much higher bias voltage than that of the 5 °C operation. Fig. 2 shows the energy resolution measured at -40 °C with γ-ray lines from various radio isotopes. The applied bias voltage is 1400 V throughout the measurement. The reduction of the low energy tail even in the 662 keV line from ^{137}Cs (Fig. 3) results in a resolution of 2.1 keV (0.3 %). From the relation between energy and resolution, we can obtain the intrinsic resolution of the CdTe diode by subtracting the contribution of electronic noise in quadrature. The intrinsic resolution is determined by the statistical fluctuation in the number of electron-hole pairs generated by absorption of a photon of a given energy [10], [11] and described as

$$\frac{FWHM}{E_\gamma} = \frac{2.35\sigma}{N} = 2.35\sqrt{\frac{F\epsilon}{E_\gamma}} \tag{1}$$

where N is the mean number of electron-hole pairs created, σ is its statistical fluctuation, F is the Fano factor, ϵ is the average electron-hole pair production energy, and E_γ is the energy of the incident photon. As shown in Fig. 2, the calculated resolution is very close to the prediction from ϵ = 4.5 eV and F = 0.15. These values are consistent with those reported from previous measurements[12]. Our results imply that the resolution of the CdTe diode with a thickness of 0.5 mm reaches the theoretical limit for a wide energy range from 10 keV to 700 keV.

The homogeneity of the crystal is of particular importance for the imaging detector, because defects in the crystal could deteriorate the energy resolution through positional variation of properties such as charge collection efficiency and leakage current. In order to study the performance of the CdTe diode with dimensions which are large enough for an imaging detector, we measured the ^{241}Am spectrum obtained with the 10×10 mm^2
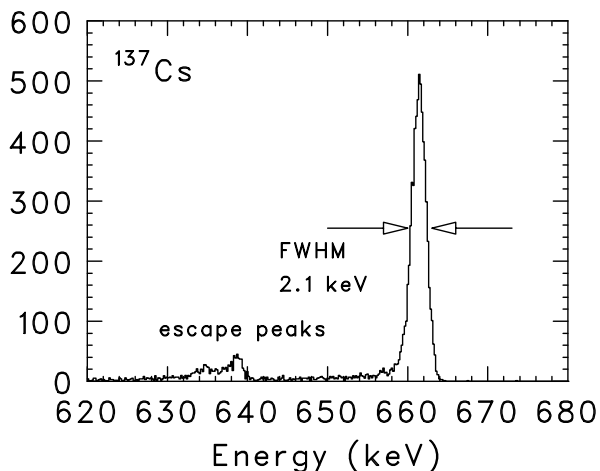
Fig. 3. High energy spectrum of ^{137}Cs above 620 keV with a 2 mm × 2 mm CdTe diode of thickness 0.5 mm. The applied bias voltage is 1400 V and the operating temperature is -40 °C . The time constant of the shaping amplifier was set at 1 μs. The energy resolution at 662 keV is 2.1 keV (FWHM).
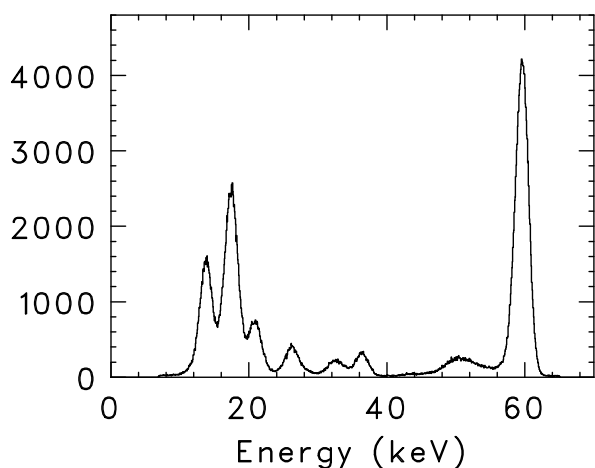

Fig. 4. ^{241}Am spectrum obtained with a large CdTe detector. The surface size is 10 mm × 10 mm and the thickness is 0.5 mm. The time constant of the shaping amplifier is 2 μs. The energy resolution at 60 keV is 2.1 keV (FWHM).

CdTe diode with 0.5 mm thickness (Fig. 4). In spite of a large capacitance of 25 pF (including the capacitance of connectors), we obtained a FWHM resolution of 2.1 keV which is consistent with the 1.9 keV resolution obtained with the test pulse. This resolution confirms the good uniformity of the wafer manufactured from the monocrystal grown using the THM method by ACRORAD [8], [13].

III. THE CdTe PIXEL DETECTOR

A prototype CdTe pixel detector with an array of 20 × 20 pixels was developed. The detector is based on the 15 mm × 15 mm CdTe diode made from the monocrystal wafer with (1,1,1) orientation fabricated with the prescription described in Ozaki et al. [9]. The indium side is used as the common electrode. After a thin layer of gold is evaporated on the Pt side, a metal pattern for pixels is etched on it. The thickness of the Pt and gold are 3000 Å and 2000 Å, respectively. The size of a pixel electrode
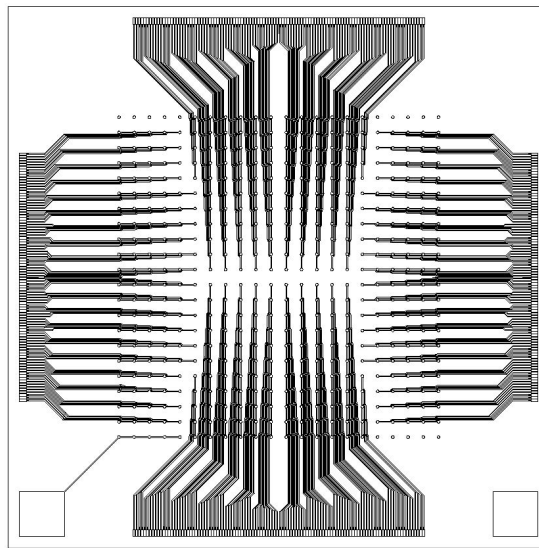

Fig. 5. Layout of the fanout board for the CdTe pixel detector. The total number of bump pads is 22×22=484. 400 pads are used for pixels and 84 pads are used for the guard ring. The size of the substrate ceramic board is 24 mm × 24 mm.
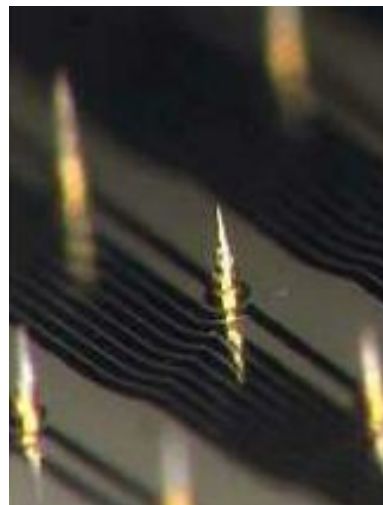

Fig. 6. The gold studs on the fanout ceramic board. The width and pitch of metal lines shown in the picture are 40 μm and 10 μm, respectively.

is 625 μm × 625 μm and the gap between electrodes is 50 μm. In order to reduce the edge leakage current, a guard ring with a width of 625 μm surrounds the periphery of the pixel.

Since a two dimensional ASIC (Application Specific Integrated Circuit) that can measure the energy of each γ-ray photon and can be attached directly to the pixel detector is not commercially available, we utilize a combination of a fanout board and front end ASICs designed for a Si strip detector. As shown in Fig. 5, the fanout board consists of bump pads and patterns to route the signal from pads on the surface of the ceramic board. Once each pixel electrode on the CdTe diode is connected to the bump pad, we can extract signals from the detector. This approach, similar to the Si pad detector developed by Weilhammer et al. [14] allows us to use well-established front-end chips with low noise performance and complex function for Si strip detector.
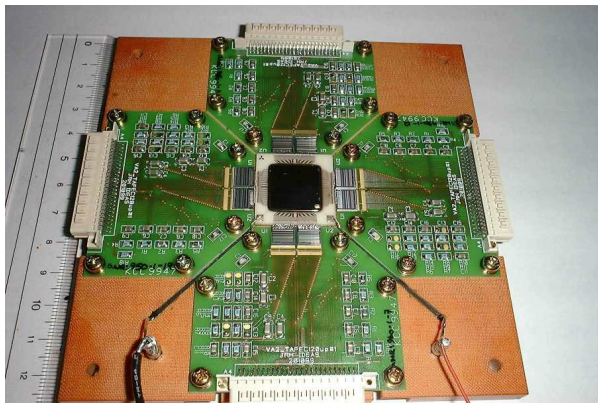
Fig. 7. Picture of a prototype CdTe pixel detector with the readout integrated circuits.
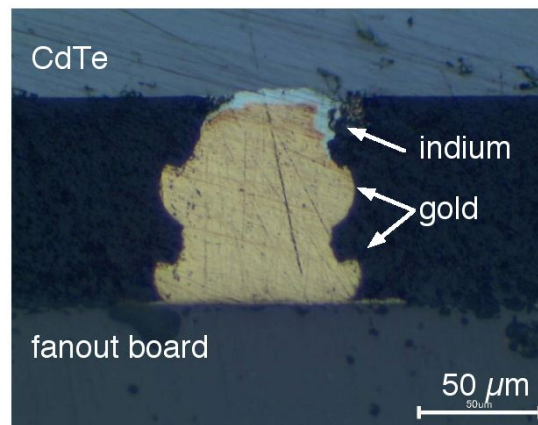

Fig. 8. Cross sectional view of the stud bump. Two stages of gold and one stage of indium are used as a stud to obtain good connectivity between the electrode on the Pt side of the CdTe diode and the bump pad on the fanout board.

One of most difficult parts of realizing fine pitch (finer than several hundred microns) CdTe and/or CdZnTe pixel detectors is to establish a simple and robust connection technology for these fragile devices. It should be noted that high compression and/or high ambient temperature would damage the CdTe crystal. Also, the co-planarity of the CdTe wafer is measured to be 2 μm at most, which is much worse than that of usual silicon wafers. Usual indium-ball soldering might not be appropriate for this purpose. Also, indium is easily oxidizable and needs flux which could contaminate the detector surface. Furthermore, placement of indium balls is usually done on large wafers and it is difficult to place them on a small board as used in the present experiment.

For the prototype CdTe pixel detector, we adopted a stud-bump method. To prevent possible stress on the device, we choose a combination of soft metal, gold and indium, as a stud. In order to attain good connection between the bond pad on the readout board and the pixel electrode on the CdTe wafer, a needle-shaped stud consisting of two stages of gold studs is prepared on the bump pad (Fig. 6). Studs are made from a gold stud bonder with a 25 μm diameter gold wire, and a thin layer of indium is printed on the top of the stud to improve connectivity. The total height of the stud from bottom to top is 150 − 200 μm. The CdTe wafer and the fanout board are then pressed together with 20 g of compression per bump under controlled temperature conditions. To increase mechanical strength, epoxy resin with low viscosity is filled into the space between the CdTe wafer and the fanout board.

Before wire bonding from the fanout board to the readout electronics, we have confirmed that all pixels have good connection by measuring the current with respect to the bias voltage (I-V curve). The I-V curve clearly shows diode characteristics. The leakage current under the reverse bias of 100 V is 5 nA at 25 °C . This corresponds to 10 pA per single pixel.

A picture of the pixel detector system is shown in Fig. 7. Fig. 8 shows the cross sectional view of the stud bump after fabrication of the detector. The CdTe detector is gold stud bonded to the fanout board and then wire bonded to the 128 input VA2TA chip developed by IDEAS[15]. The analog chain of the chip contains a charge sensitive preamplifier, a slow and a fast shaper, a sample-and-hold circuit and a discriminator. The trigger signals from each channel are wire or'ed together onto a common trig-

ger output inside the chip. The low leakage current of the CdTe diode enables the sensor to have DC coupling into the input of the preamplifier. For the initial prototype detector, 400 channels out of 1024 channels from eight VA2TA chips, mounted on four front end cards (FECs), are used. The energy resolution of the chips on the FEC is measured to be ∼7 keV, which is much worse than we anticipated.

Fig. 9 shows the image of a lead object ("star" with a hole in the center) placed on the back of the detector and irradiated with the 122 keV γ-ray line from a ^{57}Co source by selecting photons under the 122 keV photopeak. A positive bias voltage of 400 V is applied on the common electrode and the detector is operated at 5 °C . Although the yield of good connections was 100 % when we tested with a dummy detector made of silicon, we found that no signal came from 35 pixels in the first prototype. Based on subsequent experiments using a probe station, it turned out that the distance between the bump pads and the adjacent pattern etched on the fanout board is so narrow in the current version that we could not obtain perfect isolation for some of the bump pads. Fig. 10 shows the spectrum from one pixel which is taken at −20 °C with a bias voltage of 1400 V. The energy resolution at the 122 keV line is 7.3 keV, which is consistent with the energy resolution of the current readout electronics.

IV. CONCLUSION

The high energy resolution of the CdTe diode is very attractive for hard X-ray and gamma-ray detection. The further addition of good position resolution is of great importance. In order to use the detector as a hard X-ray spectrometer, the front-end ASIC has to have the capability to record both pulse height and timing information for each photon. With the CdTe diodes, the first prototype pixel detector has been developed. We establish the procedure of fine pitch bump bonding by means of gold stud. Although the energy resolution is worse in comparison with that obtained from planar CdTe diodes, we succeeded to obtain an image and spectra from the CdTe pixel detector. Fabrication of the second CdTe pixel detector with a pixel size of 200 μm × 200 μm equipped with a photon-counting 2-dim ASIC is now
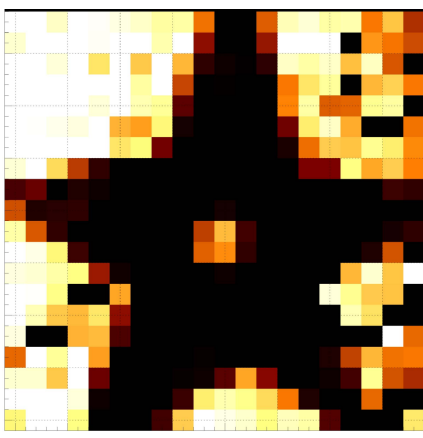
Fig. 9. Radiographic image of a lead object irradiated by γ-rays from ^{57}Co obtained with the 20 × 20 CdTe pixel detector covering 15 mm × 15 mm. The pixel size is 625 μm × 625 μm.
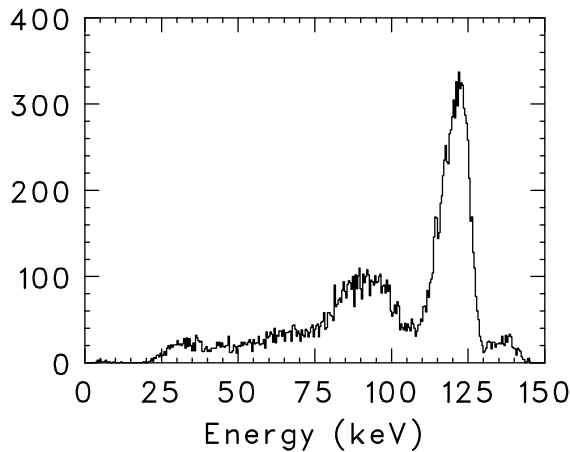

Fig. 10. ^{57}Co spectrum from a pixel obtained with a prototype of the CdTe pixel detector.

under way, as well as the development of a truly 2-dim ASIC chip capable of measuring the energy and the arrival time of each γ-ray photon.

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