Large area CdTe diode detector for space application

K. Nakazawa[a] [*], T. Takahashi[a b], S. Watanabe[a b], G. Sato[a b], M. Kouda[a b], Y. Okada[b], T. Mitani[a b], Y. Kobayashi[a b], Y. Kuroda[c], M. Onishi[c], R. Ohno[d], H. Kitajima[d]

[a]The Institute of Space and Astronautical Science, Sagamihara, Kanagawa 229-8510, Japan

[b]Department of Physics, the University of Tokyo,Bunkyo, Tokyo 113-0033, Japan

[c]Mitsubishi Heavy Industries, ltd., Nagoya Guidance and Propulsion Systems Works, Aichi, Japan

[d]ACRORAD Ltd., Okinawa, Japan

The current status of Schottky CdTe diode detectors, especially in view of their space application for hard X-ray and gamma-ray astronomy, are reported. For practical use in space science, a large area CdTe diode with a size of $21.5 \times 21.5~\mathrm{mm}^2$ and a thickness of $0.5~\mathrm{mm}$ was developed. A good energy resolution, 2.8 keV (FWHM) at $-20~^\circ\mathrm{C}$, and high homogeneity to within 0.2% over the detector were achieved for the spectral performance. This device has successfully passed a series of tests required for its use in space, in view of utilizing Japanese M-V rockets. The tests include the mechanical environment test, vacuum test, long-run for weeks and proton-beam radiation. Initial results from a 2×2 segmented electrode large area device with a guard-ring are also presented.

1. Introduction

Cadmium telluride (CdTe) and cadmium zinc telluride (CdZnTe; CZT), with their high stopping power and good energy resolution, are promising devices for the next generation of hard X-ray and gamma-ray astronomy missions [1][2][3][4]. These devices, however, currently have some restrictions in their performance. One is their incomplete charge collection due to poor charge transport properties, especially for holes. This causes a tail structure in their spectra, and degrades their photo-peak efficiency. Another issue is the homogeneity in these devices, which is sometimes reported to be poor (e.g. [5]). In addition, it is only recently that a mono crystal larger than 2 cm became available[6]. The CdTe/CZT devices required in the coming decade should overcome all these shortfalls, which means a large (∼ 2 cm or more) and homogeneous device together with good spectroscopic properties.

One approach to reduce the tail structure in the spectra is to compensate for the significant charge loss of holes by adopting sophisticated electronics or utilizing single charge induction by practical electrode design (see review [2] and references therein). As an alternative approach, we have recently developed a CdTe diode detector, using indium (In) as an anode electrode on the Te-face of the p-type CdTe:Cl wafer with (1,1,1) orientation, manufactured by ACRORAD [7]. This device works as a Schottky diode and a higher bias voltage can be applied, so that almost full charge collection is obtained for a relatively thin device. Using a Schottky CdTe diode with a size of $2 \times 2~\mathrm{mm}^2 \times 0.5~\mathrm{mm}$, we have obtained an energy resolution of 1.4 keV for 122 keV gamma-rays, operated at 5 °C with a bias of 800 V [7]. There is almost no tail structure in the spectra, due to its thin geometry and high bias.

The good charge collection efficiency of the Schottky CdTe diode is attractive for applications in high energy astrophysics. For example, a stacked CdTe diode with a total thickness of about 1 cm can be used as a high resolution MeV gamma-ray detector [7][8][9]. A pixelized CdTe diode is also attractive as a focal plane imaging detector [7] for hard X-ray mirror optics [10].

The Schottky CdTe diode, however, is a new technology and we need to verify whether the device is really suitable for space applications. For

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[*] phone: 81-42-759-8135, e-mail: nakazawa@astro.isas.ac.jp

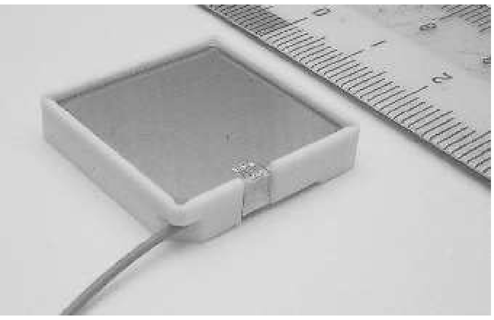

Figure 1. Photo of the large area CdTe diode, mounted on a ceramic case. The case has a through hole with a size of 20×20 mm and gamma-rays can be irradiated from both sides of the device. See [8] for details of the ceramic case.

this purpose, we have developed a large area planar CdTe diode with dimensions of $21.5 \times 21.5~\mathrm{mm}^2 \times 0.5~\mathrm{mm}^{\mathrm{t}}$ (Fig.1)[8][11]. In addition, we have developed another large area 2×2 segmented electrode detector based on the same material. These detectors are made of mono crystal. Characteristics of these detectors are presented in section 2. In section 3, we summarize the results from a series of extensive tests for the space use of the large area CdTe diodes, performed using the planar detector. These include mechanical environment tests, vacuum test, long-run for weeks, and a proton-beam experiment.

2. The Large area CdTe diode detectors

2.1. Characteristics of the planar detector

The large area CdTe diode we developed is one of the largest and thinnest CdTe/CZT detectors manufactured to date [8][11]. This means that the leakage current can be high. We can also investigate the homogeneity of the detector. We therefore characterized the detector in view of leakage current and the spectral homogeneity.

The current-voltage (I-V) curve at 20 °C is presented in Fig.2, together with those of smaller CdTe diodes. The leakage current is not proportional to the surface area of the detector, but rather to the diode perimeter. This result suggests that the leakage current is dominated by the surface current in the cut edge, rather than the leak from the material bulk. The

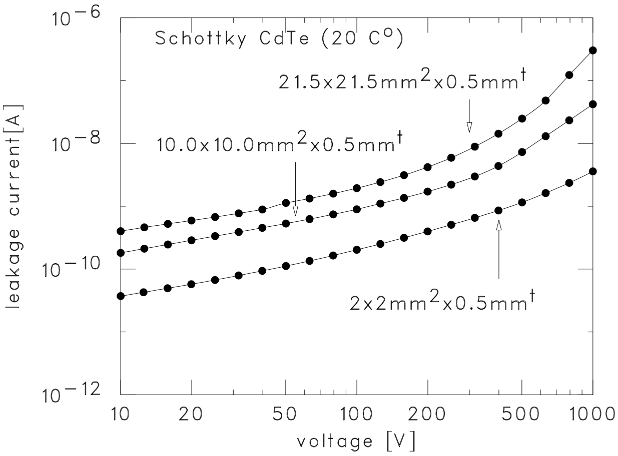

Figure 2. Current-voltage (I-V) characteristics at 20 °C of the large area planar CdTe diode, together with those of $2{\times}2~\mathrm{mm}^2{\times}0.5~\mathrm{mm}^{\mathrm{t}}$ and $10{\times}10~\mathrm{mm}^2{\times}0.5~\mathrm{mm}^{\mathrm{t}}$ devices.

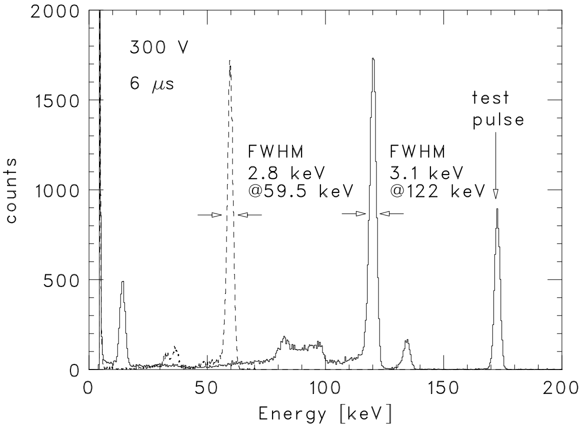

Figure 3. ^{241}Am (dashed line) and ^{57}Co (solid line) spectra obtained with the large area Schottky CdTe diode detector. The applied bias voltage is 300 V and the operating temperature is -20 °C .

leakage current decreases by lowering the operating temperature, and becomes almost two orders of magnitude lower at -20 °C (see Fig.6).

In Fig.3, we present the gamma-ray spectra obtained with the large area planar detectors at -20 °C . The detector has a capacitance of 100 pF and its leakage current was measured to be 80 pA at a bias of 300 V. The signal is integrated by a Charge Sensitive Amplifier (CP-5102 BS by Clear Pulse) and shaped by an ORTEC 570 with a time constant of 6 μs. Even with this large capacitance, these spectra show a good energy resolution of 2.8 keV and 3.1 keV for line gamma-rays of 59.5 keV and 122 keV, respectively. Resolution for test pulses is 2.7 keV, very similar to that of the gamma-ray peak, indicating that there is almost no tail structure in the spectra.

To directly examine the detector homogeneity, we utilized a 2 mm deep Tungsten slit with a size of 0.1×8 mm, mounted on an X-stage. Gamma-rays from a ^{241}Am source were irradiated through the slit to the test detector with a dimension of $20 \times 20~\mathrm{mm}^2 \times 0.5~\mathrm{mm}^\mathrm{t}$. This detector is made by the same technology and is the first lot test piece of the large area CdTe diode. By moving the slit, we obtained spectra with respect to the slit position (Fig.4). As clearly shown in the presented peak channel plot, the detector is uniform to within 0.2%. Similar results have been reported by a pinhole survey on the $21.5 \times 21.5~\mathrm{mm}^2 \times 0.5~\mathrm{mm}^\mathrm{t}$ detector [11]. From these results, it has been proven that the large area CdTe diode developed for this experiment has very good characteristics for spectral properties and detector homogeneity.

2.2. A 2×2 segmented electrode detector with a guard-ring

As a next step, we developed an advanced detector based on the same material, a 2×2 segmented electrode detector with a guard-ring (Fig.5). The crystal has dimensions of 21.5×21.5×0.5 mm^3, and the anode face is covered with a single In electrode. The cathode face has 2×2 electrodes and a guard-ring made of Pt. Each electrode has a dimension of 9.675×9.675 mm^2, while the width of the guard-ring is 1.0 mm. The separation between the electrodes is 0.05 mm. This detector is an important step toward an imaging large area CdTe diode detector.

We measured the leakage current on the five cathodes (4 electrodes and a guard-ring) separately. Positive voltages were applied to the In electrode using a Keithley 237, and thus the total leakage current was also measured. We used a Keithley 6517A to measure the current in the cathode side. During the measurement of one cathode electrode, the other four were directly connected to the ground.

The noticeable result is that more than 80% of the leakage current is going through the guard-ring (Fig.6). The current going through the segmented electrode is remarkably low, less than 100 pA and 1 pA with a bias of 300 V at 20 °C and -20 °C , respectively. It confirms that the leakage current in Schottky CdTe diodes is dominated by the surface current. In other words, the segmented electrodes in this detector can be operated at room temperature with a higher bias with very low leakage current.

In Fig.7, we present the ^{241}Am spectra obtained with one of the segmented electrodes of this detector. The set up of the measurement is the same as that of Fig.3. Even at an operating temperature of 20 °C , a bias of 300 V is applied and a good energy resolution of 2.3 keV is obtained. When operated at -20 °C , the resolution becomes as good as 1.8 keV. A 2.3 keV resolution is similar to the energy resolution of a $10 \times 10~\mathrm{mm}^2 \times 0.5~\mathrm{mm}^\mathrm{t}$ CdTe diode operated at -20 °C . A 1.8 keV resolution is at present the best for a CdTe diode detector with a detector size of as large as 10×10 mm^2, which means a capacitance of 20 pF. By measuring from the anode (In) side, the energy resolution is 3.9 keV at a bias of 200 V and a shaping time of 6 μs. This value is similar to the typical energy resolution of the large area planar device operated at 20 °C .

From these results, it has been proven that a guard-ring can efficiently decrease the leakage current in a CdTe diode. Even a large detector with a surface area of 4 cm^2 can realize a good energy resolution of 2.3 keV at room temperature, combining the electrode segmentation and adopting a guard-ring.

3. Verification study for space application

3.1. Environmental tests

As a verification study to use the large area CdTe diode in orbit, we performed a series of tests on the large area planar detector. As a first approach, we simulated replacing the 2 mm thick Si PIN diode of the Hard X-ray Detector (HXD) [12] on-board the *Astro-E2* satellite. The main sensor part of the HXD consists of 16 well-type phoswich counters (well units). The Si diodes are mounted in the bottom of the four "wells" of each well unit, just above the GSO crystals[13]. The large area planar CdTe diode is designed to match this mounting. In the ceramic case, there is a through hole with a size of 20×20 mm^2, and the diode is glued to the case only by the surrounding 0.75 mm edge.

Astro-E2, and a number of scientific satellites in Japan, are launched by the Japanese M-V rocket. To confirm the ability to endure the severe mechanical shocks and vibrations during the launch, we performed a series of mechanical environment tests. The CdTe diode was mounted in place of the Si diode of the mechanical dummy of the well unit (Fig.8). The test included a vibration and an acoustic test. We compared the I-V curve and the ^{57}Co spectra of the CdTe diode obtained before and after these tests.

The random vibration test was held at the 30 t vibration test facility in ISAS. The power spectrum density was 27 G$_{\rm rms}$ in the 20–2000 Hz range with a duration of 45 s. The acoustic test was held at a test facility in NASDA. The sound pressure level was 148.8 dB in the 31.5–8000 Hz range, also with a duration of 45 s. These mechanical test levels are among the hardest space travel standards. In Fig.9, we plot the ^{57}Co spectra obtained before and after these tests. No degradation of spectral properties or I-V curve variance was observed. The large area CdTe diode has therefore proven to be tolerant against the mechanical environment of space travel.

Next, we verified the long term stability in a vacuum environment. We performed two kinds of experiments for this purpose. One of them was operated at a temperature of -20 °C in 1 atm dry air. The bias voltage was set at 200 V and the test lasted for 12 days. Another one was operated at a temperature of -5 °C in a vacuum circumstance of 2×10^{-6} Torr. The same bias was applied and the test lasted for 18 days. In both cases, we turned off the bias once every $1 \sim 2$ days to reset the very slow but steady polarization effect (see [11]). The CdTe diode worked well throughout these test periods, and thus was proven to be able to be operated in long term, at least for weeks, in orbit.

3.2. Radiation effects by proton beam experiment

To verify the radiative tolerance of the CdTe diode, we performed a proton beam experiment. Considering the average proton spectral flux in the low earth orbit with an inclination angle of $\sim 30^\circ$, and the shielding effect of the $\sim$ 6 cm thick BGO crystal surrounding the CdTe diode, we estimated that a total number of 10^9 protons with an energy around 10–200 MeV will hit the detector within an year [14]. Because there are some results indicating the material degradation of CdTe and CZT with this irradiation level (e.g. [15]), we carefully examined the radiation damage of the detector. In this experiment, we used the synchrotron accelerator at HIMAC, Japan. The proton energy was set at 155 MeV, and the size of the beam was 10 cm in diameter.

Table 1
Parameters of the proton beam experiment at HIMAC.

Material	Radiation	Counts
CdTe diode (4.6 cm^2)	Proton 155 MeV	3×10^{10}/device (7×10^9 p/cm^2)

We irradiated $\sim 3 \times 10^{10}$ protons to the large area CdTe diode, with an exposure of 4895 s. This corresponds to about 30 years in orbit at the HXD configuration. As shown in Fig.10, the leakage current has increased by $\sim$ 50 % after the irradiation, but it rapidly settled to the same level before the irradiation within $\sim$ 2 hours. Similarly, there was no degradation in the gamma-ray spectra. Thus, the Schottky CdTe diode was proven to be tolerant against the radiation damage in low earth orbit, at least at the HXD configuration. In the same time, we have also measured the radio activation effect in CdTe. The result of this analysis will appear in Murakami, Kobayashi et al. (2002)[16].

4. Conclusion

We have developed a large area CdTe diode with a dimension of 21.5×21.5 mm^2 $\times$ 0.5 mm$^{\rm t}$. This detector shows good energy resolution of 2.8 keV for 59.5 keV gamma-rays at -20 °C . In spite of its size, the detector is proven to be very homogeneous to within 0.2% accuracy. We also developed a 2×2 segmented electrode detector with a guard-ring. With this detector, it has been directly shown that the leakage current of CdTe diode is dominated by the surface current. More than 80% of the current goes through the guard-ring, and the segmented electrode shows an excellent spectral resolution of 2.3 keV even at 20 °C .

In view of practical space application of 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. It was finally proven that the CdTe diode is ready for space use. From these results, we conclude that the CdTe diode is one of the best material candidates for the next generation hard X-ray and gamma-ray observatories, such as the *NeXT* project in Japan.

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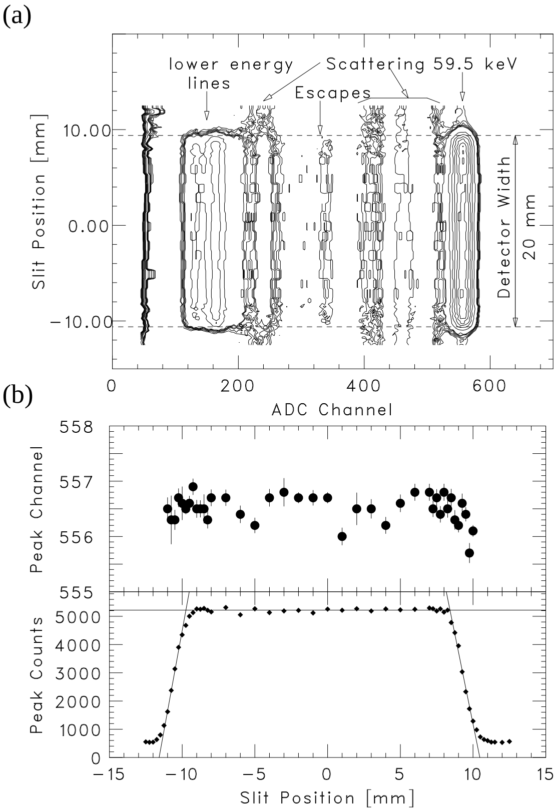

Figure 4. Spectral properties of the scanning experiment. Panel (a) presents the 2 dimensional contour plots of the pulse hight spectra vs slit position. Panel (b) presents the position and area of the 59.5 keV peak. The full width half maximum of the peak count distribution is 20.10 ± 0.05 mm, which is consistent with the detector actual size, 20 mm. The experiment was performed at −20 °C and a bias of 200 V was applied.

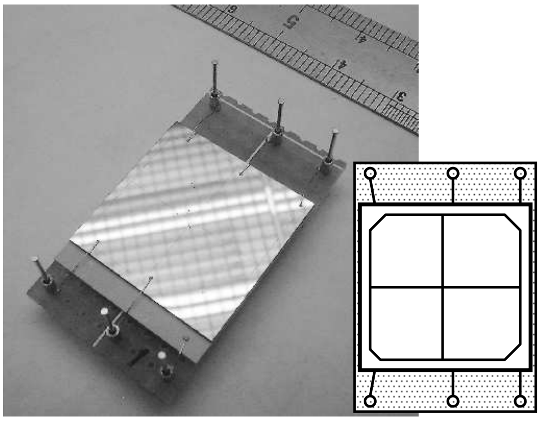

Figure 5. Photo of the 2× 2 electrode CdTe diode with a guard ring. Back side is the planar anode electrode made of In and front side is the segmented electrodes made of Pt. Right panel represents the schematic layout of the electrode design.

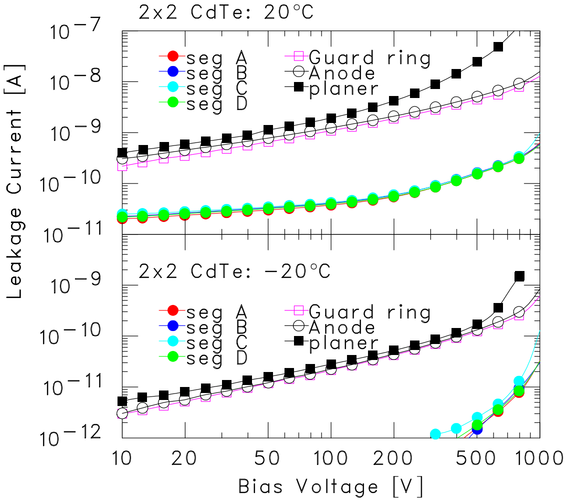

Figure 6. Current-voltage (I-V) characteristics of the 2×2 detector, at (top) 20 °C and (bottom) −20 °C . Results from a planar detector are also plotted.

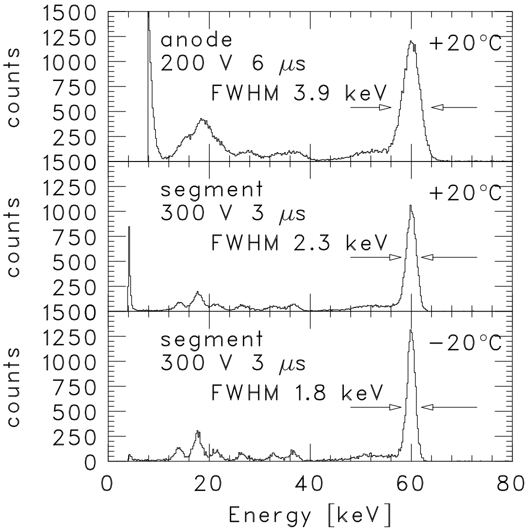

Figure 7. ^{241}Am spectra obtained by (top) anode electrode and (middle) a segment of 2×2 detector at 20 °C , and (bottom) a segment of 2×2 detector at −20 °C .

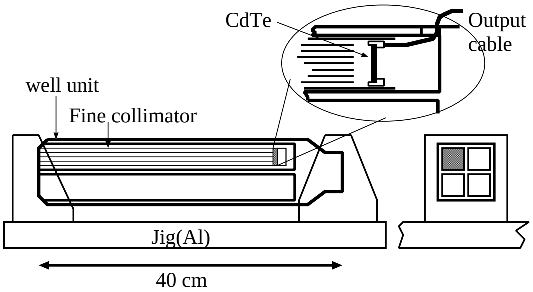

Figure 8. Setup of the mechanical tests. The large area CdTe diode are mounted at bottom of the the well-shaped shield part of the well unit.

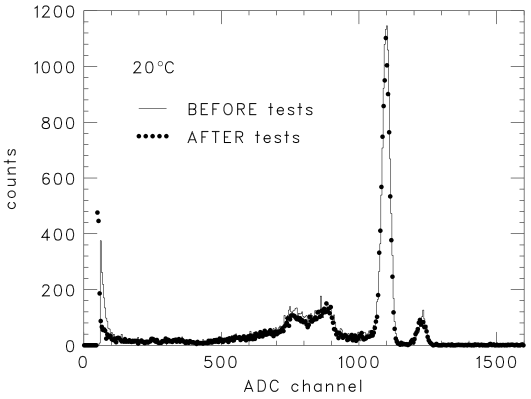

Figure 9. ^{57}Co spectra obtained before and after the mechanical tests. The operation temperature was 20 °C .

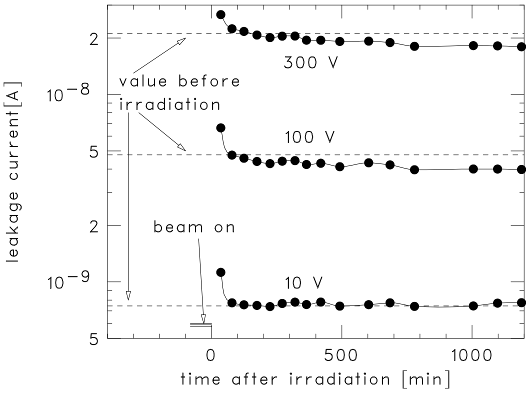

Figure 10. Time variance of leakage current of the CdTe diode at the proton beam experiment. The current at 10 V, 100 V and 300 V in room temperature, selected from a series of I-V curve measurements were plotted. No bias was applied between these measurements.