Improvement of the CdTe Diode Detectors using a Guard-ring Electrode

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***Abstract*— Recent results from the Schottky CdTe diode detectors employing a guard-ring electrode are reported. Cathode electrode, made of Platinum, was separated into an active electrode(s) and a surrounding guard-ring. Typical leakage current of a device with active area of 2×2 mm^2 and 0.5 mm thickness surrounded by a guard-ring, is 7 pA and 20 pA at a bias of 100 V and 500 V, respectively, operated at 20 °C . Spectral resolution of this device is 0.93 keV and 1.2 keV (FWHM) at 59.5 keV and 122 keV, respectively, operated at 20 °C with a bias of 800 V. Detailed study of the characteristics of these devices working as a gamma-ray detector is presented.**

***Index Terms*— CdTe, diode, gamma-ray, guard-ring**

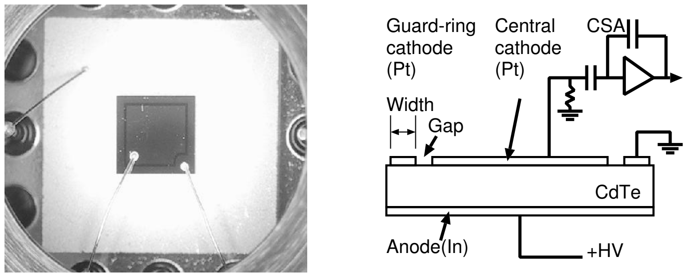

Fig. 1. (left) Photo of a test piece of guard-ring CdTe diode. The size of the active area is 2×2 mm^2 $\times$ 0.5 mm^t, and the width of the guard-ring is 200 μm. Cathode electrode is at surface and anode is on the other side. (right) Schematic cross section view of the detector.

I. Introduction

Cadmium Telluride (CdTe) and Cadmium Zinc Telluride (CZT) are promising devices for the next generation of gamma-ray detectors. They have a high photon cross section, together with good energy resolution of < 1 keV in full width at half maximum at 60 keV. In addition, their moderate band-gap energy of $1.4 \sim 1.6$ eV enables us to operate them at room temperature (see reviews [1][2][3], and references therein). These devices, however, currently suffer from incomplete charge collection due to poor charge transport properties, especially for holes. This causes a low energy tail structure in their gamma-ray spectra, and degrades photo-peak efficiency.

As an approach to reduce the tail structure, we have developed a CdTe diode detector, using indium (In) as an anode electrode on the p-type CdTe, manufactured by ACRORAD (see [4] and [5] for details of this device). This device works as a Schottky diode and can be operated with a higher bias voltage, from about 500 to 1200 V for a 0.5 mm thick device, resulting in a significant improvement of charge collection efficiency.

From systematic study of characteristics of the CdTe diode, we have recently found that the leakage current is proportional to the diode perimeter, and not the area nor the volume. We have hence introduced a guard-ring (GR) structure in cathode electrode. This improvement resulted in another order of magnitude reduction of leakage current, and enabled us to operate the device at room temperature, i.e., ~ 20 °C with good performance [6][7]. In this paper, we report the detailed study of the guard-ring CdTe diode devices, such as the size and thickness dependency of the leakage current, spectral performance at room temperature, and stability.

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II. Characteristics of the Leakage Current

A. Basic Electrode Design and Reproducibility of the Device

For detailed study of the guard-ring CdTe diode detectors, we have developed a series of test pieces. As shown in Fig.1, the cathode electrode is separated into two parts; central electrode, which is the active area for gamma-ray detection, and guard-ring electrode, surrounding the former. Typical width of the guard-ring is 0.5 $\sim$ 1mm, and typical gap between the electrodes is 50 μm. Anode surface is full contact, because of current technical difficulty to implement structures in Te/In Schottky surface. In the following leakage current measurements, positive bias voltage is applied from anode side, using Keithley 237. Hence the total current is always monitored. Leakage current of central cathode is measured by Keithley 6517A, and guard-ring electrode is directly connected to the ground.

In Fig.2, leakage current of CdTe diodes having the same active volume with and without a guard-ring is presented. Adopting a guard-ring reduces the leakage current by more than an order of magnitude, 7 pA and 20 pA at 100 V and 500

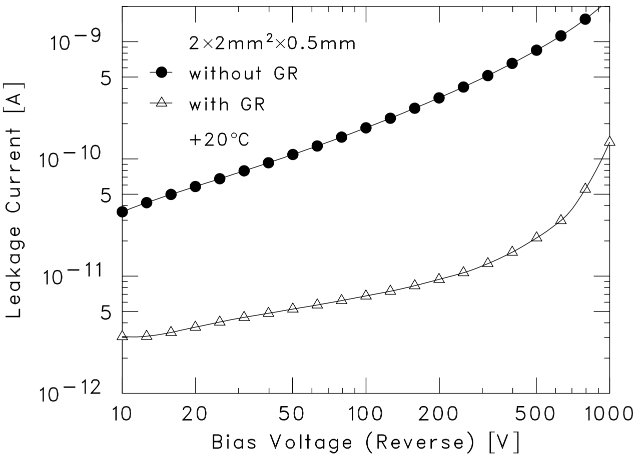

Fig. 2. Leakage current of CdTe diodes with an active area of 2×2 mm^2 and a thickness of 0.5 mm, with (triangle) and without (circle) a guard-ring. Operation temperature is 20 °C .

V, respectively, for a detector with active area of 2×2 mm^2 and a thickness of 0.5 mm. Note that the measurement is held at a temperature of 20 °C .

In Fig.3, we compare the leakage current of the central electrode only and that including the guard-ring component. Active area of this guard-ring CdTe detector has a size of $2{\times}2$ mm^2, the gap and the width of the guard-ring are 50 μm and 1 mm, respectively, and the thickness of the device is 0.5 mm. The central electrode component is negligible for reverse bias, while it is significant for forward bias. These results show that the leakage current characteristics of the bulk electrode and the detector periphery is different. In other words, the device is not a simple Schottky diode.

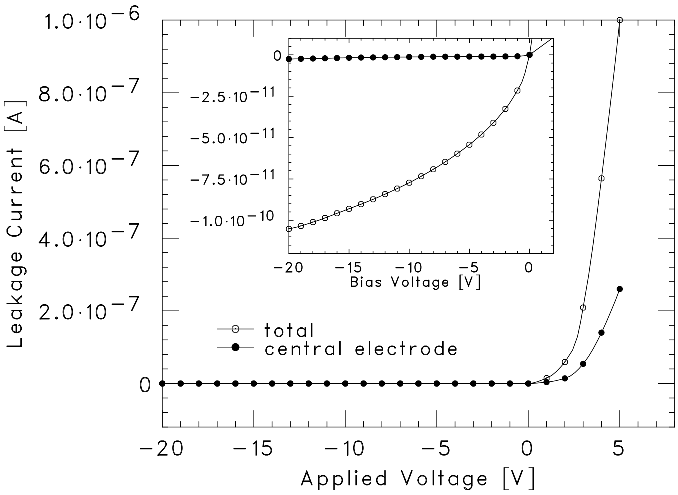

Fig. 3. Diode characteristics of the guard-ring CdTe diode. Total leakage current (open circles) and that on the central electrode (filled circles) are presented. Closeup view at reverse bias region is also plotted for clarity.

Fig.4 presents distributions of the leakage current of 20 test pieces of guard-ring CdTe diode detectors. All detectors have the same dimensions: an active area of 2×2 mm^2, surrounded by a guard-ring with a width of 0.5 mm. Gap between the electrodes is 50 μm, and thickness of the device is 0.5 mm. The plot shows a good reproducibility of the technology; 16 and 11 detectors out of 20 show leakage current within a factor of 3 one another for a bias of 100 V and 500 V, respectively.

B. Dependence on Detector and Electrode Geometry

In this sub-section, we present the leakage current dependency in size and thickness of the detector, and difference of width and gap distance of the guard-ring electrode. Because of the good reproducibility shown in the last sub-section, all measurements are held using only two test pieces with exactly the same parameters. In case there is a significant difference between the two results, which happens in a few cases, we adopted the better one.

In Fig.5, thickness and size dependence of the leakage current is shown. In this case, parameters of the guard-ring is kept the same; 1 mm wide, with a gap of 50 μm. Below $\sim$ 500 V, the leakage current does not depend on the thickness of the device. This result strongly suggests that it is the barrier height and not the bulk resistivity which dominates the leakage.

We do not currently understand the physical reason of rapid increase of the leakage current above 500 V on the 0.5 mm thick devices. From another leakage current measurement on a pixel guard-ring CdTe diode detector, we notice that the steep rise in the leakage takes place at a few local positions within the detector. Although more detailed and systematic study is required to come to a conclusion, this result suggests that the phenomena is connected with some defects or inhomogeneity in the crystal.

Looking at the size dependency, we notice that the leakage current increases by a factor of $\sim$ 3 with increasing central electrode area by a factor of 4. Thus, the leakage current of the central electrode is not proportional to the area, nor to the length of the periphery. A more detailed study of the CdTe diode,

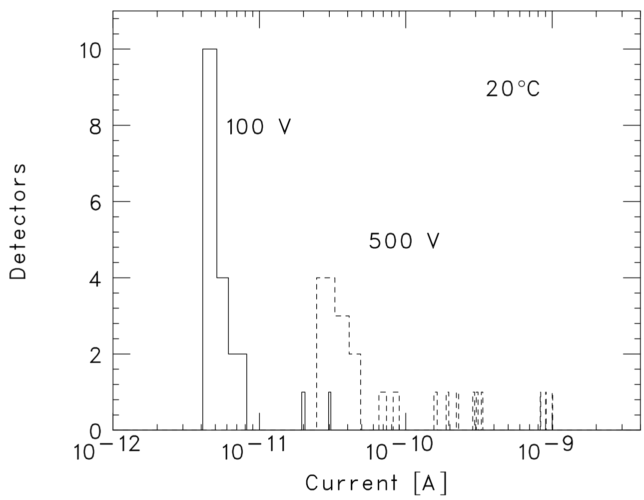

Fig. 4. Distribution of the leakage current of the 20 guard-ring CdTe diode detectors, at a bias of 100 V (solid) and 500 V (dashed). Operation temperature is 20 °C .

such as the physics of electrode/CdTe surface, carrier density gradient in the diode, will be required to finally understand the behavior of this device.

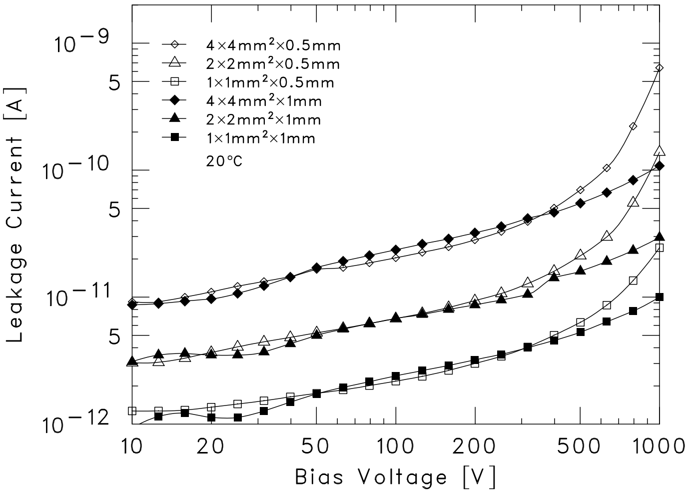

Fig. 5. Leakage current of guard-ring CdTe diodes measured at 20 °C , with different size and thickness of the material.

We also measured the leakage current of the detectors with different guard-ring design parameters, with the same detection area of 2×2 mm^2 and a thickness of 0.5 mm. First group of detectors are with different guard-ring width; 100 μm, 200 μm, 500 μm and 1 μm. The gap distance is kept at 50 μm. Another group of detectors are with different guard-ring gap distance; 25 μm, 50 μm, 100 μm and 500 μm. In this case, the width of the guard-ring is kept at 200 μm. From these measurements, we realized that the leakage current of the detectors with eight different guard-ring design is the same within a factor of two below a bias of 200 V, and a factor of 7 below 500 V. This is well within the reproducibility of the devices (§II-A). No specific tendency is observable with current data. Although these results suggest that we can make both the gap and the width as small as possible in view of the leakage current, the best spectral performance is currently achieved with devices having a guard-ring width larger than 500 μm. A comprehensive study using tens of devices will be needed to obtain the best parameters for the guard-ring design.

III. Spectral Performance and Stability

A. Gamma-ray Line Spectra obtained at Room Temperature

The low leakage current of the guard-ring CdTe diode detector and higher bias voltage applicable, lead to high resolution gamma-ray spectra free from tail structure, even at room temperature. In Fig.6, we present the best gamma-ray spectra obtained from a guard-ring CdTe diode detector with an active area of 2×2 mm^2 and a thickness of 0.5 mm. We applied a positive bias voltage of 800 V from anode side. Signals from central cathode are read by charge sensitive amplifier (CSA; CP 5109LS), filtered via ORTEC 571 with a shaping time of 2 μs, and fed into MCA (Amptek MCA 8000A). Guard-ring electrode is directly connected to the ground.

Energy resolution is 0.93 keV and 1.2 keV in FWHM for 59.5 keV and 122 keV gamma-ray lines, respectively, at the temperature of 20 °C . This value is similar to the resolution of CdTe diode detector without a guard-ring operated at a temperature lower than ∼5 °C [8].

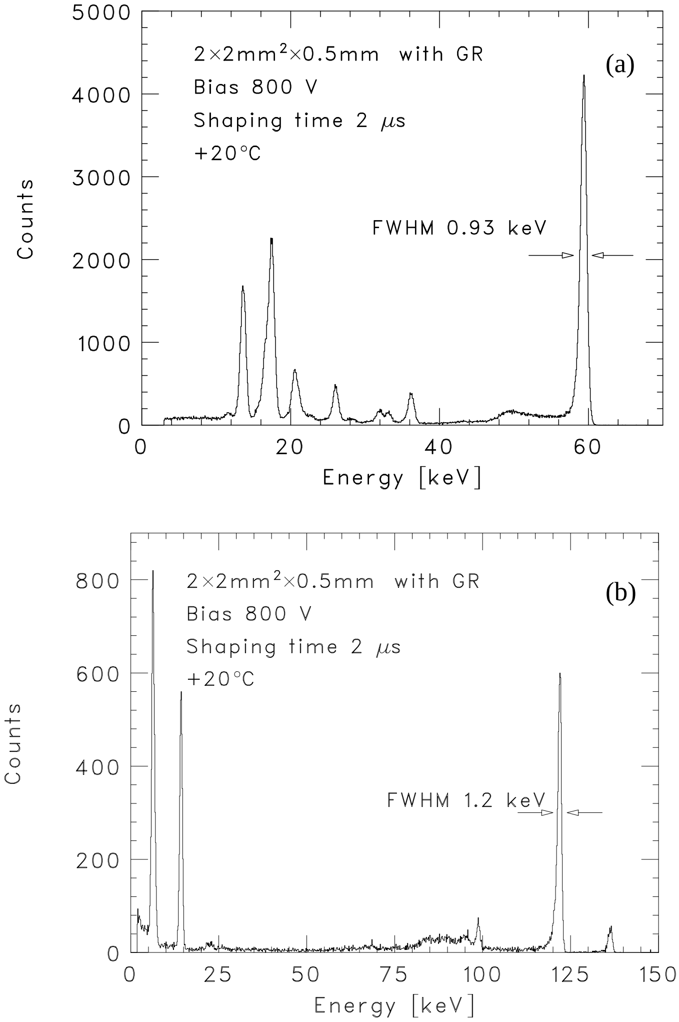

Fig. 6. (a) ^{241}Am and (b) ^{57}Co spectra obtained using a guard-ring CdTe diode with an active area of 2×2 mm^2 and a thickness of 0.5 mm.

B. Position Dependence of Detector Response to Gamma-rays

At the gap region between central and guard-ring electrodes, charge trapping due to weak electric field can happen. Fig.7 presents ^{241}Am spectra obtained using two guard-ring CdTe diode detectors with different gap width of 50 μm and 500 μm. In both detectors, the guard-ring width is 200 μm and central electrode area is 2×2 mm ^{2} with a thickness of 0.5 mm. The peak area of the latter device integrated over 52–62 keV is larger by only 5% compared to the former, while the tail area integrated over 7–9 keV is 8.5 times larger. Because the geometrical area of the central electrode is the same, while that of the gap regions are 0.41 mm^2 and 5.0 mm^2, the tail structure can be naturally explained by the gap effect.

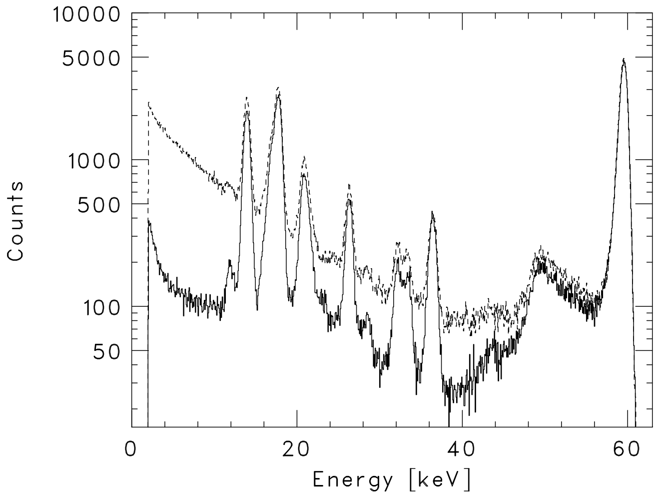

Fig. 7. ^{241}Am spectra obtained using detectors with different gap of 50 μm (solid) and 500 μm (dashed), between the central and guard-ring electrodes. The bias voltage is 500 V and the temperature is 20 °C .

To verify this effect, we performed a scanning experiment using an ^{241}Am source irradiated through a slit collimator. The slit has a typical size of 1 mm × 0.1 mm. The source and slit are mounted on a X-table. Scan direction is parallel to 0.1 mm dimension of the slit (Fig.8a). The peak area distribution integrated over 52–62 keV is presented in Fig.8b. The FWHM of this plot is measured to be 2.06 mm, which is consistent with the size of the central electrode of 2 mm. This result confirms that gap area contributes little to the peak count.

Typical spectra obtained right at the center of the central electrode, on the gap region, and on the guard-ring electrode are plotted in Fig.8c. While the central spectra exhibits a clear 59.5 keV peak with little tail, the gap and guard-ring spectra show almost no peak and huge tail-like structure. These results confirm that the peak originates from the central electrode and the gap region contributes a lot to the tail structure in the spectra.

C. Room Temperature Stability of the Device

As described in our earlier papers (e.g. [8]), CdTe diode detector shows a long-term (∼ days) instability, similar to so called "polarization effect" in semiconductor devices. We note that a good stability is obtained for CdTe detectors with anode and cathode both made of Pt. Although the nature of this effect is not yet understood well, we found that it can be suppressed if we make the detector thin (0.5 ∼ 1 mm), operate it with high bias, and at a low temperature of $-20 \sim 0$ °C . In this case, the detector works longer than a week[9].

Concerning the room temperature operation, i.e., 20 °C , higher bias voltage applicable to the guard-ring CdTe detector ensures better stability. To demonstrate this operational merit, we held a 48 hour long run experiment, continuously applying a bias of 800 V. During this operation, a ^{57}Co source with an activity of 2 μCi was mounted at a distance of ∼ 5 cm, and gamma-ray spectra were obtained every 10 minutes. In Fig.9, we present the spectra obtained, right after the turn on of bias, 7 hours, 24 hours, and 48 hours after. Note that the CdTe diode detectors without a guard-ring do not show this good energy resolution with this high bias at room temperature.

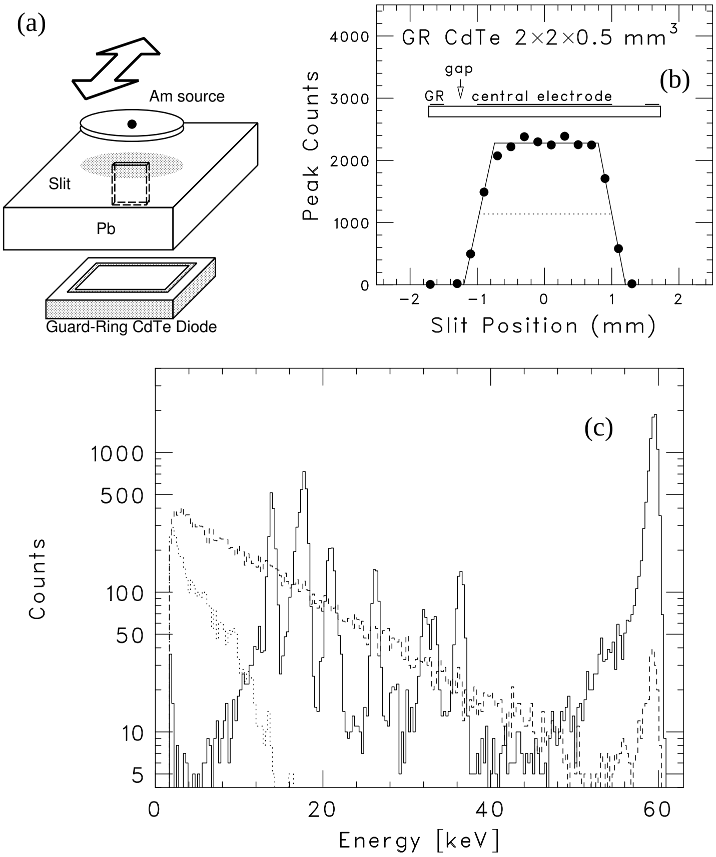

Fig. 8. Slit survey results. (a) The set up, (b) peak area with slit position, and (c) typical spectra. ^{241}Am spectra on the central electrode (solid), on the gap (dashed), and on the guard-ring (dotted) are presented. Gap between the electrodes is 500 μm. The bias voltage is 400 V and the temperature is 20 °C .

The 122 keV peak shape has changed a little within 48 hours. Shift of the position of 122 keV peak is 0.1% and 0.2% after 24 hours and 48 hours, respectively. Peak area integrated over 115–125 keV decreased by 2.1% and 4.5% after 24 hours and 48 hours, respectively. If a 1% level stability is required on the peak area, we can operate the detector for 7 hours. In addition, we note that the spectral performances recovers if we put off the bias for a moment.

Currently we do not properly understand the nature of the polarization. It can be, however, qualitatively explained by the gradual ionization of deep acceptors within the depletion region, where carrier (hole) density is extremely low (Y. Eisen and G. Sato et al., in prep). By this model, applying a higher bias is a key to reduce this effect, which can be easily achieved by implementing a guard-ring to the CdTe diode.

IV. Conclusion

Performances of Schottky CdTe diode detector employing a guard-ring electrode are presented. Adopting a guard-ring struc-

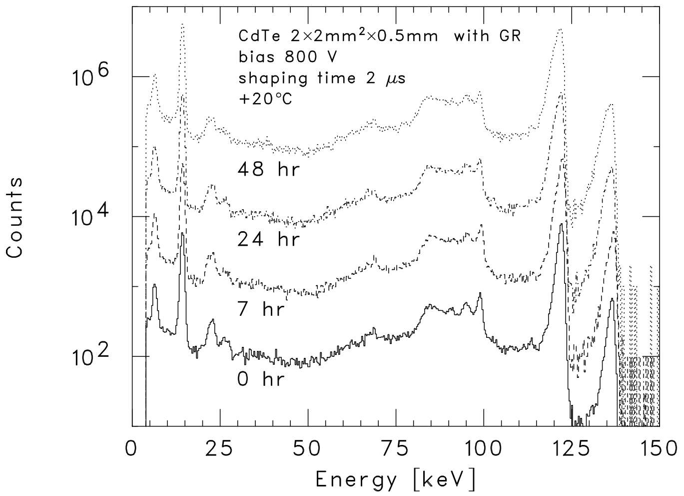

Fig. 9. Time variance of the ^{57}Co spectra obtained with a guard-ring CdTe detector at 20 °C . Spectra obtained 0 hour (solid), 7 hours (dashed: multiplied by a factor of 10), 24 hours (dash and dotted: multiplied by 100), and 48 hours (dotted: multiplied by 1000) after applying a bias are presented. Bias voltage is 800 V and temperature is 20 °C .

ture in cathode face, leakage current of the device decreases by more than an order of magnitude. Typical current at 20 °C for this device with an active area of 2×2 mm^2 and a thickness of 0.5 mm is 20 pA at a bias of 500 V.

Because of the low leakage, we can operate the device with a bias as high as 800 V at 20 °C . The best energy resolution is 0.93 keV and 1.2 keV (FWHM) for 59.5 keV and 122 keV line emission, respectively. These performances are similar to those of the CdTe diode operated at a temperature less than 5 °C . High bias voltage also improves the detector stability, sometimes referred to as a problem of the CdTe diode technology. Shift of the 122 keV peak position is 0.1% and 0.2% after 24 and 48 hours of continuous operation with a bias of 800 V, respectively.

High performance obtained at room temperature is important when considering practical applications. As an example, we have developed pixel CdTe imagers based on this technology. We can directly connect the pixels to the low noise analog LSIs and do not need any cooling system. The pixel CdTe imagers with a guard-ring has been already employed as a key element of the Si/CdTe Compton camera experiment (see T.Mitani et al., this conference), as well as the balloon flight experiment aiming at celestial gamma-ray observation (T.Tanaka and K. Nakazawa et al. in prep).

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