CdTe stacked detectors for Gamma-ray detection

Shin Watanabe, Tadayuki Takahashi, Yuu Okada, Goro Sato, Manabu Kouda, Takefumi Mitani, Yoshihito Kobayashi, Kazuhiro Nakazawa, Yoshikatsu Kuroda and Mitsunobu Onishi

Abstract— **We describe a stacked detector made of thin CdTe diode detectors. By using a thin CdTe device, we can overcome the charge loss problem due to the small mobility and short lifetime of holes in CdTe or CdZnTe detectors. However, a CdTe detector with a thickness of more than 5 mm is needed for adequate detection efficiency for gamma-rays of several hundred keV. Good energy resolution and good peak detection efficiency are difficult to obtain using such a thick CdTe detector. The stacked detector enabled us to realize a detector with both high energy resolution and good efficiencies for gamma-rays up to several hundred keV. In order to verify this concept, we constructed a prototype made of ten layers of a 0.5 mm thick CdTe diode detectors with a surface area of 21.5 mm × 21.5 mm. With this, we have achieved 5.3 keV and 7.9 keV energy resolution (FWHM) at 356 keV and 662 keV, respectively, at the temperature of −20 °C .**

Keywords— **CdTe, CdZnTe, CdTe Diode Detector, Stacked Detector.**

I. Introduction

CADMIUM telluride (CdTe) and cadmium zinc telluride (CdZnTe) are very attractive semiconductor materials for gamma-ray detection. The high density (~ 5.8 g cm^{-3}) and the high atomic number of the materials (Z_{Cd}=48, Z_{Te}=52) give a high detection efficiency for gamma-rays. However, incomplete charge collection, due to poor charge transport properties of these materials, degrades the energy resolution and lowers the effective photo peak efficiency for gamma-rays [1], [2].

Several techniques have been developed in order to maintain good energy resolution. Most of them are based on the concept of the single polarity charge-sensing method (e.g. [3], [4], [5], [6], [7], [8]).

Recently, we have succeeded to overcome the charge loss problem by adopting a thin CdTe diode device. The basic idea of the CdTe diode 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 leads us to the operation of the detector as a diode. By using this type detector with a thickness of 0.5 mm and an applied bias voltage as high as 1400 V, we have succeeded in obtaining high energy resolution: 830 eV (FWHM) at 59.5 keV and 2.1 keV (FWHM) at 662 keV [2], [10], [11].

Stacking thin CdTe devices is a new concept to realize a detector with both high energy resolution and good efficiency for gamma-rays up to several hundred keV [12], [13]. Here, we present results obtained with a prototype CdTe stacked detector made of large CdTe diode detectors of 21.5 mm × 21.5 mm.

Manuscript received February 10, 2002.

S. Watanabe is with the Institute of Space and Astronautical Science, Sagamihara, Kanagawa 229-8510, Japan, and also with the Department of Physics, The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan, E-mail: watanabe@astro.isas.ac.jp .

T. Takahashi, G. Sato, M. Kouda, T. Mitani and Y. Kobayashi are with the Institute of Space and Astronautical Science, Sagamihara, Kanagawa 229-8510, Japan, and also with the Department of Physics, The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan.

Y. Okada is with the Department of Physics, The University of Tokyo, Bunkyo, Tokyo 113-0033, Japan.

K. Nakazawa is with the Institute of Space and Astronautical Science, Sagamihara, Kanagawa 229-8510, Japan.

Y. Kuroda is with Mitsubishi Heavy Industry, Ltd., Nagoya Guidance & Propulsion Systems Works, Aichi 485-8561, Japan.

M. Onishi is with Daiichi System Engineering Co., Ltd., Aichi, 485-8561, Japan.

II. The advantage of the thin CdTe detector

Collecting full information due to the transit of both electrons and holes is important for obtaining the ultimate energy resolution from a semiconductor device. The mean drift path of the charge carrier is expressed as the product of $\mu\tau$ and E, where μ and τ are the mobility and lifetime of the charge carrier, and E is the applied electric field in the device. Due to the small $\mu\tau$ of holes for CdTe and CdZnTe, the thickness of the detector should be smaller than $\mu_h\tau_h E$.

The pulse height of the signal from a CdTe detector is given as a function of the depth of interaction by the Hecht equation [1], [14], [15]:

$$\begin{aligned} PH(z) \quad \propto \quad & n_0(\mu_e\tau_e E(1-\exp(-\frac{d-z}{\mu_e\tau_e E})) \\ & +\mu_h\tau_h E(1-\exp(-\frac{z}{\mu_h\tau_h E}))), \end{aligned} \tag{1}$$

where n_0 is the number of electron-hole pairs generated in the detector and d is the detector thickness. The depth, z is measured from the cathode. The electric field is assumed to be uniform, $E = V/d$, (V: Bias Voltage, d: Detector thickness) .

We simulated energy spectra for various thicknesses of detectors, using the Geant4 Monte Carlo code[1]. From the Monte Calro code, the energy deposit and its position are obtained event by event. Then, the pulse height is derived from these two values by using the Hecht equation.

Fig. 1 shows the spectra when gamma-rays with energy of 300 keV irradiate the surface of 0.5 mm, 2 mm and 5 mm thick CdTe detectors. In the spectra obtained with the 2 mm thick detector and 5 mm thick detector, broad low-energy shoulders, which are due to charge loss, can be seen clearly. The degradation of the energy resolution by the shoulder is more severe as the detector becomes thicker. Bias voltages of 12.8 kV and 80 kV are required for the 2 mm and the 5 mm thick detector, respectively, if one

[1] http://cern.ch/geant4

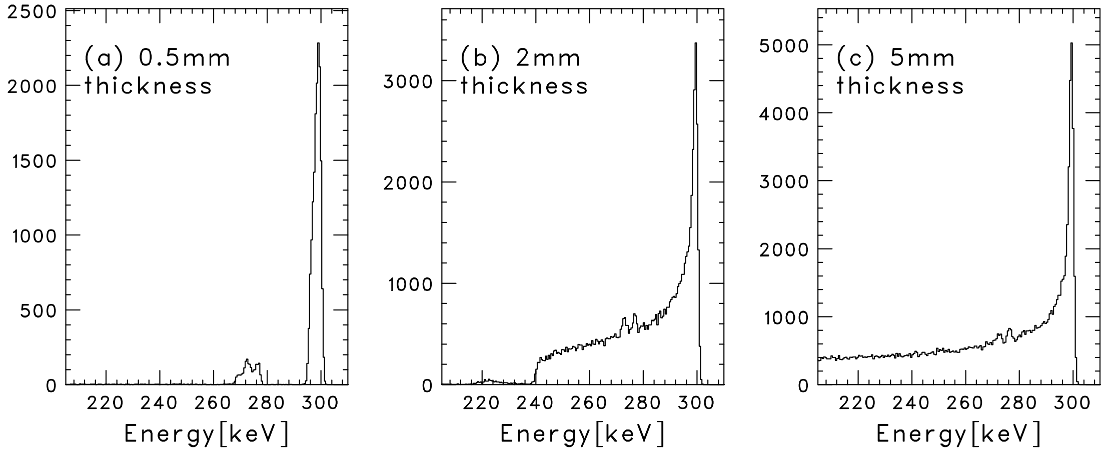

Fig. 1. Simulated spectra of the 300 keV line obtained with (a) 0.5 mm thickness, (b) 2 mm thickness and (3) 5 mm thickness. The number of radiated photons is 10^6 for each simulation. The applied bias voltage is 800 V. The assumed $\mu_e\tau_e$ and $\mu_h\tau_h$ are 2×10^{-3} cm^2/V and 1×10^{-4} cm^2/V, respectively. FWHM 3.0 keV resolution due to electronics noise and statistical fluctuation of electron-hole pairs is included. The peaks at about 275 keV are the escape peaks due to the Cd and Te X-rays.

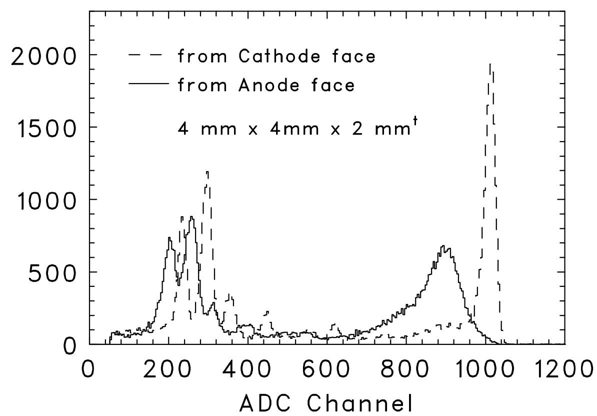

Fig. 2. ^{241}Am spectra obtained with a 2 mm thick CdTe detector. The surface area of this detector is 4 mm × 4 mm. The applied bias voltage is 800 V and the operating temperature is 5 °C . Gamma-rays irradiated the cathode face (dashed line) and the anode face (solid line).

wants as the same level of charge collection efficiency to be achieved as by the 0.5 mm thick detector under a 800 V bias voltage.

The detector having planar electrodes is the basic configuration. However, we cannot use the whole volume of a thick CdTe device as a sensitive volume for a peak detection. Due to the small $\mu_h\tau_h$, the interactions, which take place in the region close to the anode face, don't contribute to the peak components. This is clearly seen in the ^{241}Am spectra shown in Fig. 2 obtained with a CdTe diode detector with a thickness of 2 mm. When the detector is irradiated with gamma-rays from the cathode face, the gamma-ray peaks are neatly shaped. However, if gamma-rays irradiate from the anode face, the peak structure is smeared out. The position of the 59.5 keV peak is about 10 % lower. This situation is much worse in a recent CdZnTe detector, because the $\mu_h\tau_h$ of CdZnTe is about ten times smaller than that of CdTe. (See Fig. 6 in [2].)

III. A stacked detector

The energy resolution of a thin CdTe diode detector (<1 %) at higher gamma-ray energies under moderate operating conditions is very attractive in high energy astrophysics and other fields. For gamma-rays above a hundred keV, adequate detection efficiency can be obtained by a CdTe detector with a thickness of more than 5 mm. However, good energy resolution and good peak detection efficiency would be difficult to achieve with such a thick CdTe detector as long as a planar electrode is used. We, therefore, adopted the idea of a stacked detector, in which several thin CdTe diode detectors are stacked together.

Fig. 3 shows the schematics of our CdTe stacked detector. The signal from each layer is read out independently using a charge sensitive amplifier (CSA) and then shaped by a shaping amplifier (shaper). The output of each shaping amplifier is divided into two. One is fed into the ADC module, and the other goes to the discriminator. The signals from the discriminators are OR-ed and used as a trigger to make the gate signal and the start-conversion signal for the data acquisition in the ADC modules. Also, the output of each discriminator is connected to the hit pattern module to record the channels in which the signal exceeds the threshold level. With this information, we can apply various selection criteria for the analyses.

For gamma-rays up to several hundred keV, it is useful to select the events which occurs in only one layer (single layer events). Certainly, we are losing some multi layer events which will contribute to the peak detection efficiency when combined and summed up. However, assuming a CdTe stacked detector made of ten layers, each with a thickness of 0.5 mm, they are estimated to be only 8 and 3 points in the total efficiency of 67 % and 16 % for 150 keV and 300 keV, respectively. In addition, with this selection, the good energy resolution equal to that of one detector is maintained, because there is no need to add singles from some layers.

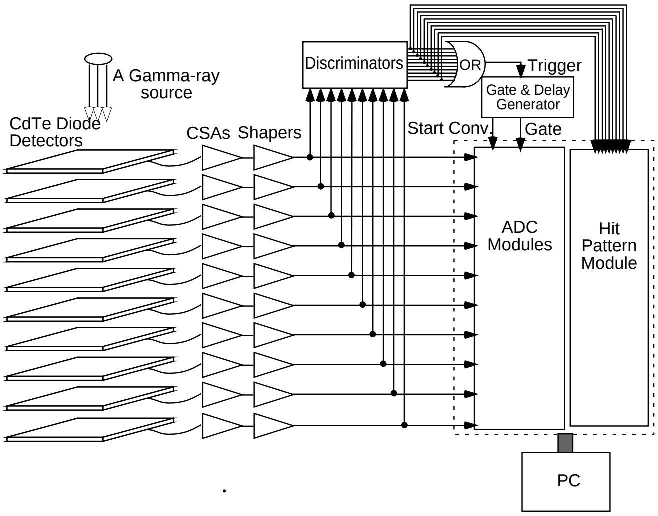

Fig. 3. Our CdTe stacked detector system.

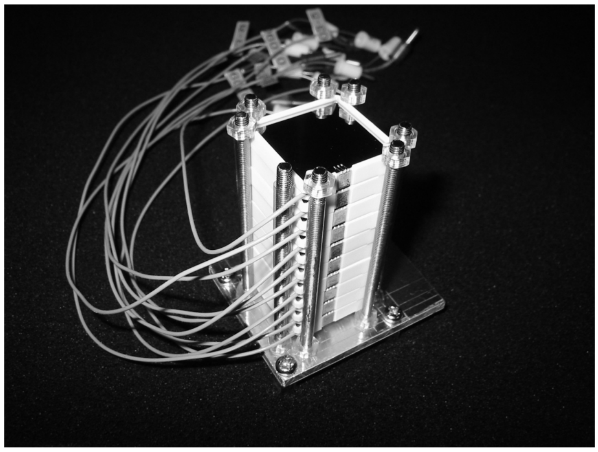

Fig. 4. Our CdTe stacked detector. Ten CdTe diode detectors of surface area 21.5 mm × 21.5 mm and thickness 0.5 mm are stacked together. Each detector is mounted on the housing made of ceramic. The gap between layers is 5 mm.

The photograph of a prototype stacked detector which consists of ten CdTe thin diode detectors is shown in Fig. 4. Each detector has a surface area of 21.5 mm × 21.5 mm and a thickness of 0.5 mm.

Each layer of thin CdTe detector is mounted on a ceramic housing. Fig. 5 shows the blueprint of the housing. Special care has been taken to reduce the amount of material while maintaining sufficient strength. The interval between the layers of the current stacked detector is 5 mm, limited by the height of the housing. From the requirement of use under a very low background environment, we use 99.5 % pure alumina for the material. The housing and the CdTe device are glued with silicone adhesive. The electrodes of the CdTe device are connected to the metalized sites on the housing using three gold wires with a 100 μm diameter, and they are glued with silver paste. The signal from the device is taken out through the fine coaxial cable. No degradation of the performance is seen in thermal cycles from −20 °C to 20 °C . In addition, we have performed mechanical verifications (including vibration testing and acoustic testing) to the CdTe detector mounted on the housing, and have found that there is no problem in the structure of the housing and the mounting method of the CdTe device even under the vibration level of 27 G_{rms} which is one of the hardest space travel standards.

The CdTe diode detectors used in the stacked detector are based on the result presented in our separated publication [16]. Fig. 6 shows the ^{241}Am spectra obtained with one of the detectors which composes the stacked detector. The applied bias voltage is 300 V and the operated temperature is −20 °C . The FWHM 3.3 keV energy resolution at 59.5 keV has been achieved. In the stacked detector, it is very important that the volume of each detector is fully active. The spectrum, when the detector is irradiated from the anode face, is also shown in Fig. 6 . The shape of the spectrum is maintained, and the difference of the 59.5 keV peak position between the two spectra is within 1 %. The result of this experiment shows that all the volume of the thin CdTe detector is sensitive to the peak detection.

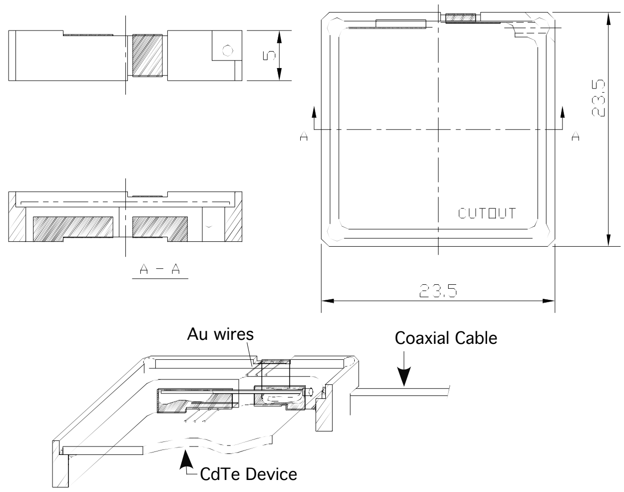

Fig. 5. The blueprint of the ceramic housing. Lengths are in units of mm.

The graph in Fig. 7 shows the peak detection efficiency of the CdTe stacked detector, calculated by Monte Carlo simulation. In the calculation, we selected only the single layer events. When gamma-rays with an energy of 300 keV irradiate this detector, 13 % of the gamma-rays can be detected as 300 keV events. The peak detection efficiencies calculated for a NaI scintillator and a CsI scintillator with the same volume are plotted together in the graph of the Fig. 7. We can attain an efficiency for the CdTe stacked detector similar to that of the same volume of NaI or CsI. Because of the modular structure, we can stack more CdTe diode detectors easily if we need greater efficiency.

IV. The results of the CdTe stacked detector

We operated the CdTe stacked detector under a bias voltage of 300 V per layer. Operating temperature is −20 °C , which is controlled with a thermostatic cham-

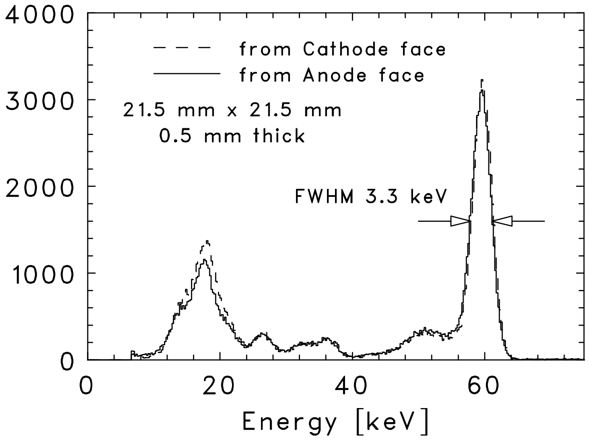

Fig. 6. The ^{241}Am spectra obtained the CdTe diode detector with the area of 21.5 mm × 21.5 mm and the thickness of 0.5 mm. The applied bias voltage is 300 V and the operating temperature is −20 °C . The time constant of the shaping amplifier is 6 μs. The dashed line and solid line show the spectra obtained when gamma-rays irradiate the anode face and the cathode face, respectively. The energy resolutions at 60 keV is 3.3 keV FWHM in the both cases.

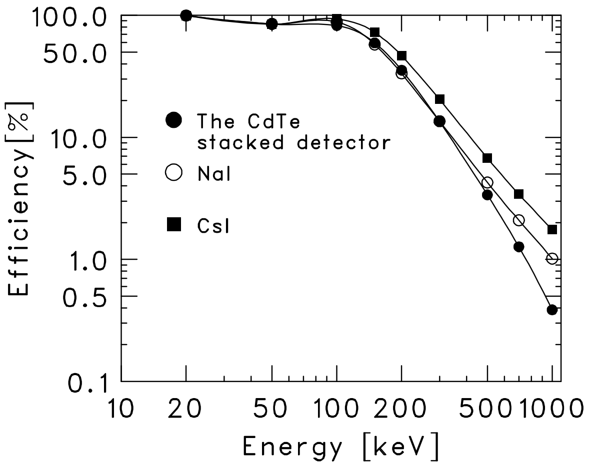

Fig. 7. The peak detection efficiency of the CdTe stacked detector, a NaI scintillator and a CsI scintillator, calculated from Monte Carlo simulation. The NaI and the CsI scintillators have dimensions 21.5 mm × 21.5 mm × 5 mm.

ber. The CSAs used in this experiment are Clear Pulse hybrid CS515-2s and the shaping amplifier is a Clear Pulse 4055 with a 6 μs shaping time. Gamma-rays from various radio isotopes (^{133}Ba, ^{22}Na, ^{137}Cs and ^{57}Co) irradiated the top of the detector to obtain the energy spectra at different energies.

Fig. 8 shows the spectra of gamma-rays from ^{133}Ba obtained with the CdTe stacked detector. In this measurement, we selected the events in which gamma-rays deposit energies in only one layer. Fig. 8 (a) shows the spectra obtained from layers 1, 2, 5 and 10 in logarithmic scales. The important feature of the stacked detector is that the information of the interaction depth is provided. It is easily noticed that the low-energy peaks at about 30 keV are present only in the first layer, and that the height of the 81 keV peak becomes smaller for deeper layers. On the other hand, the peaks from 270 keV to 390 keV are almost the same throughout all layers. The sum of the spectra from all layers is shown in Fig. 8 (b) in a logarithmic scale along with the spectrum of the first layer. Fig. 8 (c) shows a blowup of the spectra in the energy range from 200 keV to 400 keV. The FWHM energy resolution is 5.3 keV at 356 keV.

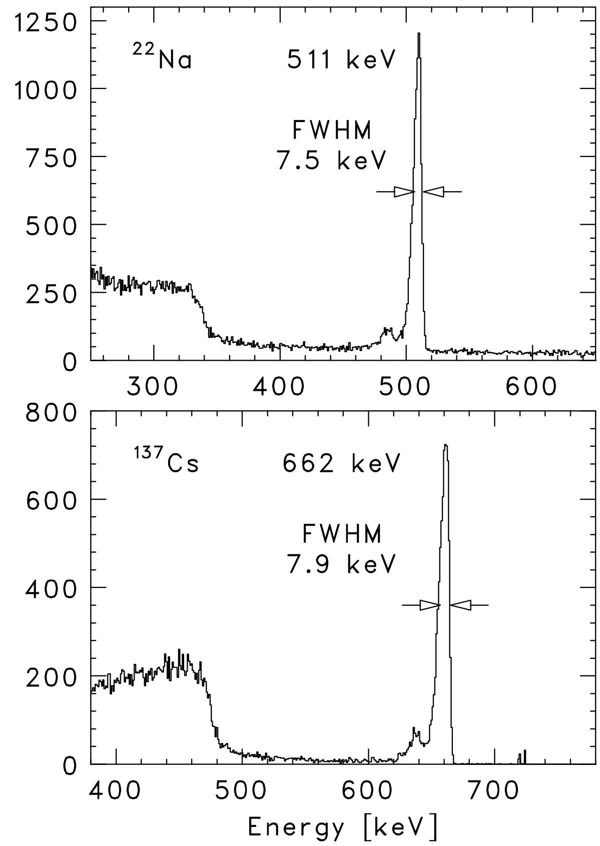

Fig. 9. The ^{22}Na and ^{137}Cs spectra obtained with the CdTe stacked detector. The energy resolutions at 511 kev and 662 keV are 7.5 keV (FWHM) and 7.9 keV (FWHM), respectively.

The performances for higher energy gamma-rays are demonstrated in Fig. 9 for the spectra obtained from the 511 keV line and 662 keV line. The achieved energy resolutions are FWHM 7.5 keV and FWHM 7.9 keV at 511 keV and 662 keV, respectively.

V. Conclusions

We constructed a CdTe stacked detector using ten thin CdTe diode detectors, each with an area of 21.5 mm × 21.5 mm and a thickness of 0.5 mm. We have succeeded in demonstrating that both good energy resolution and good detection efficiency can be achieved by this concept. The Monte Calro simulations revealed that the prototype have good efficiency, as high as that of NaI and CsI with the same volume. The energy resolutions obtained through the experiments in the temperature of −20 °C were 5.3 keV (FWHM) and 7.9 keV (FWHM) at 356 keV and 662 keV, respectively. Using thin CdTe de-

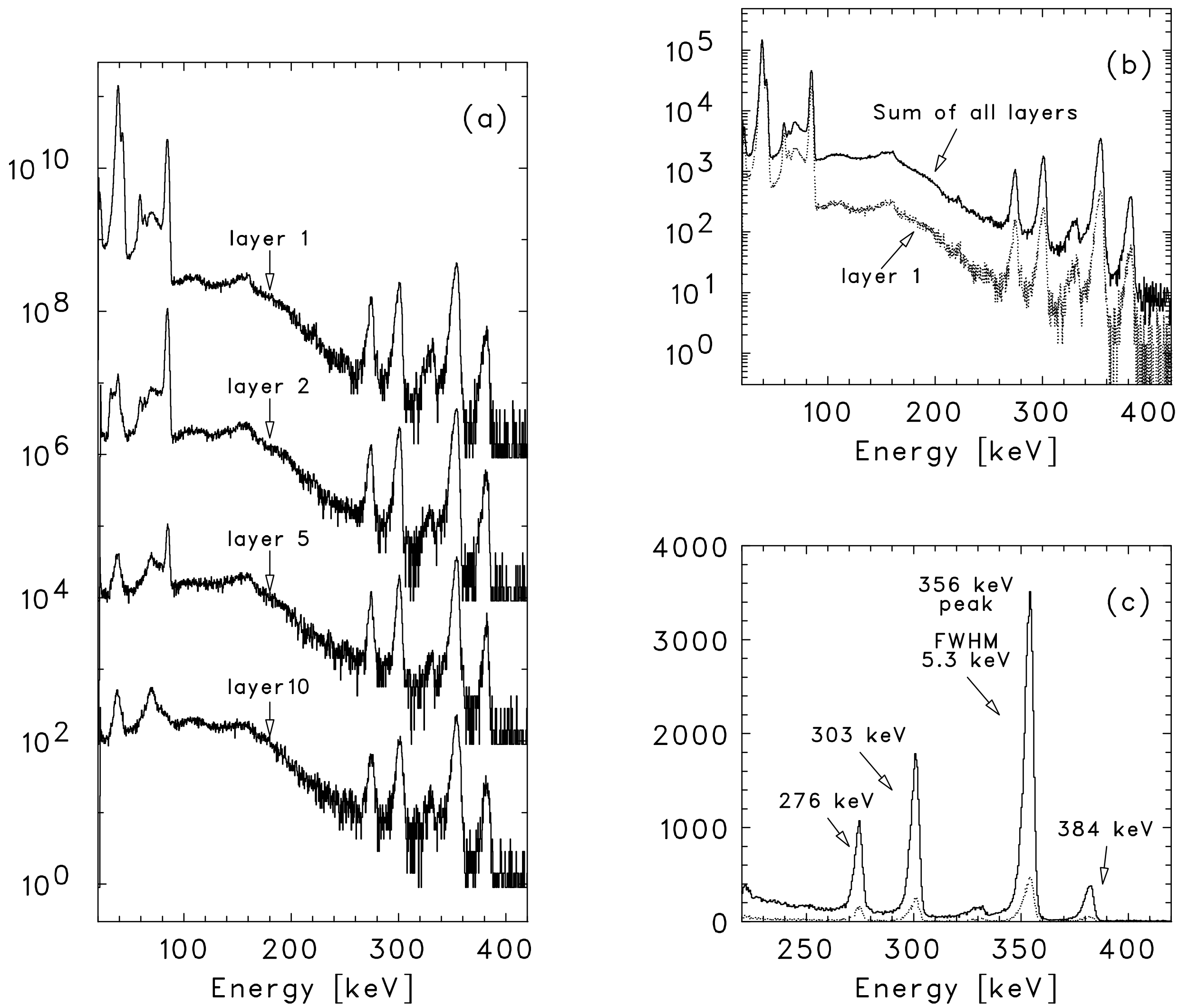

Fig. 8. The ^{133}Ba spectra obtained with the CdTe stacked detector under a bias voltage of 300 V per layer. The detector is operated in a thermostatic chamber at the temperature of -20 °C . The shaping time is 6 μs. (a): The spectra of the first layer, the second layer, the fifth layer and tenth layer. The counts of the first, the second and the fifth are scaled to 10^6 times, 10^4 times and 10^2 times, respectively. (b),(c): The spectrum added from all layers is shown together with the spectrum of the first layer. The energy resolution of the CdTe stacked detector is FWHM 5.3 keV at 356 keV.

vices, we are free from the charge collection loss problem, and can obtain good energy resolution without complex shaped electrodes or charge-loss corrections. In addition, it is a benefit of the stacked detector that stacking more detectors easily enables us to obtain more effective volume. Development of stacked detector with more layers for the detection of gamma-rays up to several MeV is underway with a compact read out system.

Acknowledgments

This work has been carried out under support of Grant-in-Aid by Ministry of Education, Culture, Sports, Science and Technology of Japan (11440066, 12554006, 13304014). We thank P.G. Edwards for his critical reading of the manuscript.

References

[1] Y. Eisen, A. Shor, I Mardor, "CdTe and CdZnTe gamma ray detectors for medical and industrial imaging system," *Nucl. Instr. Meth.*, A428, pp. 158-170, 1999.

[2] T. Takahashi and S. Watanabe, "Recent Progress in CdTe and CdZnTe Detector," *IEEE Trans. Nucl. Sci.*, vol. 48, No. 4, pp. 950-959, 2001.

[3] K. Zanio, W. Akutagawa and H. Montano, "Analysis of CdTe Probes," *IEEE Trans. Nucl. Sci.*, vol. 19, No. 3, pp. 257-262, 1972.

[4] H. L. Malm, C. Canali, J. W. Mayer, M. A. Nicolet, K. R. Zanio and W. Akutagawa, "Gamma-ray spectroscopy with single-carrier collection in high-resistivity semiconductors," *Appl. Phys. Lett.* vol. 26, pp. 344-346, 1975.

[5] S. P. Swierkowski, "A comprehensive model for predicting semiconductor detector performance," *IEEE Trans. Nucl. Sci.*, vol. 23, No. 1, pp. 131-137, 1976.

[6] P.N. Luke, "Single-polarity charge sensing in ionization detectors using coplanar electrodes," *Appl. Phys. Lett.* vol. 65, pp. 2884-2886, 1994.

[7] J.F. Butler, "Novel electrode design for single-carrier charge collection in semiconductor nuclear detectors," *Nucl. Instr. Meth.*, vol. A396, pp. 427-430, 1997.

[8] H.H. Barrett, J.D. Eskin, H.B. Barber, "Charge Transport in Arrays of Semiconductor Gamma-Ray Detector," *Phys. Rev. Lett.*, vol. 75, pp. 156-159, 1995.

[9] T. Ozaki, Y. Iwase, H. Takamura, and M. Ohmori, "Thermal treatment of CdTe surfaces for radiation detectors," *Nucl. Instr. Meth.*, vol. A380, pp. 141-144, 1996.

[10] C. Matsumoto, T. Takahashi, K. Takizawa, R. Ohno, T. Ozaki, and K. Mori "Performance of a New Schottky CdTe Detector for Hard X-ray Spectroscopy," *IEEE Trans. Nucl. Sci.*, vol. 45, pp. 428-432, 1998.

[11] T. Takahashi, S. Watanabe, M. Kouda, G. Sato, S. Kubo, Y. Kuroda et al., "High Resolution CdTe Detector and Applications to Imaging Devices," *IEEE Trans. Nucl. Sci.* vol. 48, No.3, pp.281-291, 2001.

[12] T. Takahashi, B. Paul, K. Hirose, C. Matsumoto, R. Ohno, T.Ozaki, K. Mori, and Y. Tomita "High-resolution Schottky CdTe diode for hard X-ray and gamma-ray astronomy," *Nucl. Instr. Meth.*, vol. A436, pp. 111-119, 1999.

[13] H. Nishizawa, H. Inujima, T. Usami, H. Fujiwara and H. Nakamura, "Response calculation of a stacked CdZnTe detector for ^{16}N γ-ray measurement," *Nucl. Instr. Meth.*, vol. A463, pp. 268-274, 2001.

[14] K. Hecht, "Zum Mechanismus des lichtelektrischen Primärstromes in isolierenden Kristallen," *Zeits, Phys.*, vol. 77, p. 235, 1932.

[15] G. Sato, T. Takahashi, M. Sugiho, M. Kouda, S. Watanabe, Y. Okada, T. Mitani, and K. Nakazawa, "Characterization of CdTe/CdZnTe detectors," *IEEE Trans. Nucl. Sci.*, submitted, 2002.

[16] T. Takahashi, T. Mitani, Y. Kobayashi, M. Kouda, G. Sato, S. Watanabe, K. Nakazawa, Y. Okada, M. Funaki, R. Ohno and K. Mori, "High Resolution Schottky CdTe Detector," *IEEE Trans. Nucl. Sci.*, submitted, 2002.