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Measurements on the spectroscopic performance of CdZnTe coplanar grid detectors

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HIGHLIGHTS

► The responses of CdZnTe coplanar grid detectors were studied as a room temperature γ-ray spectroscopy.
► The performance data were evaluated by using energy resolution, peak tailing and photofraction parameters.
► Better time stability and excellent spectroscopic performance are shown in high quality CdZnTe materials.

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ABSTRACT

A performance study was performed for CdZnTe coplanar grid (CPG) detectors when used as γ-ray spectrometers. The detectors have the crystal volumes of 1, 1.6875 and 2.25 cm^3, respectively. Time stability of each CdZnTe CPG detector was investigated in a long-term operation (time span of 0.25 to about 100 h). The spectroscopic performances were measured at different bias voltages and at various photon energies ranging from 59.6 keV (^{241}Am) to 1332.5 keV (^{60}Co) for each detector, and evaluated by using the following parameters: energy resolution in FWHM, peak tailing in peak-to-valley (*P/V*) ratio and in FWHM/FW.25 M ratio, and photofraction using the acquired γ-ray spectra. No polarization effect was observed in terms of count rate, energy resolution and peak centroid shift. The obtained results indicate that better time stability and excellent spectroscopic performances of the present CdZnTe CPG detectors are shown for a room temperature γ-ray spectroscopy.

1. Introduction

Cadmium zinc telluride (CdZnTe) is a promising material among wide band-gap (WBG) compound semiconductor materials such as CdTe, HgI_2 and GaAs. In particular, CdZnTe detectors are great interest for the room temperature X-ray and γ-ray spectroscopy. The use of CdZnTe detectors in several fields, for instance, industrial process monitoring, safeguards, homeland security, nuclear medicine, environmental remediation, physics research, etc., has grown considerably in recent years (Schlesinger and James,1995; He et al., 1997). In this context, there have been continuing advances in semiconductor γ-ray detector technology. The CdZnTe detectors among WBG detectors hold promise as practical and efficient radiation spectroscopy devices. Given below are the important benefits:

1) The detector does not require cooling since it has a wide band-gap energy range of 1.53–1.64 eV depending on the concentration of Zn in the crystal, which is added to the melt of Cd and Te during the crystal growth.
2) The CdZnTe material has a relatively higher bulk resistivity (10^{10}–10^{11} Ωcm) that enables improvement in leakage current properties remarkably.
3) It apparently does not suffer from the effects of polarization.

However, CdZnTe crystal material has also some disadvantages. For instance, this material suffers from the characteristic of incomplete charge collection because it does possess the characteristic of much higher electron mobility (1350 $cm^2 V^{-1} s^{-1}$) than hole mobility (120 $cm^2 V^{-1} s^{-1}$), giving rise to relatively stationary hole movement within the electron collection time (Knoll, 2000). This poor charge collection due to hole trapping results in large tailing on the low energy side of the peaks in the measured spectra. Hence, special sensing methods have been proposed to overcome the hole tailing in the peak by eliminating effects of the low hole mobility. Creating various electronic techniques to compensate for severe hole trapping via pulse rise time compensation is one of these methods. The electronic techniques measure the pulse rise time after a γ-ray interaction

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and compensate for losses in the signal generated (Baciak, 2004). The pulse-shape discrimination and charge-loss compensation techniques to treat the effect of incomplete charge collection have achieved good energy resolutions especially for CdZnTe detectors having a superior material uniformity. Nevertheless, since these electronic means rely on sophisticated electronics for pulse shape analysis, they add another level of complexity to the system, resulting in an increase in the noise sources and thus degrading its performance (Sturm, 2007).

Another way for single polarity (electrons) charge sensing is to employ a special anode electrode design. Thus, a much better way has been found to deal with the hole trapping issue in room temperature semiconductor detectors which utilize electrons' sensing by making suitable anode electrode designs such as pixels, strips, coplanar grids, steering grids, etc. (Abbene et al., 2007). Additionally, several other methods such as hemi-spherical detectors, parallel Frisch grid detectors, capacitive Frisch grid detectors and so on have also been studied to make use of single-polarity charge sensing but with the limited success when compared to the coplanar grid and pixelated anode structure designs. The advantages and limitations of the single-polarity charge sensing methods were previously discussed in detail (He, 2001).

The first major stride in single- polarity charge sensing of room temperature semiconductor detectors was made by Luke (1994), who developed an electrode structure called the coplanar grid, based on the collection of the charge carriers (electrons only). Utilization of the coplanar grid electrode structure in a device reduces tailing in the CZT crystal caused by the charge trapping. Luke's method is based on the principle of Frisch grids employed in gas ion chambers, but uses parallel narrow strip electrodes which are connected in alternate manner to give two sets of inter-digital grid electrodes (Luke, 1995). Single-polarity charge sensing is accomplished by reading out the difference signal between these two groups of electrode grids, with each set coupled to an independent preamplifier. The preamplifiers are then connected to a differential amplifier and the resulting signal is fed to an external pulse shaping amplifier. In case of coplanar grid electrode design, one set of the grids (the collecting anode) is held at a slightly more positive potential for electrons than the other set of the grids (the non-collecting anode) for holes. Hence a network of interleaved electrodes on one side (anode) of the CdZnTe crystal is connected to two different potentials to obtain the resulting signal having amplitude corresponding to the energy deposited in the crystal (eV Products, 2012). The opposite electrode (cathode) of CdZnTe device is kept at a negative bias voltage. Thus the application of coplanar grid electrode structure creates an electron-only collection device to overcome the hole trapping problem more effectively than the above mentioned pulse rise time compensation.

However, it is likely that the obtained spectrum might still be affected, at a lesser degree, mainly by only-electron trapping and asymmetry between weighting potentials of two strips on the grid anode in coplanar grid CdZnTe detectors. This requires the corrections for electron trapping that can be handled by adjusting the relative gain in the subtraction circuit of the anode preamplifiers (Luke, 1996; He et al., 1996). In addition, a method using interaction depth sensing to correct for electron trapping in material is employed. The latter method, which is alternative to the relative gain method, uses the ratio of the cathode signal and the subtracted signal to determine the depth of the gamma-ray interaction (He, 1995). It was also noted that other effects such as hole contributions, leakage current on the anode surface, or electronic noise were expected to be minor effects for the responses of high quality CdZnTe materials with coplanar grid anode structure (He et al., 1997).

Thus, CZT detectors have gained a dramatic improvement in energy resolution by employing an innovative single-polarity charge sensing methods. Especially, the introduction of coplanar grid electrode structure on the CdZnTe detectors has led to revival in interest to develop much larger volume compound semiconductor detectors that have a reasonable γ-ray response but also a good energy resolution for the X- and γ-ray spectroscopy. At state-of the-art CdZnTe detector technology, about 5–6 cm^3 crystal volumes are presently available; this covers efficiently an energy range of 30–2000 keV for the detection of X- and γ-rays. In past, spectrometric responses of a CdZnTe multiple electrode detectors were studied (Abbene et al., 2007) and similarly spectrometric performance of CdZnTe ring detectors was also investigated (Bulycheva et al., 2011). The purpose of this study is to investigate the spectroscopic responses of CdZnTe coplanar grid detectors used as γ-ray spectrometers. For this reason, performance data of CdZnTe coplanar grid detectors were obtained for three different crystal volumes at different bias voltages and various photon energies.

2. Experimental setup

In this study, three CdZnTe coplanar grid detectors having the crystal volumes of 1 cm^3, 1.6875 cm^3 and 2.250 cm^3 (purchased from eV Products Inc., now called Endicott Interconnect Technologies Inc.) have been used. Their basic characteristics such as energy resolution, crystal dimensions, and applied bias are given in Table 1. Each CdZnTe crystal was housed in an aluminum housing of 38.1 mm in outer diameter and 159.5 mm in length, associated with its built-in front-end electronics consisting of two charge-sensitive preamplifiers and a differential (difference) amplifier. Each CdZnTe coplanar grid device has a nominal spacing of 1.91 mm between the CdZnTe crystal and an Al window with a 0.35 mm in thickness.

An analog chain of NIM modules in an NIM bin was used for spectrum acquisition. The γ-ray spectrometer consists of a spectroscopy grade amplifier (Canberra 2025) and a MCA (Canberra

Table 1
Specifications for the CZT coplanar grid detectors used in the measurements.

Detector S/N[a]	Detector crystal size $X \times Y \times Z$ (mm^3)	X/Z dimension ratio[b]	Y/Z dimension ratio[b]	Applied bias (V)	Energy resolution[d] (FWHM)	
					@122 keV (^{57}Co)	@662 keV (^{137}Cs)
06–10071	$10 \times 10 \times 10$	1	1	−1200[c]	6.19 keV (5.07%)	12.82 keV (1.94%)
10–10048	$15 \times 15 \times 7.5$	2	2	−1000	8.58 keV (7.03%)	15.54 keV (2.35%)
12–10074	$15 \times 15 \times 10$	1.5	1.5	−1400	7.22 keV (5.94%)	16.68 keV (2.51%)

[a] Serial numbers(S/N) are given only in last 7 digits.
[b] X: Width, Y: Length, Z: Height (i.e., crystal thickness).
[c] Operating voltage was originally at negative 1400 V, but it was lowered after its repair, thus resulting, to a lesser degree, in degradation in energy resolution.
[d] FWHM values are given in keV and %, as specified by manufacturer (eV Products, Inc.).

Multiport-II) with a full capacity of 16 K channels ADC conversion gain/MCA memory and a power supply unit (Canberra 3106D). The ADC threshold level as lower level discriminator (LLD) was set at 12 channels (corresponding to the chosen cut-off energy) in the acquired γ-ray spectra to offset many soft X-rays, including the average electronic noise level of $\sim$10.5 keV(corresponding to the width of 9 channels) for CdZnTe coplanar grid detectors. The signals were digitized into 2048 channels MCA memory with a shaping time of 1 μs, and then the spectra were stored on a computer through a Genie 2000™ (Canberra) acquisition software for pulse height analysis,. The background spectrum was always subtracted from each source spectrum by stripping channel-by- channel basis with use of the background counts normalized by T_s/T_b, where T_s and T_b are the measurement periods for the source spectrum and the background spectrum, respectively.

The detector was shielded by using annuli cylinder shields in 1 cm thick stainless steel and 2 cm thick Pb, inside lining with 1 mm Cu to reduce Pb K X-rays and ambient background γ-rays. A lead collimator having its height/diameter ratio of 2.4 was also used in the measurements, thus giving a "good" counting geometry condition. Two collimators with different hole diameters were in turn used in the setup. Depending on the used detector, the hole of the chosen collimator was either 10 mm or 15 mm, so that it subtends to nearly active crystal surface of the detector used.

The disk sources, so-called M-type thin "scatterless" were used in the measurements and each has an active diameter of 3 mm, and a capsule of 25.4 mm outer diameter and 3.18 mm thickness for the radioisotopes, ^{22}Na (39.37 kBq $\pm$ 3%), ^{57}Co (37.96 kBq $\pm$ 3%),^{54}Mn (37.44 kBq $\pm$ 3%), ^{60}Co (40.55 kBq $\pm$ 3%), ^{65}Zn (389.24 kBq $\pm$ 3%), ^{109}Cd (35.42 kBq $\pm$ 5%), ^{137}Cs (38.41 kBq $\pm$ 5%), purchased from Eckert & Ziegler Isotope Products Inc., whose activities were certified as of 1 December 2008. The other source is ^{241}Am (16.09 kBq $\pm$ 5%) within their capsules having a 25 mm outer diameter and 3 mm thickness, purchased from Inspectorate for Ionizing Radiation (Praha, Czech), whose activity was certified as of 4 February 2002. All certified activities are given at a 99% confidence level.

3. Measurement results and discussion

The measurements were performed at a room temperature of 23 ± 1 °C. Each source was located axially with respect to the detector such that the source plane was parallel to the face of the detector.

The measurements were carried out at a source-to-detector distance of 5.2 cm, assuming to be a far geometry condition, where the count rates were normally low. Any pulse pile-up effects and true coincidence summing effects could be neglected at this counting geometry (Yücel et al., 2010). However, the measurement periods were long enough to provide statistical precisions on the full-energy peak areas in the measured source spectra when considering each source activity.

The time stability of the present coplanar grid CdZnTe detectors were first investigated at different photon energies with operating period of 15 min to about 100 h. Fig. 1 shows time stability measurements of CdZnTe coplanar grid detectors' responses to various photon energies in terms of photopeak centroid shift in MCA memory registration (in channels). Standard deviations of the observed peak centroids are always less than 1.7 channels. For the present spectrometers, the percentage variations in the observed peak centroids are generally very small, i.e., they are estimated to be 0–0.14% for 1000 mm^3, 0–0.17% for 1687.5 mm^3 and 0.06–0.11% for 2250 mm^3 CdZnTe detectors. However, overall measured channel uncertainties in the peak centroids are 2–3 times larger than theoretically estimated ones, which are about average 0.051%. For the overall channel uncertainty estimation, the uncertainty sources are mainly due to ADC/MCA, amplifier and power supply instabilities. Ideally, the widths of the channels in ADC are assumed to be equal, however, the integral non-linearity (INL) of the present ADC is less than $\pm$0.025% of full scale over the top of selected range, which corresponds to maximum 0.5 channel over the selected whole range of 2048 ADC channels. The INL for the amplifier is given as $< \pm 0.04\%$ over total output range for 2 μs shaping. Additionally, the output stability of the used power supply is taken as $\leq 0.02\%$ per 8 h at normal operating conditions. Thus, the results indicate that any polarization effects could be observed in the CdZnTe coplanar grid detectors in terms of the changes in the peak positions over a longer measurement period more than few days.

Fig. 2 shows the time stability measurements of a coplanar grid CdZnTe detector's response to different photon energies in terms of photopeak count rate (cps), energy resolution (%), peak-to-valley ratio and photofraction, where the example detector performance measurements for different photon energies are given only for a 2250 mm^3 CdZnTe detector to save space in the paper. It should be noted that the photofraction is the defined as the ratio of the Gaussian area of a full-energy peak to the total counts of the whole response function above the average electronic noise level of $\sim$10.5 keV. Therefore, as seen in Fig. 2(d) the photofractions are determined by use of only mono-energetic photons such as using low energy (59.6 keV, ^{241}Am) and high energy (834.8 keV, ^{54}Mn) γ-rays avoiding the very weak X-ray energy contributions but also not interfering to any other peak in the acquired spectrum.

For a long-term detector operation, it can be concluded that the present detectors show good stability with increasing measurement periods, taking into account small variations within the statistical uncertainties within a 68.4% confidence level estimated in the measured responses. These variations in photopeak count rate, energy resolution, peak-to-valley ratio, and photofraction of the peaks of interest are generally less than 5%.

The spectroscopic responses of the present CdZnTe coplanar grid detectors were also investigated at various bias voltages and photon energies. The spectroscopic response versus the applied bias is shown in Fig. 3 for three CdZnTe coplanar grid detectors in which the detector response was examined in terms of the photopeak centroid shift. As expected, the peak centroids at different photon energies did change very small with increasing bias voltages but no longer changed in the observed peaks when the detector reached to its normal operating voltage.

For each CdZnTe coplanar grid detector, the measured performance data was evaluated by using the following parameters: energy resolution in FWHM, peak tailing in peak-to-valley (P/V) ratio and in FWHM/FW.25M ratio, and photofraction in Gaussian peak area/total counts of the detector response in the acquired γ-ray spectra.

FWHM is full width of the full-energy peak at half (1/2nd) its maximum height above the background It is well known as a measure of the energy resolution for a detector. The measured results for energy resolution in FWHM are given in Table 2 for three different coplanar grid CdZnTe detectors. The peak-to-valley (P/V) ratio is defined as the ratio of the highest peak counts to the valley counts (the counts of the energy channel generally distant $2 \times$FWHM from the peak centroid, which is the highest peak channel). However, the P/V ratio can also be determined at energies on the low side of the peak at energies distant $0.5 \times$FWHM and $5 \times$FWHM from the center line of the peak, unless these positions correspond to the peaks in the spectrum from any cause, such as escape peaks. Additionally,

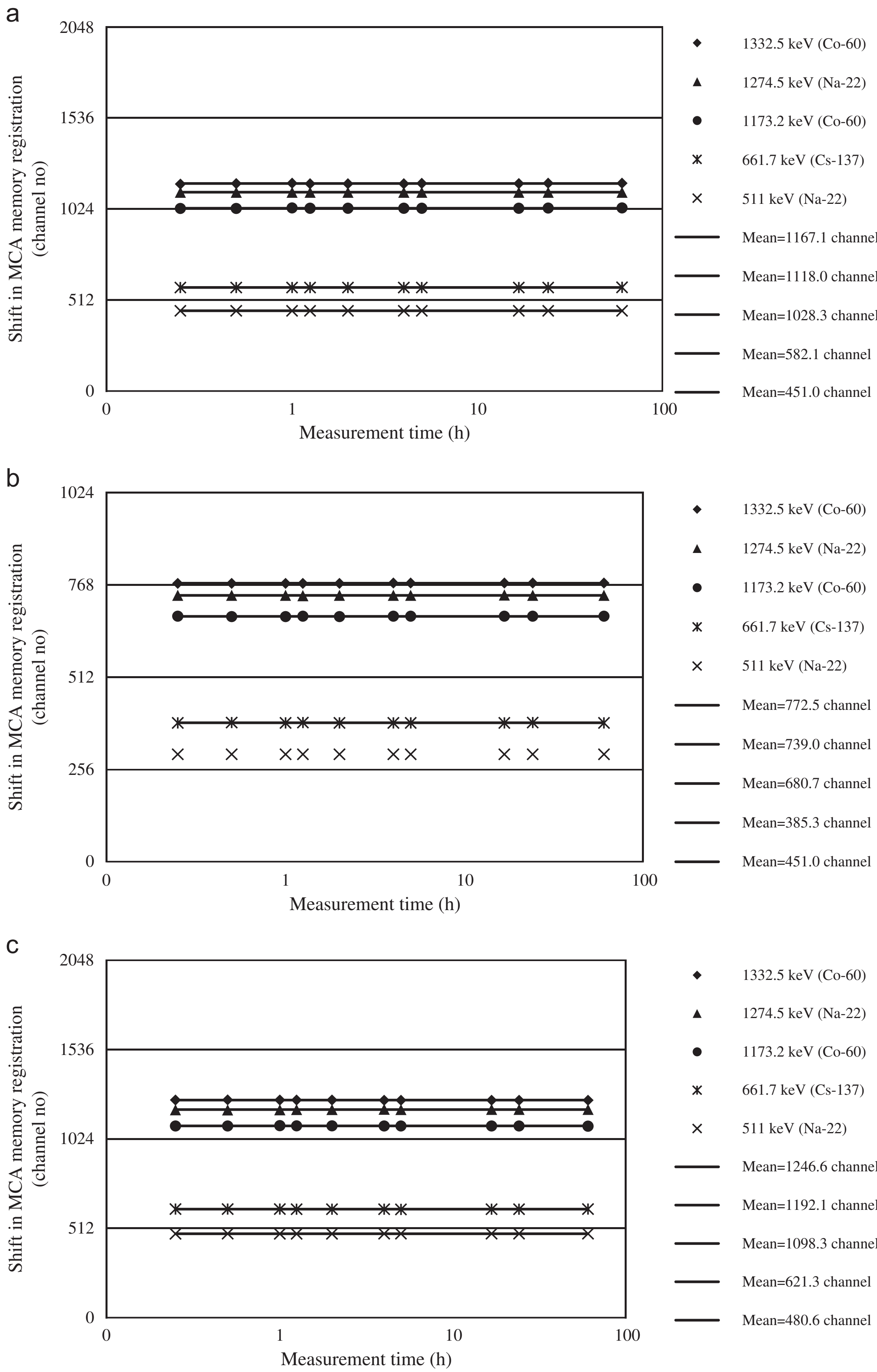

Fig. 1. Time stability of the coplanar grid CdZnTe detectors' response to various photon energies in terms of photopeak centroid shift.

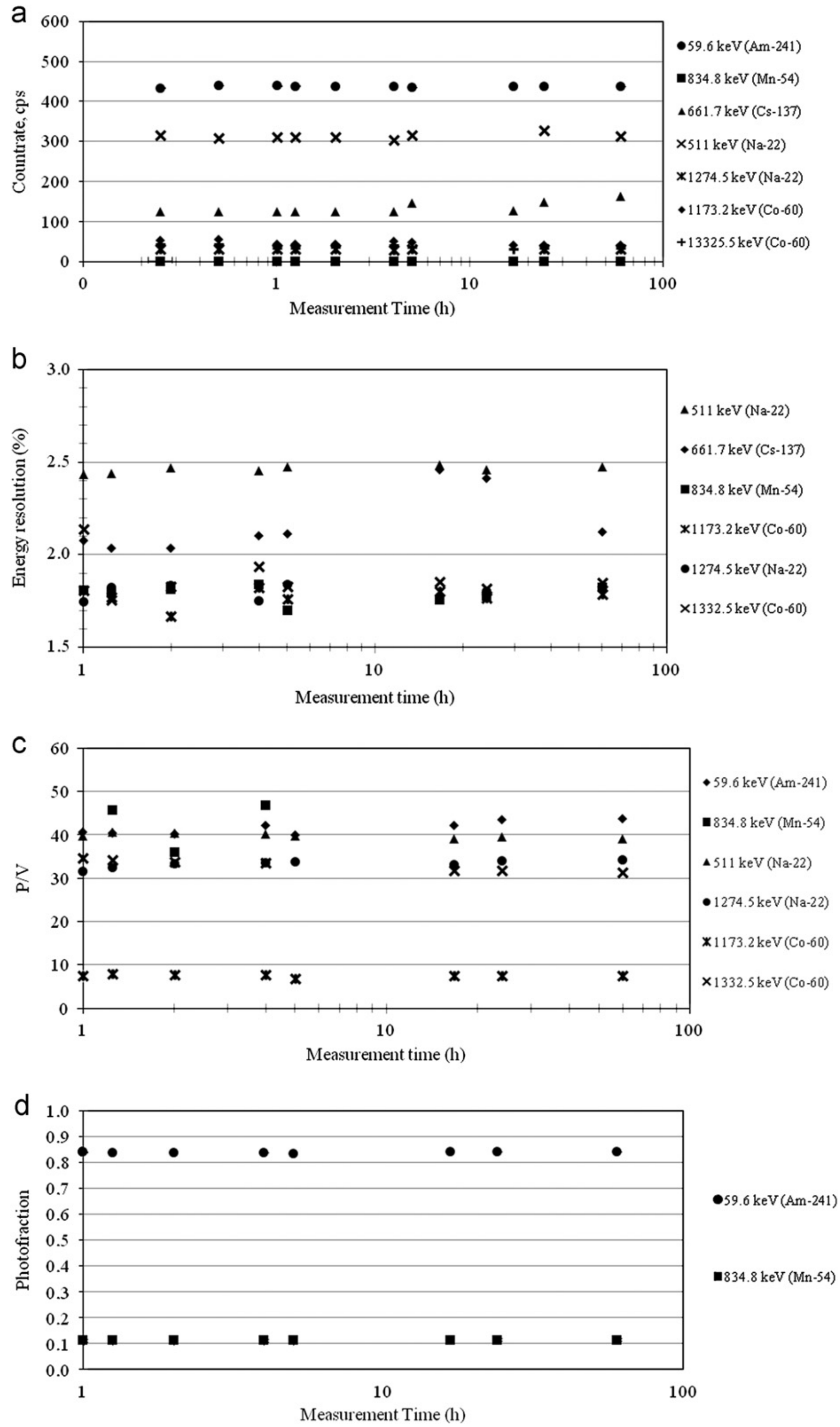

Fig. 2. Time stability measurements of a 2250 mm^3 CdZnTe detector's response to photon energies (a) Count rate vs time, (b) Energy resolution vs time, (c) Peak-to-valley vs time, (d) Photofraction vs time.

the peak-to-valley (*P*/*V*) ratio is defined for WBG detectors as the amplitude of the peak to the amplitude of the tail at a specified energy value; hence, this is another indication of the detector performance characteristics. The measure of the peak tailing in the low energy side of a full-energy peak is quantified in terms of *P*/*V* ratio. However, some *P*/*V* ratios were measured at the photon energies that are selected from almost clean peaks, which are distant from any other interfering peak. The *P*/*V* ratios of the present coplanar CdZnTe detectors are obtained for different photon energies using $0.5\times$ FWHM, $2\times$ FWHM, and $5\times$ FWHM left-side criteria, but only the *P*/*V* ratios determined from the $2\times$ FWHM distant left- side from the peak center are shown in

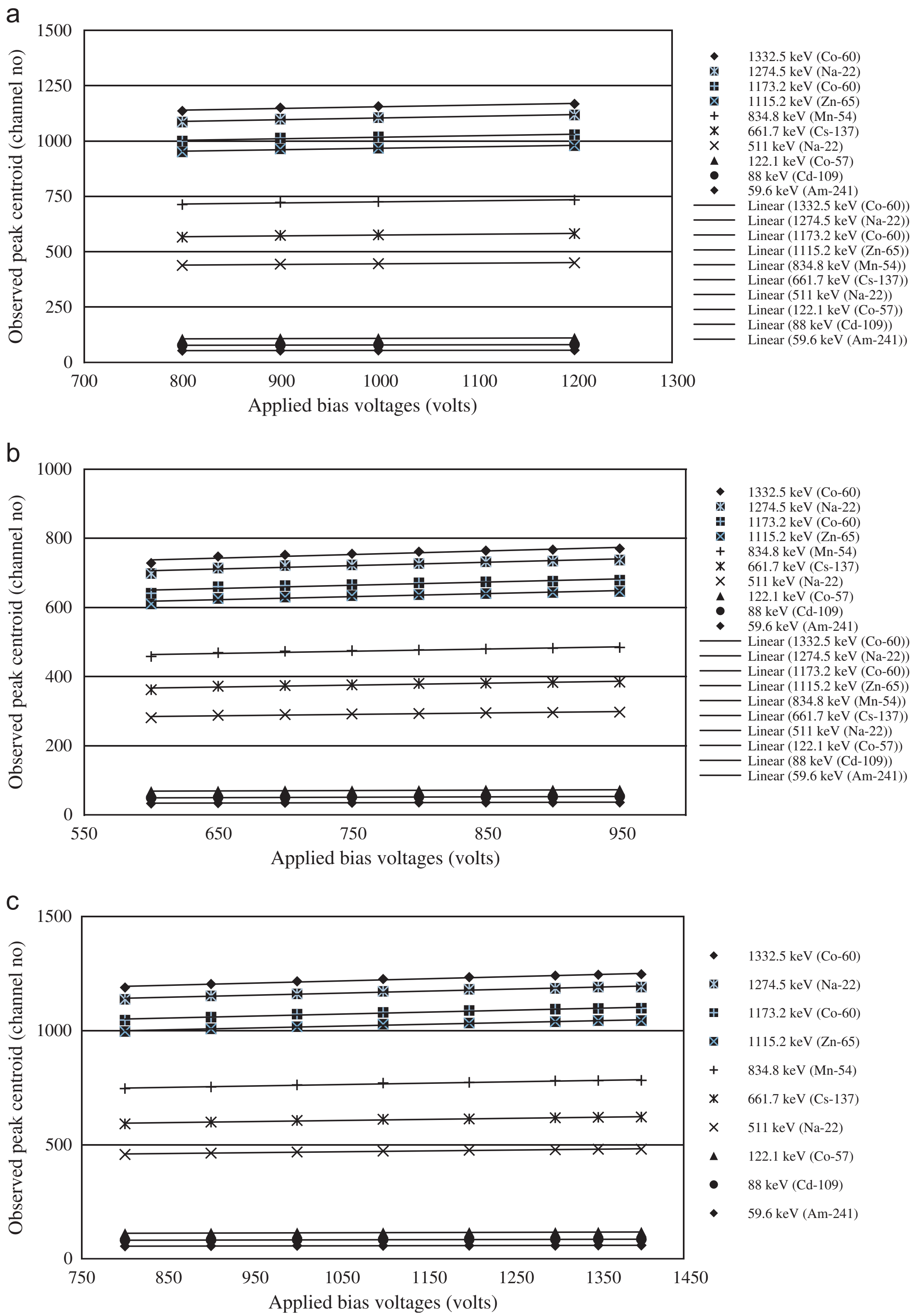

Fig. 3. Variations in peak centroids with increasing applied bias voltages for three coplanar grid CdZnTe detectors.

Fig. 2(c) as an example plot of a 2250 mm^3 detector. Secondly, the tailing is present in the spectrum of a mono-energetic peak if the ratio of FW.25M/ FWHM $> \sqrt{2}$, i.e., it is greater than 1.414 according to ANSI (2003). Hence, we also measured FW.25M besides the *P*/*V* ratio measurements, where FW.25M is defined as full width of a full-energy peak at quarter (1/4th) its maximum height above the background. The results for FW.25M and FW.25M/FWHMratio measurements at different photon energies ranging from 59.6 to 1332.5 keV are given in Table 2 for three coplanar grid CdZnTe detectors.

Table 2
Energy resolutions in FW.25M, FWHM and the ratio of FW.25M to FWHM for CdZnTe coplanar grid detectors.

Nuclide	Energy (keV)	1000 mm^3 CdZnTe			1687.5 mm^3 CdZnTe			2250 mm^3 CdZnTe		
		FW.25 M (keV)	FWHM (keV)	FW.25M/FWHM	FW.25M (keV)	FWHM (keV)	FW.25M/FWHM	FW.25M (keV)	FWHM (keV)	FW.25M/FWHM
^{241}Am	59.6	18.4 (32.0%)	13.2 (22.6%)	1.40	13.0 (30.0%)	8.8 (15.1%)	1.48	13.2 (22.3%)	9.1 (15.5%)	1.44
^{57}Co	122.1	19.5 (15.9%)	13.6 (11.1%)	1.44	12.6 (13.8%)	9.7 (8.0%)	1.31	12.5 (10.3%)	8.8 (7.2%)	1.42
^{137}Cs	661.7	25.0 (3.8%)	17.1 (2.6%)	1.46	23.5 (5.1%)	15.6 (2.4%)	1.51	21.1 (3.2%)	14.1 (2.1%)	1.50
^{54}Mn	834.8	26.9 (3.2%)	18.0 (2.2%)	1.49	27.2 (4.8%)	17.7 (2.1%)	1.54	24.1 (2.9%)	16.1 (1.9%)	1.50
^{65}Zn	1115.5	30.8 (2.8%)	20.3 (1.8%)	1.51	34.9 (4.7%)	22.2 (2.0%)	1.57	30.3 (2.7%)	19.9 (1.8%)	1.53
^{60}Co	1173.2	28.9 (2.5%)	19.5 (1.7%)	1.48	28.8 (3.5%)	20.8 (1.8%)	1.38	28.6 (2.4%)	19.4 (1.7%)	1.47
^{22}Na	1274.5	32.2 (2.5%)	21.2 (1.7%)	1.52	37.9 (4.4%)	24.2 (1.9%)	1.56	32.7 (2.6%)	21.4 (1.7%)	1.53
^{60}Co	1332.5	33.0 (2.5%)	21.3 (1.6%)	1.55	38.1 (4.1%)	24.6 (1.8%)	1.55	33.8 (2.5%)	22.1 (1.7%)	1.53

FW.25M: Full width of a peak at 1/4th its maximum height above the background. FWHM: Full width of a peak at half its maximum height above the background.

Tailing in low energy side of the photopeaks is generally observed in the spectra, obtained by wide-band gap (WBG) semiconductor detectors such as CdTe, CdZnTe and HgI_2. This is due to mainly the mobility-lifetime product, $\mu\tau$ of WBG semiconductors, thus making the charge carriers vulnerable to trapping (Knoll, 2000). This property of WBG semiconductors is inferior to that of Ge and Si. In addition to this, ballistic deficit that accompanies the collection of holes generated from the cathode results in a loss of signal height depending on event interaction point in the crystal. This deficit can also cause low-energy tailing (Knoll, 2000). The tailing effects due to mainly incomplete charge collection are observed noticeable in gamma-ray spectra when they obtained by a planar CdZnTe detector (Yücel et al., 2008). However, the present results for FW.25M/FWHM ratios given in Table 2 indicate that the requirement of FW.25M/FWHM > 1.41 is satisfactorily met by the present coplanar detectors, excepting a few ones. In fact, in quantifying low energy tailing of the full-energy peaks, the requirement of ANSI (2003) dictates the use of spectrum of a mono-energetic peak for the ratio of FW.25M/FWHM > 1.41, assuming that full-energy peak is almost Gaussian. However, in practice, it is possible that the more or less asymmetry exists in the photopeaks lying in especially high-energy regions of the spectra when they obtained by CdZnTe detectors. Nevertheless, it can be emphasized that the present coplanar detectors usually showed good peak shapes, i.e., almost near the Gaussian peak shapes.

The variations in the *P*/*V* ratios are shown in Fig.4 for three CdZnTe coplanar grid detectors when increasing the photon energies. The results seen in Fig. 4 indicate that the measured *P*/*V* ratios in the low energies below 200 keV are relatively worse than those *P*/*V* ratios in intermediate energy range of 400–800 keV. As whole, the results given in Table 2 and shown in Fig.4 indicate lack of peak tailing or negligible effect of hole charge carriers in the low energy side of any peak when the γ-ray spectra obtained by CdZnTe coplanar grid detectors, excepting some low and high energy regions. Normally, it is assumed that the dependence of the detector signal on hole transport is largely eliminated through the coplanar grid electrode structure, resulting in single charge (electrons only) sensing. However, some dependence on the hole transport could be possible that, if it is too poor, the trapped charge could lead to a polarization effect, for instance, the degradation in detector resolution could be occurred. In general, the present results imply that the CdZnTe coplanar grid detectors do not exhibit any polarization problems. That is, neither of the effects (degradation in resolution, counting rate and peak shift) appeared as a limiting factor for the present CdZnTe crystals having with coplanar grid anode structure. Additionally, separate measurements were also performed with use of ^{137}Cs source (661.6 keV) for periods of about one week. The peak positions and the counting rates for present coplanar CdZnTe detectors did not change extraordinarily with time over a period of about one week.

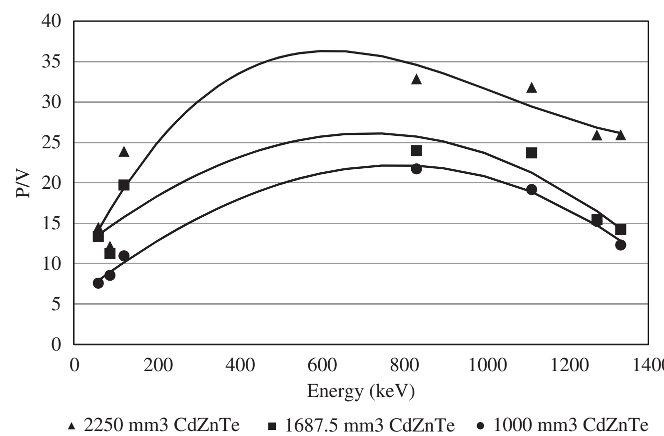

Fig. 4. Variations in peak-to-valley ratios with increasing energy for coplanar grid CdZnTe detectors.

4. Conclusions

In this study, the spectroscopic performances and characteristics of three large-volume CdZnTe coplanar grid detectors were investigated. Time stability of the coplanar grid CdZnTe detectors responses to various photon energies were evaluated in terms of photopeak centroid shift. In a long-term operation (a time span of from 100 h to 1 week), no polarization effect was observed in the present coplanar grid CdZnTe detectors. The low and high-energy responses at various bias voltages showed good performances at optimized operating voltages. For each detector, the measured performance data were evaluated by using the parameters: energy resolution in FWHM, peak tailing in peak-to-valley (*P*/*V*) ratio and in FWHM/FW.25M ratio, and photofraction of Gaussian to the total counts of the detector response of a mono-energetic peak (59.6 and 834.8 keV photons) from the acquired γ-ray spectra. The coplanar grid CdZnTe detectors show quite good spectroscopic performances to various γ-ray energies. The performance characteristics of the detectors are closely related to the material quality of CdZnTe detector. The results indicate that since a fundamental figure of merit for a semiconductor X-ray or γ-ray spectrometer is the mobility- product for electrons and holes, a further study should be performed on the electron $\mu_e\tau_e$ product value of CdZnTe coplanar grid detector to examine how the material quality affects its performance. Because the transport properties of charge carriers are important intrinsic parameters of the semiconductor materials.

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