CdTe and CdZnTe detectors for timing measurements

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Abstract— **We measured timing properties of CdTe and CdZnTe semiconductor detectors with planar configuration. We developed a new method to evaluate their performance in timing resolution utilizing an ^{241}Am doped plastic scintillator. We confirmed that the low mobility and short life time of holes are major obstacles to their timing resolution. However, their timing properties can be very much improved, either by applying a high electric field that increases the carrier speed, or by selecting those events which are dominated by the electron signal. We demonstrated the latter, through a pulse-shape discrimination technique using two different integration time constants. In conjunction with a newly developed CdTe diode, we obtained a superior timing resolution of 5.8 nsec. We also discussed the application of CdTe to Positron Emission Tomography, employing the standard 511 keV gamma-gamma coincidence method. We confirmed that a geometrical configuration in which the electrodes are parallel to the incident γ-rays gives about 3 time better timing response than a geometry when the electrodes are perpendicular to the γ-ray beam.**

Keywords— **CdTe, CdZnTe, Timing**

I. Introduction

ONE of the desired properties of radiation detectors is a fast timing response. So far, scintillator detectors have been applied successfully to various timing measurements [1] because their response and recovery times are short relative to those of other types of detectors. However, semiconductor detectors are becoming more attractive in other features, e.g. in energy and spatial resolutions. It is hence of importance to explore the fast-timing aspects of semiconductor detectors [2].

The high stopping power of CdTe and CdZnTe make them attractive for X-ray and γ-ray spectroscopy. In addition, their large band gaps and resultant low leakage currents ensure a high energy resolution at room temperature [3]. Therefore, CdTe and CdZnTe detectors are now widely regarded as a new promising semiconductor devices [4][5]. However, their application to high-time-resolution measurements has not yet been well explored.

Accordingly, we have measured the timing properties of a few samples of CdTe and CdZnTe detectors. For this purpose, we have selected two CdZnTe detectors, hereafter called CdZnTe-1 and CdZnTe-2, from a large number of samples grown by eV Products using the high-pressure Bridgman method (HPB). They both have a dimension of $4 \times 4 \times 2$ mm^3. We also selected one CdTe detector of the same size, from those grown by ACRORAD using the traveling heater method (THM). The CdTe detector has a Schottky junction, which drastically reduces the leakage current [6].

We succeeded to deduce the timing properties of these detectors by conventional method, such as α-particle and a pair of 511 keV γ-rays, and also contrive a new method, based on continuously α and γ decay of ^{241}Am. Furthermore, by utilizing a pulse-shape selection, we discussed the contribution of electrons and holes to the timing measurements.

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II. The rise time of CdTe and CdZnTe

A semiconductor detector produces the signal according to the transit of electrons and holes [7]. If the two types of carriers show the different mobilities significantly, the rise time depends on the place of the interaction. The resultant dispersion in the pulse profile usually limits the timing resolution of a semiconductor detector.

In order to study general timing properties of samples (CdTe, CdZnTe-1 and CdZnTe-2), we first irradiated them with 5.5 MeV α-particles from ^{241}Am. As discussed in [8], we can study the electron and hole transfer effects separately by irradiating from the cathode and anode side, respectively because of a very short range of α-particles (within 10 μm). In order to minimize the effect due to the energy loss in the air, we placed the α-particle source at a fixed distance from the detector. To suppress the long-term degradation ("polarization"), which is often observed by CdTe diode [6], all detectors were kept at a temperature of ~ 0°C and measured with short exposure times (within 10minutes). The signal was read out by a charge-sensitive amplifier (CSA) CP 5539 produced by CLEAR-PULSE, which has a fast rise time of a few nsec. We recorded the CSA output signals directly by a digital scope.

Fig.1 shows the waveforms of the CSA output from the three detectors, measured at various bias voltages between 100 V and 500 V. The 10%–90% rise times are also given there. As expected, higher bias voltages give shorter rise times and higher pulse heights. The hole signals from CdZnTe exhibit significantly lower pulse heights and longer rise times than those from CdTe, in agreement with the lower $\mu\tau$ product measured for CdZnTe [9]. The hole signals of CdZnTe have such dull waveforms that we can no

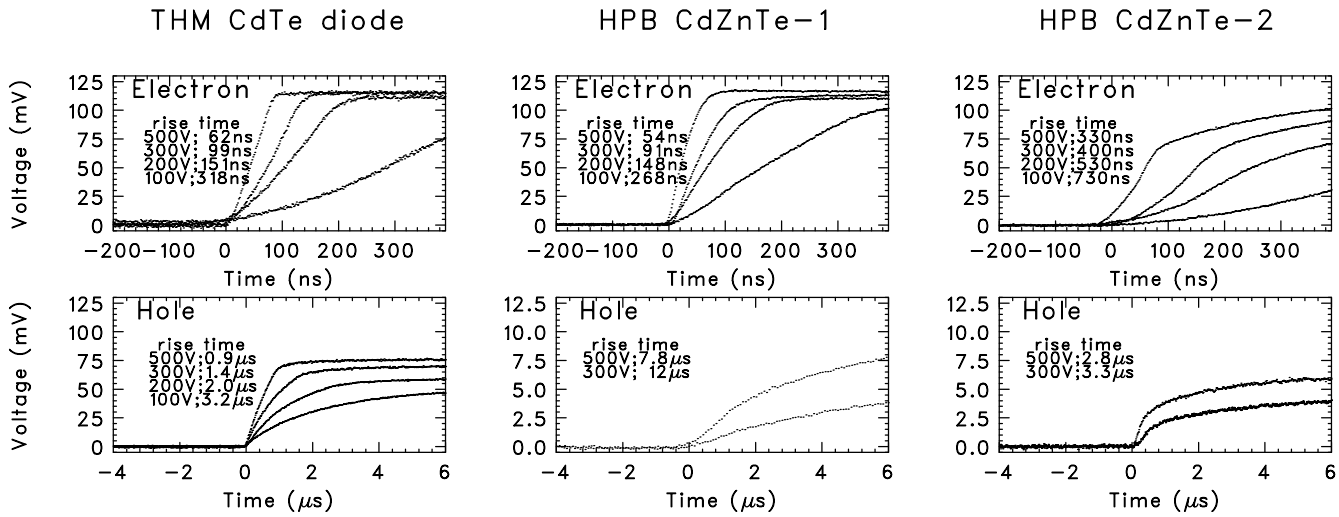

Fig. 1. The ensemble-averaged CSA output signals of CdTe (left), CdZnTe-1 (middle), and CdZnTe-2 (right), obtained in the α-particle measurement. Each waveform is average over 100 events. The top (bottom) three panels correspond to the anode (cathode) irradiation, where the signal is dominated by the electron (hole) transit. The inset numbers indicate the 10%–90% rise time. The ordinate scale (mV) of the hole transfer of CdZnTe is 10 times smaller than in the other panels.

longer measure their rise times under low bias voltages. In addition, the two CdZnTe detectors exhibit significantly different responses. Presumably, CdZnTe-2 has a larger number of material defects than CdZnTe-1, and hence a severe electron trapping effect. We therefore use only the CdTe diode and the CdZnTe-1 detector for the timing measurement.

The carrier mobility is one of the important elements to determine the timing properties, therefore we try to evaluate the electron and hole mobility of the samples. The carrier transfer properties in semiconductor devices are described by the Hecht equation [10], which yields the $\mu\tau$ product by taking into account the effect of carrier trapping and depth dependence. In the present case, however, the signal is dominated by a single carrier component because the interaction takes place at the surface. Therefore, the mobility μ can be evaluated in a simple way, using the relation

$$t_i = 0.8d/w = 0.8d/(E\mu_i) = 0.8d^2/(V\mu_i) \quad .$$

Here, t is the measured rise time, d is the thickness of the device , V is the bias voltage, $E = V/d$ is the electric field which is assumed to be constant, and $w = E\mu$ is the carrier drift velocity; the suffix i stands for either electron (e) or hole (h), and the factor 0.8 reflects that t is defined at 10%–90%.

Using this relation, we have evaluated the electron mobility (μ_e) of CdTe and CdZnTe-1 as $\sim$ 1040 cm^2 V^{-1} s^{-1} and $\sim$ 1160 cm^2 V^{-1} s^{-1}, respectively. These values did not change when we varied the bias voltage over V = 100–500 volts. At lower voltages (V $<$ 200 V), the measured value of μ_e becomes unreliable, because the electron trapping effect becomes significant. Similarly, the hole mobility (μ_h) turned out to be $\sim$ 70 cm^2 V^{-1} s^{-1} for the CdTe diode, and $\sim$ 20 cm^2 V^{-1} s^{-1} for CdZnTe-1. These values of μ_e and μ_h roughly agree with those reported previously [9], except for holes of CdZnTe-1 because we cannot obtain the reliable data at lower bias voltage.

Apparently, the high electric field is indispensable for obtaining the fast rise time. Therefore the low leakage current at high electric field is very important. In order to demonstrate this, we measured a CdTe diode with a dimension of $2 \times 2 \times 0.5$ mm^3 at a bias voltage of 1000V. With this thickness, we measured a very fast rise time of $\sim$ 3.5 nsec when the α-particle irradiated from the cathode side. This is a factor of 18 improvement over the fastest rise time (62 nsec) obtained in Fig.1, although the improvement should ideally be a factor of 32 because the device is 4 times thinner and the internal electric field is 8 times stronger: other factors, e.g., the circuit speed, begins to affect the timing properties.

The fundamental timing properties of CdTe and CdZnTe, such as a response time of carriers, have been understood in this section. On the basis of this measurement, we investigated the timing resolution, which is defined by a dispersion of a response time.

III. ^{241}Am α-γ coincidence method

The γ-ray energy range below a few hundred keV is very important for the medical [1] and astrophysical field, where CdTe and CdZnTe is particularly useful. However, the study of the timing resolution of CdTe and CdZnTe in this energy range have not been well studied. Therefore we have developed a method of timing measurement, using a plastic scintillator doped with ^{241}Am radio isotope (tagged source). In ^{241}Am each α-decay is accompanied by the emission of a 59.5 keV γ-ray with a half-life of 67 nsec, via a transition from the J$^\pi$= 5/2$^-$ excited state to the J$^\pi$= 5/2$^+$ ground state.

By using light signals from plastic scintillator emitted by the passage of α-particle as a start signal ($t_{\rm start}$), we can use 59.5 keV γ-rays detected by the CdTe/CdZnTe detector as

a stop signal ($t_{\rm stop}$).

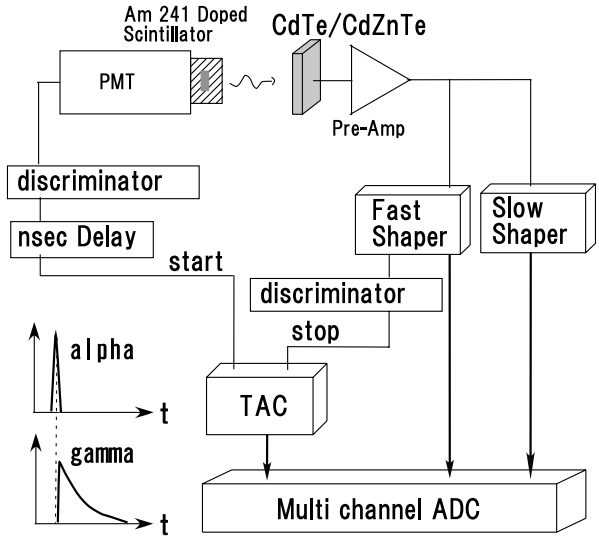

Fig. 2. Experimental setup of timing measurement using the ^{241}Am tagged source.

As shown in Fig. 2, the distribution of the interval Δt = $t_{\rm start}$ − $t_{\rm stop}$ gives the timing resolution of the system ("α–γ coincidence method"). The doped plastic scintillator is coupled to a high-speed photomultiplier (H6780; Hamamatsu), yielding a rise time of $\sim$ 1 nsec for α-particles. The γ-ray signal is then detected in CdTe or CdZnTe. The signal is processed by a charge-sensitive amplifier (CP580s1; CLEAR-PULSE) and a shaping amplifier (579; ORTEC) with a shaping time of 100 nsec. The output signal is discriminated by a SCA (552; ORTEC) and sent to a TAC (567; ORTEC). This setup also provides a timing resolution of $\sim$ 700 psec for the test pulse.

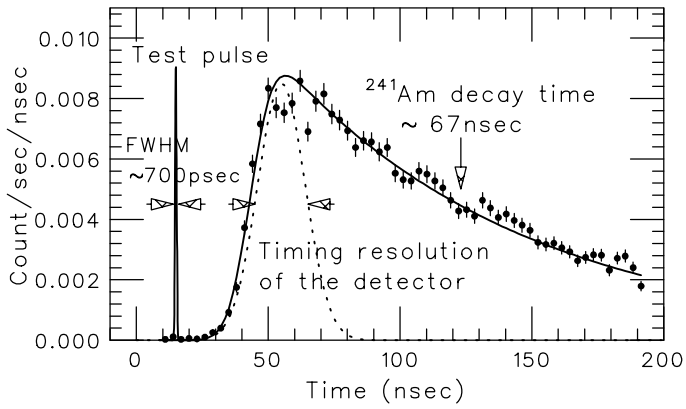

Fig. 3. A time spectrum (the TAC output) of CdZnTe-1 measured with the ^{241}Am α-γ coincidence method, at a bias voltage of 500 V. The solid line shows the exponential model convolved with a Gaussian.

In an ideal detector with infinite timing resolution, the obtained "time spectrum" should exhibit a sharp rise at time zero, followed by an exponential decay with a time constant of 67 nsec, which is the half-life of 59.5 keV γ-rays. The measured time spectrum, presented in Fig.3, shows the expected exponential decay, but the rise time is smeared due to the finite timing resolution of the detector. This smearing corresponds to the timing resolution of the detector. In practice, we fitted the time spectrum with the exponential decay convolved with a Gaussian, and measured the timing resolution of the detectors.

As summarized in Fig.4, the timing resolution of CdTe diode and CdZnTe-1 detectors improves as the bias voltage is increased. Since the CdTe diode can be operated at 800 V with a leakage current $<$ 0.5 nA, the FWHM resolution reaches 12 nsec.

In CdTe and CdZnTe detectors, the timing resolution is determined mostly by the pulse shape, which consists of the mixture of electrons and holes. Therefore it is important to study how the slow holes contribute to the signal. Since we utilize the fast shaping time (100 ns) in this experiment, the contribution of the holes is reduced. Therefore, the timing resolution is thought to be determined mainly by event-by-event variation of the electron rise time. The rise time of the electrons is inversely proportional to the bias voltage (V). Therefore we expect the timing resolution itself to be proportional to $1/V$. Actually, the resolution of the CdZnTe-1 shown in Fig.4 can be approximately expressed as the above relation. Furthermore for CdZnTe-1, the small pulse height of the hole event as shown in Fig. 1 is also supported by the assumption that Δt is decided mainly by the electron movement. In Fig. 4, the behavior of CdTe diode needs some caution: it looks like that the proportionality between Δt and 1/V did not satisfy the relationship. One possibility is that the hole component comparatively affects the timing resolution because the pulse height and rise time of holes of CdTe diode is higher and faster than that of CdZnTe-1.

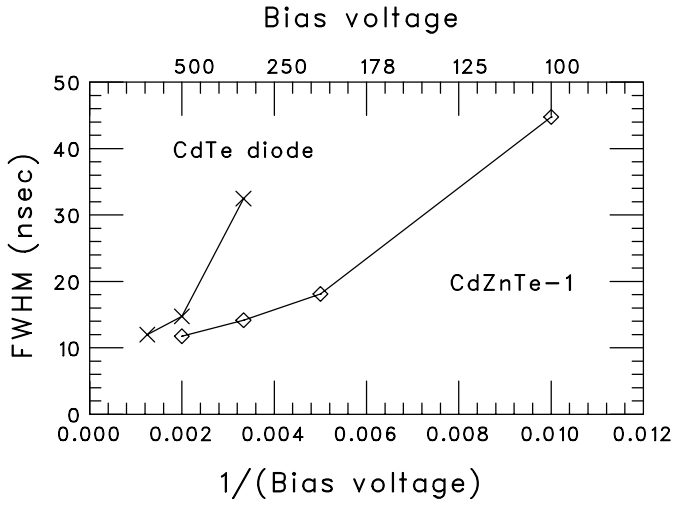

Fig. 4. The timing resolution (Gaussian FWHM) of the CdTe diode and the CdZnTe-1 detector, measured with the ^{241}Am α–γ coincidence method and shown as a function of 1/V.

IV. Pulse-shape selection with dual shaping times

In order to perform the further investigation of the effect due to the difference between the hole and electron mobility, we utilized the pulse-shape analysis by means of dual shaping times. The technique was previously employed to improve the energy resolution of HgI_2 [11][12]. With this technique, we can study the timing resolution with respect to the shape of the signal.

As shown in Fig.2, the CSA output is split into two (fast and slow) shaping chains with different time constants. Outputs from the two shaping amplifies are then sent to the multi-channel ADC, where they are converted into two pulse heights ("slow PH" and "fast PH"), which are recorded together with the TAC output. We set the "fast" shaping time at 100 nsec, so that a large fraction of the electron signal can be integrated whereas the hole signals are strongly attenuated. We set the "slow" shaping time at 3 μsec, which is slow enough even for the hole signals to be fully integrated. Consequently, the ratio between the slow PH and the fast PH becomes ~ 1 and < 1 for the electron-dominant and hole-dominant events, respectively.

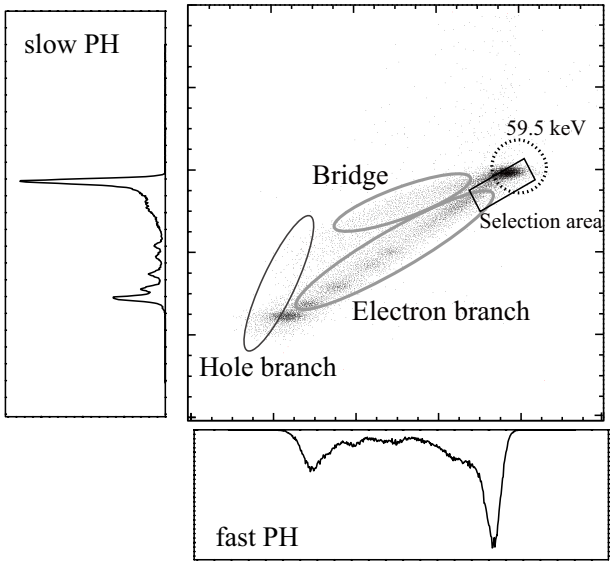

Fig. 5. Typical 2-dimensional energy spectrum of CdZnTe-1 at a bias voltage of 500 V, irradiated with ^{241}Am from the cathode face. The fast and slow shaping times are 100 nsec and 3 μsec respectively. The "branches" indicate the electron and hole dominant components, and "bridge" is their mixture. "selection area" is electron dominant region used when improving the timing resolution. Left and bottom insets show the energy spectra with the slow and fast shaping amplifier, respectively.

Fig.5 shows an example of "2-dimensional spectrum", where the slow PH of each event is plotted against its fast PH (slow-fast plane). This particular spectrum was obtained by irradiating CdZnTe-1 (thickness of 2 mm) with ^{241}Am from the cathode side. The darkest region in the plot corresponds to the photo-peak of the 59.5 keV γ-rays, from which a straight branch is seen to run to the lower left. This is "electron branch" (slow PH = fast PH), where the signal is dominated by the electron transfer. The corresponding "hole branch" (slow PH >> fast PH) is less clearly seen, because a 59.5 keV γ-ray is absorbed within $\sim$ 1 mm from the cathode. Furthermore, a "bridge" is formed between the two branches, because the electron and hole contributions vary according to the interaction depth in the detector.

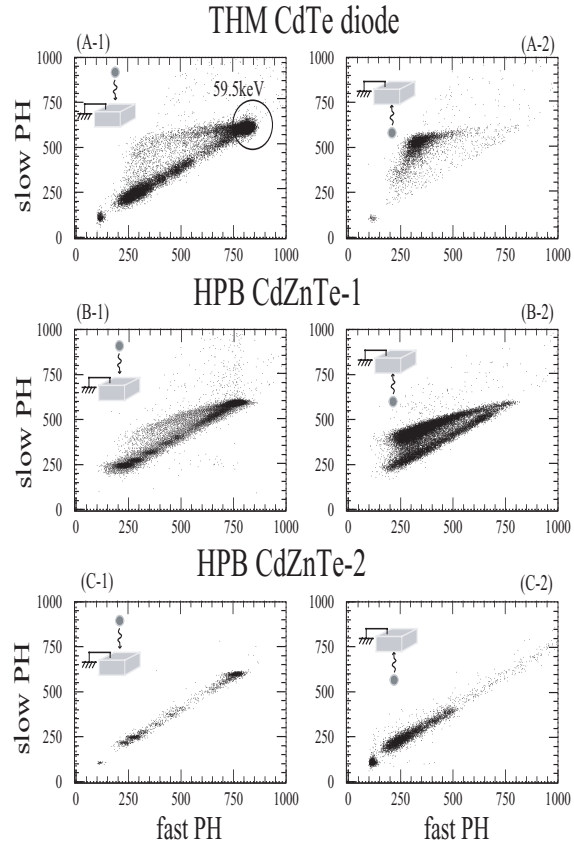

Fig. 6. The 2-dimensional ^{241}Am energy spectra of the THM CdTe and HPB CdZnTe (1,2) detectors under the same condition as Fig.5. The γ-rays are irradiated from the cathode face for the left panels (A-1, B-1, C-1), and from the anode face for the right panels (A-2, B-2, C-2). In the left panel, the 59.5 keV photons forms a photopeak at (x,y) $\sim$ (850, 600).

We applied this method to the CdTe diode and the two CdZnTe detectors. Fig.6 shows their 2-dimensional ^{241}Am spectra, irradiated from the cathode side (left) and the anode side (right). The spectra of CdTe clearly show the two branches; the electron branch in the cathode-irradiation spectrum (A-1), and the hole branch in the anode-irradiation one (A-2). Although the CdZnTe-1 spectra look similar to those of CdTe, the angle between the "electron branch" and "bridge" is somewhat different. This is because the "hole branch" of CdZnTe-1 shows the lower pulse height with both shaping time than that of CdTe, as a result of the lower $\mu_h\tau_h$ of CdZnTe-1.

The result of CdZnTe-2 looks still more different, and there is no indication of slow signals. Actually, the two branches almost overlap. A possible explanation is that τ of CdZnTe-2 is very low (Fig.1), and hence the hole contri-

bution to the signals is very small.

Since we have successfully separated the contributions from electrons and holes on the two dimensional slow-fast plane, we can study how the transit of holes and electrons affects the timing resolution separately. For this purpose, we defined a region on the slow-fast plane, as indicated by "selection area", shown in Fig.5. The "selection area" is the region that the electron is dominant because the γ-ray interaction took place in the surface of the cathode side. An acceptance efficiency of the "selection area" is 75% to almost all 59.5 keV event. This value is consistent with the efficiency of CdTe with a thickness within 1 mm to 59.5 keV γ-ray.

We then produced two time spectra, one formed by all events above the lower discriminator, while the other by events in the "selection area". In Fig.7, it is clearly shown that the events inside "selection area" has better timing resolution in comparison with an event selected only by the output of fast shaping. The timing resolution is improved from 17 ns to 8.5 ns. The same results are obtained by the data from the CdTe diode, as shown in Table I.

We applied the selection to the Schottky CdTe diode with a thickness of 0.5 mm, and obtained the better timing resolution of 5.8 nsec with a high bias voltage of 1000V.

The two-dimensional plot in this study could be used to improve the timing resolution instead of the reduction events, which have some contribution of the "hole branch". It is possible that we can correct the timing of each event with respect to its position on the slow-fast plane, based on a fact that the arrival times of hole-richer events is earlier. Actual application of this idea is one of our future tasks.

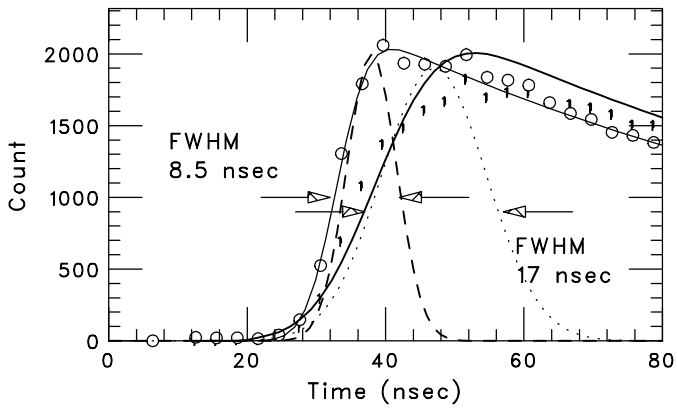

Fig. 7. TAC output of the CdZnTe-1 at a bias voltage of 500V, before and after the pulse shape selection.

TABLE I

Obtained timing resolution. before and after the 2-dimensional pulse selecting respectively.

	CdZnTe	CdTe diode	
	$4\times4\times2\text{mm}^3$	$4\times4\times2\text{mm}^3$	$2\times2\times0.5\text{mm}^3$
(A)	17ns	13ns	10ns
(B)	8.5ns	9.8ns	5.8ns

V. 511 keV γ-γ coincidence method

Positron Emission Tomography (PET) is one of the most attractive fields for the application of CdTe and CdZnTe detectors [13][14]. PET make uses of coincident detection of a pair of 511 keV positron-annihilation γ-ray lines. To reduce the background due to accidental coincidences, good timing resolution is very important [1]. Therefore, we studied the timing response of the CdTe diode and CdZnTe detector for simulating the actual environment for PET applications.

In this experiment, 511 keV γ-rays from a ^{22}Na radioactive source are detected simultaneously with two detectors. A pair of γ-ray signals are sent to the TAC module after signal processing, and their timing difference is measured. For this study, we adopt the detector with the fastest rise time among our samples, namely the CdTe diodes.

First of all, we search for the optimum set of parameters, such as bias voltage, the thickness and the size of the detectors. We changed the input bias voltages from 300 V to 800 V, and measured the width of the TAC output spectrum. The FWHM time dispersion was 38 nsec at 300 V, and 25 nsec at 800 V. We also evaluated the thickness of CdTe diode, using 0.5 mm, 1.0 mm, and 2.0 mm. The thinnest one(0.5 mm) gave the best result. These are consistent with our results presented in section II, that a high bias voltage and a thin device ensure a good time response. Therefore, we use the $5\times5\times0.5$ mm^3 CdTe diode at a bias voltage of $\sim$ 800 V.

In the next step, we studied two geometrical configurations shown in Fig.8: one is the ordinary face-on geometry (A), and the other is edge-on geometry (B). Fig.9 compares the measured TAC spectra applying these two geometries. The FWHM dispersion in setup (B) is 9 nsec, which significantly improves over that of (A), 25 nsec.

The timing dispersion mainly arises from the position dispersion where the 511 keV γ-ray is absorbed. In the face-on geometry, the interaction point scatters almost uniformly between the anode and cathode, producing a large scatter in the signal rise times. In this case, the distance of the two interaction points, X_{f1} and X_{f2} as defined in Fig.8, are distributed as

$$0 < X_{\text{f1}} < W, 0 < X_{\text{f2}} < W, \tag{1}$$

where W is the device thickness. In contrast, the edge-on geometry ensures that the two back-to-back γ-ray photons are absorbed at similar depths in the two detectors. The two interaction points are nearly distributed as

$$W/2 < X_{\text{e1}} < L_{\text{e1}}, L_{\text{e2}} < X_{\text{e2}} < W/2, \tag{2}$$

as defined in Fig.8. Thus, the position dispersion is expected to be smaller.

We attempted to confirm this interpretation by a simple calculation. We assumed that the system is set in two dimensions, and the internal electric field is uniform. We can also consider the RI size of 1 mm, the absorption probability, and the actual distance from the source to the detectors. Under this assumption, we calculated the probability

distribution of the photon interaction, as a function of the distance between the interaction point and the electrode. The distance was converted to the carrier drift time by assuming a simple proportionality. The result shown in Fig.10 actually confirms that the edge-on geometry provides a better timing resolution.

From these results, we expect that a stack of thin (~ 0.5 mm) CdTe devices, arranged in the edge-on geometry, will achieve a good timing resolution down to <10 nsec when operated under a high bias voltage. In addition, the edge-on geometry allows a higher quantum efficiency, although it suffers from a smaller solid-angle than the face-on geometry. Therefore, there is a much space for trade-off between the two geometries, depending on the required timing resolution and sensitivity.

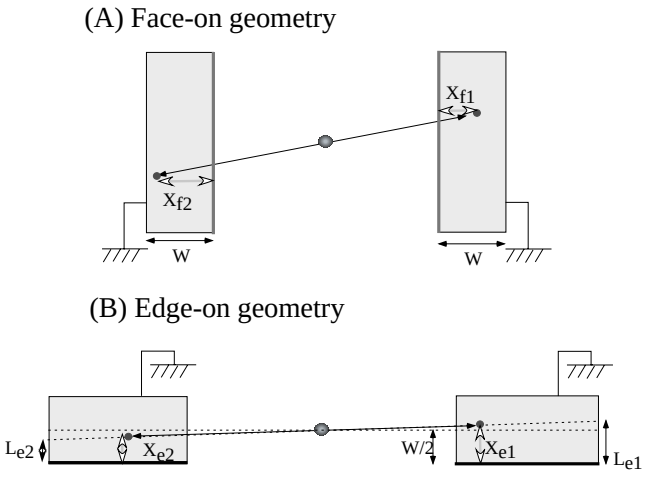

Fig. 8. The setup geometry of the γ-γ coincidence method. Top panel shows the usual configuration, while bottom panel shows our method.

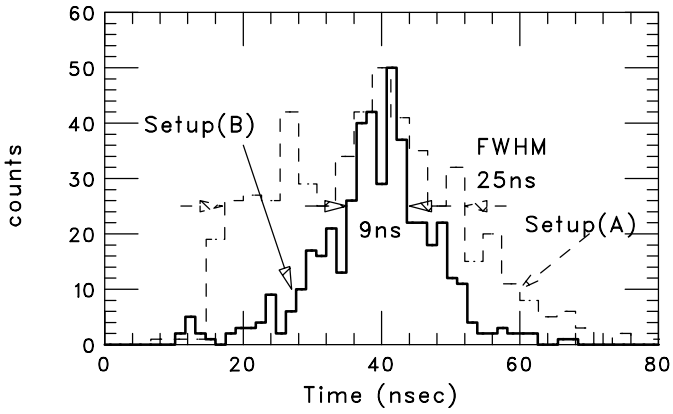

Fig. 9. TAC output of a CdTe detector with dimension 5×5 mm$^2\times0.5$ mm, for the 511 keV signal. The bias voltage is 800 V. The two geometries shown in figure 8 are compared.

VI. Conclusions

We studied the timing resolution of CdTe and CdZnTe detectors. The pulse profile of the thin (0.5 mm) CdTe diode detectors, measured with α-particles, showed a superior rise time of 5.8 nsec under a bias voltage of 1000 V. In order to measure the timing resolution below a few hundred keV, we have developed a ^{241}Am α-γ coincidence method, and successfully evaluated and applied it to a few samples of CdTe and CdZnTe detectors. To separate the electron and hole signals, we used the method of pulse-shape analysis based on dual shaping amplifiers. We find that 75% of the total event is electron dominant, and it shows the better timing resolutions. As a result, about 5.8 nsec (FWHM) was achieved with the 0.5 mm thin CdTe diode detector. Using this method, we can study the difference between CdTe and CdZnTe detectors.

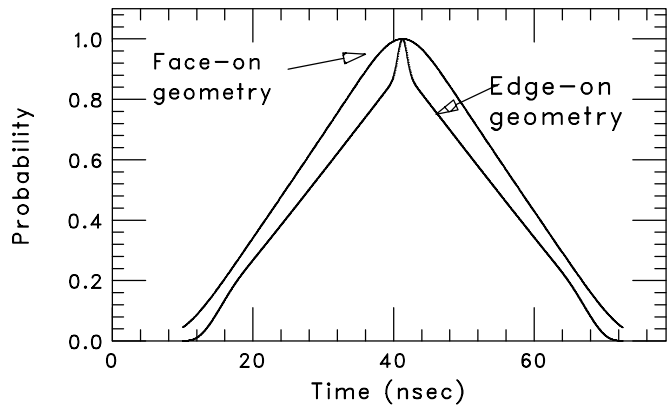

Fig. 10. Probability distribution of the timing differences between a pair of 511 keV photons, calculated for the two geometries of figure 8.

We studied the performance of CdTe against the 511 keV back-to-back γ-rays considering the PET applications. We confirmed that a geometrical arrangement in which electrodes are parallel (edge-on) to the incident γ-rays gives 3 time better timing resolution than an arrangement in which electrodes are perpendicular (face-on) to the γ-ray beam.

These results indicate that CdTe and CdZnTe are promising candidates for the future timing measurements using semiconductor detectors.

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