ANALYSIS OF CHARGE COLLECTION EFFICIENCY FOR A PLANAR CdZnTe DETECTOR

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The response property of the CZT detector (5 × 5 × 5 mm³), widely used in photon spectroscopy, was evaluated by considering the charge collection efficiency, which depends on the interaction position of incident radiation. A quantitative analysis of the energy spectra obtained from the CZT detector was also performed to investigate the tail effect at the low energy side of the full energy peak. The collection efficiency of electrons and holes to the two electrodes (i.e., cathode and anode) was calculated from the Hecht equation, and radiation transport analysis was performed by two Monte Carlo codes, Geant4 and MCNPX. The radiation source was assumed to be 59.5 keV gamma rays emitted from a ^{241}Am source into the cathode surface of this detector, and the detector was assumed to be biased to 500 V between the two electrodes. Through the comparison of the results between the Geant4 calculation considering the charge collection efficiency and the ideal case from MCNPX, an pronounced difference of 4 keV was found in the full energy peak position. The tail effect at the low energy side of the full energy peak was confirmed to be caused by the collection efficiency of electrons and holes. In more detail, it was shown that the tail height caused by the charge collection efficiency went up to 1000 times the pulse height in the same energy bin at the calculation without considering the charge collection efficiency. It is, therefore, apparent that research considering the charge collection efficiency is necessary in order to properly analyze the characteristics of CZT detectors.

KEYWORDS : Semiconductor Detector, CdZnTe, Hecht Equation, Charge Collection Efficiency, Tail Effect

1. INTRODUCTION

The use of semiconductor detectors has been gradually increasing to measure high-energy electrons or gamma rays in various radiation detection applications. Because the densities of semiconductor materials are about 1000 times greater than gas or other detection materials, the dimensions of semiconductor detectors can be reduced much more than the equivalent gas-filled detector [1]. Also, for imaging devices, their good energy resolution and ability to manufacture compact arrays are very attractive features in comparison with inorganic scintillation detectors [2].

Among the most popular semiconductor detectors, the cadmium zinc telluride (CZT) has been an excellent candidate for the detection of gamma rays because it has combined a relatively high atomic number (Cd^{48}, Zn^{30}, and Te^{52}) with sufficient bandgap energy (1.52 eV) to permit room temperature operation. Also, the CZT detector has a relatively high cross section for the photoelectric absorption of gamma rays, which is required to efficiently convert the radiation energy to electrical energy. Hence, semiconductor detectors made of CZT have been employed in scientific and technological fields, most notably in medical imaging and high energy astrophysics [3].

However, due to the low transport properties of carriers, electron-hole pairs generated in a CZT sensor by irradiated radiations cannot be completely collected in each electrode (cathode and anode)[4]. Eventually, this problem leads to a significant distortion of the spectrum and tail effect at the low energy side of the full energy peak. Therefore, additional considerations for charge drift in the semiconductor and charge induction on the electrodes are required to accurately simulate the radiation response of the CZT detector, and, thus, to fully understand the characteristics of the detector.

In this study, the mobility-lifetime parameter ($\mu\tau$) of the carriers was used to investigate the characteristics of this planar CZT detector; this parameter is a fundamental material property which is very useful to describe the transport of charge carriers [4] because it is proportional to the distance of electron or a hole travels before becoming trapped. The Hecht model [5] was also employed which is mainly used to calculate the charge collection efficiency for a planar CZT detector [4,6]. The evident difference of energy spectrum caused by considering the charge collection efficiency was evaluated for a CZT detector ($5 \times 5 \times 5$ mm^3) using the Monte Carlo codes (Geant4 [7] and MCNPX [8]). The Monte Carlo method is a well-established one with respect to the calculation accuracy for a random walk, such as the particle transport in the radiation detector. Hence, Geant4 and MCNPX codes were used to simulate the energy spectrum of incident radiations [7]. The tail effect at the low energy side of the full energy peak was also quantitatively analyzed to investigate the characteristics of the energy spectrum obtained from the CZT detector.

2. CALCULATION OF ION-PAIR DISTRIBUTION AND ELECTRIC FIELD

The number of electron-hole pairs and the interaction positions are very important to calculate the charge induction on the electrodes; hence, the MCNPX code is employed to simulate the transport of incident and scattered gamma rays and secondary electrons. The radiation source was assumed to be perpendicularly incident on the planar detector from ^{241}Am (59.5 keV gamma ray) and was located 1 m away from the negative contact (cathode). The electron-hole pairs are generated from the energy loss of the incident radiation in the CZT sensor; the deposited energy to the detector is converted to the number of electron-hole pairs by dividing the deposited energy with ion-pair creation energy of 4.6 eV. The selected CZT detector (Cd=45 %, Zn=5 %, and Te=50 %) manufactured by eV PRODUCTS was composed of two electrodes (100 nm platinum) and CZT crystal and has the preferred size of $5 \times 5 \times 5$ mm^3 for the measurement of gamma rays. In this case, the calculation of ion-pair distribution in the CZT detector was performed under the configuration shown in Figure 1.

The number of ion-pairs generated as a function of CZT depth was calculated by MCNPX, as shown in Figure 2. The spatial distribution of ion-pairs produced in the CZT sensor was also shown in the figure. It is confirmed that most energy loss (~98 %) is caused by the photoelectric effect; other interactions are caused by Compton scattering. It can be also seen that the number of generated electron-hole pairs is exponentially decreased along with the penetration depth of radiation, and electron-hole pairs are mainly produced within a 2 mm depth from the cathode. In fact, based on the spatial distribution of generated ion-pairs, it is found that most of carriers are concentrated within a 0.3 mm depth from the cathode surface.

The electrons and holes created by the radiation interactions move to the anode and cathode, respectively, under the influence of an electric field supplied by the bias potential. The electric field influences the mean free path of electron-hole pairs, trapping-detrapping, and recombination [9]; accurate analysis of the electric field distribution in the detector is required to simulate its energy response. In this study, calculations of electric field distribution are performed in two dimensions because the geometry of the planar detector is very simple and unchanged in the whole area of the detector; hence, the

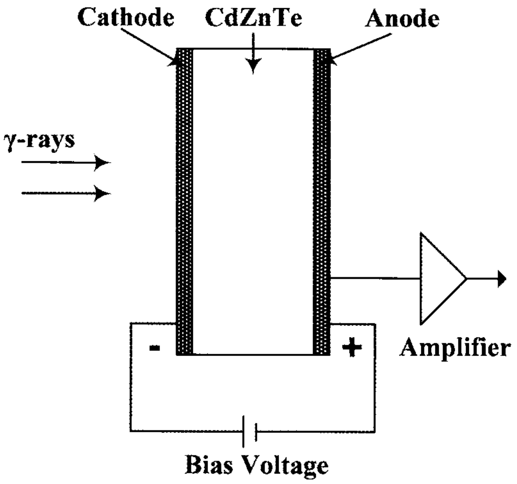

Fig. 1. Cross-sectional Geometry of the CdZnTe Detector Irradiated from ^{241}Am Source (59.5 keV Gamma-ray)

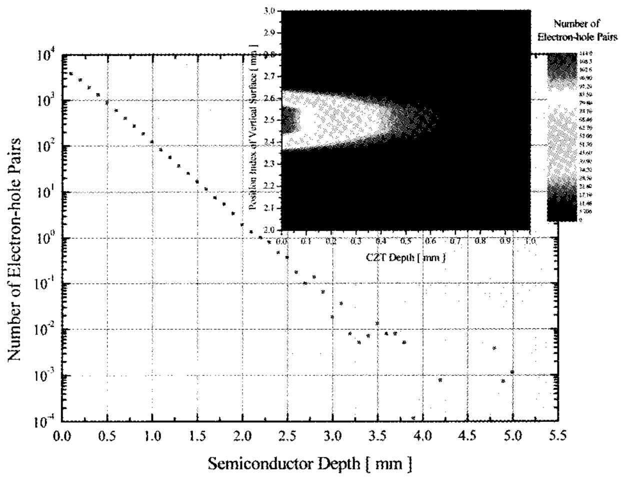

Fig. 2. Number of Electron-Hole Pairs Generated from 59.5 keV Gamma-ray as a Function of CZT Depth

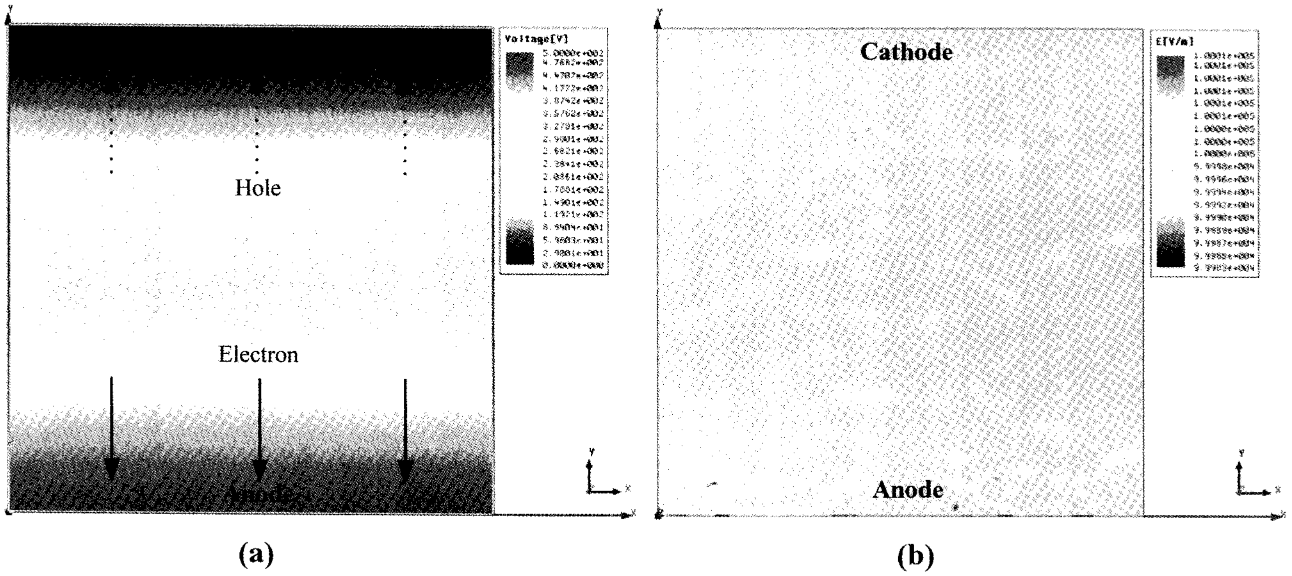

Fig. 3. Calculated Electric Field Distribution Biased 500 V between Two Electrodes (Cathode and Anode) by Using MAXWELL™ Code (a) Real Potential Distribution and (b) Strength Distribution of Electric Field

simplified two-dimensional calculations are sufficient for the purpose of analyzing the electric field distributions in a planar CZT detector.

Figures 3 (a) and (b) show the calculated bias potential inside the detector and the electric field strengths for the 5 mm-thick detector with a cross sectional view at the detector center, respectively. These calculations were assumed to be biased to 500 V between the two electrodes made of 100 nm thick platinum (cathode and anode) and were carried out by using MAXWELL™ developed by ANSOFT [10]. As shown in Figure 3 (a), the bias potential distribution in the planar detector is significantly different from that in the pixel or strip detector, and the bias potential increases linearly as it goes from cathode to anode. It is also recognized that the difference between the maximum and minimum electric field strength is only 0.027% as shown in Figure 3 (b); hence, it is found that the electric field strength of a 5 mm-thick detector has an almost constant value of 1000 V/cm.

3. ENERGY SPECTRUM IN THE CZT DETECTOR

In calculating the detector response function, most studies have simply analyzed the amount of energy deposition to the detector, assuming that the output pulse height is proportional to the deposited energy in the sensitive detection region [11-13]. However, interactions of incident radiations occur at various positions in the detector, and, thus, drift distances of produced carriers (electrons and holes) are very different according to the interaction positions. As a result, the output pulse is obtained with a different shape even if the same energy is deposited in the detector. Therefore, the common method is insufficient to evaluate the accurate response function of semiconductors, especially the CZT detector, which has a significant trapping effect of charge carriers. The CZT detector has poor carrier mobility-lifetime, especially for holes, compared to Si and Ge detectors [2].

In order to overcome the weakness of the conventional method to predict the detector response, this study has performed the simulations by considering the electron-hole pair drift. The response function of a semiconductor considering the charge collection efficiency was mainly investigated by using the Hecht equation. This equation allows calculation of charge collection efficiency represented as the ratio of the number of charge carriers collected at the electrodes to the total number of carriers created by the radiation interaction. If the effect of detrapping is neglected with a uniform electric field between the two electrodes, the charge collection efficiency, η, for the planar detector is the following:

$$\eta(z) = \frac{\lambda_e}{d}\left[1 - e^{-(d-z)/\lambda_e}\right] + \frac{\lambda_h}{d}\left[1 - e^{-z/\lambda_h}\right]$$

Where, d is the detector thickness, z is the interaction position of incident radiation with the CZT crystal, and λ_e ($=\mu_e\tau_e E$) and λ_h ($=\mu_h\tau_h E$) are the mean free paths of electrons and holes, respectively, in the case of the radiation incident from the cathode surface. E is the strength of the electric field in the CZT sensor, and τ_e and τ_h, μ_e and μ_h are their lifetimes and mobilities, respectively. To compare the distortion of energy spectrum, the Hecht equation was employed in the Geant4 simulation, whereas the MCNPX simulation was performed without consideration of charge collection efficiency. All parameters for the calculation of charge collection efficiency are shown in Table 1.

The total charge collection efficiency as a function of position within the detector was illustrated by using the Hecht equation, as shown in Figure 4. From the calculation of collection efficiency using the Hecht equation, it can be derived that the collected charge was mainly obtained from the electrons drifting to the anode and partly from the holes drifting toward the cathode. It is, therefore, confirmed that the contribution of electron and hole is inversely proportional to the distances they move [6]. Since the mean free path of electrons is much longer than that of the holes ($\lambda_e > \lambda_h$, ~ 40 times), they can be easily collected by the anode. The maximum charge collection efficiency was about 92% at 0.1 mm from the incident surface.

The energy spectrum of 59.5 keV gamma rays was simulated using Geant4 and MCNPX codes to analyze the response of the $5 \times 5 \times 5$ mm^3 CZT detector. The Geant4 result accounting for the charge collection efficiency and the ideal result from MCNPX calculation were compared in order to investigate the evident difference of the energy

Table 1. Parameters for the Hecht Equation

Detector Size	$5 \times 5 \times 5$ [mm^3]
Detector Density, ρ	6.1 [g/cm^3]
Electron-Hole Creation Energy, w	4.6 [eV]
Mobility-Lifetime (Electron, $\mu_e \tau_e$)	3×10^{-3} [cm^2/V]
Mobility-Lifetime (Hole, $\mu_h \tau_h$)	5×10^{-5} [cm^2/V]
Biasing Potential, E	500 [V]

Table 2. A Comparison of the Count Ratios Calculated by Geant4 and MCNPX Codes

Energy Bin [keV]	Counts in Each Energy Bin / Counts at Full Energy Peak	
	Geant4	MCNPX
N-1	29.0	0.03
N-2	11.0	0.02
N-3	5.0	0.02
N-4	2.0	0.01
N-5	1.0	0.01
N-6	1.0	0.01
N-7	1.0	0.01
N-8	1.0	0.01
N-9	1.0	0.01

Note: N represents the energy bin of full energy peak in each calculation

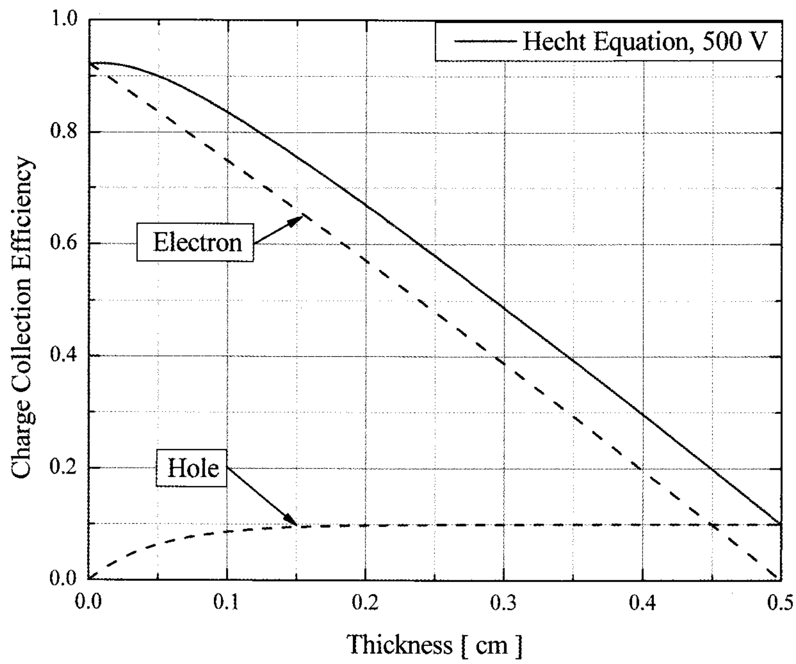

Fig. 4. Charge Collection Efficiency (η) as a Function of Position within a Semiconductor Detector with a Constant Electric Field

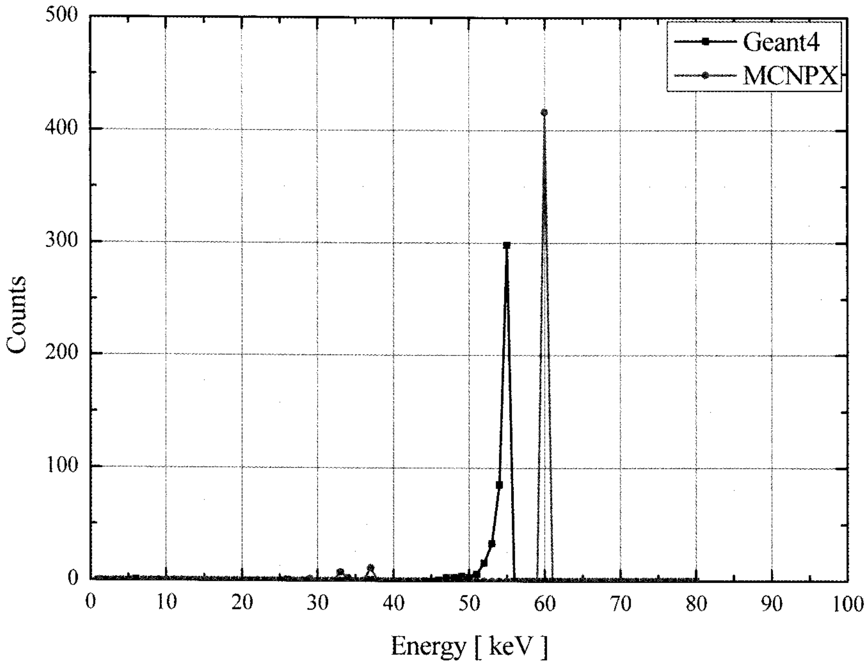

Fig. 5. The Energy Spectrum of Incident Gamma-Ray (59.5 keV) Calculated from Geant4 and MCNPX Codes

spectrum. The energy spectrum of 59.5 keV gamma rays is shown in Figure 5. Because the maximum charge collection efficiency of this detector is 92%, it can be seen that the maximum deposited energy of incident radiations corresponds to about 55 keV. As a result, it is found that the full energy peak of incident radiation has a discrepancy about 4 keV, as shown in Figure 5.

In contrast to the calculated result in the ideal condition, the shape of the photoelectric peak in the Geant4 calculation does not follow the Gaussian distribution. The tail in the Geant4 calculation can be seen in the low energy side of the full energy peak, whereas the tail in MCNPX calculation is not nearly found in the energy spectrum. To quantitatively analyze the tail effect in the energy spectrum, the ratios of the counts in each energy bin to those in the full energy peak are shown in Table 2 for both the Geant4 and MCNPX calculations. The counts in the tail region increase exponentially as they move from the low energy range to the high energy range (from N-9 energy bin to N-1 energy bin, where N is the energy bin of the full energy peak in each calculation). Specifically, it is found that the maximum ratio of tail height to the full energy peak in the Geant4 calculation is 29.0%, whereas that in the MCNPX calculation is 0.03%. Moreover, it is shown that the tail height caused by the charge collection efficiency is up to 1000 times higher than the reference to the ideal condition. It is also recognized that the tail effect is mainly produced due to the charge collection efficiency, and this significantly influences the energy spectrum obtained from the CZT detector.

4. CONCLUSIONS

When a CZT detector is used in photon spectroscopy, the spectrum distortion and tail effect are caused due to the poor charge collection and the relatively small mobility-lifetime of holes. With the aim of interpreting these problems, the Hecht equation was employed to simulate the energy spectrum of the incident radiation. The calculation results from the Monte Carlo codes have a significant discrepancy at the full energy peak position. Also, the tailing effect at the low energy range of the full energy peak can be simulated through the consideration of the charge collection efficiency. As a result, this study showed that a quantitative difference of energy spectrum distortion for a CZT detector (5 × 5 × 5 mm^3) is about 4 keV. In addition, it was confirmed that the low energy tail effect is partially caused by the incomplete charge collection of the electrons and holes, as well as the trapping and recombination. It was also found that the tail height caused by the charge collection efficiency went up to 1000 times compared to the pulse height in the same energy bin at the calculation without considering the charge collection efficiency. Therefore, this study can be applied to simulate the electron-hole motion in a CZT sensor and to analyze the measured spectrum from the semiconductor detector.

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