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Mean free paths of charge carriers in CZT crystal

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Abstract

The asymmetrical distortion of the Cadmium Zinc Telluride ((CZT) energy spectrum is mainly caused by the hole trapping in the CZT crystal, and it can be characterized by the mean free path of hole. The mean free paths of the charge carriers in the CZT crystal can be extracted from fitting the peak shape of the measured energy spectrum. The energy spectra of γ-rays from ^{241}Am, and that of α particles from ^{238}Pu were measured with a CZT with $5 \times 5 \times 5\,\mathrm{mm}^3$. The mean free path of the electron was determined from the bias dependence of α-particle response. The energy spectra of γ-ray were simulated with EGSnrc code, in which Hecht equation was included, and the mean free path of the hole was determined by comparing the measured spectrum with the simulated one. The energy spectrum of 662 keV γ-ray was measured with the CZT detector, and it was compared with the simulated spectrum, in which newly determined mean free paths of the electron and the hole were used.

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1. Introduction

Cadmium Zinc Telluride (CZT) detector is a promising material in many application areas, which include medical imaging, industrial process monitoring, national security, environmental safety, and basic science. Although novel concepts have been introduced to reduce the tail of the energy spectrum, spectral distortion of the CZT detector is still a major problem in the progress of the development of the CZT detector. The spectral distortion gets larger when higher energy γ-ray is measured with the CZT detector.

The spectral distortion of the CZT energy spectrum is mainly caused by the charge trapping during the charge transport, which can be characterized by the mean free paths of electron and hole in the CZT crystal [1]. Therefore, mean free paths of electron and hole in the CZT crystal are very important parameters to simulate the energy response of the CZT detector.

The mean free paths of the electron and the hole can be determined by using various methods [2]. One method to determine the mean free paths of the charge carriers is from the shape of the measured energy spectrum. Miyajima extracted both the mean free path of the electron and that of the hole from the shape of the γ-ray energy spectra [3]. However, the data showed a large difference with the previously known values.

In our work, the mean free paths of electron and hole were determined from the shape of the energy spectrum. At first, the mean free path of the electron was extracted from the bias dependence of α-particle spectrum, and that of the hole was extracted from the comparison between the measured and the simulated 59.5 keV γ-ray spectrum. We developed a simulation code to calculate the energy response of the CZT detector. With our new values of the mean free paths of the electron and the hole, the energy spectrum of 662 keV γ-ray was calculated, and it was compared with the measured one.

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2. Experiment

The mean free path of the electron was determined from the bias dependence of the α-energy spectrum. ^{238}Pu source was placed in front of the CZT detector, and the α-energy spectra were measured as the bias voltage was increased.

The CZT detector in the present work was obtained from eV products, a division of II–VI incorporated, with dimensions of $5 \times 5 \times 5\,\text{mm}^3$. The CZT crystal was known to be of spectroscopic grade. The signals from the CZT detector were processed through a preamplifier (5093 eV) and an amplifier (ORTEC 572). The shaping time of the amplifier was set 2 μs. The energy spectrum was stored through a Multi Channel Analyzer (ORTEC 919E, four-input multi channel buffer). The energy spectra were measured at room temperature. A pulse generator (ORTEC 480) was connected to the preamplifier to check the electronic noise.

The circles in Fig. 1 are the peak positions of the α peak at each bias voltage. Because the penetration depth of α-particle is only a few microns, the single-particle Hecht relation can be used to explain the measured circles [2]:

$$Q(V) = \frac{qVN_0(\mu\tau)_e}{d^2}\left[1 - \exp\left(\frac{d^2}{(\mu\tau)_e V}\right)\right] \tag{1}$$

where N_0 is the number of charge carriers created by the incident radiation, Q the total charge collected, q the electronic charge, V the bias voltage, d the distance between cathode and anode, $(\mu\tau)_e$ is the mobility-trapping time product for electron. The line in Fig. 1 is Eq. (1) fitted to the measured data. From the fitting result, we could determine $(\mu\tau)_e$ of the CZT detector to be $1.69 \times 10^{-3}\,\text{cm}^2/\text{V}$.

The γ-ray energy spectrum was also measured with the CZT detector. ^{241}Am with an activity of 25 mCi was placed 80 cm away from the detector. Since the distance between the radiation source and the detector was quite long, it could be expected that a parallel beam would be incident on the detector. The energy spectra were measured with the bias voltages of 100, 300, 500, and 700 V. In all the measurements, the dead times were less than 3%. The polarity of the bias voltage was inverted, and the energy spectra with the bias voltages of −100, −300, −500, and −700 V were also measured. The energy spectrum measured with the bias voltage of 500 V showed the highest energy resolution. When the bias voltage was higher than 500 V, the energy resolution got worse, and it would be from the increase of the dark current of the CZT detector.

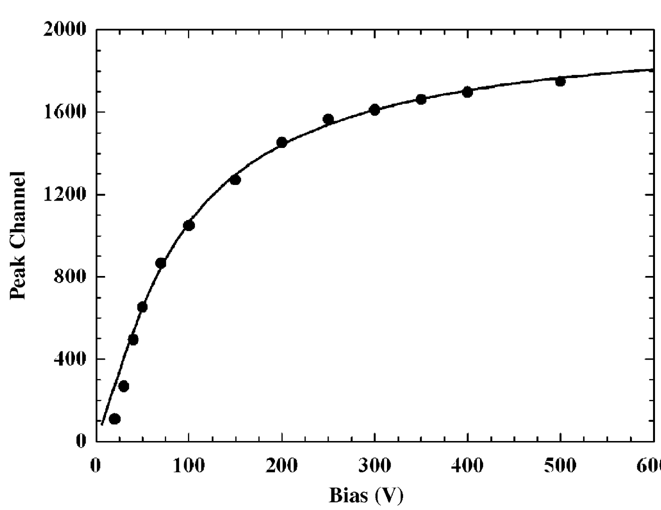

Fig. 1. Peak channel of α spectrum as a function of the bias voltage. The circles are from the measurement, and the line is the single-particle Hecht relation.

The energy spectrum of 59.5 keV γ-ray with positive polarity was quite different from that with negative polarity. One spectrum showed a clear full energy peak, while the other one was severely distorted. Since the electron–hole pairs, which were produced due to the 59.5 keV γ-ray, were generated near the front contact side, one charge carrier had to travel a relatively longer distance and the other charge carrier had to travel a relatively shorter distance to arrive at the electrode during the charge collection. When the hole had to travel a longer distance, the energy spectrum showed a clear full energy peak. The energy spectra with the clear full peak were only employed to determine the mean free paths of the charge carriers in CZT crystal.

3. Simulation of the response function

The energy spectra with the bias voltages of 300 and 500 V were calculated with the simulation, and they were fitted simultaneously to the measured ones. The radiation interactions in CZT were simulated with EGSnrc code [4]. The CZT material data were calculated with PEGS4. The energy limits in PEGS4 were chosen to be AP = 0.001, UP = 10.0, AE = 0.512, and UE = 10.0 MeV. Electron–hole pairs were created when energy was deposited in a semiconductor. W value, which is required to create an electron–hole pair, was set to 4.6 eV. The number of electron–hole pairs, which were generated due to the 59.5 keV γ-ray as a function of the generation position was calculated, which is shown in Fig. 2. As it can be seen, the electron–hole pairs were produced near the front side of the CZT detector when low-energy γ-ray is was incident on the detector. The deposited energy in the CZT crystal was also obtained from the simulation.

Each peak in the energy spectrum would be broadened. The peak broadening is divided into the symmetrical broadening and the asymmetrical broadening. The asymmetrical broadening was due to the charge carrier trapping. After electrons and holes were generated, they moved to the electrode oppositely in the CZT detector. Charge would be induced on the electrode due to the movement of the electron and the hole, and the charge carriers would be trapped during the travel in the crystal. The charge induction efficiency η, can be expressed with