A New Approach for Evaluating Charge Transport Properties of Semiconductor Detectors

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1. Introduction

The semiconductor detectors (e.g., CdTe, CdZnTe, and HgI_2) have been widely used for radiation detection and medical imaging because of its various outstanding features such as excellent energy resolution, wide bandgap energy, room temperature operation, and so on [1]. Unfortunately, the performance of these detectors is mainly limited by the charge transport properties of semiconductor, especially the mobility-lifetime products (i.e., $(\mu\tau)_e$ and $(\mu\tau)_h$). Hence, the analysis on the mobility-lifetime products is very important for evaluating correct characteristics of semiconductor detectors.

A commonly used method to analyze the mobility-lifetime products is based on their responses to α particle. However, the α particle method cannot evaluate the $(\mu\tau)_h$ product in many cases, because a semiconductor detector operating at positive bias voltages often yields the energy spectrum without the peaks. This method is also known to be very sensitive to the experimental conditions as well as surface conditions of the detector [2].

In this study, a new approach with gamma-ray instead of α particle was carried out to solve the determination difficulty of the $(\mu\tau)_h$ product with common method. The special relation between the two mobility-lifetime products, which we call the "Nural equation", was also developed to simply obtain each parameter based on Hecht equation.

2. Methods and Results

2.1 Maximum Charge Collection Efficiency

Assuming that the electric field is constant within the semiconductor material, the charge collection efficiency (i.e., the rate of charge carriers induced at the electrodes to the total number of carriers created by the radiation absorption) is given by Hecht equation [3], as following:

$$\eta(x) = \begin{cases} \dfrac{\lambda_e}{D}\left(1-\exp\left(-\dfrac{D-x}{\lambda_e}\right)\right)+\dfrac{\lambda_h}{D}\left(1-\exp\left(-\dfrac{x}{\lambda_h}\right)\right) \\ \dfrac{1}{D}\left(\lambda_e+\lambda_h-\lambda_e\exp\left(-\dfrac{D-x}{\lambda_e}\right)-\lambda_h\exp\left(-\dfrac{x}{\lambda_h}\right)\right) \end{cases} \text{..... (1)}$$

where, x is the distance from the negative electrode to the position at which the charge carriers (electron and hole) are produced, and D is the detector thickness. The λ_e and λ_h are the mean free paths of electrons and holes, respectively ($\lambda_e = E\cdot(\mu\tau)_e$ and $\lambda_h = E\cdot(\mu\tau)_h$). In case of gamma-ray incident on the positive electrode, the locations of λ_e and λ_h are mutually exchanged in Eq. (1).

The specific coordinate (x_{max}), for which the charge collection is maximal, was firstly obtained by differentiating Eq. (1) with respect to x (see Eq. (2)). And then, the maximum charge collection efficiency was finally derived by substituting Eq. (2) to x in Eq. (1), as shown in Eq. (3).

$$x_{\max} = \frac{D\lambda_h}{\lambda_e+\lambda_h} \text{ .... (2)}$$

$$\eta(x_{\max}) = \begin{cases} \dfrac{1}{D}(\lambda_e+\lambda_h)\left(1-\exp\left(-\dfrac{D}{\lambda_e+\lambda_h}\right)\right) \\ \dfrac{1}{D}E(\mu\tau)_{sum}\left(1-\exp\left(-\dfrac{D}{V(\mu\tau)_{sum}}\right)\right) \end{cases} \text{ .... (3)}$$

where, the $(\mu\tau)_{sum}$ is the sum of mobility-lifetime products for the electron and hole. It was found that the equation representing the maximum charge collection efficiency (Eq. (3)) was uncorrelated with the incident direction of gamma-ray and was relatively very simple form.

2.2 Charge Collection Efficiency at One Mean Free Path of Incident Gamma-ray

Although a large number of possible interaction mechanisms are known for gamma-ray in matter, only three reactions play an important role in radiation measurements: photoelectric effect, compton scattering, and pair production [4]. The sum of these probabilities is the probability per unit path length that the gamma-ray is removed in matter (μ = τ (photoelectric) + σ (compton) + κ (pair)). The incident gamma-ray can also be characterized by their mean free path (λ_γ) defined as the average distance traveled in the detection material before an interaction takes place, as following;

$$\lambda_\gamma = \frac{\int_0^\infty x e^{-\mu x}dx}{\int_0^\infty e^{-\mu x}dx} = \frac{1}{\mu}$$

In the case of semiconductor detectors, it can be assumed that incident gamma-rays are absorbed by only one reaction, because the probability of photoelectric effect is much higher than other reactions at low energy ranges ($E_\gamma \leq 250$ keV) [1]. Through this assumption, it is derived that most charge carriers are produced at one mean free path of incident gamma-ray, and the charge collection efficiency at this position determines the energy range of full-energy peak in gamma-ray energy spectrum. The efficiency at one mean free path of incident gamma-ray was obtained by substituting one mean free path into Eq. (1), as shown in Eq. (4).

$$\eta(\lambda_\gamma) = \frac{1}{D}\left(\lambda_e + \lambda_h - \lambda_e \exp\left(-\frac{D-\lambda_\gamma}{\lambda_e}\right) - \lambda_h \exp\left(-\frac{\lambda_\gamma}{\lambda_h}\right)\right)$$

$$= \frac{1}{D}\left(\lambda_e + \lambda_h - \lambda_e \exp\left(-\frac{D\mu-1}{\mu\lambda_e}\right) - \lambda_h \exp\left(-\frac{1}{\mu\lambda_h}\right)\right) \text{.... (4)}$$

2.3 The Relation between Two Mobility-lifetime Products

A new approach to find the special relation was performed based on the above-mentioned results. First, the x_{max} producing maximum charge collection efficiency was assumed to be equal to one mean free path of incident gamma-ray due to various gamma-rays emitted from the radioactive isotopes to be used in the experiments. The Nural equation for the two mobility-life products was finally derived from the two charge collection efficiencies at the x_{max} and λ_γ, as following:

$$\frac{1}{D}(\lambda_e + \lambda_h)\left(1 - \exp\left(-\frac{D}{\lambda_e + \lambda_h}\right)\right) = \frac{1}{D}\left(\lambda_e + \lambda_h - \lambda_e \exp\left(-\frac{D\mu-1}{\mu\lambda_e}\right) - \lambda_h \exp\left(-\frac{1}{\mu\lambda_h}\right)\right)$$

$$-\lambda_e \exp\left(-\frac{D}{\lambda_e + \lambda_h}\right) - \lambda_h \exp\left(-\frac{D}{\lambda_e + \lambda_h}\right) = -\lambda_e \exp\left(-\frac{D\mu-1}{\mu\lambda_e}\right) - \lambda_h \exp\left(-\frac{1}{\mu\lambda_h}\right)$$

$$\frac{D}{\lambda_e + \lambda_h} = \frac{D\mu-1}{\mu\lambda_e} \quad \rightarrow \quad \lambda_e = \lambda_h(D\mu-1)$$

$$(\mu\tau)_e = (\mu\tau)_h(D\mu-1) \text{............ (5)}$$

It is shown that each mobility-lifetime product of the electron and hole can be simply evaluated by the combination of the $(\mu\tau)_{sum}$ to be obtained in experiments and the derived relation in this study.

2.4 Determination of Two Mobility-lifetime Products

In order to determine the sum of two mobility-lifetime products, the experiments were progressed as the bias voltage is changed from -110 V to 110 V. A planar CZT detector (5×5×2 mm^3) manufactured by eV Products was selected to analyze the charge transport properties. This detector was also irradiated with low energy gamma-rays (59.5 keV) emitted from ^{241}Am isotope through the cathode surface. Figure 1 shows the maximum charge collection efficiency as a function of bias voltage for the full-energy peaks of gamma-ray. In this figure, the fitting graph of Eq. (3) is well agreed with experimental results. Based on the $(\mu\tau)_{sum}$ product and the Nural equation, it was found that the mobility-lifetime product of the electron and hole was 4.93×10^{-3} cm^2/V and 7.65×10^{-4} cm^2/V, respectively. Therefore, it is recognized that this approach using gamma-ray instead of α particle is efficient to investigate the transport properties of semiconductor detector.

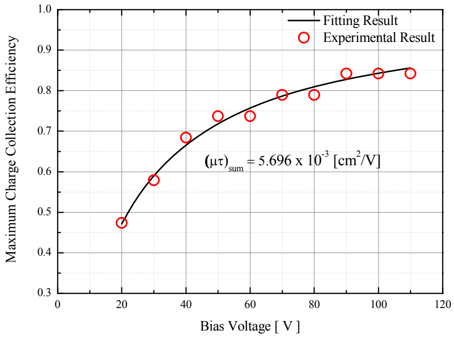

FIG. 1. Determination of the Sum of Two Mobility-lifetime Products in 5×5×2 mm^3 CdZnTe Detector

3. Conclusions

A new approach based on response to gamma-ray instead of α particle was performed to obtain each parameter by developing the relation between the two mobility-lifetime products based on Hecht equation. The Nural equation for the two mobility-life products was derived from the two charge collection efficiencies at specific coordinate (x_{max}) and one mean free path of incident gamma-ray. As a result, the $(\mu\tau)_h$ product can be simply evaluated from the $(\mu\tau)_{sum}$ product and the relation between the two mobility-lifetime products.

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