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The influence of electron track lengths on the γ-ray response of compound semiconductor detectors

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ABSTRACT

The charge-trapping effect in compound semiconductor γ-ray detectors in the presence of a uniform electric field is commonly described by Hecht's relation. However, Hecht's relation ignores the geometrical spread of charge carriers caused by the finite range of primary and secondary electrons (δ-rays) in the detector. In this paper, a method based on the Shockley–Ramo theorem is developed to calculate γ-ray induced charge pulses by taking into account the charge-trapping effect associated with the geometrical spread of charge carriers. The method is then used to calculate the response of a planar CdTe detector to energetic γ-rays by which the influence of electron track lengths on the γ-ray response of the detectors is clearly shown.

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1. Introduction

Compound semiconductor detectors such as Cadmium Telluride (CdTe), Cadmium Zinc Telluride (CdZnTe), Mercuric Iodide (HgI_2) and Thallium Bromide (TlBr) are of great interest for X- and γ-ray spectroscopy applications. The attraction of these materials for spectroscopy applications is mainly due to their high quantum efficiency and their capability of operation at room temperature. However, the energy resolution of these detectors is significantly limited by the trapping of charge carriers, i.e. electrons and holes, during their transit to the electrodes. When significant trapping occurs for either charge carrier, the induced charge becomes a function of the distance over which the charge carriers travel, leading to an asymmetric photo-peak shape. In the case of uniform electric field and negligible de-trapping, the effect of charge-trapping is commonly described by Hecht's relation [1], in which the induced charge as a function of interaction location is given by:

$$Q = eN_\circ \cdot \left\{ \frac{v_h \tau_h}{d}\left(1-\exp\left(\frac{-x_\circ}{v_h\tau_h}\right)\right) + \frac{v_e\tau_e}{d}\left(1-\exp\left(\frac{x_\circ - d}{v_e\tau_e}\right)\right)\right\}, \quad (1)$$

where N_o is the initial number of electron–hole pairs, e is the electric charge, v is the charge carriers' velocity, τ is the charge carriers' lifetime, x_o represents the γ-ray interaction location measured from the cathode, d is the detector thickness, and the e and h subscripts represent electrons and holes, respectively. However, this relation assumes that all the charge carriers are created at the γ-ray interaction location, while charge carriers are actually formed along the track of the electron created by the γ-ray interaction. Some details on the release of charge carriers along an electron track in a semiconductor material can be found in Ref. [2]. Consequently, for γ-ray interactions with a spatial distribution of charge carriers comparable to the mean free path of charge carriers, Hecht's relation is unable to produce a proper estimate of the amount of charge-trapping effect. This paper describes a method for including the effect of the geometrical spread of charge carriers on the induced charge pulses. The method is then used to study the influence of electron track lengths on the γ-ray response of the detectors.

2. Pulse-shape model

The shape of the induced pulses is calculated by using the Shockley–Ramo theorem [3,4]. A review of the Shockley–Ramo theorem and its application in semiconductor γ-ray detectors can be found in Ref. [5]. The Shockley–Ramo theorem states that the charge induced on an electrode A due to the motion of a charge carrier from a location of z_i to a location of z_f is given by:

$$Q = q[\varphi_A(z_i) - \varphi_A(z_f)], \quad (2)$$

where q is the charge on the carrier and φ_A is the potential that would exist at the position of the charge carrier under the following circumstances: the charge carrier is removed, the conductor A is kept at unit potential, and all other conductors grounded. The potential φ_A is called a weighting potential and for a planar detector is simply given

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as $\varphi_A(z)=z/d$, where z is the distance from the surface of the cathode and d is the thickness of the detector. When the charge carriers are distributed over a distance in the detector, the induced charges by electrons and holes are obtained by integrating Eq. (2) as:

$$Q_e=\int_0^d \rho_e(z)[\varphi(z)-\varphi(z_f)]dz, \quad (3)$$

and

$$Q_h=\int_0^d \rho_h(z)[\varphi(z)-\varphi(z_f)]dz, \quad (4)$$

where $\rho(z)$ denotes the charge distribution density for electrons and holes in the direction of the uniform electric field. The $\varphi(z_f)$ for electrons is unity and for holes is zero. The total induced charge is then given by the sum of induced charges by electrons and holes, Q_e+Q_h. Since $\rho(z)$ varies from event to event, we first derive the formulas of Q_e and Q_h for the case for which the charge carriers are uniformly distributed over a distance in the detector. The pulse due to a γ-ray interaction with an arbitrary distribution of charge carriers is then obtained by dividing the detector volume into several sufficiently thin slices in which a uniform distribution of charge carriers can be assumed (see Fig. 1A). Starting with the pulse formula for a uniform distribution of charge carriers, the pulse due to the γ-ray interaction is obtained by adding up the contributions calculated for the slices which form the electron's track.

To calculate the charge pulse due to a uniform distribution of charge carriers, we assume that a uniformly and randomly distributed potential trap sites exist through a detector's bulk. By ignoring the de-trapping and charge diffusion effects, the time-dependent linear charge distribution density $\rho(t)$ for a thin slice of the detector is given by:

$$\rho(t)=\left(\frac{\pm ne}{l}\right)e^{\frac{-t}{\tau}}, \quad (5)$$

where τ is the charge carrier lifetime, n is the number of charge carriers in the slice and l is the thickness of the slice. The positive sign is for the charge distribution density of holes and the negative sign is for the charge distribution density of electrons. The number of charge carriers in the slice is obtained as $\Delta E/w$, where ΔE is the amount of ionization in the slice and w is the pair creation energy in the detector. The general formula of Q_e for a typical slice (Fig. 1B) is obtained by defining two imaginary electron charge distributions, as shown in Fig. 1C and D. These electron charge distributions begin from the lower and upper limits of the slice and end at the surface of the anode. The density of these charge distributions is the same as that given by Eq. (5). By putting the electron charge distribution density of Eq. (5) into Eq. (3) and using the relation for the drift of electrons from their initial location, given by $z_e=\nu_e t$ (ν_e is the drift velocity of electrons), the induced charge due to the charge distribution of Fig. 1D is calculated as:

$$Q_{e1}(t)=\int_0^t\left(\frac{-ne}{l}\right)e^{\frac{-t}{\tau_e}}\left(\frac{Z_\circ+\nu_e t}{d}-1\right)\nu_e dt=\left(\frac{-ne\nu_e}{dl}\right)\times\left[\tau_e(Z_\circ-d)(1-e^{\frac{-t}{\tau_e}})+\nu_e\tau_e^2\left(1-e^{\frac{-t}{\tau_e}}\left(1+\frac{t}{\tau_e}\right)\right)\right], \quad (6)$$

where Z_o is the distance of the charge distribution from the cathode. Similarly, the induced charge due to the electron charge distribution of Fig. 1C is calculated as:

$$Q_{e2}(t)=\int_0^t\left(\frac{-ne}{l}\right)e^{\frac{-t}{\tau_e}}\left(\frac{Z_\circ+l+\nu_e t}{d}-1\right)\nu_e dt=\left(\frac{-ne\nu_e}{dl}\right)\times\left[\tau_e(Z_\circ+l-d)(1-e^{\frac{-t}{\tau_e}})+\nu_e\tau_e^2\left(1-e^{\frac{-t}{\tau_e}}\left(1+\frac{t}{\tau_e}\right)\right)\right]. \quad (7)$$

The induced charge by the electrons of the slice (Fig. 3B) is then given by $Q_e(t)=Q_{e1}(t)-Q_{e2}(t)$, while Q_{e1} reaches to its final value at the time T_{e1}, given by:

$$T_{e1}=\left(\frac{d-Z_\circ}{\nu_e}\right), \quad (8)$$

and Q_{e2} reaches to its final value at the time T_{e2}, given by:

$$T_{e2}=\left(\frac{d-Z_\circ-l}{\nu_e}\right). \quad (9)$$

To derive a formula for the charge induced by the holes of the slice, two imaginary hole charge distributions beginning from the upper and lower limits of the slice and ending at the surface of the cathode are used. By putting the hole distribution density, given by Eq. (5), into Eq. (4) and using the relation for the drift of holes as $z_h=\nu_h t$ (ν_h is the drift velocity of holes), the induced charges $Q_{h1}(t)$ and $Q_{h2}(t)$ are calculated as:

$$Q_{h1}(t)=\int_0^t\left(\frac{ne}{l}\right)e^{\frac{-t}{\tau_h}}\left(\frac{Z_\circ+l-\nu_h t}{d}\right)\nu_h dt=\left(\frac{ne\nu_h}{dl}\right)\times\left[\tau_h(Z_\circ+l)(1-e^{\frac{-t}{\tau_h}})-\nu_h\tau_h^2\left(1-e^{\frac{-t}{\tau_h}}\left(1+\frac{t}{\tau_h}\right)\right)\right], \quad (10)$$

and

$$Q_{h2}(t)=\int_0^t\left(\frac{ne}{l}\right)e^{\frac{-t}{\tau_h}}\left(\frac{Z_\circ-\nu_h t}{d}\right)\nu_h dt=\left(\frac{ne\nu_h}{dl}\right)\times\left[\tau_h Z_\circ(1-e^{\frac{-t}{\tau_h}})-\nu_h\tau_h^2\left(1-e^{\frac{-t}{\tau_h}}\left(1+\frac{t}{\tau_h}\right)\right)\right]. \quad (11)$$

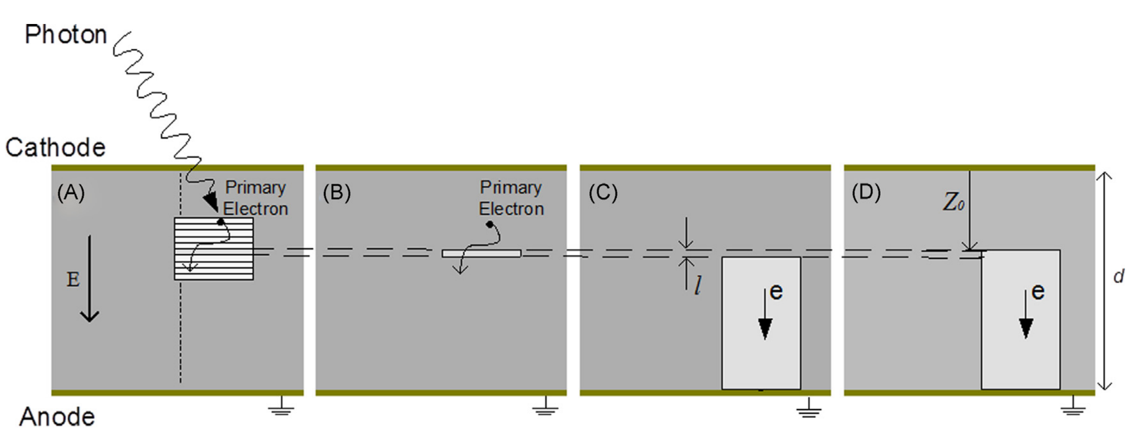

Fig. 1. Illustration of the calculation of the induced charge due to an arbitrary electron track. (A) The detector is divided into several thin slices in the direction of the electric field. The slices are sufficiently thin to assume a uniform distribution of charge carriers in each slice. (B) A typical slice shown for the calculation of a pulse due to a uniform charge distribution. (C) and (D) two imaginary electron charge distributions which are used to derive a general formula for the induced charge by the electrons of the slice. A similar approach is used to derive the formula of the induced charge by the holes of the slice.

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