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Modeling of ballistic and trapping effects on the collection efficiency of holes and electrons separately for a planar mercuric iodide detector (HgI_2)

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ABSTRACT

For the room temperature nuclear detector application, signal created in the detector depends not only to the energy of the incident photon but also to the position of the interaction. This can bring an incomplete charge collection caused by a deep-trapping or a ballistic deficit of charge carrier. Many scientists used to demonstrate their impact on the global efficiency of the charge collection. Here we show this effect, not globally but separately, according to the position where holes and electrons are created. It permits us to see the contribution of each kind of carrier in the signal formation. An analytical model of charge collection is developed firstly to take into account the deep-trapping only. Secondly, this model is improved adding the ballistic deficit effect. The deep-trapping contributes to reduce the efficiency of hole above all on thicker detector. In the other part, ballistic deficit reduce electron efficiency above all near anode in the negatively polarized detector.

1. Introduction

The gamma spectrometry is a technical method which is used to identify and quantify the radioactive elements present in a radioactive source. These radioelements emit characteristic gamma photons that interact in the detector material of spectrometer. This interaction results in the release of electrons and holes. A bias voltage is applied between the two electrodes of the detector. Then electrons and holes begin to move causing the formation of a signal whose intensity is proportional to the energy of the incident photon. The information provided by the signal should be as faithful as possible. This is ensured by a number of parameters related to

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the material, such as the atomic number and energy band gap, used for the detector design. These parameters have an influence on the collection efficiency of electrons and holes from the electrodes. In this work, we will turn our attention to this efficiency. Efficiency is defined as the ratio of charge collected by the electrodes to the total number of charges generated by incident photon.

Among the semiconductors that have the best detection performance, high purity germanium (HPGe) is a very good compromise. The gamma ray spectrum obtained by this type of material has a good energy resolution. This facilitates the distinction of the total energy peaks and identification of different radionuclides. Unfortunately, germanium is confronted to warming problems. It must be regularly cooled with liquid nitrogen (Knoll, 2000, chap. 12) to minimize leakage currents which may cause measurement errors. This phenomenon is happened because the germanium forbidden band worth 0.67 eV (Gilmore, 2008, chap. 3). This value is relatively low. The electrons from the valence band can easily go into the conduction band when there is a small rise in temperature. Then to avoid cooling detector every times, another kind of semiconductors is used. These semiconductors have a large enough gap and do not need to be cool. In the market of materials operating at room temperature, three chemical compounds are in competition. This is the cadmium telluride(CdTe), Zinc Cadmium Tellurium(CdZnTe) and Mercury iodide(HgI_2) (Schlesinger & James, 1995, chap. 1; Courtine, 2007). These materials have the best cross sections because of their high atomic number. However, it still have a serious problem of charge collection. Indeed, the detector is provided with polarized electrodes. When a gamma photon interacts in a detector, it causes the creation of charge carriers. These carriers are accelerated toward the electrodes under the influence of the bias voltage. This leads to the formation of an electrical signal. Two major problems affect the formation of the signal due to the charge collection. These are the trapping phenomena and ballistic deficit of charge carriers. Trapping is due to the presence of impurities in the semiconductor and ballistic deficit is rather observed on thick detectors. This happens when time took by carrier to reach electrode is longer than the period during which the signal is formed (He, 2001).

Several models have been developed around this issue of charge collection. In 1999, Nemirovsky used a statistical method to determine the charge carrier efficiency while Zahangir and Kasap determined it, in 2002, by solving charge carrier continuity equation. They took the trapping into account of their resolution. Kim (2006) proposed an analytical model considering the ballistic deficit in addition to trapping. All of these techniques are based on the determination of the efficiency in a global way. In this work, we propose to determine it, according to the position of carriers separately. So, we will show the contribution of each electron and hole to a signal production in a planar HgI_2 detector according to their position.

2. Methodology

The expression of the electric current created on an electrode by the motion of an electron is given by the theorem of Shockley-Ramo (1939; Shockley, 1938; He, 2001):

$$I = E_v e v \tag{1}$$

Where Ev is the component of the electric field along the displacement of the electron. e and v represent, respectively, the elementary charge and the electron speed. The intensity of the current produced by the movement of charge carriers taking into account the trapping effect is obtained by (Kim, 2006):

$$I_j(x,t) = \frac{Q_0 \mu_j V}{L^2} e^{-\frac{t}{\tau_j}} \tag{2}$$

Where $Q_0 = qn_0(x)$ is the total charge generated in the detector and μ_j is the mobility of the charge carriers. The index j will be replaced by e for electrons and h for holes. τ_j is the lifetime of the charge carriers while $n_0(x)$ is the charge density created in the detector at the position x. Fig. 1 shows the configuration of the detector in a negatively polarization. On this configuration, anode is placed at the position $x = 0$ and cathode at $x = L$. The amount of charge which participates in the formation of the signal is obtained by integrating the intensity of current of Equation (2):

$$Q_j(x) = \int_0^{\tau_c} \frac{Q_0 \mu_j V}{L^2} e^{-\frac{t}{\tau_j}} dt \tag{3}$$

τ_c is the collection time of charge carriers during which the electric signal is formed. In the model described by Equation (3), it is assumed that carriers transit time is less than collection time. Here, each carrier created is collected without any ballistic deficit problem. However, if the thickness of the detector is sufficiently large like so that the transit time is found to be higher than collection time, there will be the phenomenon of ballistic deficit. In this case, there are areas of the detector where charge carriers created will never reach their target electrode. We represent in Fig. 1 the two areas from where created electrons and holes cannot reach electrodes during the collection time in the negative polarization. Electrons released during the interaction are accelerated towards the cathode while holes are directed to anode. The motion of electrons induces a charge quantity Q_e on the cathode given by the following expression:

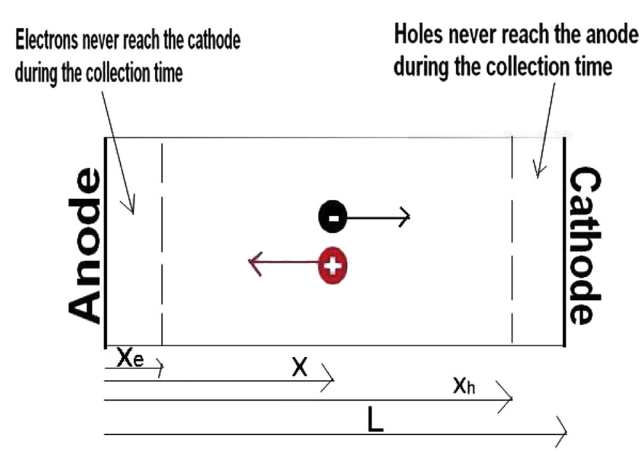

Fig. 1 – Diagram of a planar detector shown in a negative polarization.