Three-Dimensional Simulation of Signal Generation in Wide-Bandgap Semiconductor Radiation Detectors

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Introduction

We demonstrate the use of Comsol Multiphysics with Matlab to model signal generation in wide-bandgap semiconductor radiation detectors. A quasi-hemispherical detector design is compared with a simple, planar detector. Results show that the quasi-hemispherical design can simply and effectively compensate for the poor hole transport of most compound semiconductor materials.

Use of COMSOL Multiphysics

Semiconductor detectors for x- and gamma-rays are macroscopic devices with volumes measured in cubic centimeters. Consequently they can be viewed entirely as classical devices and analyzed using the methods of electrostatics. The charge carriers that are generated by an x-ray or gamma-ray interaction drift under an applied DC electric field and thereby induce a current signal on the electrodes given by Ramo's theorem as:

$$i = q\,\boldsymbol{v}.\boldsymbol{E_1} \tag{1}$$

where $\boldsymbol{v}$ is the drift velocity and $\boldsymbol{E_1}$ is the weighting field, or the electric field that would exist with the electrode in question held at a potential of 1 V and all other electrodes grounded. For practical purposes the drift velocity can be taken as:

$$\boldsymbol{v} = \mu_{e(h)}\boldsymbol{E} \tag{2}$$

where $\mu_{e(h)}$ is the mobility of electrons or holes. Because of trapping, the number of free carriers decreases with time as:

$$N(t)=N_0\, e^{-t/\tau_{e(h)}} \tag{3}$$

where $\tau_{e(h)}$ is the trapping lifetime for electrons or holes.

Computing the signal generated in a semiconductor for a given amount of charge deposited in a given location in the detector therefore consists of two parts: computing the physical and weighting fields ($\boldsymbol{E}$ and $\boldsymbol{E_1}$) by a method of electrostatics, and then integrating the current in (1) subject to the conditions given in (2) and (3). Comsol Multiphysics can easily compute the field distributions for arbitrarily complex arrangements of electrodes, and the fields can then be exported to Matlab to perform the integration as follows:

$$\frac{Q_{e(h)}}{eN_0} = \int_0^{t_{c,e(h)}} \mu_{e(h)} e^{-t/\tau_{e(h)}}\, \vec{E}\cdot\vec{E}_1 dt \tag{4}$$

Here $t_{c,e(h)}$ is the collection time for electrons (holes) – the time at which the charge carriers reach the electrode. The contributions of electrons and holes must be calculated separately and added.

For the simplest cases in which there are only two electrodes, one of which is grounded, the physical and weighting fields are identical except for a factor of the bias voltage. Figure 1 shows the computed electrostatic potential distributions for two cases – a planar detector in which the top and bottom surfaces are completely metalized, and a "quasi-hemispherical" detector, in which the top contact (anode) is circular and covers only a fraction of the crystal surface. The latter has the benefit of concentrating the field lines near the anode, thereby reducing the contribution to the signal of holes – which typically have much poorer transport properties than electrons in compound semiconductors. In both cases the crystal dimensions are 1x1x1 cm^3, and the transport properties are representative of high-quality $Cd_{0.9}Zn_{0.1}Te$ material.

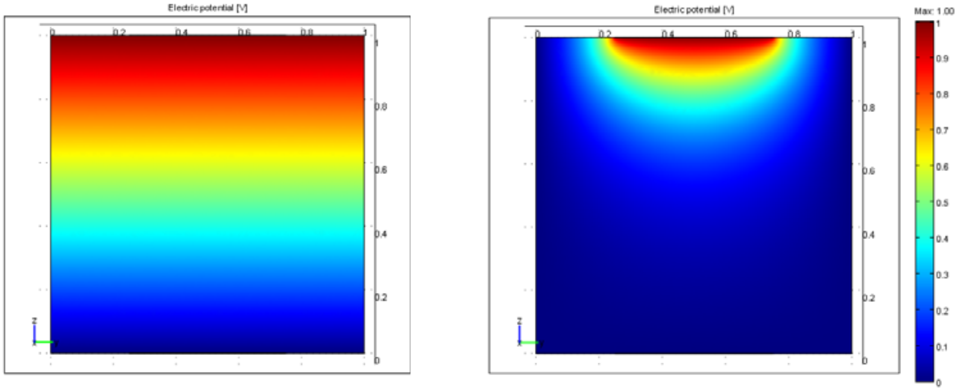

Figure 1. Cross-section of equipotential map for planar (left) and quasi-hemispherical detectors.

Expected Results

The calculation represented by equation (4) gives the signal for a single interaction. The key characteristic that determines performance of a detector is the uniformity of that signal for varying interaction locations – in other words, the charge collection efficiency profile. To get a rough picture of the spectroscopic performance of a detector at high energies, the charge collection efficiency is calculated for numerous interaction locations, and a histogram is plotted, as in Figure 2.

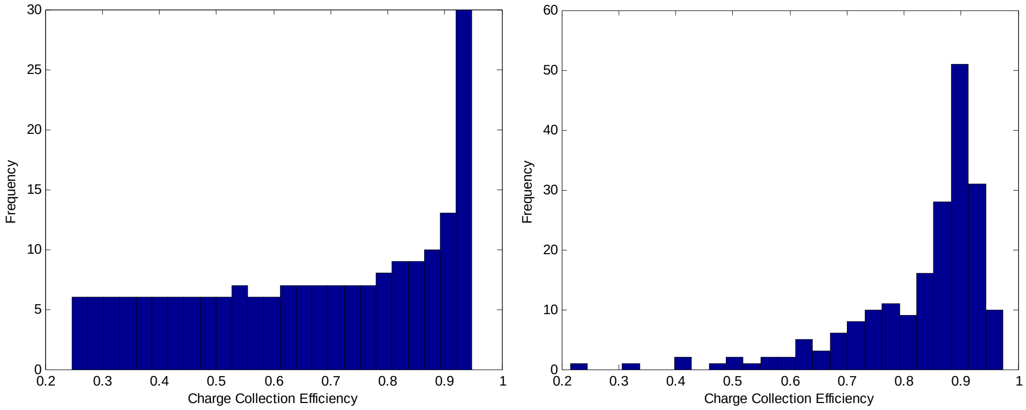

Figure 2: Charge collection histograms for planar (left) and quasi-hemispherical detectors.

The histogram for the planar detector shows the typical "hole tailing" problem of compound semiconductors, in which the charge collection efficiency depends strongly on the distance from the anode at which the interaction occurs, causing a spreading of the photoelectric absorption peak. The quasi-hemispherical detector helps to counteract this problem and confines the charge collection efficiency to a narrower range of values, improving the spectroscopic resolution and photopeak efficiency of the detector.

Conclusion

We have implemented a three-dimensional model of signal generation in semiconductor radiation detectors using Comsol Multiphysics with Matlab. Results show that a quasi-hemispherical geometry can help to correct for the asymmetrical electron and hole transport properties typical of compound semiconductor materials.