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Geometrically weighted semiconductor Frisch grid radiation spectrometers

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Abstract

A new detector geometry is described with relatively high gamma ray energy resolution at room temperature. The device uses the geometric weighting effect, the small pixel effect and the Frisch grid effect to produce high gamma ray energy resolution. The design is simple and easy to construct. The device performs as a gamma ray spectrometer without the need for pulse shape rejection or correction, and it requires only one signal output to any commercially available charge sensitive preamplifier. The device operates very well with conventional NIM electronic systems. Presently, room temperature (23°C) energy resolutions of 2.68% FWHM at 662 keV and 2.45% FWHM at 1.332 MeV have been measured with a 1 cm^3 prism shaped CdZnTe device. © 1999 Elsevier Science B.V. All rights reserved.

1. Introduction

Several compound semiconductors are suitable for room temperature operated radiation spectrometers [1]. Conventional planar semi-conductor spectrometers require efficient extraction of both electrons and holes excited by gamma ray interactions. Typically for compound semiconductors one charge carrier type is much more severely trapped than the other, and the misbalance in the carrier extraction factors causes severe degradation in the gamma ray energy resolution [2,3]. The usual method of increasing the gamma ray energy resolution for planar devices is to make them thinner, thereby increasing the charge carrier extraction factors to acceptable values. Thinning causes the devices to sacrifice the desired gamma ray interaction efficiency.

Detectors designed to sense the motion of only one carrier type over the other have shown dramatic improvement over the simple planar design [4–9]. Co-planar style devices use two sets of serpentine patterned grids on a single surface to help screen hole motion from the induced charge output signal [4,5]. Drift diode designs use a similar approach to the co-planar device to improve gamma ray energy resolution [6,7]. Most recently, a semiconductor version of the Frisch grid has

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shown promise as an easy way to perform single polarity sensing [8,9].

Semiconductor Frisch grid devices have shown an energy resolution improvement over conventional planar designs, yet the prototype parallelepiped designs with side grids are limited to thin dimensions due to weighting potential restrictions. Increasing the width improves the gamma ray detection efficiency, but causes a noticeable reduction in gamma ray energy resolution [9]. Additionally, the devices are separated into three distinct regions: the interaction region, the pervious region and the measurement region. The device operates by sweeping excited electrons into the measurement region and excited holes away from the measurement region. However, gamma ray interactions in the measurement region contaminate the spectrum and reduce energy resolution [9].

The geometrically weighted semiconductor Frisch grid radiation spectrometer is a new design that demonstrates excellent single polarity sensing. It also allows for relatively large volume detectors to be fabricated while reducing measurement region contamination. The device utilizes several physical effects to increase gamma ray interaction efficiency and energy resolution, including the geometrical weighting effect, the small pixel effect [10] and the Frisch grid effect [11].

2. Theoretical considerations

Fig. 1 shows the basic features of a geometrically weighted semiconductor Frisch grid radiation detector. The device dimensions are designated as follows: cathode width = W_c, anode width = W_a, width at the pervious region center = W_p, interaction region height = L_i, pervious region height = L_p, measurement region height = L_m, overall detector height = H and the detector length = D. The major physical effects for the device are briefly discussed in the following sections. A more comprehensive treatment of the device physics will appear elsewhere.

2.1. The geometric weighting effect

For simplicity, we assume that gamma ray interactions occur uniformly throughout the detecting

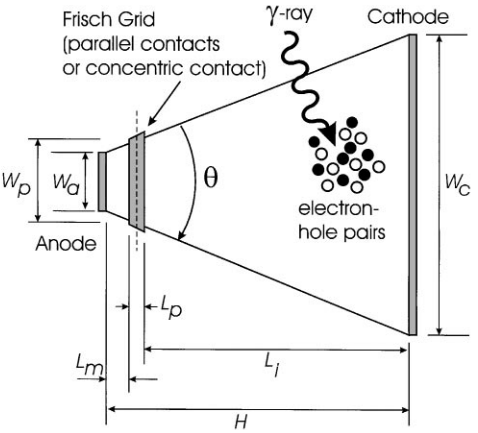

Fig. 1. Diagram of the general features for a geometrically weighted semiconductor Frisch grid radiation spectrometer.

volume. We also assume that only photoelectric absorption is taking place within the detector (no Compton scattering and no pair production). Hence, the gamma ray interaction rate is uniform and constant for any unit volume $dx\,dy\,dz$ within the detector.

For a trapezoid prism, the fraction of gamma ray interactions occurring in the interaction region is approximated by

$$F_i \approx \frac{(\frac{1}{2}(W_c + W_p))(L_i + \frac{1}{2}L_p)}{(\frac{1}{2}(W_a + W_c))(L_i + L_p + L_m)} \approx \frac{(W_c + W_p)(2L_i + L_p)}{2(W_a + W_c)(L_i + L_p + L_m)}, \quad (1)$$

which can be shown to reduce to the parallelepiped case by making $W_a = W_c = W_p$ [9]. For the following examples, a restraint of $W_a = 2$ mm is imposed in all cases. With $W_c = 10$ mm, $D = 10$ mm, $H = 10$ mm, $\theta = 43.5°$ and with the Frisch grid = 1 mm wide centered 2.0 mm back from the anode, the fraction of events occurring in the interaction region can be shown to be 85.3%. A 2 mm thick parallelepiped that is 10 mm long and 10 mm wide with a 1 mm wide Frisch grid centered 2 mm back from the anode has $F_i = 80\%$. Hence, the fraction of interactions occurring in the interaction region is increased for the trapezoidal case over the parallelepiped case. Furthermore, the volume of the parallelepiped design is 200 mm^3, whereas the volume of the trapezoid design is 600 mm^3. The overall result is a 3.2 times increase in detector gamma ray sensitivity in the interaction region for the trapezoidal design, while retaining a higher rejection ratio for gamma ray interactions occurring in the measurement region. Hence, the geometric shape of the trapezoidal detector design allows for a higher ratio of gamma ray interactions to occur in the interaction region over the measurement region than that observed for a parallelepiped parallel strip Frisch grid detector. The general trend for F_i is to approach unity for both designs until the Frisch grid ultimately contacts the anode, yet the volume of the trapezoid design remains much larger than the parallelepiped design, thereby being more efficient as a gamma ray sensor.

The gamma ray interaction probability distribution function is highest near the cathode and lowest near the anode for a trapezoid prism semiconductor Frisch grid detector. For uniform irradiation, the normalized total gamma ray probability distribution function for a trapezoidal device is

$$P_N(x)\,dx = \frac{2x\tan(\theta/2) + W_a}{H^2\tan(\theta/2) + HW_a}\,dx, \quad 0 \le x \le H, \tag{2}$$

where x refers to the distance from the anode towards the cathode and θ refers to the acute angle at the anode (see Fig. 1). As a result, the probability of electron dominated induced charge motion is much higher than hole dominated induced charge motion for simple geometric reasons.

Returning to the previous example, consider the number of gamma ray interactions that occur within 1 mm of the cathode. Integrating Eq. (2) from $x = 9$ mm to $x = 10$ mm yields a normalized interaction probability of 16.07%, whereas integrating from $x = 0$ mm to $x = 1$ mm yields a normalized gamma ray interaction probability of 3.93%. Hence, over four times as many events occur within 1 mm of the cathode than within 1 mm of the anode, which serves to demonstrate that the accumulated gamma ray pulse height spectrum will be formed primarily from electron dominated induced charge pulses.

2.2. The small pixel effect

The signal formation from a basic planar type semiconductor detector has a linear dependence between the carrier travel distance and the induced charge [2,3,12,13]. Such a relationship is not true when the contacts of a device are not the same size [10,12]. The "small pixel" effect is a unique weighting potential and induced charge dependence observed with devices having different sized electrodes [10].

In the case that a detector has a small anode and a large cathode, the weighting potential changes much more abruptly near the anode than the region near the cathode. As a result, more charge is induced as charge carriers move in the vicinity of the small anode than charge carriers moving in the vicinity near the cathode. From the natural effect of geometrical weighting, more charge carrier pairs are produced near the cathode over that of the anode. As a result, more electrons will be drifted to the region near the small anode than the number of holes "born" at the small anode. The result is that the induced charge influenced by the electron carriers becomes even greater when the small pixel effect is coupled to the geometrically weighted effect.

The combined effects of geometrical weighting and the small pixel effect cause the formation of a "pseudo-peak", a peak that is gamma ray energy dependent, but forms as a direct consequence of the geometrical shape of the device and the device electrodes. Fig. 2 shows a comparison between modeled pulse height spectra from a 1 cm thick CdZnTe planar detector and a 1 cm tall CdZnTe trapezoid detector, in which the pseudo-peak appears in the trapezoid detector spectrum. Uniform irradiation was assumed in the model (as may be expected with high energy gamma rays). A detailed explanation of this interesting phenomenon will appear elsewhere. The formation of a pseudo-peak enhances the overall resolution of a geometrically weighted semiconductor detector.

2.3. The Frisch grid effect

Device performance is best with the Frisch grid turned on due to the hole charge motion screening [8,9,11]. The Frisch grid acts as the reference plane by which charge carriers induce charge on the anode. Only after electrons pass into the measurement region (see Fig. 1) do they begin to form an

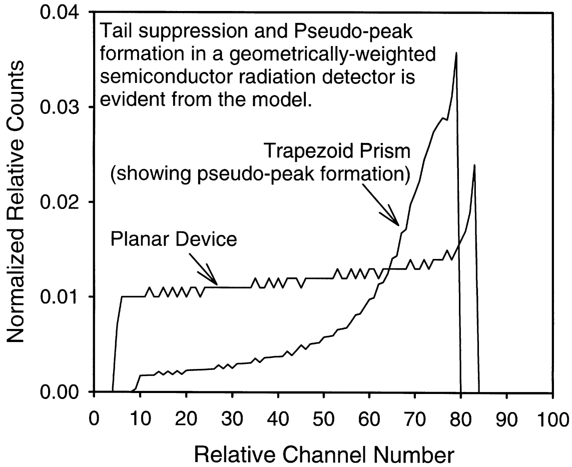

Fig. 2. Modeled results of expected pulse height spectra from a CdZnTe planar detector and a CdZnTe trapezoid prism geometrically weighted detector. The spacing between the anode and the cathode for both is 10 mm. Compton scattering and gamma ray attenuation were excluded from the model.

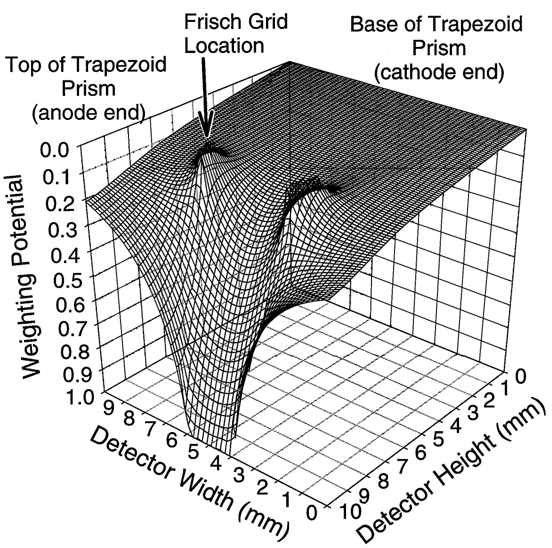

Fig. 3. The weighting potential of a trapezoid prism geometrically weighted Frisch grid radiation spectrometer.

induced charge signal on the preamplifier. Fig. 3 shows the weighting potential [14] of a trapezoid prism Frisch grid radiation spectrometer with the Frisch grid turned on. The weighting potential shows the change in induced charge on the anode as a function of charge carrier change in position along the detector height. The device maintains highly effective interaction region screening but with a much larger interaction region than the parallelepiped Frisch grid design [8,9].

3. Detector performance

Prototype geometrically weighted trapezoid prism devices were fabricated from "counter grade" CdZnTe material. The devices varied in size, the largest having a volume of 1 cm^3. The devices were operated by simply connecting the anode to the input of an Ortec 142A preamplifier, grounding the grid to a common ground, and connecting the cathode to a separate high voltage bias supply. The grid strips were allowed to "float" for tests in which the Frisch grid was turned "off". No cooling or special pulse processing techniques were used during the tests.

Fig. 4 shows room temperature (23°C) 662 keV gamma ray spectra taken with a 1 cm^3 trapezoid prism geometrically weighted Frisch grid detector. Shown is the pseudo-peak formed when the Frisch grid is off, and the full energy peak formed when the Frisch grid is connected. The device demonstrated

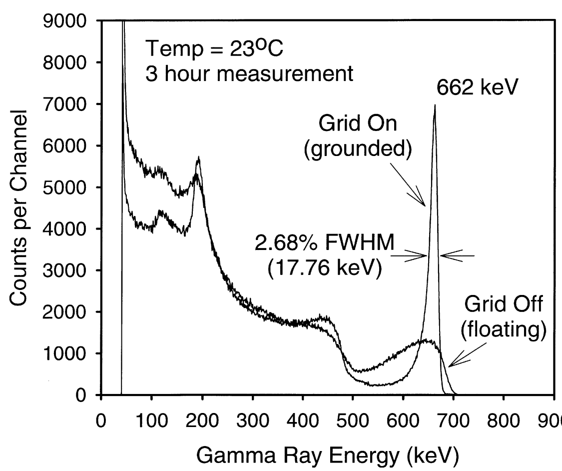

Fig. 4. Room temperature (23°C) gamma ray spectra of 662 keV gamma rays from ^{137}Cs measured with a 1 cm^3 CdZnTe trapezoid prism detector with the Frisch grid off and on.

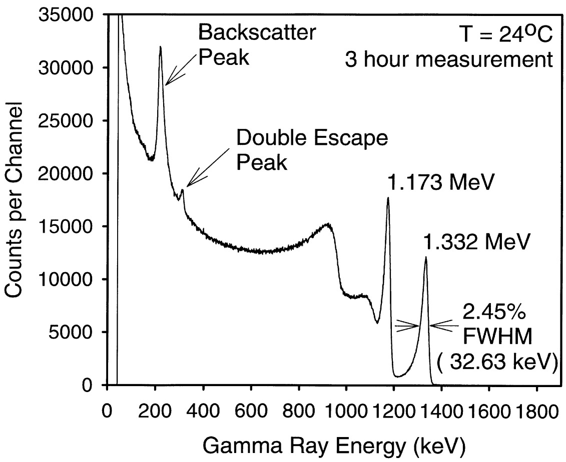

Fig. 5. Room temperature (24°C) gamma ray spectra of 1.173 and 1.332 MeV gamma rays from ^{60}Co measured with a 1 cm^3 CdZnTe trapezoid prism detector with the Frisch grid on.

2.68% FWHM energy resolution for ^{137}Cs 662 keV gamma rays. The calculated intrinsic peak efficiency (number of counts in the peak divided by the number of gamma rays intersecting the device plane) at 662 keV is 2.56%. Fig. 5 shows a room temperature (24°C) spectrum of ^{60}Co gamma rays, in which the full energy peak resolution is 2.45% FWHM at 1.332 MeV. Detail in the spectrum is apparent, including the double escape peak.

4. Conclusions

A room temperature operated 1 cm^3 CdZnTe geometrically weighted trapezoid prism Frisch grid radiation spectrometer has been designed and tested. High resolution is achieved without electronic pulse rejection, compensation or correction techniques. The device operates with standard NIM electronics and a standard charge sensitive preamplifier attached directly to the detector anode. The device dimensions have not been optimized yet, indicating that further improvements in detector performance may be achievable. Other device shapes have been fabricated, including semiconductor pyramid frustums. Detailed results on other designs will appear later.

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