

# **Possibilities to enhance the energy resolution of semiconductor gamma-ray detectors by using Frisch grids**

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## **Abstract**

One principle of energy resolving gamma-ray detection is the collection of free charges created by the interaction of gamma rays with a detector material. However, in some detector materials the energy resolution can be deteriorated by low efficiency in the collection of the positive charge component. A technique to overcome this problem can be to use a Frisch grid, which lets the electron component through and screens the positive component. This technique has been successful for gas detectors.

In this work, different ways to improve the spectroscopic performance of semiconductor gamma ray detectors, in particular CdTe detectors, by applying a Frisch grid have been considered. Previous works show that it is possible to apply the Frisch grid principle to semiconductor detectors and that it enhances the energy resolution. This work examines the possibility to put a Frisch grid at the detector material surface, and let the electrons pass through the grid. The problem to overcome is to create an interface, which allows the electrons to leave the material by having a low enough work function. Another identified possibility is to create the Frisch grid within the detector material itself, so that the electrons do not have to leave the material. Further work has to be done in order to find materials suitable for this purpose.

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# 1 Introduction

Detecting ionizing radiation is important in many different applications. It is used in medicine as well as in different nuclear industries.

In spectroscopic measurements, the emphasis is on determining the energy of the radiation. By analysing the energy spectrum from a radiating source, the components of the source can be identified.

Semiconductor detectors are commonly used for gamma radiation spectroscopy because of the high energy resolution achievable in such devices. Germanium is an often-used semiconductor for gamma detection. Germanium is not the primary choice in portable detectors, because it has to be cooled. For that reason, Cadmium Telluride (CdTe) is interesting as a detector material. CdTe holds a number of properties, which are desirable in gamma detectors, such as room temperature operation and high stopping power. However, CdTe detectors suffer from decreased energy resolution due to poor charge collection efficiency.

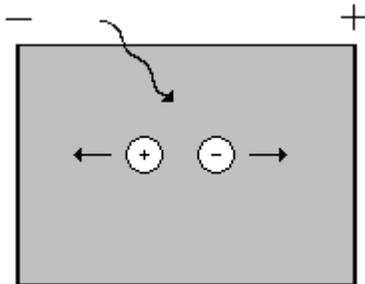
The purpose of this paper is to investigate the possibility of improving the performance of the CdTe gamma-ray detector using a Frisch grid. Frisch grids are commonly used in gas detectors.

## 2 Gamma-ray detection using semiconductors

### 2.1 General principle

Gamma radiation interacts with a semiconductor crystal in different ways, such as Compton and photo effect and pair production. The energy of the gamma radiation is deposited in the semiconductor and electron-hole pairs are generated. It can be noted that only a fraction of the total energy is converted into electron-hole pairs. The number of pairs is however proportional to the deposited energy [1].

A bias voltage is applied over the crystal making the electrons and the holes move towards the anode and the cathode respectively, as seen in figure 1. The moving charge carriers induce a signal that can be measured.



*Fig. 1 Schematic illustration of a semiconductor gamma-ray detector. The energy deposition of the incident gamma quantum generates electron-hole pairs. The electrons and the holes move towards the anode and the cathode respectively.*

### 2.2 Statistical limit for the energy resolution

The FWHM (full width at half maximum) of the peaks in the spectrum is used as a measure of the energy resolution. The FWHM gives an idea of the minimum energy

separating two distinguishable peaks. The relative resolution is defined as

$$R = \frac{FWHM}{E_\gamma} \quad (1)$$

where  $E_\gamma$  is the energy of the incoming gamma.

There is a statistical limit to the resolution, because of statistical fluctuations in the number of charge carriers generated for each interacting gamma. Assuming that the charge carriers are generated in a Poisson process, the statistical limit of the resolution is

$$R = \frac{2.35}{\sqrt{N}} \quad (2)$$

where  $N$  is the average number of electron-hole pairs generated for each gamma and  $\sqrt{N}$  is the standard deviation [2]. It turns out however, that it is not a true Poisson process. To correct for that, the Fano factor  $F$  is defined as

$$F = \frac{\text{observed variance}}{\text{Poisson predicted variance}} \quad (3)$$

The statistical limit for the resolution thus becomes

$$R = 2.35 \sqrt{\frac{F}{N}} \quad (4)$$

For CdTe the Fano factor is somewhere around 0.1 [1].

The ionization energy for CdTe is 4.43 eV [2], which for gamma radiation of 662 keV gives the number of charge carriers

$$N = \frac{6.62 \cdot 10^5}{4.43} = 1.49 \cdot 10^5 \quad (5)$$

and hence the statistical limit of the resolution

$$R = 2.35 \sqrt{\frac{0.1}{1.49 \cdot 10^5}} = 0.0019 \quad (6)$$

which means a resolution of 0.19%, or 0.93 keV, at 662 keV.

## 2.3 Stopping power

To function as a gamma detector, the detector material must meet certain criteria. To detect gamma radiation of high energy, ~1MeV, a high stopping power is needed. The stopping power of a material depends on its atomic number,  $Z$ , and its density. The larger the  $Z$ , the higher the detection efficiency. As an example, the atomic number for germanium is 32, and for CdTe it is 48/52. To some extent, a larger detector volume could compensate for a small  $Z$ . However, for some materials it is difficult to make large crystals of high purity.

## 2.4 Ionization energy and band gap

The statistical limit of the energy resolution of a particular semiconductor detector depends on its ionization energy. If the number of electron-hole pairs created for each incident gamma quantum of certain energy is large, a better resolution can be expected (see section 2.2 about the statistical limit for the resolution). Accordingly, a material with low ionization energy is required for a detector of high energy resolution.

Following from equation (4), the energy resolution can be expressed as

$$R = 2.35 \sqrt{\frac{F}{N}} = 2.35 \sqrt{\frac{F}{\frac{E_\gamma}{E_i}}} = 2.35 \sqrt{E_i} \sqrt{\frac{F}{E_\gamma}} \quad (7)$$

where  $E_\gamma$  is the energy of the incoming gamma quantum and  $E_i$  is the ionization energy. Figure 2 shows how the statistical limit for the resolution depends on the ionization energy, assuming that the Fano factor,  $F$ , is about 0.1 and that there is no dependency between the ionization energy and the Fano factor. The energy resolution is thus proportional to the square root of the ionization energy, as shown in equation (7).

However, the ionization energy is closely related to the size of the band gap [2]. As a rule of thumb, the ionization energy is about three times the band gap. In order to work properly at room temperature, the band gap has to exceed 1.5 eV. Otherwise the thermal noise level will be too high. This results in a trade off between low ionization energy and wide band gap.

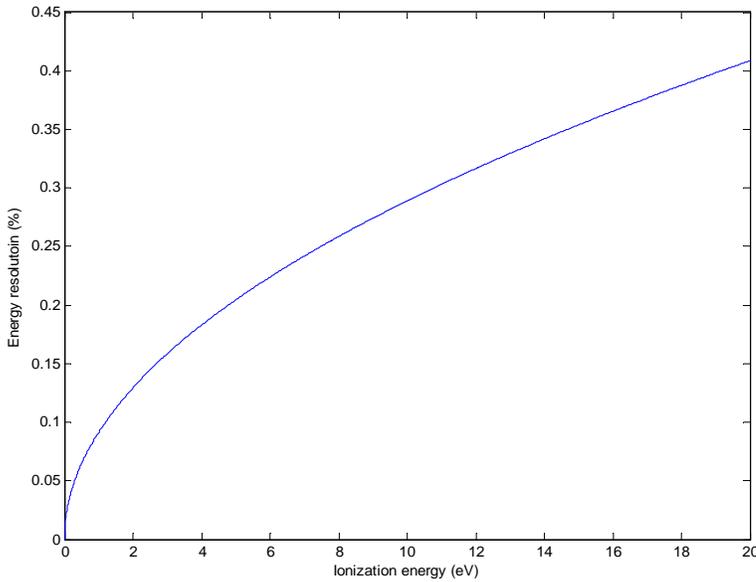


Fig. 2 Energy resolution vs. ionization energy, calculated at 662 keV using a Fano factor of 0.1.

## 2.5 Charge carrier mobility

The charge collection efficiency is crucial for the resolution. For an efficient charge collection, the charge carrier must travel easily through the material. If the mean distance traveled by both the electrons and the holes is shorter than the distance they have to travel to reach the electrodes, i.e. the thickness of the detector, some of the charge carriers will be lost and never collected. The mobility of the electrons,  $\mu_e$ , and the holes,  $\mu_h$ , tells us which velocity they gain at a certain bias voltage. The mean distance the charge carrier travels through the crystal is then determined by its average lifetime,  $\tau_e$  and  $\tau_h$ . Consequently, it is important that the semiconductor has a high mobility for both electrons and holes, and that the lifetime of the charge carriers is long enough. An example of a detector material with good mobility is germanium, which has  $\mu_e = 36\,000$

$\text{cm}^2/\text{Vs}$  and  $\mu_h = 42\,000\text{ cm}^2/\text{Vs}$  (at the normal operating temperature for germanium of 77 K).

The reason that charge carriers do not survive is due to trapping. Where there is an impurity in the crystal, there can be a potential well, in which the charge carrier is trapped. Even though detrapping may occur, the signal is still distorted because of the time delay. Therefore the purity of the crystal is very important to the charge collection process.

## 3 Cadmium Telluride

### 3.1 Advantages of CdTe

The semiconductor CdTe fulfils most of the criteria to be a detector material. It has high Z of 48 for Cd and 52 for Te, which provides for a good stopping power. A large number of charge carriers are produced for each incident gamma quantum because of the fairly low ionization energy of 4.43 eV per electron-hole-pair.

In addition, the band gap of 1.5 eV allows for use at room temperature without cooling. For these reasons, CdTe is very interesting as a semiconductor gamma detector.

### 3.2 Disadvantages of CdTe

Despite all positive properties accounted for above, the energy resolution of the CdTe detector is severely reduced due to poor charge collection efficiency. The mobility of the charge carries in the crystal is  $1000\text{ cm}^2/\text{Vs}$  for the electrons and  $80\text{ cm}^2/\text{Vs}$  for the holes. Impurities in the crystal form trapping centers where the charge carriers, particularly the holes, are trapped and therefore never are collected. When a significant fraction of the holes are trapped, the signal will not reach the amplitude corresponding to the deposited energy. Since the trapping occurs quite randomly, the resolution is deteriorated.

### 3.3 Commercially available CdTe detectors

Portable CdTe detectors are today commercially available. They offer a resolution of down to 0.5 %. Different methods are used to achieve this:

- Amptek offers two kinds of CdTe detectors that use two different ways to enhance the energy resolution. The XR-100T-CdTe is equipped with a rise time discriminator (RTD). The discriminator is set to accept only pulses with a rise time lower than a certain value. The rise time of the pulse depends on where the interaction takes place in the crystal, near the anode or near the cathode. When the interaction occurs near the cathode, there is a higher risk of trapping, because the holes have a longer way to travel. The rise time for these pulses will be longer because the holes are traveling slower than the electrons. By excluding the pulses with long rise time, only the pulses with full, or nearly full, charge collection – corresponding to interaction near the anode – are taken into account. This enhances the resolution, but lowers the efficiency. More than 50 % of the pulses can be discarded, which means that half of the detector volume is never used. This detector has a resolution of 1 % (1.2 keV) at 122 keV [3].

- Amptek's XR-100T-CdTe-stack consists of three thin, stacked detectors. Each detector is 0.75 mm thick. Since the charge carriers have a shorter way to travel in a thinner detector, the risk of trapping is lower and the charge collection is more efficient. However, if the detector is too thin, most of the radiation will just pass through it. Three detectors are therefore stacked to increase the stopping power. This detector has a resolution between 0.75 and 1.5 % (5.0 – 10.0 keV) at 662keV [4].
- Gammadata's Radiant 200 Portable CdTe has a resolution of 0.5 % (3.0 keV) at 662keV and 1.6 % (2.0 keV) at 122 keV). This detector's resolution is enhanced using charge loss correction (CLC) [5]. Instead of discarding the pulses with long rise time, as in the RDT-method, the CLC-method makes a correction for the charge loss in each pulse. This way, a high efficiency of the detector can be sustained.

All of these detectors are cooled, using a Peltier cooler, to allow for a higher bias voltage. A high bias voltage facilitates the charge collection, but requires cooling to avoid leakage current.

## **4 Applying a Frisch grid to semiconductor detectors**

### **4.1 Information carriers**

The information about the energy of the detected gamma is brought to us through the movement of the charge carriers. The movement of the electrons and the holes cannot be distinguished from each other, though the electrons seem to be safer as information carriers than the holes. Since the number of electron-hole pairs is proportional to the deposited energy, the number of electrons is also proportional to the energy and looking at the electrons alone would suffice. The problem is to separate the electron component of the signal from the hole component.

### **4.2 The principle of the Frisch grid**

The Frisch grid is used in ion chambers to separate the electron component from the hole component of the signal. It works as shown in figure 3. There is an electrode in the form of a grid between the cathode and the anode. The electron-hole pairs are created in the active volume to the left in the figure. The electrons pass through the grid and move on towards the anode. The signal is then measured over the volume between the grid and the anode. This way, the hole component is excluded because the only charge carriers moving between the grid and the anode are the electrons.

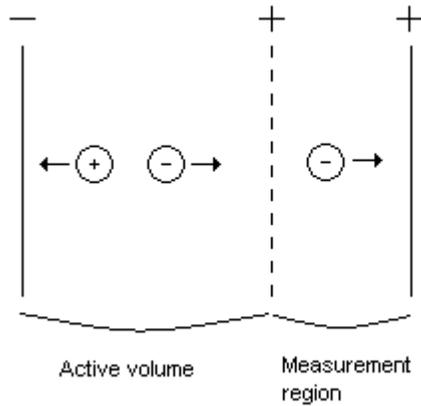


Fig. 3 The electrons pass through the Frisch grid in the ion chamber. The signal is measured between the grid and the anode, and the contribution of the holes is screened.

### 4.3 Applied approaches of a Frisch grid on CdTe

#### 4.3.1 Control electrode

Applying the principle of the Frisch grid to semiconductor detectors creates complications because of difficulties placing a grid inside the crystal. Successful attempts have been made to do Frisch-like designs on the surface of the crystal. By alternating the electrode geometry, single-charge sensing can be achieved.

A simple approach is the use of a control electrode. The anode is centered in the middle of the side opposite to the cathode. The anode is surrounded by the control electrode, which is at a lower bias than the anode, see figure 4. The purpose of the control electrode is to enhance the near-field effect and to shape the electric field in such a way that the electrons reach the anode faster than they otherwise would. An energy resolution below 3% at 662 keV, and as low as 0.72 % at 511 keV, is reported for this design [6].

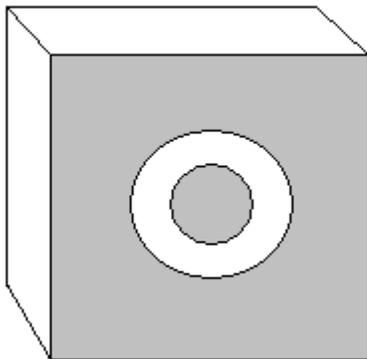
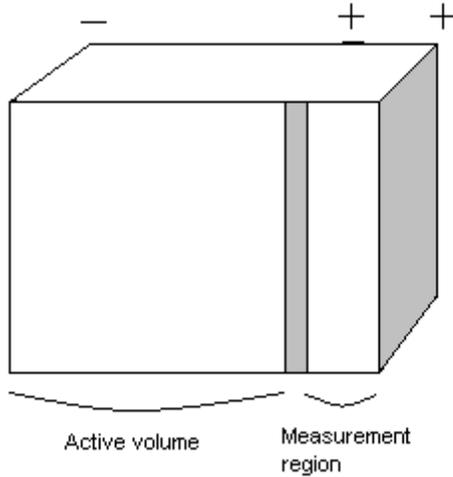


Fig. 4 A control electrode design. The anode is centered in the middle of the surface, surrounding it is the control electrode.

#### 4.3.2 Parallel-strip design

In the parallel strip design, strip contacts are placed on the crystal to resemble the Frisch grid. The crystal is divided into an interaction region (to the left in figure 5) and a measurement region. The output signal is read between the strips and the anode. The

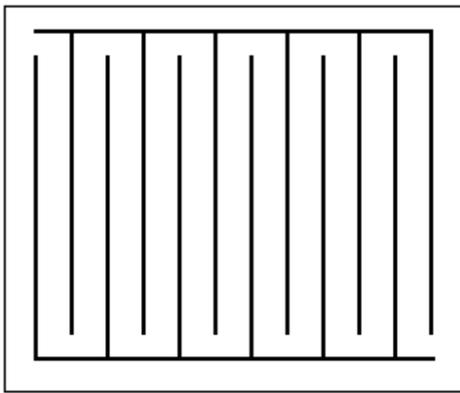
strips are at a lower bias than the anode. An energy resolution of 5.9% at 662 keV is reported for this design [7].



*Fig. 5 The strip electrodes on the sides of the detector are similar to a Frisch grid. The measurement region is so much smaller than the active volume that interactions within the measurement region do not contribute significantly to the signal.*

### 4.3.3 Coplanar grid

The most common Frisch-grid design is the coplanar grid pattern. The anode is divided into two grid electrodes, as shown in figure 6, at different bias. The signal is taken as the difference between them. The electrode at the lower bias corresponds to the Frisch grid in the ion chamber, and the one at the lower bias corresponds to the anode. An energy resolution of 3.2% at 662keV is reported for this design [8].



*Fig. 6 Schematic view of the coplanar grid pattern on the surface of the detector crystal.*

## 4.4 Alternative Frisch-grid approaches

### 4.4.1 CdTe – grid – vacuum

Theoretical considerations suggest that the possibility of making a true Frisch grid on the crystal surface is quite difficult to realize. The problem seems to be the need to make an interface at the grid, through which the electrons can pass easily.

One approach to apply a true Frisch grid could be to put a grid electrode on the crystal surface, allowing the electrons to leave the surface through the grid, see figure 7. The electrons may then be accelerated over a vacuum towards the collecting anode. The output signal can then be measured over the vacuum.

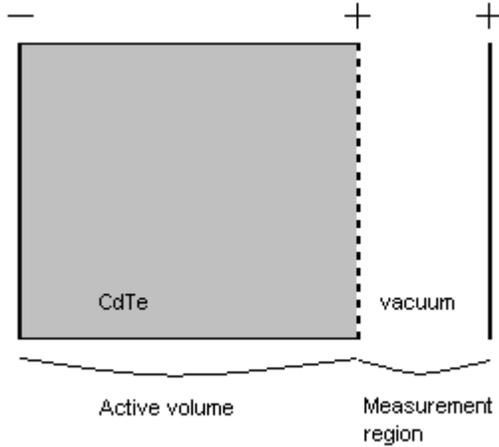


Fig. 7 A schematic illustration of a Frisch grid on the surface of the CdTe crystal. The electron-hole pairs are generated in the crystal. The electrons then leave the crystal through the grid and are collected at the anode. The vacuum acts as the measurement region.

Another option could be to cover the entire side, opposite to the cathode, of the crystal with an electrode, as shown in figure 8. Provided that the electrons have enough kinetic energy, they would then pass through the metallic layer and be collected at the anode on the other side of the vacuum.

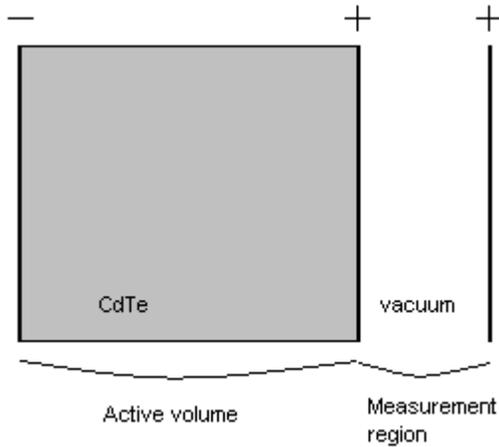


Fig. 8 Similar to figure 7, but the grid electrode is replaced by a solid surface electrode.

The first thing that needs to be considered in both of these designs is ability of the electrons to leave the surface of the crystal or the metal. This ability is expressed by the work function of the material.

To leave the surface of the crystal, the electrons must have energy higher than the work function of the material. The work function of a semiconductor is typically a few

eV. The kinetic energy of the electrons moving in the CdTe crystal is of the order  $10^{-7}$  eV, depending on the bias voltage. The work function cannot be overcome by increasing the bias voltage, because a breakdown will occur if the bias is too high [9].

It can be noted that the work function is lower for a transition from a semiconductor to a metal. However, the work function for the electrons to leave the metal is still of the order a few eV, and accordingly the kinetic energy of the electrons is too low. By applying a very strong electric field over the vacuum, the electrons can leave the metallic surface by field emission. But a problem associated with field emission is that it may make the electrons leave the surface in a random manner. Not only will the electrons constituting the signal take part in the field emission, but as will all the electrons in the metal. Therefore it is plausible that this approach will not work.

#### 4.4.2 CdTe – grid – semiconductor

A second approach would therefore be to fill out the vacuum in figure 7 with a suitable material, see figure 9. This material should possess high resistivity, e.g. a semiconductor. The crucial point here is how the electrons pass from one semiconductor to another.

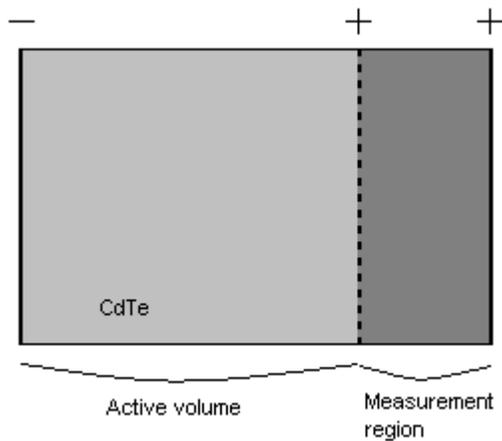


Fig. 9 A schematic sketch of a semiconductor detector with an embedded Frisch grid. The measurement region should contain a material for which the work function will not stop the electrons from leaving the active volume.

The preparation of the contact surfaces is important to make the transition easy. Both the surfaces should be highly n-doped. But only a very thin layer at the surface has to be doped.

For good contact between the two semiconductors, the second one may be put there by chemical vapour deposition (CVD). The first layer should be doped. The potential difference between the two materials depends on their band gaps and electron affinity. These have to match to facilitate the passage from one semiconductor to another [10].

## 5 Summary and discussion

The need for portable gamma radiation detectors, that may operate at room temperature, have resulted in many different solutions to the problem of poor charge collection efficiency, exhibited by CdTe detectors. The energy resolution of commercially available detectors at 662 keV is about 1%. For some detectors a resolution as low as 0.5% have

been demonstrated, which is quite close to the statistical limit of 0.2% for the resolution. The best detectors use techniques such as pulse shape discrimination (PSD) or charge loss correction (CLC).

Various methods of using a Frisch grid in semiconductor detectors has earlier been proven to improve the energy resolution. But it has not yet reached the resolution achieved using PSD or CLC.

An alternative way to use a Frisch grid in semiconductor detectors could be to put a grid on the detector material surface, as suggested in this work. However, as noted, the work function is too high for the electrons to leave the crystal and enter a vacuum.

Accordingly, it's necessary to find a way to create an interface between the detector crystal and the additional material where the electrons do not get trapped, leading to a CdTe – grid – semiconductor design. The contact between the two semiconductors depends not only on the material properties, but also on the crystal growth process. The next step towards a CdTe detector of this design is to find a matching semiconductor to put on the other side of the grid. In connection to this choice, one has to consider how to grow the crystals on each other with the grid in between.

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