New Results from Performance Studies of Frisch-Grid CdZnTe Detectors

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ABSTRACT

New data regarding performance studies of Frisch-grid CdZnTe (CZT) detectors are presented. The Frisch-grid detector configuration under investigation is a bar shaped CZT crystal with the side surfaces coated with an insulating layer. A Frisch grid is fashioned by inserting the CZT bar into a metallic sleeve, or by depositing the metal directly upon the insulator; hence the semiconductor material does not come in contact with the metal grid. The simple design operates well as a single-carrier-sensitive device. Despite the simplicity of this device, its performance depends on the balanced combinations of several factors, including the bulk and surface conductivity, $\mu\tau$ product, and geometrical aspect ratio. Described are several effects that determine charge collection in such drift devices and, consequently, the performance of the non-contacting Frisch-grid configuration.

Keywords: CdZnTe, Frisch-grid, gamma-ray detectors

1. INTRODUCTION

Many application fields presently using gamma-ray spectrometers, ranging from gamma-ray astronomy to homeland security, will greatly benefit from the realization of large area/volume room-temperature-operated CdZnTe (CZT) detectors. Unfortunately, two major obstacles still inhibit their practical use. First, the size of commercially available CZT crystals is small, typically less than 15x15x10 mm$^3$, which means that discrete crystals have to be assembled into arrays or stacks in order to produce large effective area detectors with increased active volumes. Further, the cost of the CZT starting material and the yield of high-quality crystals of such size is poor, which tends to greatly inflate the cost of CZT detectors. The second problem is related to the fact that CZT detectors suffer from poor “hole” carrier transport, which works to reduce the achievable resolution for these devices, especially for moderate to high energy gamma rays (> 100 keV).

Single-charge-carrier detector designs have been implemented to overcome the deleterious effects of incomplete hole collection upon gamma-ray energy resolution. The most successful designs include the small pixel effect device, the co-planar grid device, and the virtual Frisch-grid device [1]. The small pixel effect device delivers good energy resolution, and also has the advantage of rendering information on spatial interaction locations; hence, allowing for operation as an imaging array. The devices do suffer from charge sharing between pixels, and the electronics can be challenging. The co-planar configuration is another successful detector concept, yet the configuration operates only as a single element spectrometer and is not an imaging device.

The third detector configuration, the virtual Frisch-grid device, has been successfully used for crystals > 1 cm$^3$ volume [2,3]. The principal difference to that of pixel and coplanar-grid detectors is that the virtual Frisch grid device is actually designed to mimic the charge shielding effect introduced by O. Frisch [4,5]. The first such semiconductor
detector was presented as a simple semiconductor bar with side conductive sides strips acting as the Frisch grid [6]. A variety of permutations on the design have been proposed [7,8], yet the basic concept uses a semiconductor slab with the Frisch grid fashioned on the sides or otherwise around the circumference of the device. The charge collection electrodes are generally fabricated such that free charge carriers must transit between the Frisch grid elements to the measurement electrode. Variations on the concept, including geometrically-weighted devices, coated-periphery devices, and virtual Frisch grid devices, have been documented in the literature [2,9,10-12].

The Frisch-strip (or ring) device [1,7] uses parallel strips fabricated on either side, or the circumference, of a semiconductor block. Such detectors are three terminal devices, but require only one preamplifier for the output signal. The side strip can be negatively biased to assist the steering of electrons toward the anode. A variation of the Frisch ring device that is commercially available is a coated-periphery detector [9]. The device has a conductive ring around the circumference of the device that extends from the planar cathode up the sides of the detector. However, in such geometry, only the area close to the cathode is effectively shielded, consequently, the device works as an excellent spectrometer for low energy photons, but only for events absorbed near the cathode. In another version of the Frisch-strip (or ring) device [7], the shielding electrodes are separated from the crystal surface by a thin layer of dielectric material. The electrodes can be kept either at ground or the cathode potentials. The non-contacting strip (or ring) device greatly reduces the leakage current between the grid and anode, a common problem for co-planar grid and Frisch-strip devices. Further, the drift field can be tailored to be more uniform than the simple Frisch-strip design. A unique aspect to the non-contacting Frisch grid device is the simplicity, yet the spectral performance can be outstanding.

The simplest version of the non-contacting Frisch grid device is configured from a CZT parallelepiped bar, in which the ends of the bar are coated with conductive electrodes. The configuration resembles a common planar detector. The device sides are then coated with an insulator, which is then inserted into a conductive ring or tube that serves as the Frisch grid [7,8,10-12]. One such variation of the non-contacting Frisch ring detectors has the ring covering the entire region between the anode and cathode electrodes [10]. The bar-like shape of such Frisch-grid devices makes them ideal building blocks for assembling large arrays, which can provide a large effective area, excellent energy resolution, and good spatial resolution at comparatively low production cost.

The goal of the present effort is to develop an array of virtual Frisch-grid CZT detectors for gamma-ray imaging and spectroscopy. Previous reported results from prototype virtual Frisch-grid devices demonstrated excellent energy resolution of <1.7% FWHM at 662 keV[12]. However, it was observed that the detectors, when re-fabricated from the same CZT crystal, had wide variations in performance (from poor to excellent), thereby demonstrating the importance of the sample preparation and fabrication procedure. Temporal changes were also observed with the detector responses, still not yet fully understood. New results on the development of the fabrication technology for CZT non-contacting Frisch grid bar detectors are presented in this paper.

2. EXPERIMENTAL SETUP

CZT crystals were acquired from eV-Products and Saint-Gobain, originally sized at 5x5x7 mm³ and 5x5x6 mm³, respectively. The commercial CZT samples were re-shaped into the bar detectors with the different length-to-width ratios. Fabrication of the bar-shaped CZT detectors was conducted as previously described [12].

Crystals obtained from Saint Gobain were hand polished and etched briefly with a 2% bromine/methanol solution. Electroless Au contacts were applied only to the ends [14], thereby forming the anode and cathode contacts. Afterwards, the side surfaces were polished further to reduce side-surface leakage current. The samples acquired from eV Products were already formed as detectors [9], hence the original Pt-sputtered contacts that came with the devices were kept at the ends, and only the sides were hand polished. For the initial measurements, chemical treatment of the side surfaces (except for cleaning in acetone and DI water) was excluded from the process. However, after taking radiation measurements, the results of which indicated further surface treatment was necessary, the devices were treated with a NH₄F/H₂O₂ solution [13].
The basic design of the virtual Frisch-grid devices investigated is shown in Fig. 1. After the bar devices were fabricated, the side surfaces of the device were wrapped with Teflon tape. Afterwards, Cu tape was wrapped around the device over the Teflon tape such that one side of the Cu tape was flush with the cathode. A small tab of Cu bent over the edge connected the Frisch ring and cathode together, thereby allowing the same voltage to be applied to both. During the measurements, the detector under test was placed inside a standard eV-Products device holder (Fig. 2). With the cathode grounded, a pogo-pin was used apply voltage to the anode. Radioactive check sources, including $^{68}\text{Ge}$, $^{137}\text{Cs}$, and $^{60}\text{Co}$, were used to observe the spectroscopic properties of bar detector. For $^{137}\text{Cs}$ irradiation, the source (2-mm thick metal disk) was placed underneath the cathode. The radioactive area of the $^{137}\text{Cs}$ source is a 5-mm diameter area located in the center of the disk. The CZT Frisch-ring detector was installed in the holder such that the cathode was located directly above the radioactive spot, thereby irradiating the cathode side of the detector. The signals were measured from the positively biased anode with a capacitively-coupled eV Products 550 preamplifier. The data acquisition system included a spectroscopy shaping amplifier, MCA card, digital oscilloscope to store waveforms, and standard NIM electronics. The readout signals could be digitized and electronically shaped for further analysis.

It should be mentioned that the approach described to fabricate the Frisch-ring detectors has two drawbacks. First, the Teflon tape introduced a ~300 µm gap between the CZT surface and the cooper layer which slightly reduces the shielding effect of the Frisch ring. Second, since the eV-Products holder used provides only a single BNC connector for the detector, the Frisch ring and cathode were both grounded and positive bias was applied to the anode. As a result, a ~1 mm wide gap was kept between the edge of Cu tape and the anode, which works to reduce the shielding effect of the Frisch ring in the region close to the anode.

3. DEVICE MODELING

There is a direct analogy between a virtual Frisch-grid CZT device and a classic gas ionization chamber with a shielding grid actually located near the anode. The shielding grid inside the gas ionization chamber, which allows for nearly 100% electron transmission, electrostatically shields the anode from the charges in the region between the cathode and grid. Charge induction upon the anode is mainly generated as the electrons travel in the space between the grid and the anode, whereas the grid screens charge induction from slow moving positive ions drifting towards the cathode. In a semiconductor device, electrodes placed on the lateral surfaces create a virtual Frisch grid inside the crystal, thereby shielding charge carrier induction. The shielding efficiency of the virtual grid depends on the grid separation distance (or diameter) and the aspect ratio (L/W ratio). In both types of detectors, “poor” shielding or, using terminology applied for gas ionization chambers, shielding inefficiency of the grid, results in poor energy resolution. Device performance optimization, which includes a balance between efficiency and energy resolution, depends strongly upon the L/W ratio, device volume, and grid separation distance.

3.1 Induced signals

The virtual Frisch-grid devices presently under investigation can be considered as rectangular metal boxes with square cross-sections, of which the top and bottom surfaces form the anode and cathode, while the side surfaces are outfitted to form the Frisch ring. The problem of finding the electrostatic potential created by a point-like charge inside a grounded metal box can be solved analytically [15]. Hence, by modeling the detector in the same fashion such that all sides are...
coated with a conductor while retaining the fact that an insulator separates the anode from the other conductors, it is possible to demonstrate the single-carrier dependence upon the anode. The total charge induced on the anode can be calculated by integrating the normal component of the electric field strength over the anode area.

Fig. 3 shows the dependence of the induced charge on the anode versus the distance from the anode for different ratios of the anode width to the detector length. A source charge is located in the middle of the box. The same curves represent temporal dependencies of the signal from a charge-sensitive preamplifier as the charge drifts between the cathode and the anode. As is seen, for small aspect ratios, the majority of the signal is induced near the anode. This illustrates a formation of the virtual grid.
Continuing with the metal box model, Fig. 4 shows four sets of the normalized voltage pulses from the charge sensitive preamplifier as induced within a 3x3x6 mm$^3$ detector operated at 1500 V. In Figure 4a the hole lifetimes were modeled as 0.1 µs, and in Figure 4b the hole lifetimes were modeled as 1.0 µs. The pulse shapes were calculated for interaction points located along the detector’s central axis at several distances from the anode (denoted on the graphs as ranging from 1 mm to 6 mm). In the calculations, it was assumed that the electron and hole mobilities were 1000 and 50 cm$^2$/V·s, respectively. Also, the electron lifetime was modeled as 5 µs with a uniform drift field inside the detector. As shown, the long-rising pulses from the Frisch ring detector, which corresponds to the hole movement, are generated only by a very small fraction of the events interacting within a 1 mm space near the anode. Further, the effect is worse for long hole lifetimes (~1 µs). Figure 4c shows the waveform calculated for the same conditions as before, except the cathode bias and hole lifetime are 600 V and 0.1 µs, respectively. Finally, Fig. 4d shows the pulses calculated for the events along the line located 2.5 mm off center of the detector (in the corner). The latter illustrates that for the events produced close to the edge, where the Frisch ring provides better shielding, the induced signals are generated close to the anode for all cases.

3.2 Pulse-height spectra

Figure 5 shows the dependence of the amplitude of the induced signals versus the position of the point of interaction calculated under the same conditions as described above (it is assumed that the points of interactions to be located along the central axis of the detector). The amplitude of the induced signal stays almost unchanged between the cathode and imaginary grid, which serves to demonstrate the formation of the virtual Frisch grid. For the events located off center of the detector, the shielding effect of the Frisch ring is even stronger.

Another method of visualizing the expected charge induction dependence is by using the “weighting potential” concept [16]. Laplace’s equation can be solved to yield the expected charge induction distribution for a Frisch ring device. Figure 6 shows a numerical solution to the expected charge induction distribution across and center of a 3x3x6 mm$^3$ Frisch ring device with a 5mm long Frisch ring extending from the cathode towards the anode, leaving a 1 mm gap between the anode and ring edge. The change in induced charge is evidently most salient as charge carriers pass beyond the ring edge and move in the volume between the Frisch ring and the anode. Notice that the shielding separation improves for charges moving off center towards the anode.

Figure 7 shows a succession of pulse-height spectra simulated for 7 mm thick Frisch ring detectors with different lateral sizes: 15x15, 10x10, and 5x5 mm$^2$. The electron and hole mobilities were modeled as 1000 and 50 cm$^2$/V·s$^{-1}$, respectively, the electron and hole lifetimes to be 5 and 0.1 µs, respectively. The drift field inside the detector was modeled as being uniform. The geometry of the simulated experiment is shown in Fig. 2. The simulation indicates that the peak width in the spectrum for the 5x5 mm$^2$ detector is mostly determined by the electronic noise, which was modeled using a value of 2 keV FWHM.
Fig. 7. Simulated spectra from $^{137}$Cs for three bar detector geometries: (a) 15x15x7, (b) 10x10x7, and (c) 5x5x7 mm$^3$. Electronic noise was modeled as 2 keV FWHM, and an electron $\mu$-product was modeled as 5x$10^{-3}$ cm$^2$V$^{-1}$.

Fig. 8. Examples of pulse-height spectra measured with Frisch ring detectors that had poor responses.
4. RESULTS AND DISCUSSION

Significant variations in the pulse-height spectra were observed with Frisch ring detectors fabricated as previously described. Detectors re-fabricated (re-polishing, new shield, etc.) from the same material yielded varying results, which suggests that internal crystal defects cannot completely explain poor detector responses. Fig. 8 shows examples of pulse-height spectra measured with the detectors that had poor responses. The spectra were collected for two orientations of a CZT crystal inside the detector’s assembly (top and bottom sides were switched by placing the crystal up-side down). Generally, satellite peaks, strong tailing, and large low-energy background are very common features of the “bad” detectors. Similar behavior was observed with commercially purchased devices (eV Products) configured with the coated-periphery technology [9].

To better understand the cause of the poor detector responses, output signal waveforms from the preamplifier were collected and processed digitally to accumulate pulse-height spectra. The measured waveforms were classified into two categories according to the duration of the leading edge, those being: “fast” and “slow” rising pulses. Examples of fast and slow rising pulses are shown in Fig. 9. The fast-rising pulses correspond to the ordinary events that produce a good pulse height spectrum. In contrast, the slow-rising events, which were unexpected, result in a degraded pulse height spectrum, most likely due to the ballistic deficit. As illustrated in Fig. 10, there is a demonstrated improvement in pulse-height spectra with increasing shaping time measured with a “bad” detector.

As shown in Fig 9b, the slow-rising pulses have a specific shape. The fast-rising leading edge expected from the device (see Fig. 4) is followed by a slow-rising portion with an extended rise time of a several microseconds (even with high cathode bias voltages). It was observed that poor spectral response correlates with devices having a large fraction (>50%) of pulse rise-times with a significant slow-rising component (slow-rising pulses), while the “good” detectors have only a small fraction of such events. Comparing the measured slow rising pulses to the expected ones calculated above, one observes that the slow-rising pulses cannot be explained by the contribution of the slow moving holes, otherwise, one should assume unrealistically long hole lifetimes and very poor shielding provided by the Frisch ring. It is postulated that the slow-rising pulses are resultant from electrons slowly drifting inside the detector volume where weak electric fields may be present (or, perhaps, low electron mobility may be present). Furthermore, some detectors showed very good spectral responses; in which there was observed a general tendency that CZT detectors fabricated with the rougher lateral surfaces yielded better spectra, even though they had higher electronic noise and leakage current. These observations have a straightforward explanation: the less polished crystal surfaces cause a higher surface leakage current, which, in turn, results in more uniform electric field distribution inside a detector, thereby improving the charge collection efficiency. However, reliable surface control is difficult to achieve with simple mechanical polishing. A more reliable method of producing such a conducting channel upon the surface is with a chemical process.

Fig. 9. Examples of normal and abnormal waveforms measured from a “bad” Frisch ring detectors.

Fig. 10. Improvement of a detector response by increasing the shaping time.
Fig. 11. Pulse height spectra measured with a “good" 3x3x6 mm³ Frisch-ring detector.
Good detectors were fabricated by applying a chemical treatment as described in Ref. [13], in which highly polished crystals were submersed for several minutes in a NH$_4$F/H$_2$O$_2$ solution. The best results obtained thus far are with detectors processed with the treatment.

Fig. 11 shows the best spectra thus far achieved with a 3x3x6 mm$^3$ Frisch ring device. The energy resolution was measured at 1.3% FWHM for 662 keV and 1.5% FWHM for 511 keV, are excellent results for a 6 mm thick CZT detector. The Compton continuum in the $^{137}$Cs spectrum is suppressed, perhaps as a result of the placing the radioactive source near the detector cathode. In contrast, the detectors with poor response usually show enhanced Compton continua in the low energy regions, most likely a consequence of low energy tailing from the full-energy peaks. The modeled results of Fig. 7a and the measured results of Fig. 11 are quite obviously similar, except for a small low energy tail on the left side of the measured peak.

Digital pulse processing was used to analyze the waveforms measured from the “good” and “bad” detectors. For every waveform, the algorithm evaluates the rise times of the fast and slow portions of the signal as illustrated in Fig. 9b. The fast rising time is the time interval between the beginning of the pulse and the moment corresponding to the intersection of two extrapolating lines: the first line extrapolates a fast leading edge (calculated by fitting a leading edge around the point corresponding to one half of the amplitude); the second line extrapolates the saturating part of a waveform (calculated by fitting the last 500 points of the recorded waveform). The slow-rise time corresponds to the curved portion of the waveform that “smoothes” the corner between the fitted lines. The fast-rise time represents an expected drift time of the electron cloud transiting from the point of interaction to the anode. The slow-rising time is due to the “slow-drift-regions” located close to the anode. The physical interpretation and origin of these slow-drift-regions is under investigation, and yet not fully understood. To evaluate the amplitude of the signals, the algorithm takes the difference between the base line and the pulse level as calculated by averaging the waveform data points over two 100 ns long time intervals (in the present case, these time intervals provide the optimal signal-to-noise ratio). To avoid the ballistic deficit a time delay of ~ 500 ns between the first and second integration windows was used.

Fig. 12 shows the correlation between the amplitude of the signals and the slow and fast rise times, with Fig. 12a and Fig. 12b exhibiting “good” and “bad” detectors, respectively. The detectors were irradiated with gamma rays from a $^{137}$Cs source. While the “good” detector shows no correlation, the “bad” detector shows that the decay of the amplitude for the long rise times is due to ballistic deficit. Moreover, in the later case, the track of the data points corresponding to the 662 keV peak enlarges towards the low amplitudes as the slow rise time increases, which indicates that the slow events are associated with charge losses, which means that extending the delay between the time windows (to overcome a ballistic deficit) will yield only moderate improvement in the energy resolution. It is believed, therefore, that these two factors result in a poor spectral response of the detectors, which is supported by the data of Fig. 13, where we show two pulse-height spectra evaluated by using analog (Fig. 13a) and digital pulse processing (Fig. 13b). A notable improvement in the energy resolution can be achieved by rejecting the events with the slow rising times above 300 ns as shown in Fig. 13c; however, this improvement is gained at the expense of the detection efficiency. Spectra evaluated in a similar way for the “good” detector are shown in Fig. 14. As shown in the uncorrected spectra, the 662 keV peaks have a low energy tails, which can be explained as interaction events occurring close to the anode where the Frisch ring does not provide effective shielding. Using the analogy with the gas ionization chamber, this effect corresponds to the interactions taking place between the grid and the anode. Such undesirable events can be rejected by appropriately setting the threshold on the fast rising times, and such a “corrected” spectrum is shown in Fig. 14c. As demonstrated in Fig. 14c, the amplitude of the peak is practically unchanged, while the tail and Compton background are notably reduced.

5. CONCLUSIONS

The virtual Frisch-grid detector has a simple design and operates as a single-carrier device. Despite a simplicity of this device, its performance depends on the balanced combinations of several factors. One of the critical factors is the electric field distribution inside the detector, which also shows a strong correlation with the CZT surface treatment. It was observed that poor spectral responses correlated to those devices with a high percentage of events with the slow rising pulses, which, due to ballistic deficit, cannot be corrected or processed with a standard shaping amplifier. The origin of such events is presently believed to be resultant from a “defocusing” drift-field inside the detectors. That is, a fraction of the electric field lines intersect the detector surfaces instead of extending to the anode. The charges drift to the surface regions with electronic properties different from the bulk of CZT, which include lower mobility, higher trap concentration, etc. New measurements with a highly collimated X-ray beam at the BNL the synchrotron light source at are presently being arranged as attempt to measure the proposed “defocusing” electric field effect.
Fig. 12. Correlation between the amplitude of the signals and the slow and fast rise times: (a) "good" and (b) "bad" detectors.
Fig. 13. Pulse-height spectrum of $^{137}$Cs measured for a "bad" detector: (a) using a standard shaping amplifier, (b) digital pulse-processing, (c) digital pulse processing with events rejection.
Fig. 14. Pulse-height spectrum of $^{137}$Cs measured for a "good" detector: (a) using a standard shaping amplifier, (b) digital pulse processing, (c) digital pulse processing with events rejection.
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