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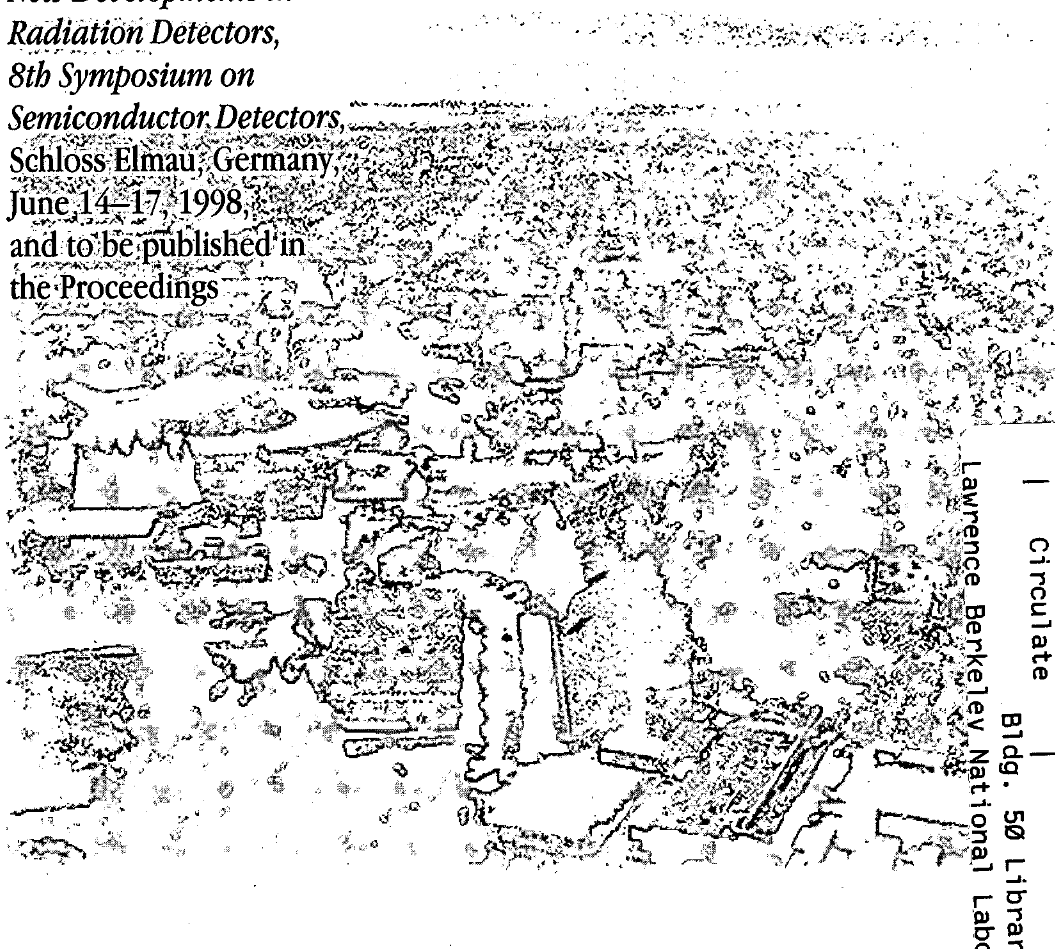

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Coplanar-grid CdZnTe detector with three-dimensional position sensitivity

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Abstract

A 3-dimensional position-sensitive coplanar-grid detector design for use with compound semiconductors is described. This detector design maintains the advantage of a coplanar-grid detector in which good energy resolution can be obtained from materials with poor charge transport. Position readout in two dimensions is accomplished using proximity-sensing electrodes adjacent to the electron-collecting grid electrode of the detector. Additionally, depth information is obtained by taking the ratio of the amplitudes of the collecting grid signal and the cathode signal. Experimental results from a prototype CdZnTe detector are presented.

PACS codes: 29.40.-n, 29.40.Wk, 29.40.Gx, 29.30.Kv

1. Introduction

The coplanar-grid detector technique [1] has been developed over the past several years as a method to overcome the effects of poor hole transport found in compound semiconductor detector materials. This technique has been successfully used with CdZnTe, and good energy resolution (~2% FWHM for 662 keV gamma rays) combined with high volumetric efficiency have been obtained for detectors with volumes up to 2.2 cm^3. In addition to good energy resolution, many applications require detectors with spatial sensitivity. For example, gamma-ray imaging often requires the use of 2-dimensional (x-y) position-sensitive detectors. Furthermore, in certain imaging schemes where gamma rays may enter the detector in an off-normal direction, improved accuracy in event localization and image reconstruction can be achieved if the depths (z) of gamma-ray interactions are also known. Therefore, detectors with 3-dimensional (3-D) position sensitivity would be very desirable. Besides imaging, 3-D position information may also be used to correct for some of the effects of non-uniform charge transport often found in CdZnTe materials. In this paper, we present a new design for a coplanar-grid detector with 3-D position readout capability.

2. Coplanar-Grid Technique

Gamma-ray detectors based on compound semiconductors typically have poor spectral response when a simple planar detector configuration is used. This primarily results from the hole transport characteristics of the semiconductor material being substantially inferior to those of the electron. Consequently, the holes are collected much less efficiently, which causes the amplitude of the detector signal to vary widely as a function of the depth of gamma-ray interaction. The coplanar-grid technique overcomes this problem by changing the charge induction characteristics of the detector such that a highly uniform response as a function of depth is achieved.

The coplanar-grid technique as originally proposed makes use of two interdigitated coplanar anodes (grids) to sense the collection of carriers in a detector. A simple electrode design for a coplanar-grid detector is shown in Fig. 1a. The two grid electrodes are formed by interconnecting a series of strip electrode elements. During detector operation, a voltage is applied between the two grids so that electrons are collected to only one of the grids. The induced signals on the collecting and non-collecting grids (Fig. 1b) are subtracted to give a net output signal as shown in Fig. 1c. If holes are poorly collected while electrons are perfectly collected, then the optimal response is obtained by subtracting the two grid signals with equal gain (G=1). This results in charge induction occurring only in the near-grid region of the detector, with the amplitude of the net signal depending only on the number of electrons passing through the near-grid region. Therefore, the net induced signal will show no dependencies on hole collection or depth of charge generation for events occurring outside the small near-grid region. This effectively eliminates the problem of poor hole transport. However, present-day CdZnTe materials also exhibit significant levels of electron trapping. This re-introduces a depth dependence on the net induced signal since electrons created farther from the grid will suffer from more trapping loss and thus give a smaller signal as the remaining electrons traverse the near-grid region. This can be remedied by adjusting the relative gain G of the two grid signals before subtraction such that an appropriate amount of net charge induction is provided outside the near-grid region. The resulting charge induction profile consists of a linearly rising signal in the far-grid region followed by a rapid rise in the near-grid region (Fig. 1c). The slope of the far-grid signal can be varied by adjusting G. The particular shape of the charge induction profile achieved in this method is near ideal, and it gives a highly uniform detector response as a function of depth for the typical charge transport properties found in CdZnTe. Other electrode configurations such as pixel [2] and strip detectors [3] can also give large improvements in detector response, but they generally cannot provide the near ideal charge induction profile of the coplanar-grid configuration [4].

A single-electrode readout method for coplanar-grid detectors has also been developed in which only the collecting grid signal is processed and signal subtraction is not needed [5]. In this case, the optimization of detector response is accomplished by adjusting the relative areas of the two grid electrodes. Fig. 2 shows the calculated charge induction profile for the collecting grid with different electrode geometries. Again, a near ideal charge induction profile, as in the conventional coplanar-grid technique, is achieved. Unlike the conventional coplanar-grid technique in which the charge induction profile can be easily changed through gain adjustments, the electrode geometry of the single-electrode readout technique has to be designed to match the electron transport characteristics. Generally, a smaller collecting grid electrode is needed for materials with longer electron trapping lengths. Since the electron trapping length depends on electric field strength as well as on material properties, final optimization of the detector performance can be achieved by adjusting the operating bias voltage of the detector. With this technique, the electrode design should be chosen to ensure that the optimal bias voltage is sufficiently high to minimize material nonuniformity and ballistic deficit effects.

3. 3-D Position Sensing

The new 3-D position-sensitive detector design is based on the single-electrode readout coplanar-grid technique. Position readout in two dimensions (x-y) is accomplished by segmenting the non-collecting grid into a number of elements and measuring the induced signals on these elements as electrons are collected at the collecting grid. As carriers drift towards the collecting grid, transient signals are induced on the non-collecting anode elements. The strength of the induced signal on an element depends on the proximity of the carrier trajectory to that element. Therefore, by comparing the amplitudes of the signals from these non-collecting anode elements, the position of the interaction can be determined in two dimensions. Using typical charge sensitive amplifiers for readout, the anode elements are maintained at virtual ground. Therefore, the charge induction characteristics of the collecting grid are not affected by the fact that the signals from the non-collecting electrodes are readout rather than grounded.

The use of non-collecting strip electrodes on a CdZnTe detector for position sensing along one direction has been proposed recently [6]; position information in the orthogonal direction was provided by charge-collecting electrodes. In the present detector design, readout in two dimensions is accomplished entirely with non-collecting electrodes. Charge collection and energy readout from the whole detector is done independently by the collecting grid. To minimize the number of readout channels required for position sensing, an orthogonal position readout scheme can be used. One possible electrode design and connection scheme is shown in Fig. 3.

The induced signals on the position-sensing electrodes with the design of Fig. 3 have been calculated using the weighting potential method [1]. Fig. 4 shows the calculated signals on each of the anodes for a single interaction event taking place near the detector cathode. After the interaction event, each anode signal increases as the generated electrons drift towards the anode surface under the influence of the applied bias. These signals then decrease prior to the collection of the electrons at the collecting grid. The relative amplitudes of these pulses can be used to determine the proximity of the charge trajectory to each of the position-sensing anodes. A larger pulse height indicates a closer proximity. For the signals shown in Fig. 4, the location of the interaction in the x direction was chosen to be near the center of the detector; hence, pulses are largest on the two center x anodes. The slightly larger pulse amplitude from one of the two center anodes is a result of the interaction event taking place 0.1 mm closer (in the x direction) to that anode than the other center anode. This indicates that in principle position resolution much finer than the center-to-center spacing of the position-sensing anodes can be achieved. Likewise, the y anode with the largest pulse amplitude is the one closest to the interaction event, and the relative amplitudes of these y signals can be used to precisely locate the event.

Information on the depth of interaction of an event can be obtained by comparing the signals from the collecting grid and the cathode. Signals from the cathode have a strong dependence on the depth at which charge carriers are produced due to the poor hole transport of the material, just as in the case of a simple planar detector. As discussed previously, the signal from the collecting grid, when properly optimized, is independent of position over most of the detector volume. Therefore, the ratio of the amplitudes of these two signals (cathode signal divided by collecting grid signal) gives directly the depth of interaction. A similar technique of depth sensing for conventional coplanar-grid detectors was developed earlier [7].

This 3-D detector design maintains the advantages of the coplanar-grid technique in that good energy resolution can be obtained from compound semiconductors with substantial charge transport deficiencies. Since energy readout is obtained entirely from the collecting grid, only a single electronic channel is used to provide spectroscopic information. This avoids the complications of multiple spectroscopy channels and multiplexing circuits that are needed in conventional position-sensitive detector configurations such as orthogonal-strip or pixel detectors. In addition, using the connection scheme in Fig. 3, only two readout channels require AC coupling. This is in contrast to the orthogonal-strip method in which a high-voltage coupling capacitor and biasing resistor are needed for each strip electrode on the biased side of the detector.

4. Experimental Results

A prototype 3-D position-sensitive coplanar-grid detector was fabricated from a 10mm X 10mm X 7mm thick CdZnTe crystal. A full-area electrode was formed on one 10mm X 10mm surface of the detector to serve as the cathode. Anode elements with the pattern shown in Fig. 3 were formed on the opposite surface. The line width of the anodes was 0.25 mm with a gap spacing of 0.25 mm. All electrodes were deposited through thermal evaporation of Au, and the pattern definition was accomplished by performing the evaporation through a shadow mask. A set of 6 strip electrodes was connected together to form the collecting grid electrode. This grid electrode was then connected to a charge-sensitive amplifier which provided the energy signal readout. AC coupling was used to allow the application of the grid bias voltage (V_g). Each of the strip electrodes that made up the collecting grid was surrounded by a set of position readout electrodes. The independent strips on one side of the collecting grid were used to provide readout in the x direction. The pads on the other side of the collecting grid were interconnected orthogonal to the x readout strips to provide y-direction readout. In this design, a total of six x and six y readout channels were provided to effectively give 36 2-D position elements. The 12 position readout electrodes were DC coupled to 12 charge-sensitive amplifiers, which maintained the electrodes at near ground potential. The cathode signal was readout by another charge-sensitive amplifier, and AC coupling was used to allow application of the detector bias voltage (V_b) to the cathode.

The detector was evaluated for spectroscopic performance using only the signals from the collecting grid. A standard pulse shaping amplifier and a multi-channel analyzer were used to obtain spectra of gamma-ray sources. Figure 5 shows a ^{137}Cs and a ^{57}Co spectrum taken at a detector bias of -480 V, a grid bias of +40 V, and a pulse peaking time of 4 μs. These spectra demonstrate that good spectral performance is obtained; tailings in the spectral lines typically found in planar CdZnTe detectors are largely eliminated. Since the main objective of this work is to demonstrate the new position sensing scheme, the present detector design has not been optimized in terms of spectral performance.

As explained above, depth sensing can be achieved by taking the ratio of the amplitudes of the cathode signal and the grid signal. This was accomplished experimentally using an analog divider circuit. A single-channel analyzer with the grid signal as input was used to provide a gating signal to the output of the divider. This allows depth information to be obtained for events within a selected energy window. The output pulses were fed to a multi-channel analyzer to produce depth distribution spectra. Fig. 6 shows the depth distribution spectra obtained for 122 keV gamma rays from a ^{57}Co source. The exponential decrease in the number of counts from the entrance surface for gamma rays entering through the cathode and through the anodes can be clearly seen. An absorption length of ~2 mm was obtained from these measurements, in close agreement with the expected value for 122 keV gamma rays in CdZnTe. The position resolution obtainable with this method depends on the energy resolution of the cathode signal and that of the grid signal. At low energies, the resolution is dominated by electronic noise. The position resolution due to electronic noise contributions was obtained by injecting fixed amplitude pulses into the inputs of the cathode and grid amplifiers and measuring the width of the pulser peak in the depth distribution spectrum. Fig. 6c shows the resulting pulser peak, which gives a position resolution of 0.3 mm FWHM. In this measurement, the pulser was adjusted to give a grid signal amplitude matching that of the 122 keV gamma rays. Higher signal-to-noise ratios and thus better position resolution are expected for higher energy gamma rays.

To demonstrate the x-y position sensing capability of the detector, a collimated alpha particle source was used to scan the detector. The alpha particles were allowed to enter through the cathode so that electrons are drifted across the full thickness of the detector and collected at the grid electrode. Signals from each of the six position readout channels on one axis were captured simultaneously using a digital oscilloscope. Fig. 7a shows the resulting signal traces for the x-axis channels. The location of the electron trajectory is clearly identified by the channel that has the highest induced signal. As the source was moved in the x direction, the amplitude of the induced signal at that channel gradually decreased as the signal on the adjacent channel rose. A similar behavior was observed for the y readout channels with the source scanning in the y direction (Fig. 7b). The measured waveforms closely resemble the calculated waveforms as can be seen by comparing Fig. 7 with Fig. 4. The location of interaction used in the calculation was chosen to match the measured waveforms. These results indicate that the x-y location of the electron trajectory can be found by determining the channel with the largest amplitude signal for each axis. As discussed above, a more precise location can be obtained by comparing the signal amplitudes of adjacent channels.

In the measurements using alpha particles, a large signal-to-noise ratio is obtained because of the high energy (~5MeV) of the alpha particles. The energy range of interest in gamma-ray detection is generally ~100 keV to ~1 MeV. This results in significantly lower signal-to-noise ratios. In addition, with gamma-rays interacting at various depths, different pulse shapes can be generated even for events at the same x-y location. Fig. 8 shows two sets of x signals obtained from 356 keV gamma rays from a ^{133}Ba source. One set of signals (Fig. 8a) shows similar characteristics as those from the alpha particles. The other set of signals, however, shows negative going pulses. The negative signals were generated from an event that occurred close to the anode surface. Although it is easy to pick out visually the location of an event from these varied signals, an electronic means to determine the location is needed in practice. One possible method is to select the signal with the highest amplitude in either polarity. An implementation similar to the "winner-take-all" integrated circuit developed for PET detectors may be used [8]. Alternatively, if gamma rays of a fixed energy are measured, it may be possible to use fixed level discrimination to determine the event location. These and various other methods to perform the position recognition are being studied in order to develop an effective position readout technique.

5. Conclusions

A new 3-D position-sensitive coplanar-grid detector design and the performance of a CdZnTe detector with this design have been presented. Unlike most other position detection schemes, the position sensing and energy readout functions of the detector are decoupled. This allows energy readout from the full detector to be made using only one channel of electronics. Additionally, the technique has the advantage of good energy resolution resulting from the coplanar-grid electrode configuration. Position sensing in 2 dimensions is accomplished through the use of proximity sensing electrodes, which take the place of the non-collecting grid in a non-position-sensitive coplanar-grid detector. Depth sensing is achieved using a simple analog divider circuit to take the ratio of the cathode and collecting grid signals.

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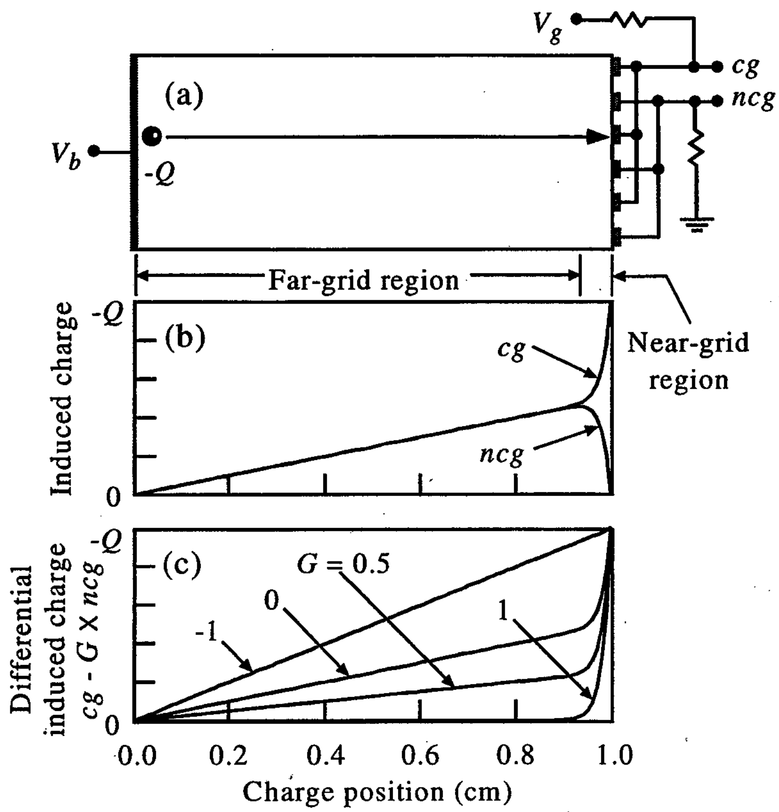

Figure 1

Figure 1. (a) Schematic drawing of a coplanar-grid detector. (b) Calculated induced charge signals on the collecting grid (cg) and noncollecting grid (ncg) as a function of the position of a drifting charge -Q originating near the full-area cathode and ultimately collected by the collecting grid as illustrated in (a). The detector was assumed to be 1 cm thick and infinite in size in the lateral dimensions, and the line width of the grid electrodes was 0.25 mm with a gap spacing of 0.25 mm. Charge trapping was not included in the calculation. The region of the detector in which the drifting charge produces the greatest change in the induced charge signals is defined as the near-grid region, whereas the remainder of the detector volume is referred to as the far-grid region. (c) Difference between the collecting- and noncollecting-grid signals for various values of the relative gain G.

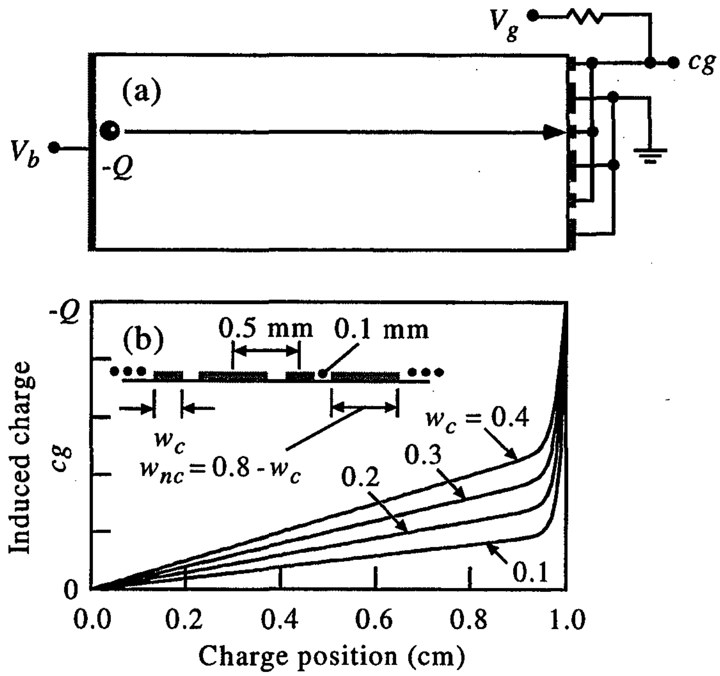

Figure 2

Figure 2. (a) Schematic drawing of a single-electrode readout coplanar-grid detector. (b) Calculated induced charge signal on the collecting grid (cg) as a function of the position of a drifting charge -Q originating near the full-area cathode and ultimately collected by the collecting grid as illustrated in (a). The detector was assumed to be 1 cm thick and infinite in size in the lateral dimensions. Charge trapping was not included in the calculation. The induced charge signal is shown for a number of different collecting grid line widths, w_c. As w_c is varied, so is the noncollecting grid line width (w_{nc}) in order to maintain a constant center-to-center electrode spacing of 0.5 mm and constant gap spacing of 0.1 mm.

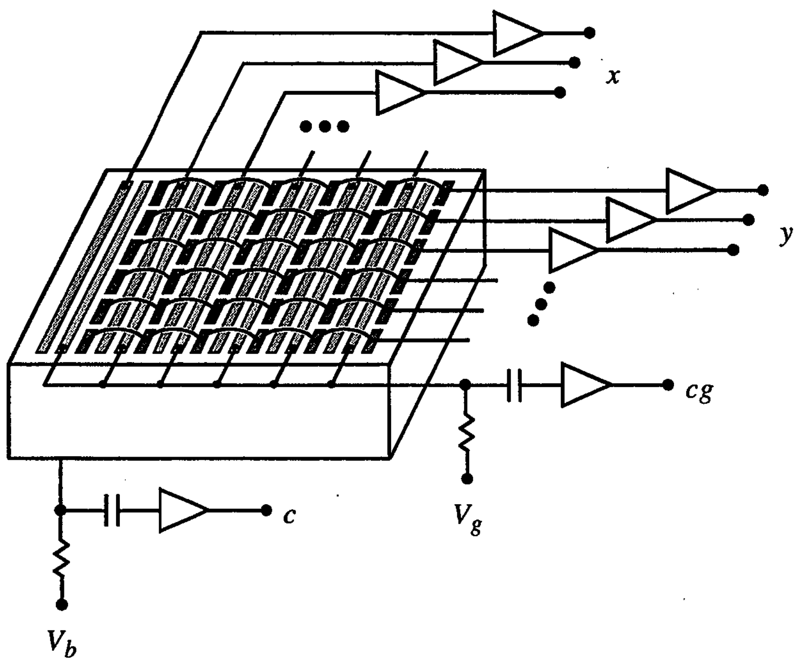

Figure 3

Figure 3. Schematic drawing of a 3-D position-sensitive coplanar-grid detector. Similar to the single-electrode readout detector scheme, energy readout is accomplished by measuring the induced charge on a single set of interconnected anode strips which are biased in order to collect the generated electrons. On each side of these collecting-grid strips are noncollecting anodes that are used to perform position sensing in the lateral (x-y) dimensions. Based on the transient proximity signals induced on the noncollecting anodes, the interaction event can be located in the x and y directions. Locating the depth of the interaction (z) is accomplished by taking the ratio of the cathode signal (c) and the collecting-grid signal (cg).

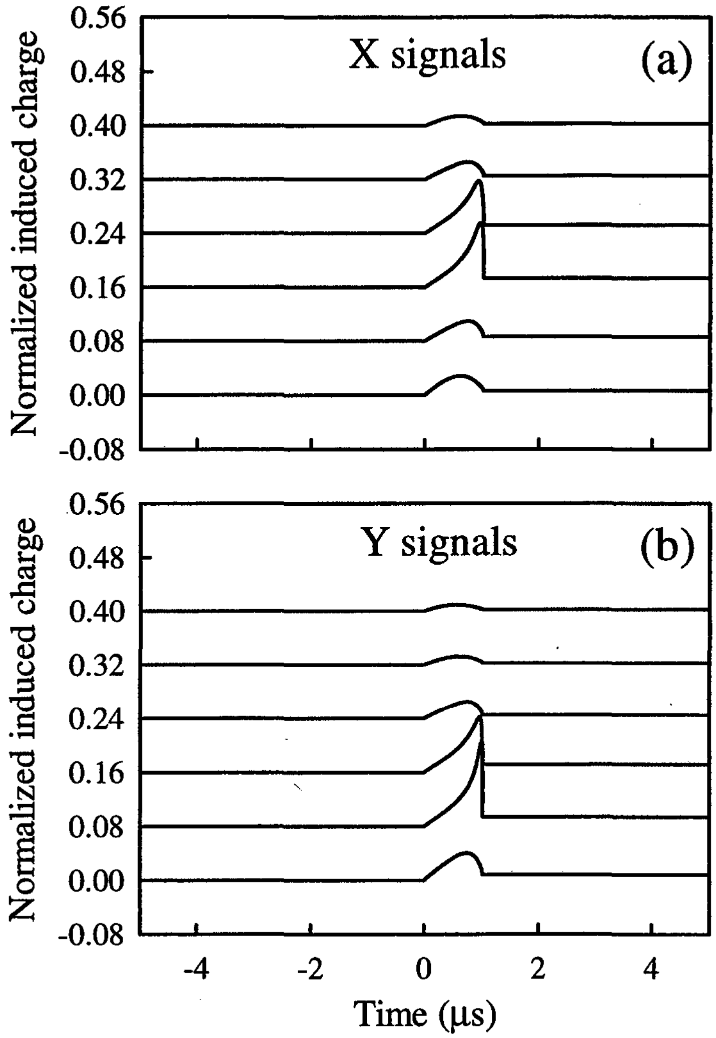

Figure 4

Figure 4. Calculated induced charge signals on the noncollecting position-sensing anodes of the 3-D position-sensitive coplanar-grid detector described in Fig. 3. The signals result from the collection of the electrons generated by a radiation interaction event near the cathode. The lateral location of the interaction event was chosen to match the experimental results of Fig. 7. The detector was assumed to be 10 mm × 10 mm × 7 mm in size, and the line width of the anodes was 0.25 mm with a gap spacing of 0.25 mm. The assumed electron mobility and lifetime were 930 cm^2/Vs and 2.6 μs, respectively, and the detector biases were V_b = -480V and V_g = +40V. (a) Signals from the x position-sensing anodes. (b) Signals from the y position-sensing anodes.

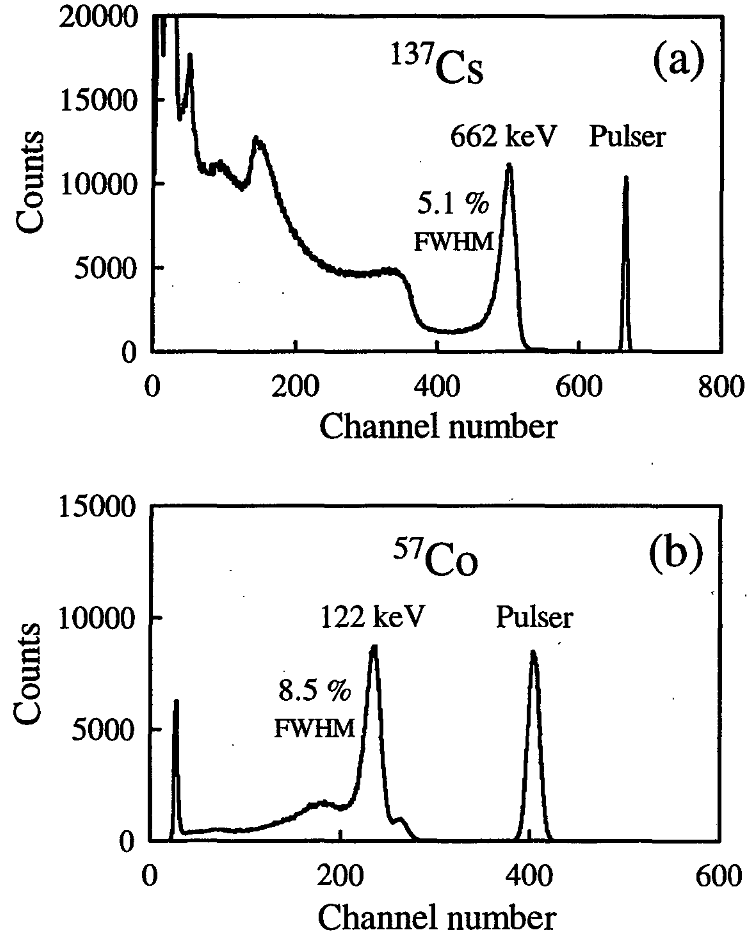

Figure 5

Figure 5. Gamma-ray spectra measured with a 3-D position-sensitive CdZnTe detector with the design described in Fig. 3. The detector was 10 mm × 10 mm × 7 mm in size, and the line width of the anodes was 0.25 mm with a gap spacing of 0.25 mm. The detector biases used were V_b = -480 V and V_g =+ 40 V, and the amplifier peaking time was 4 μs. (a) ^{137}Cs spectrum. (b) ^{57}Co spectrum.

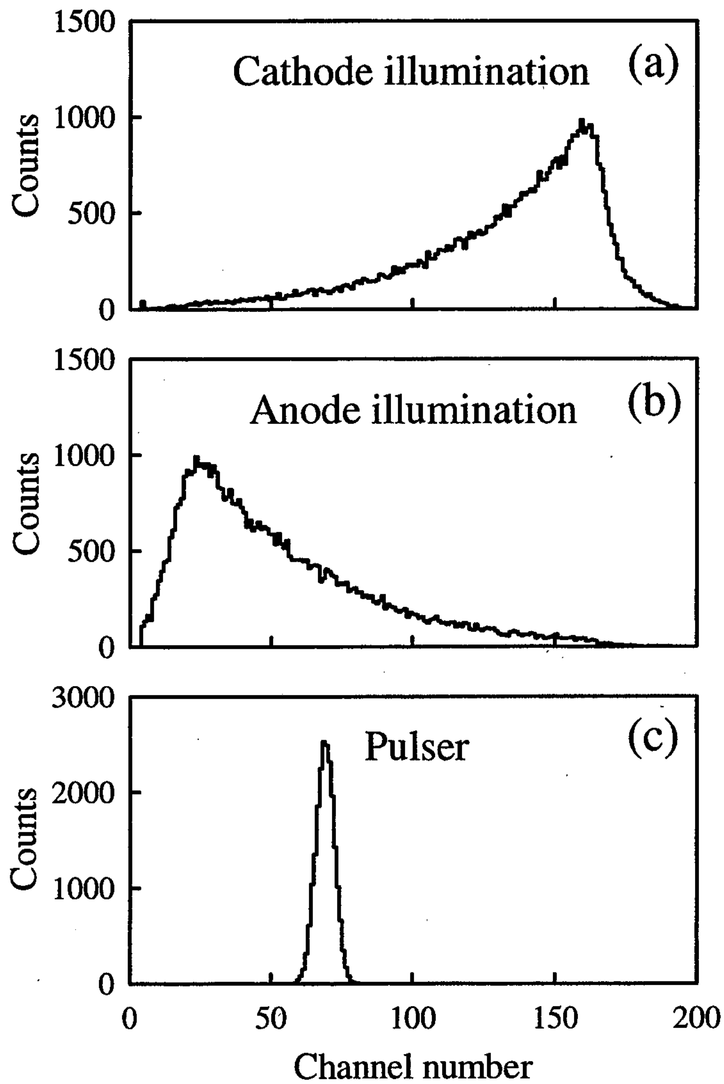

Figure 6

Figure 6. Depth distribution pulse-height spectra measured with the 3-D position-sensitive detector described in Fig. 5. The depth pulse data was generated by dividing the cathode signal by the collecting-grid signal. (a) Depth distribution acquired when the cathode was illuminated with gamma rays from a ^{57}Co source. (b) Depth distribution acquired when the anode was illuminated with gamma rays from a ^{57}Co source. (c) Depth distribution acquired when fixed amplitude pulses were injected into the cathode and collecting-grid amplifiers. The pulse amplitude was adjusted to produce a collecting-grid signal matching that of the 122 keV ^{57}Co gamma rays. The pulser peak width characterizes the position resolution broadening caused by electronic noise contributions.

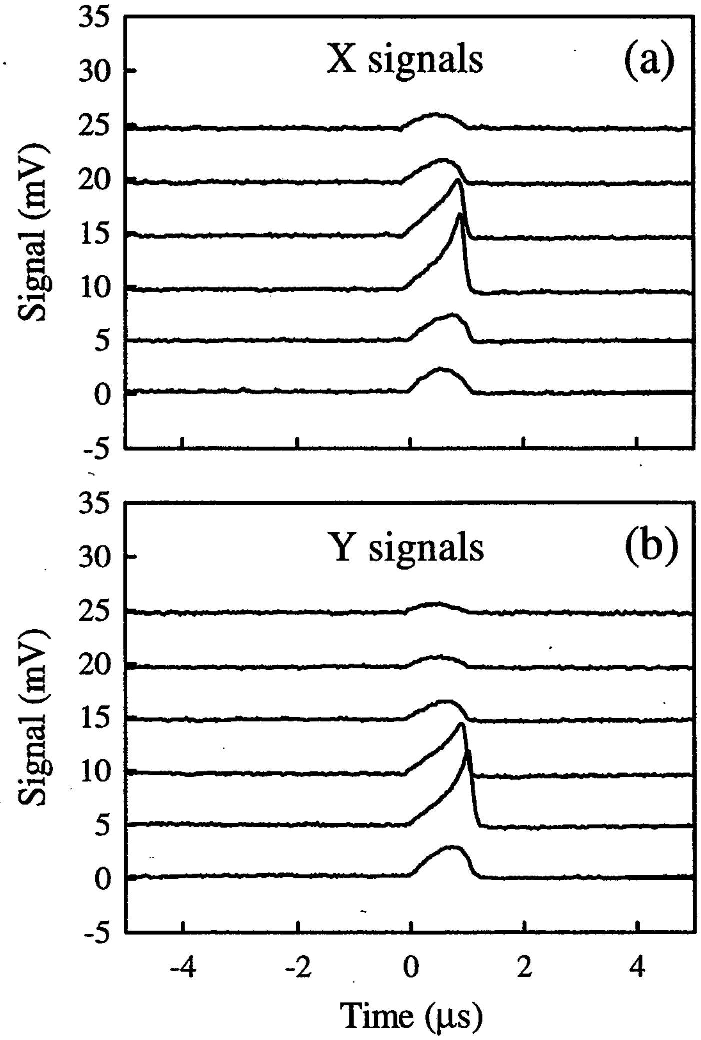

Figure 7

Figure 7. Measured induced charge signals on the noncollecting position-sensing anodes of the 3-D position-sensitive coplanar-grid detector described in Fig. 5. The signals result from the collection of the charge generated by an alpha particle that entered the cathode side of the detector from an ^{241}Am source. The electrodes with the largest pulses are those under which the interaction event took place. (a) Signals from the x position-sensing anodes. (b) Signals from the y position-sensing anodes.

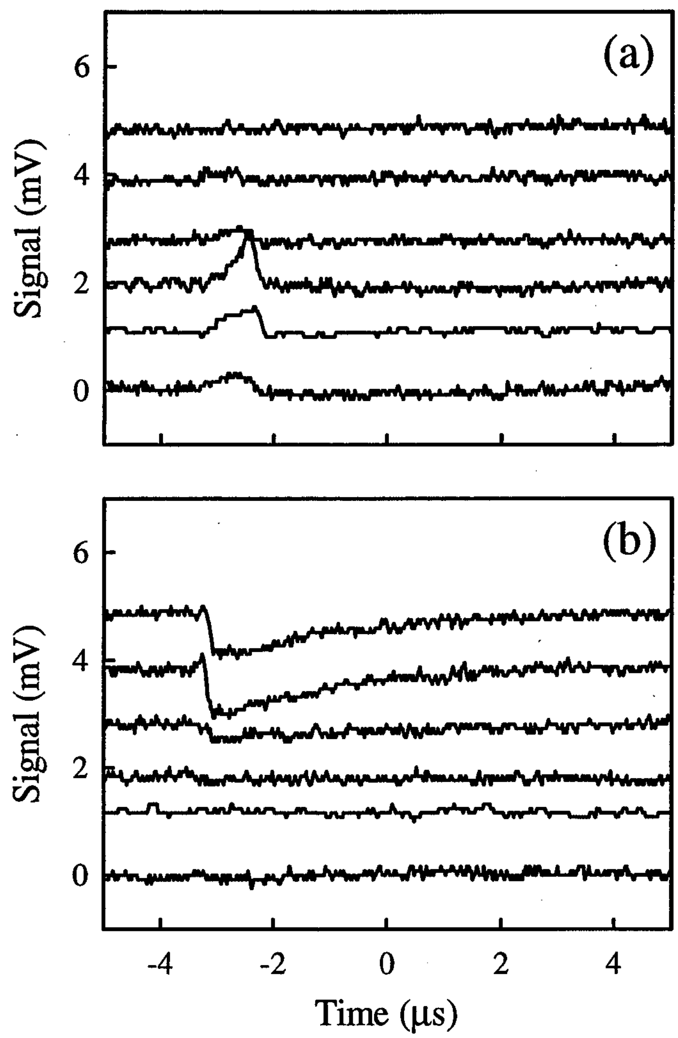

Figure 8

Figure 8. Measured induced charge signals on the noncollecting x position-sensing anodes of the 3-D position-sensitive coplanar-grid detector described in Fig. 5. The signals result from the collection of the charge generated by gamma rays from a ^{133}Ba source. (a) Signals from an interaction event that occurred near the cathode. (b) Signals from an interaction event that occurred near the anodes.

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