LBL-37962
UC-406

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Engineering Division

Presented at the IEEE 1995-Nuclear Science Symposium and Medical Imaging Conference, San Francisco, CA, October 21-28, 1995, and to be published in IEEE Transactions on Nuclear Science, Conference Issue (IEEE '95)

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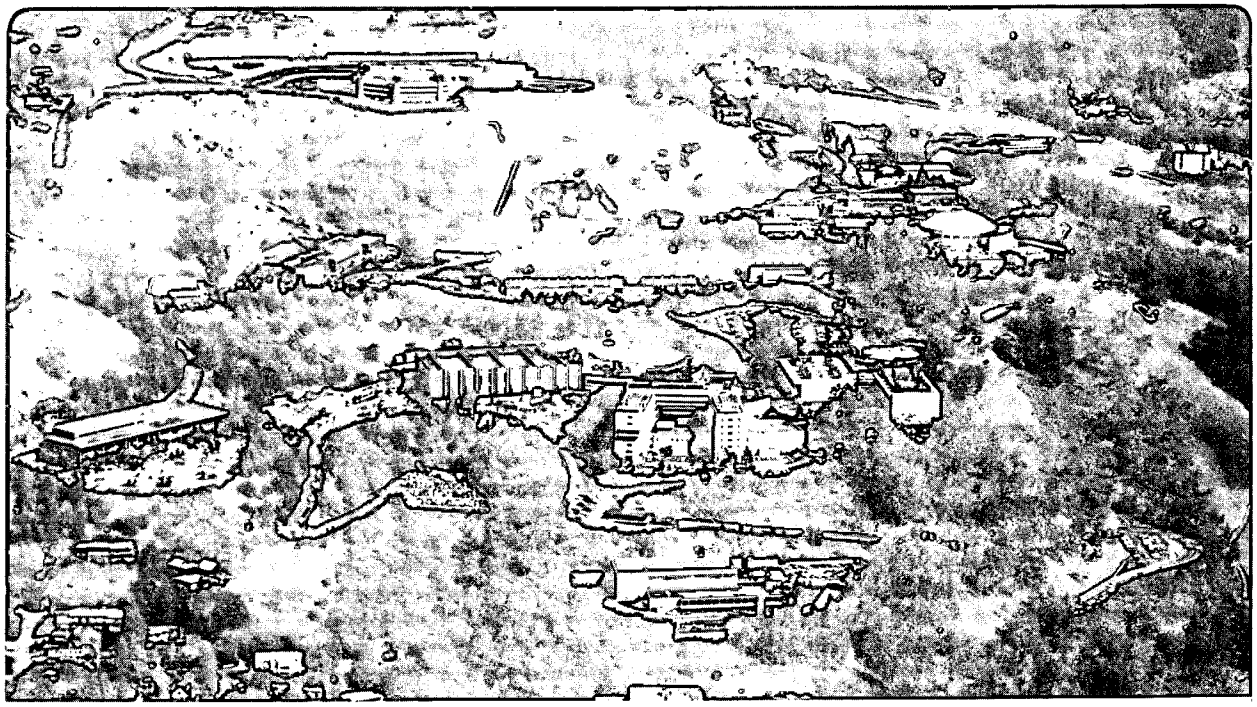
November 1995



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This work was supported by the Director, Office of Energy Research, Biological and Environmental Research, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

Performance of CdZnTe Coplanar-Grid Gamma-Ray Detectors

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Abstract

The spectral performance of coplanar grid detectors using currently available CdZnTe materials is examined theoretically and experimentally. Calculated spectral response based on the typical carrier mobility-lifetime products of current CdZnTe materials shows that energy resolution close to the charge-statistics limit can be achieved. Charge transport nonuniformity, which may limit the spectral performance of present detectors, is studied using alpha particle scanning.

I. INTRODUCTION

CdZnTe crystals grown using the high-pressure Bridgman method exhibit many properties that are desirable for radiation detector fabrication, such as high resistivity, stable operation, relative ease of processing, and the availability of large volume crystals. However, as is common with other compound semiconductor materials, currently available CdZnTe crystals have poor charge transport characteristics. This seriously degrades the spectral performance of detectors, especially in gamma-ray detection. The coplanar-grid detection technique was recently developed to address such charge collection problems. This technique was first demonstrated using a 5 mm cube CdZnTe detector, and a dramatic improvement in spectral response has been achieved [1]. These early results verified the effectiveness of this technique and suggested that large-volume gamma-ray detectors with high energy resolution can be realized. To further the development of such detectors, it is important to understand the various factors that affect detector performance.

The purpose of this paper is to examine the effects of material properties on the spectral performance of CdZnTe coplanar-grid detectors. Theoretical spectral response is derived to show the level of performance that can be achieved given the typical carrier mobility-lifetime ($\mu\tau$) properties of present-day materials. Nonuniformity in the charge transport properties of the material, which could limit the energy resolution of the detectors, has been studied experimentally and some of the results are presented here.

II. THEORETICAL SPECTRAL RESPONSE

When charge carriers are not perfectly transported across a detector, the gamma-ray spectral response will be degraded because the detector response becomes spatially non-uniform.

In other words, the charge induced at the detector electrode depends on the location where the radiation interaction occurs. This spatial dependence can be characterized as the charge induction efficiency, which is defined as the total induced charge resulting from the collection of carriers, normalized to the amount of charge initially created in the detector. Figure 1 is a graph of the calculated charge induction efficiency as a function of the position of charge generation for a 1 cm thick simple planar detector. The values of $\mu\tau$ for electrons and holes used in this calculation ($\mu_e\tau_e$=3X10 $^{-3}$cm^2/V, $\mu_h\tau_h$=1X10 $^{-4}$cm^2/V) are representative of present CdZnTe crystals. A detector bias of 1000V was assumed. As can be seen, the amplitude of an induced signal varies over a wide range depending on the location of charge generation. Since gamma rays interact at random depths in a detector, such position-dependent signal variations give rise to poor spectral response.

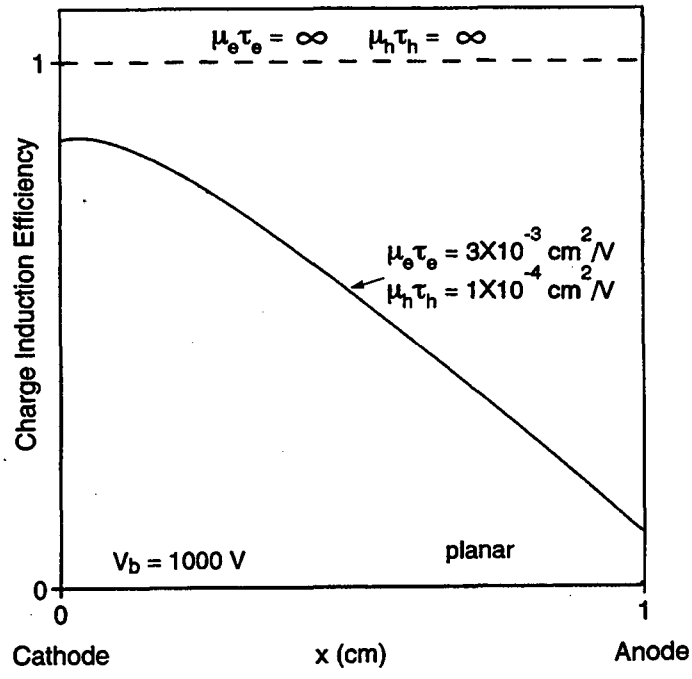

Fig. 1. Calculated charge induction efficiency as a function of position for a simple planar detector. The values of $\mu\tau$ products for the solid curve are typical of currently available CdZnTe material. V_b=1000V is the detector bias.

The wide variation in detector response for the simple planar detector is mainly a result of poor hole transport. The coplanar grid technique addresses this problem by modifying

the charge induction characteristics of the detector so that electrons are preferentially sensed. It utilizes two sets of interdigitally connected strip electrodes (grids) formed on the surface of the detector to sense the movement of charge carriers, as illustrated in Figure 2. Under typical operating conditions, the opposing full-area electrode is biased at a negative voltage so that electrons are drifted towards the grids. In addition, a small voltage is applied across the two grid electrodes so that electrons are collected only on one grid electrode. The induced signals at these two grid electrodes are measured using two conventional charge-sensitive preamplifiers. The relative gain of the two signals can be adjusted by simply varying the gain of one of the preamplifiers. In the following discussions, G will be used to denote the amplifier gain of the non-collecting grid signal relative to that of the collecting grid.

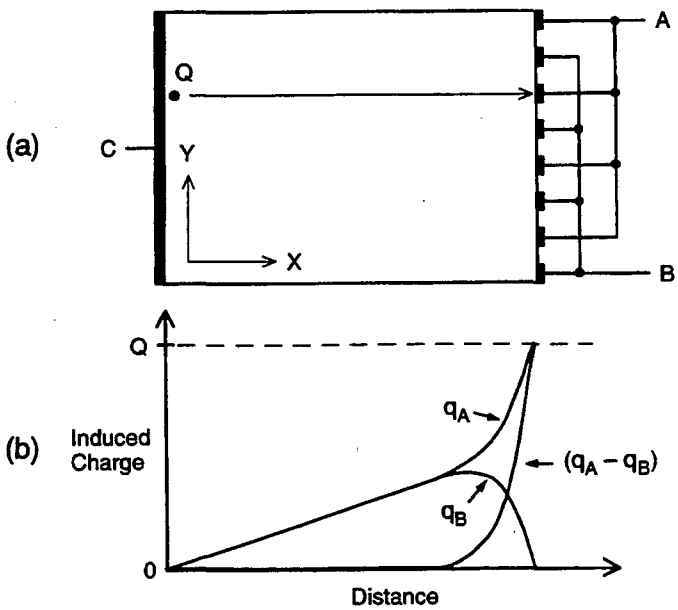

Fig. 2. (a) Basic structure of a coplanar grid detector. (b) Induced signals at the two electrodes and the subtracted signal.

In the coplanar grid technique, the two grid signals are subtracted to yield a difference signal that is then processed as in conventional detectors. When the subtraction is made with the two signals at equal gain, i.e., G=1, the difference signal will show a null response to charge movement that occurs over much of the detector volume. A net signal is produced only from charge movement in the near-grid region. Therefore, for events that occur away from this near-grid region, only the collection of electrons contributes to the charge signals. As long as the electrons are fully collected, full amplitude signals are generated. The effect of poor hole transport is eliminated since their movements do not contribute to the final signal. In this mode of operation, the detector behaves essentially like a gas ionization detector with a Frisch grid [2].

While operation of the coplanar-grid detector in this "Frisch-grid" mode effectively eliminates the problem of poor hole transport, it does not provide the optimal response for the materials presently available. This is because electron transport is far from perfect in these compound semiconductor materials. The loss of electrons during their transit to the grid electrode will result in fewer electrons crossing the near-grid region. This results in signal loss, which is more pronounced for events that occur further away from the grid electrodes. This gives a position-dependent detector response as shown in Figure 3. The effect of electron trapping can be counteracted by reducing G. When G<1, the subtracted signal will show a finite response in the region where there was a null response before. The additional signal contribution from electron movement in this region can then be used to compensate for the trapping loss. In the present case, G=0.49 provide the optimal response. If materials with different charge transport properties are used, G can be adjusted accordingly to yield the best response. The ability to change the detector response to accommodate different material properties through simple gain adjustments is a major advantage of this technique.

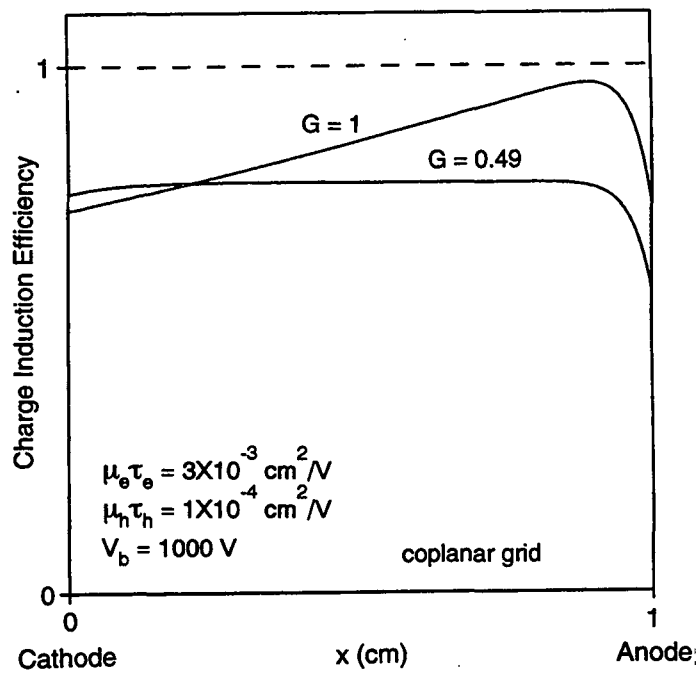

Fig. 3. Calculated charge induction efficiency as a function of position for a coplanar grid detector at G=1 and G=0.49.

When operating the coplanar grid detector at G not equal to 1, the detector is no longer totally insensitive to hole movements. For events occurring in much of the detector volume, most of the holes do not reach the cathode because of the short trapping length (0.1 cm). The holes therefore drift across the same average distance and contribute a fixed amount of charge to the total signal. This does not significantly affect the uniformity of detector response. However, for events occurring within roughly a hole trapping length from the cathode, the collection distance for the holes will depend on position. This creates a small decrease in the detector response

near the cathode. The variation will be more pronounced if the hole trapping length is increased. Although this suggests that decreasing the hole $\mu\tau$ would yield a more uniform detector response, this is probably not a good practical approach since other problems may well arise with increased hole trapping. On the other hand, improving electron $\mu\tau$ would be advantageous as this allows optimal operation at G closer to 1, which would diminish the effects of hole transport. In addition to the near-cathode region, the near-grid region also shows a significant variation in detector response. This is because in this region both electrons and holes contribute to the signal, and the poor collection of holes causes a variable deficit to the detector signal. The width of this region can be reduced by decreasing the strip pitch of the strip electrodes. In this calculation, the strip pitch was taken to be one-tenth the detector thickness.

Figure 4 shows the simulated spectral response of the detector obtained from the optimal response curve in Figure 3 (G=0.49). In this simulation, the following simplifying assumptions were made:

1. All the charge created in an event is confined to a single point (e.g., Compton scattering is ignored). The amount of charge created in each event is assumed to be $1.4X10^5$e, which is roughly equivalent to that created by the absorption of a 662 keV gamma ray in CdZnTe.
2. The events are distributed uniformly over the whole detector.
3. Statistical effects due to charge trapping are ignored.
4. Statistical effect of charge generation is included assuming a Fano factor of 0.1.

The energy resolution of the simulated spectral response is 0.3% FWHM, whereas the resolution due to charge generation statistics alone would be 0.2% FWHM. This shows that it is possible, given the typical carrier $\mu\tau$ characteristics of current CdZnTe material, to achieve energy resolution close to the statistical limit. The events contributing to the narrow photopeak are from a large fraction of the detector volume. The small fraction of events occurring near the grid electrodes and the cathode gives rise to the slight tailing at the low energy side of the photopeak.

III. EXPERIMENTAL RESULTS

The above discussion indicates that very good energy resolution can in principle be obtained from current materials using the coplanar grid technique. This however assumes that the material's charge transport properties are constant throughout the detector volume. Non-uniformity in the degree of carrier trapping in a detector will produce additional signal variations that cannot be compensated and thus degrade the spectral response.

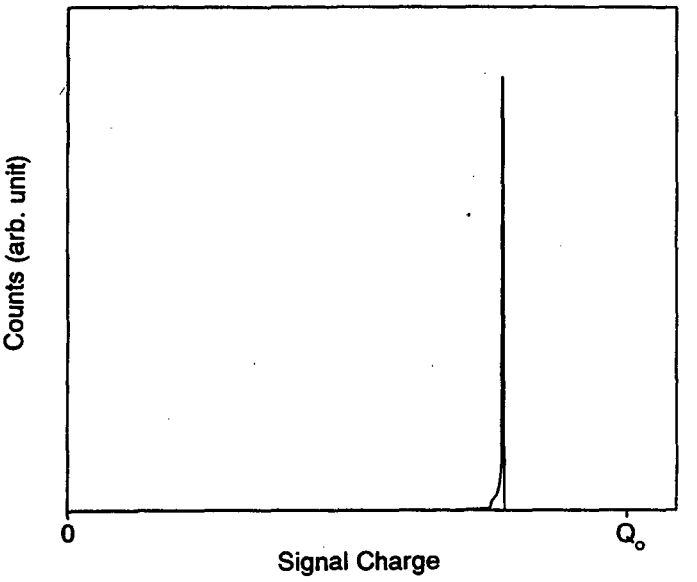

Fig. 4. Simulated spectrum from the charge induction efficiency curve in figure 3 (G=0.49). Initial charge is $Qo=1.4X10^5$ e.

Figures 5 and 6 show ^{137}Cs spectra taken from two 1 cm^3 coplanar grid CdZnTe detectors. Detector #1 exhibits relatively good spectral response with energy resolution of 2.4% FWHM. In this case, it is difficult to determine the contribution of material effects to the spectral line width since other factors such as electronic noise and edge effects may account for much of the peak broadening. Detector #2, however, gave a significantly broadened photopeak even though it has the same electrode design as that of the first detector. The degraded spectral performance of this detector is attributed to material effects and particularly to the non-uniform charge transport characteristics of the material.

Figure 7 is a photograph of a slice of high pressure Bridgman grown CdZnTe crystal. It contains a number of random crystal grains as well as twins. It is possible that a detector crystal cut from such materials will contain some of these grain boundaries or twin planes. If enhanced carrier trapping occurs at these boundaries, charge transport will no longer be uniform and spectral performance will be affected. To investigate this, we have examined both single-crystal detectors and detectors that contained crystal boundaries. The detectors were of simple planar configuration. The study was carried out using collimated alpha particles from an ^{241}Am source. The spot size of the collimated beam was roughly 1 mm in diameter. The alphas entered the detector through the cathode so that signals were derived from electron collection.

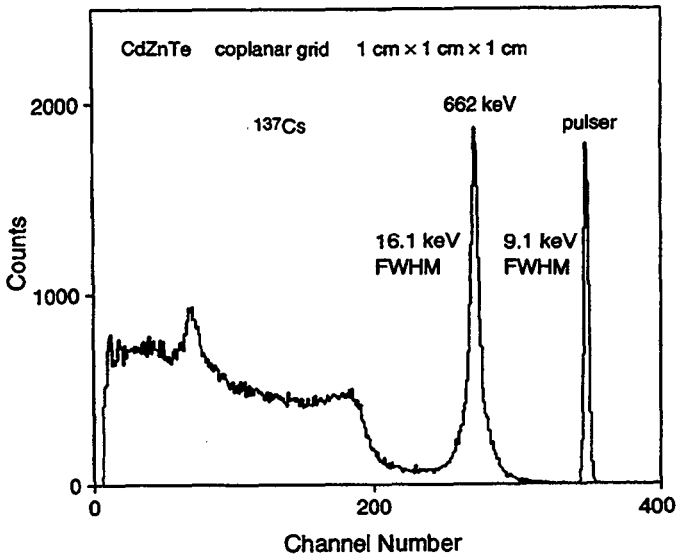

Fig. 5. ^{137}Cs spectrum from a coplanar grid detector (Detector #1).

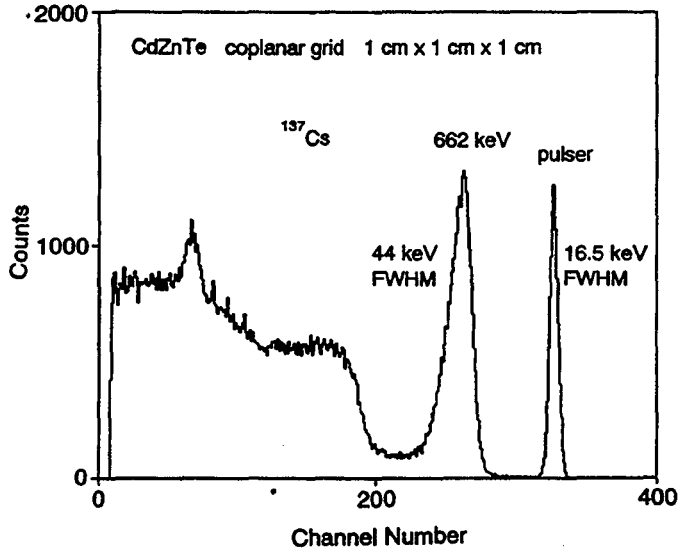

Fig. 6 ^{137}Cs spectrum from a coplanar grid detector (Detector #2).

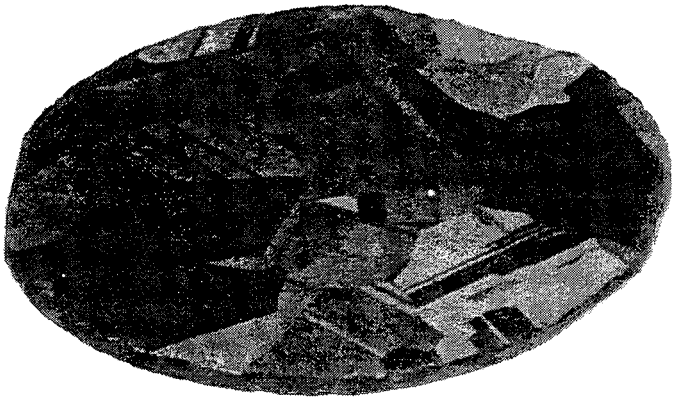

Fig. 7 Photograph of a slice of CdZnTe crystal. The diameter of the crystal is 3.5 inches.

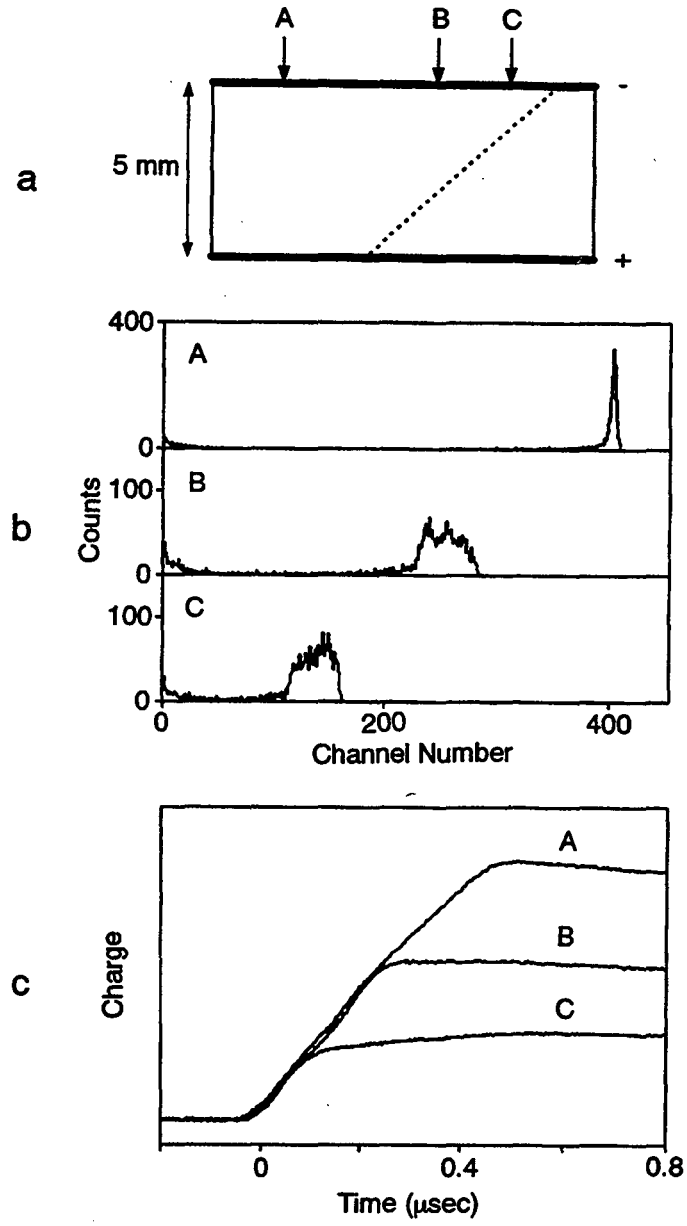

Fig. 8. (a) Schematic view of a planar detector showing the alpha scan positions and the location of a random grain boundary (dashed line). (b) Alpha spectra obtained at the three scan positions. (c) Induced charge signal captured at the three scan positions.

Figure 8a shows schematically the cross-sectional view of a detector and the locations of the alpha particle scan positions. This detector contains a random grain boundary which is indicated by the dashed line. Energy spectra obtained at the different scan positions are shown in Figure 8b. A full-energy peak is observed at position A, but the spectra obtained at position B and C show broadened peaks that are shifted towards low energies. By examining individual charge signals from the output of the charge-sensitive amplifier, one can track the movement of the electrons inside the detector and determine how the signal charge is lost. Figure 8c shows representative signals captured at the different scan positions. The signal obtained at position A shows that the electrons are transported

efficiently from the cathode to the anode. At position B and C however, the electrons initially proceeded normally but were then stopped abruptly. The depths where the electrons were stopped are directly correlated to the locations of the grain boundary. It can also be observed that, at position B, virtually all the electrons are stopped at the grain boundary while at position C, a small fraction of the electrons apparently made their way pass the grain boundary and then continued their drift toward the anode. Electron trapping at the grain boundary explained the reduced amplitudes seen in the energy spectra.

Figure 9 shows the results for another detector. In this case, the crystal contains numerous twin layers with boundaries indicated by the dashed lines. In contrast to the previous detector, no significant electron trapping can be observed at the twin boundaries. The spectra and charge signals look very similar for the different scan positions. The increase in the slope of the charge signals starting at their midpoints suggests that the electrons were drifting at a higher velocity in the bottom half of the detector. This could be a result of higher electric field or higher electron mobility. The cause for this variation is not known but since the transitions occurred at the same depth for the different scan positions, it does not seem to be related to the crystal twins. This crystal is the same as that used to fabricate Detector #1, which showed good spectral response.

The crystal used for Detector #2 actually does not contain any visible grain boundaries or twins. However, scanning across the detector revealed a shift in the peak position of the alpha spectra. Figure 10 is a plot of the peak position, in channel numbers, as a function of scan position. The amount of variation is ~2%. Such variations could at least partly account for the observed broadening of the gamma-ray peak. This result shows that significant charge collection variations that affect detector performance can also occur in apparently single-crystal materials.

IV. CONCLUSIONS

The results of this study indicate that currently available CdZnTe material exhibits adequate hole and electron $\mu\tau$ to produce excellent energy resolution in detectors using the coplanar grid technique. In fact, improving only the hole $\mu\tau$ of the material may have a negative effect on the spectral response of the detector. On the other hand, improving the electron $\mu\tau$ would be beneficial as it allows the detector to operate in a mode that reduces the effect of partial hole transport. A more important consideration for present detectors appears to be the spatial uniformity of charge transport of the materials. Nonuniform carrier trapping was observed using alpha particle scanning. Serious electron trapping was observed at a random grain boundary while twin boundaries appear to have no effect on electron collection. Nonuniform charge collection not directly correlated with any visible grain boundaries was also observed and appears to contribute to the degradation in spectral resolution. Further progress in detector performance would require a better understanding and control of these charge transport problems. Finally, although this study has focused on CdZnTe detectors, some of the general conclusions are also applicable to other compound semiconductors as well.

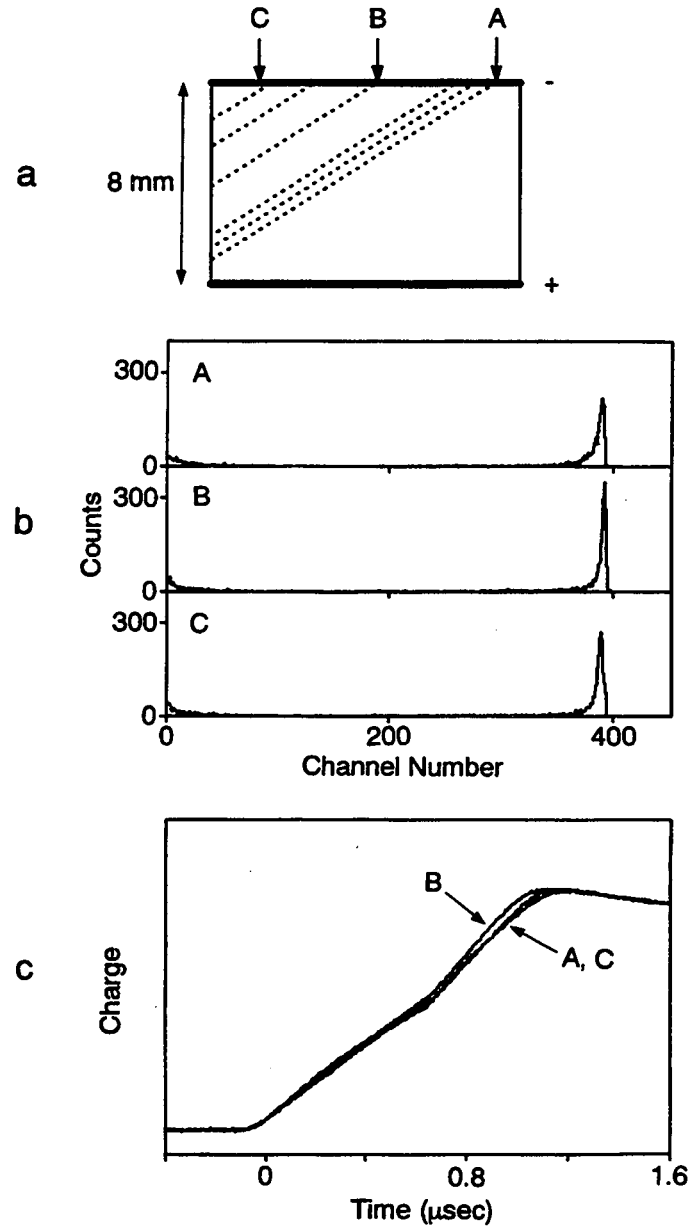

Fig. 9. (a) Schematic view of a planar detector showing the alpha scan positions and the locations of twin boundaries (dashed line). (b) Alpha spectra obtained at the three scan positions. (c) Induced charge signal captured at the three scan positions.

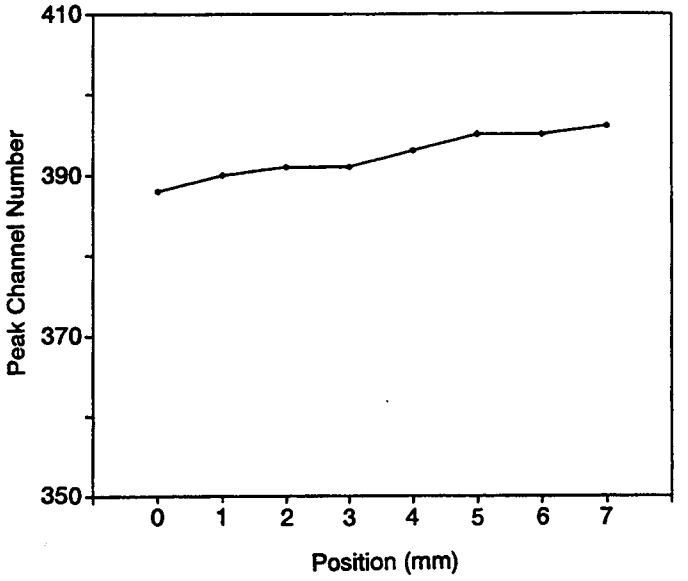

Fig. 10. Position of the alpha peak as a function of scan position for a planar detector.

V. ACKNOWLEDGMENTS

This work was supported by the Director, Office of Energy Research, Biological and Environmental Research, of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

VI. REFERENCES

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