Hard X- and gamma-ray measurements with a large volume coplanar grid CdZnTe detector

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Abstract

The recent introduction of coplanar grid techniques has led to resurgence in interest in developing large volume compound semiconductor detectors that have a reasonable gamma-ray response but also good spectroscopic resolution. We report the results of a series of hard X- and gamma-ray measurements on a large $15 \times 15 \text{ mm}^2$, 10 mm thick CdZnTe coplanar grid detector. The measurements were carried out at the HASYLAB and ESRF synchrotron radiation facilities using highly monochromatic pencil beams across the energy range 20 keV to 800 keV. Additional full-area measurements were carried out using radioactive sources. All measurements were carried out at room temperature. The measured energy resolution under full-area illumination was 8 keV and 12 keV FWHM at 59.95 keV and 662 keV, respectively. Under pencil beam illumination, the measured resolutions were essentially the same. The detector energy response function was found to be linear over the energy range 20 keV to ~ 1400 keV with an average rms non-linearity of 1.4%, consistent with statistics. The spatial uniformity of the detector was evaluated at 30 keV, 60 keV and 180 keV by raster scanning a $20 \times 20 \mu\text{m}^2$ monoenergetic X-ray beam across the active area. Apart from a few localized areas, the detector response was found to be uniform at the few percent level, consistent with statistics. At 180 keV, the nonuniformity in the energy response due to the grids was estimated to be at the 0.7% level.

Keywords: Compound semiconductors, CdZnTe, X-ray detectors, gamma-ray detectors

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1. Introduction

In compound semiconductor materials, the electron μ - τ product is usually about 2 to 3 orders of magnitude greater than for the holes, which means that for present detection systems, the spectral performances are limited by the carrier with the poorest transport properties. By analogy with gas counters, a significant improvement in spectral acuity can be achieved using single carrier collection techniques - in other words discarding the carrier with the poorest transport properties. The co-planar grid technique [1] is essentially an evolution of the classical Frisch grid, introduced to reduce position dependent charge collection effects in gas detectors. By including a grid within the gas volume near the anode of the device, it is possible to bias the electrodes such that electrons are drifted towards the anode through the grid and positive ions are drifted in the opposite direction. According to the Shockley-Ramo theorem [2,3], the induced charge on the anode is primarily due to electrons moving from the grid to the anode, hence the gamma-ray interaction position dependence of the pulse shape is greatly reduced. A similar concept has been shown to work with semiconductor devices - coplanar grid devices [4]. Compared to a simple planar contacted detector, a coplanar gride detector has two anode electrodes in the form of inter-digitated grids that are connected to separate charge-sensitive preamplifiers. An electric field is established in the detector bulk by applying bias to the cathode, which is a full-area contact located on the side opposite the grid electrodes. The two grid preamplifiers are connected to a subtraction circuit to produce a difference signal. Bias is applied between the grid electrodes so that one of the grids preferentially collects charge. Charge motion within the bulk of the detector is sensed equally by the grid electrodes. Consequently, the difference signal is essentially zero. However, when charge approaches the anode, the grid signals begin to differ due to the difference in grid potentials and a signal is registered at the output of the difference circuit. In a well-designed detector and in the absence of electron trapping, the magnitude of the difference signal is the same no matter where the charge is generated in the device. This results in a large improvement in performance for gamma-ray spectroscopy when compared to conventional planar device technology (*e.g.*, see [5]). In addition, these detectors have a number of advantages over many other single carrier sensing techniques including the ability to operate at room temperature.

2. Detector fabrication

The detector was fabricated on a single $17 \times 17 \times 17 \text{ mm}^3$ CdZnTe crystal, grown by high pressure Bridgeman (HPB) by Yinnel Tech. USA. The electrical characterization of

the device is described in detail in Gostilo *et al.* [6] and will only be summarized here. To assess the crystals electrical properties, a simple planar electrode system was first deposited by electroless Au solution. At room temperature, the I/V characteristics were found to be very nearly linear with typical leakage currents of ~ 10 nA being recorded at 60V bias. The specific resistivity was $\sim 5 \times 10^{10} \Omega \text{ cm}$. Using an ^{241}Am radioactive source, the electron mobility and mobility-lifetime product were determined by a modified time of flight method to be $750 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ and $7 \times 10^3 \text{ cm}^2\text{V}^{-1}$, respectively [6]. The corresponding values for the holes could not be measured, being below the sensitivity of the measurement. The volume homogeneity of the crystal was then assessed using a collimated ^{241}Am source and recording the shape of the 59.54 keV X-ray peak

Fig. 1. Photograph of the detector crystal and coplanar grid structure.

at low biases. The presence of grains or extended structure defects is revealed by changes in peak shape and/or the presence of multiple peaks. From a quantitative analysis of the data, no distortion in peak shape or position was observed.

After the acceptance and electrical tests, the planar test contacts were then removed and co-planar contacts deposited on both sides of the crystal using photolithographic techniques. After assessing the electrical properties of both faces separately, *i.e.*, alternately, operating one side as coplanar anodes while shorting the grids on the other to form a cathode, the side that gave the best performance was then chosen as the anode, and the coplanar structure and guard ring on the other side soldered together to form a “solid” planar cathode. Differences between the two sides may be expected in orientated crystals. For example, Wright *et al.* [7] have shown that for Cd and Te-terminated surfaces, surface processing conditions significantly affect surface recombination velocities underneath the electrodes, which in turn affect the electron and hole charge collection efficiencies. The resulting differences in the electron $\mu\tau$ product can be as great as 25%. After selecting the electrodes, the surfaces are passivated.

A photograph of the processed detector crystal and its completed coplanar grid structure is shown in Fig.1. The grid structure defines an active area of $15 \times 15 \text{ mm}^2$. For operation, the optimum operating bias of the collecting electrode was found to be 1700 V and the inter-grid bias 60 V. The inter-grid resistivity was $\sim 6 \text{ G}\Omega$ and the guard ring was found to suppress the leakage current by a factor of 5 [6]. All connections to the electrodes take place by wire bonding. The detector is mounted on a dielectric substrate, which in turn is enclosed in an Al package. The detector is irradiated through the cathode *via* a thin Be window. The system uses a standard resistive feedback preamplifier on both grids with no attempt to reduce noise, such as optimizing or cooling the front-end components. After subtraction, the rest of the analog chain consists of an ORTEC 671 spectroscopy amplifier.

3. Experimental

X- and gamma-ray measurements were carried out in our laboratory and at the Hamburger Synchrotronstrahlungslabor (HASYLAB) radiation facility in Hamburg, Germany and the European Synchrotron Research Facility (ESRF) in Grenoble, France. The hard X-ray response was determined using the X1 beamline [8] at HASYLAB. This beamline utilizes a double crystal monochromator to produce highly monochromatic X-ray beams across the energy range 10 keV to 100 keV. A Si[511] reflection was used, yielding an intrinsic energy resolution of $\sim 1 \text{ eV}$ at 10 keV rising to 20 eV at 100 keV. The gamma-ray measurements were carried out on the ID15 high energy scattering beamline [9] at the ESRF. This beamline also utilizes a double crystal monochromator to produce highly collimated photon beams across the energy range 30 keV to 1000 keV. A single crystal set was used (Si[311] reflection). To achieve usable photon fluxes over

such an extreme energy range, 2 insertion devices were also used - an asymmetrical multipole wiggler (AMPW) followed by a superconducting wavelength shifter (SCWS). The spectral resolution is typically around 20 eV at 30 keV rising to ~ 1 keV at 1 MeV.

Fig. 2. The measured response of the detector at room temperature to ^{109}Cd , ^{241}Am , ^{137}Cs , ^{22}Na and ^{60}Co under full-area illumination. The FWHM energy resolutions ranged from 8 keV at 59.54 keV to 17 keV at 1333 keV.

At both beamlines, the detector was mounted on an X-Y table capable of positioning the detector to a precision of $<1 \mu\text{m}$ in each axis. The beam spot size was set by a pair of precision stepper-driven slits located immediately in front of the detector. The spot size used in most measurements was typically $20 \times 20 \mu\text{m}^2$, normally incident on the detector. For completeness, additional full-area illumination measurements were carried out using ^{55}Fe and ^{241}Am radioactive sources.

3.1 Measurements

In Fig. 2, we show measured energy-loss spectra for a number of radioactive calibration sources (^{109}Cd , ^{241}Am , ^{137}Cs , ^{22}Na and ^{60}Co) under full-area illumination. The measurements were carried out at room temperature. The FWHM energy resolutions of the principal lines at 59.5 keV and 662 keV are 8 keV and 12 keV FWHM, respectively. The corresponding system noise, as determined by a precision electronic pulser, was 7 keV FWHM.

Fig. 3. Composite pulse height spectra of monoenergetic lines measured at HASYLAB. The beam size was $20 \times 20 \mu\text{m}^2$, incident at the center of the detector.

Fig. 3 shows a composite of the detectors response to a series of highly collimated monochromatic spectral lines taken at HASYLAB. The beams were incident at the center of the detector. Below ~ 50 keV, the recorded events are confined almost entirely to the photopeaks and the level of continuum is extremely low, being $< 1\%$ of the photopeak amplitude. Above ~ 50 keV, the Te and Cd K-edge escape peaks begin to become apparent in the spectrum at energies of 26.7 keV and 31.8 keV below the photopeaks.

The noise floor, which we define to be the lowest energy for which the low energy noise attains an amplitude of 0.5 of the photopeak, occurs at ~ 13 keV.

In Fig. 4, we show the high-energy response measured at the ESRF, from which we can see that the deleterious effects of charge trapping are not apparent. In fact, the energy response looks very more similar to that of a lanthanum halide scintillator, rather than a compound semiconductor. The response at 800 keV is particularly interesting in that it shows all the classical features of a gamma-ray spectrum. In addition to the photopeak, we see the Compton edge, Compton continuum and backscatter peak.

Fig. 4. Composite pulse height spectra of monoenergetic lines measured at the ESRF. The beam size was $20 \times 20 \mu\text{m}^2$, incident at the center of the detector. The spectra have been offset to highlight the evolution of the Compton distribution with energy. Here E is the energy of the incident photons, E_{edge} is the energy of the Compton edge and $m_o c^2$ is the rest mass energy of the electron.

In Fig. 5, we show the detector linearity curve. The non-linearity was determined from the residuals of a best-fit linear regression (reduced χ^2 of 0.90 for 24 degrees of freedom) to the measured line centre energies ranging from 20 keV to 1333 keV. For the entire data set, the rms non-linearity is 1.4% and an average error on individual data points of

0.3% across the useable energy range. The lower panel in Fig. 4 shows a plot of the residuals - that is, the percentage deviation from the best linear fit (measured-calculated /calculated $\times 100$). Above ~ 200 keV the residuals show no systematic trend with energy with a mean deviation of 0.0%. However, the residuals below the K-edges are systematically higher with a mean value of $(2.7 \pm 0.4)\%$. If real, it is not clear what the source of this non-linearity is.

Fig. 5. The measured linearity of the detector under pencil beam illumination. The lower panel shows the residuals, *i.e.*, the percentage deviation from the best linear fit (measured-calculated /calculated $\times 100$). The inset shows the linearity at lower energies. The dotted lines indicate the Cd and Te K edges at 26.7 keV and 31.8 keV, respectively.

The energy resolutions determined from Figs. 3 and 4, range from 8.4 keV FWHM at 20 keV to 12.9 keV FWHM at 800 keV and are shown in Fig. 6. From the Fig., we note that although electronic noise contributes substantially to the overall FWHM, another form of noise begins to rise above ~ 50 keV and is dominant above 1000 keV. Clearly this

Fig. 6. The energy resolution ΔE measured using full-area and $20 \times 20 \mu\text{m}^2$ pencil beam illumination. The electronic noise was determined using a precision pulser. The solid line shows a best-fit linear function to the total dataset.

is not Fano noise, which is insignificant in this energy region or trapping noise since its characteristic signatures are not apparent in the energy loss spectra shown in Fig. 5. Therefore this noise must be due an artefact of the co-planar grid implementation.

For completeness, we also plot energy resolutions measured under full-area illumination, from which we see there is no difference with pencil beam illumination. This illustrates the uniformity of the response across the crystal.

3.2. Spatial response

The spatial response of the detector was evaluated using 30 keV, 60 keV and 180 keV collimated beams of size $20 \times 20 \mu\text{m}^2$, normally incident on the detector. The beam was raster scanned across the active area with a spatial resolution of $40 \mu\text{m}$. Spectra were accumulated at each position for a fixed time interval and the total count rate above a 20

Fig. 7. The spatial response of the detector measured at the ESRF using a $20 \times 20 \mu\text{m}^2$, 180 keV X-ray beam. (a) shows the variation in count rate profile, (b) the fitted centroid of the photopeak (*i.e.*, gain), and (c) the resolving power, *i.e.*, $E/\Delta E$. Both surface and contour plots are shown. Note the vertical distortion apparent in the contour plots is due to a slippage in the Y motor drive.

keV threshold, the peak centroid position (*i.e.*, the gain) and the FWHM energy resolution determined by best-fitting. The results for 180 keV data are shown in Fig. 7, for each of the recorded parameters. These data represent the output of 10,702 spectral accumulations. Note, the energy resolution is displayed in terms of its resolving power (*i.e.*, $E/\Delta E$) to ensure numerical stability across the detector boundaries (*i.e.*, the function goes to zero outside the active area). From the individual distributions, we note that apart from some localized areas, the overall detector response is very uniform. In fact, globally the non-uniformity is typically no worse than a few percent across the surface and is consistent with a flat response – *i.e.*, the variations seen in each distribution being consistent with the expected statistical variation, *i.e.*, a) = 2%, b) = 0.12% and c) = $\sim 10\%$ (limited primarily by the fitting algorithm). The average FWHM energy resolution recorded at each data point was 8.3 keV. For comparison, the energy resolution of the sum of all 10,702 spectral accumulations was 8.7 keV.

The count rate and centroid-position contours shown in Fig. 7 show a number of localized areas where the response is less than the average. These areas account for approximately 1% of the detection area. A spectral analysis showed that the positions of photopeak for the bulk of the data lay within ± 1 sigma of the summed spectra peak position. However, in the localized areas, the fitted photopeak positions lay exclusively in the energy range 120 keV to 168 keV of the summed spectrum. Only exactly at the edges of the detector did the fitted photopeaks lie at energies less than 120 keV. Lastly, evidence for the grid structure can be seen in the centroid map. It is only apparent in this map because of the much higher statistical precision that can be obtained in locating the centroid (*i.e.*, $\sigma_{\text{peak}}/\text{SNR}$), and is in fact a direct representation of the spatial distribution of the gain of the device. Note the vertical distortion apparent in the contour plots is due a slippage in the Y motor drive. By summing across the device, the inhomogeneity of the energy response due to the grids (*i.e.*, $\Sigma^N (E_{\text{fit_grid}} - E_{\text{fit_non-grid}})/N$) is estimated to be 1.2 keV (0.7%).

4. Discussion and conclusions

While, carrier transport properties currently limit detector thicknesses to a few mm in conventional planar designs, coplanar grid techniques offer a simple and effective means to improve spectral resolution. Using such a technique, effective detector thicknesses can, in theory, be increased up to at least several cm, given that electron trapping lengths in CdZnTe are typically of the order of 5 cm under nominal operating conditions (~ 1000 V/cm). This corresponds to useful detection volumes of up to 10 cm^3 . Additional improvements in energy resolution can also be achieved by careful design [10]. However,

ultimately, it is the quality of the material that has to improve if significant increases in detector volume are to be achieved.

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