**COMPOUND SEMICONDUCTOR DETECTORS FOR X-RAY ASTRONOMY:
SPECTROSCOPIC MEASUREMENTS AND MATERIAL CHARACTERISTICS**

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COMPOUND SEMICONDUCTOR DETECTORS FOR X-RAY ASTRONOMY: SPECTROSCOPIC MEASUREMENTS AND MATERIAL CHARACTERISTICS

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ABSTRACT

The use of some specific compound semiconductors in the fabrication of high energy X-ray detectors shows significant potential for X-ray astrophysics space missions. We are currently investigating three high purity crystals - CdZnTe, GaAs and TlBr - as the basis for future hard X-ray detectors (above 10 keV). In this paper we present the first results on CdZnTe and GaAs based detectors and evaluate the factors currently still constraining the performance.

Energy resolutions (FWHM) of 0.9 keV and 1.1 keV at 14 keV and 60 keV, respectively, have been obtained with an epitaxial GaAs detector, while 0.7 keV and 1.5 keV FWHM were measured at the same energies with a CdZnTe detector. Based on these results it is clear, that the next generation of X-ray astrophysics missions now in the planning phase may well consider extending the photon energy range up to ~ 100 keV by use of efficient detectors with reasonable spectroscopic capabilities.

INTRODUCTION

The next generation of X-ray astrophysics missions now under development (AXAF, XMM, Spectrum X-Gamma and Astro-E) all are limited to the energy range below 10 keV. However, a significant number of astrophysical problems associated with non-thermal processes in such objects as active galactic nuclei and black hole binary systems will require the extension of the current capabilities up to about 100 keV and beyond.

The imaging telescopes required to collect these high energy photons and to focus them onto small imaging detectors in the focal plane, together with the focal plane detectors, will require significant development. In this spectral region, where photon rates are very low indeed (in comparison with the region below 10 keV), a high absorption efficiency in the detector is essential, combined with medium spectral, imaging and temporal resolution. In figure 1 the X-ray penetration depth and the absorption efficiency of 1 mm thick detectors is shown. Data for silicon and germanium are also shown together with that of TlBr. It is clear that above 100 keV only TlBr and CdZnTe have adequate efficiency while both GaAs and Ge are good in the region 10 keV to 100 keV.

In a previous paper we investigated the limitations on the response of CdZnTe detectors due to crystal structure and defects applying a wide range of diagnostic tools and characterizing the detector performance using low energy (≤ 6 keV) Synchrotron Radiation (SR) [1]. In this paper we continue our earlier investigations of the X-ray response of compound semiconductors, but now extend the assessment of performance to well above 10 keV, not only for a detector based on CdZnTe but also for an epitaxial GaAs detector.

Figure 1: Comparison of X-ray detector materials, Ge and Si with GaAs, CdZnTe and TlBr. (a) the mean penetration depth and (b) the absorption efficiency for 1 mm thick detectors as functions of X-ray energy. The mass absorption cross sections are from Kaman [2].

EXPERIMENT

Detector Characteristics

Common to all the detectors used for this work is the packaging in an evacuated aluminium housing, the use of thermoelectric cooling and matched low noise FET mounted very close to the detector crystal on a boron-nitride mount. The front-end electronics is also very similar for all detectors, except for the use of resistive feedback for GaAs and of transistor reset for the CdZnTe.

Both detector materials were subject to a range of diagnostic probes which included Photo-Luminescence (PL), SR-topography, Scanning Electron Microscopy (SEM), etc [1].

CdZnTe Detectors

The crystals used were $5 \times 5 \times 2 \text{ mm}^3$ in size and were grown by the High Pressure Bridgman (HPB) technique. The composition was $\text{Cd}_{1-x}\text{Zn}_x\text{Te}$, with $x \approx 0.1$ and $\rho = 5.9 \text{ gcm}^{-3}$. After cutting from the boule the crystals were chemically polished in a 5% bromine/methanol solution to remove surface damage [3], then Platinum contacts were applied by sputtering. All crystals were of spectroscopic quality, and priority was given to single crystals. No significant improvement in spectral response was gained compared to the detectors with electroless Au contacts. It was found that the detector performance is mainly limited by the crystal material defects. The crystals to be packaged were selected based on current-voltage and spectroscopic measurements. The room temperature resistivity was found to be $5 \times 10^{10} \Omega\text{cm}$, with ohmic contact behaviour. From α -radiation measurements the electron mobility/lifetime product was measured as $\mu\tau = 3.8 \times 10^{-3} \text{ cm}^2/\text{V}$ at room temperature, and that of holes as $\mu\tau = 4 \times 10^{-4} \text{ cm}^2/\text{V}$, in good agreement with values in the literature [4, 5].

Figure 2: Am^{241} spectrum acquired with the CdZnTe detector; full area illumination.

GaAs Detectors

Epitaxial GaAs was grown by Chemical Vapor Phase Epitaxy (CVPE) onto a 100 μm thick n^+ GaAs wafer produced by the Vertical Gradient Freeze (VGF) method. On top of the 40 μm thick intrinsic CVPE layer a 5 μm thick p^+ layer was grown. Metallic contacts were applied to both sides, resulting in a p-i-n detector structure. The p^+ side was patterned with circular structures, producing individual detectors with different design geometries. Parameters varied included detector diameter and use/omission of guard rings. Again, current-voltage and spectroscopic measurements were used to assess the detectors prior to packaging. The X-ray measurements presented here were performed with a detector of 1.77 mm^2 , having a guard ring present but not grounded.

Experimental Set-up

The detector performance measurements were carried out using radioactive sources, including Am^{241} , Fe^{55} and Co^{57} , and at SR facilities, namely Hasylab and Bessy. The latter offers highly collimated monochromatized radiation, suitable for detailed quantitative studies of the detector response functions and uniformities. The measurements were typically performed at $\sim -30^\circ\text{C}$.

RESULTS

CdZnTe Detector

This detector has been extensively studied both at low and high energies. Figure 2 shows the spectral response of the detector when fully illuminated with X-rays from an uncollimated Am^{241} source. The main peak at 59.5 keV is clearly detected with a total FWHM of 1500 eV including also the low energy tail component. The FWHM of the gaussian component is 1020 eV or 1.7%. Below ~ 50 keV the spectral lines show appreciably less tailing, and the total FWHM are practically identical to the FWHM of the gaussian components. In figure 3 the detector linearity and energy resolution are shown as functions of X-ray energy.

Figure 3: CdZnTe detector linearity (a), and energy resolution (b), as functions of X-ray energy.

In order to assess those factors, which constrain the spectroscopic performance of the detector, particularly the low energy tail distortions, with a view to provide relevant data for further crystal and process improvements, the detector was probed with very clean monochromatized radiation with very low background. To ensure the spectra were uncontaminated by second order factors, the illuminated area was limited, reducing detector edge effects or spatial dependant response variations. Here we limit ourselves to results obtained at lower energies around the L-edges of Cd and Te, and will examine the K-edge effects in a later publication. The detectors were illuminated with highly collimated SR between 2 keV and 5 keV. In figure 4 (a) the mean penetration depth is shown for this range, with the L-absorption edges of Cd and Te indicated. Around the Cd- L_{III} edge at 3.538 keV the change in penetration depth below and above the edge is $4.5 \mu\text{m}$ and $2.5 \mu\text{m}$, respectively. In figure 4 (b) the spectra measured ~ 5 eV below and above the Cd- L_{III} edge are shown. While the mean charge collected has not effectively changed, a significant difference in the low energy tail is observed. A significant decrease in the number of tail events occurs for photons with an energy 5 eV below the edge, due to their larger penetration depth.

A detector model has been developed to fit the measured data, which takes into account the movement of the hot electrons, which are initially generated by the stopping process of the primary photo- and Auger electrons, before they are thermalized and collected by the electric field [6]. The electron cloud created by the absorption of an X-ray photon is assumed to be spherical with a radius R . Thus all photons interacting at a depth $x \leq R$ contribute to the tail, because some electrons can reach the top electrode and can be lost there. Further, the escape effect [7] together with the shelf produced by transmission of primary (photo- and Auger) electrons from the top electrode to the CdZnTe and by electron escape from CdZnTe to the top electrode, are considered in our model. The individual components contributing to the response function of the CdZnTe detector are shown in figure 5 (a). Next to the gaussian component, the tail component generated by partial charge collection and the shelf component produced by events absorbed in the top electrode are shown. The escape component is negligible.

The tail component is a strong function of the X-ray energy, having discontinuities at the absorption edges of the detector material, see figure 5 (b), resulting in the observed changes of the detectors energy response function at the absorption edges. The tailing decreases with

Figure 4: The penetration depth of X-ray photons into the CdZnTe detector as function of energy (a), in the vicinity of the Cd-L_{III} and Te-L_{III} edges. In (b) the difference in the detector response ~ 5 eV below and above the Cd-L_{III} absorption edge is shown. The solid line is the modelled energy response function for the CdZnTe detector.

Figure 5: The response function of the CdZnTe detector can be modelled by a gaussian component, a tail and a shelf (a). The ratio of the number of events in the tail component to those in the main gaussian component is shown in (b), as a function of X-ray energy. Note the clear correlation with the Cd-L_{III} and the Te-L_{III} edges.

Figure 6: Am^{241} spectrum acquired with the GaAs detector; full area illumination.

increasing photon energy as the number of photons absorbed in the top layers of the detector crystal decreases. As the energy increases further, however, another tail generating process starts to become dominant. The photons start to penetrate through the intrinsic layer of the detector material and are increasingly absorbed in the only partly depleted lower layers of the detector. Free charge created by photons absorbed in the field-free region of the detector are only partly collected by diffusion into the depleted layer. At photon energies above 50 keV, far above the edges of Cd and Te, we observe this increase in the tailing due to the increasing penetration depth of the incident photons. Even the best available CdZnTe material still shows many defects (structural, crystallographic, purity), which reduce the resistivity. The leakage current then prohibits the increase of the applied voltage to a sufficient level so as to fully deplete the detector crystal.

GaAs Detector

This detector has also been studied both at low and high energies. The high energy response of the tested GaAs detector is limited by its 40 μm effective thickness ($\sim 4\%$ absorption efficiency at 60 keV), but shows remarkable energy resolution for all the lines produced by an Am^{241} source, as shown in figure 6. In comparison with the response of the CdZnTe detector, see figure 2, the spectral shape of the 59.5 keV Am^{241} line is much cleaner with considerably less tailing. The 40 μm epitaxial film is considered to be fully depleted with a very sharp boundary to the conductive n^+ GaAs substrate. Events absorbed in the depleted region therefore produce a uniform signal, while those absorbed in the base material generate no measurable charge. The noise due to the leakage current increases towards lower energies and starts to become significant at ~ 1.7 keV. Of course the distortion of the spectral lines due to loss of hot electrons to the top electrode still exists, although the faster diffusion in the epitaxial GaAs may mitigate against this being a major effect.

The energy linearity and the spectral resolution are shown as functions of energy in figure 7. Note that the deviations from linearity are mainly due to peak shifts induced by superimposed and not considered minor source lines, rather than an intrinsic detector effect. At 13.95 keV and 59.5 keV the energy resolution is ~ 900 eV and ~ 1120 eV, respectively. These are some of the

Figure 7: GaAs detector linearity (a), and energy resolution (b), as functions of X-ray energy.

best energy resolution data recorded to date from GaAs detectors at $\sim -30^\circ\text{C}$ [8, 9].

Figure 8 illustrates specific lower energy spectra obtained with the same detector when illuminated with collimated monochromatized synchrotron radiation at 3 keV, 3.9 keV and 5.4 keV. Here the mean penetration depth is below $10\ \mu\text{m}$ so tailing from loss of hot electrons and sub-surface defect effects may come to the fore.

CONCLUSIONS

We have shown that detectors based on CdZnTe or GaAs can meet the spectroscopic requirements of Hard X-ray Astronomy (10 to 100 keV), even when operating close to room temperature. Energy resolutions (FWHM) at 14 keV and 60 keV of 0.9 keV and 1.1 keV respectively for the GaAs detector were obtained. For CdZnTe the corresponding values are 0.7 keV and 1.5 keV (gauss only: 1.0 keV) respectively. Both types of detectors have considerable spectroscopic capability well below 10 keV, providing an invaluable overlap with current or future low energy telescopes ($\leq 10\ \text{keV}$), such as XMM containing silicon based detectors in the focal plane. To ensure the practical application of these detectors in future missions, the subsequent activity will involve the optimisation of the detector geometry (for example the current $40\ \mu\text{m}$ epitaxial GaAs thickness needs to be increased by a factor of 5 or more), the production of large format arrays with a maximised packing fraction coupled to large scale pre-amplifier arrays. Finally the background rejection capabilities of these detectors need a thorough characterization so as to be able to discriminate against cosmic rays and soft electrons observed in a space environment.

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Figure 8: The response of the GaAs detector to low energy X-rays, where the fast electron tail component can be probed as function of penetration depth. Here however the leakage current induced noise dominated over the second order tail.

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