The hard X-ray response of a large area HgI₂ detector

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We summarise the results of a number of X-ray measurements on a 1.06 cm², 0.18 cm thick HgI₂ detector carried out at the European Synchrotron Research Facility in Grenoble, France. The detector energy response function was found to be linear over the energy range 8 keV to 27 keV with an average rms non-linearity of 0.6%, consistent with statistics. At room temperature, under full area illumination, the FWHM energy resolution was 1.4 keV at 5.9 keV rising to 3.9 keV at 59.54 keV. Under pencil beam illumination, the measured energy resolution at 8 keV was 1.4 keV FWHM at a detector temperature of 9°C. Using a 50 × 50 μm² 10 keV monoenergetic X-ray beam, the spatial uniformity of the detector response was determined by a raster scan technique to be at the ± 5% level.

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I. INTRODUCTION

Mercuric iodide (HgI₂) has been investigated as a room temperature X- and gamma ray detector since the early 1970's [1,2]. Its wide band-gap, in conjunction with the high atomic number of its constituent atoms makes it an attractive material for room temperature X- and γ-ray spectrometers. The first detectors were initially grown from solution, but due to impurity and solvent inclusion problems, vapour phase processes (both vertical and horizontal ampoule methods) have largely taken over and are now the preferred growth method. The fabrication of a pn-junction is usually not necessary, as dark currents are generally very low.

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The Space Science Department of ESA has an active compound semiconductor research program aimed at developing large area X-ray imagers and monolithic detectors for future planetary and astrophysics missions. A number of materials are presently under study, including GaAs, TlBr, CdZnTe, InP, and HgI₂. In this paper, we report the results of an experiment to characterize the performance of a large area HgI₂ monolithic detector. The detector was provided, under loan, by Constellation Technology Corporation of Florida, USA, for test and evaluation.

FIG. 1. The detector used in the present measurements. The HgI₂ monocrystal is mounted on a boron nitride substrate. The input FET is located immediately adjacent on a ceramic mount.

II. DETECTOR FABRICATION

The crystal used in the present study was produced by the Constellation Technology Corporation® and has dimensions $12.4 \times 14.0 \times 1.76 \text{ mm}^3$. Palladium contacts of area $10.3 \times 10.3 \text{ mm}^2$ were then deposited by sputtering and the crystal coated with a thin (few microns) polymer coating (Parylene) for surface passivation and to protect it from evaporative degradation. With this coating the detector performance has remained stable for ~1 year. The crystal mounted on an aluminum oxide substrate and signals extracted from the lower contact by a 2N4416 input FET (see fig. 1), located adjacent to the detector on a ceramic substrate. The entire assembly is enclosed in a vacuum vessel filled with 1 atmosphere of dry nitrogen and coupled to a mechanical cooler capable of cooling the detector to $+9^\circ\text{C}$. X-rays are

incident through a thin (25 μ m) Be window. The rest of the analog chain consists of a transistor reset charge sensitive preamplifier mounted externally on the detector housing. Shaping and amplification is provided by an ORTEC 671 spectroscopy amplifier whose output is digitized by an Amptek MCA8000 12-bit ADC and stored on a PC. Real time analysis is carried out by pipelined software based on IDL. Negative bias is applied to the illuminated (upper) contact to ensure the most efficient collection of holes, whose mobility-lifetime product in HgI₂ is at best about half that of the electrons. The detector capacitance is 8 pF and the leakage current at the nominal operating bias of -1500 V was measured to be <100 pA.

III. EXPERIMENTAL

X-ray experiments were carried out in our laboratory and at the open bending magnet (BM5) high-energy beam line at the European Synchrotron Research Facility (ESRF) [3]. This beamline uses a double crystal monochromator to produce highly monochromatic X-ray beams tuneable over the energy range 8 keV to 27 keV. A Si[311] reflection was chosen with an intrinsic energy resolution of ~15 eV. The detector was mounted on a 2-axis X-Y table capable of positioning the detector to a precision of ~ 1 μ m with respect to the beam. For the majority of measurements, the beam was normally incident on the centre of the detector and had a typical spot size of 50 $\times$ 50 μ m². For completeness, additional full-area illumination measurements were carried out using two radioactive sources (⁵⁵Fe and ²⁴¹Am).

The initial characterization of the device was made using ⁵⁵Fe and ²⁴¹Am radioactive sources. The optimum performance, in terms of energy resolution, was found at a bias of ~ -1500 V and electronic shaping time of 8 μ s. The leakage current was low enough to permit room temperature operation, with measured FWHM energy resolutions at 5.9 keV and 59.54 keV of 1.43 keV and 3.9 keV, respectively. The system noise was determined with a precision pulser to be 1.2 keV FWHM; thus the detector contributes the bulk of the noise. Cooling the detector to 9°C resulted in a marginal improvement in ΔE to 3.7 keV FWHM.

Fig. 2 shows a composite of energy spectra measured at the ESRF. The detector temperature was +9°C. The noise threshold (defined to be the lowest energy for which the low energy noise attains an amplitude of 0.5 of the photopeak) is 2.6 keV. As can be seen, for incident energies < ~20 keV, the individual photopeak responses are symmetric about the centroid. Above this energy the photopeaks become increasingly tailed due to hole trapping. From the pulse height data, the detector linearity curve was determined and is shown in fig. 3. The non-linearity was measured from the residuals of a best-fit linear regression ($\chi^2 = 5/6$ dof) to the measured line centre energies.

FIG. 2. A composite of pulse height spectra measured at the ESRF. The beam size was $50 \times 50 \mu\text{m}^2$, incident at the center of the detector. The detector temperature was $+9^\circ\text{C}$.

FIG. 3. The linearity of the detector measured at the ESRF using pencil-beam illumination. The lower panel shows the residuals (*i.e.*, the percentage deviation from the best-fit linear regression (measured – calculated/calculated $\times 100$). The vertical dotted lines indicate the Hg L-III, II, and I edges.

It was found to be no worse than 1% across the useable energy range. The lower panel in fig. 3 shows a plot of the residuals from which we can see that there is tentative evidence for a gain change across the Hg L-edges (indicated by the dotted lines). This is presumably to the rapid increase in charge trapping caused by the abrupt change in penetration depth across the edges.

FIG. 4. The energy resolution ΔE under pencil-beam illumination at $+9^\circ\text{C}$ measured at two different positions on the crystal. The solid lines show the best-fit resolution function to the combined data set. The individual components of the FWHM for position (a) are also shown.

The energy resolution function of the system is shown in fig. 4. Two curves are shown which correspond to the positions of the best and the worst measured resolutions on the crystal surface. For the best position (position a), the measured FWHM resolutions range from ~ 1.3 keV at 8 keV to 1.6 keV at 27 keV. For the worst position (b), the measured resolutions are $\sim 20\%$ worse. Both curves were found to be dominated by electronic noise (1.2 keV FWHM). Since the measured resolution at 8 keV is essentially the same as that measured at 5.9 keV, we deduce there is no difference between pencil-beam and full-area illumination, thus indicating uniform crystallinity and stoichiometry.

The resolution was found to be well-fit by a function of the form

$$\Delta E = 2.355 \sqrt{\sigma_F^2 + \sigma_r^2 + \sigma_t^2} \quad (1)$$

where, σ_F^2 is the variance of the noise due to carrier generation or Fano noise ($\sigma_F^2 = FE\epsilon$), σ_r^2 is the variance of the noise due to the detector leakage current and amplifier noise and σ_t^2 is the variance of the noise due to incomplete charge collection due to carrier trapping. The solid lines show the best-fit resolution functions to the two data sets. For comparison, the individual components of the FWHM are also shown for position (a) (*i.e.*, ΔF , Δe and Δt). The contribution due to Fano noise, ΔF , was calculated assuming a Fano factor of 0.1 derived from the data of Iwanczyk et al. [3] under the assumption that trapping noise is negligible (*i.e.*, $\Delta t=0$). The electronic noise of the system was measured with a precision pulser to be 1.2 keV FWHM. The contribution due to incomplete charge collection is more difficult to quantify, since trapping noise is non-gaussian and therefore eqn. 1 is not strictly valid. We have therefore assumed that it can be approximated by a normal distribution and further assumed a linear dependence on energy (*i.e.*, $\Delta t^2 = kE$) as predicted by the Hecht relation [4]. Here k is a semi-empirical constant determined by best fitting. From the figure we see that electronic noise dominates the resolution function at all energies. We next attempted to access the charge collection efficiency (CCE) by fitting the resolution function to data assuming both the Fano factor and the magnitude of the trapping noise to be free parameters. The best fit Fano factor is 0.23 and the trapping factor $k=0.034$, *i.e.*, a CCE of $\sim 97\%$. Fixing the fano factor to be 0.1 [5], yields a CCE = $(96.6 \pm 0.8)\%$.

IV. SPATIAL RESPONSE

The spatial response of the detector was evaluated using a 10 keV collimated beam of size $50 \times 50 \mu\text{m}^2$, normally incident on the detectors forward detection area. The beam was then raster scanned across this 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 3 keV threshold, the peak position (*i.e.*, gain) and the FWHM energy resolution determined by best-fitting. The results are shown in figs. 5 and 6, in which we show both surface and contours plots for each of the recorded parameters. Note, the energy resolution is displayed in terms of its resolving power (*i.e.*, $E/\Delta E$) to ensure numerical robustness at the boundaries. From the individual distributions, we see that apart from a large dead area ($\sim 3 \text{ mm}^2$) near the center of the detector, the spatial response is reasonably uniform. The dead area is believed to have been caused during handling. Outside the dead area, the uniformity in response is typically better 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. Lastly, it should be noted that since the physical dimensions of the active

FIG. 5. The detectors spatial response measured at the ESRF using a $50 \times 50 \mu\text{m}^2$, 10 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.*, $E/\Delta E$.

FIG. 6. Contour plots of the spatial response measured at the ESRF using a $50 \times 50 \mu\text{m}^2$, 10 keV X-ray beam. (a) count rate profile, (b) the fitted centroid of the photopeak (*i.e.*, the gain), and (c) the resolving power, *i.e.*, $E/\Delta E$. The dotted line delineates the boundaries of the detector (see text)

detection area are bigger than the detector entrance window ($10.3 \text{ mm} \times 10.3 \text{ mm}$ as opposed to 8 mm diameter), the boundaries of the spatial distributions reflect the and not the crystal boundaries (the actual detectors boundaries are delineated by the dotted lines in fig. 6).

FIG. 7. Calculated efficiency of the Constellation 1.76 mm thick detector. For comparison, we also show the efficiency for a 0.5 mm thick Eurorad HgI_2 detector [6] and a 500 μm Si PIPS detector.

V. DISCUSSION AND CONCLUSIONS

Our measurements can be summarised as follows. The results show that mercuric iodide detectors of reasonably large detection area are useful as room temperature X-ray spectrometers down to a few keV. For incident energies above $\sim 20 \text{ keV}$, the shape of the photopeak becomes increasingly tailed due to the geometrical effect of hole trapping. Below this energy the radiation will be absorbed in a sufficiently short distance within the active region for the holes to be efficiently collected, even with the transport properties of present material. Hole collection problems, therefore, limit the useful thickness (and ultimately high energy performance) of the detector to about ~ 2

mm. Active hole trapping compensation employing bi-parametric techniques can be used to improve the shape of the spectra at high energies, but at the expense of counting efficiency. Alternative techniques involving risetime compensation have been developed which result in no loss of efficiency, although because of their complexity, these systems are not yet commercially available.

Finally, in fig. 7 we show the calculated efficiency of the detector, which clearly demonstrates the high stopping power of HgI_2 . In fact, the detector still has a usable efficiency of $\sim 10\%$ at 600 keV. The lower noise floor is set by the leakage current at ~ 2.6 keV at room temperature. Such a dynamic range is ideally suited for a wide range of applications, such as isotopic measurements for environmental redemption, nuclear medicine and chemical analyses using X-ray fluorescence. For comparison we also show the efficiency of a Eurorad 0.5 mm thick HgI_2 detector [6].

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