HARD X-RAY CZT DETECTOR DEVELOPMENT AND TESTING ON STRATOSPHERIC BALLOON PAYLOADS

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ABSTRACT

We report on the R&D activities on the development of room temperature semiconductor detectors (CZT detectors) for high energy space instrumentation. Our groups have been involved in the development of new hard X and soft gamma ray telescopes (e.g. Laue lens telescopes) and focal plane detectors. We present the characteristics and the performance of various CZT detector prototypes coupled with custom read-out electronics. The main target of this R&D activity is an end to end system for domestic growth CZT crystals, new sensor configurations and related read out architecture to provide an effective 3D focal plane able to perform contemporaneously imaging (spatial resolution mm or better), timing (few tens of µs), spectroscopy (2% @100keV) and polarimetry over a wide energy band (5-500 keV). On going activities on stratospheric balloon missions with CdTe and CZT detectors are also presented and discussed.

1. INTRODUCTION

The importance of hard X-ray astronomy (>10 keV) is now widely recognized. The results obtained with the most recent satellite missions (BeppoSAX, Rossi XTE, INTEGRAL) on many classes of X-ray celestial sources have demonstrated the importance of broad band spectroscopy. Recently both ESA and NASA have indicated in their guidelines for the progress of X-ray and γ-ray astronomy in the next decade the development of new instrumentation working in the energy range from the keV to the MeV region, where important scientific issues are still open. They have identified various priorities for the development of new instrumentation: concentrating telescopes (e.g. multilayer mirrors) for hard X rays (1 – 100 keV) and focusing instruments based on Laue lens operating from about 60 keV up the MeV. To exploit the performance of both multilayer hard X ray mirrors and Laue lenses, focal plane detectors with high efficiency, fine spectroscopy (e.g. a few % FWHM at 60 keV) and with a moderate spatial resolution (between 0.5 and 2 mm) are required. In particular for hard X-ray focal plane detectors and wide field instrumentation for gamma ray burst (GRB) monitoring, an energy threshold close to 1 keV will be very important allowing the measure of critical feature such as the Fe lines and a good overlapping with soft X-ray telescopes ranges. The high segmentation of the detectors and the required spectroscopic performance would also allow very sensitive measurements of the flux polarization level from high energy sources.

Over the last decade, cadmium telluride (CdTe) and cadmium zinc telluride (CZT) are considered promising materials for position sensitive spectrometers. Due to the high detection efficiency and the good room temperature performance, these detectors have obtained a great attention from the scientific community involved in the X- and gamma-ray band applications [1,2]. Moreover, the recent improvements on crystal growth technology with adequate homogeneity and purity is a favourable condition that contributed to confirm CdTe/CZT as promising semiconductors for high performance spectrometers. Currently CdTe and CdZnTe detectors are successfully used in space missions. The International Gamma-Ray Astrophysics Laboratory (INTEGRAL), launched in 2002, carries the Imager on Board the Integral Satellite (IBIS [3]) based on CdTe detectors and the SWIFT satellite, launched in 2004, carries the Burst Alert Telescope (BAT [4]) based on CZT detectors.

In this scenario, our groups have been involved, since several years, in the development of new hard X and soft gamma ray telescopes and focal plane detectors based on CdTe/CZT. Here we present the activities on CZT detectors as focal plane detectors for imaging, spectroscopy and polarimetry in the hard X and soft gamma ray energy range. Stratospheric balloon experiments, essential for both background information and testing of systems in severe environmental conditions, are also presented.

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2. CZT DETECTOR PROTOTYPES

CZT solid state detectors have several features which make them attractive as a focal plane imagers of focusing mirrors or coded mask aperture for the next generation of hard X-ray and γ-ray astronomy satellites. The high atomic number (Z_{max} = 52), the high density (ρ = 5.76 g/cm^3) and the wide band gap (E_G ~ 1.6 eV) ensure high quantum efficiency and good room temperature performance to CZT detectors. Difficulties in producing detector-grade materials and in growing chemically pure and structurally perfect crystals have been a critical issues of CZT detectors. In fact, the great potential of this compound has not been exploited for many decades due mainly to the limited commercial availability of high-quality crystals. This situation has changed dramatically during the mid-nineties with the emergence of a few companies committed to the advancement and commercialization of these materials. Moreover, the development of single charge carrier sensing detectors, i.e. based on the collection of the electrons, ensured good charge collection efficiency to these detectors overcoming the poor transport properties of the holes. Single charge carrier sensing techniques are widely employed for CZT detectors (unipolar detectors), by using both electronic methods (pulse rise time discrimination and biparametric analysis) and by developing careful electrode design (Frisch-grids, pixels, coplanar grids, strips and multiple electrodes).

2.1. CZT pixel detectors

CZT pixel detectors show good performance for imaging, spectroscopy and polarimetry in the hard X- and soft gamma-ray energy band. We have developed two CZT pixel detectors [5,6] as focal plane detector prototypes for hard X-ray focusing telescopes (1 – 100 keV). The detectors (10×10×1 and 10×10×2 mm^3 single crystals) were designed by our collaboration and fabricated by eV Products, USA. The anode layout is based on an array of 256 pixels with a geometric pitch of 0.5 mm in order to ensure an angular resolution of 30 arcsec (HPD). Both anode and cathode are made by platinum sputtered on the crystal surface in order to realize ohmic contacts. The detectors are mounted by using a "flip-chip bumping" electrical interface on a custom board, as shown in Fig. 1. Spectroscopic tests showed good energy resolution at room temperature (5.8 % FWHM at 59.5 keV for the 1 mm thick detector; 5.5 % FWHM at 59.5 keV for the 2 mm thick detector, Fig. 2) and low tailing in the measured spectra, confirming the single charge carrier sensing properties of the CZT detectors equipped with a pixellated anode layout. Figure 3 shows preliminary results on the spatial resolution of the detectors. We irradiated a square region of 3×3 pixels with a collimated source (^{241}Am, 59.5 keV) and read out the nine illuminated pixels together with all the neighbourhood pixels. As is clearly seen in the figure, almost 90% of the photopeak counts are detected by the irradiated pixel. This data confirm that the achievable spatial resolution is comparable to the pixel dimension or better.

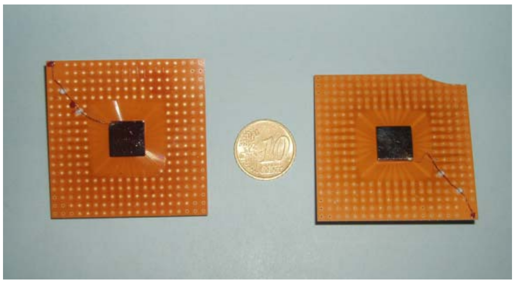

Figure 1. CZT pixel detectors (cathode side view). Both detectors are characterized by an anode array of 256 pixels (pitch 500 μm).

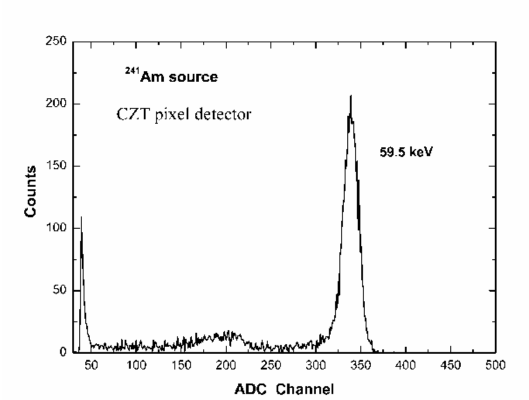

Figure 2. Measured ^{241}Am spectrum for the 2 mm thick detector at room temperature (T =25 °C). The detector shows an energy resolution of 5.5% FWHM at 59.5 keV.

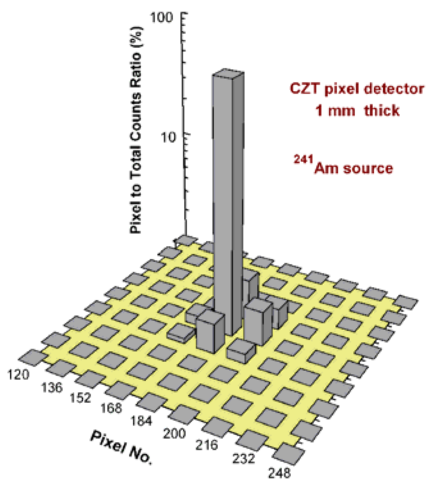

Figure 3. Histogram of the pixel to total counts ratio for the 1 mm thick CZT pixel detector.

A 5 mm thick CZT detector was also developed for polarimetric tests within the POLCA II experiment [7]. The detector, fabricated by Imarad, is characterized by an array with 16×16 pixels and a pixel area of 2.5×2.5 mm^2 (Fig. 4). The detector shows an energy resolution of 5% (FWHM) at 122 keV (room temperature). Polarimetric Q factors of 0.35 and double event relative detection efficiency of 20% were obtained with a monochromatic linearly polarized beam over the energy range between 150 and 750 keV [7].

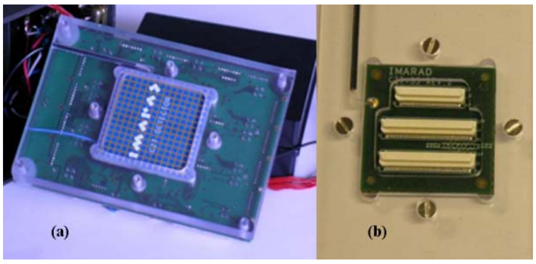

Figure 4. CZT pixel detector: (a) cathode side vie and (b) anode side view. The 5 mm thick detector is characterized by an anode array of 256 pixels (2.5 ×2.5 mm^2).

2.2. CZT drift detectors

Drift electrodes on the anode surface of CZT detectors provide an electrostatic shield so that the movement of the positive charge carriers will induce only a small signal at the collecting anode, thus reducing the sensitivity to holes. Besides the unipolar properties of the drift electrodes, it is possible to improve the collection of the electrons by applying a voltage between the drift electrodes and the collecting electrode. Fig. 5 shows the layout of a CZT drift ring detector [8] developed within the XPRESS experiment [9]. The detector (5×5×0.9 mm^3) is characterized by a planar gold cathode covering the whole detector surface, while the anode surface consists of a circular gold electrode (the collecting electrode; ϕ = 80 mm) surrounded by two ring electrodes (gap = 100 µm; radial width Δr = 100 µm) and by one electrode that extends to the edge of the crystal.

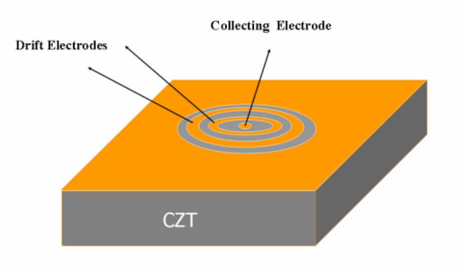

Figure 5. The anode layout of the CZT drift detector. The small anode electrode is surrounded by two ring electrodes .

Fig. 6 shows the excellent spectroscopic performance of the detector: an energy resolution of 2 % FWHM at 59.5 keV (T = -10 °C).

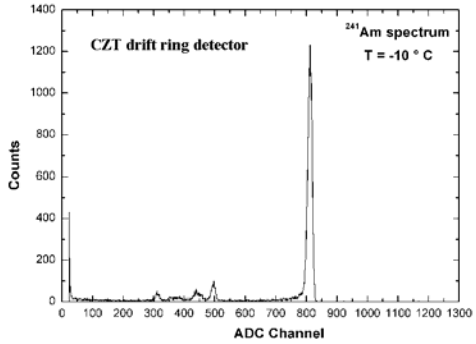

Figure 6. The measured ^{241}Am spectrum with the CZT drift ring detector (T = -10 °C). The detector shows an energy resolution of 2% FWHM at 59.5 keV.

It has been demonstrated that the presence of drift strips on the anode surface improve the performance of CZT detectors [10,11]. Figs. 7-8 show the layout of a three-dimensional (3D) CZT drift strip detector [12].

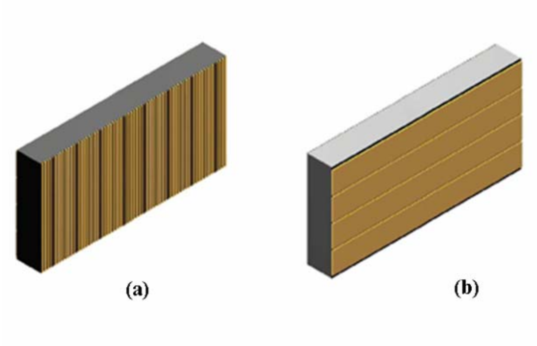

Figure 7. The layout of the 3D CZT drift strip detector: (a) the anode side, showing the guard strips set (light brown) and the 8 anodes (dark brown), with a constant pitch of 2.5 mm; (b) the cathode side segmented in a set of 4 strips (2.5 mm pitch) orthogonal to the anode set.

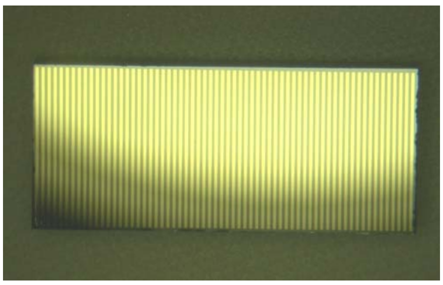

Figure 8. The anode side view of the 3D CZT drift strip detector.

The detector, currently on development by our group within the INAF PRIN 2007 project, is a 3D depth-sensing position sensitive device for a Laue lens telescope such as the Gamma Ray Imager (GRI) [13], a hard X and soft gamma ray mission recently submitted to ESA in the framework of the Cosmic Vision programme. Within this mission proposal, our collaboration has proposed a focal plane based on a stack of thick (up to 20 mm) CZT layers that will allow operation between ~few keV up to 1 MeV and to perform high sensitivity measurements contemporarily in imaging, spectroscopy and polarimetry. The sensitive unit is a drift strip detector based on a CZT crystal, (10×20 mm^2 area, 2.5 mm thick), irradiated transversally to the electric field lines direction (PTF). The anode is segmented into 8 detection cells, each comprising one collecting strip and 8 drift strips. The drift strips are biased by a voltage divider, whereas the anode strips are held at virtual ground. The cathode is divided in 4 horizontal strips, orthogonal to the anode strips, for the reconstruction of the Z interaction position. These orthogonal strip configuration, designed for the 3-D position sensing, ensures fewer readout channels than a pixellated structure, thus reducing the electronic complexity and the power consumption of the focal plane detector.

3. STRATOSPHERIC BALLON EXPERIMENTS

Balloon missions are an essential key to measure the background radiation, to confirm the performances of the background rejection system and to test both the detector and the readout electronics under flight conditions and at high altitudes.

Because of the weakness of many astrophysical X-ray sources and of the high radiation environment of the upper atmosphere, nearly all X-ray astronomy observations are completely background dominated. Thus, minimizing the instrumental background is essential for obtaining a good signal to noise ratio and high sensitivity. The instrumental background in hard X-ray detectors is mainly due to diffuse cosmic X-rays, galactic cosmic rays, solar energetic particles (SEP) and cosmic rays trapped in the Earth's radiation belts. At balloon altitudes the background, influenced by the environment created by the geomagnetic field, consists of an aperture-dependent diffuse component plus direct and indirect effects of charged particles acting with the detector and surrounding structures. The background rate on a detector will depend on the field of view of the detector, the detector/shield material and geometry. Therefore, understanding the dependence of background components on parameters such as the shield thickness, the detector thickness and the amount of passive material surrounding the detectors is important in order to minimizes background and optimizes the detection efficiency of the detectors.

In the last decade, several balloon flight background measurements with CdTe/CZT detectors coupled with both passive and active shielding have been performed [14-16]. The background measurements pointed out as the active shielding, based on scintillators such as Bismuth Germanate (BGO) or Sodium Iodide (NaI), is very effective in reducing the rate of background events in CZT detectors operating at balloon altitudes. This demonstrates as a high number of events deposit energy in CZT in coincidence with events that trigger a nearby active shield. These events include Compton scattering of high energy photons by the shield, charged particle interactions that trigger both the shield and the CZT, and internal background processes in CZT that can produce prompt photons that leave the detector and are intercepted by the shield. It has been shown that prompt (n,γ) reactions in CZT are also an important source of internal background due to the large neutron capture cross sections in Cd. Activation of Cd and Te by neutrons produce isomeric states that decay radiatively on a timescale too long to be vetoed by active shields.

A completely shielded small CZT detector (zero aperture, active lateral and bottom shielding) flown on balloon (Alice Springs) has measured volumetric rates of about ~ 10^{-3} and ~ 2.5 × 10^{-4} counts cm^{-3} s^{-1} keV^{-1} at 100 keV and 200 keV, respectively [16].

Fig. 9 shows the balloon background spectrum measured with a CdTe strip detector in the CACTμS (Compact Array of Cadmium Telluride Micro μ-Spectrometers) experiment [15].

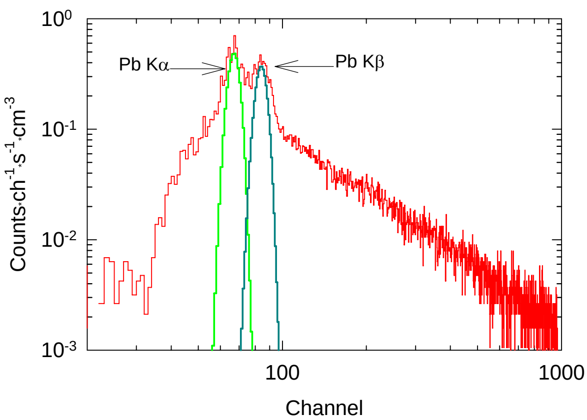

Figure 9. The background spectrum measured in the CACTμS balloon flight (single events at float integrated over~5 h). The two visible spectral features are compatible with the K-edge lines from the Pb shield. The count rate integrated over the full operational energy range is ~22 c/s/cm^3.

CACTμS was flown as a 'piggy-back' experiment on a stratospheric balloon platform as part of the summer

2002 trans-Mediterranean flight campaign from the Italian Space Agency balloon facility in Milo (Sicily). The detection system is based on two CdTe strip detectors and is actively shielded by an anticoincidence (AC) plastic scintillator. Each detector is characterized by four strips (pitch: 2 mm) and a thickness of 10 mm. The main objective was to study the instrumental background at stratospheric balloon altitudes over the 20–1000 keV energy range with particular respect to the spectrum and the distribution of Compton scattered events that trigger two pixels (double event). The analysis of double events and of the effect of the active shield on their distribution and rate is necessary to decide whether a veto system in a polarimeter operating at above 100 keV is required. The count rate of the background spectrum acquired at an altitude of 40 km and integrated over the full operational energy range was of 22±5 c/s/cm^3.

Within the development of the 3D CZT depth-sensing position sensitive device different flight scenarios are suitable for scientific-technological balloon tests: (a) antartic/artic long duration balloon flight to asses the reliability, the hardness of the proposed detector configurations in a high charge particle radiation environment as well as to evaluate the effectiveness of the 3D events reconstruction in background rejection; (b) low latitude ballon flight (e.g. trans-Mediterranean) for evaluation of the diffuse and intrinsic X and gamma ray background over a wide band (30-1000 keV). Balloon tests on a new modular telemetry system (MSITel), recently developed by the INAF/IASF-Bologna in collaboration with ASI, will be also performed. This system will allow an easy on-board implementation of real time control of critical parameters as well as data back up, contemporaneously providing a continuous duplex link with ground at any place without requiring any ground infrastructure.

4. CONCLUSIONS AND PROSPECTS

On going R&D activities on the development of new hard X and soft gamma ray telescopes and, in particular, focal plane detectors based on CdTe/CZT are presented. CdTe and CZT detectors have shown great maturity as focal plane detectors due to both their intrinsic spectroscopic performance and the good test-results obtained from recent balloon flight missions. Within the development of a three dimensional CZT focal plane detector for a Laue lens telescope, our group will propose Artic and trans-Mediterranean balloon flight missions in order to provide a strong tool in analysing and improving the prototype responses in severe environmental conditions.

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