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CZT detector technology for medical imaging

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ABSTRACT: Over the last two decades, the II–VI semiconductors CdTe and CdZnTe (CZT) has emerged as the material of choice for room temperature detection of hard X-rays and soft γ-rays. The techniques of growing the crystals, the design of the detectors, and the electronics used for reading out the detectors have been considerably improved over the last few years. CdTe/CZT materials find now applications in astrophysics, medical imaging and security applications. The paper discusses recent progress in CZT detector technology and outlines possible new application opportunities.

KEYWORDS: Pixelated detectors and associated VLSI electronics; Materials for solid-state detectors; Instrumentation for gamma-electron therapy; X-ray mammography and scinto- and MRI-mammography

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Contents

1 CZT crystal growth and detector fabrication

CZT material originally started to be grown using various flavours of Bridgman technique (BM). High Pressure Bridgman growth (HPBM) offers great electrical transport properties but limited singularity and hence higher cost [1]. Horizontal Bridgman (HBM) results in limited electrical transport properties despite great singularity and uniformity [2, 3]. Finally, Vertical Bridgman technique [4] offers improved singularity and electrical transport properties but lack manufacturing capability due to high cost and difficulties with reproducibility. Other growth techniques like vapour phase growth, vertical gradient freezing, and physical vapour transport (VPT) were tried but none yields effectiveness of travelling heater method THM which remains a workhorse industrial technique for CZT crystal growth.

The introduction of large single crystal and high performance CdZnTe (CZT) grown by THM has defied conventional myths about the capability of this crystal growth method with respect to the production of spectroscopic grade CZT and its commercialization prospect in medical imaging application [5, 6]. Since its development very significant progresses have been made, both in the crystal growth and device manufacturing [7]. In particular control of crystalline defects that challenge the thickness scalability of large volume CZT detectors was effectively addressed. Advances in THM CZT crystal growth include 100 mm diameter ingot and state-of-the-art detector fabrication.

The cost of the CZT technology is significantly affected by required fabrication steps to convert CZT crystal into functional CZT detectors. These steps include wafer cutting, surface passivation, lithography and side polishing. Many of these operations are performed manually but future fab equipment automation will significantly reduce these costs. One new trend in commercial CZT manufacturing is movement towards silicon like wafer level processing. Due to high yield of THM it is now possible to process entire CZT wafer instead of traditional good detector "mining" process used in the past [8].

2 CZT detector performance characteristics

The use of CZT detectors improves the energy, spatial resolution, and contrast resolution of imaging systems through direct conversion of the energy and location of the detected photon into an electronic signal, in contrast to the indirect conversion used in conventional scintillator based detector instruments. In scintillator based cameras, the energy of the photon is first absorbed by the crystal and converted to a large number of visible photons that have to leave the crystal to be detected by photomultiplier tubes, which then convert the photons to individual electronic signals. The sum of the signals from all photomultiplier tubes is used as an energy signal, and the weighted sum is used as the position of the event in the crystal. Any loss of visible photons contributes to miscalculation of the energy and location of the event. In the CZT direct conversion scheme, the photon is absorbed by one of the imaging pixels and directly converted to an electric pulse providing both the energy and the location of the event.

CZT detectors are used in principal in two modes of operation: photon counting and spectroscopy. X-ray or γ-ray photons can be counted like in a standard digital camera for visible light. This mode of operation is called photon counting and can work at very high flux rate up to 50 Mcps/mm^2. Alternatively for each photon the system can detect precisely its energy. This mode of operation is called spectroscopy. As extracting energy information takes more processing time the spectroscopic systems are inherently slower than the photon counting ones. In typical CZT applications used today the spectroscopic systems perform at the rates up to 1 kcps/mm^2. Between these two traditional product areas there is a sizeable window where the count rates are significantly higher than spectroscopy but energy resolution much better than required for photon counting.

2.1 Low flux operation

CZT detectors fabricated for low flux applications have good electron mobility-lifetime product ($\mu\tau \sim 1 \times 10^{-2}$ cm^2/V), but poor hole mobility-lifetime product ($\mu\tau \sim 1 \times 10^{-4}$ cm^2/V). For that reason most detectors in this class use "single polarity" readout schemes, where the main information about the energy of the detected radiation is inferred from the anode signals. Coplanar grid detectors (CPG), pixelated detectors, and Frisch grid detectors can overcome the severe hole trapping problem and greatly improve the energy spectra resolution of large-volume CZT detectors. Some state-of-the-art detector systems utilize also cathode signals in order to improve energy resolution (ER) using various depth of interaction (DOI) correction algorithms.

The continuous progress in CZT detector fabrication has been reported in the literature. Energy resolution (ER) less than 1% is now routinely achieved with 10–15 mm thick pixelated detectors with best pixels achieving under 0.5% ER (close to Fano-Factor which is fundamental limit) using sophisticated DOI corrections developed by Zhong He and his group [13]. Slightly worse but still similar level of performance can be achieved using co-planar grid detectors (CPG), where no DOI

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correction is required. These results clearly demonstrate high quality and low defect density of the CZT crystal volume.

2.2 High flux operation

High flux operation of CZT detectors brings additional challenges due to well-known polarization effect [9–11]. The origin of this effect can be traced back to high densities of impurities and defects that in turn lead to severe charge-carrier trapping. Under high flux conditions, the trapped charge builds up inside the detector affecting its stability, and in extreme condition leads to complete collapse of electric field and device operation. A quantitative comparison between areas where polarization is induced, and the electron- and hole-collection X-ray maps obtained at low flux was demonstrated [12].

Recent advances in THM growth that require additional processing steps have enabled to dramatically improved hole mobility-lifetime product by an order of magnitude. As a result high flux operation at the rates of several Mcps/mm^2 is routinely demonstrated. These improvements make application requiring high flux operation like Computed Tomography (CT) realistic. Preliminary results indicate that a CT system using an energy resolving CZT detectors reduces the dose to the patient while increasing image quality for various imaging tasks.

3 CZT for medical imaging

CZT technology has been applied to various medical imaging modalities in SPECT, PET, CT and flat-panels [14–24]. In this section we are describing state-of-the-art status in medical imaging equipment and prospects for future developments.

3.1 CZT for Single Photon Emission Computed Tomography (SPECT)

Nuclear medicine diagnostic applications are growing in search for more disease specific relevant imaging. The data are obtained non-invasively from large field γ cameras or from miniaturised probes. As far as single photon emitters are concerned, often labelled with ^{99m}Tc (140 keV, γ), nuclear instrumentation deals with poor counting statistics due to the method of spatial localisation and low contrast to noise due to scatter in the body. As discussed earlier room-temperature semiconductor detectors such as CdTe and CZT have favourable physical characteristics for medical applications. As a result of a considerable research work on material, contacts and dedicated electronics small field of view compact pixellated γ cameras have been introduced to the marketplace. Although extended clinical evaluation has to be conducted and long-term reliability assessed, the available data already confirm the expected gain in image contrast.

3.1.1 CZT for cardiology

The new ultrafast cardiac single photon emission computed tomography (SPECT) cameras with CZT based detectors are faster and produce higher quality images as compared to conventional SPECT cameras. As compared to images on a conventional SPECT camera, stress myocardial perfusion images acquired on a CZT camera have sharper contrast; require lower radiation dose and much shorter imaging time (2 mins vs. 30 mins).

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The first SPECT system to offer a totally different design was D-SPECT, manufactured by Spectrum Dynamics that used CZT detectors mounted on 9 vertical columns. Each of the 9 detector assemblies is equipped with a square (2.46 mm) tungsten parallel-hole collimator and due to its large collimator size camera offers significantly increased sensitivity. Data are acquired by first obtaining a 1-min scout scan for the 9 detectors to identify the location of the heart and set the limits of the detectors' fanning motion. The diagnostic scan is then performed with each detector module fanning within the limits determined by the scout scan. Reconstruction is performed using a modified iterative algorithm that compensates for the loss of spatial resolution that results from using large, square holes in the collimator by mathematically modelling the acquisition and collimator geometry.

The second SPECT system to offer a revolutionary design was the system developed by GE Healthcare known as the Discovery NM 530c. This design uses Alcyone technology, consisting of an array of 19 pinhole collimators, each with 4 solid-state CZT pixilated detectors, with all 19 pinholes simultaneously imaging the heart with no moving parts during data acquisition. Nine of the pinhole detectors are oriented perpendicular to the patient's long axis whereas 5 are angulated above and 5 below the axis for a true 3-dimensional acquisition geometry. The use of simultaneously acquired views improves the overall sensitivity and gives the complete and consistent angular data needed both for dynamic studies and for the reduction of motion artifacts. In addition, attenuation artifacts may be reduced because not all views are through the attenuator — some may view the heart from above or below.

3.1.2 CZT for oncology

Although cardiology is currently the largest market for CZT based scanners numerous new technologies are being developed for cancer detection. The most advanced of them is called molecular breast imaging (MBI). MBI is a new nuclear medicine technique that utilizes CZT detectors in a mammographic configuration to provide high-resolution functional images of the breast. Clinical studies have confirmed that MBI has a high sensitivity for the detection of small breast lesions. In patients with suspected breast cancer, MBI has an overall sensitivity of 90%, with a sensitivity of 82% for lesions less than 10 mm in size. MBI is highly complementary to existing anatomical techniques, such as mammography, tomosynthesis and ultrasound. Its use for women with dense breast tissue is bound to increase dramatically in the near future due to low sensitivity of traditional mammography.

3.2 CZT for bone densitometry

Bone densitometry is used to measure the bone mineral content and density. Bone densitometry is used primarily to diagnose osteoporosis and to determine fracture risk. The testing procedure measures the bone density of the bones of the spine, pelvis, lower arm, and thigh. Bone densitometry testing may be done using X-rays, dual-energy X-ray absorptiometry (DEXA or DXA) or by quantitative CT scanning using special software to determine bone density of the hip or spine. CZT detectors are ideally suited for high-performance DEXA systems and are currently used widely on a commercial basis.

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3.3 CZT for dental applications

Dental application demand very low cost and good performance at high count rates. Several generations of detectors produced for 10 Mcps/mm^2 OCR (Output Count Rate) panoramic dental imaging show that CZT technology is an excellent candidate due it excellent pixel-to-pixel uniformity. Challenges remain as the required thickness is only 1 mm and the pixel pitch (100–200 μm) pushes CZT attachment technology to the extreme.

3.4 CZT for Computed Tomography (CT)

Computed Tomography (CT) market is estimated to grow to $5 Billion by 2017 and represents one of the major diagnostic modalities in the medical imaging markets worldwide. Commercial CZT providers continue to target the development and provision of CZT based CT solutions [25]. Although dramatic progress has been made in high-flux characteristics of CZT material challenges remain in building commercial grade CZT based CT scanners.

3.5 CZT for Photon Emission Computed Tomography (PET)

Scintillator crystals currently employed in PET scanners have limited energy resolution due to non-uniform light output along the crystal length and limited photo-electron yield. Therefore, PET scanners use 10 to 20 mm long crystals to keep the variance of the light output within the target limit but the large energy resolution makes it very difficult to eliminate scattered events. Because of the wide range in energy of both true events and scattered events, placing a hard cut on the detected energy will remove the scattered events as well as a significant part of true events. With room temperature semiconductor detectors, such as CdTe and CZT, it is much easier to apply an energy cut to reduce the number of scattered events in the PET image event sample.

Due to the clear advantages of these new semiconductor materials several research centers have been working towards building CZT based PET cameras. As an example in 2011 Hitachi introduced a brain PET scanner with 152,024 CdTe detectors. Spanish Voxel Imaging PET (VIP) project is currently developing a high granular brain PET detector with 6.3 million channels, using pixel CdTe detectors coupled to dedicated readout ASICs. Stanford group have made very impressive gains in building small animal PET scanner using CZT detectors. Challenges remain; in particular drift time across detectors needs to be small and tightly controlled. More importantly with millions of pixels per PET camera required (more than order of magnitude compared to SPECT) detector cost is clearly the issue.

4 Conclusions

According to many experts there is a pyramid of room temperature semiconductor materials that can be sorted according to their suitability for nuclear radiation detection [9]. The peak of the pyramid consists of CZT and CdTe. The next level is TlBr, CdMnTe and HgI_2. The 3rd layer consist of CdTe and CdSe based alloys, GaAs and a-Se. The lowest level of the pyramid contains the rest of the currently known solid state materials: PbI_2, AlSb, IP, ZnSe, SiC, BiI_3, Ga_2Se_3, Ga_2Te_3 and Tl_4HgI_6 family. While many materials from the bottom layers have hoped to get to the top CZT remains the king of room temperature radiation detector and is in the process of replacing traditional scintillator-based devices in numerous applications as discussed in this paper.

CZT technology has achieved maturity required for commercial deployment. CZT based SPECT machines, BMI camera and bone densitometry devices have been shipping in volume for several years. Recent major improvements in crystal quality by implementing new growth and wafer annealing processes have enabled Wafer Level Fabrication (WLF). WLF in turn significantly improves yields, costs, capacity and product quality. CZT researchers have solved high flux polarization problem making future large volume commercial applications like dental, flat-panel X-ray or Computed Tomography within development reach. Further research efforts are required to address the most demanding application like PET.

References

[1] F.P. Doty, J.F. Butler, J.F. Schetzina and K.A. Bowers, *Properties of CdZnTe crystals grown by a high pressure Bridgman method*, *J. Vac. Sci. Technol.* **B 10** (1992) 1418.

[2] P. Cheuvart, U. El-Hanany, D. Schneider and R. Triboulet, *CdTe and CdZnTe crystal growth by horizontal Bridgman technique*, *J. Cryst. Growth* **101** (1990) 270.

[3] I. Jung, H. Krawczynski, A. Burger, M. Guo and M. Groza, *Detailed studies of pixelated CZT detectors grown with the modified horizontal Bridgman method*, *Astropart. Phys.* **28** (2007) 397.

[4] S. Sen et al., *Crystal growth of large-area single-crystal CdTe and CdZnTe by the computer-controlled vertical modified-Bridgman process*, *J. Cryst. Growth* **86** (1988) 111.

[5] H. Chen et al., *Characterization of traveling heater method (THM) grown $Cd_{0.9}Zn_{0.1}Te$ crystals*, *IEEE Trans. Nucl. Sci.* **54** (2007) 811.

[6] H. Chen et al., *Characterization of large cadmium zinc telluride crystals grown by traveling heater method*, *J. Appl. Phys.* **103** (2008) 014903.

[7] J. Mackenzie et al., *Recent advances in THM CZT for nuclear radiation detection*, *MRS Proc.* **1164** (2009) L10-04.

[8] H. Chen et al., *Development of CdZnTe detector for low energy X-ray photon counting*, in Proceedings of *2012 IEEE NSS-MIC-RTSD*, Valencia Spain.

[9] A. Bolotnikov and R. James, *New developments in wide bandgap CdZnTe (CZT) semiconductor detectors*, Brookhaven National Laboratory, New York U.S.A. (2012).

[10] U. El-Hanany, A. Shahar and A. Tsigelman, *CZT pixel detectors equipped with effective Ohmic contacts; their spectroscopic performance and the enigma of why they thus behave*, *Proc. SPIE* **3768** (1999) 2.

[11] S.A. Soldner, D.S. Bale and C. Szeles, *Dynamic lateral polarization in CdZnTe under high flux X-ray irradiation*, *IEEE Trans. Nucl. Sci.* **54** (2007) 1723.

[12] G.S. Camarda et al., *Polarization studies of CdZnTe detectors using synchrotron X-ray radiation*, *IEEE Trans. Nucl. Sci.* **55** (2008) 3725.

[13] F. Zhang and Z. He, *New readout electronics for 3-D position sensitive CdZnTe/HgI_2 detector arrays*, *IEEE Trans. Nucl. Sci.* **53** (2006) 3021.

[14] H. Le, J. Ducote and S. Molloi, *Radiation dose reduction using a CdZnTe-based computed tomography system: comparison to flat-panel detectors*, *Med. Phys.* **37** (2010) 1225.

[15] C. Scheiber, *CdTe and CdZnTe detectors in nuclear medicine*, *Nucl. Instrum. Meth.* **A 448** (2000) 513.

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[16] M. Mouden et al., *Impact of a new ultrafast CZT SPECT camera for myocardial perfusion imaging: fewer equivocal results and lower radiation dose*, *Eur. J. Nucl. Med. Mol. Imaging* **39** (2012) 1048.

[17] D.J. Wagenaar et al., *In vivo dual-isotope SPECT imaging with improved energy resolution*, *IEEE Nucl. Sci. Symp. Conf. Rec.* **6** (2006) 3821.

[18] K.B. Parnham, S. Chowdhury, J. Li, D.J. Wagenaar and B.E. Patt, *Second-generation tri-modality pre-clinical imaging system*, *IEEE Nucl. Sci. Symp. Conf. Rec.* **3** (2006) 1802.

[19] M. Tamaki et al., *Development of 4-sides buttable CdTe-ASIC hybrid module for X-ray flat panel detector*, *IEEE Trans. Nucl. Sci.* **56** (2009) 1791.

[20] D.S. Berman et al., *Stress thallium-201/rest technetium-99m sequential dual isotope high-speed myocardial perfusion imaging*, *JACC Cardiovasc. Imaging* **2** (2009) 273.

[21] S. Ben-Haim et al., *Simultaneous dual-radionuclide myocardial perfusion imaging with a solid-state dedicated cardiac camera*, *Eur. J. Nucl. Med. Mol. Imaging* **37** (2010) 1710.

[22] B.A. Herzog et al., *Validation of CT attenuation correction for high-speed myocardial perfusion imaging using a novel cadmium zinc-telluride detector technique*, *J. Nucl. Med.* **51** (2010) 1539.

[23] Y. Morimoto et al., *Development of a 3D brain PET scanner using CdTe semiconductor detectors and its first clinical application*, *IEEE Trans. Nucl. Sci.* **58** (2011) 2181.

[24] E. Mikhaylova et al., *Simulation of the expected performance of a seamless scanner for brain PET based on highly pixelated CdTe detectors*, *IEEE Trans. Med. Imaging* **33** (2014) 332.

[25] *Kromek sells its CZT detectors into SPECT and CT markets*, http://medicalphysicsweb.org/cws/article/newsfeed/55208.

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