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Multispectral photon-counting for medical imaging and beam characterization — A project review

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ABSTRACT

Central focus of the MPMIB project – funded via the Academy of Finland's RADDESS 2018–2021 programme – has been research towards a next-generation radiation detection system operating in a photon-counting (PC) multispectral mode: The extraction of energy spectrum per detector pixel data will lead to better efficacy in medical imaging with ionizing radiation. Therefore, it can be an important asset for diagnostic imaging and radiotherapy, enabling better diagnostic outcome with lower radiation dose as well as more versatile characterization of the radiation beam, leading for example to more accurate patient dosimetry.

We present our approach of fabricating direct-conversion detectors based on cadmium telluride (CdTe) semiconductor material hybridized with PC mode capable application-specific integrated circuits (ASICs), and will give a review on our achievements, challenges and lessons learned. The CdTe crystals were processed at Micronova, Finland's national research infrastructure for micro- and nanotechnology, employing techniques such as surface passivation via atomic layer deposition, and flip chip bonding of processed sensors to ASIC. Although CdTe has excellent photon radiation absorption properties, it is a brittle material that can include large concentrations of defects. We will therefore also emphasize our quality assessment of CdTe crystals and processed detectors, and present experimental data obtained with prototype detectors in X-ray and Co-60 beams at a standards laboratory.

1. Introduction

The project Multispectral Photon-Counting for Medical Imaging and Beam Characterization [1] (MPMIB) is a consortium project conducted as part of the Academy of Finland RADDESS (Radiation Detectors for Health, Safety and Security [2]) programme, during the funding period 2018–2021. It has contributors from different research groups in Finland, including Helsinki Institute of Physics (HIP), Aalto University (AU), Lappeenranta-Lahti University of Technology (LUT), and the Radiation and Nuclear Safety Authority (STUK). The goal was to develop a next-generation radiation detection system operating in a photon-counting (PC) multispectral mode, a technology that can prove as a valuable asset for future medical imaging systems: In detecting not only the integrated radiation along the lines of radiation, but registering the spectrum-per-pixel data, additional energy information can be obtained. The research area of photon counting for medical imaging has also attracted industry, resulting e.g. in the recent (09/2021) FDA approval of the SIEMENS photon counting CT device NAEOTOM Alpha [3]. The implementation of a multispectral PC device can lead to a better efficacy in medical imaging with ionizing radiation, enabling improved diagnostic outcome with lower radiation dose, as well as providing the possibility to simultaneously detect more than one radiation type. One application example would be Boron Neutron Capture Therapy (BNCT), a radiation therapy for severe cases of cancer [4]. In

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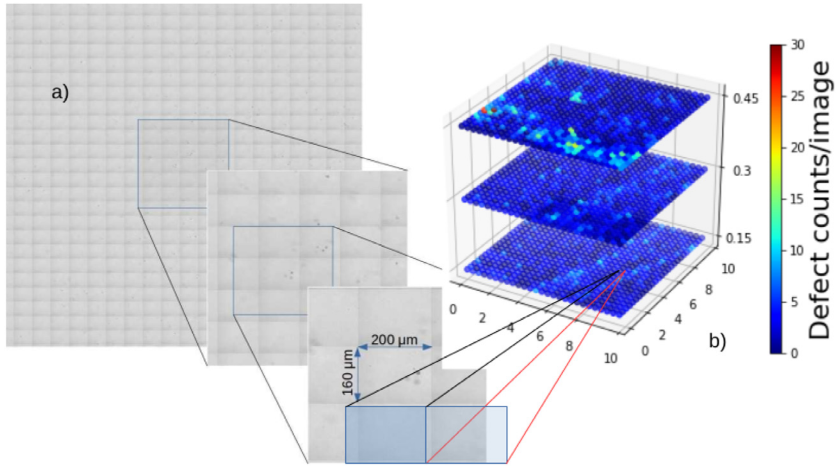

Fig. 1. (a) Stitched images of a raw CdTe crystal (b) visualization of defect counts/image for three crystal layers after NN evaluation, dimensions in mm.

order to have simultaneous monitoring and dosimetry capability and measure the dosage applied to the patient in tumour cells as well as in healthy tissue, it is necessary to distinguish radiation originating from the boron neutron capture reaction in the cancer cell from background radiation [5–7].

Towards the conclusion of the project, we want to discuss the outcomes, including the challenges and the lessons learned. We present our approach to manufacturing direct-conversion semiconductor detectors hybridized with PC mode capable ASICs. We focused on the high-Z material cadmium telluride (CdTe, $Z_{CdTe} = 48/52$) [8] as a detector material, which has excellent photon radiation absorption properties and allows room temperature operation due to a large energy band gap of 1.44 eV [9]. However, the processing of the CdTe crystals to pixel sensors is a complex procedure (see Section 3 and [9]). Moreover, CdTe is a brittle material and can include large concentrations of extended crystallographic defects which can deteriorate the detector's performance [10–12]; furthermore we encounter challenges during processing, such as cracking damage and delamination of insulation material. Therefore, we put emphasis on quality assessment measurements prior and during the complex detector processing procedure. Methods include e.g. infrared microscopy [13] (IRM) for studying the defect density in the bare crystals as well as current voltage (IV) measurements and transient current technique (TCT) for processed detector structures. Additionally, simulations with Technology Computer Aided Design (TCAD) were performed, to investigate the effects of local defects on the charge collection efficiency (CCE) of detector structures, and then compared with measurements obtained with TCT. The fabricated detectors were furthermore tested using X-ray and radioactive calibration sources.

2. Quality assessment and characterization

2.1. Quality assessment with Infrared Microscopy (IRM)

For the quality assessment of unprocessed CdTe, we employ infrared microscopy. IRM is a non-invasive method, with which the crystal interior can be scanned. Tellurium (Te) inclusions become visible, and consequently information on the Te defect density, locations and size of defects, and thus the overall quality of the crystal can be obtained. We scan complete crystal layers (dimension $1\,mm^2$) by moving the stage holding the sample in respect to the focus, evaluate the defects in the obtained IRM images with a neural network, and construct 3D-defect maps from the data. Fig. 1 gives an impression on how we can obtain a three-dimensional defect map from counting the defects in every single IRM image. In these, areas of higher local defect density become visible. Furthermore, the total defect count gives us an estimate on the material quality. For further information we refer to [14], where the procedure and results are thoroughly presented.

2.2. Characterization and simulation with TCT and TCAD

With TCT, the charge collection efficiency of test detectors can be evaluated, thereby analysing the uniformity of the detector [15]. With TCAD, a local defect model was developed for a CdTe test structure to simulate the effect of a 10 μm inclusion close to the surface on the current transients. The results were then compared to TCT measurements of a similar structure [16]. Main results were that the simulated charge collection at a defect position decreased visibly in comparison to the defect-free case. The transient currents of the simulation reproduced the measured transients well. There are ongoing characterization studies to map areas of higher defect density and other defect structures from the IRM maps to simulation and measurement results from TCAD, TCT and other imaging methods such as optical imaging or scanning electron microscopy (SEM).

3. Detector processing

3.1. Detector patterning and challenges

The CdTe material has (111) orientation and was obtained from Acrorad Ltd. It has a resistivity $> 10^9\ \Omega$ m and the samples have a size of $10 \times 10 \times 1\,mm^3$. The detectors are processed in Micronova, Finland's national research infrastructure for micro- and nanotechnology, employing techniques such as surface passivation via atomic layer deposition (ALD) [17,18] and contact metallization with titanium–tungsten and gold. The processed sensors are then flip chip bonded to read-out chips (PSI46dig design, with 52 × 80 pixels). The individual pixel size is $150 \times 100\ \mu m^2$. Fig. 2 gives an overview on the processing procedure, which includes three photolithography steps employing a mask-less laser writing tool instead of a mask aligner tool, to reduce the possibility of corner damages of the brittle material. We refer to [9] for more elaboration. The stability of the CdTe material properties as well as the different processing cycle steps were identified as the main challenges in the process of creating a working PC detector as they have a direct impact on the detector performance. With the current pixel detectors, we experience higher leakage currents than expected already at lower bias voltages. We investigate the reasons for this, as a higher bias voltage would be needed to improve the charge collection efficiency. Fig. 3 pictures an example IV curve for a test pad detector. Each data point is an average of three measurement points and the error is about the size of the measurement points and thus not visible. The characteristic Schottky behaviour emphasizes the fact that it is important to distinguish the crystal surfaces before processing. As we want to apply negative bias from the back and read out from the front, it is important to know which side exhibits less leakage current at

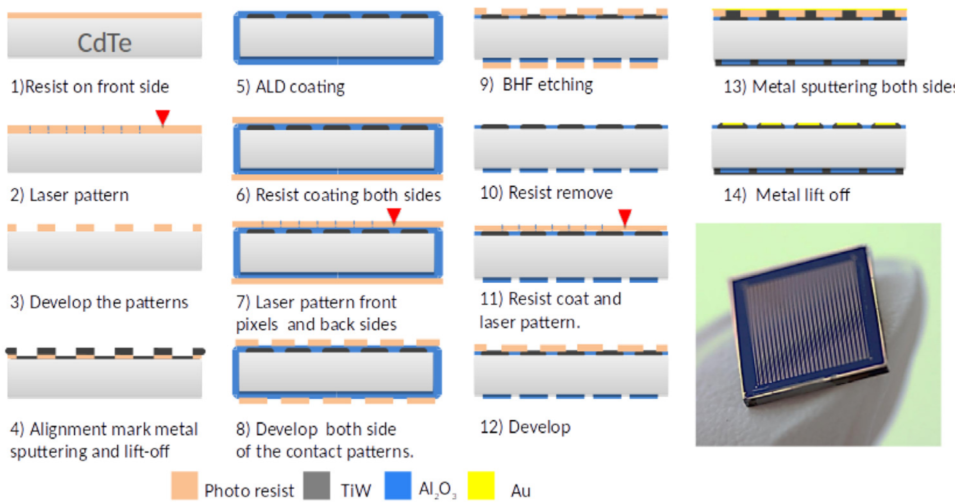

Fig. 2. Schematic of the processing steps (cf. [9]).

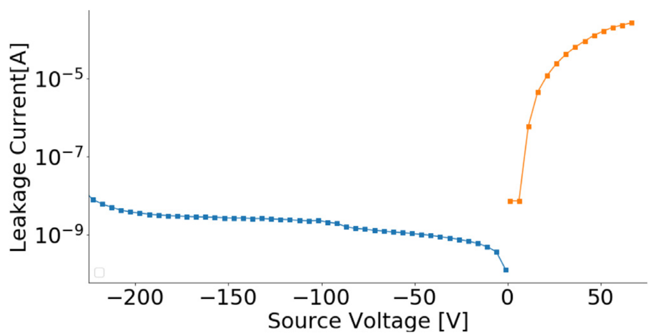

Fig. 3. Example IV curve for a CdTe pad detector. The amount of leakage current depends on the polarity of the bias voltage applied (cf. [19]).

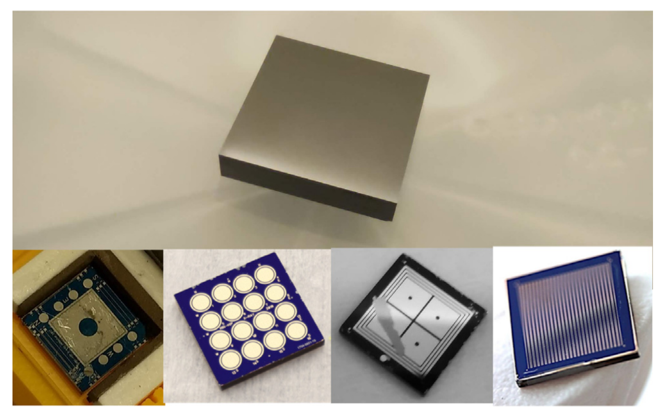

Fig. 4. *up*: raw CdTe, 1×1 cm^2 surface. *down*: four different test pattern structures. Detector with central optical opening; 16-pad structure; 4-pad structure; pixel detector.

negative bias as mentioned in [19]. Looking at the IV behaviour of different bare and processed crystals, a negative bias from the A side – which is the Cd-terminated face in CdTe(111) [8,20] – seems to be the preferred option [19].

Another challenge is the adhesion of the alumina passivation layer, with which we encountered adhesion instabilities during the processing. We are currently restudying the processing cycle to better understand the interplay of the different processing steps with the CdTe material to see how we can improve the detectors. For this, also alternatives for passivation material will be considered as well as differences in design and semiconductor material.

4. Prototype testing and results

The processed CdTe pixel detectors (see Fig. 4, lower right) have been exposed to different radiation sources (Americium-241, Barium-133, Cobalt-57, Caesium-137), to study the detector's performance in collecting spectra. As presented in [19], characteristic peaks were visible. However, the energy resolution was sub-optimal and the detector was biased only with −300 V to keep the leakage current below 2 μA.

4.1. Testing of prototypes in an imaging setup

Furthermore, to investigate the detector's possibilities for medical imaging, a small tomographic setup was built and used for a test measurement campaign. X-ray radiation is sent through a small, rotating phantom with implants and is detected by the CdTe pixel detector at different measurement points during one rotation. As the radiation passing the implants is attenuated more, the movement of implants during one rotation can be made visible in consecutive hitmaps. A description of the functionality of the setup (cf. Fig. 5) and first results can be found in [19]. We are however also interested in the spectrum-per-pixel information. For the reconstruction of the phantom interior including the spectral properties, an advanced reconstruction algorithm is necessary which is still under development.

4.2. Beam characterization

Another part of the MPMIB project was to investigate the suitability of pixel detectors for radiation therapy beam profile measurements, with the goal to make more accurate patient dosimetry in small beams possible than can be achieved with traditional ionization chambers. For the measurements, a silicon-based pixel detector was employed, which has the same pixel design as the CdTe detector discussed before and uses the same read-out system. The beam profile measurements were performed at a standards laboratory at the Radiation and Nuclear Safety Authority Finland, using a Cobalt-60 source, and a beam field size of 10×10 cm. During the measurements, the detector – situated inside a water-tight box and placed inside a water phantom – was moved stepwise along the beam field. Fig. 6 shows a profile scan of a corner of the beam with a silicon pixel detector, demonstrating how the profile changes in respect to the position of the detector inside the field. First results look quite promising and the analysis of the data is currently ongoing and will be presented soon.

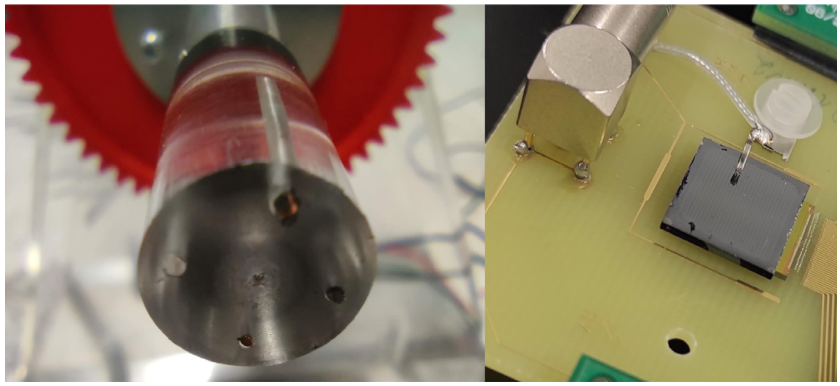

Fig. 5. A small rotating setup is used to obtain exemplary tomographic data (cf. [19]). *Left*: small phantom, connected to a gear wheel plus stepper motor for rotation. *right*: CdTe pixel detector connected to a read-out board.

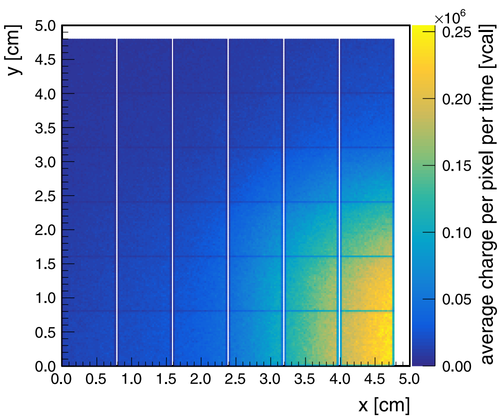

Fig. 6. Profile scan of a corner of the beam with a silicon pixel detector.

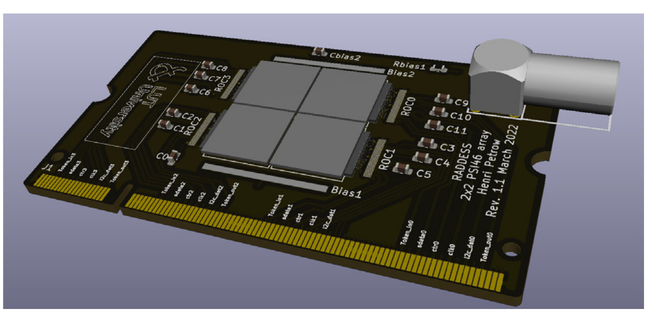

Fig. 7. Design of the PSI46 quad board, which will be able to host four pixel detectors tiled in a two by two array.

4.3. Development of a detector array board

At LUT a detector array board is constructed, to act as a technology demonstrator for a PC panel detector for imaging larger areas. It consists of two main parts: A carrier board hosting up to four single pixel detectors, as well as a high density interconnect adapter board to which the carrier board is connected. Separate communications lines exist to each read-out chip. The adapter board hosts an integrated circuit that controls and combines the data from the separate pixel detectors and synchronizes the detectors, e.g. by sending the readout trigger and clock signals. Currently, a slight redesign is needed, after which detectors will be mounted to the board and tested. Fig. 7 shows the design of the detector panel board.

5. Conclusions

We successfully tested prototypes at Helsinki Institute of Physics and at a testing facility of the Radiation and Nuclear Safety Authority Finland (STUK), but also identified issues with the stability of material properties and processing cycle steps that we investigate further. As next steps we plan measurements with the detector panel board, starting first with lower energy measurements with silicon pixel detectors as a proof of concept and then, once we have improved our CdTe detectors, switching to those. In order to improve our understanding of the CdTe material, we will continue our material science research, characterizing simple CdTe structures electrically and optically.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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