Material reconstruction with the Medipix2 detector with CdTe sensor

E. Guni, J. Durst, T. Michel and G. Anton

ECAP University of Erlangen,
Erwin-Rommel-Str. 1, 91058 Erlangen, Germany

E-mail: ewald.guni@physik.uni-erlangen.de

ABSTRACT: The new generation of photon counting pixelated X-ray detectors like the Medipix2 detector are gaining increasing interest in medical imaging. In contrast to conventional systems which integrate the charge released in the sensor they are able to count single photons. With this imaging detector it is possible to determine the energy of the incoming X-rays which opens up a new field of applications. One application is the detection of contrast agents in medical imaging which was shown for a silicon sensor. However the absorption efficiency of silicon is very low for the X-ray energies used in medical imaging. High-Z materials such as Cadmium Telluride (CdTe) are therefore promising candidates for the sensor material. With the hybrid design of the Medipix2 detector we are able to realize a photon counting pixelated X-ray detector with CdTe sensor. Crucial for material reconstruction are the energy response functions. With our simulation tool RoSi we are able to simulate these response functions. In this work first results and simulations concerning material reconstruction with a Medipix2 detector with CdTe sensor are shown.

KEYWORDS: X-ray detectors; Medical-image reconstruction methods and algorithms, computer-aided so; Detector modelling and simulations I (interaction of radiation with matter, interaction of photons with matter, interaction of hadrons with matter, etc)

1Corresponding author.
1 Introduction

X-ray attenuation is material- and energy dependent. While in conventional X-ray systems only the cumulative attenuation is accessible photon counting detectors allow energy sensitive X-ray imaging. New techniques such as material reconstruction [1] have been developed to exploit the capabilities of photon counting detectors like the Medipix2 detector [2]. This technique is particularly interesting for the detection of high-Z contrast agents such as iodine and gadolinium in medical X-ray imaging because it helps to reduce dose.

For medical X-ray imaging a highly absorbing sensor material is needed. Silicon (Si), being the common sensor material for the detection of charged particles in high energy physics, can not be used in most X-ray imaging systems due to its low atomic number \( Z_{\text{Si}} = 14 \). Therefore there is a huge demand for high-Z sensor materials such as Cadmium Telluride (CdTe). This II-VI compound semiconductor which can be operated at room temperature due to its large band gap \( (1.5 \text{ eV}) \) has a high atomic number \( (Z_{\text{Cd}}=48 \text{ and } Z_{\text{Te}}=52) \) [3]. This makes it a promising candidate for the sensor material. As there has been made great progress in the last years concerning quality in terms of homogeneity and charge transport properties on the one hand and commercial availability on the other hand photon counting detectors with CdTe sensor are now available.

Very important for material reconstruction are the energy response functions to monochromatic irradiation. Those can be obtained by using synchrotron radiation [4] or by developing a simulation model. With the development of our simulation tool RoSi [5, 6] we were able to simulate the response functions to monochromatic illumination from 5 keV to 100 keV in 1 keV steps.

This paper has the following structure: in section 2 we introduce the theoretical background of material reconstruction. Section 3 describes the simulation tool which was used for the simulation of the energy response spectra and the simulation of a setup for material reconstruction. And finally in section 4 we present our results of the energy response spectra and the material reconstruction from our simulation.
2 Theory of material reconstruction

X-ray absorption is material and energy dependent. The intensity I(E) behind an object is given by:

\[ I(E) = I_0(E) e^{-\sum_k \bar{\mu}_k(E) a_k}. \] (2.1)

where \( I_0(E) \) is the incident intensity, \( k \) the material index, \( \bar{\mu} \) the mass attenuation coefficient and \( a \) the areal density.

Due to physical processes in the sensor layer (charge sharing, fluorescence photon escape etc.) and electronic noise the signal \( M \) registered in the detector is:

\[ M(E') = \int R(E', E) I(E) dE. \] (2.2)

where \( E \) is the incoming energy, \( E' \) the deposited energy and \( R \) the monoenergetic energy response functions of the detector.

In a discrete notation and with equation 2.1 we obtain:

\[ M_i = \sum_j R_{ij} I_{0j} e^{-\sum_k \bar{\mu}_{jk} a_k}. \] (2.3)

with \( i \) being the index for the deposited energy, \( j \) the index for the incoming energy and \( k \) the index for the basis materials.

Provided \( R_{ij}, I_{0j} \) [7] and \( \bar{\mu}_{jk} \) are known, we can determine the areal densities \( a_k \) with the maximum likelihood approach:

\[ L(bin_i; a_1, a_2, \ldots, a_k) = \prod_i \frac{1}{\sqrt{2\pi M_{\text{meas},i}}} e^{-\frac{(M_{\text{meas},i} - M_i)^2}{2M_{\text{meas},i}}}. \] (2.4)

where \( L \) is the likelihood function, \( M_{\text{meas},i} \) the measured counts and \( M_i \) the expected counts from equation 2.3.

The areal densities \( a_k \) can be determined by maximising \( L \) or by minimizing:

\[ -\ln(L(bin_i; a_1, a_2, \ldots, a_k)) = \text{const.} + \sum_i \frac{(M_{\text{meas},i} - M_i)^2}{2M_{\text{meas},i}}. \] (2.5)

3 Simulation setup

In [6] a photon counting detector class with a CdTe sensor for the Monte Carlo simulation package RoSi was presented. In this simulation all relevant processes for signal generation are taken into account. Starting from the electron-hole pair creation in the sensor (including Fano noise) to the propagation of the charge clouds to the electrodes (taking into account drift, diffusion and repulsion). The induced current on the pixel electrode was modelled by taking into account the charge collection properties of CdTe (lifetime, trapping) and the small pixel effect (weighting potential). The electronic noise was obtained from measurements.

In our simulation setup the pixel pitches of our detector were 220 \( \mu \)m. The sensor thickness was 1600 \( \mu \)m. The number of pixels was 400 (20x20). In front of our detector a water phantom
Table 1. Projected concentrations a.

|         | water          | gadolinium    | iodine        |
|---------|----------------|---------------|---------------|
| Concentration | 1 g cm^{-2}   | 0.01 g cm^{-2}| 0.01 g cm^{-2}|
|          |                | 0.005 g cm^{-2}| 0.005 g cm^{-2}|
|          |                | 0.002 g cm^{-2}| 0.0015 g cm^{-2}|

Figure 1. Left: simulation setup. Right: photon counting image.

Figure 2. Left: Comparison of measurement and simulation of the energy response function. Right: Energy response matrix from 5 keV to 100 keV in 1 keV steps.

with different gadolinium and iodine concentrations was positioned (see table 2). The phantom was irradiated by $10^9$ photons coming from a 100 kV tungsten spectrum filtered with 1.4 mm aluminum and the transmitted photons were registered by the detector. The left part of picture 1 shows a picture of the simulation setup. In the right part of figure 1 a photon counting image with 19 keV threshold is shown. The different concentrations of gadolinium and iodine are visible.

4 Results and discussion

The left plot of figure 2 shows the energy response spectra for two pixels with a pixel pitch of 220 μm and a thickness of 1600 μm to irradiation of 59.5 keV photons of a $^{241}$Am source and the respective simulation. As can be seen the simulation describes the measurement very well. The right plot of figure 2 shows the energy response spectra from 5 keV to 100 keV in 1 keV steps.
Figure 3. Reconstructed images for the projected concentrations a.

Table 2. Reconstructed projected concentrations a.

| Material   | Concentration | Concentration | Concentration |
|------------|---------------|---------------|---------------|
| water      | 0.98±0.13 g/cm² |               |               |
| gadolinium | 0.0091±0.0030 g/cm² | 0.0041±0.0030 g/cm² | 0.0005±0.0006 g/cm² |
| iodine     | 0.0090±0.0006 g/cm² | 0.0043±0.0013 g/cm² | 0.0012±0.0018 g/cm² |

Figure 3 shows the reconstructed images of the areal densities a for the 3 basis materials water, gadolinium and iodine. As can be seen the reconstructed images depict the position and the quantity of the basis materials correctly. Table 2 gives an overview of the reconstructed values of the areal densities.

In this work we showed that material reconstruction with a photon counting detector with CdTe sensor is possible. In our simulation the pixels are assumed to be equal in the response to radiation and the position of the thresholds. In practice however there are material impurities (tellurium inclusions etc.) and electronic properties (deviation of the thresholds) which degrade the spatial homogeneity. Thus projective material reconstruction becomes difficult. A better possibility is material reconstruction in computed tomography. We found that it is possible to find a row or column of pixels with similar behaviour. The thresholds of those pixels can be adjusted in a way that we will be able to apply the technique of material reconstruction to computed tomography.

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