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# On the energy response function of a CdTe Medipix2 Hexa detector

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ABSTRACT

X-ray imaging based on photon counting pixel detectors has received increased interest during the past years. Attached to a semiconductor of choice, some of these devices enable to resolve the spectral components of an image. This work presents the results from measuring the energy response function of a Medipix2 MXR Hexa detector, where six individual Medipix detectors were bump bonded to a 1 mm thick cadmium telluride sensor in order to form a $3 \times 2$ array of $4.2 \times 2.8$ cm$^2$ size. The average FWHM of the photo peak of an $^{241}$Am source was found to be 2.2 and 2.1 keV for single pixels and bias voltages of 200 and 350 V, respectively, across the whole Hexa detector. This corresponds to a relative energy resolution of less than 4%. Adding up all pixel spectra of individual chips lead to an only small deterioration of energy resolution, with line widths of 2.7 and 2.5 keV. In general, a lower detection efficiency was observed for the lower voltage setting, along with a shift of the peak position towards lower energies.



## 1. Introduction

Conventional digital X-ray imaging relies on measuring a signal proportional to the integrated amount of energy deposited in a pixel during exposure, which normally follows the conversion of X-ray photons into visible light in a scintillating material. During the last decade, this approach has been supplemented by direct conversion techniques based on pixelized semiconductor detectors [1]. While many of these devices are capable of counting individual photons and thus providing spectral resolution, there is ongoing debate as to which combinations of pixel sizes, sensor materials and thicknesses to choose in order to achieve both high spatial and spectral resolution in combination with a high quantum efficiency. Depending on detector properties and sensor material, the recorded spectrum can significantly differ from the actual one. In order to interpret and reconstruct these spectra, a careful measurement of the so-called energy response function is necessary. This work presents the results from measuring this function at a single photon energy of about 60 keV for a Medipix2 MXR [2] Hexa detector attached to cadmium telluride (CdTe) single crystal. With a size of $4.2 \times 2.8$ cm$^2$, this device represents the largest Medipix detector assembled to a single sensor so far, and is intended to be used for small animal imaging at DKFZ.

In the following section, we will briefly describe the detector and the processing steps we employed in order to obtain the results presented in Section 3. Section 4 will then give a summary as well as an outlook on future experiments.

## 2. Materials and methods

The energy response function of pixelized semiconductors can be severely biased by electric charges shared among neighboring pixels. In order to mitigate these effects, a pixel pitch of 165 μm was chosen rather than the 55 μm which is provided by the Medipix architecture. This was achieved by connecting only every ninth pixel to the sensor ($3 \times 3$) by means of intentionally ohmic contacts, resulting in $258 \times 172$ pixels (44 376 in total). The sensor was a 1 mm thick CdTe single-crystal manufactured by Acrorad. These single-crystals represent the state-of-the-art of high resistivity, detectorgrade material and are commercially available with a diameter of 75 mm and thicknesses of 1 and 2 mm. The crystals were grown by the travelling heater method, which offers the advantage of a low growth temperature that reduces the concentration of defects and increases homogeneity. Characterization of these wafers obtained a homogeneous distribution of the resistivity with an average value of $5 \times 10^9$ Ω cm and a variation of less than 10%. Tellurium inclusions (second phase defects) were identified by infrared microscopy with an average diameter of less than 10 μm and a concentration of about $10^3$ cm$^{-2}$. Hybridization was performed at FMF with low temperature solder bumps. The overall process temperature was kept below 130 °C, which is of crucial importance in order to maintain high level sensor properties. All

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measurements described below were performed using the Medipix USB interface [5] and the Pixelman software [6].

As every other Medipix2 detector, the Hexa detector introduced here offers two modes of operation: The single threshold mode, where every event above a predefined energy threshold is counted, and the dual threshold or window mode, which introduces an additional threshold in order to obtain an energy window.

The response of every pixel can be calibrated with two sets of three adjustment bits to bring each of the two thresholds more in line with their neighbors. The process determining the optimal values of these bits is called threshold equalization and was performed according to standard procedures. In detail, the $K_\alpha$ fluorescence of a silver foil was used to equalize the lower thresholds, while the upper thresholds were equalized employing the switching point between single and dual threshold modes as described by Tlustos et al. [3].

Energy calibration was performed using the $K_\alpha$ lines of molybdenum (17.4 keV) and silver (22.2 keV) as well as the photo peak of an $^{241}$Am source (59.6 keV), which is described below. Here, one has to keep in mind that charge sharing shifts the maximum position of the peak to slightly lower energies. This shift was determined using a Monte Carlo simulation as developed by Durst et al. [4]. The corrected energy values used for the three sources were 16.4, 21.4 and 59.0 keV for a bias voltage of 350 V.

In principle, the window mode can be used to obtain spectroscopic information about the incident X-rays. However, the energy window must not be chosen too small as manufacturing tolerances lead to a slight variation of each pixel's response to radiation even after threshold equalization, also called residual threshold dispersion. The remaining small differences become more and more dominant as the energy window gets thinner, and so the effective window size cannot be set below a few keV, which in turn leads to a blurring of the spectra recorded. While this behavior does not represent a drawback in most imaging applications, it prevents the precise characterization of the detector under study. For this reason, the energy response function is usually measured differently by scanning in single threshold mode across the energy range of interest, yielding an integrated spectrum. This spectrum is then differentiated to obtain the actual photon energy spectrum.

In order to determine the energy response function, i.e. the detector's response to monochromatic radiation, we employed the same $^{241}$Am source that we already used for energy calibration. It emits X-ray photons with an energy of about 59.6 keV and is therefore well suited for the investigation of the energy response function at an X-ray energy typical for medical diagnostics, when other monochromatic sources such as synchrotron light are not available.

The $^{241}$Am used here has a nominal activity of about 1.1 GBq and was placed in front of the detector at a distance of about 5 cm. The measurement was performed at a bias voltage of 350 V for an energy range of 10–60 keV and took about 18 h in order to acquire enough photons to perform the peak fitting without any significant low-pass filtering, which would have biased the width of the photo peak. Another measurement of just the photo peak was performed at 200 V to investigate the dependance on the bias voltage.

The full width at half maximum (FWHM) of the photo peak was determined by fitting a Gaussian to individual pixels as well as the sum over each of the six chips' pixel spectra. A binomial filter of size three was applied to the spectra prior to fitting in order to make the results more stable (which broadens the peak by less than 0.05 keV). The medians and the standard deviations obtained from the fits on the single pixel level can then be considered a measure for the inter-pixel dissimilarity, while the fits on the sum spectra give an impression of how much the residual dispersion of the lower thresholds' responses affect the energy resolution of a whole chip.

In order to demonstrate how the energy response function affects the acquisition of broad band X-ray spectra, the tube spectrum from a medical Siemens Powerphos X-ray tube was measured at a voltage of 110 kVp and a current of 1 mA. The tube features a built-in aluminium filter, which is normally used to reduce the skin dose in patients and blocks almost every photon below 20 keV from exiting. The detector was placed about 1.2 m from the tube to prevent both signal pile-up in the detector electronics as well as polarization of the CdTe sensor caused by the low hole mobility. Again, the spectrum was recorded by a scan in single threshold mode between energies of 10 and 110 keV using exposure times of 4.5 s per value of the internal Medipix channel (about 0.2 keV).

To finally give an impression of the overall quality of our Hexa detector, we acquired two images of a plastic lighter in window mode at two different photon energies (30–35 and 65–70 keV). Furthermore, we discuss the influence of the two bias voltages on the resulting image quality using the example of the $^{241}$Am scan.

## 3. Results and discussion

The energy response function of nine pixels measured at 350 V is depicted in Fig. 1. The spectra in this figure have been aligned by means of a cross-correlation to enhance the visibility of the peaks. It demonstrates the occurrence of not only the charge sharing background, but also of the $K_\alpha$ lines of cadmium (23.2 keV) and tellurium (27.5 keV) plus their associated escape peaks (36.3 and 32.0 keV). It follows that the pixel pitch of 165 μm is not large enough to reduce the number of fluorescence photons that escape a pixel down to a level where their influence would be neglectable.

The medians and the standard deviations of the FWHMs for the single pixel spectra are shown in Table 1 for the two voltages investigated. It can be seen that increasing the bias voltage from 200 to 350 V only amounts to a decrease of the peak width by 0.1 keV. However, this goes along with a further movement of the peak position to lower energies by about 0.6 keV on average, which is due to charge sharing (data not shown).

The same conclusion can be drawn for the spectra summed over the whole chip, as listed in Table 2. Furthermore, the increase due to the summation is found to be only about 20%, a result that is certainly depending on the quality of the adjustment bits obtained from the lower threshold equalization procedure. Fig. 2 shows the same spectra as Fig. 1 without alignment to give a visual impression of the residual variations in the threshold equalization which are responsible for this behavior.

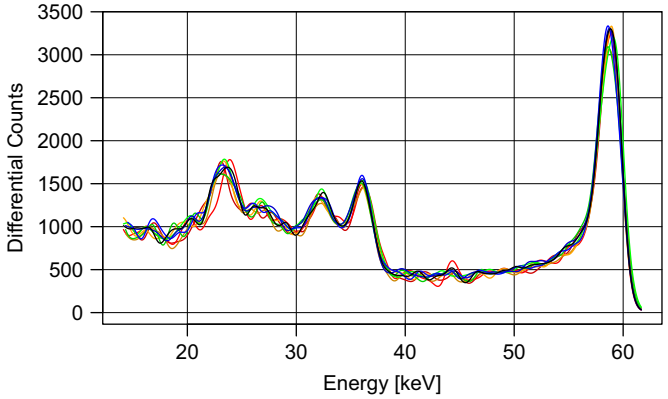


**Fig. 1.** Single pixel spectra found in a 3 × 3 neighborhood of a randomly chosen pixel ($V_{bias}$ = 350 V). Note that these spectra were low-pass filtered using a binomial kernel of size $n$ = 25 (for visualization only).