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Characterization of a pixellated CdTe detector with single-photon processing readout

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Abstract

A 1 mm thick pixellated CdTe detector bonded to the MEDIPIX2 [X. Llopart, M.Campbell, R. Dinapole, D. San Segundo, E. Pemigotti, IEEE Trans. Nucl. Sci. NS-49 (5, Part 1) (2002) 2279] readout chip has been characterized using a monoenergetic microbeam at the ESRF. This is an extension of the tests previously reported in Chmeissani et al. [IEEE Trans. Nucl. Sci. NS-51(5) (2004)]. The results show that a full energy peak can be obtained when a narrow beam is focused in the center of the pixel. There is also evidence of significant charge diffusion and fluorescence. The results indicate that the charge sharing is the most important problem and will cause loss of the energy information in an imaging application. The second problem is the fluorescence which limits the number of counts in the full energy peak even for hits in the center of the pixel.

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Keywords: Pixel detector; CdTe; Medipix; Charge sharing; Photon counting

1. Background and experimental conditions

Pixel detectors using single-photon processing readout (see Refs. [1–3]) are interesting because of low noise operation and their ability to record the energy of each individual photon [3]. One such readout chip is the MEDIPIX2 chip[1] with a pixel size of $55 \times 55\,\mu m^2$. It has, however, been observed that significant charge sharing occurs for most detectors with small pixels [4]. For detectors made from heavy materials, the charge sharing can be caused both by charge diffusion and fluorescence in the detector.

In this experiment we have been using a 1 mm thick CdTe detector bonded to the MEDIPIX2 readout chip and measured its response to a narrow monoenergetic X-ray beam. Readout was done using the MUROS2 interface and the Medisoft4 program.

The measurements were performed at the ESRF, where previous versions of the MEDIPIX chip have been characterized [5], using a beam with a photon energy of 40 keV. A set of motor-driven slits, located about 10 cm from the detector were used to adjust the beam width to $10 \times 10\,\mu m^2$. The detector was mounted on an XY-translation stage to move between the pixels and a rotation stage to align the detector perpendicular to the beam. During the calibration phase a 300 μm silicon detector was used as a reference. After calibration the CdTe detector was inserted in the same position as the Si detector. The beam width was verified both by measuring the flux of X-ray photons through the slit and by scanning the beam across a pixel. Almost no scattered photons were visible in the neighboring pixels. The final beam intensity was around 65 000 photons/s.

The detector was operating in electron collection mode with positive bias on the pixel contact and negative bias on the uniform back contact. Radiation was entering from the backside.

2. Theoretical model

When a beam of 40 keV photons enter a CdTe detector most of the photons are absorbed close to the detector

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surface (Fig. 1). As a consequence the generated electrons have to be drifted through the full depth of the detector, to the pixel contact, while the holes only travel a short distance to the back contact. This is the best case in order to get full charge collection. Since we do not know the internal field structure in the detector we have used the simplified concept that the electrons contribute to the signal when they reach the pixel contact in our discussion.

In a thick CdTe detector charge can be lost either due to fluorescence, where secondary photons contribute in a different pixel, or due to charge diffusion where part of the charge cloud is detected in neighboring pixels [6].

The charge transport in the detector was simulated using MEDICI. Since the internal field structure in this detector is not very well known, the charge diffusion was simulated both for a diode-like structure (linear field case) and for a semi-insulating structure (constant field case) using the same bias voltage as in the experiment. The resulting charge distribution is shown in Fig. 2. It is clear that only 75% of the charge hits the pixel contact even if the photon is absorbed in the center of the pixel. This information was

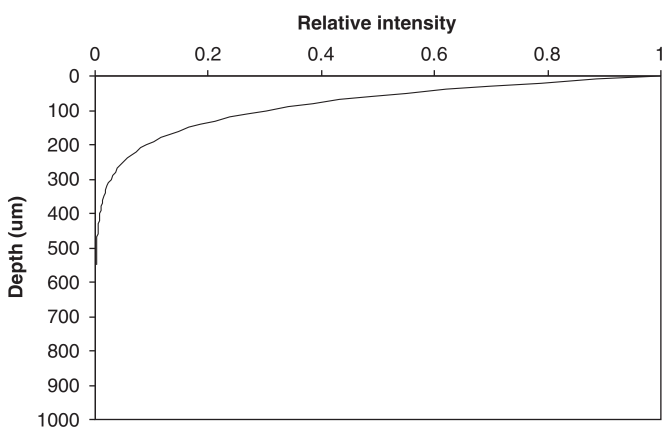

Fig. 1. Relative beam intensity as a function of the depth in the detector. More than 90% of the radiation is stopped within the first 200 μm.

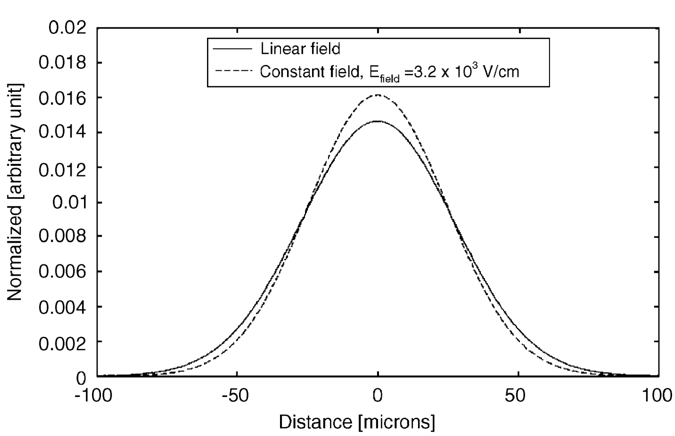

Fig. 2. Average extension of the charge cloud at the pixel contact for an X-ray photon captured in the detector under the bias condition in the experiment. Both linear field case and constant field case give similar results.

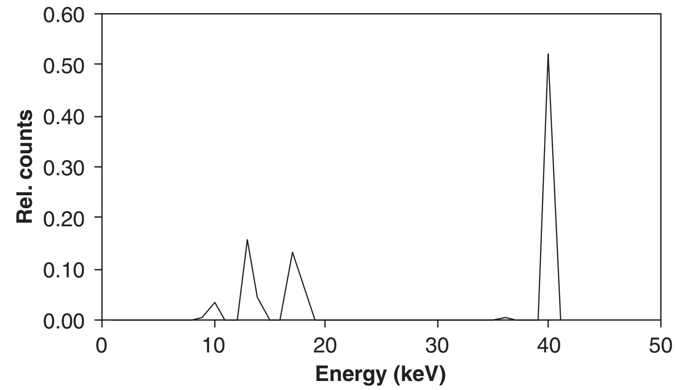

Fig. 3. Simulated response in the center pixel. Only 55% of the photons contribute in the full energy peak. The effect of fluorescence is seen as escape peaks.

then used in order to calculate the energy scale of the system. The energy scale was calculated starting from the position of the full energy peak of a hit on the silicon detector, taking into account the differences in the energy to create an electron–hole pair between Si and CdTe, the difference in gain in the readout electronics and the expected charge collection efficiency of the CdTe detector according to simulation. The resulting energy scale was 1.05 keV/ADC unit, which has been used in the following figures.

The effects of fluorescence were simulated using MCNP. The number of incident photons was 1×10^6. The absorbed energy was counted in 40 energy bins with a width of 1 keV corresponding to the built in energy cutoff in MCNP. The effect of fluorescence is seen as escape peaks in the central pixel and as peaks at the characteristic energies in the neighboring pixels. It should be noted that charge diffusion is not taken into account in this simulation (Fig. 3).

3. Experimental results

3.1. Operating point and bias

Initially a bias sweep was made to establish an operating point for the detector. The bias current was time-dependent and a diode-like behavior was observed as previously reported in Ref. [2]. The current started at a high value when power was turned on and then stabilized after a couple of minutes.

The X-ray response as a function of bias voltage for the detector was measured. There is almost no response at low voltages, then a sharp increase (Fig. 4). The response reaches a plateau at about 300 V. This behavior, together with the IV-curve indicates that the pixel contact is rectifying and that the electric field is penetrating from that contact since most photons are absorbed close to the back contact. The rise of the response is seen when the field reaches the back side of the detector. During measurements the bias voltage was kept at 320 V with a current of 60 μA.

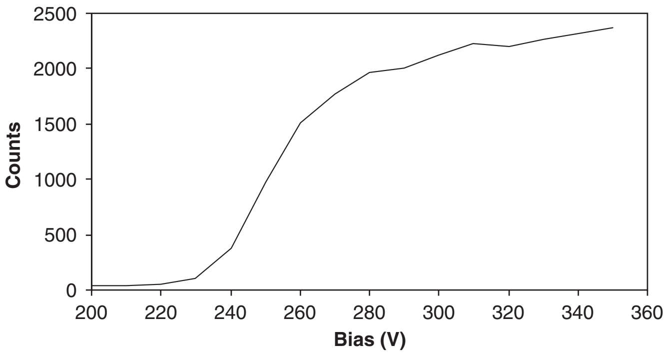

Fig. 4. Response of the detector as a function of bias. The operating point was chosen to be 320 V, in a region with flat response and reasonably low currents, 60 μA.

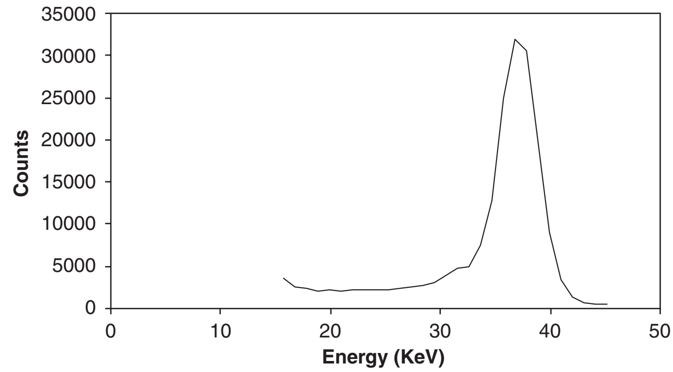

Fig. 6. Spectral response from a pixel with the beam centered in the pixel. The energy scale is adjusted for incomplete charge collection.

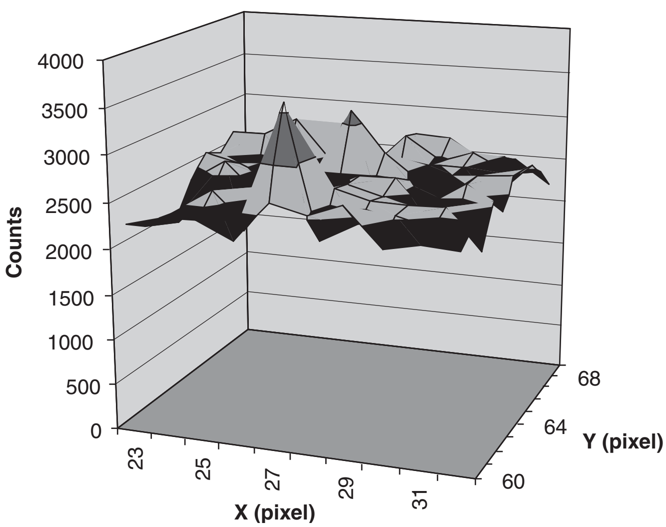

Fig. 5. Response from an area of 100 pixels. The beam was centered in each pixel. A low threshold energy was used.

3.2. Response uniformity

To get an indication of the uniformity of the central part of the detector the beam was scanned over a number of pixels. The response was measured using a low threshold of the readout circuit. The average number of counts per pixel was 2456 with a standard deviation of 229 counts (Fig. 5). It is hard to determine to what extent this variation is caused by the detector or by variations in the threshold of the readout circuit. Since the objective of this experiment was to measure the X-ray response in single pixels no threshold calibration was used. The conclusion is, however, that the response in the area of interest is reasonably uniform.

3.3. Response in the center pixel

The spectral response for a pixel was measured by positioning the beam in the center of the pixel scanning an energy window. Beam alignment was made by adjusting the beam position in small steps measuring the response in the neighboring pixels using a low threshold. The beam is assumed to be in the center when there is equal response in the surrounding pixels. A low threshold was selected to capture shared events.

During the experiment the exposure time was varied in the interval 100 ms–10 s to get a comparable number of counts for each energy interval. The resulting spectrum is shown in Fig. 6. A clear energy peak is observed with a FWHM of 4.9 keV and a peak to valley ratio of about 15. The energy scale used in the figure is calculated as described above.

A small number of hits were recorded with energies up to twice the beam energy. These are double hits which could easily be explained by the time properties of the synchrotron beam and the finite peaking time of the MEDIPIX chip [5].

3.4. Response in neighboring pixels

The response in a number of neighboring pixels was measured. This response is mainly caused by fluorescent photons recorded in these pixels. However, due to the random position where they are captured in the pixel and the strong charge diffusion they do not show up as peaks in the spectrum.

The response in a number of neighboring pixels, recorded at different threshold energies is shown in Fig. 7. In addition the simulated number of hits is included. Even if no charge diffusion was included in the simulation the numbers match. Contributions due to charge diffusion will have too low energy to be recorded.

3.5. Scanning the beam over the pixel

In order to get better understanding of the energy deposition and transport in the pixel the beam was scanned over the pixel area and the spectral response was measured using an automatic threshold scan and subtracting the response between the energy steps. The advantage of this

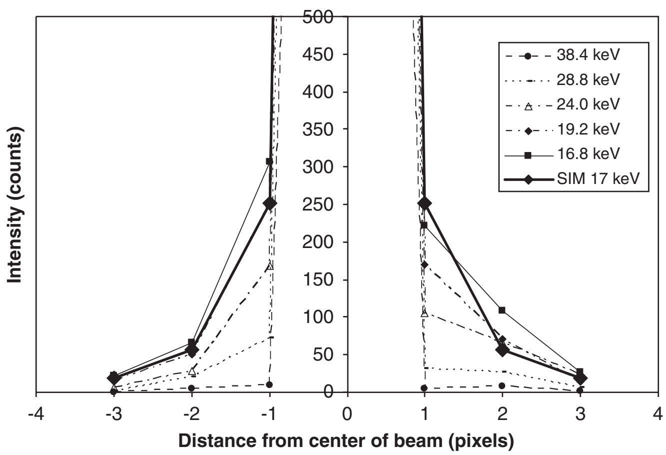

Fig. 7. Response in neighboring pixels as a function of the threshold energy. The bold line indicates results form a simulation at 17 keV without taking charge transport into account.

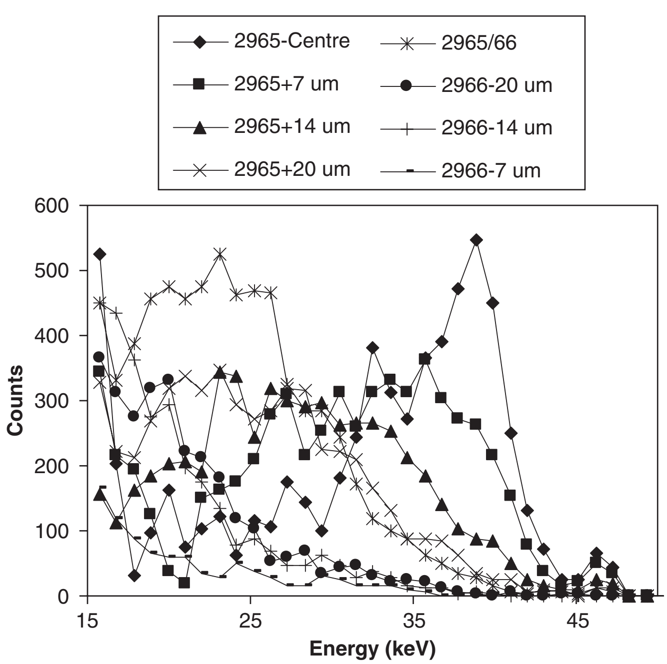

Fig. 8. Response from pixel 2965 when the beam is scanned from the center towards pixel 2966. Since the scan was made using only the low threshold and subtracting consecutive images the data is very noisy.

method is that it is fast but a major drawback is that the subtraction introduces significant noise.

Fig. 8 shows the spectral response in one pixel (2965) with the beam in the center of the pixel and for beam positions offset 7, 14, 20, 27, 31 and 38 μm from the center. It is evident that the peak position shifts to lower energies as the beam is offset from the center of the pixel. This effect is explained by the fact that the fraction of the charge cloud that falls outside the pixel increases as the beam moves from the center of the pixel.

Even if the data is very noisy an attempt was made to find the peak position of each spectrum, mainly using the leading edge of the peak. The results are presented as dots in Fig. 9, together with a line representing the theoretical peak position calculated from the size of the charge cloud. There is good agreement between calculations and experiment. It should be noted that the energy scale of Fig. 9 reflects the incomplete charge collection of the detector.

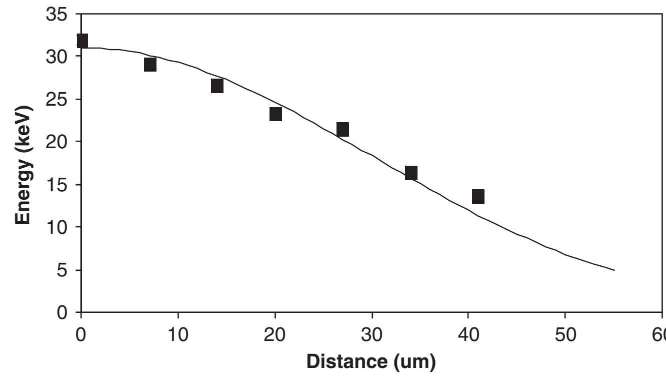

Fig. 9. Position of the energy peak as a function of beam distance form the center of the pixel. The line is simulation results. The dots represent experimental data without correction for incomplete charge collection.

It is evident that such a position-dependent energy deposition will destroy any energy information when the detector is uniformly illuminated. A good spectrum can only be obtained for a narrow beam.

4. Summary and conclusions

We have characterized a 1 mm thick CdTe detector with 55 μm pixels using a narrow monoenergetic beam. The results have been verified by simulations. An energy peak has been obtained in the center pixel. Effects of fluorescence are seen as counts in neighboring pixels, with a range of several pixels. However, due to the random distribution of the hits and the charge diffusion no energy peaks are observed in the fluorescence. The effects of fluorescence limits the height of the full energy peak and will cause escape peaks in the spectrum.

Due to the charge diffusion the contribution from a photon is strongly dependent on its position in the pixel indicating that no valid energy information can be recorded under flood illumination. It is clear that for a small pixel on a thick detector full charge collection will not be achieved without charge summing over several pixels. Charge summing will also, to some extent, limit the effects of fluorescence, but the range is probably too large to capture all events.

Acknowledgments

This work has been done within the framework of the MEDIPIX2-collaboration. The MEDIPIX2-chip is designed at CERN. The MUROS2 readout electronics is designed at NIKHEF and the MEDISOFT4 readout

software is developed at University of Napoli. The CdTe detectors are designed by IFAE, Barcelona.

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