CdTe linear pixel X-ray detector with enhanced spectrometric performance for high flux X-ray imaging

A. Brambilla, P. Ouvrier-Buffer, J. Rinkel, G. Gonon, C. Boudou, *IEEE Member* and L. Verger

***Abstract*–A growing interest has recently been observed in energy sensitive pixel array for high flux X-ray imaging. These devices provide compositional analysis of the imaged objects and would be useful in a wide range of applications in the field of security, non destructive testing and medical imaging. CEA-LETI has developed a CdTe linear array pixel detector coupled with a novel 16-channels fast readout circuit. For each channel, the signal is continuously digitized by a 100 MHz 12 bit ADC and a FPGA controls acquisition and reconstructs the energy spectra on 256 bins. The readout circuit is coupled with a 3 mm thick CdTe 16 pixels linear array detector 0.8 mm pixel pitch.**

Thanks to this innovative architecture of the read-out circuit it is possible to perform advanced signal processing in real time including pile-up rejection and charge sharing correction.

In this work, we study the possibility of correcting the effect of charge sharing. Although the pixel size is relatively large, charge sharing events contribute to 40 to 60 % of all events and significantly degrade the spectrometric response of the detector. By summing the amplitude pulses from two neighboring pixels, we can recover the accurate information from the photon energy. This correction technique has been successfully tested with a monochromatic X-ray micro beam at ESRF.

I. Introduction

The potential benefit of compound semiconductors such as Cadmium Telluride (CdTe) or Cadmium Zinc Telluride (CdZnTe) for energy sensitive X-ray imaging is already well known [1]. They provide excellent energy and spatial resolution at room temperature. However they have to be able to operate under very high X-ray flux. The detector pixel size is usually limited to less than 1 mm² to provide good spatial resolution, but also to reduce the count rate at a given X-ray flux. However reducing the pixel size increases the effect of charge sharing between pixels and thus degrades the spectrometric response of the detector.

Fast readout electronic circuits have been developed to reach count rates of several millions counts per second [2-5]. These systems provide a coarse energy resolution given by a limited number of discriminators and counters. CEA-LETI has developed a read-out circuit that continuously digitizes the signal for each pixel. In this approach, full resolution energy information is available for each pixel in real time. Also, advanced correction algorithms for pile-up reduction and charge sharing correction can be performed.

In this work we present our detector performances obtained with the use of these corrections. Special attention was given to the correction of charge sharing. Measurements at the European Synchrotron Radiation Facility (ESRF) have been performed. This study shows how the contribution of charge sharing and the efficiency of our correction method depend on where the X-ray interacts in the detector pixel.

II. Detector and electronic

The CdTe 16-pixel linear detector array was purchased from ACRORAD (Japan). Pixel pitch is 0.8 mm. Detector thickness is 3 mm, ensuring good stopping power for X-rays of up to 150 kV.

The read-out circuit represented in figure 1 was designed to perform high resolution spectrometry at count rates above $2\ 10^6$ counts per second. The charges induced by X-rays interacting in the detector are amplified by a fast charge sensitive preamplifier and a shaping amplifier with a very short shaping time. A 100 MHz 12 bit ADC then continuously digitalizes the signal. A FPGA controls acquisition and reconstructs the energy spectra on 256 energy bins for the 16 channels. Spectra can be acquired in real time with an acquisition time as low as 3 ms.

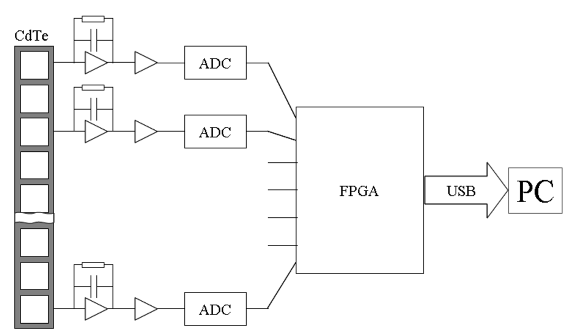

Fig. 1. Read-out electronic circuit architecture.

Figure 2 gives an example of pulse at the output of the shaping amplifier obtained with a 122 keV ^{57}Co gamma ray source. The bias voltage was set to 1000V. The short pulse duration, with a peaking time peaking time of 50 ns, allows to reach several millions of counts per second. It is important to notice that transit time for electrons is estimated to 90ns. The detector takes advantage of the small pixel effect by which the rise time is faster than the real transit time of electrons [6].

Manuscript received November 4, 2011.

A. Brambilla, P. Ouvrier-Buffet, G. Gonon, J. Rinkel and L. Verger are with CEA-Leti, MINATEC Campus, Recherche Technologique, F 38054 Grenoble, France (e-mail: andrea.brambilla@cea.fr).

C. Boudou is with MultiX, 460 rue du Pommarin, 38340 Moirans Cedex, France

Despite the very fast peaking time, the detector can achieve a correct energy resolution, as shown in the pulse-height spectra in Figure 3. The energy resolution deduced from these measurements is 10.5% at 59.5 keV (^{241}Am) and 6.7% at 122 keV (^{57}Co).

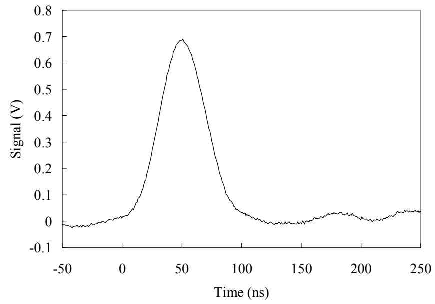

Fig. 2. Pulse shape measured with a ^{57}Co gamma ray source .

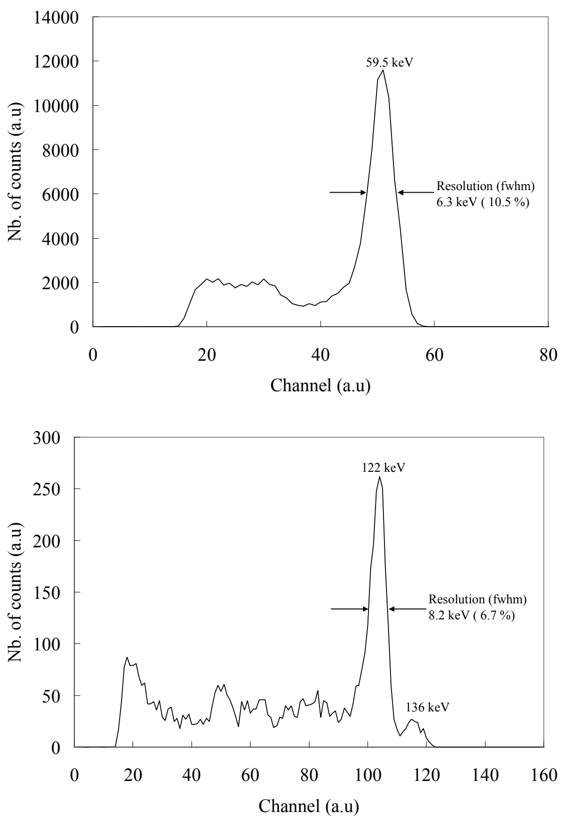

Fig. 3. Pulse-height spectra from a ^{241}Am (top) ^{57}Co (bottom) gamma-ray source obtained with the CdTe 16-pixel linear detector arrays.

III. Response under high X-ray count rates

The dynamic range of the detector has been measured under X-rays with an Yxlon MGC401 4.5kW generator by varying the X-ray tube anode. The tube has a 0.8 mm thick Beryllium window and a 3 mm Aluminum filtration was added. The distance between the focal spot and the detector was 1 m. The tube voltage was set to 120 kV and the anode current can vary from 0.1 to 20 mA. The detector count rate is the sum of all counts from all the energy bins divided by the acquisition time.

Figure 4 shows the count rate as a function of the X-ray tube current. The curve is relatively linear for count rates of up to 2 10^6 counts/s, and saturate at 7 10^6 counts/s. At high X-ray flux, count rate is limited by the pulse pile-up effect. Experimental data were fitted with a classical model for non-paralyzable detectors [7]. The resulting dead time is 73 ns. This value is slightly higher than the peaking time, but significantly shorter than the total pulse duration. This result is achieved by implementing a specific digital pulse processing technique that is able to separate two successive pulses as long as a negative slope is detected between them. In comparison, for a classical solution with a comparator to trigger the signal, two successive pulses can be separated only if the signal level drops below the comparator threshold between the two pulses.

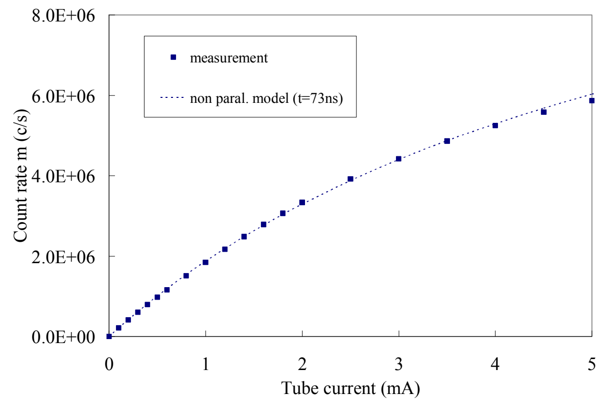

Fig. 4. Output count rate taken from a single pixel of the CdTe detector arrays versus X-ray tube current. The experimental data were fitted with the classical non-paralyzable model.

IV. Charge sharing measurement and correction

A. Charge sharing correction method

The pulse-height spectra from ^{241}Am and ^{57}Co represented in Figure 3 show the important contribution of charge sharing. Charge sharing is the result of the spread of the charge cloud generated from a single X-ray photon of high energy in the detector bulk. It may also be due to the creation of secondary photons due to K-shell fluorescence or Compton scattering, which carry a fraction of the energy of incident photons outside the pixel where the interaction took place. Since the mean free path of fluorescence photons is much smaller than the pixel size [8, 9], we can consider that the charges are shared between two adjacent pixels only. Assuming that all charges are properly collected by the two neighboring pixels, the incident photon energy is obtained by summing the amplitude of the two pulses.

Figure 5 shows the effect of charge sharing correction on the pulse-height histogram for a ^{57}Co source. The low energy tail is clearly reduced by the charge sharing correction. We consider that channels 20 to 90 correspond to the low energy tail due to loss through charge sharing or escape. Channels 90 to 120 correspond to the 2 photoelectric peaks (122 keV and 136 keV) of the ^{57}Co source. In the uncorrected (raw) acquisition, only 55% of the pulses are recorded in the photoelectric peak region. The remaining 45% correspond to the contribution of charge sharing. In the charge sharing corrected acquisition, the photoelectric peak represent 65% of

the total pulse-height spectrum and the contribution of charge sharing is reduced to 36%.

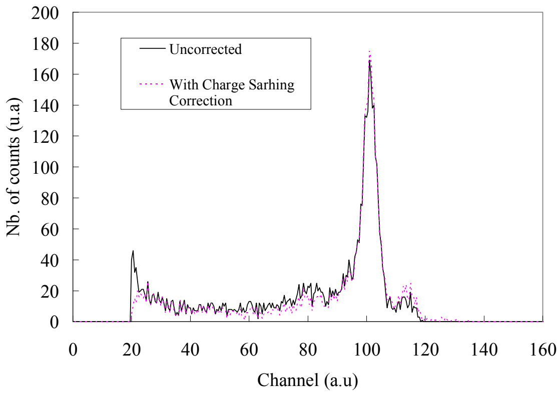

Fig. 5. Pulse-height spectra from a raw acquisition and with charge sharing correction.

Although the charge sharing correction significantly reduces the number of counts measured outside the photoelectric peaks, there is still a significant number of events in the low energy tail. Charge sharing correction only works if the charges are shared between two active pixels. A significant portion of events may take place between a pixel and the guard ring and cannot be corrected.

B. Measurements under synchrotron radiation

To measure the effectiveness of the correction, we have tested it with a collimated beam to measure the detector response function of the position of interaction of X-rays at the European Synchrotron Radiation Facility (ESRF). Synchrotron radiation is a powerful tool to study charge sharing effects by scanning the pixel area with an X-ray micro-beam. The measurements were carried out on the ID17 beamline. The photon energy was set to 70 keV and the beam size was reduced to 50µm x 50µm by two pairs of parallel slits. The detector was placed on a motorized X-Y translation stage and the response for different beam positions was recorded.

We measured the response of the detector by moving the beam from the center of pixel 8 to the center of pixel 9. Four beam positions along the horizontal axis were studied in particular, as shown in fig.6.

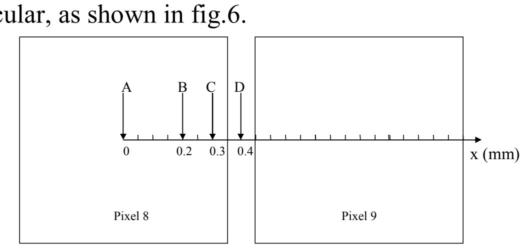

Fig. 6. Beam positions chosen to study the effect of charge sharing on the detector response.

Figure 7 shows the pulse-height spectra from pixel 8 acquired for the different position indicated in figure 6. The first spectrum (fig.7.a) corresponds to the X-ray beam hitting the center of pixel 8. Almost all detected pulses are in the photoelectric peak. The small peak centered around 40 keV corresponds to the K-shell fluorescence escape energy. There is no difference between the raw acquisition and the corrected spectrum, and the number of events recorded in the adjacent pixel is negligible. At x=0.2 mm (fig.7.b) we observe a small degradation of the pulse-height spectrum from pixel 8. This degradation is mainly due to the increase in fluorescence peak, indicating that at this distance from the adjacent pixel, fluorescence is the main contribution to charge sharing. The charge sharing correction effectively restores the pulse-height spectrum. Peak broadening is a consequence of increased noise due to the summation of the two pulse amplitudes.

When the beam is close to the edge of the electrode of the pixel, the degradation of the spectrum is more severe, as seen in fig.7.c. In this case, the pulses are measured on all channels below the photoelectric peak. Charge sharing is also induced by the spread of the charge cloud during collection. The correction significantly improves the pulse-height spectrum, but there are still events in the low energy tail. The situation is even worse for fig.7.d. Here the X-ray beam hits the middle of the gap between the two pixel electrodes. The number of counts recorded by the two adjacent pixels is approximately the same. In the uncorrected pulse-height spectrum the energy information is completely lost. The charge sharing correction partially restores the photoelectric peak, the low energy tail remains important.

The incomplete restoration of the photoelectric peak in fig.7.c and fig.7.d suggests that charges generated in the gap between two pixel electrodes are incompletely collected. In theory these charges should be shared between the two electrodes along the electric field lines. This is true if the surface resistivity of CdTe between the electrodes is high enough. If not, the field lines between the pixels do not converge to the electrodes, but end on the semiconductor surface. The charges collected by these field lines are lost. To overcome this problem, special attention should be paid to the preparation of the CdTe surface after pixel electrode deposition in order to increase the surface resistivity.

In summary the low energy tail of the pulse-height spectra can be explained by fluorescence photon escape on the one hand and by charge sharing from photons hitting the gap between two adjacent pixel electrodes. On the orher hand fluorescence photon escape can be corrected if the secondary particle is reabsorbed in the adjacent pixel. It is also the case of photons absorbed in the space between pixels, although in this case there is a loss that makes the correction less effective. Similar results were obtained by moving the beam along the vertical axis, but in this case no charge sharing correction could be performed.

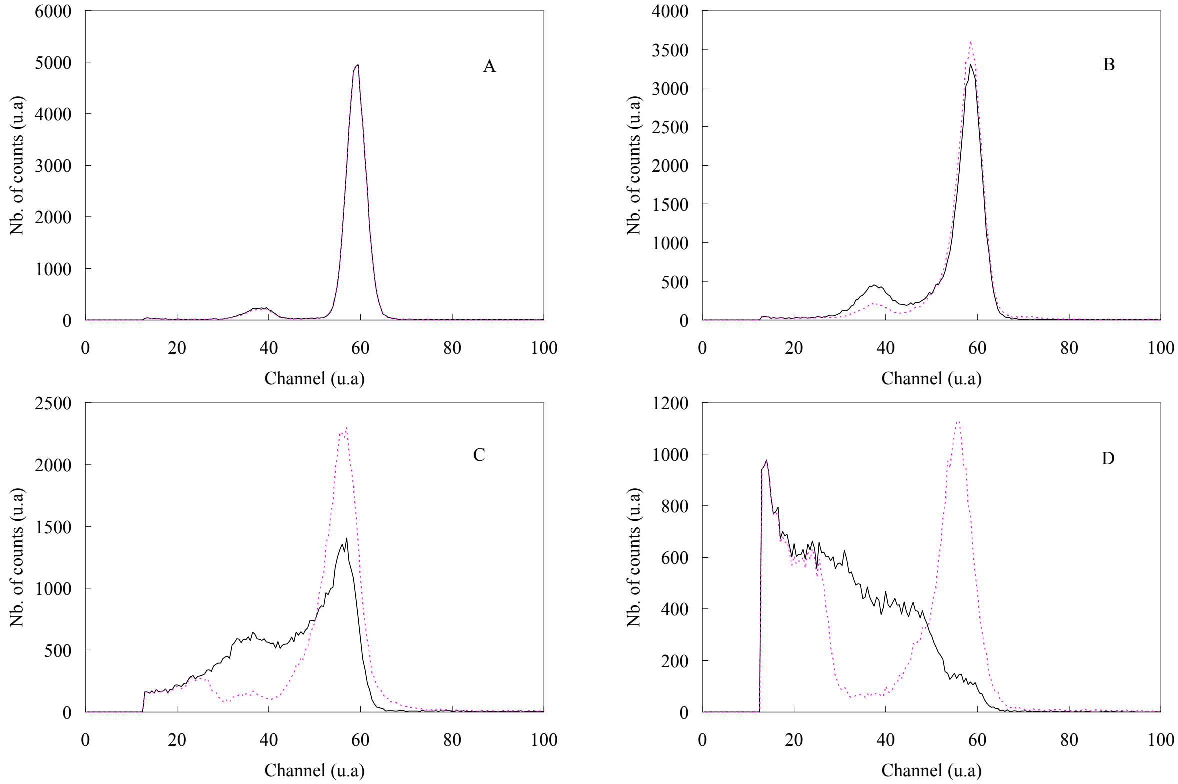

Fig. 7. Pulse-height spectra from pixel 8 from a raw acquisition (full line) and with charge sharing correction (dotted) for 4 different beam positions.

V. Conclusion

The architecture of the readout circuit improves the performance of our detector by reducing the effects of pile-up and charge sharing using real time digital pulse processing. A detector dead time of 73 ns, close to the peaking time of 50 ns, is obtained. A simple correction based on the summation of the amplitude of pulses from two adjacent pixels significantly reduces the low energy tail of the detector response. The proposed signal processing algorithms were simple enough to be implemented in the FPGA. They can run in real time during the acquisition and contribute to a significant improvement of the spectrometric of the detector.

Measurements under synchrotron radiation using a 50x50 µm² X-ray monochromatic micro beam showed that charge sharing is dominated by photon fluorescence escape and by photons hitting the gap between two adjacent pixels. These events are effectively corrected although some charge loss is observed in the inter pixel gap.

Leti has developed an ASIC version of the readout circuit. Multix company is currently producing the first 128 pixels (10 cm) detection modules with this ASIC. First tests under X-rays show that performance is in good agreement with the prototype.

Acknowledgment

We are indebted to the European Synchrotron Radiation Facility (Grenoble, France) for providing beamtime. We thank Alberto Bravin and Herwig Requardt for assistance in preparing the experiment and for technical support.

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