Nuclear Instruments and Methods in Physics Research A 777 (2015) 54–62

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Digital performance improvements of a CdTe pixel detector for high flux energy-resolved X-ray imaging

L. Abbene*, G. Gerardi, F. Principato

Dipartimento di Fisica e Chimica, Università di Palermo, Viale delle Scienze, Edificio 18, Palermo 90128, Italy

ARTICLE INFO

Article history:
Received 4 August 2014
Received in revised form
19 December 2014
Accepted 19 December 2014
Available online 29 December 2014

Keywords:
Energy-resolved photon counting detectors
CdTe detectors
Pixel detectors
High photon counting rate
Digital pulse processing
Pulse shape analysis

ABSTRACT

Photon counting detectors with energy resolving capabilities are desired for high flux X-ray imaging. In this work, we present the performance of a pixelated Schottky Al/p-CdTe/Pt detector (4 × 4) coupled to a custom-designed digital readout electronics for high flux measurements. The detector ($4 \times 4 \times 2\ \text{mm}^3$) has an anode layout based on an array of 16 pixels with a geometric pitch of 1 mm (pixel size of 0.6 mm). The 4-channel readout electronics is able to continuously digitize and process the signals from each pixel, performing multi-parameter analysis (event arrival time, pulse shape, pulse height, pulse time width, etc.) even at high fluxes and at different throughput and energy resolution conditions. The spectroscopic response of the system to monochromatic X-ray sources, at both low and high rates, is presented with particular attention to the mitigation of some typical spectral distortions (pile-up, baseline shifts and charge sharing). At a photon counting rate of 520 kcps/pixel, the system exhibits an energy resolution (FWHM at 59.5 keV) of 4.6%, 7.1% and 9% at throughputs of 0.9%, 16% and 82%, respectively. Measurements of Ag-target X-ray spectra also show the ability of the system to perform accurate estimation of the input counting rate up to 1.1 Mcps/pixel.

The aim of this work is to point out, beside the appealing properties of CdTe detectors, the benefits of the digital approach in the development of high-performance energy resolved photon counting (ERPC) systems for high flux X-ray imaging.

1. Introduction

Photon counting detectors with energy resolving capabilities have been recently proposed and developed in the fields of diagnostic medicine (computed tomography and mammography), industrial imaging and security screening [1–10]. As widely shown in several theoretical and experimental studies [11–13], energy-resolved photon counting (ERPC) systems allow better performance than the conventional X-ray systems, in terms of imaging capabilities (signal to noise ratio, contrast) and radiation dose. However, due to the high fluxes of X-ray beams ($>10^6$ photons $\text{mm}^{-2}\ \text{s}^{-1}$), the assignment of the correct energy to each interacting photon is still a great challenge. Direct detectors coupled to pulse mode readout electronics, able to perform measurements with suitable throughput and energy resolution, are required. The potential benefits of cadmium telluride (CdTe) and cadmium zinc telluride (CdZnTe) detectors for spectroscopic X-ray imaging are already well known [1–4,7–9,14–17]. CdTe/CdZnTe detectors with thicknesses of 2–3 mm are able to effectively absorb X-rays in the 1–140 keV range and to provide both good energy resolution and spatial resolution (pixel sizes less than 1 mm^2). ERPC systems, based on CdTe/CdZnTe detectors, are generally equipped with fast analog electronics (i.e. characterized by shaped pulses with peaking times ranging from 20 ns to 500 ns) coupled to pulse height comparators for energy binning [1–4,7]. These systems generally provide coarse energy resolution even at low fluxes ($>11\%$ FWHM at 59.5 keV [2] and $>5\%$ FWHM at 122 keV [1–4]), mainly due to the fast shaping, and perform the energy binning in a limited number of energy windows (comparators from two to six). ERPC systems with higher energy bins (e.g. 256 bins) and more flexible analysis are developed by using digital readout electronics [8,9].

In this work, we present the performance of a CdTe pixel detector (4 × 4) coupled to an innovative custom-designed digital readout electronics for high flux measurements. The readout electronics is able to continuously digitize and process the signals from each pixel, providing a variable energy binning and performing multi-parameter analysis (event arrival time, pulse shape, pulse height, pulse time width, etc.) even at high fluxes. The digital pulse processing (DPP) uses a *fast shaping*, able to perform pulse detection and fast pulse height analysis (PHA) for high throughput measurements; while a *slow shaping* is used to perform a pulse shape and height analysis (PSHA) for high energy resolution measurements (low and medium throughputs). The spectroscopic response of the system to monochromatic X-ray sources and an X-ray tube, at both low and high rates, is presented with particular attention to the mitigation of some

---

* Corresponding author. Tel.: +39 091 23899081; fax: +39 091 23860815.
E-mail address: leonardo.abbene@unipa.it (L. Abbene).

http://dx.doi.org/10.1016/j.nima.2014.12.084
0168-9002/© 2014 Elsevier B.V. All rights reserved.

typical spectral distortions (pile-up, baseline shifts and charge sharing).

The aim of this work is to point out the spectroscopic benefits of the digital approach in the development of high-performance ERPC systems for high flux X-ray imaging.

2. Detection system and experimental procedures

2.1. Detector and physical properties

The detector is based on a CdTe crystal ($4 \times 4 \times 2\ \text{mm}^3$), manufactured by Acrorad (Japan), with pixelated anode (Al/Au/Ti/) and planar platinum (Pt) cathode. The anode surface consists of 16 pixels arranged in a 4×4 array. The array is characterized by a pixel pitch of 1 mm in both directions: 0.6 mm is the pixel size with a gap of 0.4 mm.

Cadmium telluride (CdTe), thanks to its high atomic number and wide band gap has been widely proposed and used for room temperature X-ray and gamma ray detectors [14,15]. A CdTe detector with a thickness of 2 mm is able to effectively absorb X-rays in the 1–140 keV range (detection efficiency of 98% at 80 keV and 59% at 140 keV) [14,15]. To enhance the charge collection, CdTe detectors are typically developed with blocking contacts (i.e. working as diodes), with indium (In) as the anode electrode on a p-type CdTe and platinum (Pt) as the cathode [14,15]. Blocking contacts are characterized by lower leakage currents than an ohmic configuration (Pt/CdTe/Pt), allowing high bias voltage operation and accordingly better spectroscopic performance. Recently, new CdTe diode detectors are fabricated by using aluminum (Al) as blocking contact [17–23], allowing pixelization of the anode (critical issue of In contacts) and then the development of unipolar devices [14]. As widely reported in the literature [14,15], pixelization of the anode gives to CdTe detectors unipolar properties (signals are mainly influenced by the electrons when the pixel size is much smaller than the detector thickness, phenomenon known as small pixel effect), very helpful to minimize the effects of the poor transport properties of the holes (critical issue of CdTe) in detector signals. Therefore, the high bias voltage operation and the fine segmentation of the electrodes of Al/CdTe pixel detectors make them very attractive for high-resolution spectroscopic imaging.

Time instability under bias voltage (generally termed as polarization) is the major drawback of CdTe diode detectors, as well documented in the literature [14,18–23]. Polarization is mainly related to the accumulation of negative charge on deep acceptor levels during the application of the bias voltage. From the electrical point of view, polarization produces strong changes of the reverse current with time (both monotonic and non monotonic current transients) [19–21], while losses in detection efficiency, energy resolution and a progressive shift of the photopeaks towards lower energies are clearly visible in the measured X-ray spectra. Degradations occur more rapidly at high temperatures, at low bias voltages and for thick detectors. Several solutions have been proposed to suppress polarization: high bias voltage operation, low temperature, low detector thickness and switching off the bias voltage at regular time intervals.

2.2. Digital readout electronics

The detector is coupled to a readout electronics able to digitize and process the signals from four pixels. Fig. 1 shows a schematic view of the readout electronic circuit architecture. The detector signals (central pixels) are amplified by four commercial AC-coupled charge sensitive preamplifiers CSPs (A250,Amptek,USA), equipped with resistive-feedback circuits.

To digitize and process the CSP output signals, we used a commercial digitizer (DT5724, CAEN S.p.A., Italy), housing four high speed ADCs (16 bit, 100 MS/s), four buffers of external memory (1 Mbyte wide each) and four ALTERA Cyclone EP1C20 FPGAs. Each ADC channel, AC coupled, is characterized by one full scale range (± 1.125 V). Using a set of 14 bit from the 16 bit array, we realized three full scale ranges (± 1.125 V, ± 0.5625 V and ± 0.2813 V). The digital pulse processing (DPP) is carried out by the FPGA, in which our DPP method is implemented. The channel FPGA packs output data and sends them to another FPGA that collects asynchronously the packets from all 4 channels and transmits them, via USB channel (or via optical link), to a PC. The PC runs a C++ program able to control all digitizer functions, to acquire packed data, to produce on-line histograms, counting rate display and to store all received information in dedicated files.

The DPP firmware is based on a revised version of DPP methods, developed by our group and successfully used for both off-line and on-line analysis [24–30]. A detailed description of the DPP method is reported in our previous work [30]. A general overview of the method is presented below. The DPP firmware is based on a *fast* and a *slow* shaping (Fig. 2); through the *fast shaping* it performs the following operations: (i) pulse detection and triggering, (ii) pulse width measurement, (iii) fast pulse height analysis (PHA) and (iv) pile-up rejection (PUR). The PUR performs a selection of time windows of the CSP waveform for slow shaping. For each CSP pulse detected from the fast shaping, a fixed time window of CSP waveform, centered in the temporal position of the pulse peak, is inspected; the time window is selected for the slow shaping only if it contains a single pulse. Each selected time window of the CSP waveform is termed *Snapshot*, while the width of this window, user-chosen, is termed *Snapshot Time* (*ST*). We stress that the PUR only works on the temporal positions of the CSP pulse peaks, i.e. it selects the snapshots before any useful operation for slow shaping. The *slow shaping* is characterized by two main features: (i) it performs the pulse shape and height analysis (PSHA) on each selected Snapshot, and (ii) due to an automatic baseline restoration (based on the analysis on single pulses), it allows high rate measurements. The pulse height (event energy) estimation is performed by applying an optimized low-pass filter (e.g. trapezoidal filter) to all the samples of each shaped pulse.

The energy resolution strongly depends on the *ST* values; as the shaping time of classic analog systems, long *ST* values give better energy resolution.

Both the time width of the pulses from the fast shaping and the *ST* are dead times for the system with a well defined modeling (paralyzable dead time).

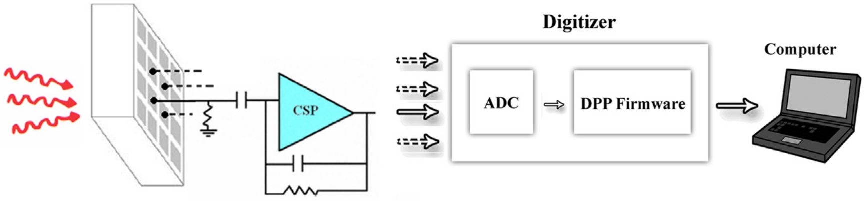

Fig. 1. Schematic view of the readout electronic circuit architecture.