Nuclear Instruments and Methods in Physics Research A 862 (2017) 18–24

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

ChromAIX2: A large area, high count-rate energy-resolving photon counting ASIC for a Spectral CT Prototype

Roger Steadman [a,*], Christoph Herrmann [a], Amir Livne [b]

[a] Philips Research Europe, High Tech Campus, 5656 AE Eindhoven, Netherlands
[b] Philips Healthcare, 31004 Haifa, Israel

ARTICLE INFO

Article history:
Received 3 February 2017
Received in revised form
19 April 2017
Accepted 7 May 2017
Available online 8 May 2017

Keywords:
Photon counting
Computed tomography
Spectral CT
ASIC
K-edge imaging
CZT
CdTe

ABSTRACT

Spectral CT based on energy-resolving photon counting detectors is expected to deliver additional diagnostic value at a lower dose than current state-of-the-art CT [1]. The capability of simultaneously providing a number of spectrally distinct measurements not only allows distinguishing between photo-electric and Compton interactions but also discriminating contrast agents that exhibit a K-edge discontinuity in the absorption spectrum, referred to as K-edge Imaging [2]. Such detectors are based on direct converting sensors (e.g. CdTe or CdZnTe) and high-rate photon counting electronics.

To support the development of Spectral CT and show the feasibility of obtaining rates exceeding 10 Mcps/pixel (Poissonian observed count-rate), the ChromAIX ASIC has been previously reported showing 13.5 Mcps/pixel (150 Mcps/mm^2 incident) [3]. The ChromAIX has been improved to offer the possibility of a large area coverage detector, and increased overall performance. The new ASIC is called ChromAIX2, and delivers count-rates exceeding 15 Mcps/pixel with an rms-noise performance of approximately 260 e-. It has an isotropic pixel pitch of 500 μm in an array of 22 × 32 pixels and is tile-able on three of its sides. The pixel topology consists of a two stage amplifier (CSA and Shaper) and a number of test features allowing to thoroughly characterize the ASIC without a sensor. A total of 5 independent thresholds are also available within each pixel, allowing to acquire 5 spectrally distinct measurements simultaneously. The ASIC also incorporates a baseline restorer to eliminate excess currents induced by the sensor (e.g. dark current and low frequency drifts) which would otherwise cause an energy estimation error.

In this paper we report on the inherent electrical performance of the ChromAXI2 as well as measurements obtained with CZT (CdZnTe)/CdTe sensors and X-rays and radioactive sources.

1. Introduction

While in recent years the focus in clinical CT has been to reduce the X-ray dose by image reconstruction methods, technology (especially in the area of X-ray conversion materials) has in the mean-time matured such that single photon-counting detectors seem possible, which allow for significantly improved exploitation of spectral information when compared to known dual energy CT approaches. The advent of energy-discriminating photon-counting detectors will result in a further significant increase of sensitivity (X-ray and contrast agent dose reduction) and higher specificity (improved quantification, e.g. due to elimination of beam hardening [4]).

Exploiting energy information of the impinging photons of the polychromatic emission of the X-ray tube allows distinguishing the two main physical causes of energy-dependent attenuation (Photo-electric effect and Compton effect). This energy dependency is not resolved in conventional CT detectors, causing so-called beam-hardening artefacts. Correction algorithms in place are limited and the remaining artefacts can potentially lead to misdiagnosis. Energy-resolving detectors will eliminate beam-hardening artefacts.

Currently a number of dual-energy methods based on conventional indirect conversion detectors are available (dual source [5], tube kVp switching [6] and dual layer stacking [7]) that can provide two spectrally distinct measurements, allowing Photo-electric and Compton effects to be distinguished. There is however more information to be obtained, further contributing to higher diagnostic specificity. By acquiring more than two spectral measurements, advanced material decomposition based on K-edge imaging [2] can be achieved. That is, a contrast agent exhibiting a K-edge discontinuity in the CT-relevant energy range can be clearly separated from other materials present in the body (e.g. separation of a Gadolinium contrast agent and calcification). The

* Corresponding author.
E-mail address: roger.steadman@philips.com (R. Steadman).

http://dx.doi.org/10.1016/j.nima.2017.05.010
0168-9002/

diagnostic value resides not only in providing contrast-agent only images, but also in the capacity to resolve the local mass density of the contrast agent, thus allowing additional quantification [8].

This requires the introduction of direct-conversion sensors and energy-resolving photon-counting readout electronics both fast enough to separate individual X-ray photons, referred henceforth to as Photon-Counting Spectral CT.

To show the experimental feasibility of such electronics, a proprietary test ASIC called ChromAIX has been reported earlier [3]. The ChromAIX (ChromAIX1 henceforth to differentiate it from the ASIC reported in this paper), achieved observable count rates (OCR) exceeding 13.5 Mcps/pixel, corresponding to an impinging rate (ICR) of 37 Mcps/pixel. The OCR closely followed the expectations from a paralyzable model [9]. It incorporated four independent energy thresholds and input referred rms-noise lower than 350 e-. The ChromAIX1 consisted of a 4×16 pixel array at an isotropic pitch of 300 μm.

The ChromAIX2 is meant to consolidate the performance of its predecessor and to allow integration on a CT gantry for evaluation [10]. It therefore already exhibits a large area coverage to facilitate evaluating the Spectral CT image quality.

2. ChromAIX2 pixel design

The ChromAIX2 ASIC features 22×32 pixels at an isotropic pitch of 500 μm. The ASIC is 3-side tile-able, allowing to arrange many ASICs side by side in a row of two along the gantry rotation axis. Such an arrangement therefore may yield up to 64 slices at a 500 μm pitch. Along one of its sides the ASIC features the I/O and power connections.

Table 1
ChromAIX2 specifications.

Pixel Size	500 μm pitch, flip-chip to sensor
Observable count-rate	> 10 Mcps/pixel, Paralyzable
Input referred noise	< 350 e⁻
Leakage compensation	Static 200 nA
	Dynamic 60/600 nA 3 dB at 10 kHz
Thresholds	5
Energy range	> 160 keV
Energy resolution	0.5 keV/lsb
Frame rate	> 10 kHz, zero dead-time

The pixel pitch has been increased from the 300 μm featured in ChromAIX1 to 500 μm. The larger pixels ensure a better energy response as it is less affected by charge sharing. Table 1 shows a short list of specifications.

The analogue front-end consists of a two-stage amplifier topology. Fig. 1 shows a simplified block diagram of the pixel electronics. The first stage is a Charge-Sensitive Amplifier (CSA) followed by a pole-zero cancellation network. The second stage is a fast shaper with a < 10 ns peaking time and nominally 23.5 ns dead-time at an equivalent 25 keV threshold. A dead-time of 23.5 ns offers sufficient margin to ensure achieving observable count-rates (OCR) significantly higher than the specified 10 Mcps/pixel. Fig. 2 shows the simulated waveform at the output of the Shaper stage.

Each pixel is equipped with 5 independent energy thresholds and the corresponding counters with a bit-depth of 16 bits. In order to enable K-edge imaging applications, the number of spectrally distinct measurements must equal or exceed the number of desired energy decomposed images. To obtain separate photo-electric, Compton and K-edge images, a minimum of three thresholds are required [2]. Furthermore, dual-contrast applications [11] require that the readout channel is equipped with at least four energy thresholds. The choice of 5 energy thresholds therefore addresses these needs with some additional flexibility, for example allowing the use of the 5th threshold as a measure of pile-up [12]. The thresholds are implemented as single-sided bins, i,e, each of them counts all photons above the equivalent threshold energy. Energy windowing is obtained by subtraction of the single-sided bins later in the image chain when required. The thresholds each consist of a 9-bit DAC covering a range exceeding 160 keV and with a resolution of 0.5 keV/lsb.

In contrast to the ChromAIX1 device, a baseline restoration circuit (BLR) has been included in the front-end. The BLR senses the baseline at the Shaper output and compensates any deviation from the reference potential by injecting a current at the input node. Although the ASIC is temperature compensated, a BLR circuit has been introduced to stabilize the baseline in response to changes of the sensor's leakage current. The BLR circuit can be completely switched off if unnecessary and it has been equipped with two current compensation ranges. The low current range can compensate leakage currents and drifts of up to 60 nA. A high current mode that can deal with up to 600 nA is also available to accommodate a plurality of sensors and material qualities. The BLR has been designed to effectively cancel out any drifting current

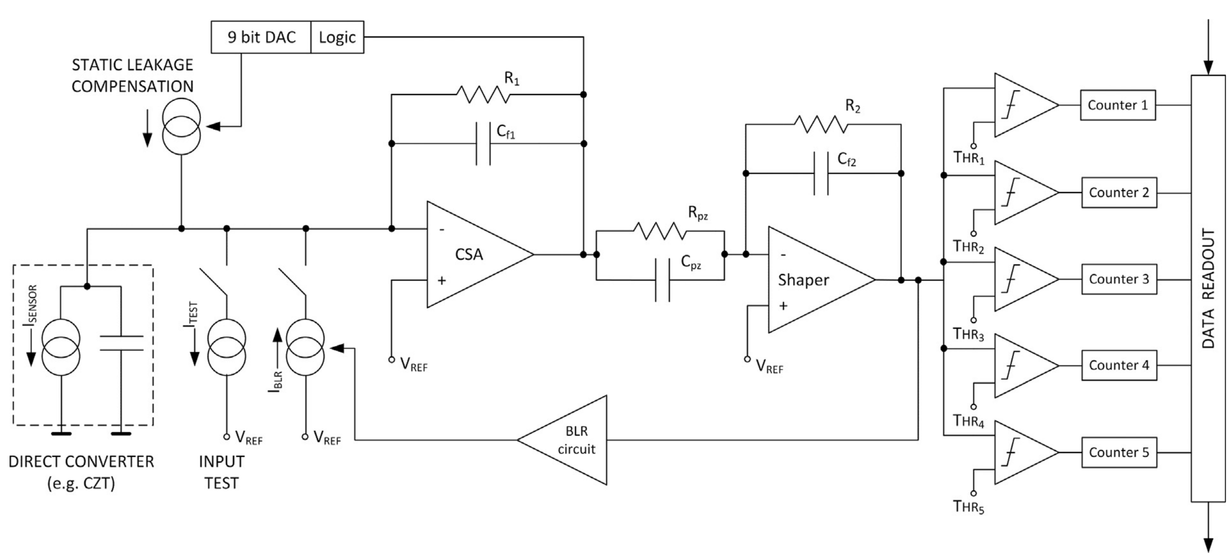

Fig. 1. Simplified block diagram of the pixel front-end in ChromAIX2.