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Chromatic X-ray imaging with a fine pitch CdTe sensor coupled to a large area photon counting pixel ASIC

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ABSTRACT: An innovative X-ray imaging sensor based on Chromatic Photon Counting technology with intrinsic digital characteristics is presented. The system counts individually the incident X-ray photons and selects them according to their energy to produce two *color* images per exposure. The energy selection occurs in real time and at radiographic imaging speed (GHz global counting rate). Photon counting, color mode and a very fine spatial resolution (more than 10 LP/mm at MTF50) allow to obtain a high ratio between image quality and absorbed dose. The individual building block of the imaging system is a two-side buttable semiconductor radiation detector made of a thin pixellated CdTe crystal coupled to a large area VLSI CMOS pixel ASIC. Modules with 1, 2, 4, and 8 block units have been built. The largest module has $25 \times 2.5\,\mathrm{cm}^2$ sensitive area. Results and images obtained from testing different modules are presented.

KEYWORDS: Solid state detectors; X-ray detectors; Pixelated detectors and associated VLSI electronics; X-ray radiography and digital radiography (DR)

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Contents

1 Introduction

The continuous progress and down-scaling in deep-submicron CMOS technology has allowed to produce ASICs which can integrate hundreds of thousands of full electronic chains (analog front-end and digital counting). Each individual chain is characterized by increasing complexity and functionalities [1–11]. By coupling a custom VLSI pixel ASIC to a thin pixellated CdTe crystal, we have realized an innovative X-ray imaging sensor (PIXIRAD) based on Chromatic Photon Counting technology. The device can produce two '*color*' X-ray images from a single exposure thanks to the double-threshold discrimination system which is capable of counting the photons in two different energy bins in real time.

2 The X-ray imaging sensor

The basic building block of the PIXIRAD imaging system consists of a pixellated solid-state sensor (CdTe) connected to a geometrically and physically matching CMOS readout ASIC by a *flip-chip bonding* technique. The system has therefore a hybrid architecture in which the sensor and readout electronics are manufactured, processed and optimized separately. The individual block is buttable on two opposite sides, therefore several blocks can be placed side-by side minimizing the dead-space between them. The width of the dead-space area (currently set to two pixels) is determined by the width of the high voltage guard-ring built on the radiation sensor.

The CdTe detector (ACRORAD Co., Ltd., Japan) is a pixellated 650 μm thick Schottky type diode, which collects electrons on the pixels. The pixels are arranged on a hexagonal matrix with 60 μm horizontal pitch and 51.96 μm vertical pitch. The radiation receiving side of the CdTe crystal is metalized with a continuous Pt layer while the contacts on the pixel side are made through

Table 1. The CdTe main characteristics.

Atomic numbers	48, 52
Effective atomic number	50
Density	5.85 g/cm^3
Band-gap energy	1.5 eV
Relative dielectric constant	11
Mean Energy per e-h pair creation W	~ 5 eV
Resistivity	$10^9\,\Omega$ cm
Electron mobility μ_e	1100 cm^2/Vs
Electron mean lifetime τ_e	3×10^{-6} s
Hole mobility μ_h	100 cm^2/Vs
Hole mean lifetime τ_h	2×10^{-6} s
$(\mu\tau)_e$	3.3×10^{-3} cm^2/V
$(\mu\tau)_h$	2×10^{-4} cm^2/V

the deposition of successive Al/Ti/Au/Ni/Au thin metal films. A negative bias voltage is applied to the sensor using a tiny wire glued in a corner of the top Pt layer. The sensor is characterized by a very low leakage current at 300–400 V when operated at reasonably low temperature (typically -20°C in our case). Table 1 summarizes the main characteristics of the CdTe sensor.

The CMOS ASIC has an active area of 30.7×24.8 mm^2. It has been fabricated in 0.18 μm CMOS technology using six metal and two poly-silicon layers. The ASIC is organized as a matrix of 512×476 hexagonal pixels that match the identical pixel arrangement of the CdTe crystal. The chip integrates more than 350 million transistors. Each pixel pad is connected to a charge amplifier that feeds two discriminators and two 15-bit counters/registers. To reduce unavoidable pixel to pixel DC offset variations on the discrimination level, an auto-zero or selfcalibration circuit has been implemented in each pixel. In this way a single global threshold per discriminator can be applied to the entire matrix. The intrinsic pixel amplifier noise is 50 electrons (rms). This level of electronic noise is achieved by taking advantage of the extremely low pixel capacitance (few fF) and of the relatively long amplifier shaping time (pulse width $\sim 1\,\mu$s at the base).

The counters are implemented in the form of linear feedback shift registers generating a pseudo-random sequence which uniquely relates the number of events with the 15-bit register content.

During data acquisition, the shift registers are clocked by the trigger generated by their respective discriminators. The pixels in the matrix are organized as 256 column pairs, each column pair having its own controller. In readout mode, the registers of several columns of pixels are serialized under the control of an external clock signal. The serialization of the column pairs is user-programmable: groups of 16, 32, 64 or 128 columns can be built, corresponding respectively to 32, 16, 8 or 4 active data output pads.

Two different data acquisition modes are selectable: dual-threshold mode (2 *colors* mode) or, alternatively, single-threshold continuous reading mode. The latter modality is dead-time free, i.e. it allows counting in one counter while reading the other one.

Table 2 summarizes the main characteristics of the CMOS ASIC.

Table 2. The CMOS ASIC characteristics.

Pixel characteristics	
Shaped pulse duration (at the base)	1 μs (adjustable)
Linear range	$>$ 3000 electrons ($>$ 15 keV for CdTe, $W = 5$ eV)
Saturation level	$>$ 6000 electrons ($>$ 30 keV for CdTe, $W = 5$ eV)
Equivalent noise charge (ENC)	50 electrons (rms)
Residual offset after self-calibration	$\pm$30 electrons
Dynamic range	32768 counts (15 bit) per threshold
Input signal polarity	positive or negative
ASIC power consumption	3 W
Possibility to disable or by-pass pixels	user-selectable
Pixel readout	
Serialization of number of columns for best readout time	16, 32, 64, 128
Max readout clock frequency	200 MHz
Typical readout clock frequency	50 MHz
Readout time for 32 data outputs = 16 columns serialized (16 columns $\times$ 476 pixels $\times$ 15 bits $\times$ 20 ns) @ 50 MHz	2.4 ms (per counter)
Readout time for 16 data outputs = 32 columns serialized	4.8 ms (per counter)
Readout time for 8 data outputs = 64 columns serialized	9.2 ms (per counter)
Readout time for 4 data outputs = 128 columns serialized	18.4 ms (per counter)

3 Images and performance

Testing of several configurations of the PIXIRAD imaging system has been performed. Modules with one, two, four and eight PIXIRAD blocks have been assembled. The two pixels dead-space between the blocks is usually removed from the images by off-line interpolation.

The modules are able to deliver clear, highly detailed, noise free X-ray images to be used in medical, biological, industrial or scientific applications over the energy range 1–100 keV. The low energy limit is set by the minimum applicable global threshold, which is 200 electrons.

Images are usually obtained at very high count rate ($>$ 30 GHz for a 4 tile module) by illuminating the samples with radiation from high power medical or diffraction X-ray tubes.

Table 3 lists the main specs of PIXIRAD-1, a single block system with 250 K pixels, 500 K counters and $3 \times 2.5\,\text{cm}^2$ active area.

3.1 Chromatic photon counting

Figure 1 shows an example of chromatic photon counting with a single block module, PIXIRAD-1.

Two images of a small gecko are obtained by simultaneously counting the X-ray photons with a low energy threshold, figure 1a, and a higher threshold, figure 1b. Figure 1c shows the image obtained by subtracting the two previous pictures and contains mainly the low energy photons of

2013 JINST 8 C02028

Table 3. Main characteristics of the PIXIRAD-1 unit.

PIXIRAD-1 specs: *a single unit Schottky type CdTe diode (650 μm thick)*	
ASIC + CdTe hybrid block	512×476 pixels
Active area	$31 \times 25\,\text{mm}^2$
Total number of pixels	243712
Total number of counters	487424
Pixel size	60 μm with hexagonal arrangement
Pixel density	323 pixels/mm^2
Pixel rate capability	106 counts/pixel/s (dead-time corrected)
Global rate capability	2.4×10^{11} counts/s (1 chip)
Pixel dead-time	300 ns
Position resolution	11 LP/mm at 50% MTF
Energy range	1–100 keV (with pulse height saturation above 30 keV)
Detection efficiency @10 keV, 50 keV, 100 keV	100%, 98%, 45%
Counter depth	15 bits
Readout time at 50 MHz clock	5 ms
Frame rate	200 readouts/s
Minimum applicable global threshold	200 electrons
Sensor bias voltage	$200 \div 400$ V
Leakage current density	5 nA/cm^2 at 400 V, -20°C
Typical number of defective pixels	less than 1%
Number of independent threshold levels (*colors*)	2 pairs (with possibility of frame by frame fast switching between the 2 pairs during exposure)
Module size (W $\times$ L $\times$ H)	$14 \times 14 \times 7\,\text{cm}^3$
Module weight	< 2 Kg
Module power consumption	60 Watts (mainly used for cooling)
Module cooling	Liquid or forced air
Module operating temperature	$+40$ -40°C

the incident X-ray beam. Note that the photons in b) are also counted in a), so that the two images are largely correlated and thus no further statistical noise is introduced by the subtraction process.

3.2 Low energy sensitivity

The sensitivity of the PIXIRAD sensors to image low energy X-ray photons is shown in figure 2.

Here, images of a very low contrast object (a jasmine flower) are taken at a global threshold of 200 electrons (corresponding to 1 keV energy, figure 2a) for counter 1, and 1200 electrons (corresponding to 6 keV energy, figure 2b) for counter 2.

For a better visualization of the differences in contrast between the images at 1 and 6 keV thresholds, two different Look-Up Tables (Grays and ICA) are used.

2013 JINST 8 C02028

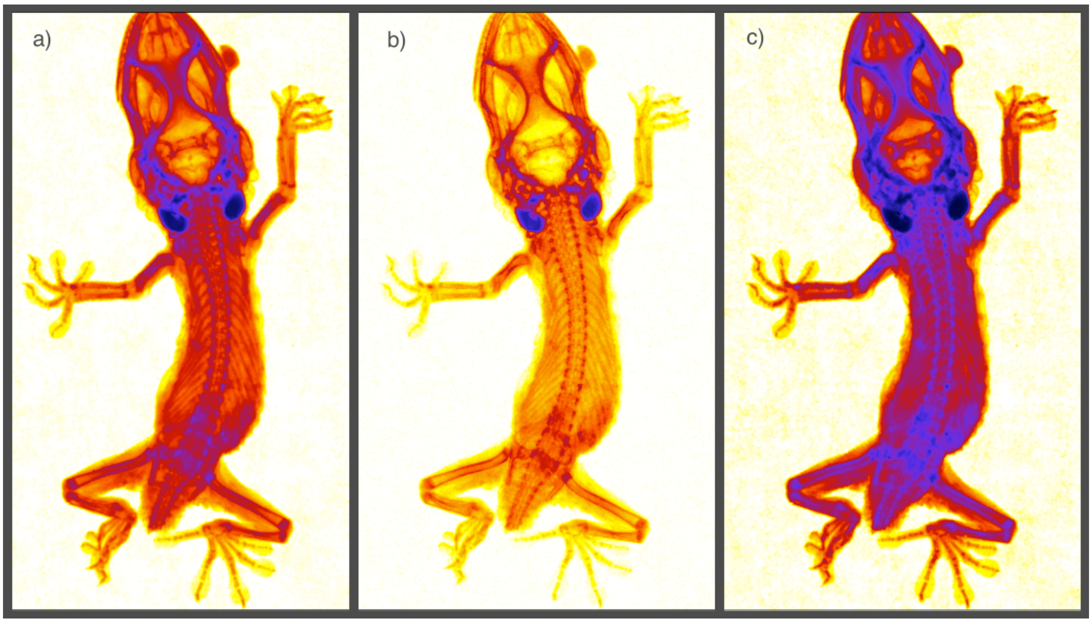

Figure 1. Images of a small gecko obtained by simultaneously counting the X-ray photons with: a) a low energy threshold for counter 1 (all photons); b) a high energy threshold for counter 2 (high energy photons); c) subtracting the counts in the pixels of image b) from the corresponding counts in the pixels of image a). The result is a higher contrast, low energy, image.

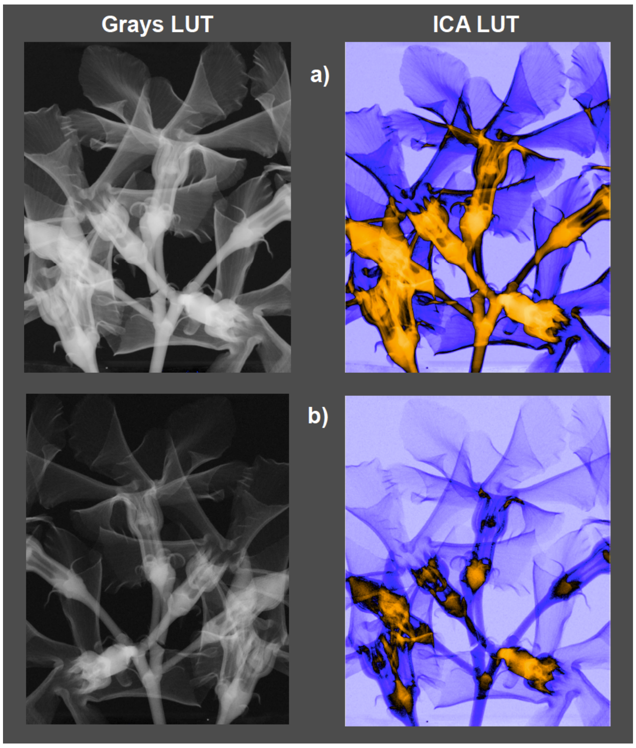

Figure 2. Images of a very low contrast object (a jasmine flower) taken: a) at a global threshold of 200 electrons (1 keV energy, LOW counter), and b) at 1200 electrons (6 keV energy, HIGH counter). Falsecolours are used to improve contrast.

2013 JINST 8 C02028

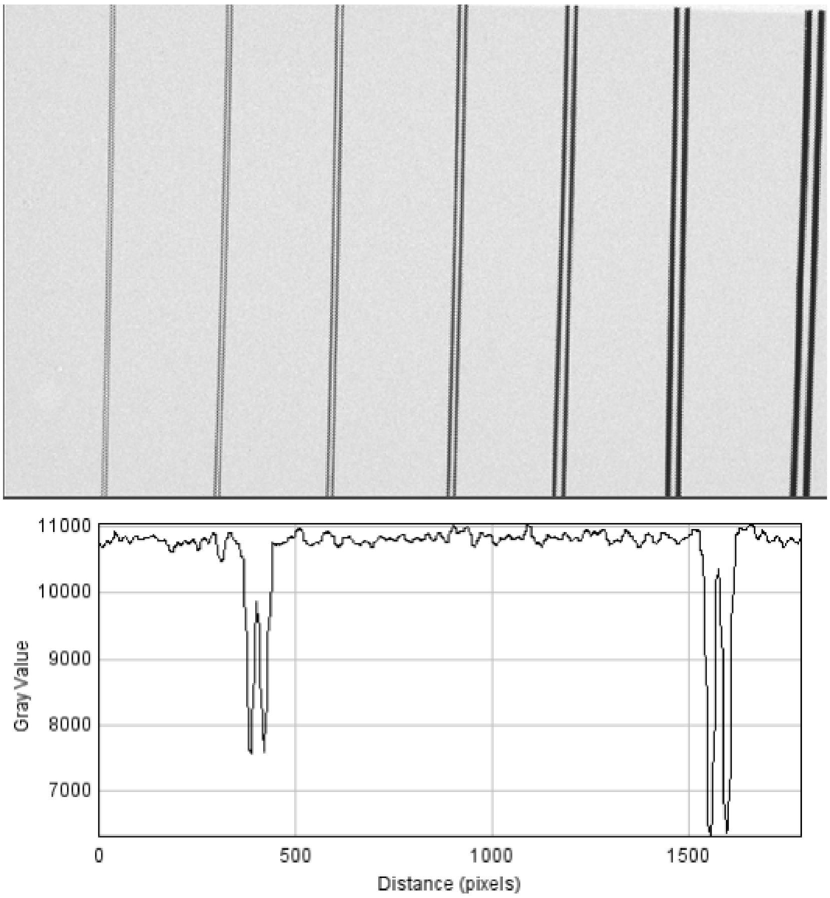

Figure 3. Image of a resolution phantom taken with a W anode X-ray tube set at 90 kVp. The plot is a profile across the last two couples of lines on the left. The closest lines are 50 μm wide with 50 μm separation.

3.3 High energy sensitivity

The image of a resolution phantom taken with a tungsten anode X-ray tube set at 90 kVp with 2 mm Aluminum filter, is shown in figure 3. The lines are metal strips embedded in a 5 mm thick FR4substrate (vetronite). In the bottom panel of figure 3 is a profile plot taken across the last two couples of lines on the left side. No significant geometrical magnification has been used in the experimental set-up (source-detector distance = 50 cm, object-detector distance = 5 mm). This figure illustrates how the resolving power of the imaging system is good even at such high photon energies and is proven by the capability to distinguish the two closest lines (50 μm wide with 50 μm separation).

3.4 Spatial resolution

To measure the spatial resolution, a Hüttner type spatial frequency grating (see figure 4a) has been used. The phantom is made of groups of lead bars, whose highest density is 10 line pairs per mm (LP/mm). Figure 4b shows a profile plot across the last four groups of bars including those at 10 LP/mm. At 50% MTF the resolution is 11 LP/mm.

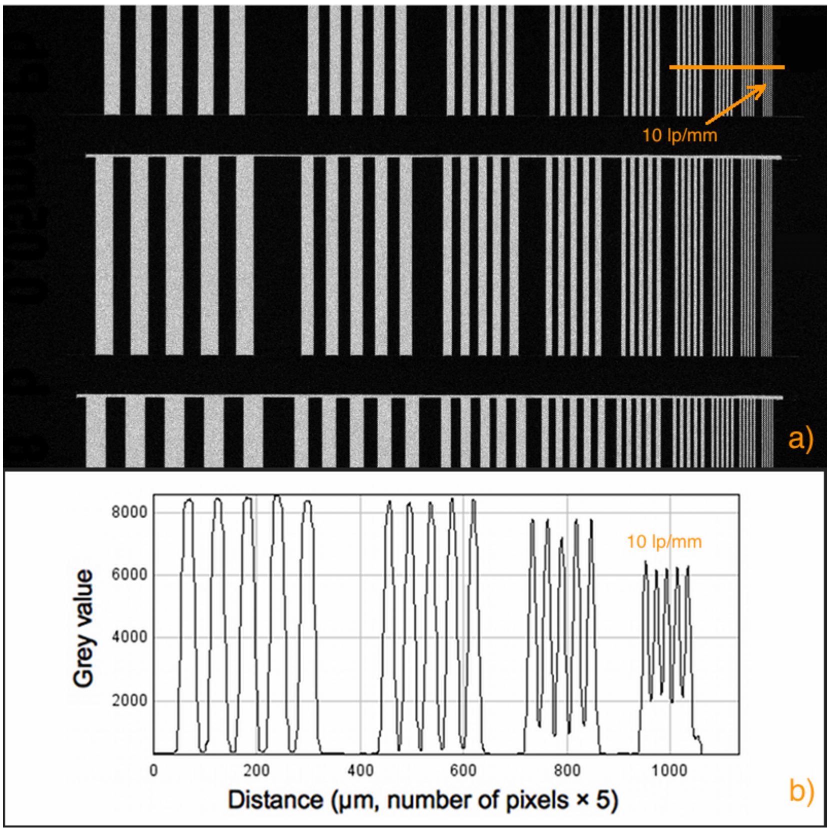

Figure 4. a) Image of a Hüttner test object for spatial resolution measurement. b) A profile across the last four sets of bars. The highest density bar pairs (10 LP/mm) are well resolved.

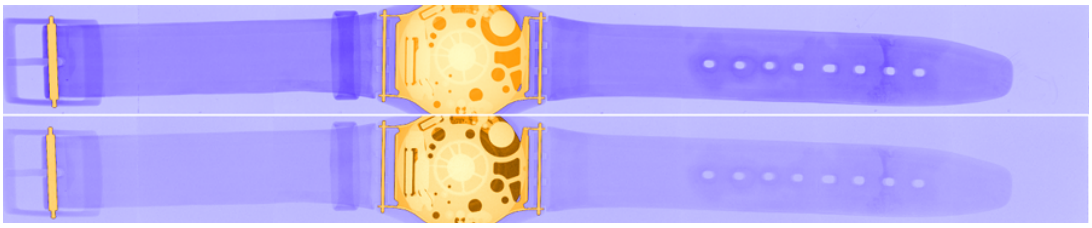

Figure 5. A single shot X-ray image of a man watch with its leather band taken with PIXIRAD-8.

4 PIXIRAD-8, an eight blocks module

The largest PIXIRAD module that has been assembled to date, is a 8 block unit with $25 \times 2.5\,\mathrm{cm}^2$ active area. The system has 2 M pixels and 4 M counters.

A single shot X-ray image of a wrist watch with its leather band taken with PIXIRAD-8 is shown in figure 5. The watch is made of plastic and metal parts. The top image (taken at low threshold) better visualizes weakly absorbing materials (plastic, leather) while the bottom image (high threshold) is better to visualize the metal parts.

A prototype system for Digital Mammography realized with the PIXIRAD-8 module, operating in slot-scanning imaging mode, is under development by STM Electronics (Verona, Italy) in

2013 JINST 8 C02028

collaboration with PIXIRAD in the framework of an R&D project supported by Regione Friuli-Venezia Giulia (Italy).

Digital Mammography is one of the most demanding X-ray imaging applications characterized by very fine position resolution, high sensitivity and DQE [12].

5 Conclusions

The PIXIRAD X-ray sensor is an innovative, high quality, noise free, chromatic imaging system.

Its main characteristics are:

- large area of the elementary building block;
- high values of contrast and spatial resolution;
- wide energy range (CdTe radiation sensor);
- high frame rate;
- capability to separate the image in various color components depending on the incident radiation energy;
- capability to operate in dead-time free mode (reading one counter while taking data in the other one).

The presented X-ray imaging system is the technological platform of PIXIRAD Imaging Counters s.r.l., a recently constituted INFN spin-off company (see http://pixirad.pi.infn.it/).

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