A 1½D CMOS Active Pixel Sensor for X-ray imaging

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We present a novel 1 ½ D CMOS Image Sensor for X-ray application. This sensor was developed within the EU-funded project *Intelligent Imaging Sensors for Industry, Health and Security* (I-ImaS).

The main target of the project is the development of a system for mammography and X-ray extraoral dental imaging. The camera concept (figure 1) is novel and is patented by the consortium. The camera consists of two lines of sensors. The image is built-up by scanning the sensors across to cover the full area. In the first scan, about 80% of the normal dose is delivered. The obtained image is processed in real time and information about interesting areas is extracted. Only those areas are imaged in the second scan. Simulations show the image quality is preserved while reducing the dose.

For the scanning approach, we considered both Time Delayed Integration (TDI) and Step-and-shoot approaches (S-S). TDI in CMOS sensors reduces the signal-over-noise [1]. In the S-S approach, the sensor integrates light for a fixed time in a each position before moving to the next one. In order to optimize the integration time, 32 lines of pixels are laid out on the sensor, hence the name 1½ D.

The floorplan of the sensor is shown in figure 2. It consists of 520x40 pixels, including 4 lines on each side for edge effect reduction. The 8 extra rows can be read out, although they would not normally be. Only the central 512 columns are readout. They are organized in 16 blocks of 32x32 pixels. Rolling shutter readout is used.

The pixel size is 32x32μm^2 and the estimated collected charge per pixel changes with the energy of the X-ray, the scintillator used and the exposure time. The estimated value ranges (in electron/hole pairs) used for this design are reported in Tab 1, assuming a structured CsI scintillator and a 10 ms exposure as for the mammography case.

The collected charge for the dental imaging application is approximately the same, considering that the X-rays have higher energy (around 100keV) but the best exposure time is about a third (3ms), so one detector can fulfill both needs. Choosing to resolve at least 4 times the average tissue level to reach the skin line level [3], and keeping some dynamic range available in case the scintillator performs next to the its expected best, we chose a full well capacity for the diode of around 200000 e$^-$. With a 3.3V reset voltage and a 5V drive on the reset transistor's gate, the available output voltage range is about 2.2V. The required diode capacitance can then be defined as:

$$C_d = \frac{Q_{max}}{\Delta V_{max}} = 14.5\,fF$$

The k_BTC noise is then fixed at 48.4 e$^-$ ENC (@300K) and the maximum S/N rate is 72.2dB.

Different pixel reset schemes are possible, including hard, soft and flushed, in order to reduce the KTC noise [4, 5].

At the bottom of each column (on the left in figure 3), a 3-bit circuit for FPN reduction is implemented together with an analogue multiplexer. There is no sampling capacitance as in normal camera operation the sensor is illuminated only during data taking. For testing with constant illumination or in other application, Correlated Double Sampling (CDS) is used: each time the pixel is addressed, the floating node voltage is first read, the pixel is then reset and the reset voltage is read out and stored in memory. It will then be subtracted at the next reading. Each block of 32 columns is analogue multiplexed into a Programmable Gain Amplifier (PGA), with gain settings of 1 and 2. The output of the PGA is digitized on chip by a 14-bit SAR ADC. The SAR ADC (figure 4) has a hybrid architecture [2], using a resistive ladder for the 4 MSB and a capacitance bank for the other 10 bits. The capacitor bank is split into two banks, each taking care of 5 bits. The two banks are connected together by a series capacitance with a 5-bit calibration network. This architecture was chosen as the best compromise between capacitance matching, noise and area. The ADC can run at 20 MHz and takes 16 clock cycles (2 cycles for sampling the pixel voltage) for one conversion. The sampling rate is then 1.25MHz. Most of its power consumption is due to the dc current through the resistor string, around 2.5mA per ADC. The digital output multiplexer scans through all ADCs' outputs and splits them to be sent out on a 7 bit bus at 40MHz rate. Since there are 16 ADCs and it takes 16 clock cycles for a conversion, there's no dead time and all data are read out before a new sample (next pixel value) is converted.

Tab 1: Estimate of the collected charge per pixel

		minimum	maximum
White level		250000	500000
Tissue		30000	60000
Dense	max	25000	50000
tissue	min	12500	25000

The sensor (figure 5) was designed and manufactured in 0.35 μm CMOS Image Sensor technology on a 14 um thick epitaxial layer. The sensor was characterised optically (figure 6) and for direct X-ray conversion (figure 7) and then with a CsI scintillator mounted on it for indirect X-ray detection (figure 8). The test results shown here were obtained at the synchrotron machine Elettra in Trieste, Italy. The spatial resolution of the sensor plus scintillator is dominated by this latter. A structured scintillator will be used for the camera design as this would give the best MTF.

Images (figure 9 and 10) of different objects were obtained by scanning a single sensor across the imaging area. All images were then stitched together by using the correct pixel overlap. Gain corrections were then applied to take into account both variations in gain within the sensor and variation in beam intensity during the scan. Below is an image of a sensor mount ceramic card. The image shown below was taken at 75 kVp and 4 mA. The card is 30x10mm and the distance between each scanning step was taken equal to 832 μm, corresponding to 26 pixels. The integration time for each single step was 10 ms. For this image, the sensor was coupled to an unstructured CsI scintillator.

The full camera would consist of two lines of 10 sensors. A prototype is currently being developed and its construction should be completed in the next few months.

Acknowledgements

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Reference

[1] H. Michaelis et al., *CMOS-APS Sensor with TDI for High Resolution Planetary Remote Sensing*, Extended programme of 2005 IEEE Workshop on CCDs and AIS, Japan, 31-34

[2] A. I. Krymski et al., *A High-Speed, 240-Frames/s, 4.1-Mpixel CMOS* Sensor, IEEE Trans. on Electron Devices, vol. 50, no. 1, January 2003, 130-135

[3] M.M. Tesic, M. Fisher Piccaro, and B. Munier, *Full field digital mammography scanner*, European Journal of Radiology 31 (1999) pp. 2-17

[4] H. Tian, B. Fowler, and A. El Gamal, *Analysis of temporal noise in CMOS photodiode active pixel sensors*, IEEE JSSC, vol. 36, no. 1, Jan 2001

[5] B. Pain, G.Yang, T.J. Cunningham, C. Wrigley, and B. Hancock, *An enhanced-performance CMOS imager with a flushed-reset photodiode pixel*, IEEE Electron Devices, vol. 50, no. 1, Jan 2003 pp. 48-56

Figures

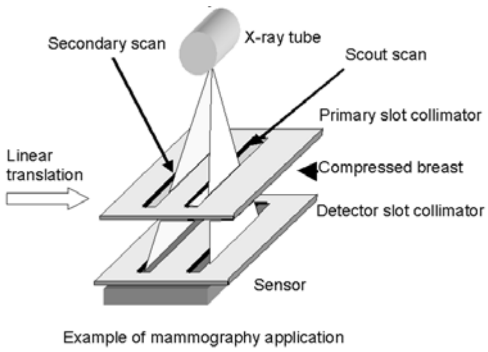

Figure 1. I-ImaS X-ray camera, with the double-scanning concept

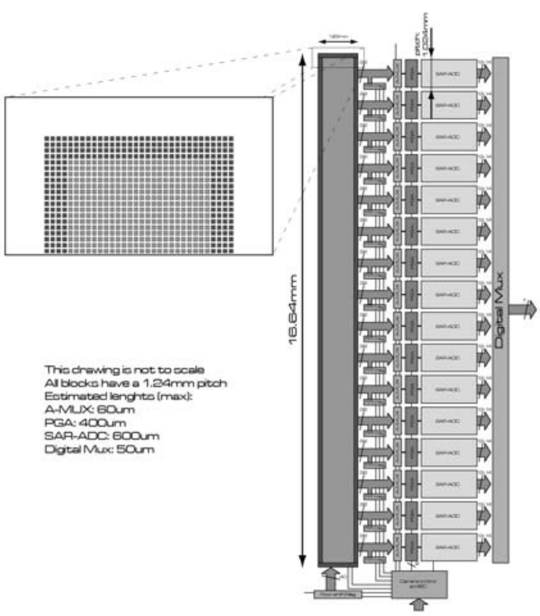

Figure 2. Floorplan of the I-ImaS 1½D sensor

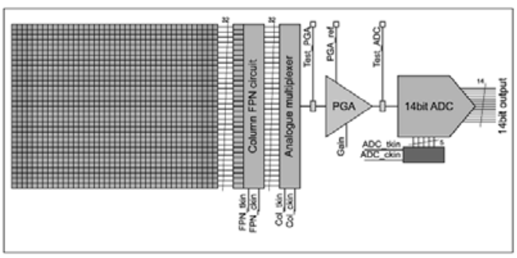

Figure 3. Schematic diagram of one readout channel

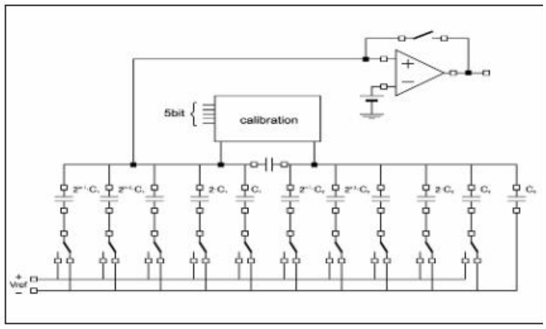

Figure 4. Block diagram of the SAR ADC, resistive ladder not included

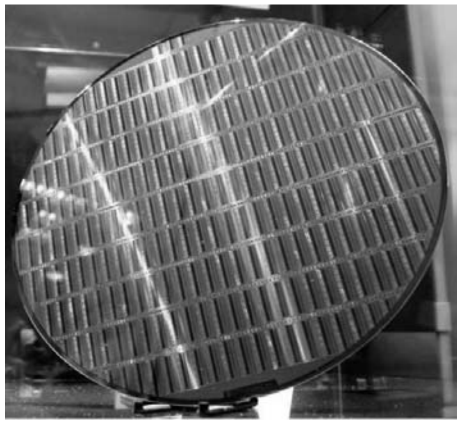

Figure 5. I-Imas sensor wafer

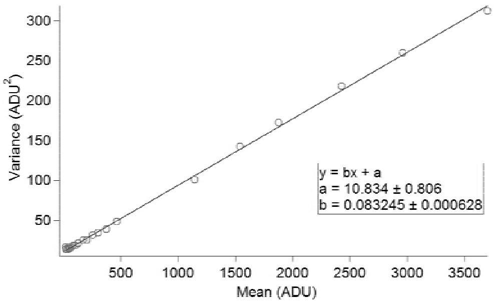

Figure 6. Optical PTC

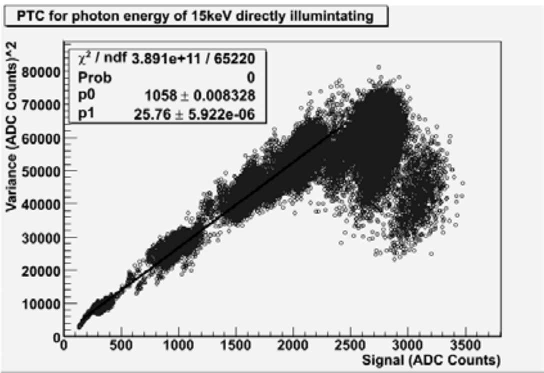

Figure 7. Direct X-ray detection PTC

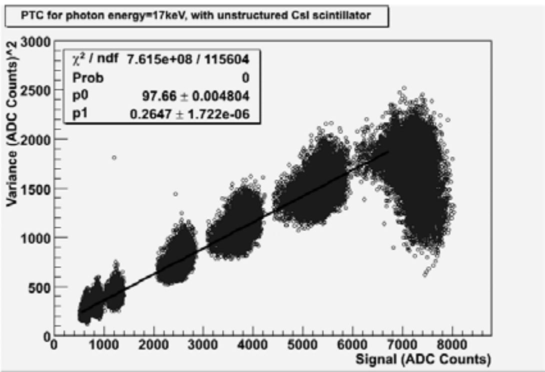

Figure 8. Indirect X-ray detection PTC.

Figure 9. Image of a ceramic PCB; taken at 75kVp and 4mA current.

Figure 10. Image of a tooth taken at 70kVp and 6mA current.