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Characterisation of HEPAPS4 - a family of CMOS active pixel sensors for charged particle detection

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Abstract

Monolithic active pixel sensor technology is a relatively inexpensive and reliable alternative to that of CCDs. Potential scientific applications for these devices include charged particle detection, indirect X-rays and neutron imaging. This paper reports on the characterisation and timing parameters optimisation of three different sensor variants from the HEPAPS4 family. The sensors feature standard three nMOS design but differ in the implementation of the photosensitive element. They have an array of 1024×384 pixels of 15×15 μm^2 and 20 μm epi-layer. Photonic methods are used to measure conversion gain, linearity, signal to noise ratio, dynamic range, pixel to pixel uniformity, dark current and read noise.

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1 Introduction

Charged Couple Device (CCD) technology has dominated the imaging market since its invention in the early 1970s. CCD performance outweighed that of CMOS sensors in the majority of applications. Nevertheless, the CCD has some fundamental limitations. In a CCD basic functions have high power consumption. Unlike the CMOS image sensor, the CCD can not be monolithically integrated with analog and digital readout electronics and requires specialised fabrication facilities that increase production costs.

CMOS Active Pixel Sensors (APS) have become a strong alternative to the CCD. Since the early 1990s they promise several advantages over existing imaging devices with respect to functionality, radiation hardness, power consumption, readout speed and fabrication costs [1], [2]. Initially they were used in low-end imaging products such as web cameras, mobile phones etc. Advances in the fabrication process combined with continuous improvements in the design, resulting in a significant reduction in dark current and electronic noise, have made the APS a relatively inexpensive and reliable alternative to CCDs. Nowadays CMOS sensors are becoming the dominant image sensing device and gaining ground in high-end applications. It is anticipated that the use of APS will expand in the next 5-10 years [3].

Scientific applications impose even higher requirements on imaging devices. Noise performance is always of vital importance. It is also critical to many application to have a high dynamic range. In applications, like particle physics, where the image has a very low occupancy, on-chip data processing could become important, using complex in-pixel electronics for zero-suppression. A broad range of integration times required, from nanoseconds, e.g. in measurements of fluorescence decay, up to minutes and more in astronomy, puts challenges on the enhancement of the readout rates from one side and the leakage current compensation from another side. High energy physics applications, such as tracking detectors and calorimeters, raise the issue of radiation hardness.

2 The HEPAPS4 family

The HEPAPS4 sensor is a large area device (384 x 1024 pixels and 15 μm pitch) designed with high energy physics applications (HEP) in mind. It is based on the most promising test structure from the previous parametric sensor HEPAPS2 [4]. The HEPAPS4 features standard three nMOS design and was produced in three variants with different configuration of the sensing element. The "D1" version [5] has one 1.7×1.7 μm^2 n-well diode with enclosed geometry transistors (EGT) [6]. Charged particles induce charge in the field oxide layer which leads to source to drain leakage current in the conventional transistor design. EGT gives improved radiation tolerance. The "D2" and "D4" versions benefit from two and four photo diodes connected in parallel with 3.0×3.0 μm^2 and 1.7×1.7 μm^2 size respectively. The use of multiple diodes gives an increased uniformity of the charge collection across the matrix but the increase of the capacitance reduces the charge to voltage conversion factor and hence the gain. The p-type epi-layer is 20 μm thick. The in-pixel circuitry consists of the standard three nMOS transistors implemented in a p-well. The sensor is read out by addressing pairs of rows and sampling their signals on the capacitors at the end of each column. The read out cycle loops through these capacitors and multiplexes their voltages on four differentials outputs where they are digitised using 14-bit off-chip ADC. The read-out system for the HEPAPS4 sensor has 33 MHz clock and features configurable current and voltage biases. The timing parameters in the read-out sequence are variable and the integration time, the region of interest (ROI) and the reset sequence can be changed.

3 Photon Transfer Curve

The photon transfer curve (PTC) [7] provides a reliable method of estimating many parameters of the sensor, e.g. gain, read noise, dynamic range etc. It is based on the fact that the arrival of photons from a source is a Poisson process and one can use statistical methods for deriving sensor parameters. Use of photon shot noise as a test stimulus to the camera is very convenient as characteristics of the Poisson distribution are well known. Plotting the mean number of photons against the variance gives a linear dependence. One can say that any deviation from the straight line is caused by the sensor (Fig. 1). There are three regions that can be identified on the PTC plot. The read noise region is represented by the flat region and is associated with the sensor and its readout electronics. The linear region is dominated by the photon shot noise. As the input light amplitude level increases, the noise becomes dominated by the photon shot noise. Gain variation (gain fixed pattern noise (FPN)) dominates at high illumination levels which results from differences and non-uniformities between pixels. Usually the gain FPN is eliminated by subtracting two consecutive frames at one illumination level as pixel to pixel variations are present in both images.

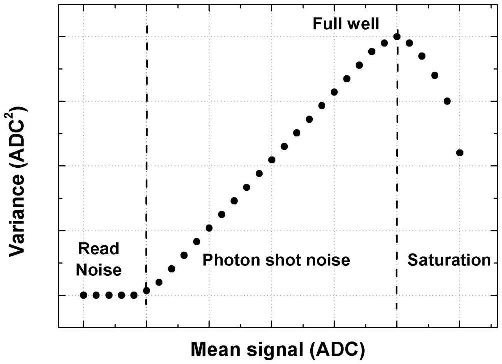

Figure 1: *Theoretical photon transfer curve for an imaging sensor where three regions can be identified: read noise, photon shot noise dominated region and saturation.*

4 Optimisation of the timing parameters

Readout sequence tuning is an essential part of the characterisation of any sensor. In order to understand the behaviour and optimise readout timing parameters, series of PTC lots for full frame were produced. Row sample duration (RSD), column sample duration (CSD) and MUX wait duration (MWD) of the sensor were varied one a time while keeping other parameters to arbitrary default values: 14 clock cycles for RSD, CSD and 28 for MWD. The best combination of the parameters in terms of highest gain, lowest noise floor and fastest readout time were chosen (Fig. 2). All three variants of the HEPAPS4 were characterised using these parameters and the ROI readout.

5 Gain

The measurement is performed in a light tight box by uniformly illuminating the sensor and gradually increasing the intensity of the source. The measured signal in ADC units is $\hat{\mathrm{S}}_{ADC} = \mathrm{G} \cdot \hat{\mathrm{n}}_e$, where G is the camera gain, n_e is number of electrons generated by incoming photons. In the shot noise dominated region the variance in ADC is $\sigma^2_{ADC} = (G\cdot \sigma_e)^2$ where σ_e is the standard deviation of the number of generated electrons. From the Poisson process follows that $\sigma^2_e = \hat{\mathrm{n}}_e$. Thus the camera gain is determined from the slope in the shot noise dominated region: $G = \sigma^2_{ADC}/\hat{\mathrm{S}}_{ADC}$.

The camera gain constant was calculated by fitting the slope in the photon shot noise dominated region for each pixel in the ROI of 200 × 200 pixels. The resulted gain for the pixels was plotted as a distribution and depicted in Fig. 3, which also provides information on the uniformity of the gain across pixel matrix.

6 Noise

Noise of the sensor was determined for every pixel in the ROI of 200 x 200 pixels. To this purpose, 800 dark frames were acquired. The resulting standard deviation of the pixel value from the respective pedestal value is noise. Fig. 4 shows noise distributions for three versions of the HEPAPS4 sensor. Pedestal variation FPN was estimated as standard deviation of the pedestal distribution resulting in 2500 e^-, 2900 e^- and 2400 e^- for "D1", "D2" and "D4" respectively.

7 Dark current

Dark current is a major consideration for imaging devices. It comes from the leakage current of the photo diode in the pixel due to thermal excitation of electrons to the conduction band. Dark current is dependent on ambient temperature of the sensor and integration time. It can be derived using the equation $I = dQ/dt$, where I is dark current, Q is charge per pixel, t is the integration time. By plotting the mean signal vs. the integration time and fitting line one can estimate the dark current which is usually given per unit area (Fig. 5).

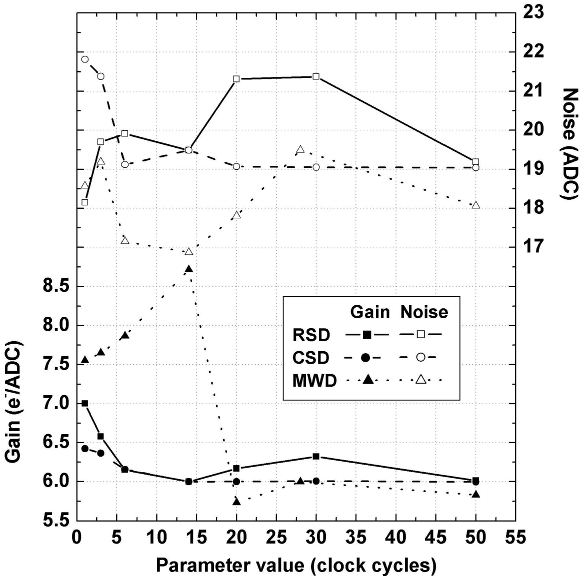

Figure 2: *Optimisation of the timing parameters using gain and noise as a benchmark. Optimised configuration was chosen as 10, 10 and 20 clock cycles for RSD, CSD and MWD respectively.*

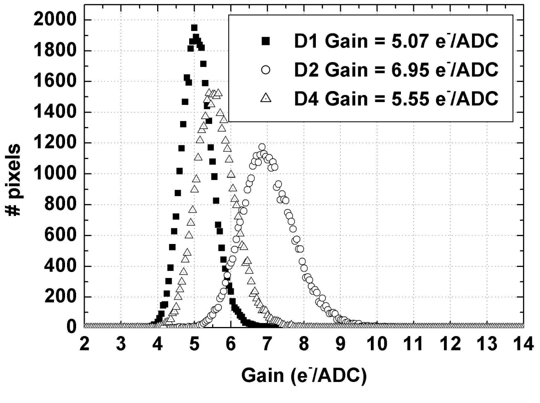

Figure 3: *Gain distribution for the ROI* 200 × 200 *pixels calculated for every pixel.*

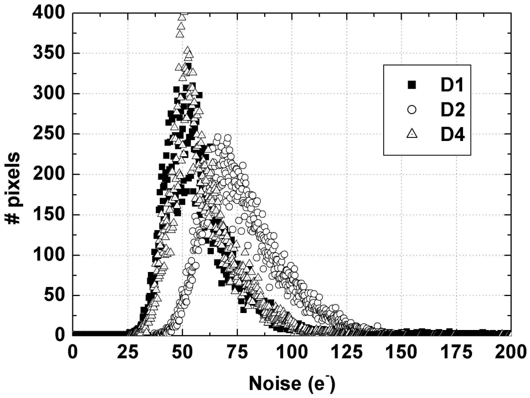

Figure 4: *Noise calculation for each pixel in the ROI 200 × 200.*

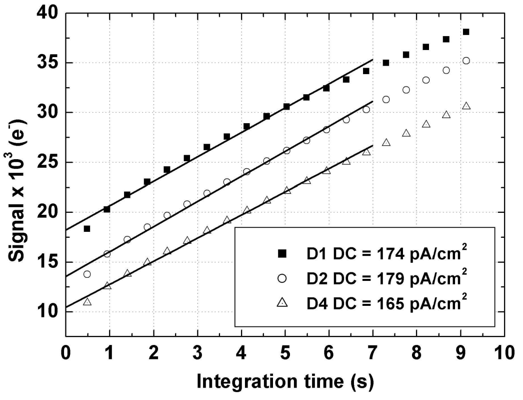

Figure 5: *Dark current measurement at room temperature (300K).*

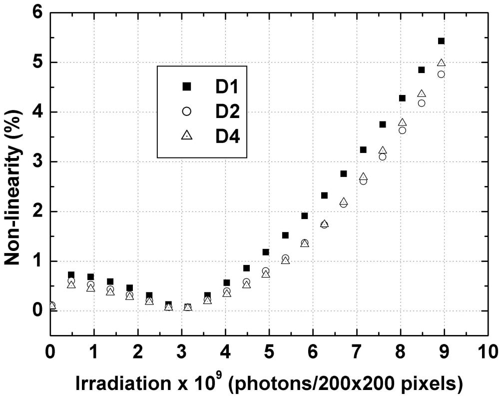

Figure 6: *Non-linearity of the sensor.*

Measured values	D1	D2	D4
Design	Single diode	Two diodes in parallel	Four diodes in parallel
Diode size (μm^2)	1.7×1.7	3.0×3.0	1.7×1.7
Gain (e^-/ADC)	5.1	7.0	5.6
Gain ($\mu V/e^-$)	24	18	22
Noise (e^-)	54	78	57
Dark Current (pA/cm^2)	174	179	165
Dynamic range (dB)	62	63	64
Full well capacity (e^-)	38000	53000	47000
Simulated values [8]			
Gain ($\mu V/e^-$)	16	11	9.6
Noise (e^-)	37	45	47

Table 1: Summary of the performance characteristics of the HEPAPS4 family.

8 Linearity

The major component of the non-linearity in the sensor comes from the sensing element non-linearity. The potential on the source follower gate, V_g, is the ratio of the charge on the photo diode, Q_d, and the capacitance of the photo diode, C_d. As the photo diode charges up the capacitance increases, hence the charge to voltage conversion factor is reduced resulting in a non-linear response.

The measurement is performed by illuminating the sensor in the shot noise dominated region just above the dark level and reading out a series of frames without resets between the frames. As the added charge between each frame remains the same due to the constant illumination and integration time, any deviation from the straight line indicates the non-linearity. Fig. 6 depicts percentage deviation of the sensor response from the linear fit in the range from zero signal to saturation.

9 Summary

The HEPAPS4 active pixel sensor is a family of large area devices designed with charged particle detection applications in mind. The optimal timing parameters of the sensor in terms of noise and gain were found. Photonic techniques were used to estimate gain, noise, non-linearity and dark current of three versions of the sensor. The characteristics of the sensor family are summarised in Table 1. Measured parameters are close to the simulated ones in terms of gain, but noise estimation is slightly different from what was expected. Some part of this excess most likely is due to high intrinsic system noise of the readout electronics of the sensor.

References

[1] B. Pain, S. K. Mendis, R. C. Schober, R. H. Nixon, E. R. Fossum, Proceedings of the SPIE 1946 (1993) 365.

[2] B. Dierickx, G. Meynants, D. Scheffer, IEEE CCD and Advanced Image Sensors Workshop, Brugge, 1997.

[3] R. Turchetta, et al, *CMOS Monolithic Active Pixel Sensors (MAPS): New "eyes" for science*, NIMA 560 (2006) 139-142.

[4] J. J. Velthuis *et al.*, *A monolithic active pixel sensor for particle detection in 0.25 μm CMOS technology*, NIMA **560** (2006) 40.

[5] L. Eklund *et al.*, First results from the HEPAPS4 Active Pixel Sensor, NIMA, in press.

[6] D. G. Mavis *et al.*, *Employing radiation hardness by design techniques with commercial integrated circuit processes*, Proceedings of Digital Avionics Systems Conference, 1997, pp. 2.1-152.1-22.

[7] J. Janesick, *Scientific Charge Coupled Devices*, SPIE Press, ISBN 0819436984 (2001)

[8] P. P. Allport *et al.*, *R&D on monolithic active pixel sensors (MAPS): Towards large-area CMOS sensors for particle physics*, NIMA, Volume 573, Issues 1-2, 1 April 2007, Pages 16-18