UNIVERSITY of GLASGOW

Department of Physics & Astronomy
Experimental Particle Physics Group
Kelvin Building, University of Glasgow,
Glasgow, G12 8QQ, Scotland
Telephone: +44 (0)141 339 8855 Fax: +44 (0)141 330 5881

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Spectral Characterisation and Noise Performance of Vanilla – an Active Pixel Sensor

A Blue[1], R. Bates[1], A. Laing-C[1], D Maneuski[1]
V. O'Shea[1], A. Clark[2], T. Greenshaw[4]
R. Turchetta[2], C. Arvanitis[3], S.E. Bohndiek[3]

[1] University of Glasgow, Glasgow, G12 8QQ, Scotland
[2] CCLRC, Rutherford Appleton Laboratory, Oxfordshire, UK
[3] Medical Physics and Bioengineering department, University College London
[4] Department of Physics, Liverpool University, UK

Abstract

This work will report on the characterisation of a new active pixel sensor, Vanilla. The Vanilla comprises of 512x512 (25μm squared) pixels. The sensor has a 12 bit digital output for full frame mode, although it can also be readout in analogue mode, whereby it can also be read in a fully programmable Region-Of-Interest (ROI) mode. In full frame, the sensor can operate at a readout rate of more than 100 frames per second (fps), while in ROI mode, the speed depends on the size, shape and number of ROIs. For example, a ROI of 6x6 pixels can be read at 20,000fps in analogue mode. Using Photon Transfer Curve (PTC) measurements allowed for the calculation of the read noise, shot noise, full well capacity and camera gain constant of the sensor. Spectral response measurements detailed the quantum efficiency (QE) of the detector through the UV and visible region. Analysis of the ROI readout mode was also performed. Such measurements suggest that the Vanilla APS will be suitable for a wide range of applications including particle physics and medical imaging.

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1 Introduction

In 2004, A UK consortium (MI3) was formed under an RC-UK Basic Technology Programme to develop CMOS active pixel sensors for a broad range of scientific applications including space science, particle physics and medical imaging. This work will report on results from Vanilla, the most recent MI3 produced active pixel sensor (APS). Despite the continuing success of the charge couple device (CCD), the last 2 decades have seen APS devices become increasingly popular in their use as portable, low cost imagers [1]. Despite suffering from higher readout noise than the CCD, APS have a number of advantages. These include lower power consumption, lower cost, random access and selective readout [2]. The possibility to incorporate on-chip functionality such as analogue-to-digital conversion (ADC), timing logic for thresholding and gain adjustment is driving an increased interest in these devices from the scientific community [3].

2 Vanilla APS

The Vanilla APS comprises of 520x520 (25 μm squared) pixels. The sensor has a 12 bit digital output for full frame mode, although it can also be readout in analogue mode. The sensor can operate at a readout rate of more than 100fps for full frame, and at higher speed when reading smaller regions-of-interest (ROI). For example, a set of square 6x6 pixels can be read out at 20,000fps through the analogue ports. At this high speed, the amount of light entering the pixels is lower, requiring only a 10 bit analogue-to-digital conversion to be performed. The maximum frame rate is limited by the data acquisition setup.

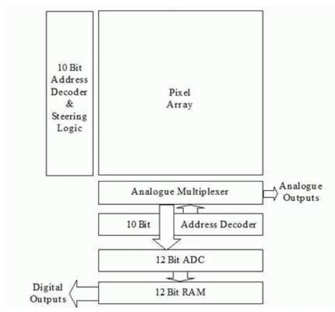

Figure 1: Floor plan for Vanilla APS

Vanilla comprises a standard three transistor pixel with diode, with 3 possible reset modes - soft, hard and flushed. Soft reset results in a lowered reset noise $(KTC/2)^{1/2}$ instead of $(KTC)^{1/2}$ [4]. However, frames taken utilizing soft reset are affected by image lag, where the current image is affected by the previous frame. Using hard reset, image lag is overcome, but results in full $(KTC)^{1/2}$ and reduced full well capacity. By using a hard reset followed by a soft reset, it is possible to get the best of both reset methods. This is known as flushed reset. The sensor has been designed to operate with a readout noise of <25 electrons, achieving a full well capacity of 100k electrons. As well as having the capacity of ROI readout with any number and shape of the regions, the pad layout allows for the butting of sensors on two sides.

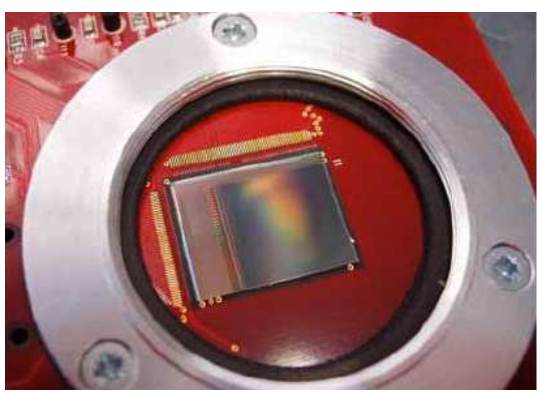

Figure 2: The Vanilla APS

3 Characterisation and Testing

For the following measurements, the sensor was positioned in a light tight box. Dark field measurements were made before each run to allow pedestal subtraction. Full frame readout measurements were taken at a rate of 4fps. All offline analysis was performed using a combination of ROOT and LabVIEW. The DAQ system is centred on an AVNET-Memec Virtex-II Pro 20FF1152 FPGA development board. The board generates the required control signals for the target device, and is equipped with an optical transceiver to enable upload of the image data to a host PC at Gbit/s speeds. Once uploaded to the host PC the image data is transferred efficiently to a LabVIEW based GUI via dedicated C++ middleware. The following work was carried out exclusively in analogue mode utilizing hard reset.

4 PTC

The average conversion gain of detected electrons to raw digital numbers (DN) generated by the ADC of a quantum-limited detector can be determined by measuring the noise variance in the mean observed signal [5]

$$\overline{g_d}(e^-/DN) = \frac{\overline{S_d}(DN)}{\overline{\sigma_q}(DN)^2} \tag{1}$$

Where $\overline{g_d}$ is the camera mean gain, σ_q is the input signal variance and $S_d = g_d \times q$ is the output mean signal. Eq 1 is used to calibrate CCD and CMOS sensors in absolute units and is related to the photon transfer curve. The relative digital signal generated by the on-chip ADC of a digital camera, expressed in ADC units (referred to here as Digital Numbers, DN) can then be converted to absolute electron units (e^-/DN) through the camera gain constant, k. PTC measurements were performed using a super bright led (620nm) with the light diffused across the sensor to within 1% deviation. The optical power of the LED at varying illuminations was recorded using a calibrated Hamamatsu photodiode. Fixed pattern noise (FPN) and read noise was removed through differencing of consecutive frames. Table 1 shows the results obtained for the Vanilla APS utilizing hard reset.

Parameter	Value	e-(rms)/DN
Camera gain (k)	10.9	e^-(rms)/DN
Read Noise	51	e^-(rms)
Full Well Capacity	$4 \times 1-^4$	e^-(rms)
Shot Noise Limited SNR	47	dB
Dynamic Range	70	dB

Table 1: Parameters extracted from the PTC measurements of the Vanilla APS

5 Spectral Response

An important parameter to measure for imaging detectors is the interactive quantum efficiency (QE), which represents the fraction of the visible photons interacting with the sensor with respect to the number of photons incident on the sensor. The interactive QE is the product of the photodiode QE and fill factor, since the entire area of the sensor is not photosensitive.

An automated monochromator with 0.25nm reproducibility controlled by LabVIEW software was connected to a stable, L7893 series Hamamatsu light source to produce monochromatic light at wavelengths from 300-810nm. An optical fibre from the monochromator was used to guide the light directly onto the surface of sensor. An example of the APS response to the light can be seen in Fig 3. Dark frame subtraction was performed to remove pedestal values, and the ADC values were integrated over the exposed area. A calibrated photodiode was then used to measure the incident photon flux on the sensor. The camera gain constant from the PTC measurement was then used to convert the measured output into electrons. It was found that the interactive QE measured 58% at 520nm, and reached a maximum of 69% at 600nm. (Fig 4)

6 Region of Interest Readout

Vanilla has the capability of reading ROIs. Data from the ROI is read out in analogue form and digitised off chip using a fast ADC. The ROI is read out in parallel down the columns and stored on capacitors before being read out serially through an analogue multiplexer. Readout speeds of 20,000fps (or 20kHz) allow the

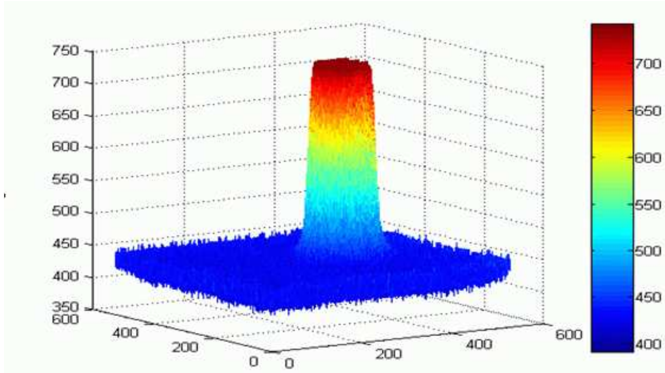

Figure 3: Beam profile of monochromatic light through the optical fibre incident on the Vanilla APS

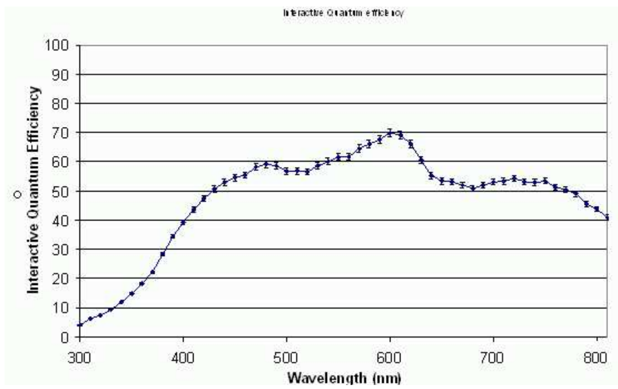

Figure 4: Measurement of the interactive QE for the Vanilla APS

sensor to be used in medical applications requiring high speed imaging, such as optical tweezers [6] or digital mammography [7]. ROI is also highly beneficial in particle physics applications where incident particles may only traverse through a very low number of pixels contained on a large area sensor, e.g. for vertex detector at the International Linear Collider [8]. A camera lens was attached to the sensor, and was run to select various ROI of pixels. The results can be seen in Fig 5. At full frame, the readout rate was set to 4fps. A maximum rate of 24,395fps was achieved for a 6x6 region, and was limited by the data acquisition setup.

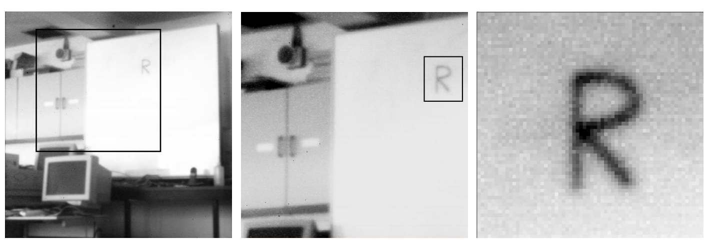

Figure 5: Varying ROIs for Vanilla

7 Future Work and Conclusions

This work has detailed the optimisation of novel features of an active pixel sensor, Vanilla. PTC measurements were successfully performed on the Vanilla APS in analogue mode utilizing hard reset. The camera gain constant was found to be 10.9 e^{-}/DN. Spectral response measurements have also been made. Using the measured camera gain constant, the sensor was shown to have an interactive QE of 58% at 520nm, and reached a maximum of 69% at 600nm. ROI measurements have been shown to be operational to over 24,000fps. Such a speed makes Vanilla highly suitable for object location and tracking, ideal for medical applications. The ability of ROI readout is also highly beneficial in particle physics applications, where high speed readout for large scale devices is essential.

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