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Optical & Electrical Characterization of a back-thinned CMOS Active Pixel Sensor

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Abstract

This paper summerises the first work on the characterization of a back-thinned Vanilla - a 512x512 (25μm squared) active pixel sensor. Characterization of the detectors was carried out through the analysis of Photon Transfer Curves to yield a measurement of full well capacity, noise levels, gain constants and linearity. Spectral characterization of the sensors was also performed in the Visible and UV regions. A full comparison against non back-thinned front illuminated Vanilla sensors is included. Such measurements suggest that the Vanilla APS will be suitable for a wide range of applications including particle physics and biomedical 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 APS

CMOS active pixels sensors (APS) are integrating sensors that integrate charge on a photoelement, (photodiode capacitance) as the sensing method [4]. Such circuits operate by resetting the photoelement, allowing charge to accumulate and then sensing the charge value. A CMOS APS incorporates at least three transistors per pixel: a reset transistor that resets the photoelement, a source follower input transistor that converts the accumulated photocharge to voltage, and a row select transistor that selects the row to be read (Fig 1). The term active refers to the incorporation of the active amplifier within each pixel (source follower input transistor).

2.1 Vanilla APS

The Vanilla APS comprises of 520x520 (25μm 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 100 fps 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 20,000 fps 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.

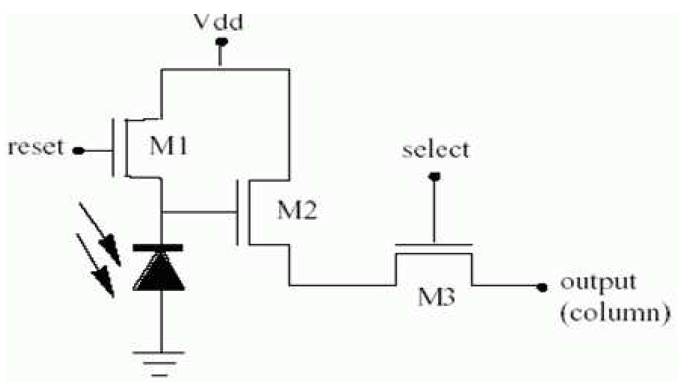

Figure 1: Floor plan for CMOS APS

2.2 Backthinned Vanilla

For some time, it has been predicted that the removal of the supporting substrate section of the sensor to allow detection via direct backside illumination would result in many potential benefits to applications in fields such as particle physics (lower mass)[5] and biomedical science (enhanced UV detection)[6]. However, whilst common practice in CCDs, such back thinning techniques have been rarely used on active pixel sensors. In this work, on wafer Vanilla sensors were back thinned (by E2V) through a combination fabrication methods including lapping, RIE (Reactive Ion Etching) and laser annealing. Subsequently the substrate was removed to within the epi-layer for the Vanilla APS. The sensor was then wire bonded to the readout PCB (figure 2)

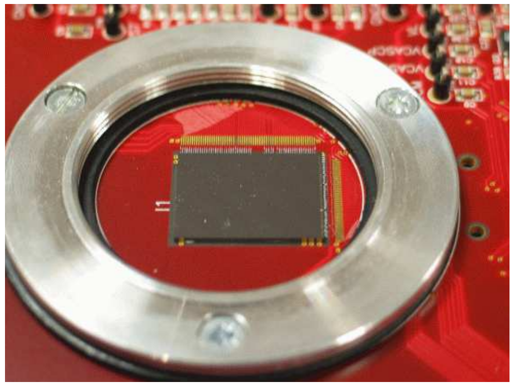

Figure 2: Picture of the BT Vanilla sensor bonded to PCB

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 centered 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.

3.1 PTC

The average conversion gain, g, 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 [7] as follows:

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

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. 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. FPN noise and read noise was removed through differencing of consecutive frames. Table 1 shows the results obtained for both the normal and backthinned Vanilla APS utilizing flushed reset[8]. An examination of the dark current levels through measurement of read noise levels for varying integration times [9] showed an increase from 47.1 pA/cm^2 to 87.6 pA/cm^2 for the back-thinned device. This is believed to be a result of the post fabrication processing required for the removal of the supporting substrate.

3.2 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. A 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 200-480nm. 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 2. 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 backthinned Vanilla showed a considerable increased value of interactive QE for the UV-visible region. (Fig 3)

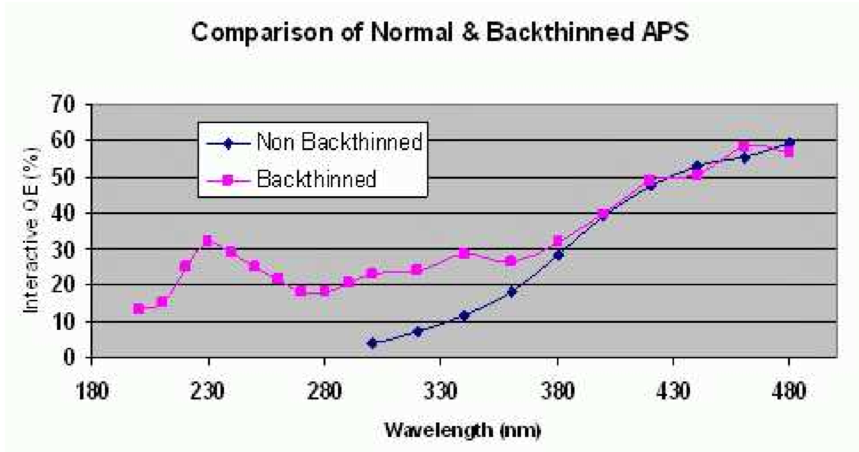

Figure 3: Measurement of the interactive QE for the normal and backthinned Vanilla APS

4 Future Work and Conclusions

This work has detailed the characterization of the noise, gain and interactive QE of a backthinned active pixel sensor, Vanilla. PTC measurements were successfully performed on both types of Vanilla APS in analogue mode utilizing flushed reset. The camera gain constant was found to be comparable for both, as was the dynamic range and full well capacity. However, there was a notable rise in dark current levels for the backthinned sensor, believed to be an artifact from the post-processing. Spectral response measurements have also been made. Using the measured camera gain constant, the backthinned sensor was shown to a significantly higher interactive QE between 200-480 nm. Such results indicated backthinned Vanilla would be highly suitable for low mass particle detectors, and also a range of biomedical applications, such as H^3 autoradiography [10], where measurements with excellent sensitivity and very low noise have already been demonstrated.

Acknowledgments

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