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A review of MI3 produced Active Pixel Sensors

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Abstract

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. 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. 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. 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. During the programme 6 APS' were designed, fabricated and tested. Highlights from the project include: the LAS (Large Area Sensor), a novel stitched sensor designed for use in medical imaging; eLeNA (Low Noise), a test structure which develops a range of low noise pixels and OPIC (On Pixel Intelligent CMOS), a test structure designed for in-pixel intelligence including sparse read-out, ADC and storage in each pixel and thresholding.

This paper reports on the results and conclusion from highlight of some of the 6 active pixel sensors produced by the MI3 consortium.

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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 Sensors

The collaboration designed, fabricated and tested 5 sensors which are detailed in table 1

Name	Features
OPIC	On Pixel Intelligent CMOS
Vanilla	ROI, Flushed Reset, A/D readout
LAS	Large area & Multiple reset regions
HDR	High Dynamic Range
eLeNa	Low Noise Sensor

Table 1: - The range of APS devices produced by the MI3 collaboration

The work in paper will feature some results from LAS and variants of Vanilla (backthinned and increased epi devices). The Startracker sensor was also used for comparative tests [4]

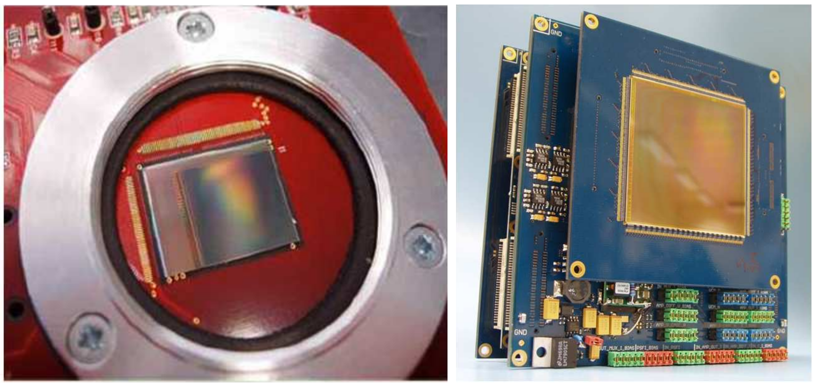

Figure 1: The Vanilla and LAS devices

2.1 Vanilla

The Vanilla [5] 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 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. Vanilla comprises a standard three transistor pixel with diode, with 3 possible reset modes - soft, hard and flushed. 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.

2.2 LAS

The large area sensor (LAS) has 1350x1350 $40\mu m^2$ pixels fabricated in a 0.35μm CMOS process, giving it a 54mm x 54mm sensing area [6]. It has 10 analogue outputs and can run at 20 frames per second. It also employs multiple resets whereby three different integration times can be set on the array to achieve a large dynamic range for imaging of static scenes. LAS utilizes CMOS stitching to allow a large sensing. Combined with the high dynamic range, this makes LAS a modular and scalable image sensor suitable for scientific applications such as diffraction imaging and direct digital X-ray imaging for medicine.

3 Characterisation and Testing

All sensors were fully characterised through noise analysis, Photon transfer curve measurements, dark current measurements and linearity curves. A full explanation of the testing methodology for these sensors can be found elsewhere [4-5]

3.1 Epi-layer thickness

Vanilla was fabricated on 2 thicknesses of epi. Although for the visible light region, the majority of incident radiation will be absorbed and interact within the first 10 m of the silicon layers, there should be a noticeable improvement in the detection of ionizing particles with a thicker epi-layer. For example, for minimizing ionizing particles (MIPS) such as the β particles emitted from a ^{90}St source, approximately $70e^-$ will be deposited for every 1μ of silicon epi. Assuming 100% charge collection and minimal charge sharing, the recorded signal for the 2 epi thicknesses would be $980e^-$ (14μm) and $1400e^-$ (20μm).

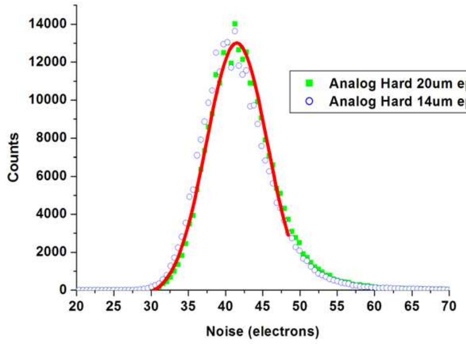

Figure 2: - Comparative noise levels in 14μm and 20μm thick epi-layers

The design of the DAQ system did not allow for the implementation of a triggering system (necessary for e.g. MIPS detection). However the noise levels were measured and found to be comparable at $\sim 41e^-$ (fig 2). This then gives an improvement in S/N from 23:1 to 35:1.

3.2 Back-thinned Devices

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)[7] and biomedical science (enhanced UV detection)[8]. 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 up to the epi-layer of the Vanilla APS. The sensor was then wire bonded to a readout PCB. Noise measurements were performed using both the normal and backthinned Vanilla. The backthinned detector was fully characterised and compared to the conventional Vanilla (table 2). It was shown that in all areas, the backthinned detector was comparable to the conventional

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. Such results

Performance Parameters	Normal	Backthinned	Units
Gain (k)	24.8	25.8	e- ADC
Read Noise	18.3	22.7	e-
Full Well Capacity	62x10-4	62x10-4	e-
Shot Noise Limited (SNR)	47	47	dB
Dynamic Range	71.38	71.27	dB
Non-Linearity	0.4	0.5	%

Table 2: Parameters extracted from the PTC measurements of the normal and backthinned Vanilla APS.

show that such back thinned APS devices are acheivable without detrimental effects to the properties of the detector.

3.3 LAS - Multiple Regions of Reset

One of the features of the large area sensor (LAS) is the ability to operate with multiple regions of reset, whereby three different integration times can be set on the array to achieve a large dynamic range for imaging of static scenes. To achieve this, 6 transistors erre added to the conventional '3-T' APS layout which included the standard reset, row select and source follower transistors. An example of the benefit of the multiple reset regions can be seen in Fig 3

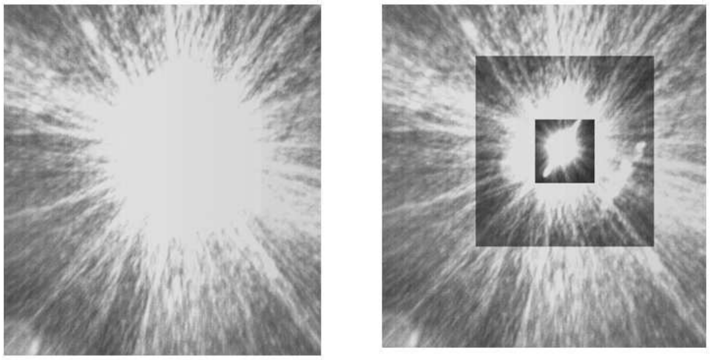

Figure 3: : LAS operating with and without multiple regions of reset (output from an LED laser pointer)

A dynamic range of 140dB [6] was measured using the integration time range provided by the multiple regions of reset on the detector. Such dynamic range makes LAS a candidate for use in applications with a large variation in the magnitude of signal being detected (such as X-ray diffraction experiments)

4 Future Work and Conclusions

This work has detailed some of the work and results from the MI3 collaboration. Using the Vanilla sensor it was seen that an increased epi layer thickness for APS devices does not increase the inherent noise of the sensor. This is very promising for particle based detection. It was also shown that backthinned devices show no increase in read noise or a decrease in gain or full well capacity, making such devices candidates for direction particle or UV detection. An increase in dark current is noted, but this could be controlled by cooling the device. An example of the multiple reset ability of the large area sensor was also shown, allowing for the possible use of such devices in experiments such as direct digital X-ray imaging.

Acknowledgments

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