e2v CMOS and CCD sensors and systems for astronomy

Conference or Workshop Item

e2v CMOS and CCD sensors and systems for Astronomy

Paul R Jorden[a], Paul A Jerram[a], Martin Fryer[a], Konstantin D Stefanov[b]

[a] *Teledyne-e2v, 106 Waterhouse Lane, Chelmsford, Essex, CM1 2QU, UK*

[b] *Centre for Electronic Imaging, Open University, Milton Keynes, MK7 6AA, UK*

E-mail: Paul.Jorden.at.Teledyne-e2v.com

ABSTRACT:

Teledyne-e2v designs and manufactures a wide range of sensors for space and astronomy applications. This includes high performance CCDs for x-ray, visible and near-IR wavelengths. In this paper we illustrate the maturity of CMOS capability for these applications; examples are presented together with performance data. The majority of Teledyne-e2v sensors for these applications are back-thinned for highest spectral response and designed for very low read-out noise; the combination delivers high signal to noise ratio in association with a variety of formats and package designs. The growing Teledyne-e2v capability in delivery of sub-systems and cryogenic cameras is illustrated- including the 1.2 Giga-pixel J-PAS camera system.

KEYWORDS:

CCD, CMOS, back-thinned, low-noise, mosaic focal plane, cryogenic camera, custom design sensors

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1. CMOS Image Sensors (CIS)

CMOS sensors have been developed for astronomical and space applications and complement CCDs that are already widely used. CMOS image sensors have now achieved maturity and high performance for such applications. Large areas, high quantum efficiency and low read-noise are all available. The CMOS architecture particularly allows higher readout rates as well as integrated digital signal processing if required. The parallel internal architecture allows slow signal sampling for low noise at the same time as high frame rates. In the sections below we present examples and outline details of recent developments to highlight current status.

Some sensors were presented at the PACCD2016 meeting but are omitted here for brevity; these include the CIS111 (MTG FCI) and CIS116 (Metimage) sensors; see reference[1]. These are high performance specialised sensors currently in development for space programmes. The former has novel rhombus-shaped pixels and is designed for good charge transfer through large pixels. The latter has even larger 250 µm pixels and is optimised for low lag and charge-to-voltage factor.

1.1 The CIS113 device

This device has been developed originally for the TAOS-II project[2, 3]. The sensor is designed in a large-area buttable format to allow an array of 10 sensors to form an 88 Megapixel mosaic focal plane; this represents a large field of view to enable efficient trans-Neptunian Object detection. Figures below illustrate the sensor and show quantum efficiency.

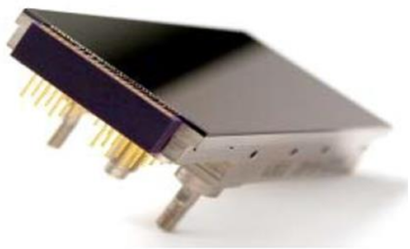


Figure 1. Picture of CIS113

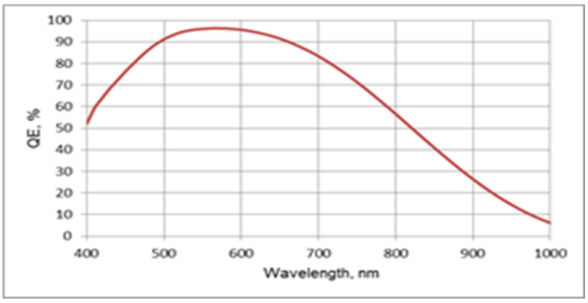


Figure 2. Quantum Efficiency (at -25C)

The table below indicates primary performance parameters for this sensor. This device has eight analogue readout ports. Further information is available on the device datasheet[4].

Table 1. CIS113 performance

Item	Performance
Number of pixels	1920 (H) × 4608 (V)
Pixel size	16.0 µm square
Image area	73.73m × 30.72 mm
Output ports	8 (REF and SIG each)
Package size	82.34 mm × 31.7 mm; 3-side buttable
Package format	76 pin ceramic PGA attached to invar block
Focal plane height	14.0 mm
Flatness	< 30 µm (peak - valley)
Conversion gain	90 µV/e^-
Readout noise	3 e^- at 2 MP/s per channel
Maximum pixel rate	2 MP/s per channel
Maximum charge	19,000 e^- per pixel
Dark signal	70 e^-/pixel/s (at 21 °C)
Frame rate	2 fps (full frame mode) ; 20 fps (multiple ROI's)

A full set of science grade sensors have been delivered (Jan-2017) for use on TAOS-II cameras.

1.2 The Onyx EV76C664 device

This sensor has been developed for industrial use; however it has high performance with a sophisticated digital functionality. This sensor has low read noise, digital outputs and multiple operating modes with potential for astronomical applications. This standard product is supplied as a front-side illuminated sensor with micro-lens. See table and figure below or datasheet[4] for further information.

Table 2. Onyx key features

Item	Parameter
Number of pixels	1280 X 1024 (1.3 Megapixel)
Pixel size	10.0 µm square
Shutter modes	Global and Rolling
Output	8, 10, 12, 14 bit LVDS
Package format	Ceramic 67-pin PGA
Readout noise	6 e^- (min, depending on mode)
Spectral Response	Monochrome or sparse colour (with micro-lens)
Maximum charge	16,000 e^- per pixel

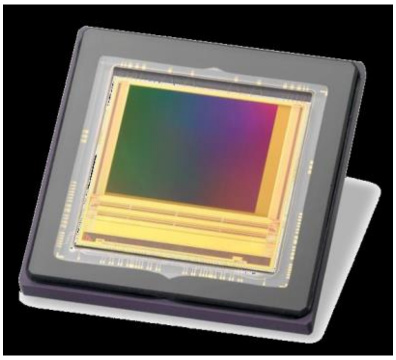
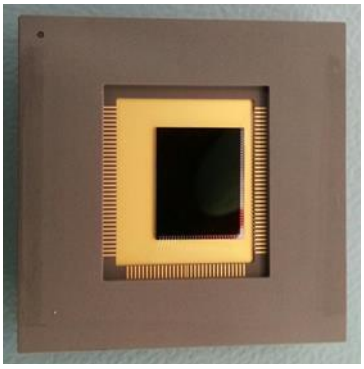


Figure 3. Picture of Onyx sensor

1.3 The CIS115 device

This sensor has been derived from a previously-designed CIS107 sensor. It is back-thinned with low read-noise and designed for space applications. Samples have been evaluated, and the sensor is currently completing space qualification. It is proposed for use on the ESA JANUS (Juice) mission.[5]

Table 3. Key features of CIS115

Number of pixels	1504(H) × 2000(V)	
Pixel size	7.0 µm square	
Number of output ports	4 pairs of analogue outputs (reset and signal pins)	
Package size	48.26 mm square	
Package format	140 pin ceramic PGA	
Flatness	< 10 µm (peak to valley)	
Conversion gain	35 µV/ e^-	
Readout noise	7 e^- (Rolling shutter)	
Maximum pixel data rate	8 MP/s per channel	
Maximum charge per pixel	55,000 e^-	
Frame rate	Up to 10 Hz	
Min. time to read one line	66.25 µs [at 6.2 MP/s]	
Frame rate at full resolution	Up to 7.5 fps	
		Figure 4. CIS115 sensor

1.4 TDI CMOS development

The charge-coupled architecture of CCDs has traditionally been used to enable the Time-Delay-Integrate (TDI) mode of use which has been used in many scanning satellites including the very successful ESA GAIA mission. The CMOS architecture does not automatically offer this mode of use, but Teledyne-e2v has been developing structures to allow modest TDI lengths. This can promise the lower power consumption of the CMOS design yet offer a CCD-like structure. See figures below for illustrations and also refer to paper[6].

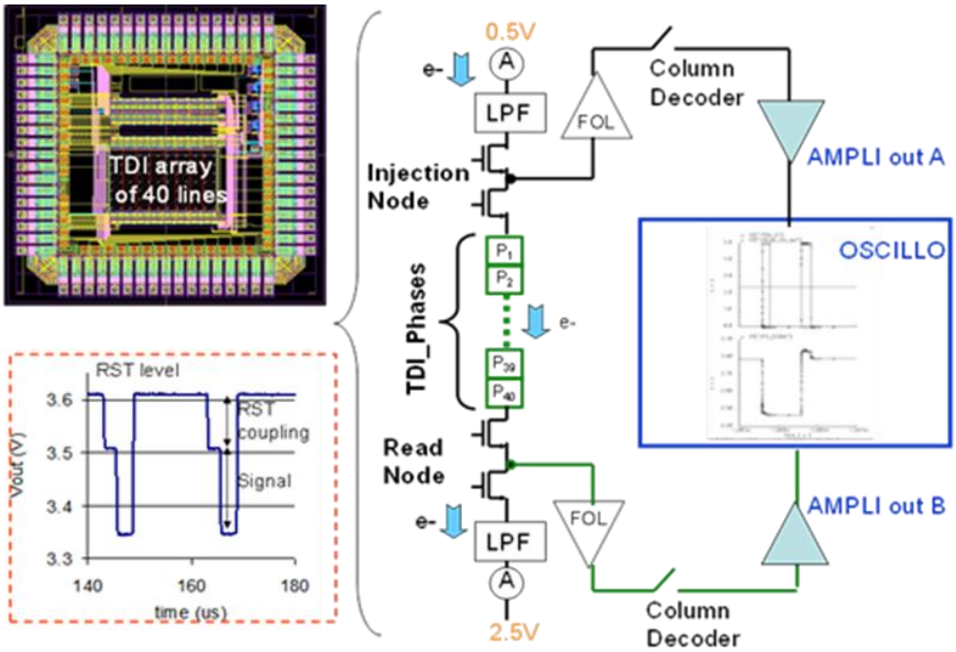


Figure 5. TDI CMOS concepts

1.5 CIS120 (GPSI)

The General Purpose Space Imager (GPSI) is in development as a digital platform using modules to enable re-use for differing formats and standard interfaces. It is designed for radiation tolerance, high sensitivity, and digital functionality. Key features are shown below.

Table 4. Key features of CIS120

Number of pixels	2048(H) × 2048(V)
Pixel size	10.0 µm square
Package format	Ceramic-PGA
Maximum charge	50,000 e^- per pixel
Readout noise	4 e^- Rolling shutter
Conversion gain	45 µV/ e^-
Back-thinned QE	90% at 550 nm
Frame rate	30 fps @ 8 bit resolution
Power consumption	<350 mW
4 LVDS outputs	8, 10, 12, 14 bits ADC

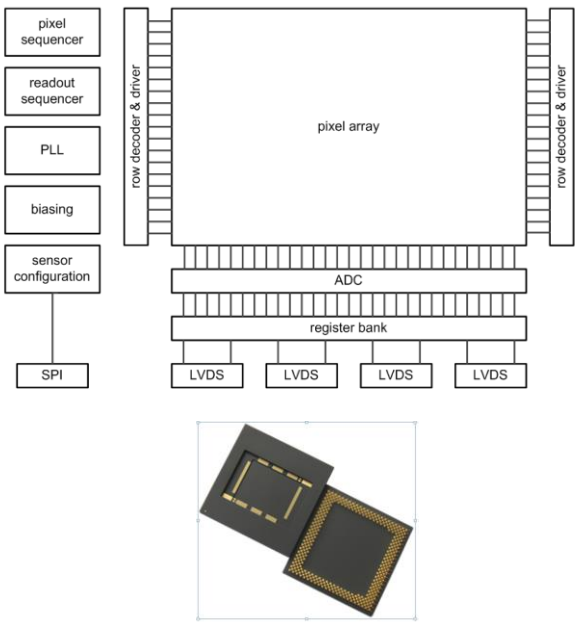


Figure 6. GPSI CIS120 sensor

1.6 Fully-depleted CMOS development

Monolithic CMOS imagers use photodiodes biased at low voltages (1-2V) which give a small depletion depth; this means that fully depleted silicon is rather thin (< 10 µm) and has correspondingly small red/NIR wavelength sensitivity. This is a disadvantage compared to CCDs which use larger voltages, can achieve depletion depths in excess of 40 µm and deliver high long wavelength QE. [Hybrid CMOS Imagers can deliver higher red sensitivity but are more expensive and have higher read-noise].

Monolithic pinned photodiode (PPD) CMOS image sensors have excellent noise performance and very low dark current on a par with the best CCDs, and are very attractive for a large number of science applications. Recently, a new pixel design using a fully depleted PPD has been developed and tested[7]. The sensor can be fully depleted by means of reverse substrate bias, allowing a sensor to be manufactured with thick (and therefore red-sensitive) silicon. Custom implants are required in order to allow reverse biasing without severe parasitic currents. This has potential to allow scientific CMOS imagers with significantly enhanced near-infrared and soft X-ray quantum efficiency.

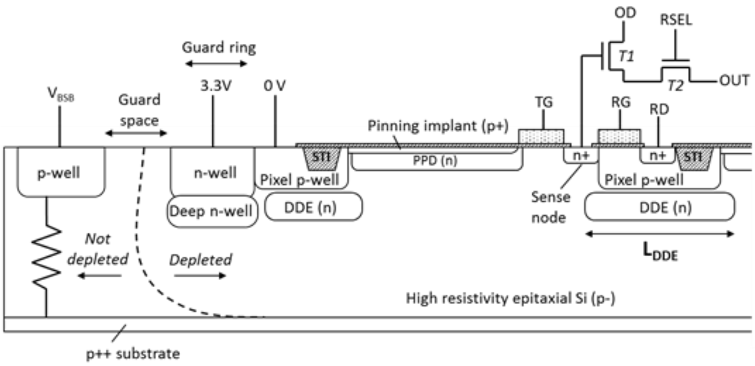


Figure 7. Cross section of the newly developed backside biased and fully depleted PPD pixel.

Figure 7 shows the cross section of the new pixel design and the additional deep implants (DDE) introduced under the in-pixel p-wells. The first prototype, named BSB1 and shown in Figure 8, contains several pixel types on 10 µm and 5.4 µm pitch, and is made on 18 µm thick, 1000 Ω.cm epitaxial wafers using 180 nm image sensor process from a commercial foundry. The principle of operation allows the potential to manufacture devices with large thicknesses in excess of 100 µm (on bulk high resistivity silicon) and is not limited by the epitaxial material used in BSB1.

Characterisation of the front side illuminated BSB1 showed that the device can be reverse biased to achieve full depletion to depths beyond 18 µm without parasitic reverse currents. The electro-optical characteristics of the newly developed pixel are nearly identical to the reference PPD designs, demonstrating that the additional implant has no adverse effects on charge collection, charge transfer and the response of the sense node. Subsequently, BSB1 wafers were processed at Teledyne- e2v Technologies to produce backside illuminated (BSI) variants of BSB1, which will be evaluated soon.

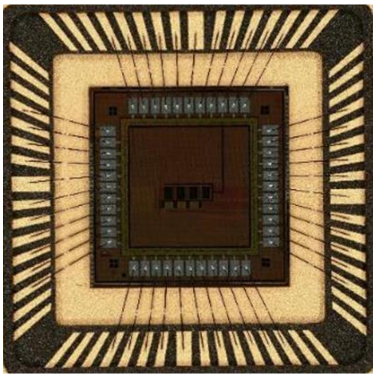


Figure 8. Photomicrograph of BSB1, the first reverse biased PPD CMOS image sensor prototype.

Further developments will include a larger scale imager using the same epitaxial substrate and possibly a much thicker sensor made on bulk silicon. This development promises to realize CMOS image sensors with high QE in the near-infrared and soft X-ray bands, able to compete with state-of-the-art CCDs.

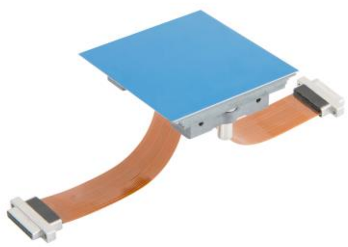
2. Specialised CCDs

As shown above, the CMOS architecture can be used to provide high performance sensors for multiple astronomy instruments. However, CCDs continue to be used for astronomical applications and we briefly present a few state-of-the art CCD sensors below. Many more are presented on the Teledyne-e2v web site[4].

2.1 CCD250

This large-format sensor has been custom-designed for the LSST programme and illustrates a device that is optimised for high red wavelength sensitivity together with a precision package for use in a very large format focal plane for survey use. A total of 189 sensors will provide a 3 Gigapixel focal plane. Outline details are shown below. See LSST web site for more information on the project[8] and also camera description[9].

Table 5. Key features of CCD250

Item	Parameter	
Pixels	4096 X 4096	
Pixel size	10.0 µm square	
Outputs	16	
Package	High precision; 5 µm flatness	
Read noise	5 e^- at 500 KHz pixel rate	
QE	>90% peak; >75% at 900 nm	
Read-time	2 seconds	
		Figure 9. Picture of CCD250

2.2 CCD282

Although modern CCDs offer very low readout noise there are applications such as photon counting that benefit for sub-electron read-noise. The sensor shown below represents the largest format electron-multiplying CCD developed to date; see also[10].

Table 6. Key features of CCD282

Item	Parameter
Pixels	4096 X 4096 (image)
Pixel size	12 µm square
Outputs	8
Package	Ceramic
Read noise	Sub-electron
QE	90% peak
Read-rate	>4 frames/sec

Figure 10. Picture of CCD282

3. Custom Sensor Systems

Teledyne-e2v develops sub-systems to complement its supply of sensors. Such systems are optimised for each application and use common modules where appropriate. An advantage for the astronomical end-use is that performance of sensors combined with the system can be guaranteed; this compares with the common practice of procuring sensors from one source and then building systems with electronics from another source.

3.1 WUVS CCD272

The World Space Observatory UV Spectrograph (WUVS) uses a set of three UV-optimised CCDs that are embedded in custom sealed vacuum cryostat enclosures. They operate at -100ºC, cover the 115-310 nm wavelength range, and operate with flight electronics developed in association with RAL-Space. The figures below illustrate the sensor together with its custom enclosure. This is an example of a custom sensor, coupled with dedicated flight electronics, designed for space use[11].

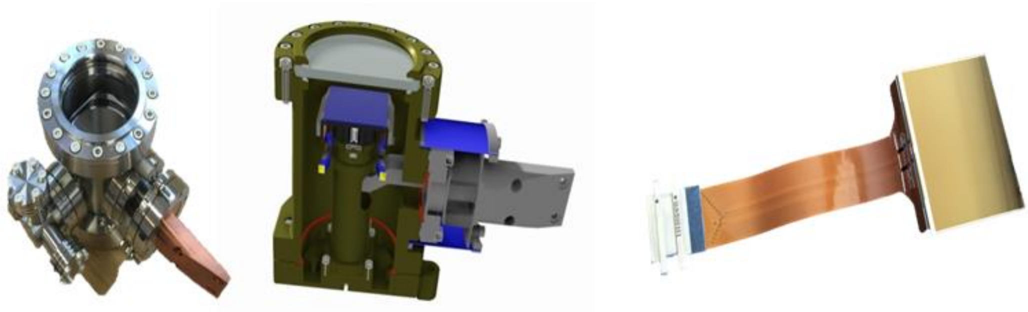


Figure 11. Illustrations of WUVS custom sensor and sealed cryostat

3.2 KMTNet focal planes

The Korea Micro-lensing Telescope Network has three telescopes each with its own camera- custom designed to conduct microlensing surveys with high efficiency. The figures below illustrate the 350 mm diameter cryogenic focal plane with 4 large-area science detectors and 4 guide sensors. The science detectors each have 9K X 9K pixels with high sensitivity. A key feature is the precision silicon carbide plate which ensures better than 30 µm flatness across the whole focal plane at cryogenic vacuum operating conditions. Three focal planes of this design have been manufactured and delivered; the camera has been described elsewhere[12].

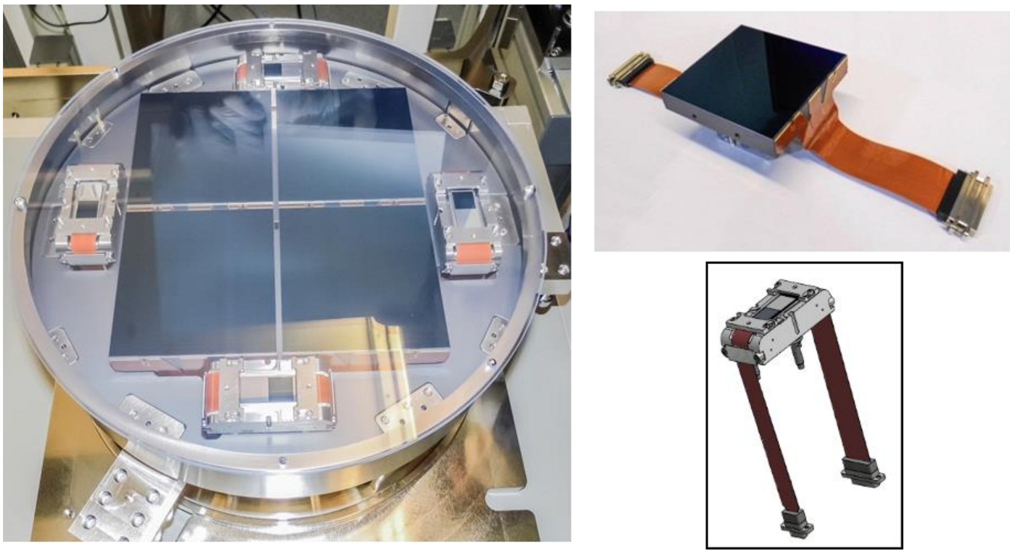


Figure 12. KMTNet focal plane and sensors [CCD290-99 and CCD47-20]

3.3 J-PAS Cryocam

In 2016 Teledyne-e2v completed and delivered the complete cryogenic camera system for use on the OAJ 2.5m telescope[13]. This is to be used for the JPAS five-year survey project. It is one of the first commercially-supplied cameras of its kind- offering a 1.2 Gigapixel focal plane, with multi-channel readout from the 500 mm focal plane array of sensors; see table and figures below.

Table 7. Key features of JPCAM

450 mm focal plane diameter	-100ºC operating temperature	Stable to +/- 0.5ºC
27 µm peak-valley flatness	Measured/confirmed at -100C	Stable against flexure
14 science sensors:	1.2 Gig pixels	CCD290-99 9K X 9K
8 wavefront sensors:	CCD44-82 FT	Custom packages
4 guide sensors:	CCD47-20 FT	Custom packages
Integrated electronics	224 science channels	<5 e- read-noise at 400 kHz
Modular CCD drive units	Synchronized readout	Local frame stores
Integral LN2 cooling system	Integrated vacuum system	Post-delivery support
Cold light baffle	High Quantum Efficiency	Min. reflectivity AR coat

Figure 13. JPCAM 1.2 Gigapixel cryocam (a) exploded view (b) assembled instrument

Acknowledgments

Many colleagues have contributed to the developments presented here. Thanks to all.

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