e2v new CCD and CMOS technology developments for astronomical sensors

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ABSTRACT

We present recent development in the technology of silicon sensors for astronomical applications. Novel CCD and CMOS sensors have been designed for low noise and high sensitivity astronomical use. High resistivity sensors allow thicker silicon for higher red sensitivity in several types of new CCD. The capability to manufacture large sets of CCDs to form large focal planes has allowed several very large mosaics to be built for astronomy with increasing formats on the ground and in space. In addition to supplying sensors we discuss increasing capacity and interest in the commercial supply of integrated "camera" systems.

Keywords: CCD, CMOS, sensor, EMCCD, backthinned, quantum efficiency, FPA, high-rho, DCDS, camera system

1. INTRODUCTION

In this paper we present an overview of recent e2v activities in the development of high performance image sensors for astronomical applications. Many previously developed sensors can be seen on the web site[1].

A key part of e2v technology is the ability to manufacture back-thinned sensors with high quantum efficiency; such CCD sensors have been available for several decades but more recently CMOS (or APS) back-thinned sensors have been developed specifically for astronomical use and are described below.

Another important device type is the EMCCD (also known as L3Vision by e2v) in which internal electron gain allows sub-electron readout noise and single photon detection. Several devices (including the 1024 X 1024 pixel format CCD201) are standard products; here we describe the largest EMCCD ever made- the CCD282 sensor with a 4k X 4K pixel image area.

Astronomers have always sought greater red sensitivity and this has been a theme of e2v developments. We discuss below three detector types with increased silicon thickness to enhance near-IR sensitivity.

In addition to supplying sensors for ground-based astronomy a major part of e2v sensor business is directed at supplying the custom sensors for space use. Several examples of recent successful designs and some new ones are illustrated.

Finally, we have been designing and supplying an increasing degree of "valued added" systems to the astronomy market. These include- assembled focal planes, integrated electronics, and complete cryogenic cameras as shown below.

2. BACK-THINNED CMOS SENSORS FOR ASTRONOMY

2.1. TAOS-II CIS113 sensor

The TAOS-II project requires a large area mosaic sensor capable of 20 fps readout with multiple regions-of-interest in order to detect Trans-Neptunian-Objects by occultation[2, 3]. The CIS113 device is a 3-side buttable CMOS (APS) sensor to allow a large focal plane capable of the required readout rate. The figures below illustrate the sensor and the mosaic FPA layout. Ten sensors will form the complete focal plane assembly (FPA) and three telescopes each with their own FPA will be built.

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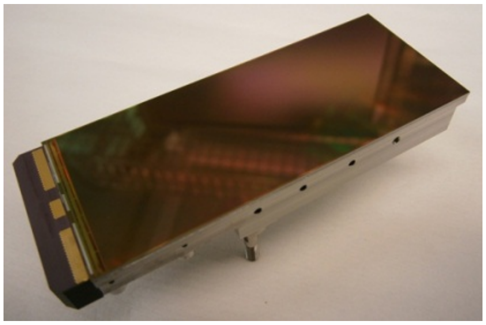


Figure 1. Image of CIS113

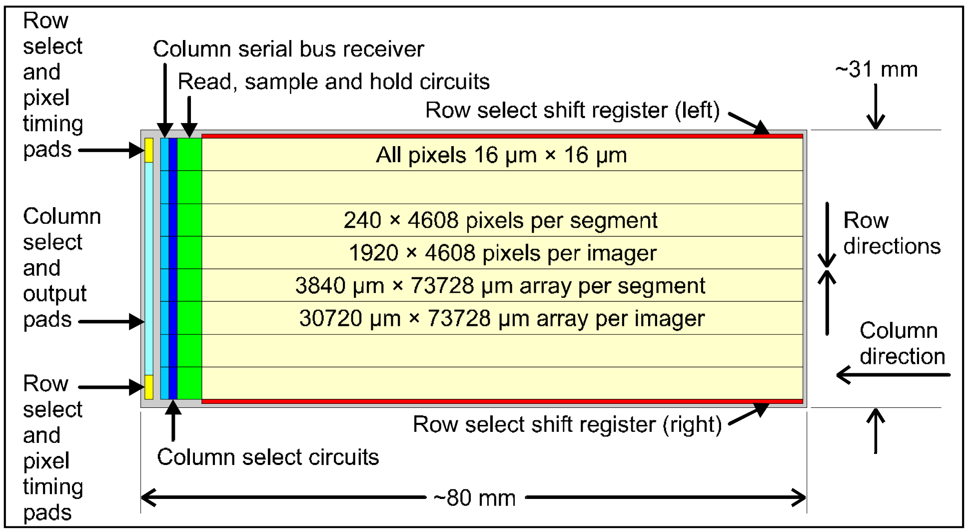


Figure 2. Architecture of CIS113

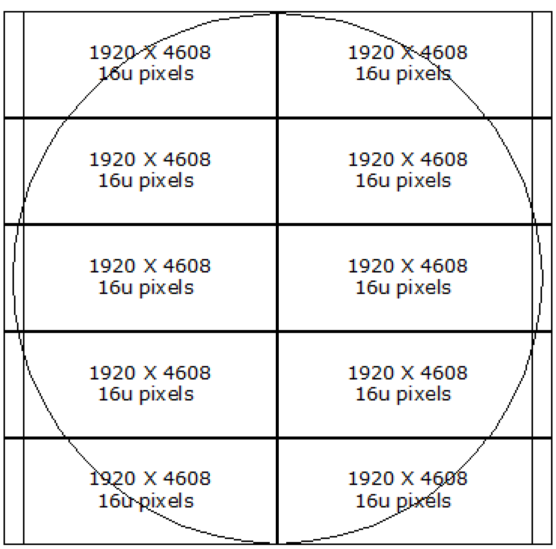


Figure 3. Focal plane layout

Key elements of the sensor are tabulated below:

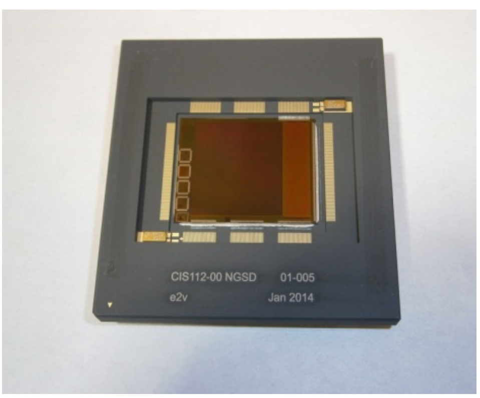
Table 1. Key features of CIS113

- Sensor: 1920 x 4608 16 µm square pixels.
- 8 segments for parallel read-out from 8 outputs
- Independent access of left and right sides
- Multiple ROI mode for 20 fps sampling rate
- Noise floor < $5e^{-}_{RMS}$ and low dark current.
- Backthinned for 90% peak QE
- Saturation at signal (node) ~ 18 ke-

Frontside samples are under test at present (June 2014), backthinned prototypes are being manufactured and expected to be tested by the end of this year. The project will be concluded with the manufacture of 40 backthinned sensors for use on the three telescopes.

2.2. NGSD/LGSD CIS112 sensor

The planned European Extremely Large Telescope requires a large-area high-frame rate sensor for wavefront correction. e2v has developed a “stitchable” large area active pixel sensor (APS) designed for backthinned operation with extremely low read-noise for this adaptive optics application. The first prototypes have been tested and have 880 X 840 pixel format; designed for Natural Guide Star Detection (NGSD). A planned following phase of work will involve the manufacture of a Laser Guide Star Detector (LGSD) of four times the size [1760 X 1680 pixels]. Pixel size is 24 µm, peak quantum efficiency 90%, and the read-noise target is less than 3 e- rms. Both device formats have significant parallelism of architecture (including many ADCs) to achieve close to 1000 fps frame rate. The figures below illustrate this sensor. Full details are presented in an associated paper[4].



NGSD 880 X 840

Figure 4. Image of CIS112; NGSD size

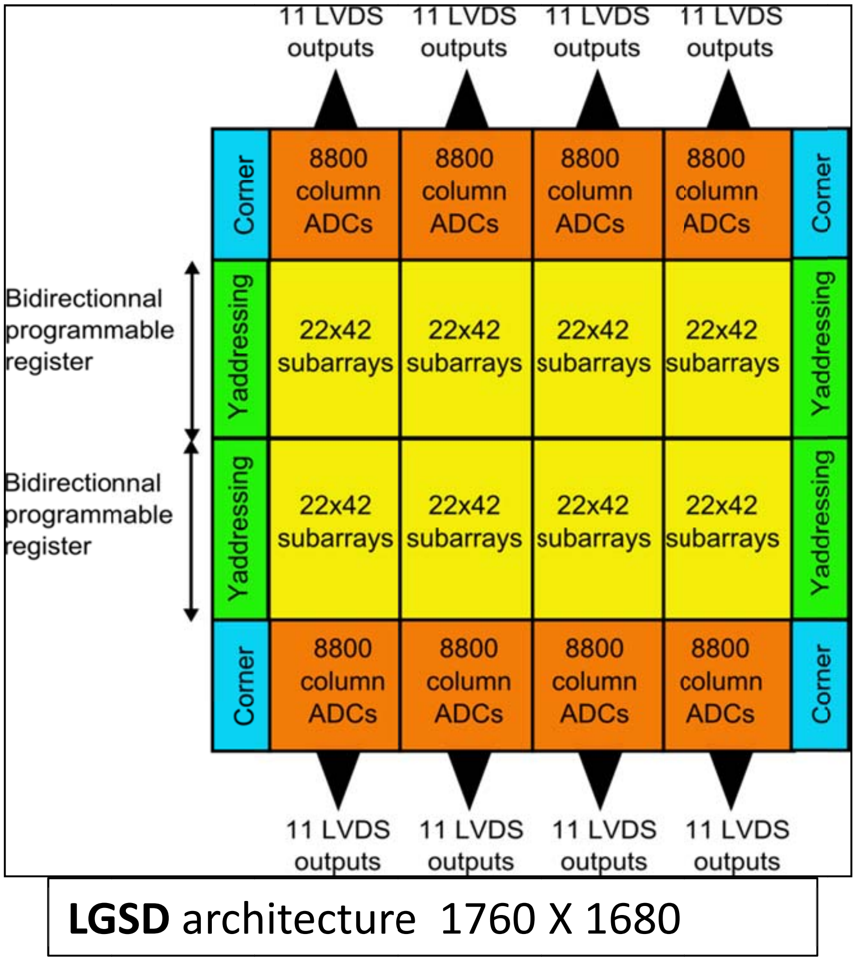


Figure 5. Architecture of CIS112; LGSD size

2.3. CIS115 sensor

The CIS115 is derivative from a previous CIS107 active pixel sensor primarily as a demonstrator for prospective space missions. The CIS107 device had multiple pixel variants for evaluation of optimal designs. The CIS115 has the same format but only incorporates the selected “optimal” pixel variant. It is intended for the ESA JUICE mission. The device is designed as one quadrant of size 1504 X 2000 pixels of 7 µm size. The figures below illustrate this format. However, it is also designed to allow manufacture of a full-sized 3008 X 4000 pixel sensor.

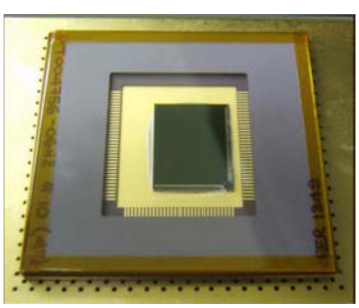
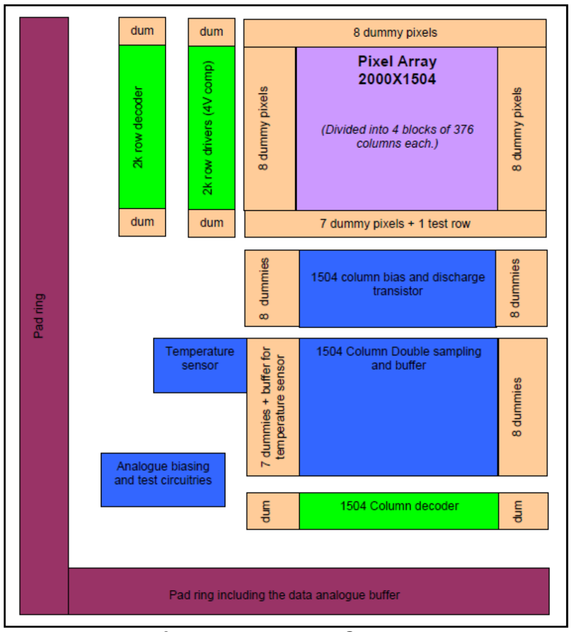


Figure 6. Image of CIS115



CIS115 architecture; four outputs

Figure 7. Architecture of CIS115

The device is designed for space use, with preliminary radiation tests performed, has low read-noise and high back-thinned quantum efficiency (90%). See also the associated paper in which the CIS107 device has been tested for ground-based astronomical use[5]. The first samples of the CIS115 are under evaluation, with key characteristics tabulated below.

Table 2. Key features of CIS115

Performance overview	**CIS115**	**CIS107**		
	Pixel 4	**Pixel 1**	**Pixel 6**	**Pixel 10**
Dark Current at 21 °C				
Mean (µV/ms)	0.24	0.32	1.46	0.32
DSNU rms (µV/ms)	0.69	0.67	1.94	0.35
Mean dark current (e-/pix/sec)	4			
Readout Noise in Darkness				
Readout Noise (µV)	257	264	280	213
Readout noise (e-)	4.5			
Signal Characteristics				
Peak output voltage	~1800 mV	~1300 mV	~1100 mV	~800 mV
Peak signal (e-)	36,000			
CVF (µV/e-)	50	57	62	13

3. EMCCD DEVELOPMENTS

e2v has developed a series of EMCCDs (L3Vision) and the largest commercially available size is the CCD201 with 1024 X 1024 pixels. As a custom development for the University of Montreal we have designed the CCD282-00 device which has a 4096 X 4096 pixel image area[6, 7]. The figures below illustrate the device.

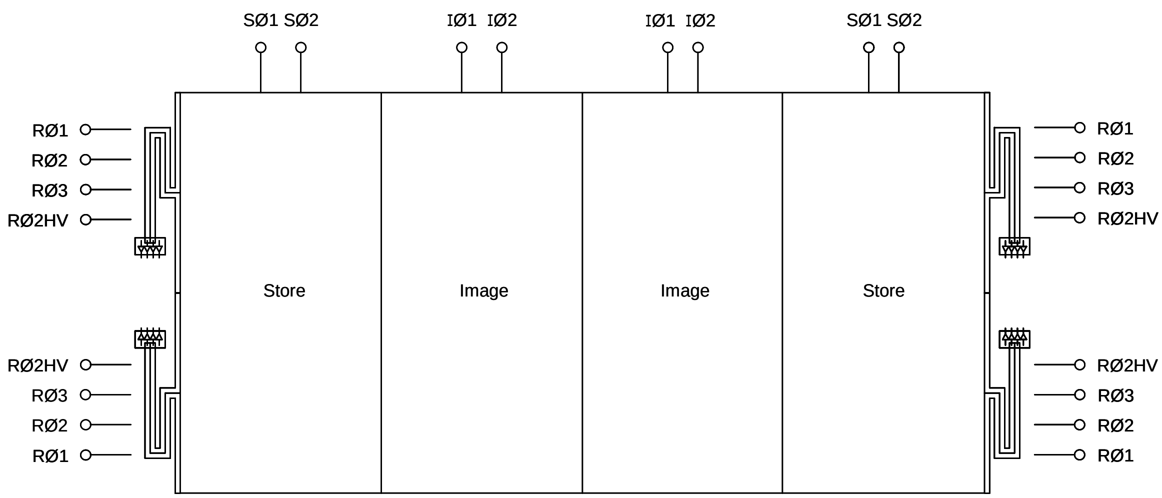


Figure 8. Architecture of CCD282

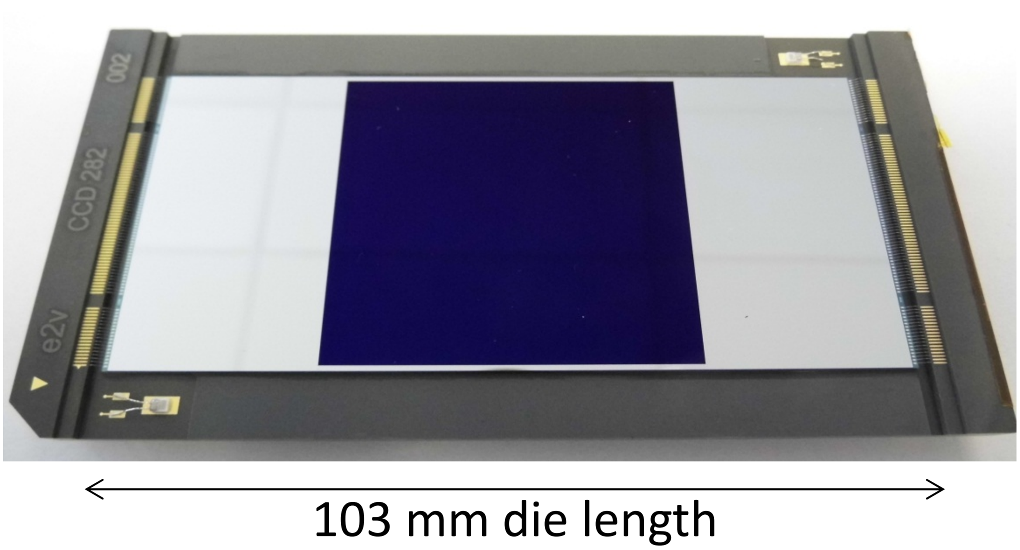


Figure 9. Image of CCD282

The device was designed for the primary purpose of very low noise readout in photon counting mode. It operates in non-inverted mode for optimal performance (low clock-induced charge) and is intended for cryogenic operation with low dark current. It has a split-frame-transfer architecture and eight outputs for high frame rate. The device is backthinned for high quantum efficiency and fitted in a large Aluminium Nitride ceramic package with on-board temperature sensors. The table below present key features of this device, which is anticipated to be available early in 2015 to custom order.

Table 3. Key features of CCD282

- 4k X 4k image area
- 12 µm pixels
- Split frame transfer sections
- 8 EMCCD outputs
- Sub-electron readout noise
- Min. 4 fps at 10 MHz pixel rates
- Designed for photon counting
- Non-inverted (non-MPP) operation at cryo temperatures
- Backthinned for high spectral response; 90% peak
- Alternate formats possible; TBC

4. RED-SENSITIVE CCDS

4.1. LSST CCD250

The CCD250 is designed for the LSST survey telescope. The figure below illustrates the sensor (fitted within its handling jig).

Figure 10. Image of CCD250

The sensor is specifically designed for high red sensitivity combined with excellent PSF; this requires a 5 µm surface flatness and a "high-rho" fully depleted sensor design. The device is built with 100 µm thickness which is a trade-off between enhanced red sensitivity and minimal charge spreading (best PSF) for this challenging focus requirement. The sensor is designed for close 4-side butting for maximum fill factor in the full 189-sensor focal plane of the telescope. It has 30% QE at 1 µm wavelength together with low read noise and 2 second read-time. The table below presents key features; see also a paper describing tests of such CCDs[8].

Table 4. Key features of CCD250 and LSST focal plane

- 4k X 4k 10 µm format
- 189 science sensors
- 100 µm thick; 5 µm flat
- High precision SiC buttable package
- 16 outputs; 2 s readout
- 5 e- read-noise

4.2. CCD261-84

The CCD261 family has been designed to provide "high-rho" fully depleted operation with thick silicon for high red response[9]. The figure below illustrates the primary 2k4k image sensor.

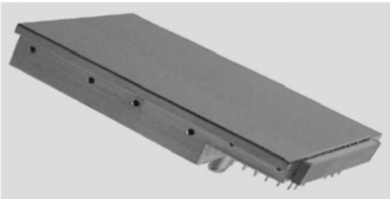


Figure 11. Image of CCD261-84

The device is designed for cryogenic operation, in a precision buttable package with high QE and low noise. A high-voltage back-bias ensures full depletion and maintains good PSF despite the thick silicon. Unlike the CCD250 (above) this device has 15 µm pixels and delivers good PSF with a 200 µm thickness. Key performance features are tabulated below.

Table 5. Key features of CCD250

- 2k X 4k, 15 µm pixels
- 200 µm thick
- 2.5 e- noise floor
- Precision Buttable package

Two examples of spectral response are shown in the figure below. The device can be fabricated in various thicknesses from 100 to 300 µm, giving increasing red sensitivity- but at the expense of increasing cosmic ray detection. Several AR coatings can be supplied with differing wavelength optimisations.

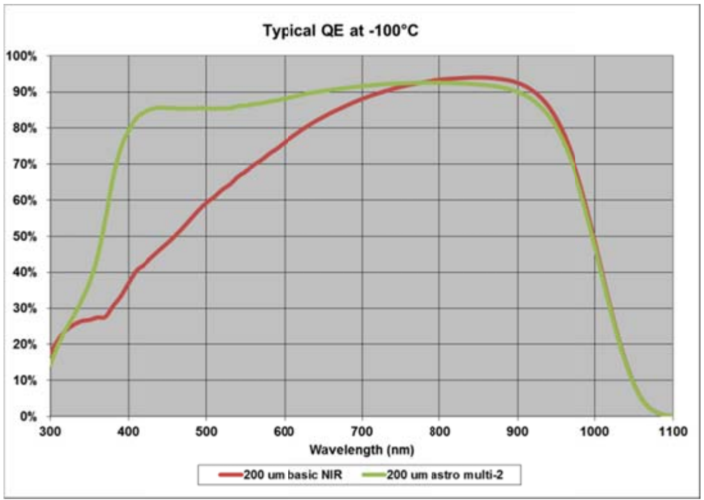


Figure 12. Spectral response of two variants of CCD261-84

Another application of this device design is illustrated in a camera (made by Andor). The CCD261 (2000 X 256 pixels) is used in a spectroscopy camera which offers deep depletion (high red sensitivity) together with inverted mode operation (patented). The novelty of this application is that the design allows full depletion (i.e. good MTF/PSF) from the thick silicon inverted mode device by utilising the back bias voltage. See illustration below.

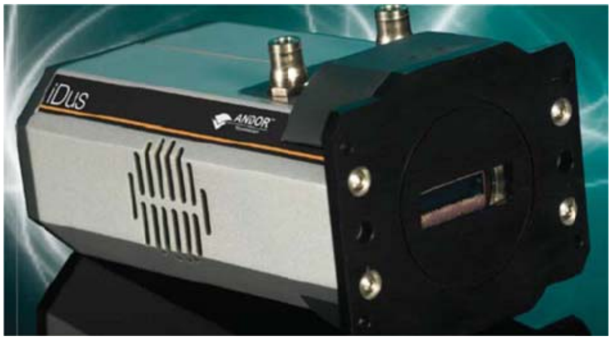


Figure 13. Picture courtesy: Andor iDus 416 spectroscopy camera

4.3. X-ray sensors

The CCD262-50 sensor was designed as a first generation sensor for use at x-ray wavelengths using a traditional deep depletion device[10]. A second generation CCD292-50 sensor of the same size using a “high-rho” design allows use of thicker silicon for increased 12 KeV sensitivity.

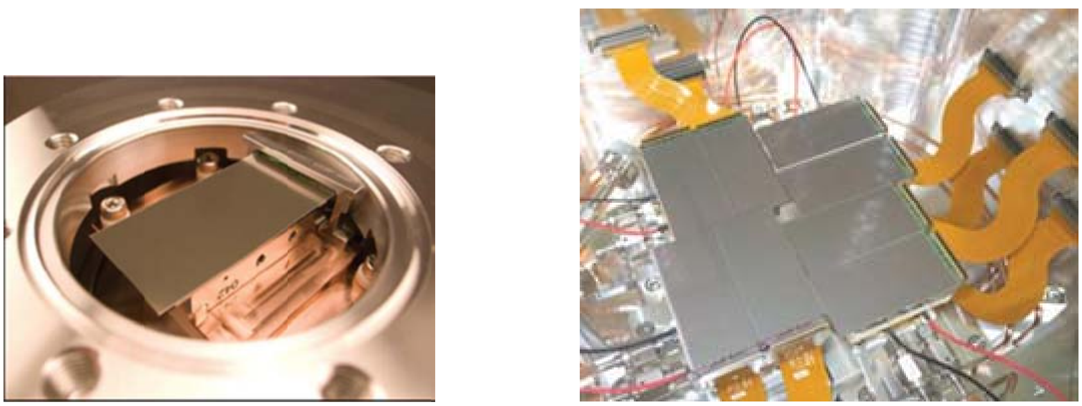


Figure 14. (a) Single sensor in test camera and (b) eight sensors in x-ray free-electron-laser camera

Key features of these two devices are tabulated below.

Table 6. Key features of x-ray sensors

CCD262-50	**CCD292-50**
1024 X 512 50 μm pixels	1024 X 512 50 μm pixels
Deep depletion (40 μm) for 80% QE at 6 KeV	High-rho (200 μm) for higher QE at 12 KeV
Fully depleted for good MTF (front illuminated)	Back illuminated

5. MAJOR SPACE PROGRAMMES

Here we present overview details of three devices designed for major European Space Agency missions. All utilise large-area back-thinned CCDs to form large focal plane areas with high performance scientific imaging capability.

5.1. GAIA CCD91

The ESA GAIA mission was launched successfully in December 2013 and incorporates the largest focal plane yet launched in space. The satellite is designed for precision astrometry and uses a set of 106 CCD91-72 sensors. These CCDs have 4500 X 1966 pixels of 10 X 30 µm size in devices designed for TDI mode operation. The sensor has a precision buttable package with several variants to form the focal plane as shown below.

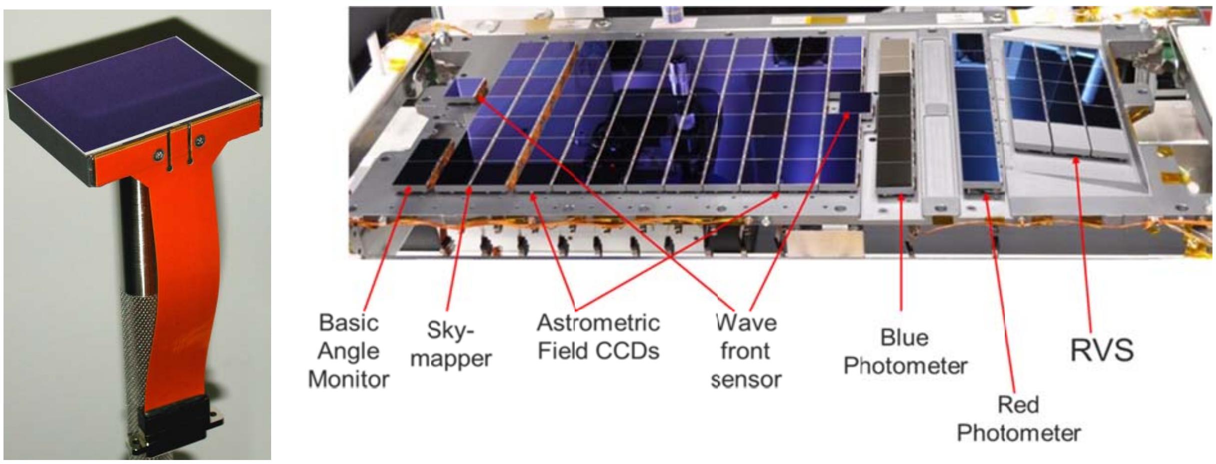


Figure 15. (a) Single sensor and (b) completed focal plane assembly (Courtesy: Astrium, Toulouse).

5.2. Euclid CCD273

The ESA dark energy Euclid mission is currently in development. The CCD273-84 sensor offers a 4096 X 4096 12 µm pixel format in a precision buttable package with low noise and high back-thinned quantum efficiency. The sensor has completed its development phase, with a qualification phase in progress, and flight manufacture phase planned to follow in 2015. The flight focal plane will utilise a set of 36 such devices and is due for launch in 2020. The figure below illustrates the device.

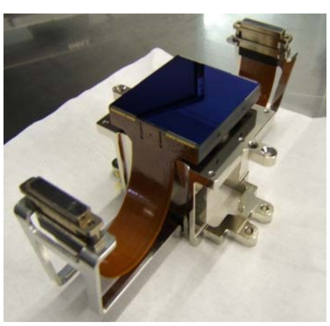


Figure 16. CCD273 in support jig.

5.3. Plato CCD270

The ESA PLATO mission is designed to find a study terrestrial exoplanets and associated studies, with a prospective 2024 launch date. The sensor with 4510 X 4510 18 µm pixel format will be built into FPAs with four CCDs each. The whole mission incorporates a set of 34 telescopes, each with one FPA, which will make it the largest visible wavelength focal plane area when launched in space. The development phase is complete and a sensor validation phase is planned to start soon. The picture below illustrates the sensor.

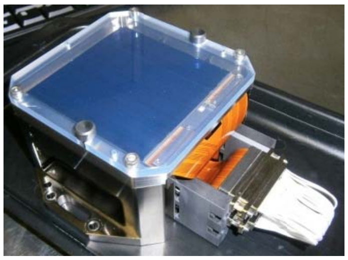


Figure 17. CCD270 in protective jig.

5.4. Rosetta

The Rosetta mission can hardly count as new since it was launched a decade ago; however it is timely since the satellite is due to reach comet 67P/Churyumov–Gerasimenko in August 2014 after covering 6.3 billion km. There are six e2v instruments on the craft including- Orbiter and Lander cameras; see figures below. The largest sensor used is the CCD42-40 (2048 X 2048 pixels) used on the orbiter and has been returning images whilst en route.

Figure 18. Three e3v Rosetta sensors

6. SYSTEMS AND LARGE MOSAICS

In this section we present three examples of sub-system assemblies/ cameras that have been designed and supplied (or under development) at e2v.

6.1. OSU-KMTN

The Korea micro-lensing telescope network consists of three telescopes each with its own camera for monitoring of micro-lensing events in the galactic bulge. Each camera has four CCD290 sensors (see section 6.2) to form a 340 megapixel mosaic. e2v has designed, constructed and delivered the three assembled FPAs as illustrated below. The FPAs are integrated into cryogenic cameras being built by Ohio State University[11].

The figures illustrate the precision silicon carbide plate, together with science sensors and guide sensors in the process of insertion. Finite Element Analysis was performed to validate the temperature distribution and deformation to ensure a 40 µm peak-valley cryogenic flatness specification for all focal plane surfaces. The guide sensors (CCD47-20) are fitted in a custom package to match the height of the science sensors. Multiple components were designed in order to facilitate precision assembly of the sensors which have flex-cable connectors for use in a compact buttable mosaic.

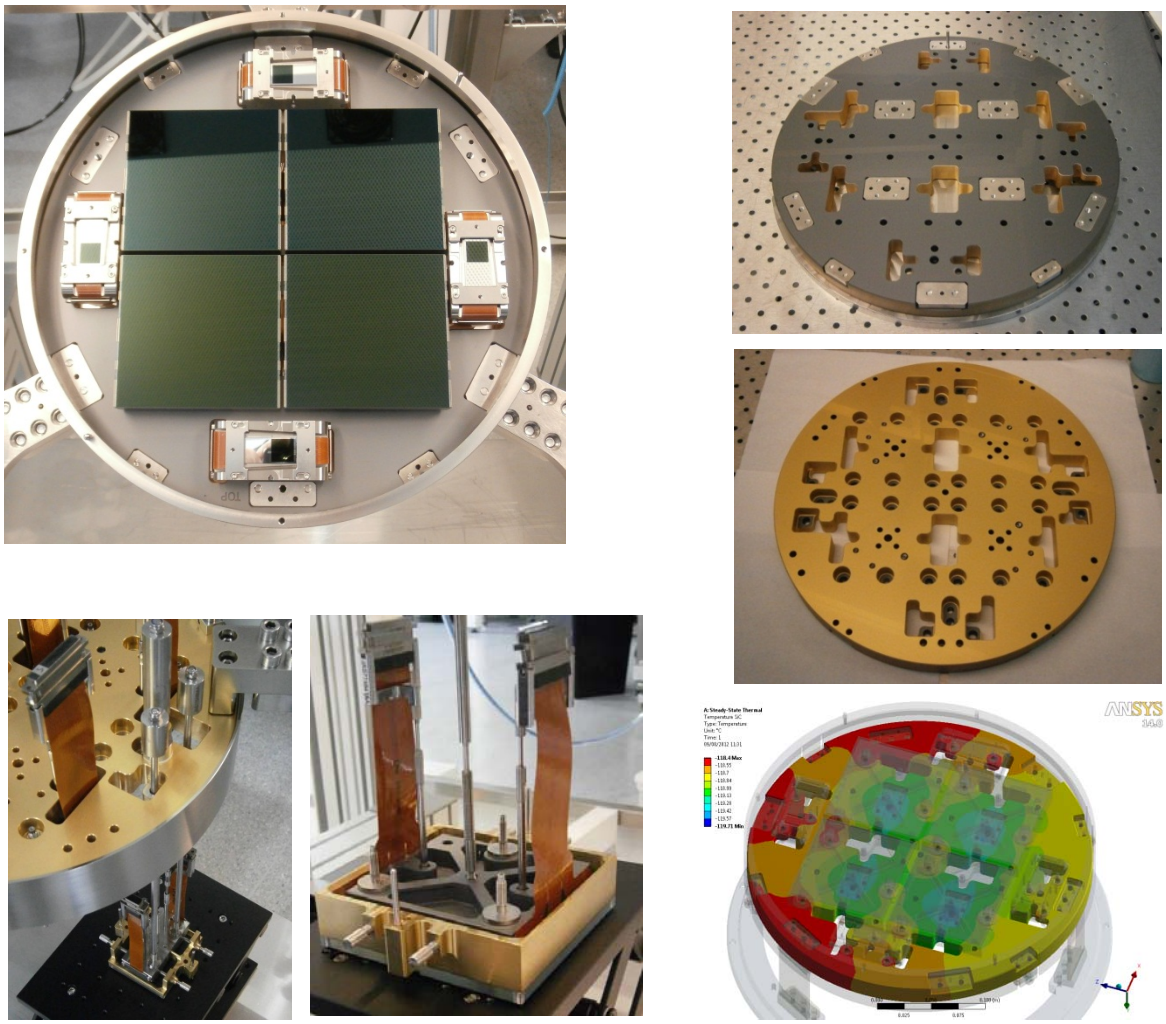


Figure 19. The assembled FPA together with component illustrations and FEA model.

6.2. J-PAS

JPAS is a five-year planned dark-energy survey to be performed at the Javalambre site in Spain. e2v has designed and is currently assembling a 1.2 gigapixel cryogenic camera for the 2.5m telescope[12]. The telescope will use four banks of fourteen narrow-band filters which project onto each of the fourteen CCD290 science sensors. The focal plane also includes eight wavefront sensors and four guide sensors. The JPCAM includes a precision cryogenic focal plane within a custom cryogenic vessel, liquid nitrogen cooling, vacuum pumping, PLC systems/thermal control and sets of custom electronics modules to operate all 26 sensors in the focal plane. Figure 20 below illustrates the telescope and the cryogenic camera.

6.3. The electronics CCD modules perform digital correlated double sampling (for optimum read-noise performance) and differential signal outputs (for common mode noise rejection). The system is designed for < 5 e- read-noise using 224 channels to achieve a 10 second readout time to **a** local frame store buffer. The following pictures (

Figure **21**) illustrate the three sensor type used- all mounted to achieve a matched focal plane height and with flex-cables for ease of mosaic integration.

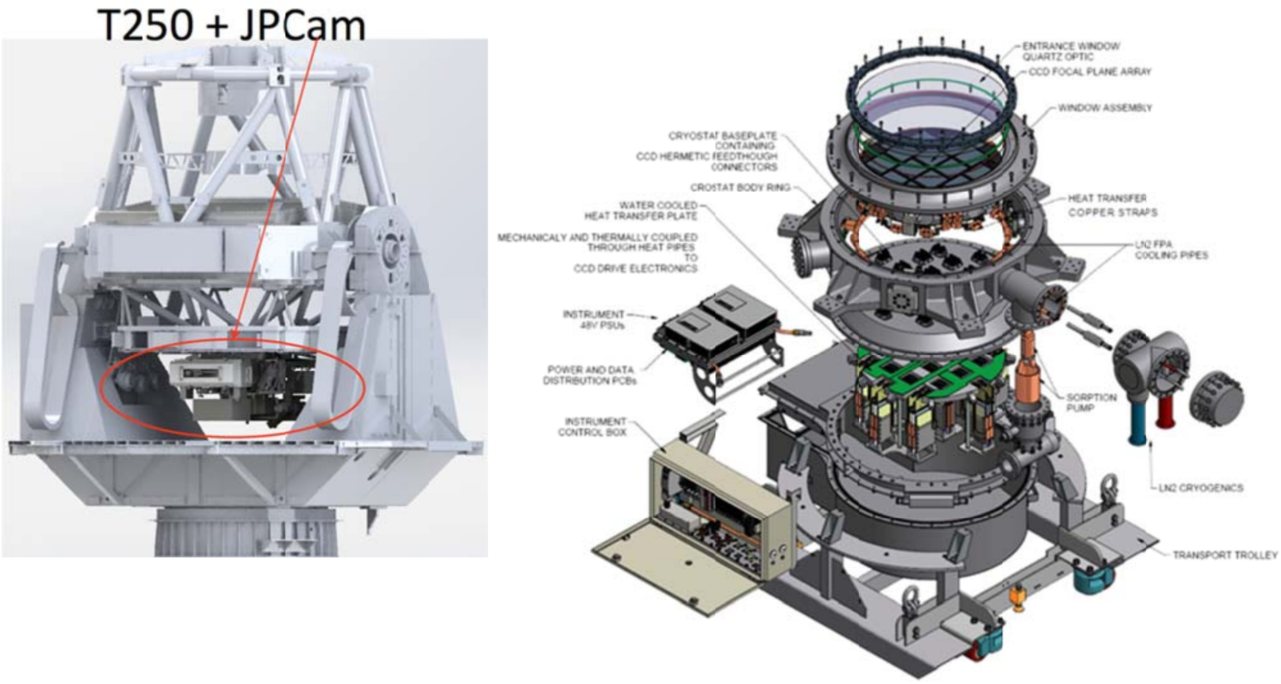


Figure 20. The T250 telescope (courtesy AMOS) and exploded view of JPCAM.

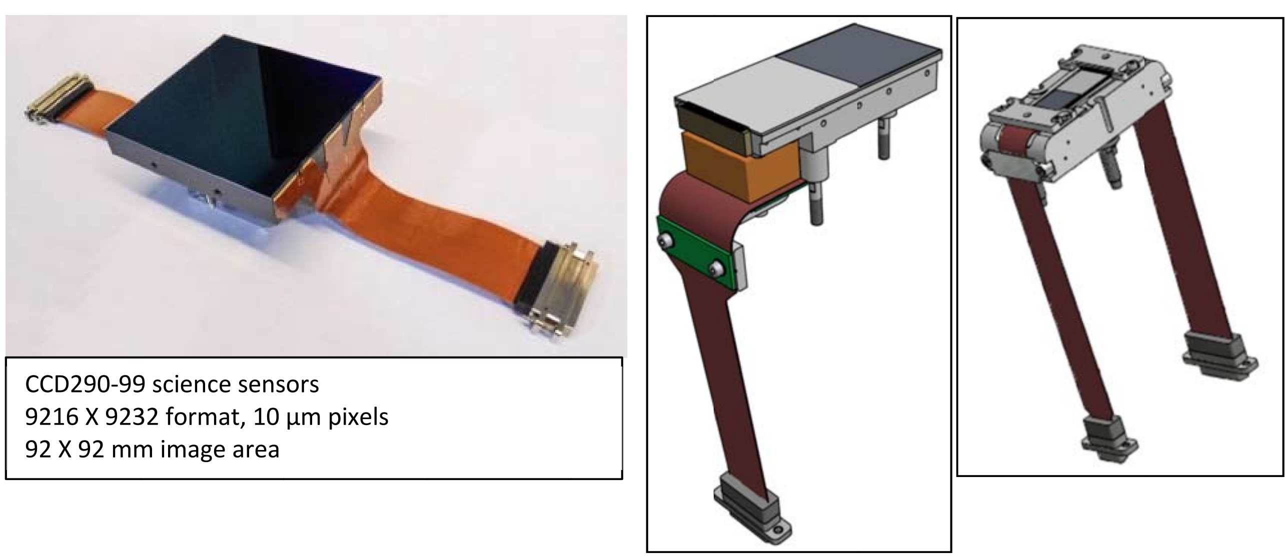


Figure 21. (a) CCD290-99 science chip, (b) CCD44-82 wavefront sensors, and (c) CCD47-20 guide sensors.

6.4. WSO-UV

The WUVS (**W**orld Space Observatory **U**ltra-**V**iolet **S**pectrograph) consists of high-resolution spectrographs to be used on a 2m space telescope. e2v is supplying sensors covering the UV (115-310 nm) range with three channels integrated into custom sealed enclosures together with flight electronics (associated with RAL Space) [13] in a three year programme. Key detector characteristics are shown in the table below together with figures illustrating customised AR coatings, the custom enclosure concept, and the triple detector system concept.

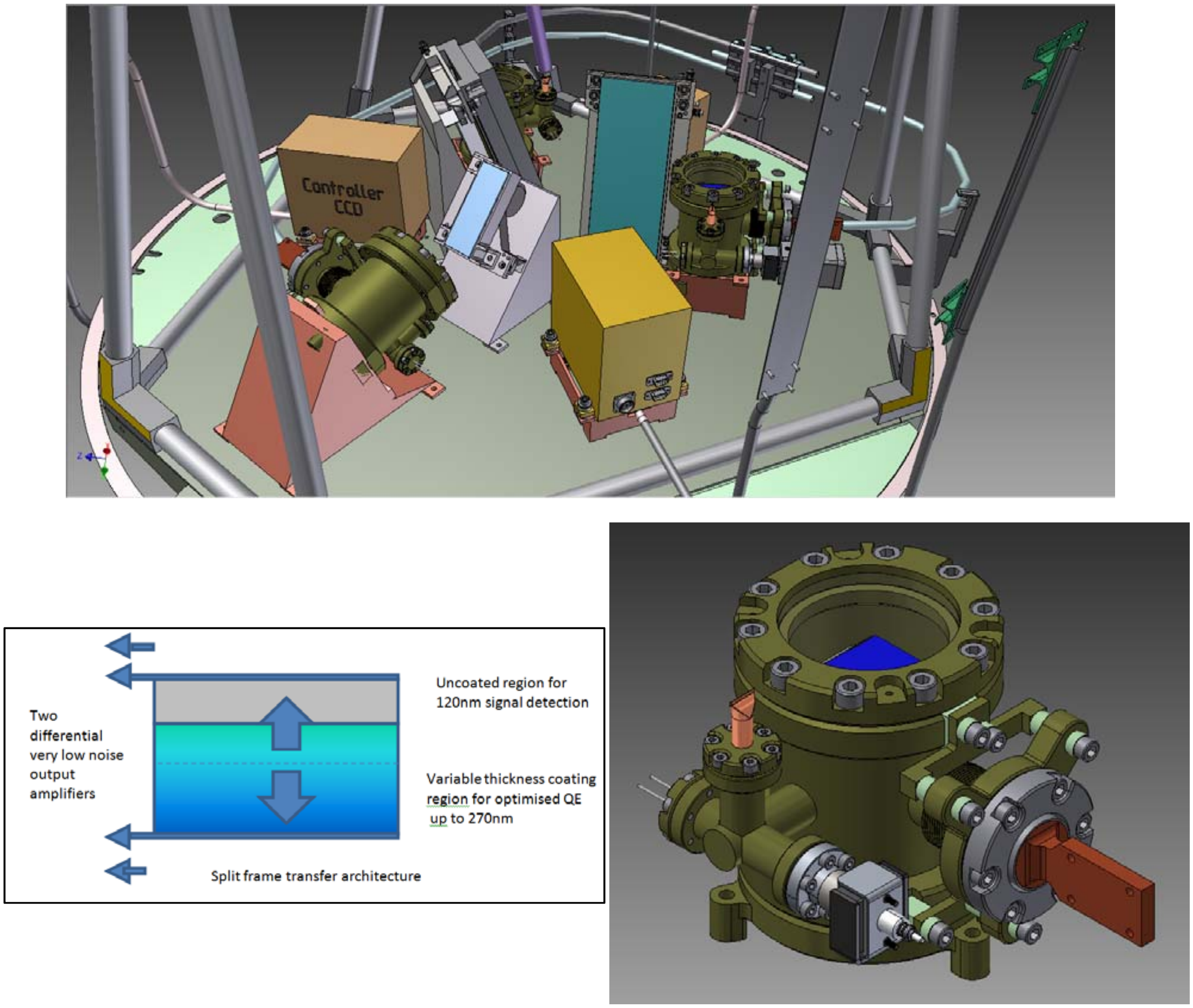


Figure 22. (a) Triple detector instrument concept, (b) Custom AR coating, and (c) Enclosure concept for CCD272

Table 7. Key features WUVS sensors

Detector characteristics- CCD272

Characteristics	VUVES	UVES	LSS
Spectral range, nm	115-176	174-310	115-310
Size of photosensitive , mm	37.3 x 49.1	37.3 x 49.1	37.3 x 49.1
Pixel size, µm	24	24	24
Quantum efficiency, not less than, %			
at wavelength 120 nm	20	-	20
at wavelength 150 nm	30	-	30
at wavelength 175 nm	25	25	25
at wavelength 250 nm	-	50	50
at wavelength 300 nm	-	50	50
Readout noise, not more than, e^-, sd	3	3	3
Digitalization, bits	14	14	14
Dark current, not more than, e^-/pixel/hour			
At beginning of life	12	12	12
At end of life	36	36	36
Exposure time, sec	1-3600	1-3600	1-3600
Dynamic range in one frame, not less than	10000:1	10000:1	10000:1

7. SUMMARY

We have presented multiple themes of ongoing technical development with examples of specific devices and projects. e2v continues to be active in designing and manufacturing the highest performance sensors for astronomical and scientific use. These include CCDS and CMOS devices with back-thinned technology for high quantum efficiency and advanced designs for lowest read-noise. Sensors are also integrated into focal plane assemblies or supplied in complete camera systems.

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