

Sensor developments at e2v

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Abstract

High performance sensors for astronomy and science applications are in continuous development at e2v. New devices and ongoing developments are described, including- EMCCD types, enhanced red sensitive CCD products, and APS (CMOS) back-illuminated sensor designs. Lower read noise, higher quantum efficiency, high frame rates, multiple formats and package types continue to be primary goals of our design teams. Operational features and performance parameters relevant to astronomy will be highlighted together with recent application examples.

1 Introduction

In this paper we present details of various development themes at e2v with examples of new devices: electron-multiplying sensors offer sub-electron readout noise in several formats, high-rho and similar devices offer enhanced red sensitivity, whilst active pixel sensors provide high-performance and high speed, and finally the e2v stitchable design philosophy allows families of devices with custom formats.

2 L3 (electron-multiplying) sensors

e2v manufactures a series of devices in the L3Vision family. Here we illustrate some of these electron-multiplying CCDs that are likely to be of interest for astronomy. Some are only available to special order.

2.1 Large format scientific sensor: CCD207-40

The largest currently-manufactured e2v EMCCD is shown in the figure below, with key features listed here.

Key features

Format: 1632 X 1608; Full Frame architecture
Image size: 26 X 26 mm
Pixels: 16 X 16 μm
Pixel rate; 3-20 MHz (depends on output, and required settling time)
Number of outputs: Two: one EM-type; one normal low noise
QE: Backthinned for high QE
Ceramic package
Designed for scientific use.

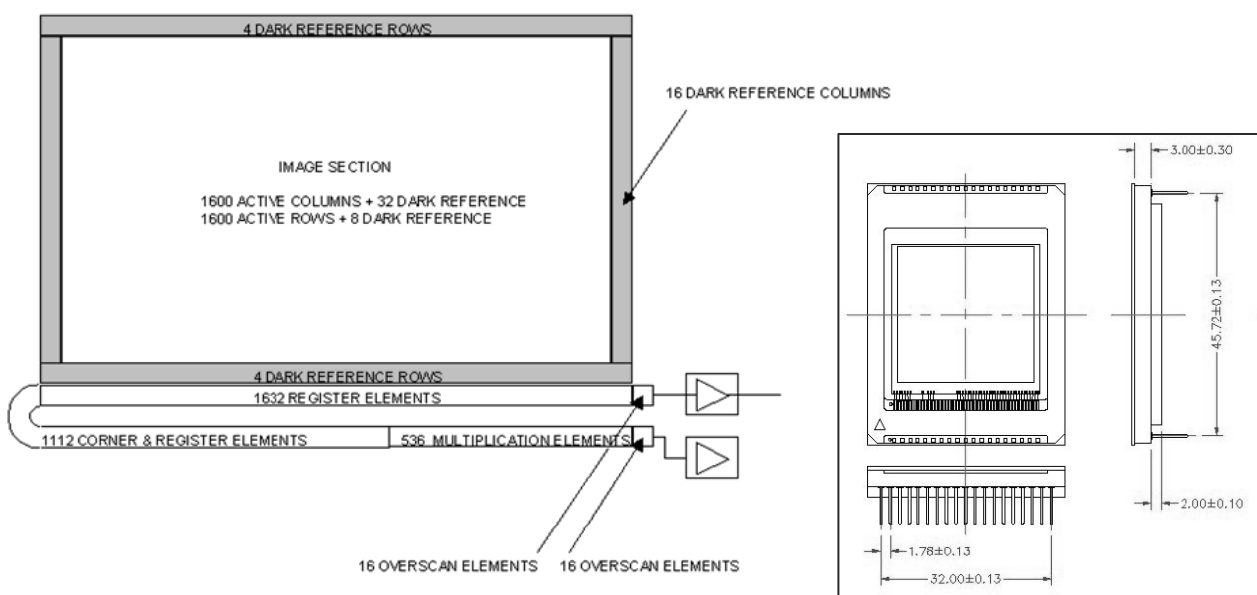


Figure 1. CCD207-40

2.2 A new sensor: CCD251

A new small-pixel EMCCD sensor is in the final stages of prototyping, with sample results anticipated in 2010.

Key features

Format: 1024 X 1024; FT architecture
 Image size: 8 X 8 mm
 Pixels: 8 X 8 μm
 Pixel rate; >30 MHz
 Number of outputs: One, EM-type; sub-electron noise
 QE: Backthinned for high QE
 Frame rate: 35 fps
 Ceramic package

Designed for scientific & camera use.
 Backthinned samples due mid-2010.

2.3 The CCD220 wavefront sensor

EMCCDs have particular advantages for adaptive optics applications because they allow operation at high frame rates and can simultaneously deliver very low noise. The figure below illustrates a new sensor that has been developed initially for ESO/Opticon. [ESO/ Opticon project: refs- 1, 2]

Key features

- 240 x 240 pixels; split FT format
- 24 X 24 μm pixels
- 5.8 X 5.8 mm image
- 100% fill factor
- Back-illuminated for high QE
- Deep depletion (red) variant
- High frame rates (1000 fps nominal)
- 8 L3Vision™ outputs
- Sub-electron noise
- Integral Compact Peltier package

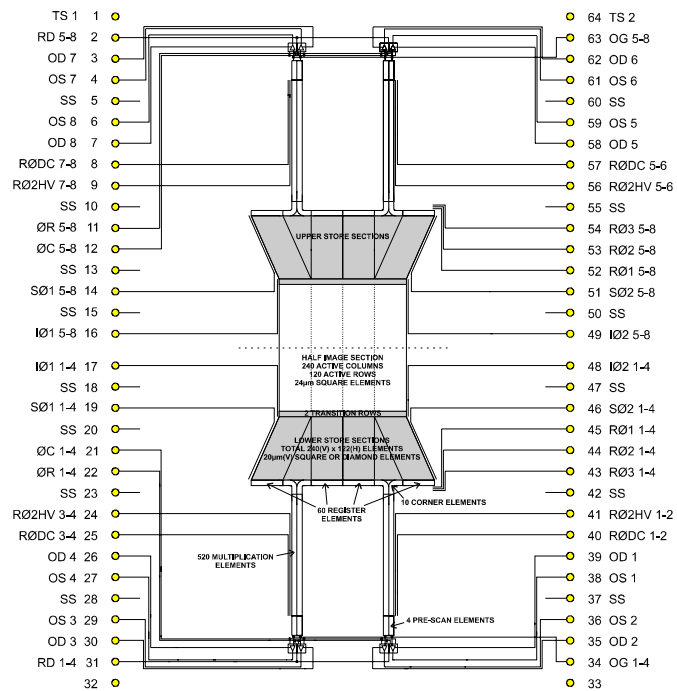


Figure 2 (a) and (b). CCD220 WFS device

2.4 A new EM camera: L3CCD216

Here we illustrate (Figure 3) a new EMCCD camera designed for industrial/commercial applications primarily. It has an integrated cameralink interface.



Key features

- New L3 camera with 768 pixels per line
- 2/3" format to allow use of smaller lenses.
- 9.0 X 6.6 mm image
- CameraLink interface
- Backthinned CCD
- Manual or automated gain control
- 525- line or 625- line formats
- Provides real time images down to overcast starlight; outperforms intensified camera

Figure 3. CCD216 camera

3 High-rho sensors

3.1 Introduction to high-rho

There is a growing demand for red-sensitive CCDs, for dark energy and many other astronomical programmes. The following Figure 4 illustrates how increasing red sensitivity can be obtained by using increased silicon thickness to give higher red wavelength absorption.

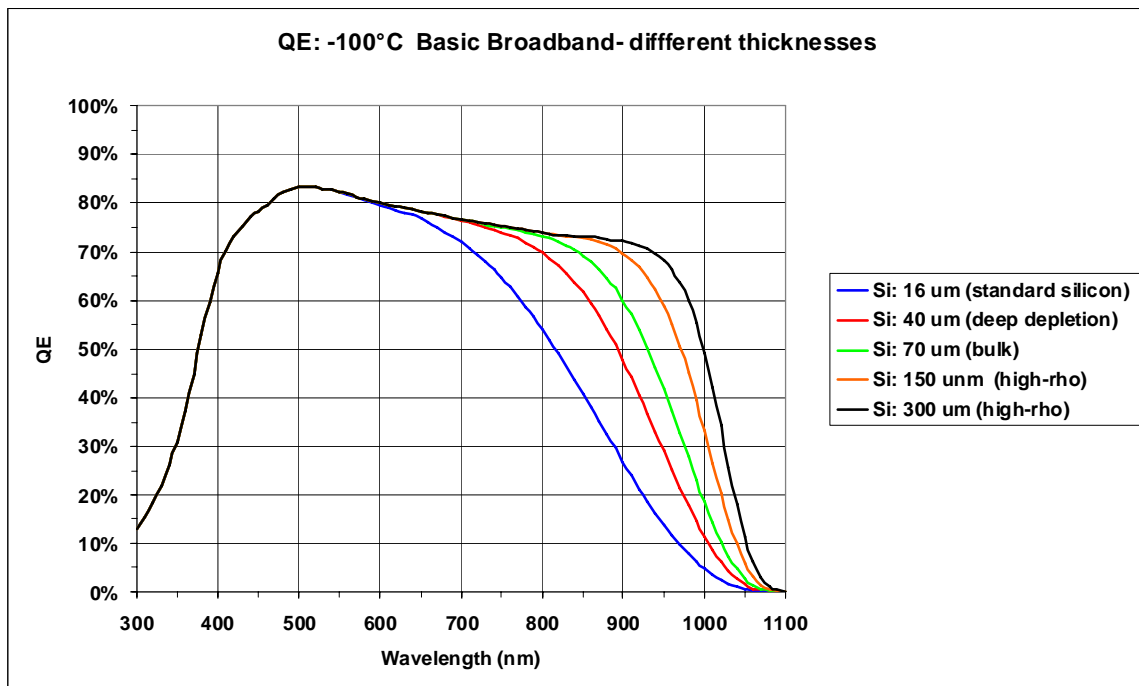


Figure 4. Red sensitivity for increasing silicon thickness

The lower two thicknesses are typically manufactured from epitaxial silicon of moderate resistivity and high quality. For greater resistivity it is necessary to use bulk silicon, which typically exhibits increased white defect levels. e2v uses the term “bulk” to refer to devices made of this silicon, but operated at normal voltage levels (eg 10V clocks relative to substrate). Such “bulk” devices can operate with a typical thickness of order 70 μm . We use the term “high-rho” to refer to higher resistivity silicon which is also used with a higher operating voltage. This allows greater depletion depth (active charge collection region) to ensure full depletion for typical device thickness that exceeds 100 μm .

3.2 Bulk CCDs

Use of bulk silicon, and normal device voltage levels, has allowed manufacture of existing device designs with increased thickness. The figure below illustrates examples of typical spectral response. See Downing et al [3] for results of characterisation tests of an e2v bulk CCD44-82 (2k X 4k) sensor.

Same design; same operation; more red QE.

(See also Downing et al; wed pm)

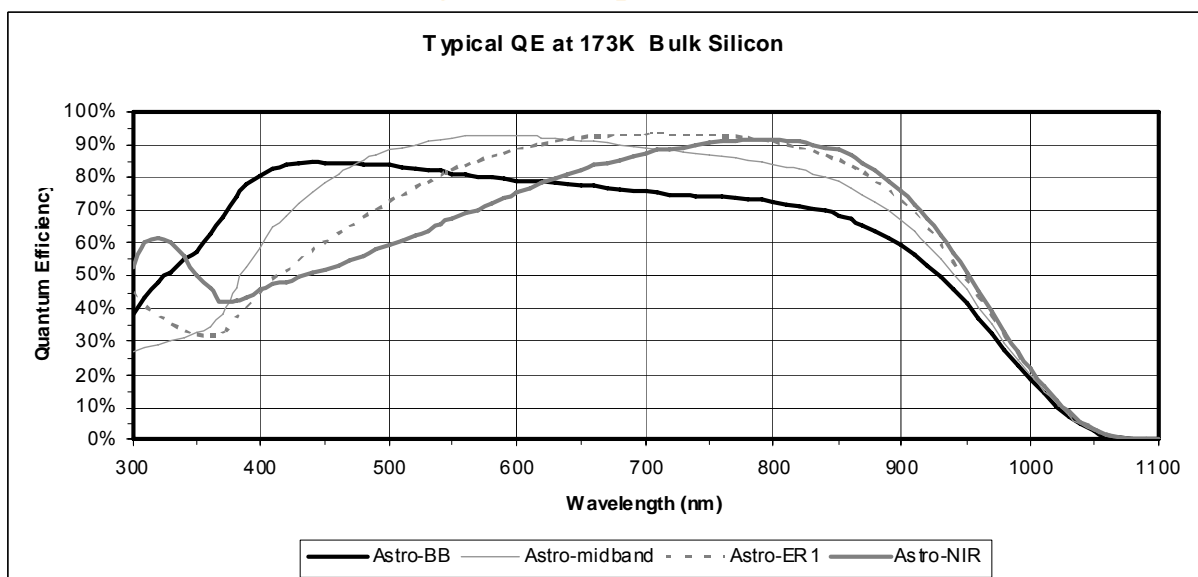
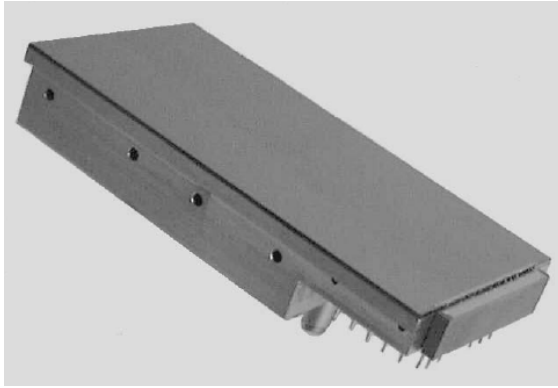


Figure 5. Bulk CCDs: examples of typical spectral response for different AR coatings

3.3 The CCD261 development

Previous generations of e2v high-rho devices demonstrated high red QE and low noise [ref 4]. This has led to the development of a new design of a true scientific sensor, with the same noise as other standard e2v CCDs: The CCD261 is a new family of devices; the first devices, which are currently in final stages of prototype manufacture, are the CCD261-84 (2k X4k; 15 μm pixels). These are designed to provide enhanced red sensitivity and require a substrate bias to the backside. The devices operate with normal polarity and voltage levels (as other e2v sensors) apart from the additional negative backside substrate bias.

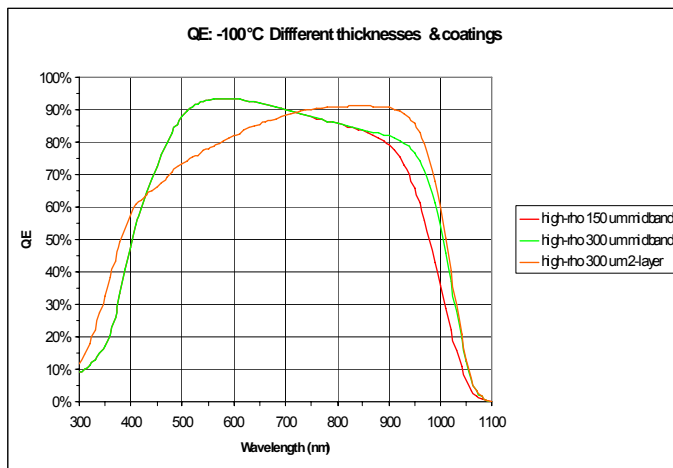
Figure 6 illustrates the CCD261-84 sensor, together with key features tabulated. Figure 7 shows typical QE for a few thickness and coating variants. Other coating developments (not discussed here) are anticipated to offer higher broadband response levels using multilayer coatings.



Key features

- Package design based on standard devices
- “stitchable” design
- Other formats planned-
- Four output versions
- 4k X 4k formats
- Frame transfer variants
- Other sizes
- CCD260 variant- has larger charge capacity

Figure 6. CCD261 high-rho device



Pixels:	2048(H) x 4104(V)
Pixel size:	15 μm square
Image area	30.7 mm x 61.6 mm
Outputs	2
Package size	31.9 mm x 66.6 mm
Package:	Invar & PGA connector
Focal plane:	14.0 mm above base
Connectors	40-pin PGA
Flatness	20 μm p-v
Amplifier responsivity	6 $\mu\text{V}/\text{e}^-$
Readout noise	2 e^- at 20 kHz
Maximum data rate	~ 1 MHz
Image pixel charge storage	230,000 e^-
Dark signal	0.01 $\text{e}^-/\text{pix}/\text{hour}$ (at 153K)

Figure 7. CCD261 examples of expected QE

3.4 LSST: an example of a high-rho application

The LSST project requires high red sensitivity across a large focal plane with good MTF. Prototype detectors are in development in order to demonstrate these goals, for an intended production phase. The figures below (with acknowledgements to LSST) illustrate this system. [See 5]

The detectors are designed to have a short readout time (multi-output), high fill factor/efficiency (back-illuminated, highly buttable package), high MTF (precise flatness). These requirements lead to the sort of device design illustrated in the following figure.

The device thickness is anticipated to be 100 μm as a trade-off between achieving excellent MTF (with full depletion) and high red wavelength quantum efficiency. This requires use of bulk silicon with high voltage bias.

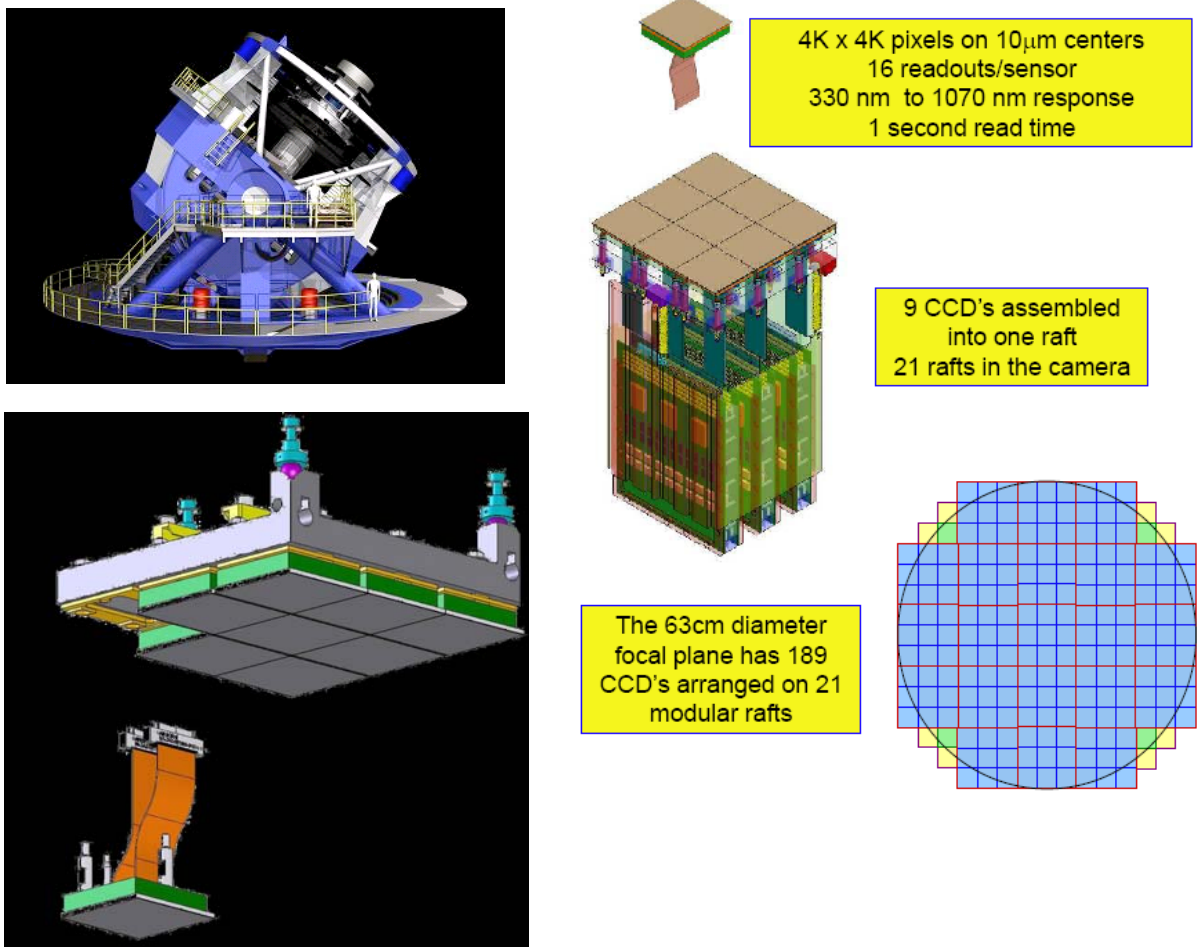


Figure 8. LSST; telescope and “raft” concept for focal plane (Outline from 2008)

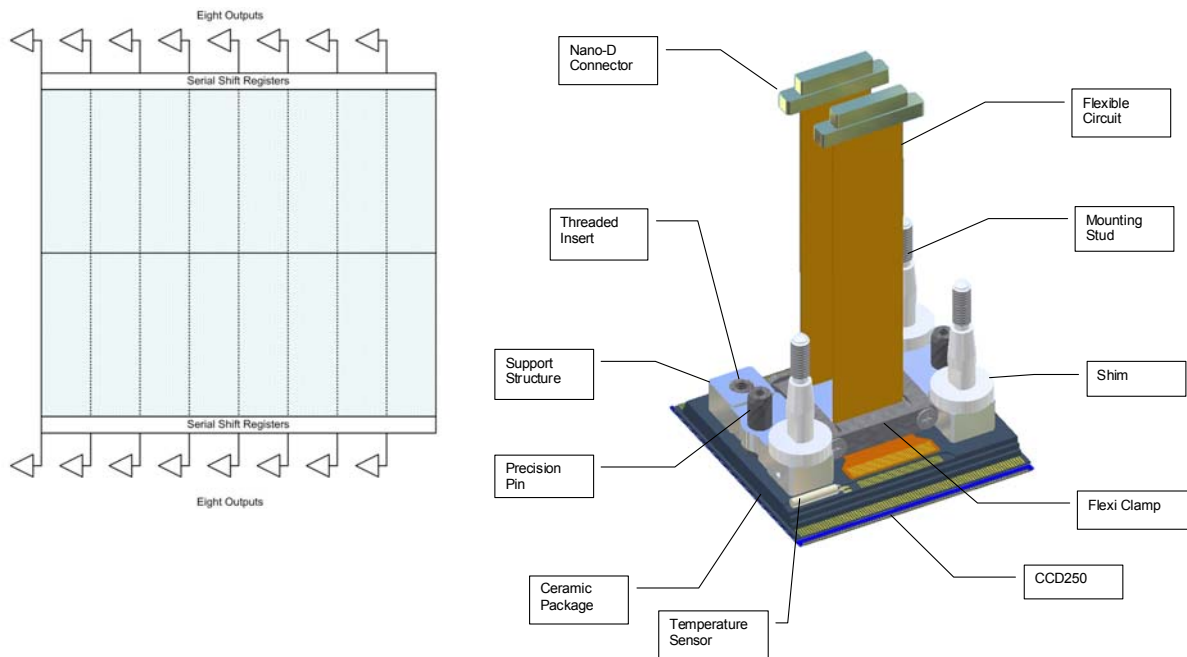


Figure 9. LSST detector design and package concept (in development)

4 CMOS/APS

A major part of e2v's activity in recent years has been the development of high performance CMOS (active pixel) sensors. Backthinning of these devices is a key part of the manufacture which builds on established CCD processes. The e2v backthinning process is used on APS wafers to achieve high quantum efficiency- the same process as used for CCDs allows high short wavelength response. Many APS devices are fabricated on low resistivity silicon which only allows a very thin active region with correspondingly poor red wavelength sensitivity. [This is often desirable for visible imaging chips]. For scientific use e2v uses higher resistivity silicon and specialist foundries to yield devices with improved red sensitivity.

The table below illustrates a few established devices and a few in development:

Device	Pixels	Main Application
ev76c454	860 X 640	Industrial
ev76c560	1280 X 1024	Industrial
CIS101-00	1415 X 1430	Space
Hyper Spectral Imager (HSI)	1024 X 256	Space
High frame rate WFS	> 1024 X 1024	Scientific/astronomy

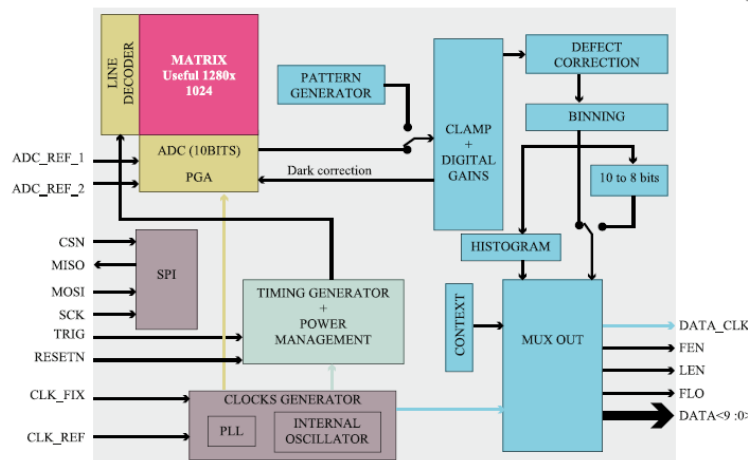
Details of these devices are outlined in the following figures.

The ev76c560 APS device has a 1.3 MPix format and significant functionality, as shown below.

Sensor characteristics

Sensor Characteristics		
Resolution	pixels	1280 (H) x 1024 (V)
Image size	inches	1/1.8
Pixel size (square)	µm	5.3 x 5.3
Aspect ratio		5 / 4
Max frame rate	fps	60 @ Full format >100 @ VGA format
Pixel rate	Mpixels/s	90 to 120

Pixel performance		
Bit depth	bits	10
Dynamic range	dB	66 (linear) >100 (HDR mode)
SNR max	dB	42
Responsivity	LSB ₁₀ /(nJ/cm ²)	48

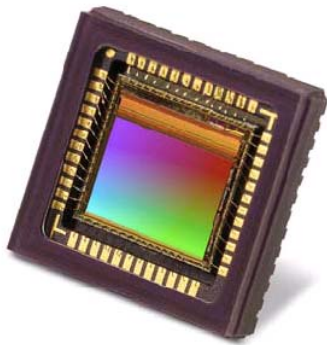


- Electronic rolling shutter and electronic global shutter
- High-readout speed of 60 fps in full resolution.
- Multi ROI and histogram output embedded on-chip
- Very low power consumption (battery powered use)

Figure 10. ev76c560

First samples have 6.5 e- rms noise

The ev76c454 is an APS sensor with functionality and performance as shown below. Sample devices have been backthinned, with performance as predicted.



Sensor architecture

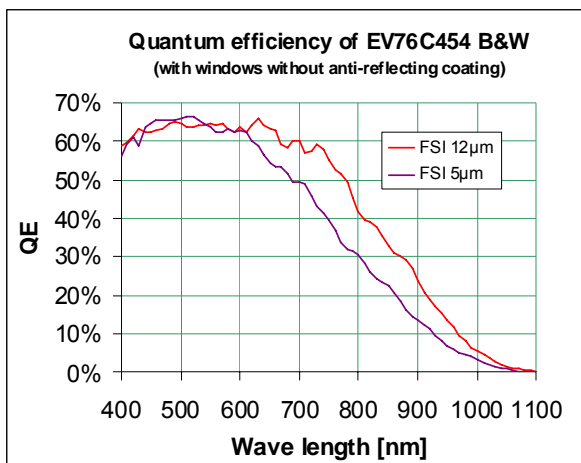
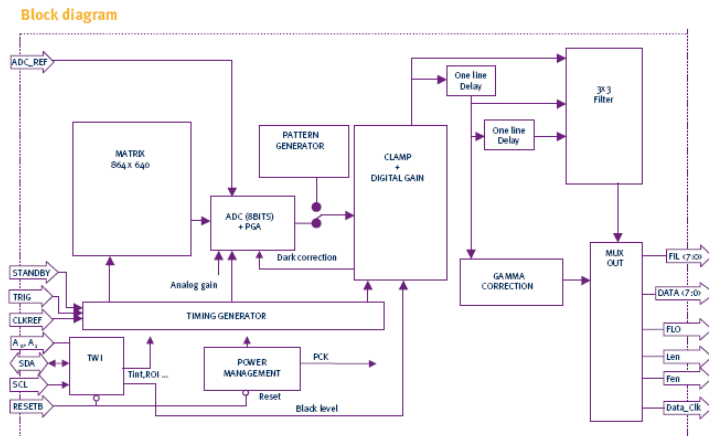


Figure 11. ev76c454

e2v has developed a HyperSpectral Imager (HSI), for pushbroom imaging providing spectral information (via a grating).

Sensor characteristics	
Resolution pixels	838 (H) x 640 (V)
Image size mm	5 (H) x 3.7 (V) – 6.3 (diagonal)
Inches	1/2.9
Pixel size (square) µm	5.8 x 5.8
Aspect ratio	4 / 3
Max frame rate fps	60 @ Full format 80 @ VGA format
Pixel rate Mpixels / s	48
Pixel performance	
Bit depth bits	8
Dynamic range dB	>50
Qsat ke ⁻	10
SNR Max dB	40
MTF at Nyquist, λ=600 nm %	50
Dark signal ⁽¹⁾ LSB ₈ /s	8
DSNU ⁽¹⁾ LSB ₈ /s	6
PRNU ⁽²⁾ (RMS) %	1
Responsivity ⁽³⁾ LSB ₈ /(nJ/cm ²)	15
Mechanical & electrical interface	
Power Supplies V	3.3 & 1.8
Power consumption Functional ⁽⁴⁾ mW Standby µW	80 40

Samples have been backthinned
(Results not shown here; see later)

Devices have been made with increased
silicon thickness; see QE of frontside-
illuminated devices, as shown.

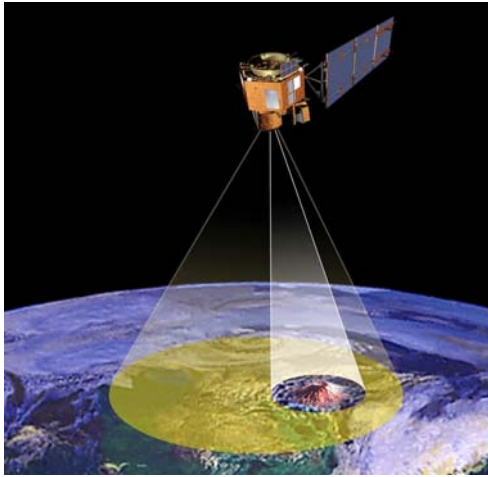


Figure 12. HSI application

This is designed to achieve the difficult combination of-

- Fully pipelined synchronous shutter to remove frame-shift smear (which gives cross-talk)
- High frame rate with random access to lines of interest
- CDS operation for low noise
- Programmable sensitivity row-by-row for optimum sensitivity for spectral lines in different rows
- Standard CMOS technology, but with thick epi and backside illumination for high QE

Multiple modes of operation are possible.

Note. QE.

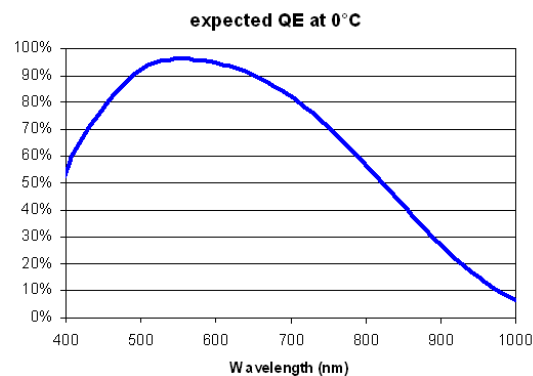
APS devices operate at 2 or 3V

Depletion depth is small

100 ohm-cm → 5 μm

500 ohm-cm → 12 μm

[Needs high resistivity for good red QE and good blue PSF]



Resolution	1024 x 256 (n*512 x 256)
Pixel pitch	24μm
Number of spectral bands	256
Readout speed	250 frames per second
ROI, windowing	Random access in Y-direction (spectral direction) only
Full Well charge for 1% linearity	100ke- and 300ke- (programmable)
Line-by-line programmable charge conversion factor	12fF or 13 μV/e ⁻ 36fF or 4 μV/e ⁻
Total noise	<50 e ⁻ _{RMS} in basic mode without CDS <20 e ⁻ _{RMS} with CDS
QE	>90% in VIS(+NIR)

Figure 13. HSI predicted performance Wafers just out of fab (Apr 2010)

Demonstration CIS101-00 APS devices have been made, in conjunction with Astrium. These devices are fully qualified flight devices.

Number of pixels 1415(H) x 1430(V)
 Pixel Size 14.81 μm x 11.53 μm
 Image area 20.96 mm x 16.49 mm
 Optical Fill factor 65%
 Conversion gain 4.75 $\mu\text{V}/\text{e}$
 Dynamic range 0.98V
 Data rate 10 MHz
 Connectors Pin Grid Array (PGA)
 Power consumption 50mW

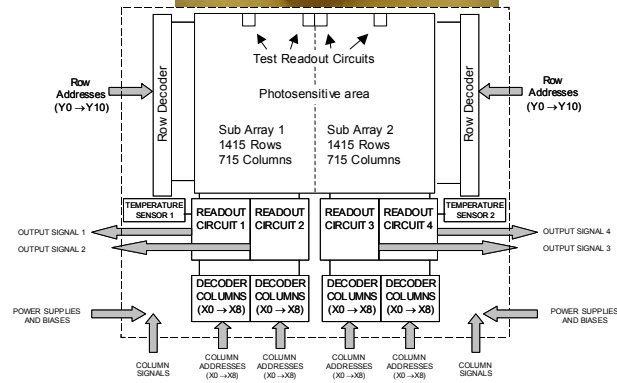
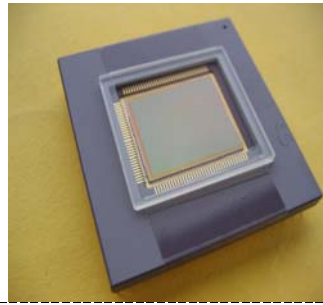


Figure 14. CIS101-00

An APS wavefront sensor is in development, with primary goals as shown below. Only an Active pixel sensor (APS) can meet this format/frame-rate requirement.

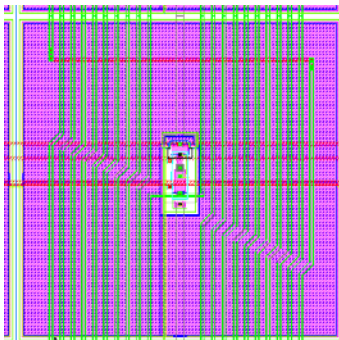


Illustration of 24 μm pixel with multiple tracks in each pixel

Figure 15. Wavefront sensor

Overview of main requirements

- Format: >1024 X 1024 pixels
- Pixels: 24 X 24 μm nominal
- Frame rate: 700 fps nominal
- Readout noise: < 3 e- rms
- QE: 90% at 590 nm
- Low dark current
- Good PSF
- Good pixel non-uniformity and cosmetics

Backthinned for high QE, very low readout noise

Overview of e2v CMOS development & capability

Most of the main process steps are identical for scientific CMOS and CCD manufacture. Devices from 3 foundries have been backthinned results and all results look good. Several CMOS programmes are in progress, including space and astronomy applications; more are planned. e2v is pursuing multiple development strands, including- backthinning, space qualification, low noise, higher resistivity thick epi. The initial focus was on dental and industrial APS devices but is now shifting to space and scientific applications. e2v has an extensive IP library already developed in CMOS imaging.

The figure below illustrates recent results of backthinning an ev76c454 sensor. This device was backthinned with the e2v basic ER1 process, on a device of 8.5 μm silicon thickness. It can be seen that performance is exactly as expected- ie the same as a CCD of similar processing.

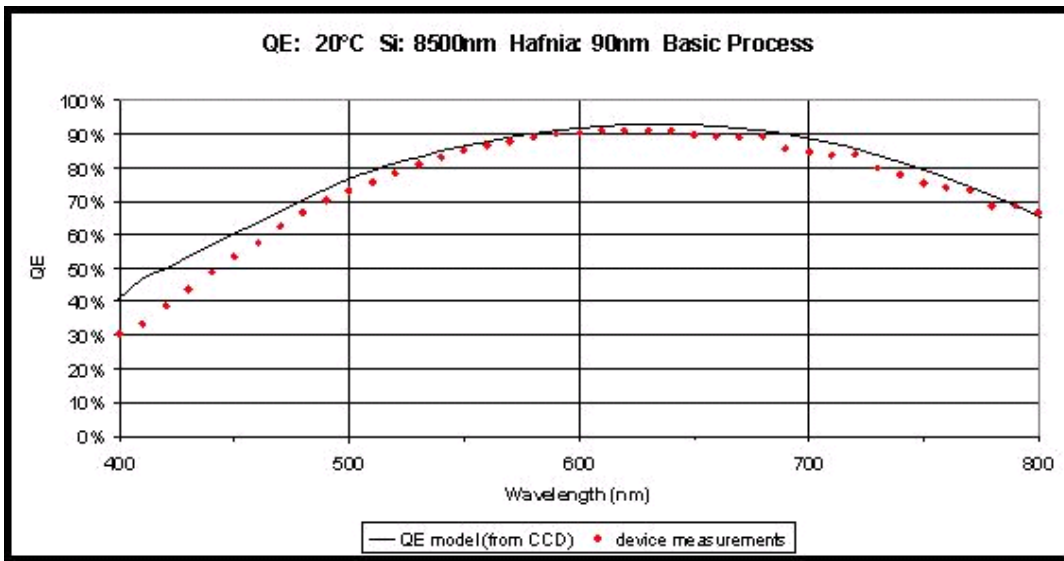


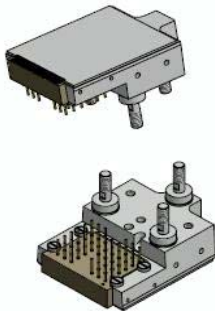
Figure 16. Predicted and measured QE of backthinned CMOS sensor

e2v has also backthinned CIS101-00 sensors using our enhanced process and measurements indicate that 320 nm response corresponds to that predicted for this process. In summary, we expect to manufacture CMOS image sensors, backthin them with essentially the same process as used for CCDs, and obtain predictable high performance spectral response.

5 Other new e2v CCDs

e2v continues to design and manufacture custom variants of sensors, and a few examples are illustrated here, showing a progression of sizes.

CCD44-42
2048 X 2048



Key features:

- 1/2-size variant of popular CCD44-82
- Buttable package; minimal footprint connector
- 2k x 2k 15 μm pixels
- Backthinned with high QE
- Low readout noise
- Standard and deep depletion silicon
- Precision flatness and package height

Figure 17. CCD44-42

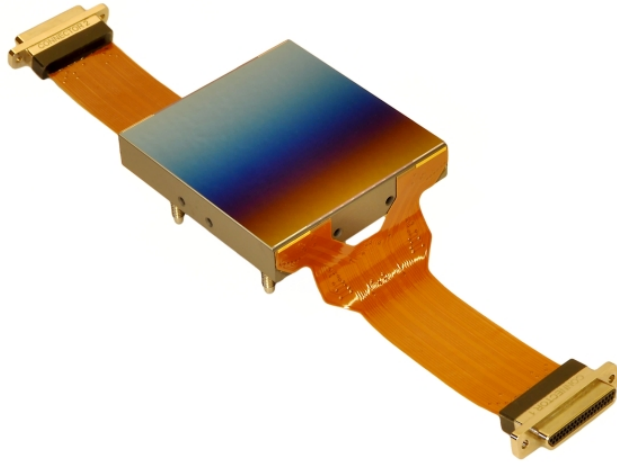


Figure 18. Graded AR coating (CCD231-84)

Graded coatings

See [reference](#) for details of this concept

e2v designs and manufactures custom graded AR coatings on various scientific sensors. The coating optimises the sensitivity for fixed format spectral applications. It has an important secondary benefit of minimising reflection, which reduces ghost images and minimises red-wavelength fringes.

The figure here illustrates an example of the 4kX4k CCD231-84, as used in the ESO MUSE instrument.

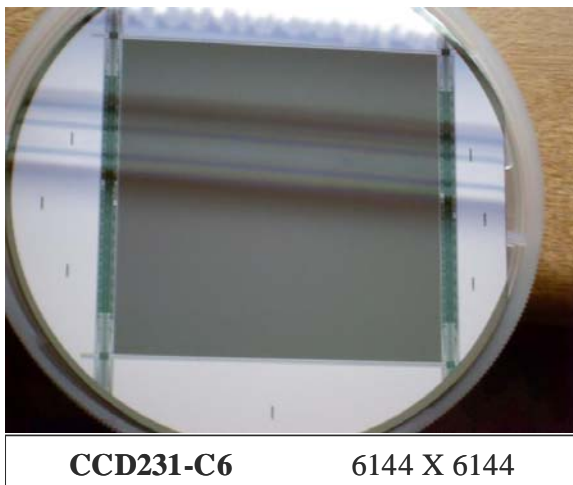


Figure 19. CCD231-C6

The CCD231- series of devices already exist in several formats (2kX2k, 4kX4k, and 8kX3k).

A wafer-sized CCD231-C6 (6kX6k 15 um pixel) device is currently in prototype manufacture. This device has a 92 X 92 mm image area, with high (backthinned) spectral response, 2 e- readout noise, and precision package.

6 References

- [1] Feautrier P, Jorden P, et al, Proc SPIE 7021-14, 2008. *New low noise fast detectors for adaptive optics applications in Europe*
- [2] Feautrier et al, DFA 2009 this conference. *OCam and CCD220: world's fastest and most sensitive astronomical camera*
- [3] Mark Downing: Dietrich Baade, Sebastian Deiries, Paul Jorden, DFA 2009, this conference. *Bulk Silicon CCDs, Point Spread Function and Photon Transfer Curves: CCD Testing Activities at ESO.*
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