Teledyne e2v- design and development of sensors for Astronomy

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SDW 2017

26 Sept 2017

e2v was acquired by Teledyne in March 2017- now part of a larger family!

Contents

Teledyne e2v sensors for astronomy

Introduction

Company Changes

- e2v was acquired by Teledyne in March 2017
- Teledyne e2v continues to operate in its established technical areas and markets
- The “Space Imaging” division continues to design and manufacture sensors and systems for ground-based and space applications

We are working together with other parts of Teledyne- especially Teledyne Imaging Sensors, Camarillo and Teledyne DALSA

Jim Beletic will present information on the new Teledyne sensor business structure on Wednesday

This presentation

We illustrate recent developments of CMOS sensors for astronomy and the advantages they can offer

- Wavefront sensors for large telescopes require a higher pixel count at around 1,000 frames/sec and are forced to move to CMOS technology
- Area sensors are moving toward CMOS as the noise reduces – the two remaining issues are dynamic range and depletion depth (see later)
- For space radiation hardness is significantly better than CCDs so we will see an increasing trend

We then show current CCD sensor types and CCD system developments

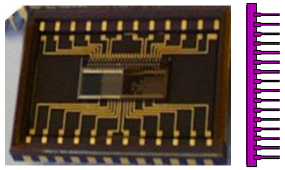
- Popular and large-area CCDs are presented together with performance data
- Major programmes are illustrated for ground-based and space applications
- CCD systems are described together with an overview of Teledyne e2v assembly and test facilities

Wavefront sensor evolution

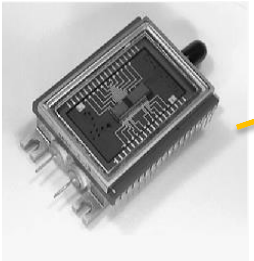
From small CCDs to large CMOS sensors: 1000 frames/sec

CCD → EMCCD → CMOS

1995 2000 2018



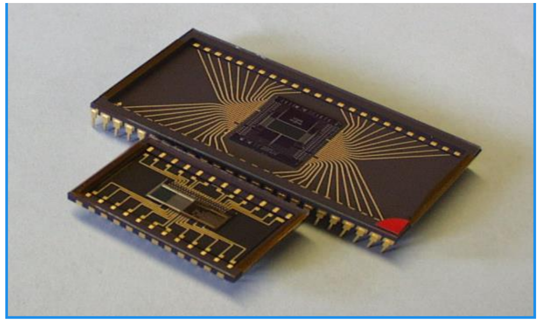
CCD39 80X80

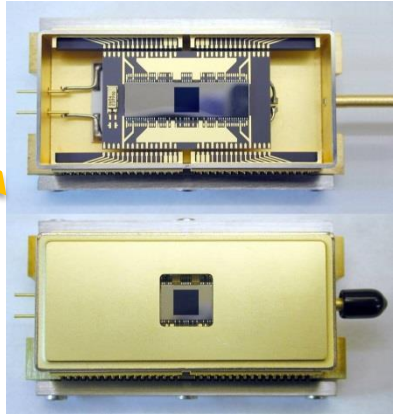


CCD50
128X128

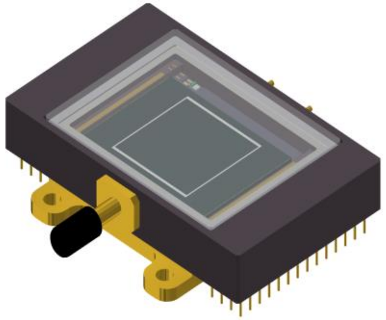
&

EM CCD60
128X128





EM CCD220 240X240



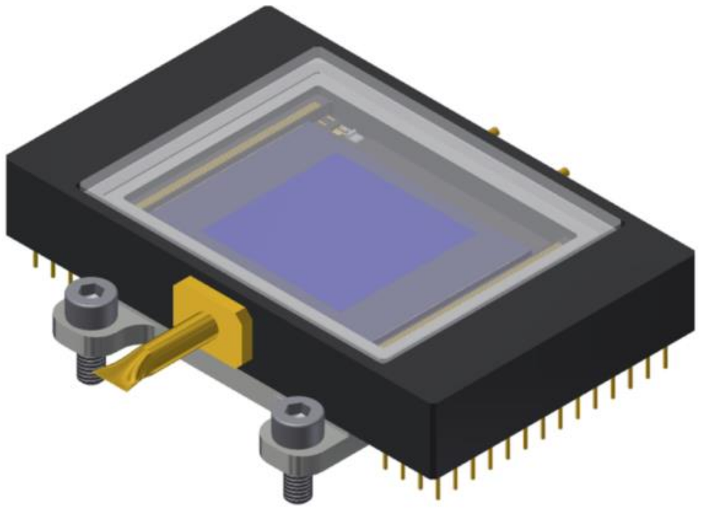
LVSM CIS124 800X800

Large Visible Wavefront Sensor-1

CIS124: A new CMOS sensor- in development for large telescopes

Key features

- **800 × 800** pixels: 80 × 80 sub-apertures of 10 × 10 pixels each.
- **Back illuminated** for highest QE and best intra-pixel uniformity.
- **24 µm** square pixels
  + Each sub-aperture is 240 µm square.
- **700 fps** specified continuous readout (with 1000 fps goal).
  + Lower frame rates/ longer integration times are also available.
- **< 3 e^-** rms total readout noise.
- Nominal operating temperature –10 °C to minimise dark current.
- Rolling shutter for lowest noise.
  + Parallel architecture allows low noise bandwidth with high frame rate.
- **On-chip ADC** giving digital outputs in LVDS.
- Low cross-talk and high uniformity between pixel readout paths.
- Hermetic package with internal **Peltier cooling**.



Large Visible Wavefront Sensor-2

Overall architecture

Sensor:

- Pixel:
  - Low noise/low lag 4T pinned photodiode
  - 24 µm square
- Single slope ADC with gain
- On-chip sequencer for the pixel and ADC access
- SPI interface for detector configuration
- LVDS format running at 260Mb/s for the video output data

Large device:

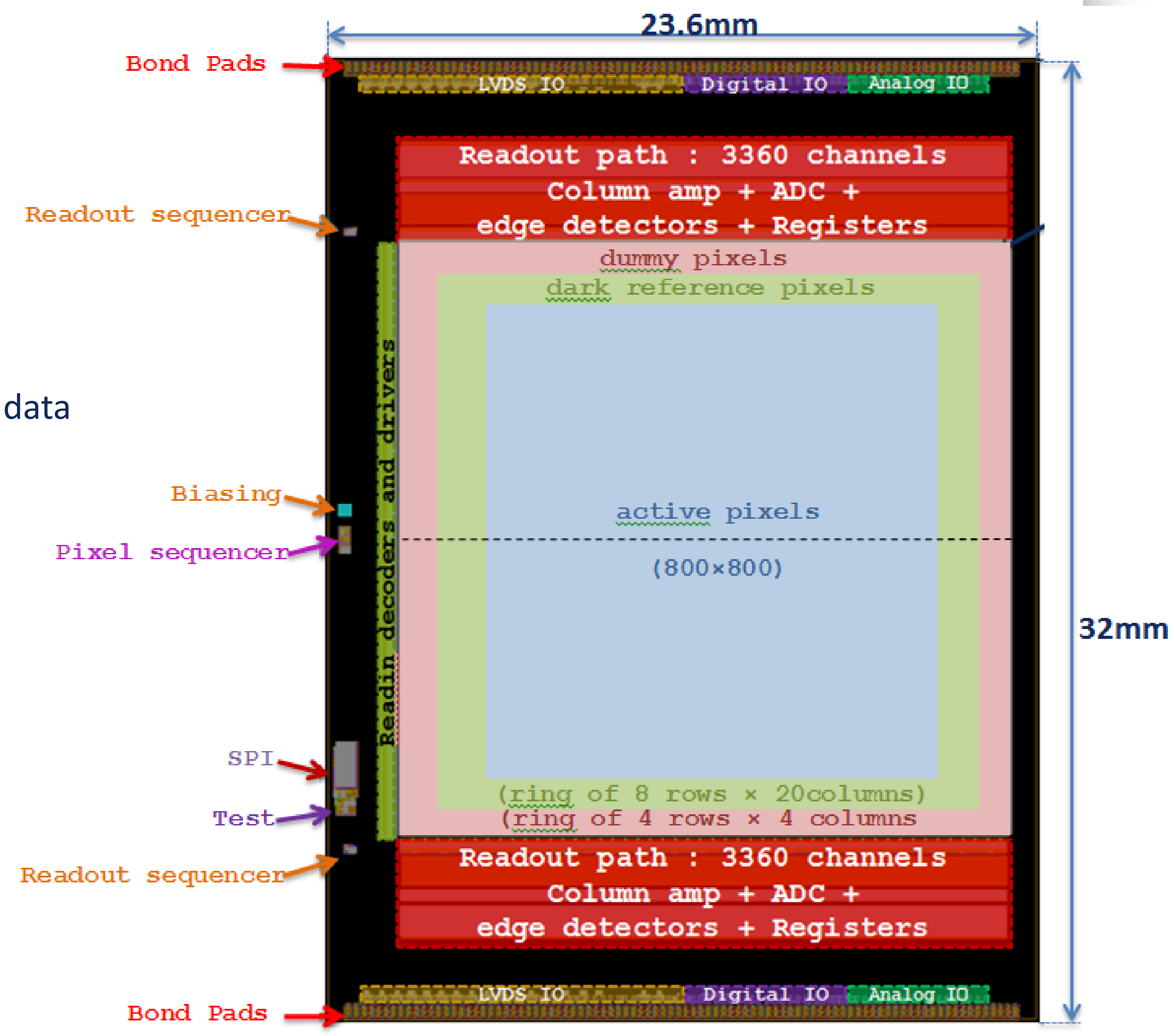
- 23.6 mm by 32 mm detector
- 19.2 mm square of image area (800 x 800 pixels)

High frame rate - 714fps:

- Up and down readout path
- 8 rows readout in parallel (4 up and 4 down)

Low temperature application (-10°C, -20°C):

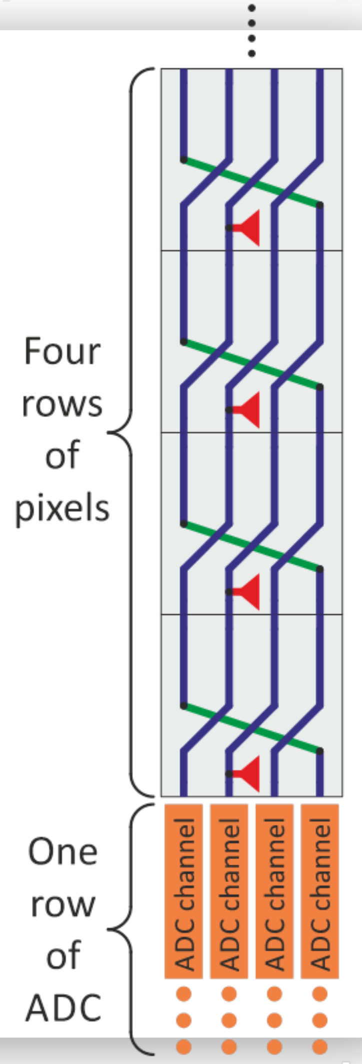
- Peltier package
- I/O pad on two sides only to ease the package design



Large Visible Wavefront Sensor-3

ADC and data output

- Each ADC block has a single row, but the channel pitch is one quarter of the pixel pitch to allow two groups of four rows of pixels to be quantised in parallel.
    - Pixel output tracks (columns) are in sets of four.
    - Good non-synchronicity within each sub-aperture (< 2%).
    - Low latency within each sub-aperture (< 2% of exposure time).
- 3360 parallel channels in each half sensor.
    - ADC channels have great immunity to cross-talk.
- LVDS outputs for image data, dark reference pixels and data synchronisation.
- Multiple test and diagnostic features for both factory and field use.
- **This means that the same format can also be used with 6µm pixels with minimal design changes to give a 3.2k x 3.2k array that will run at ~60Hz (12bits)**



Large Visible Wavefront Sensor-4

Pixel Type – 4T

Main pixel challenge:

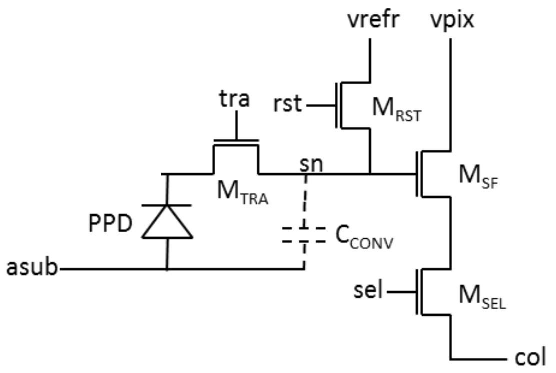
- Having a good charge transfer while having a low noise with a large pixel
- Compromise between high CVF and large transfer gate

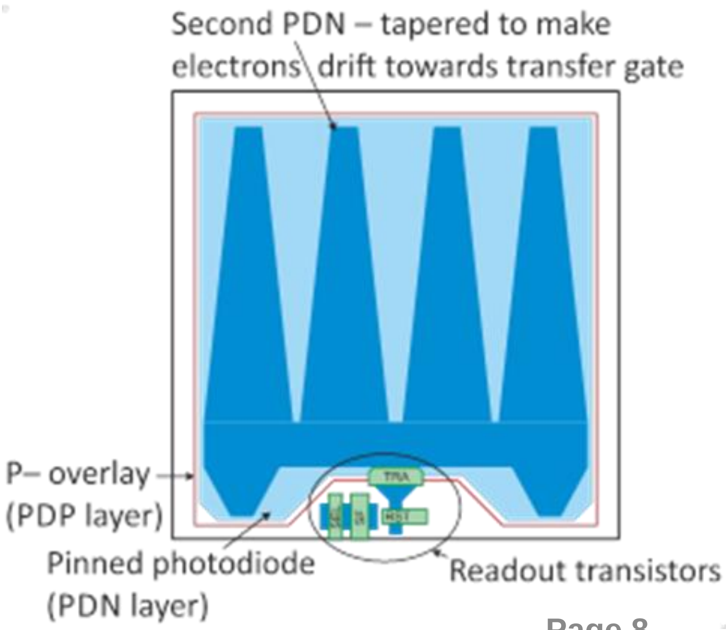
First focus on the charge transfer:

- Photodiode N implant will be done in 2 steps:
  - First step is the implant to form the photodiode with standard voltage pinning
  - Second step is the shaped implant that will modulate the pinning voltage to introduce a natural gradient for the electrons to drift to the transfer gate

Second focus on noise (target <2e):

- To lower the dark current, the STI is kept as small as possible.
- High CVF is reached of about 80µV/e-
- Low noise process is used for the in-pixel Source follower





Large Visible Wavefront Sensor-5

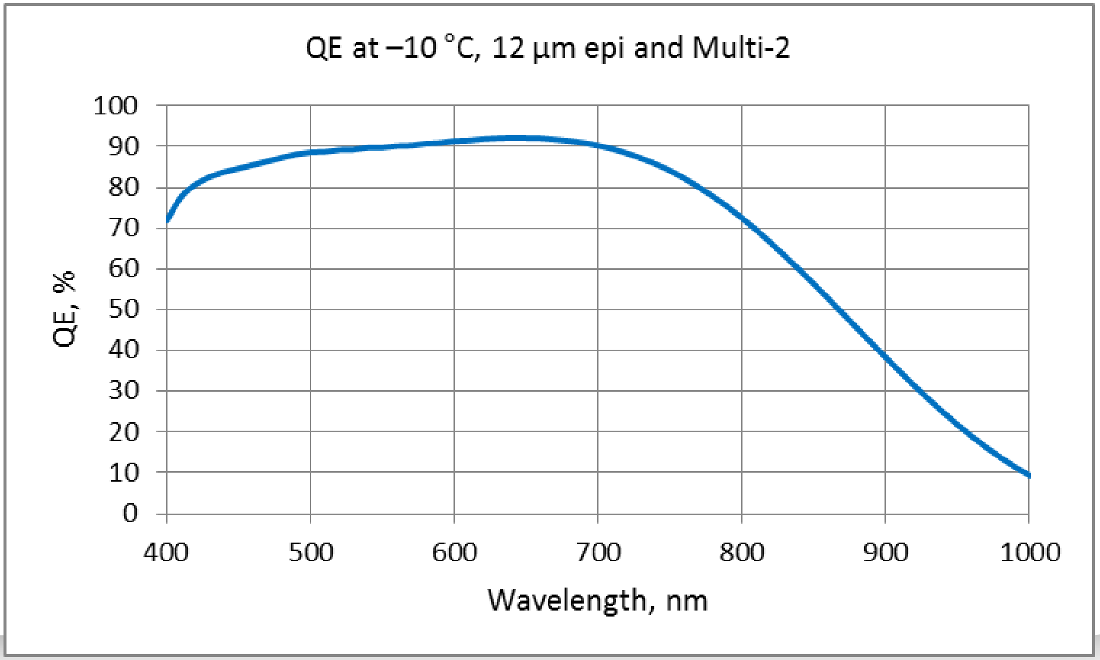
Back-illumination for high spectral response and good uniformity

- With front illumination the front face features on CMOS image sensors reduce both photo-response uniformity and overall QE

- Back illumination allows a good AR coating to be used and then typically gives around 90 % QE at visible wavelengths. These sensors have a uniform detection surface and give superior intra-pixel uniformity compared to front illuminated sensors.

- This high resistivity epi is used to give high QE at longer wavelengths

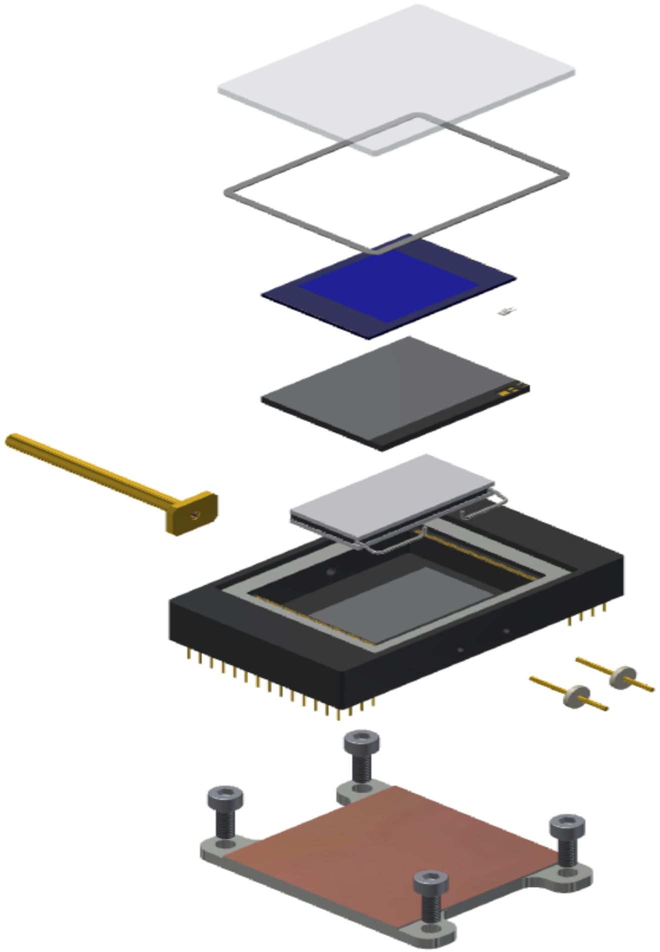
Typical BI QE curve:



Large Visible Wavefront Sensor-6

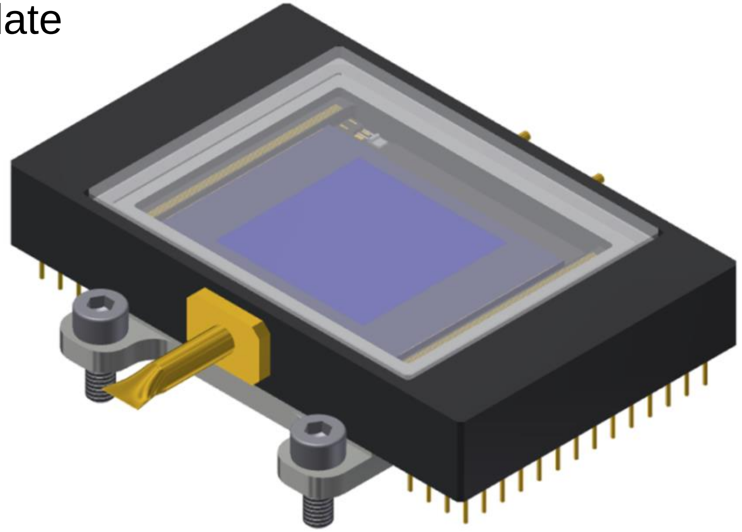
TELEDYNE e2V
Everywhereyoulook™

Package



A ceramic body with:

+ Internal Peltier cooler with its power feedthroughs
+ Metal baseplate for mounting the module and for cooling the hot side of the Peltier
+ Hermetically sealed window
+ Low thermal conductivity inert gas filling
+ Pinched-off pump tube after filling with inert gas.
+ Pin grid arrays each side of baseplate
+ Temperature sensor

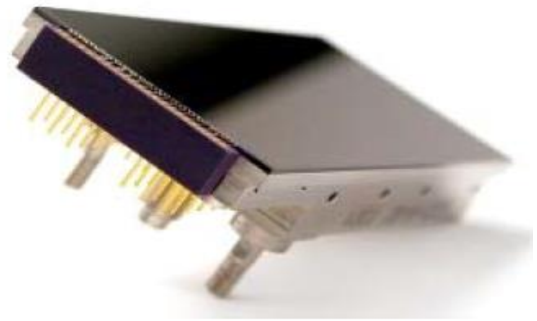


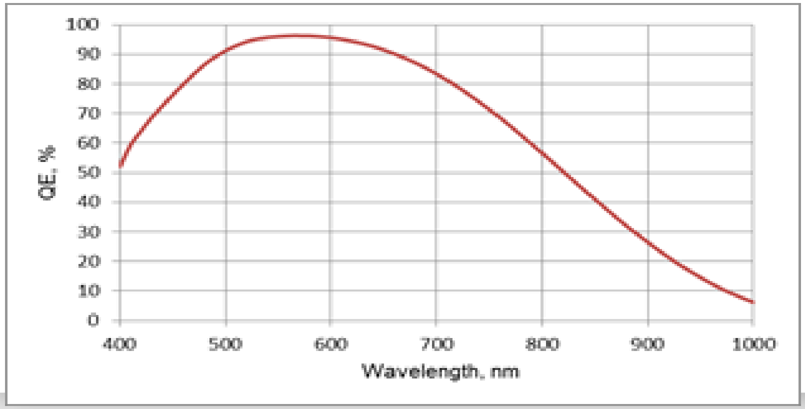
CMOS sensors for astronomy-1

CIS113

Developed for the TAOS-II project.

Development complete; 40-off devices delivered





Number of pixels	**1920 (H) × 4608 (V)**
Pixel size	16.0 µm square
Image area	73.73m × 30.72 mm
Output ports (analogue)	8 (REF and SIG each)
Package size	82.39 mm × 31.7 mm
Package format	76 pin ceramic PGA attached to invar base
Focal plane height	14.0 mm
Flatness	< 30 µm (peak - valley)
Conversion gain	75 µV/e⁻
Readout noise	3 e⁻ at 2 MP/s per ch.
Maximum pixel rate	2 MP/s per channel
Maximum charge	22,000 e⁻ per pixel
Dark signal	70 e⁻/pixel/s (at 21 °C)
Frame rate	2 fps (full frame mode) 20 fps (~1000 ROI's)

CMOS sensors for astronomy-2

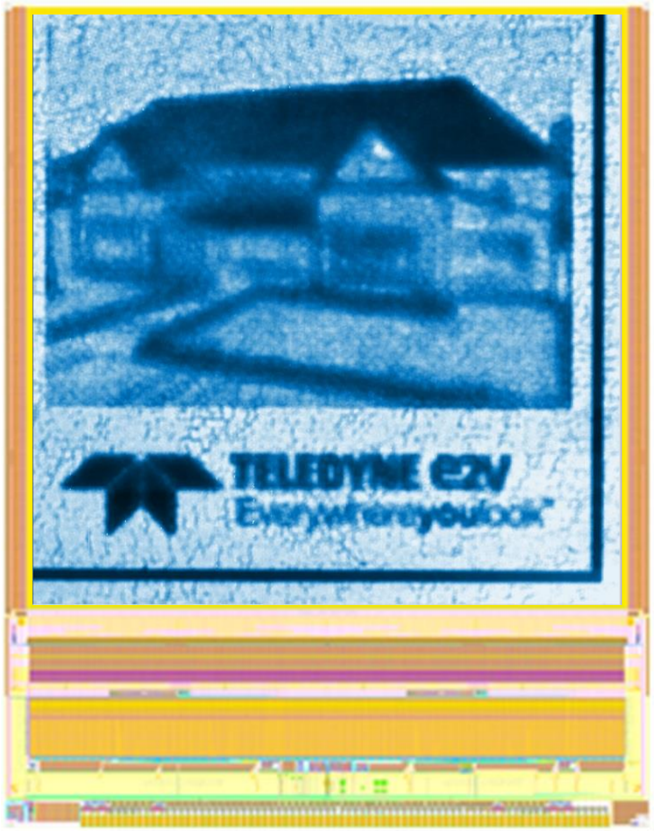
New development – CIS 120 (modular digital platform)

General Purpose Space Imager (GPSI)
- CIS120 -

Parameters	GPSI (CIS120)
Format (pixels)	2048 x 2048
Pixel size (um^2)	10x 10
Frames Per Second	20fps with 12 bit output
Full well charge (ke-)	50ke- with low noise >80ke- with additional cap.
Read noise (e- rms)	
Rolling Shutter	4e at 20fps with 4 outputs
Global Shutter	11e
GS with DCDS	~6e at 12fps
Quantum Efficiency FSI x fill factor (%)	55 @444nm 62 @ 550nm 18 @ 914nm
Quantum Efficiency BSI (%)	70 @ 400nm 90 @ 550 nm 35 @ 900 nm
Output	4 x 12bit LVDS
Packaging	Ceramic, sealed with a window[6]
Radiation tolerance	TID >100krad[7], SEL >67MeV/cm^2/mg
Focal plane	3 side buttable

- Characterisation in progress
- Full Front Illuminated results in October and back-illuminated results by end of year 2017
- Draft Datasheet available

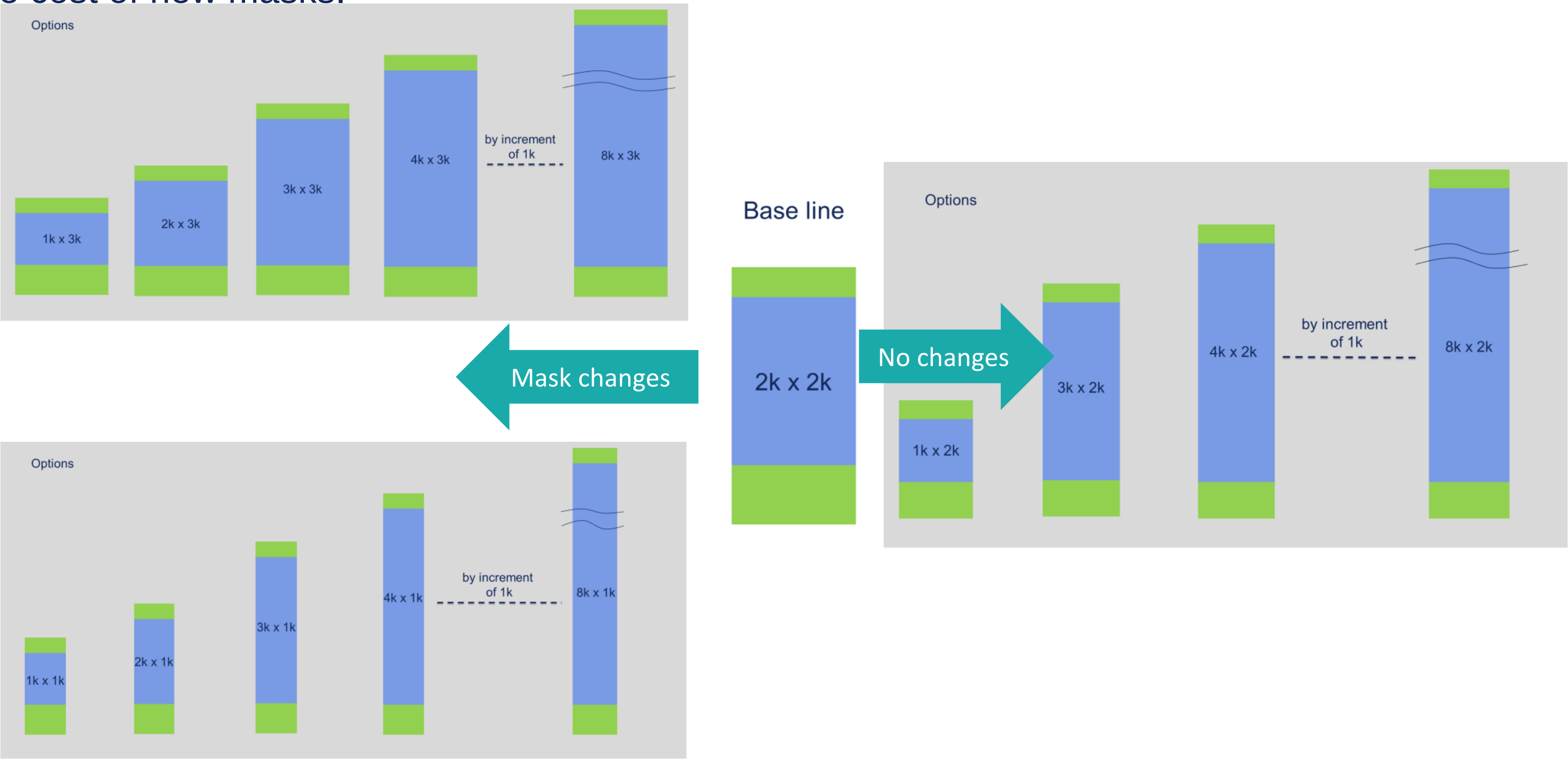
With a first image



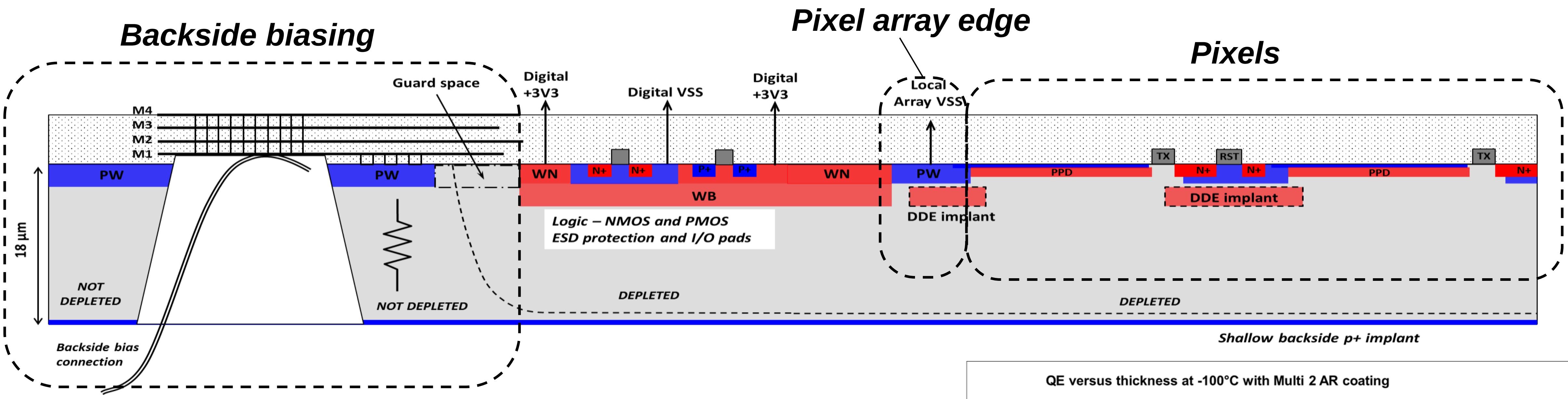
CMOS sensors for astronomy-2

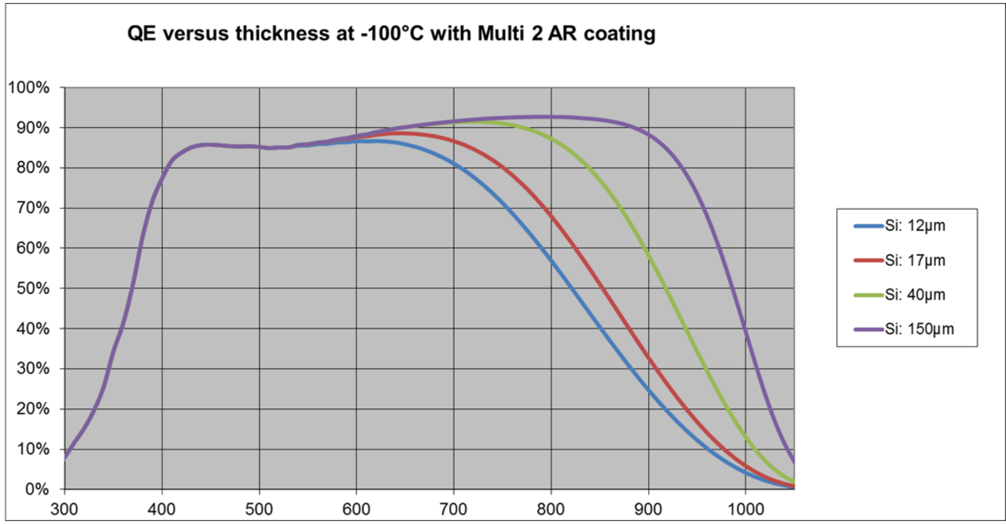
CIS120 format options

- It is a matrix sensor which will enable a product family to be created with minimal or no design changes.
- CIS120 is stitched, so other sizes are possible from 1024 × 2048 up to 3072 × 8192 pixels, without the cost of new masks.



Hi Rho CMOS





Developed and patented by Konstantin Stefanov at the Open University

Allows a back bias to be applied to CMOS

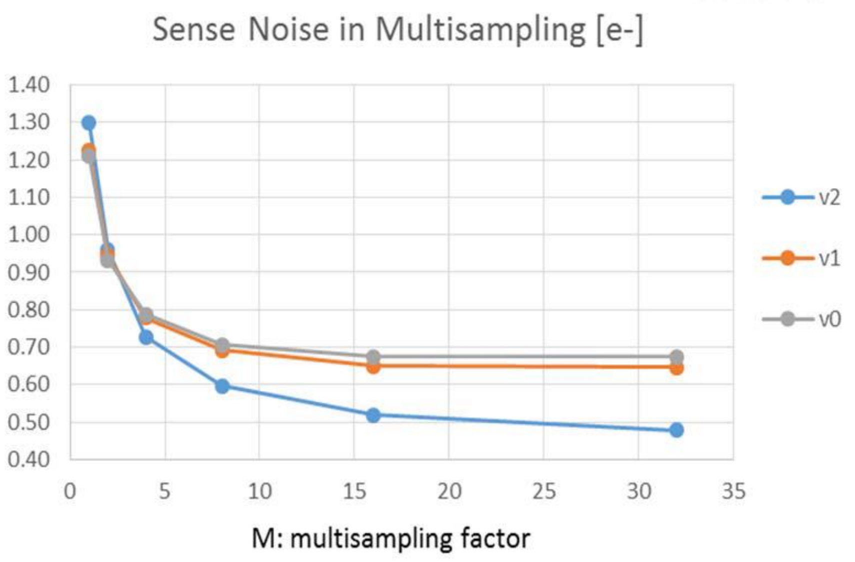
Enables CMOS devices to be made up to 300 µm thick with ideal MTF

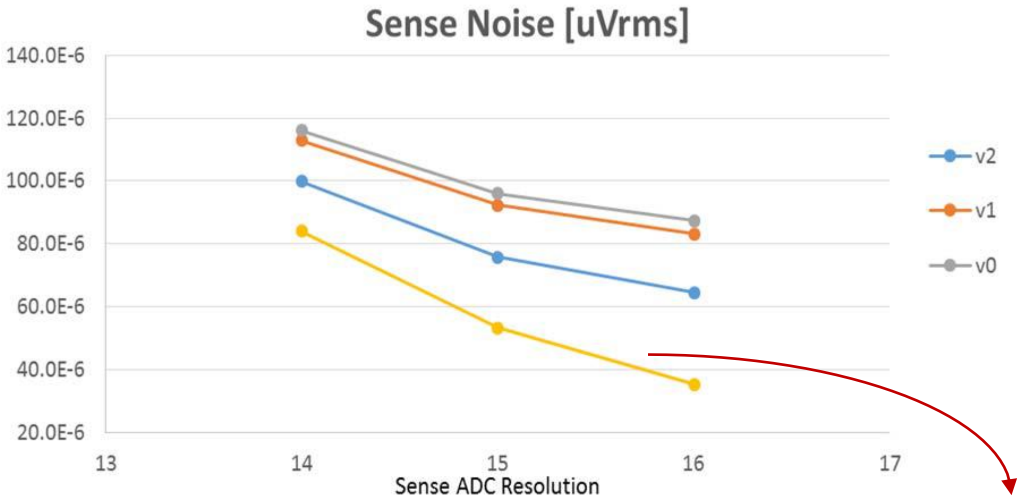
CMOS sensors for Astronomy - 4

Noise of <1e is becoming standard

Very low noise CMOS being worked on by Anafocus (<1e noise)

- Data shown is as measured on LONIS test chip
- Full size high resolution device is currently in test





readout

The future

A combination of

- low noise CMOS <1e is now becoming standard
- Large area 2D stitching
- HiRho technology to give thickness of 30µm with epi or 300µm with bulk silicon for high red QE
- Backthinning

Could give a 12cm square astronomy CMOS sensor with low noise and excellent QE with performance as below:

  - Noise <1e
  - Peak signal ~80ke (with dual readout chain)
  - Pixel size 10µ
  - 12k x 12k
  - Backthinned 30 µm thick fully depleted
  - 14 bit digital output
  - Frame read time ~2s

Digital processing on chip?

- Not clear for general astronomy but could be good for wavefront sensors

Contents

Teledyne e2v sensors for astronomy

A suite of imaging CCDs for astronomy

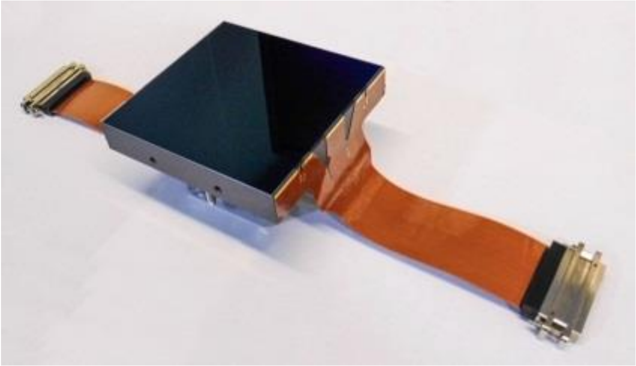
Overview of "ground-based" sensors; Space sensors not included here

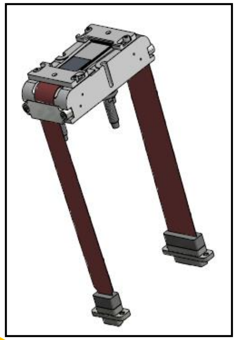
- CCDs of many formats and types available-   see www.teledyne-e2v.com

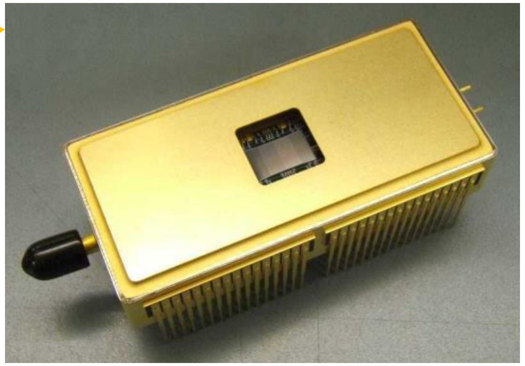
Standard products and custom variants

Key ones used for astronomy:

• CCD290-99	9K x 9K	Imaging/spectroscopy
• CCD231-C6	6K x 6K	Imaging/spectroscopy
• CCD231-84	4K x 4K	Imaging/spectroscopy
• CCD44-82	2K x 4K	Imaging/spectroscopy/WFS
• CCD47-20	1K x 1K FT	Guiders
• CCD220	240 X 240	AO

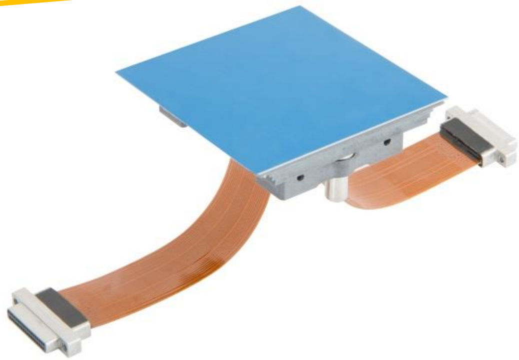






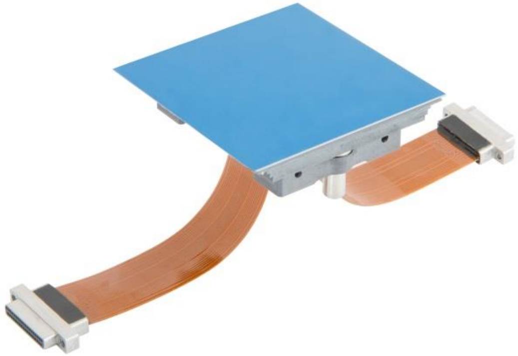
Also, deserves a highlight:

- CCD250 LSST   4K x 4K



CCDs with high red sensitivity

LSST CCD250



4k X 4k 10 µm format

189 science sensors

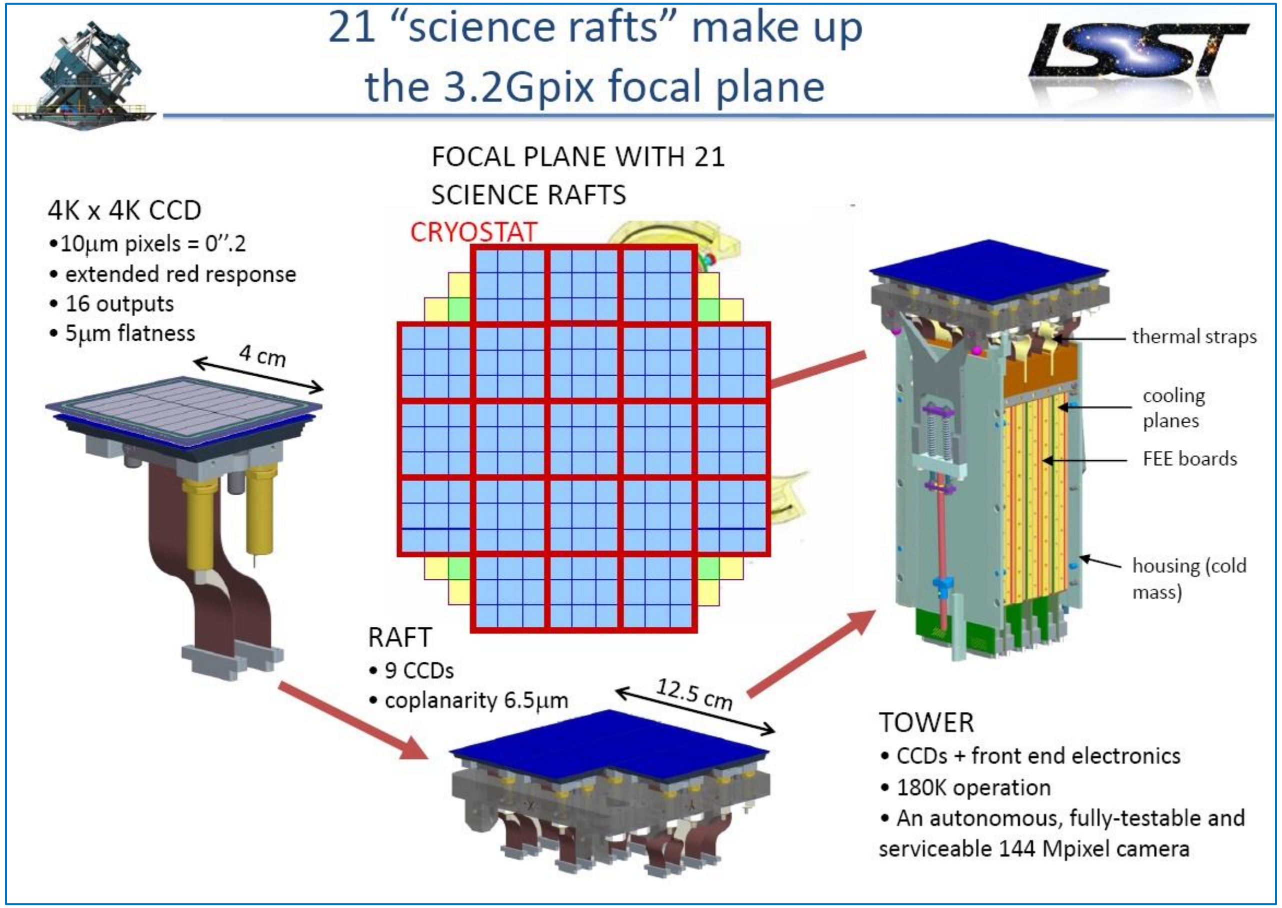
100 µm thick; 5 um flat

High precision SiC buttable package

16 outputs; 2 s readout

5 e- read-noise

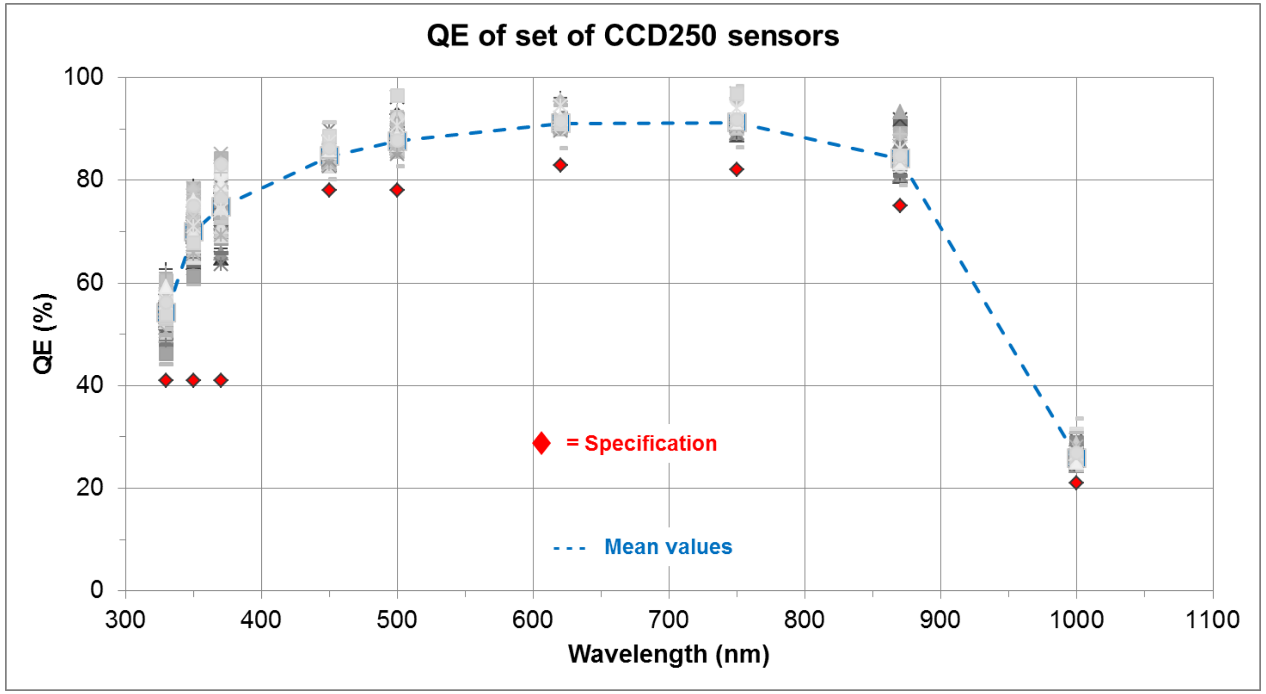
65 sensors delivered; remaining ones in production



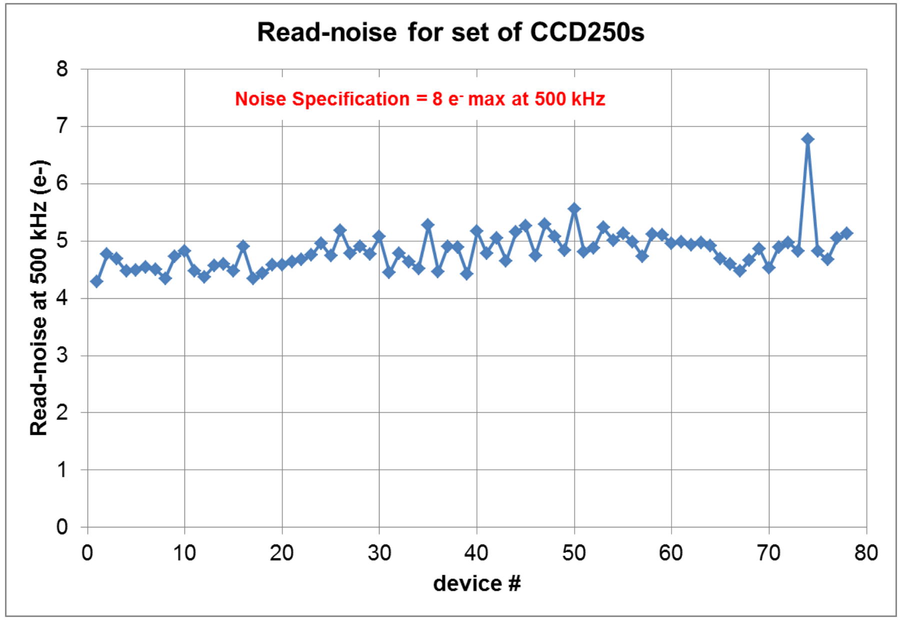
Pictures courtesy: LSST

CCD250 performance

Repeatable performance of large set of science-grade devices



- Devices operate at 500 kHz from 16 outputs
- 2 second frame read time
- Results from one test camera are illustrated
- Data set represents > 1200 amplifier outputs

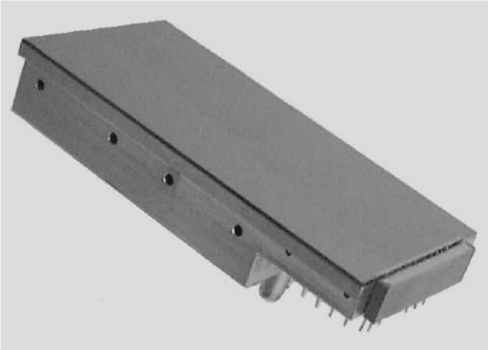


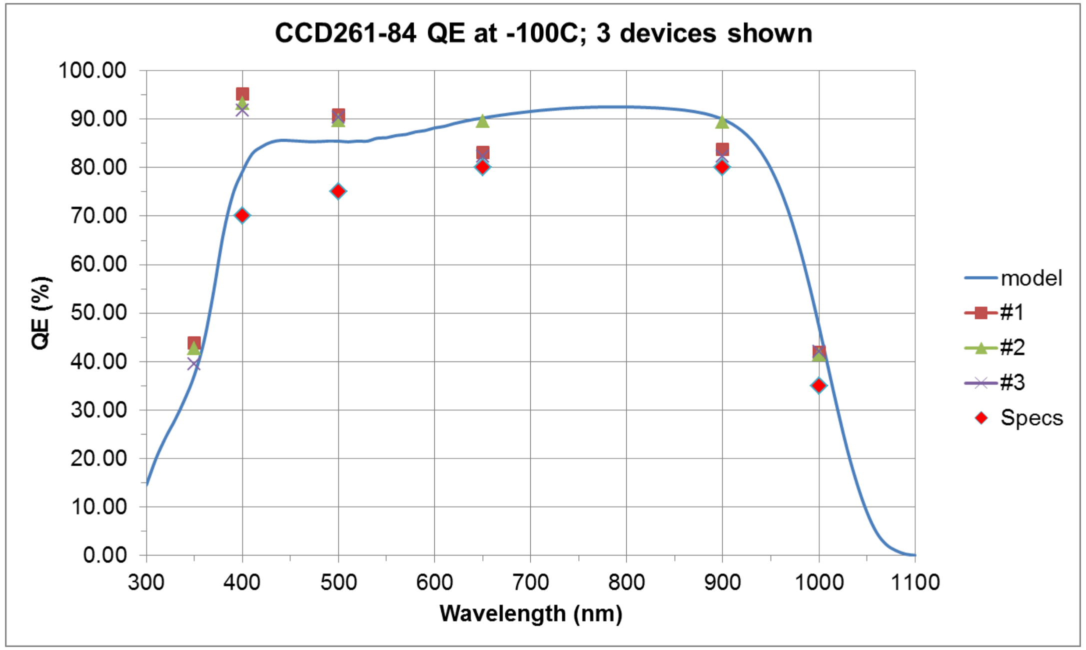
- Multlayer AR coating- for high QE to match LSST-specification bands
- Some spread of QE values- due to process variation and test accuracy
- Data set for > 100 devices; 16 measurements (in sectors) per device

CCD261-84

A standard high-rho sensor

- Test camera recently passed TRR for standard production
- Device performs as expected
- 200 µm thick silicon for high red QE with -60V back bias voltage
- Grade-0 devices delivered: 3.3 e$^-$ rms noise measured; spec = 4.0 e$^-$ at 50 kHz
- No defective columns; minimal defective pixels



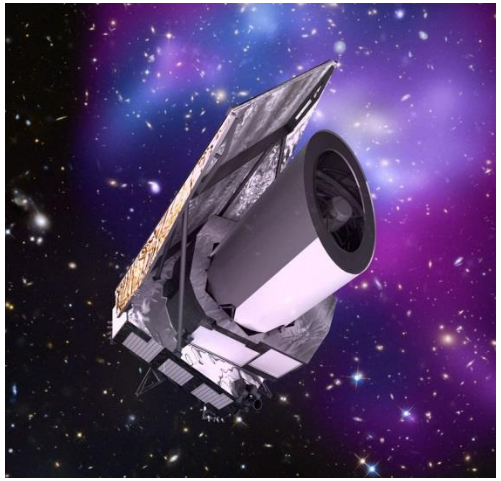


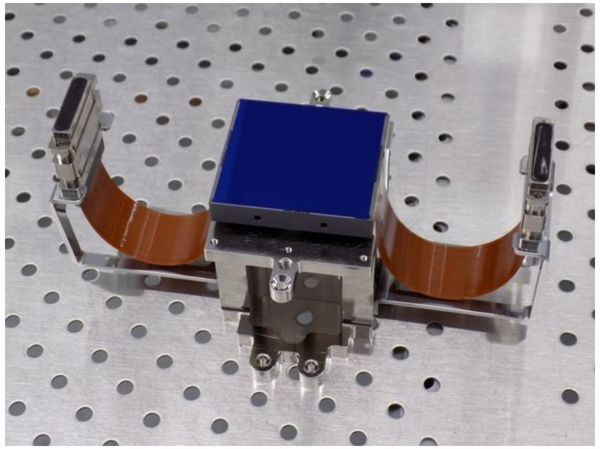
Summary (typical) performance	
Number of pixels	2048(H) x 4104(V)
Pixel size	15 µm square
Image area	30.7 mm x 61.6 mm
Outputs	2
Package size	31.8 mm x 66.4 mm
Package format	Buttable Invar package with PGA connector
Focal plane height, above base	14.0 mm
Connectors	40-pin PGA
Flatness	20 µm p-v
Amplifier responsivity	7.5 µV/e$^-$
Readout noise	2.8 e$^-$ at 50 kHz
Maximum data rate	1 MHz
Image pixel charge storage	200,000 e$^-$
Dark signal	10 e$^-$/pixel/hr (173K)

Large area CCD performance

Space sensors- Euclid CCD273-84

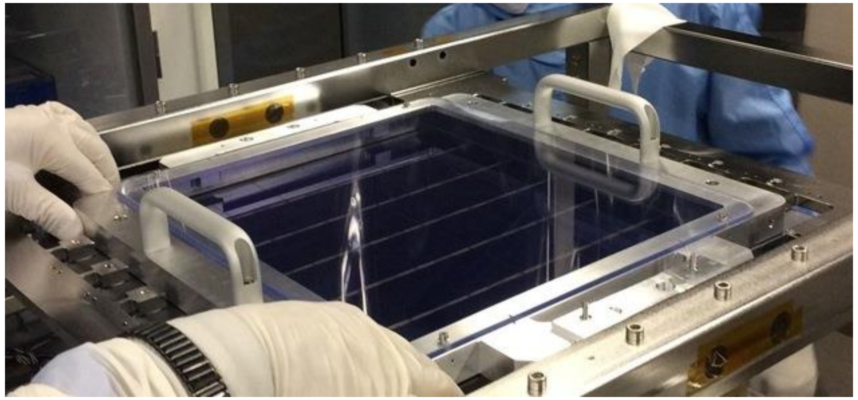
MISSION: To map geometry of the dark universe.





- 4096 X 4096 12 µm pixels
- Low voltage process
- 4 x low noise high responsivity amplifiers ~7µV/e
- Low noise typically ~2e at 70kHz readout frequency
- Image full well capacity ~220ke
- Deep depletion silicon back-thinned for high QE at 900nm
- 4 side SiC buttable package with flexi connectors
- 36 FM devices in the 600 MPixel focal plane

49 FMs delivered to ESA



Focal plane picture courtesy of M Berthé CEA

EUCLID CCD273-84 performance

TELEDYNE e2V Everywhereyoulook™

An example of test sheet for one FM

All science grade devices are delivered with full test data; an example is shown here

Not all parameters are reproduced here

This sheet is a post-burn in result sheet

This is typical of data provided for ground-based sensors also

TEST	AMPLIFIER QUADRANT				LIMITS (Min/Max)		UNITS	PASS/ FAIL
	OS-E	OS-F	OS-G	OS-H				
Amplifier Responsivity	6.84	7.19	7.12	7.22	6.5	Min	µV/e-	PASS
					8.5	Max		
Readout Noise	2.2	2.1	2.1	2.1	-	Min	rms e-	PASS
					3.6	Max		
Mean Dark Signal at -80°C (measured)	84.2	42.1	44.5	44.5	-	Min	e-/pix/hr	N/A
					FIO	Max		
Mean Dark Signal at -120°C (Calculated)	0.008	0.004	0.004	0.004	-	Min	e-/pix/hr	PASS
					2	Max		
Image Full Well (SatCTE)	265.1	259.3	247.7	254.4	175	Min	ke-/pix	PASS
					-	Max		
Image Full Well (SatLin)	374	370	369	360	FIO	Min	ke-/pix	N/A
					-	Max		
Register Full Well (SatCTE)	497.8	450.4	461.1	478.6	300	Min	ke-/pix	PASS
					-	Max		
Register Full Well (SatLin)	424	402	418	414	FIO	Min	ke-/pix	N/A
					-	Max		
Absolute Maximum Non-Linearity	-1.5	-1.9	-1.1	-1.3	-	Min	%	PASS
					4	Max		

CTE (Serial)		100.0000	100.0000	100.0001	99.9999	99.9995	Min	%	PASS
						-	Max		
CTE (Parallel)		100.0000	100.0001	100.0000	99.9999	99.9995	Min	%	PASS
						-	Max		
Quantum Efficiency	550nm	83.0	83.5	83.5	**82.9**	83.0	Min	%	FAIL
						-	Max		
	650nm	92.9	93.0	93.1	92.8	83.0	Min	%	PASS
						-	Max		
	750nm	92.0	91.7	91.8	91.9	83.0	Min	%	PASS
						-	Max		
	850nm	73.0	72.9	72.9	73.3	70.0	Min	%	PASS
						-	Max		
	900nm	51.8	51.4	51.5	52.3	49.0	Min	%	PASS
						-	Max		
PRNU	550nm	1.1	0.9	1.0	0.9	-	Min	%	PASS
						2.0	Max		
	750nm	0.8	0.8	0.8	0.7	-	Min	%	PASS
						2.0	Max		
	900nm	0.9	0.8	0.8	0.7	-	Min	%	PASS
						2.0	Max		

Large area CCD performance

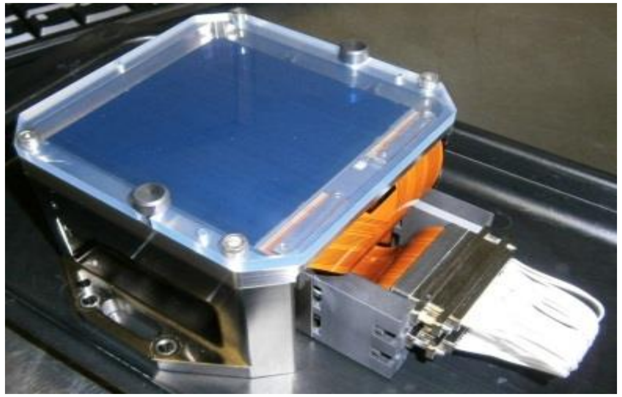
Space sensors- Plato CCD270

MISSION: To find and characterise many extra-solar planets- Especially earth-like planets in the habitable zone

- 4510 X 4510 pixels — 81 x 81 mm area
- 18 µm square 4 phase pixels
- Thin gate high full well capacity process
- 2 x high signal amplifiers ~2µV/e on one side
- Amplifier noise ~20e at 4MHz readout speed
- Peak signal >1Me
- 4 side buttable SiC package with flexi connectors

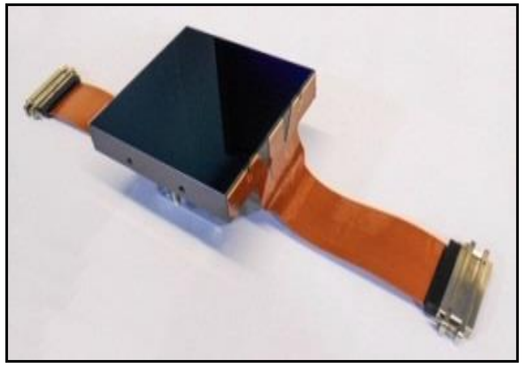
- Four CCDs per FPA; 26 FPAs:- — 2100 MPixels total
- Largest visible focal plane area in space- — 0.7 m^2 area total

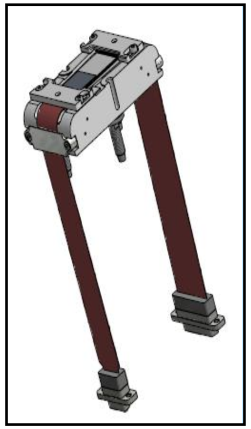
FM production started in 2017



Systems-1

Focal plane assembly- Korea Micro-lensing Telescope Network





KMTNet precision focal planes

350 mm focal planes

340 Megapixel each

Three assembled plates, each with-

Four science sensors [9K x 9K each; buttable]

Four guide sensors [1K x 1K; custom package

Precision Silicon carbide plate; < 30 µm p-v flatness

Guaranteed at cryogenic temperature

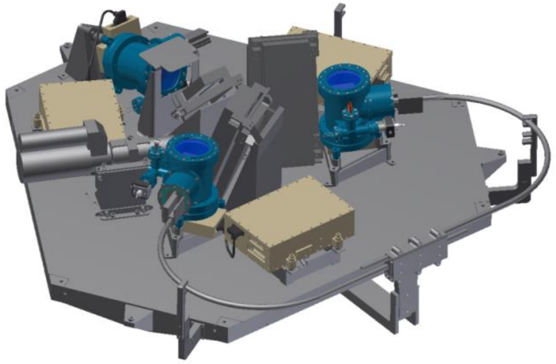
Three focal planes delivered by early-2014 and installed at OSU

Systems-2

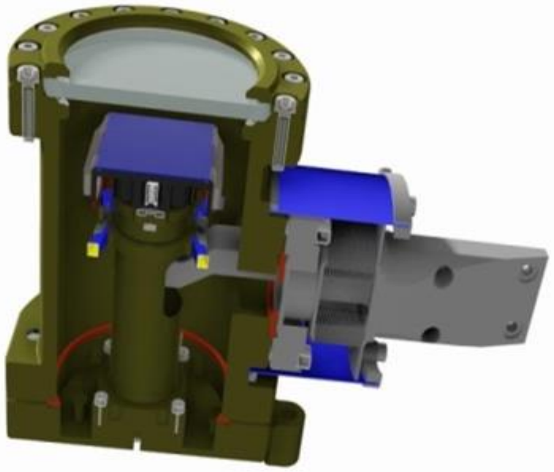
WSO-UV space systems

World Space Observatory UV Spectrograph sensors & electronics

- Three custom sensor channels for 115-310 nm range
- Custom sealed vacuum cryostat enclosures for 9 year life
- Flight electronics (associated with RAL Space)
- UV optimised CCD272 operated at -100°C
- Components maintain alignment after shock & vibration of launch



Instrument with triple detector units & electronics



J-PAS Cryocam

J-PAS Cryocam: A 1.2 Gigapixel cryogenic camera

For use on OAJ 2.5m telescope

- 450 mm focal plane with 14 science CCDs;
- **Flat to 27 µm; stable against flexure; -100C operation**
- 14 science CCD290-99 detectors
- 8 CCD44-82 wavefront sensors
- 4 CCD47-20 guide sensors
- Custom packages for focal plane co-mounting
- 224 synchronous readout channels with < 5 e^- noise
- Integrated vacuum cryogenic system & thermal control
- Modular electronics
- System noise guaranteed with installed detectors

Complete system accepted and delivered in June 2016

Systems-4: In house assembly and test

Test room (1 example); 4 cameras shown; multiple cryostats

Extensive clean rooms

Used for all phases of device assembly-
Wafers → packaged devices

Multiple test cameras

(a) initial characterisation & (b) production test

In-house camera designs

Customised for specific projects. Replicated for production flow- eg GAIA (concluded), PLATO & LSST (in progress)

Electronics expertise

Camera design & device operation
Utilised in system supply contracts

Systems-4: In house assembly and test

Clean rooms shown- Assembly, Parts Prep, and Test room

Movie here

Extensive clean rooms

Used for all phases of device assembly-
Wafers → packaged devices

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(a) initial characterisation & (b) production test

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Summary

Teledyne e2v designs and supplies CCD and CMOS sensors and systems

- An increasing number of sensors are being developed using CMOS architectures
  - Most of these are backthinned and offer low read-noise (comparable to CCDs)
- CCDs continue to be used in larger quantities and with greater heritage
  - CCDs offer better red response in general (thicker silicon)
- “Full wafer” sized sensors are manufactured in quantity and with excellent performance
- e2v offers custom system solutions including cryogenic cameras and electronic modules to complement its supply of sensors- and with guaranteed system performance

Finally-   Thank you for your attention

Any questions?

We also make silent movies!

Movie here