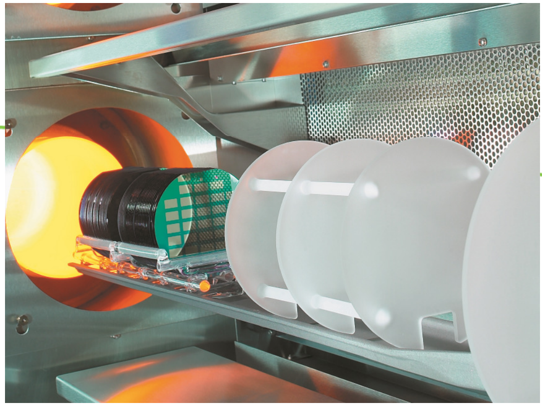
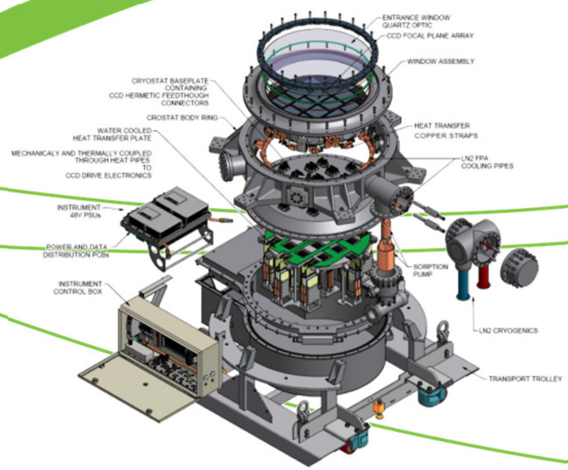
e2v Bringing life to technology

e2v CMOS (and CCD) sensors (and systems) for astronomy





Paul Jorden

BNL PACCD2016   1 Dec 2016

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Contents-1

E2v manufactures silicon sensors and systems for ground-based astronomy and space use

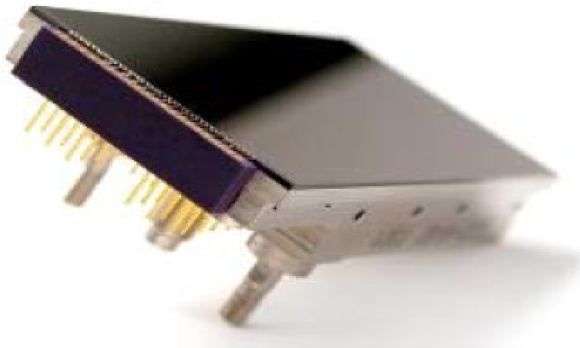
e2v designs and manufactures an increasing suite of CMOS imagers for high performance use

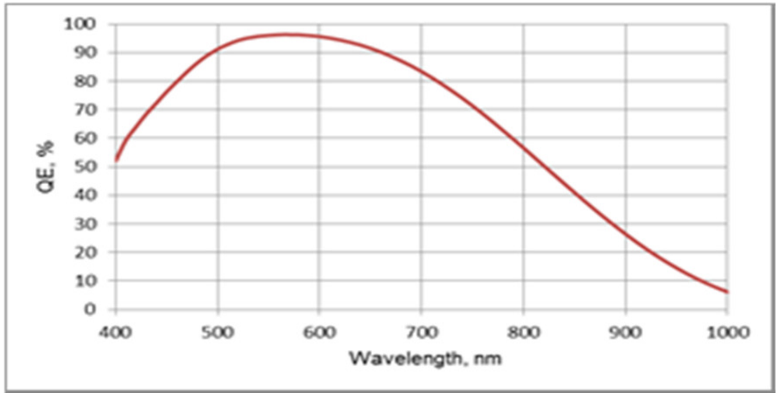
CMOS detectors-1

CIS113

Developed for the TAOS-II project.

Development complete; production in progress; 10 delivered; full set of 40 due for completion by Jan 2017





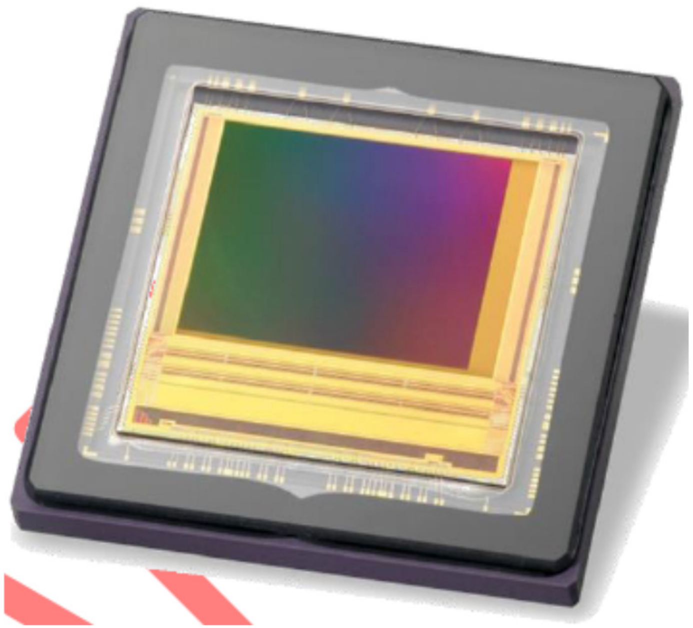
Paper by Jérôme Pratlong, 9915, Tues am, S8

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	82.39 mm × 31.7 mm
Package format	76 pin ceramic PGA attached to invar block
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 (multiple ROI's)

CMOS detectors-3

Onyx EV76C664

- Standard product with low noise
- Fully digital sensor with multiple modes
- Frontside illuminated with micro-lens



Key Features

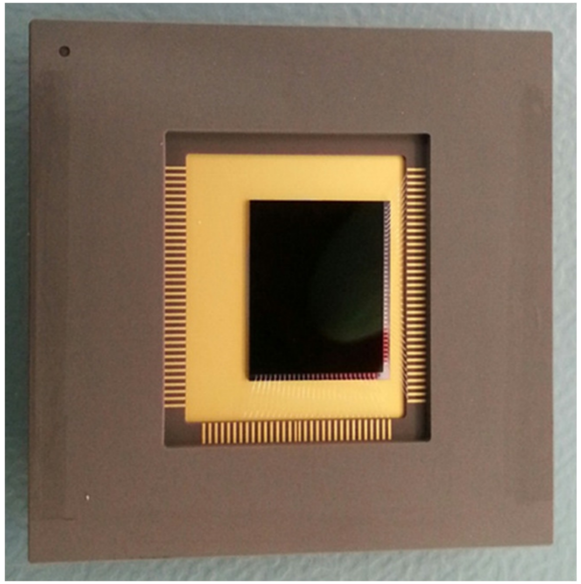
Number of pixels	**1280 X 1024 (1.3 Megapixel)**
Pixel size	10.0 µm square
Shutter modes	Global and Rolling
Output	8, 10, 12, 14 bit LVDS
Package format	Ceramic 67-pin PGA
Readout noise	6 e^- (min, depending on mode)
Quantum Efficiency	Monochrome or sparse colour (with microlens)
Maximum charge	16,000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

See e2v.com for datasheet

CMOS detectors-4

CIS115

- Backthinned sensor with low read-noise
- Designed for space applications
- Planned for JANUS (Juice) ESA mission
- Being qualified for space use by end-2016
- Samples available; FMs to follow



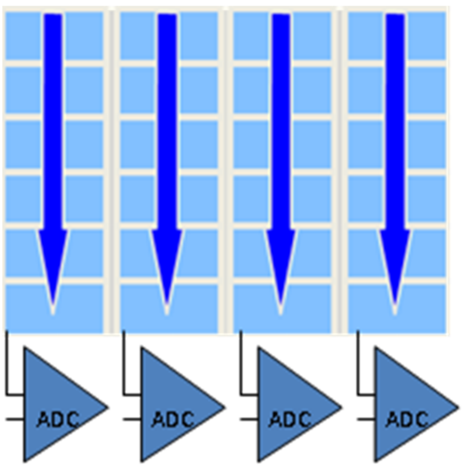
Number of pixels	1504(H) × 2000(V)
Pixel size	7.0 µm square
Number of output ports (reset and signal pins)	4 pairs of analogue outputs
Package size	48.26 mm square
Package format	140 pin ceramic PGA
Flatness	< 10 µm (peak to valley)
Conversion gain	35 µV/e^-
Readout noise	7 e^- (Rolling shutter)
Maximum pixel data rate	8 MP/s per channel
Maximum charge per pixel	55,000 e^-
Frame rate	Up to 10 Hz
Minimum time to read one line at 6·2 MP/s	66.25 µs
Frame rate at full resolution	Up to 7.5 fps

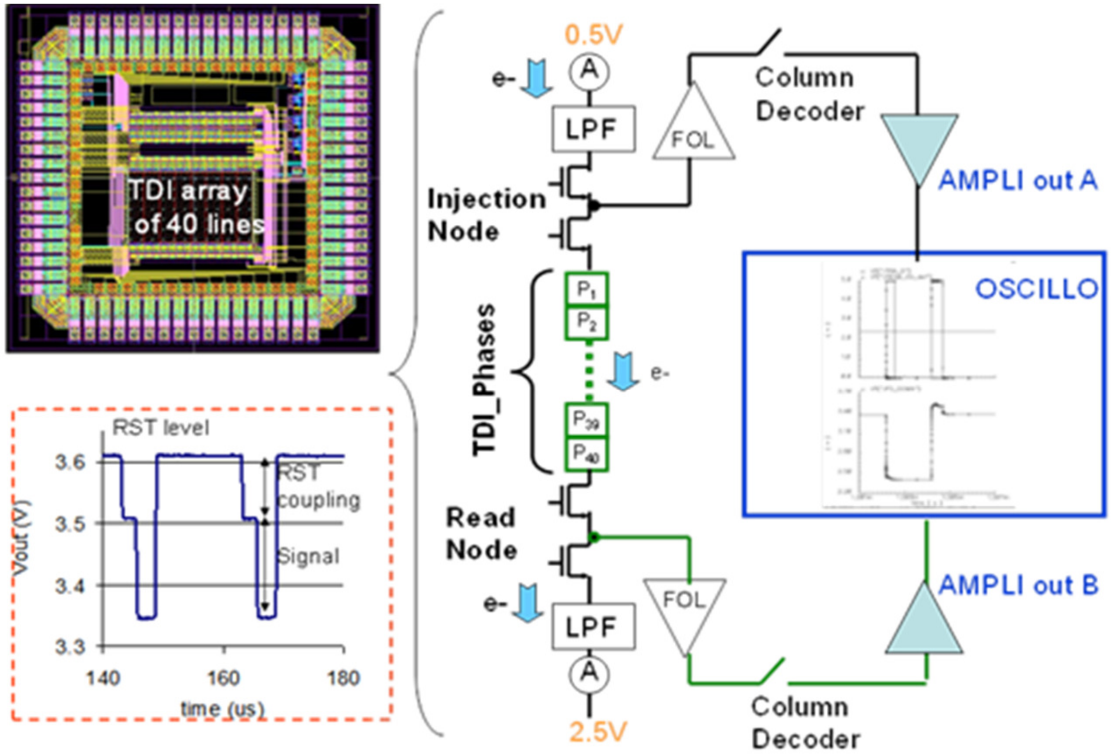
CMOS detectors-5

TDI CMOS development

Time-Delay-Integrate used for scanning space applications; eg GAIA uses TDI CCDs

- **TDI CMOS offers digital architecture & low power**
- **Most promising technique is a CCD-like structure-**
- **Charge summation along track**
- **Good CTE after irradiation is important**
- **Small test devices made & tested**
- **Full sized device planned**



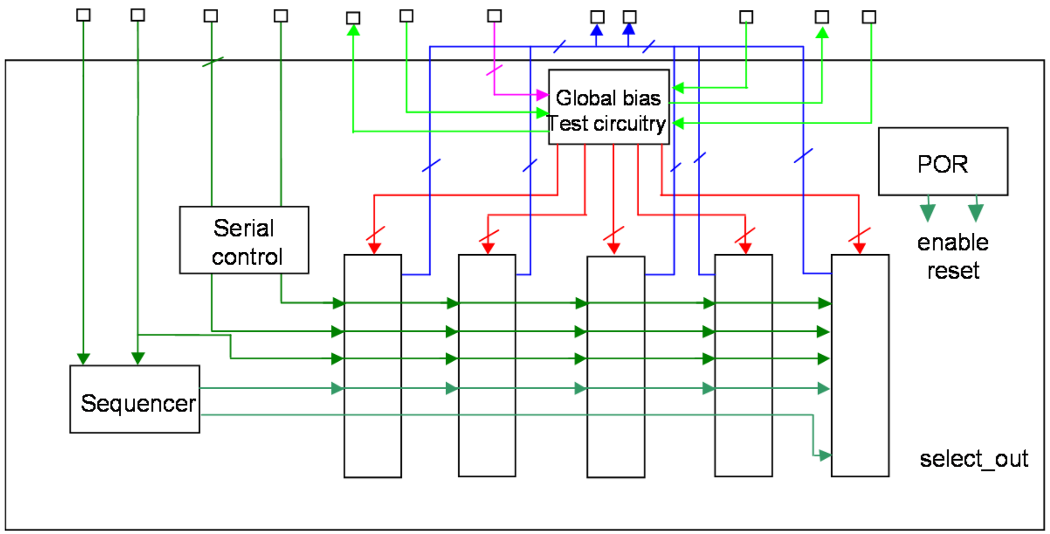


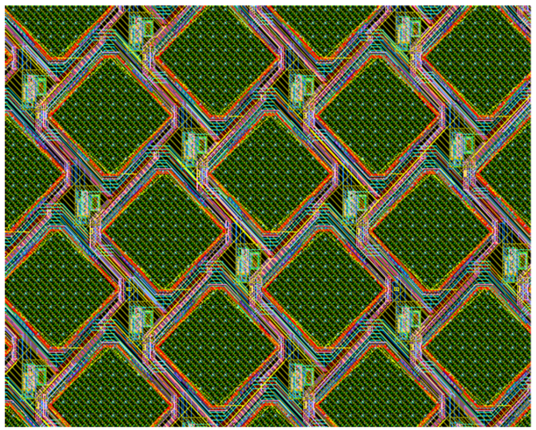
See paper by F Mayer, IISW 2015 on e2v.com

CMOS detectors-6

CIS111 (MTG FCI)

- Example of imager used for earth observation-
- Offers higher frame rate and lower crosstalk than an equivalent CCD
- CIS111 to be used on Meteosat Third Generation Flexible Combined Imager
- 5 independent imager blocks with in-package filters
- Rhombus shaped pixels in outer blocks
- Optimised for good transfer through large pixels and low lag





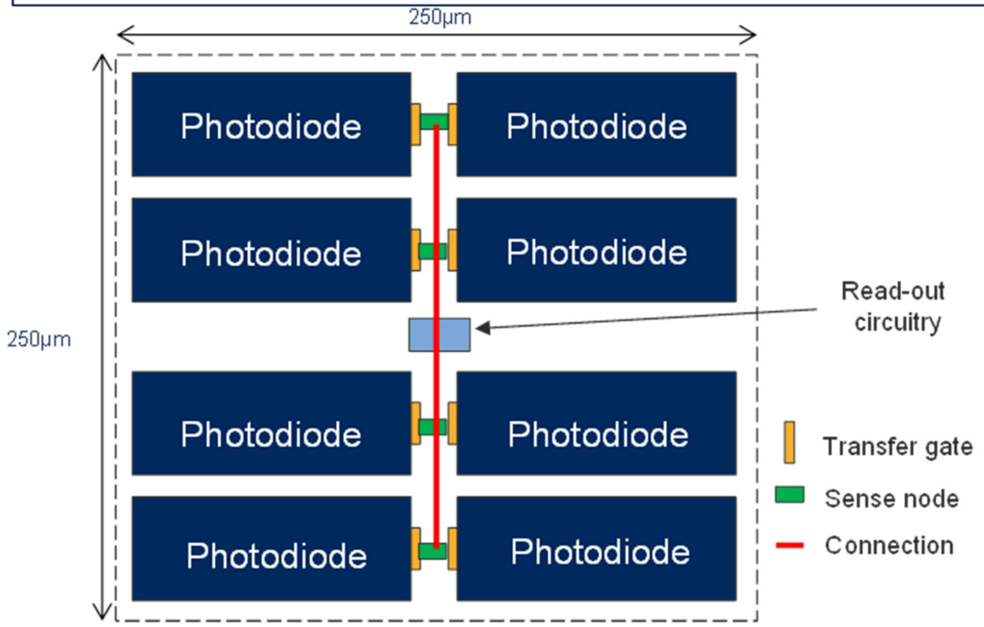
CIS111 architecture

CMOS detectors-7

CIS116 (Metimage)

Custom test vehicle with 250 um square pixels

- **Each pixel has 8 photodiodes with a common sense node**
- **Aims to optimise lag and Charge-Voltage-Factor**
- **2.5 Me- peak signal; 84 dB dynamic range**
- **Designed for backthinning**
- **Test devices have been characterised**

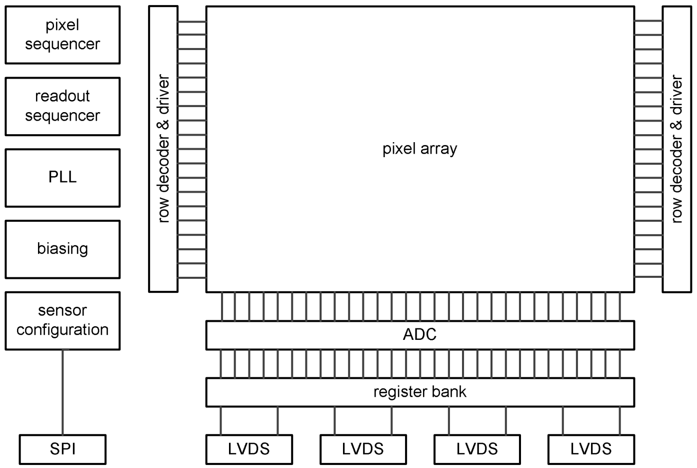


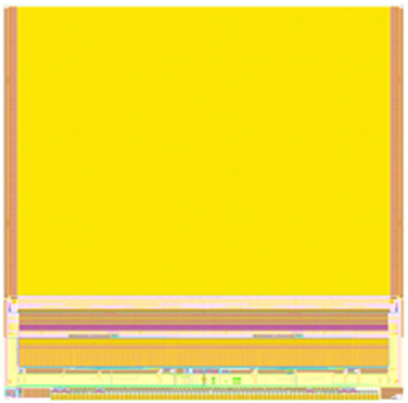
CIS116 pixels

CMOS detectors-8

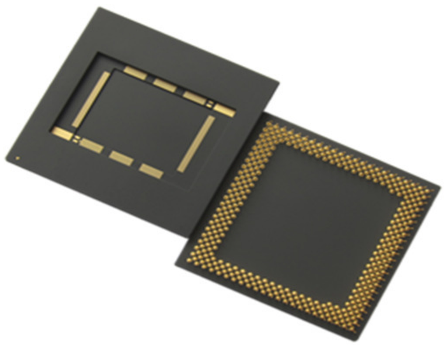
CIS120

Easy to use general purpose imager for space





Layout plot



Package example

Number of pixels:	**2048(H) × 2048(V)**
Pixel size:	10.0 µm square
Package format:	Ceramic-PGA or 3-side buttable option
Maximum charge per pixel:	50,000 e⁻
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 mV (full LVDS)
4 LVDS outputs	8, 10, 12, 14 bits ADC

Rolling and global shutter; SPI programmable configuration
Digital outputs. Designed to be radiation tolerant

Front-illuminated samples due for test- Mar 2017
Back-illuminated samples due for test- 4Q 2017

CMOS detectors-9 …

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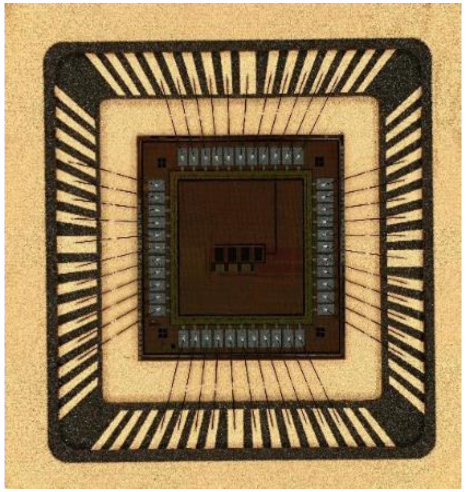
The Open University



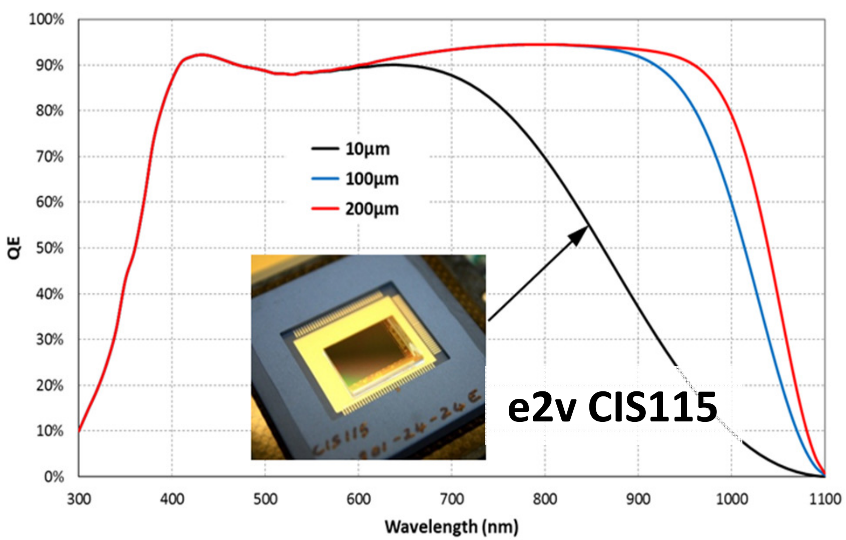
Fully Depleted, Monolithic PPD CMOS Image Sensor Using Reverse Substrate Bias

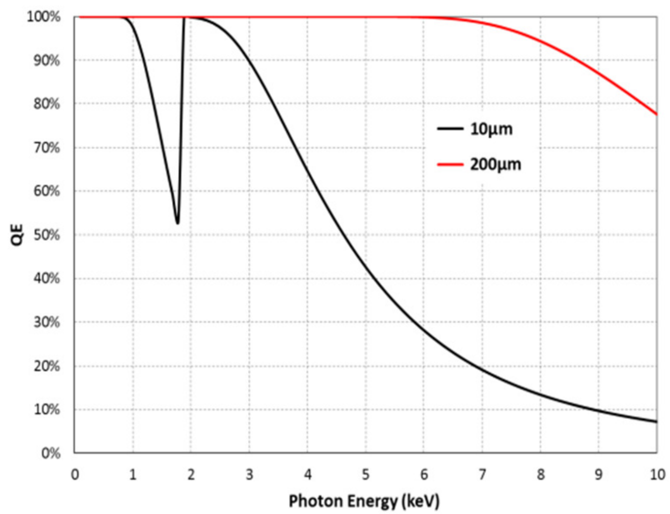
Konstantin Stefanov

Centre for Electronic Imaging (CEI)

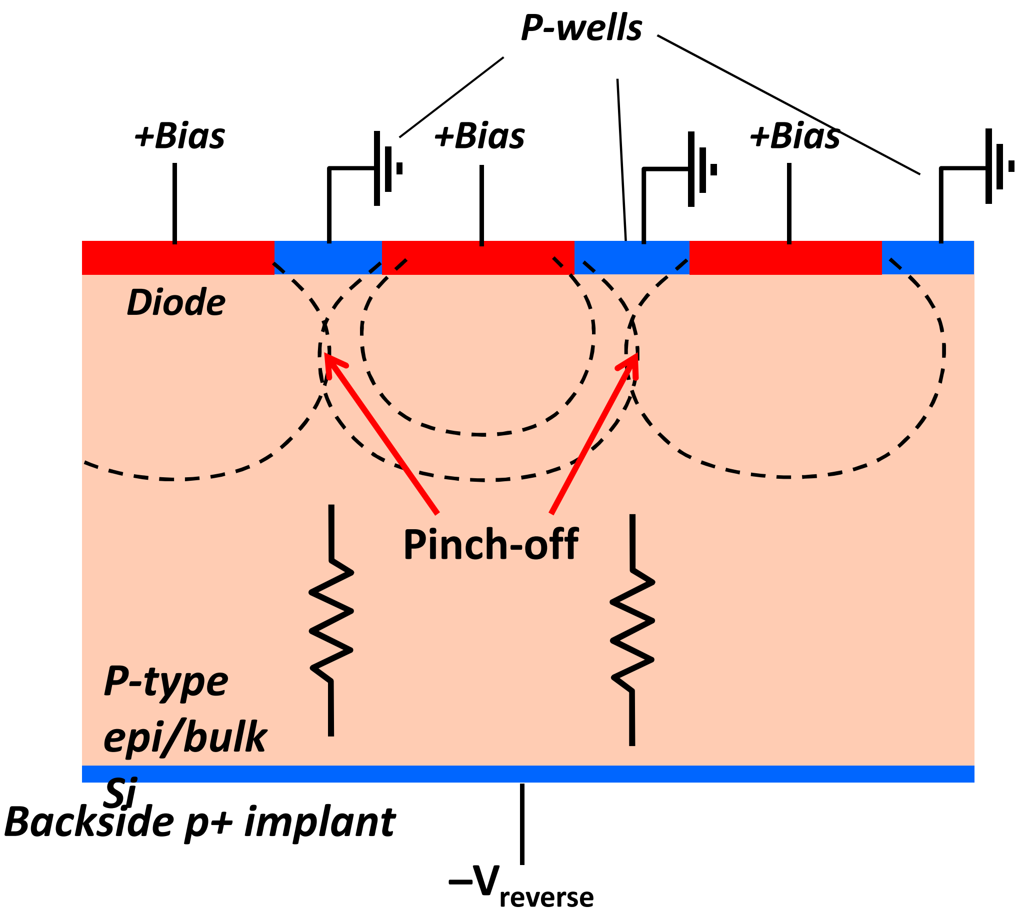
Background

- Demand for thick (>100 µm), fully depleted CMOS sensors for high QE
- Near-IR imaging for astronomy, Earth observation, hyperspectral imaging, high speed imaging, spectroscopy, microscopy and surveillance.
- Soft X-ray (<10 keV) imaging at synchrotron light sources and free electron lasers requires substrate thickness >200 µm
- Low voltage CMOS sensors normally have small depletion depths





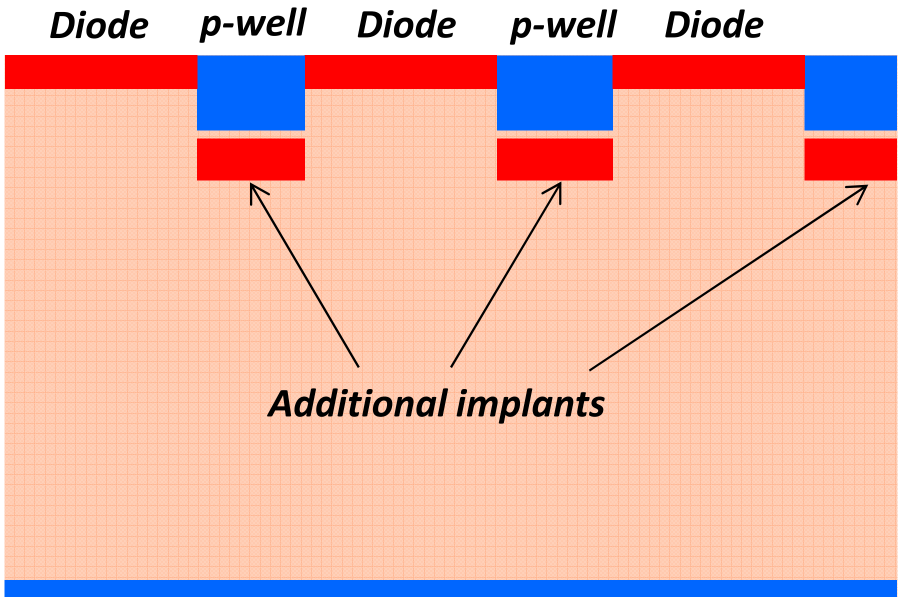
Reverse biasing PPD pixels



- If reverse bias $V_{reverse}$ is applied:
  - p+/p/p+ resistor is formed, leakage current flows
  - This has to be eliminated for a practical device
- Pinch-off under the p-wells is needed at all times (merged depletion regions) to prevent leakage
- The pinch-off condition depends on:
  - Doping and junction depth
  - Photodiode and p-well sizes
  - Bias voltages
  - Stored signal charge
- P-wells should be narrow and shallow
- Photodiodes should be deep

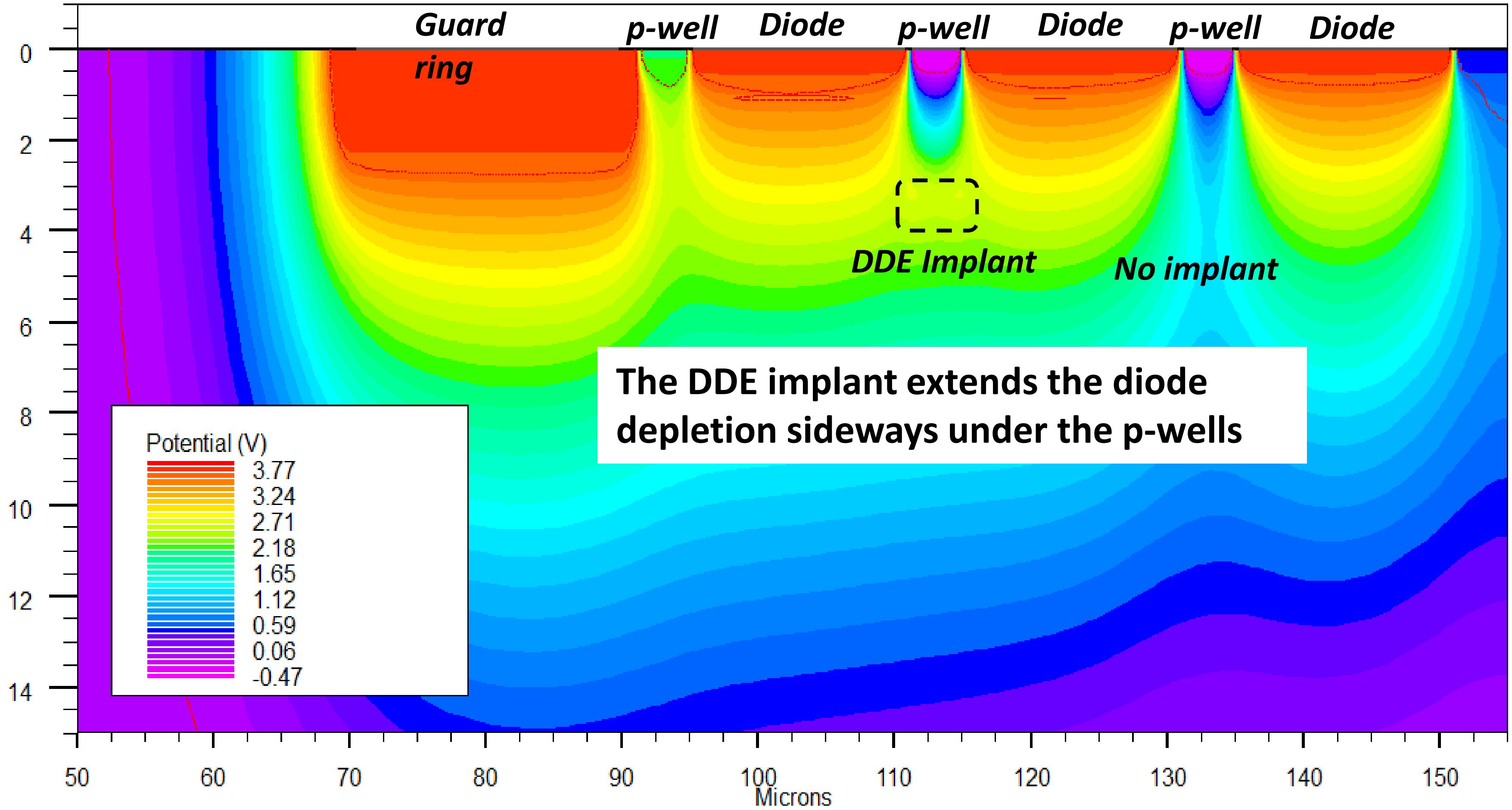
Substrate current suppression

Simplified PPD pixel structure



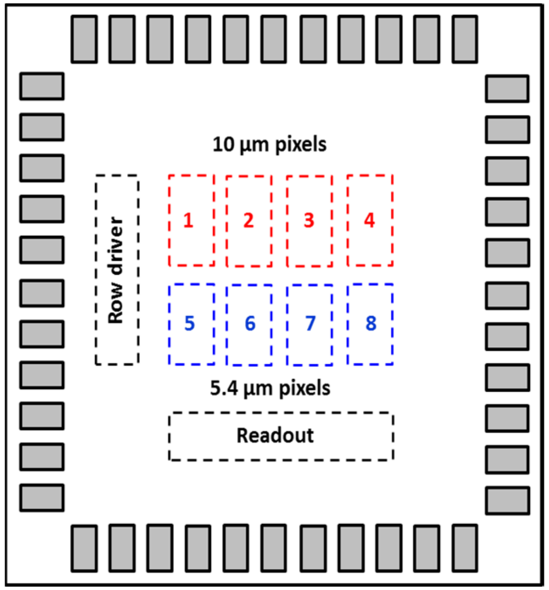
- If the p-wells are deep (as they are usually), pinch-off may not occur
- The p-well should be made to be as narrow as possible, but this is not sufficient
- The CMOS structure makes pinch-off harder to achieve than “high rho” CCDs
- Additional n-type implant added:
  - Under the p-wells
  - Floating
  - Not connected to anything
  - Called Deep Depletion Extension (DDE)
- Patent pending (owned by e2v Technologies)
- Can be applied to any existing design

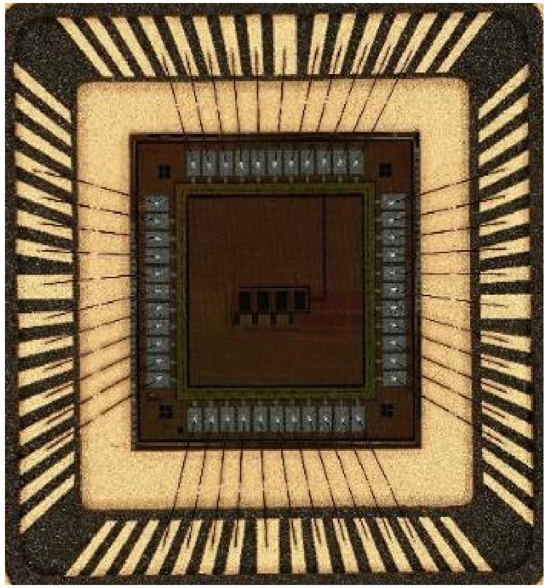
Potentials


Guard ring
p-well
Diode
p-well
Diode
p-well
Diode
DDE Implant
No implant
The DDE implant extends the diode depletion sideways under the p-wells
Potential (V)
3.77
3.24
2.71
2.18
1.65
1.12
0.59
0.06
-0.47
0
2
4
6
8
10
12
14
50
60
70
80
90
100
110
120
130
140
150
Microns

The first chip (BSB1)

- Made on 18 µm 1 kΩ.cm epi, as a proof of principle
  - This reverse bias method applies to any thickness
- Prototyping 10 µm and 5.4 µm pixel designs
  - 8 pixel arrays of 32 (V) × 20 (H) pixels each
- Each array explores different shape and size of the DDE implant
  - One reference design without DDE (plain PPD pixel)
- Custom ESD protection designed
- Delivered in July 2016
- Characterisation goals:
  - Reverse bias and current, prove full depletion
  - Gain, linearity, image lag; comparison with non-modified PPD pixel
  - Over-illumination
  - X-ray response

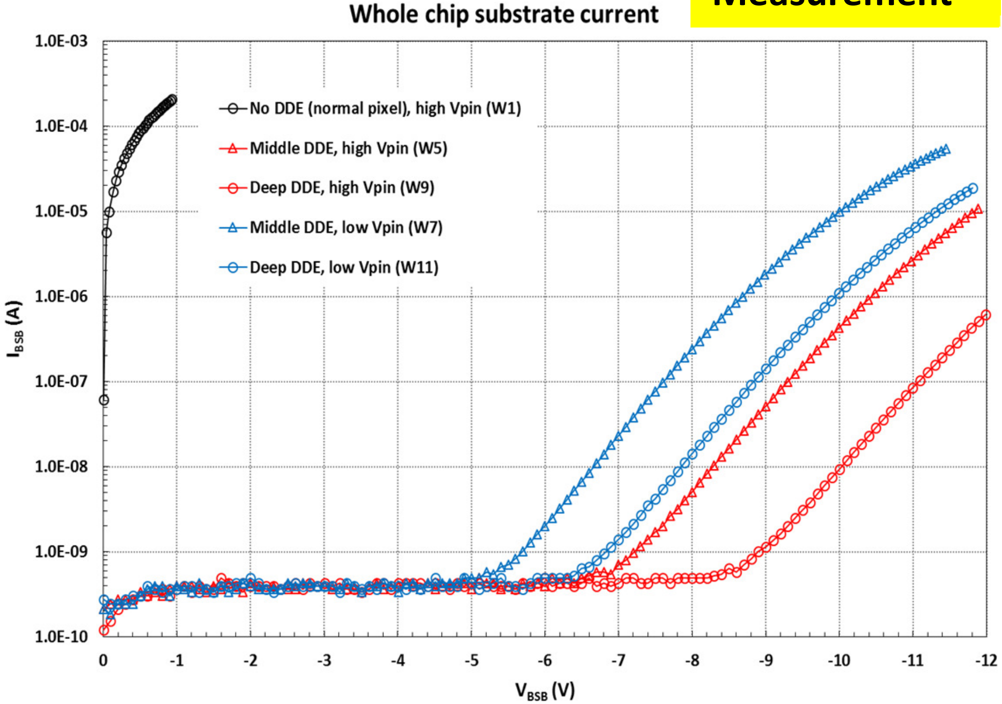




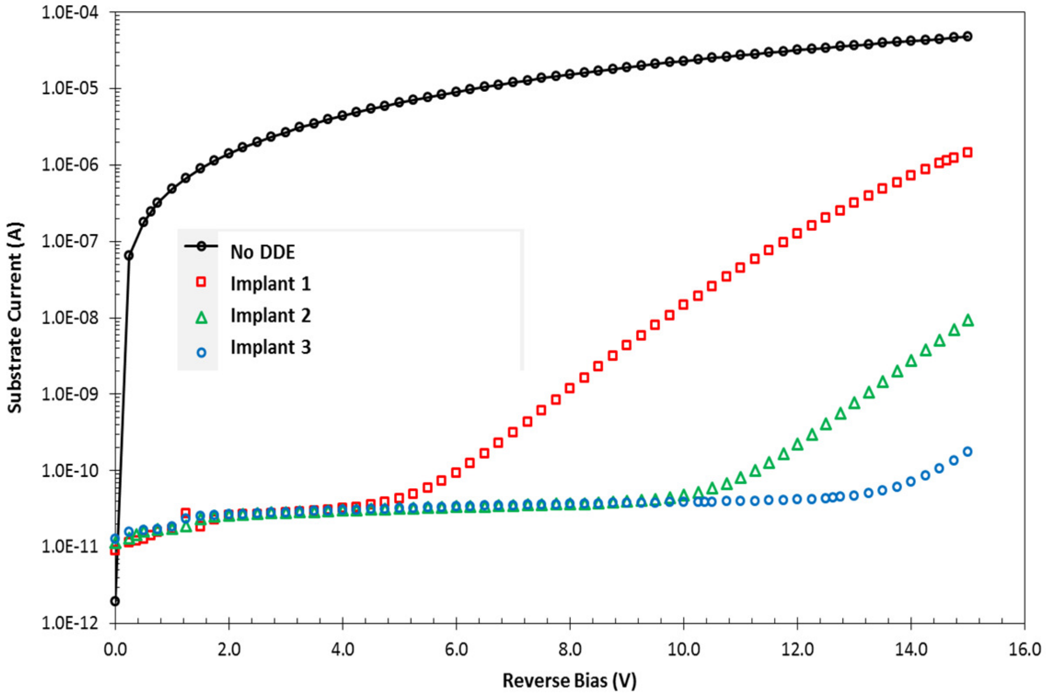
The Open University

Reverse biasing

Measurement

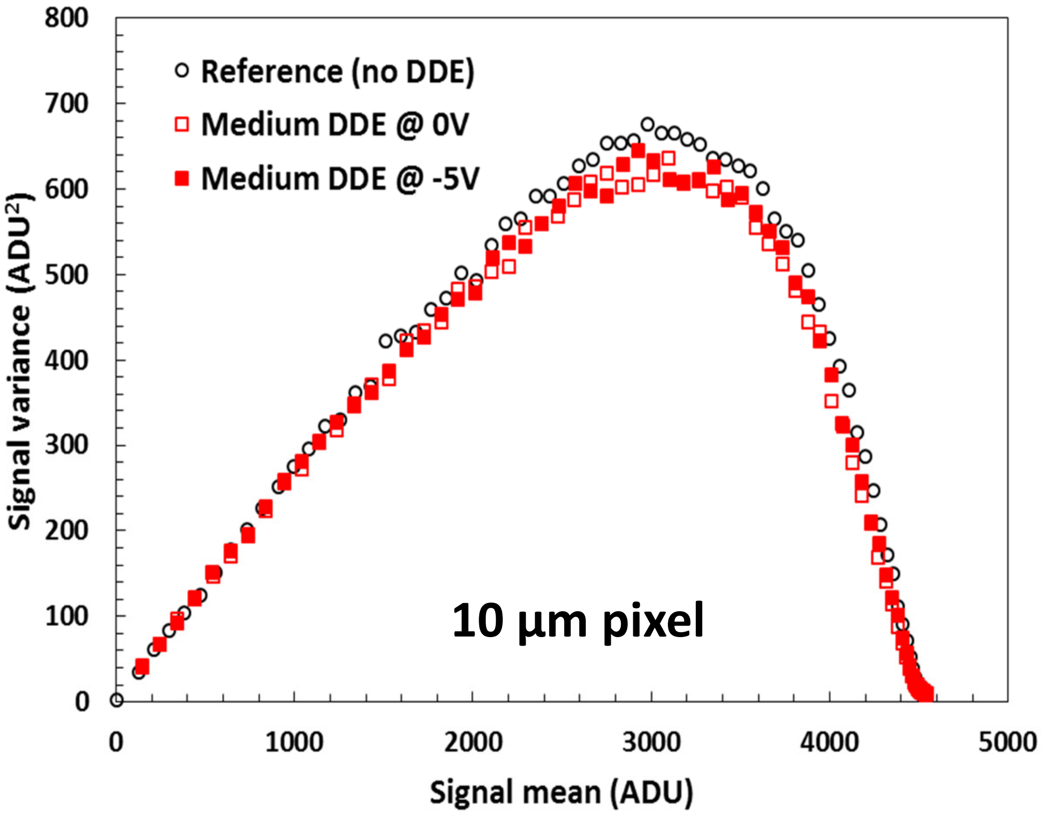


Simulation for high Vpin



- This shows the reverse current for the whole chip, including the logic and ESD pads
- All pixel variants work
- Reverse bias above -5V with no leakage means that any thickness can be depleted
  - V_{BSB} = -4V fully depletes 18 µm thick epi, 1 kΩ.cm
- Qualitative agreement with the simulations
  - The measurement is for all 8 variants in parallel, simulation is for one variant only

Electro-optical performance

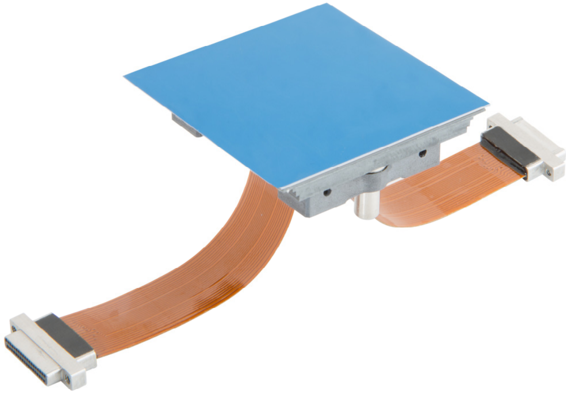


- Photon transfer curves taken under various conditions
- 10 µm pixel:
  - CVF ≈ 80 µV/e- (design = 70 µV/e-)
  - FWC ≈ 15 ke- (design = 20 ke-, limited by the sense node)
  - Noise (in our system) ≈ 8 e- RMS
- 5.4 µm pixel:
  - CVF ≈ 36 µV/e- (design = 33 µV/e-)
  - FWC ≈ 15 ke- (design = 45 ke-, limited by the sense node and off-pixel circuits)
- The new pixels appear identical to the "normal" pixels
- The DDE implant and the reverse bias do not seem to affect the electro-optical performance – great!

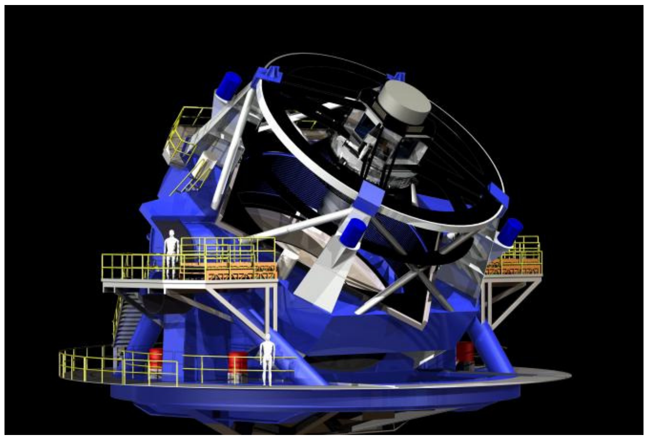
Conclusions

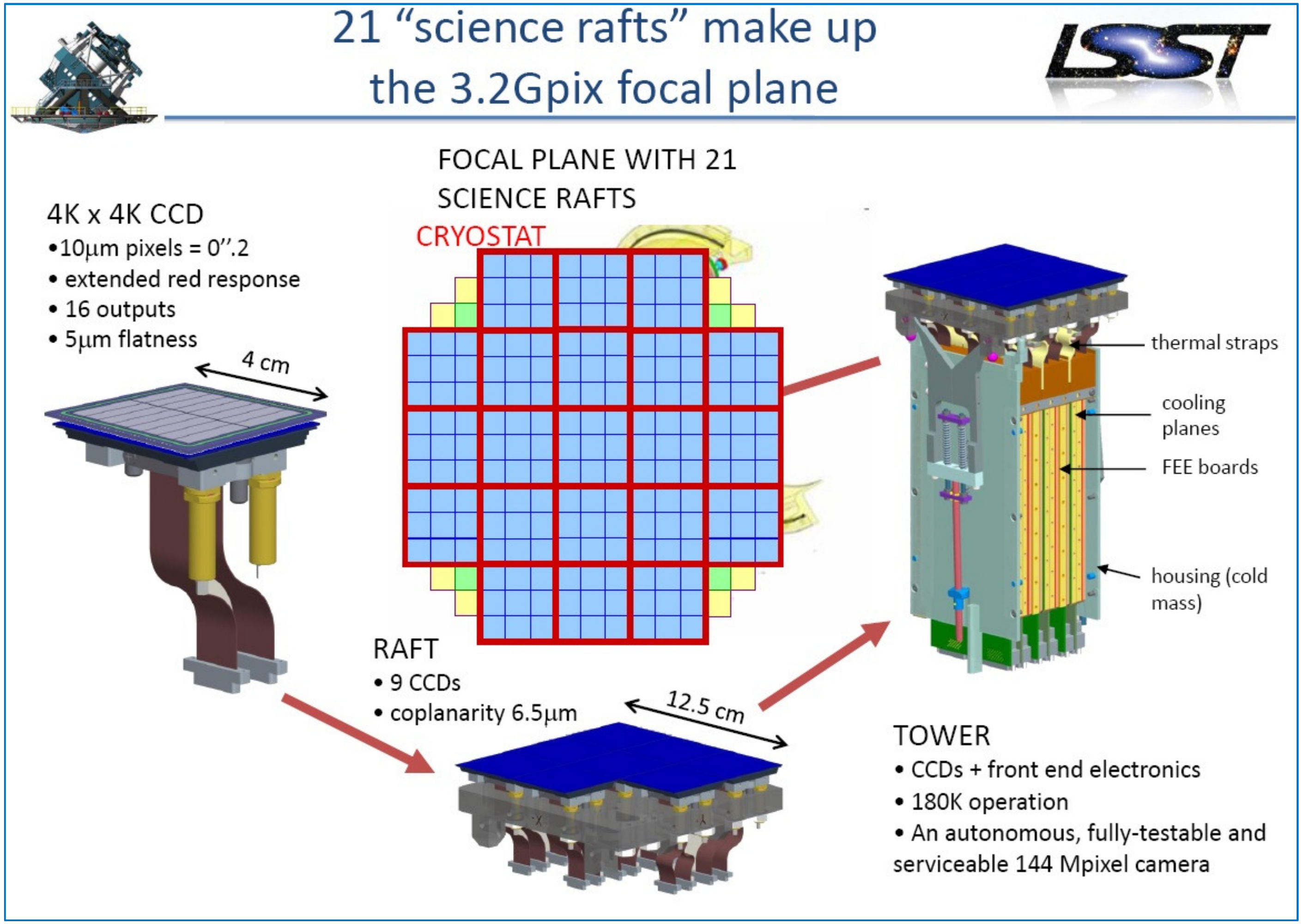
- New development of fully depleted monolithic PPD CMOS sensors using reverse substrate bias
  - A paper in IEEE Electron Device Letters (in press)
- Based on the idea of “depletion extension”
- First prototype designed on 18 µm, 1 kΩ.cm epi as a proof of principle
  - Can be scaled to much thicker epi/bulk substrates
  - Front-face results shown here
  - Back-thin (demo device) to be tested ~ March 2017
  - Aim to design & make 40 um thick imager next……
- Can be attractive to large number of applications
  - High QE on a par with thick CCDs and hybrid CMOS
  - Low noise, 4T architecture with minimum changes
- Competitor to scientific CCDs?

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





Pictures courtesy: LSST

Contents-2

Bringing life to technology

We illustrate selected EMCCDs

Internal electron gain allows sub-electron read-noise

Combined with backthinned spectral response for very high sensitivity

Several formats and sizes available

Standard (non EMCCDs) are not discussed in this presentation- many are visible on e2v.com

2. EM CCDs
    - Standard L3Vision sensors
    - Custom sensors for astronomy & science

CCD sensors-1

e2V Bringing life to technology

CCD201

- Standard product
- 1024 X 1024 pixels; 13 μm pixels
- Larger format than CCD97 (512 X 512 pixels)
- Widely used for commercial applications
- Also useful for astronomy at low signal levels
- Sub-electron read noise
- Backthinned for high spectral response
- Inverted mode dark current

Planned for Space use : NASA WFIRST Coronagraph

Harding L, et al, "Technology advancement of the CCD201-20 EMCCD for the WFIRST-AFTA Coronagraph Instrument...," JATIS 011007, (2016).

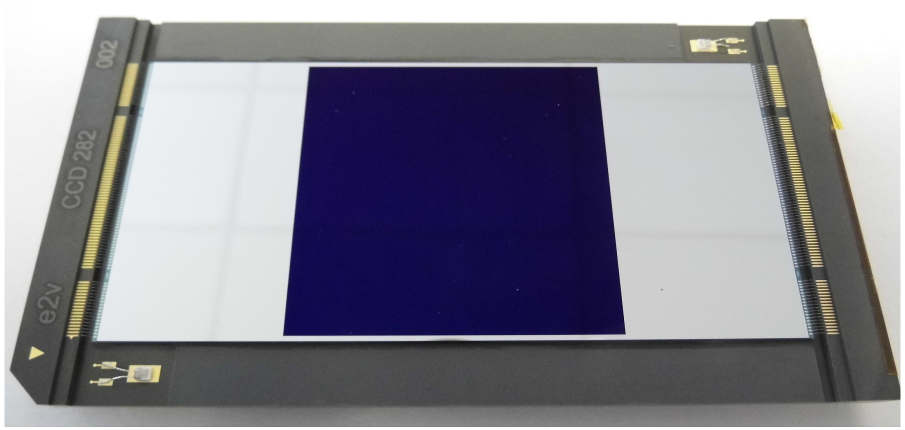
See poster by Nathan Bush, 9904, Tues pm

CCD sensors-2

e2V Bringing life to technology

CCD282

- Largest EMCCD manufactured to date
- 4096 X 4096 pixel image area
- Split frame-transfer read-out with 8 outputs
- > 4 frames per second
- Sub-electron read-noise
- Backthinned for high Quantum Efficiency
- Very low levels of clock-induced charge
- Non-inverted operation at cryogenic temperatures
- Development is complete; sensors have been delivered

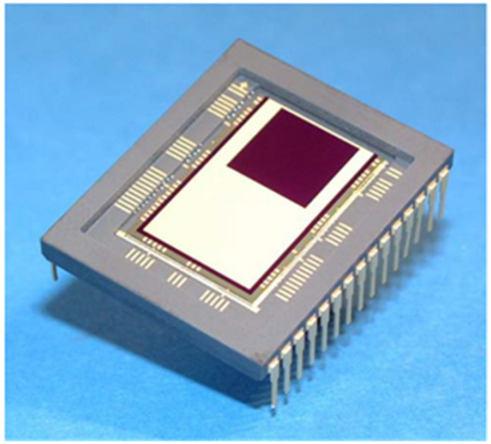


Gach Jean-Luc, et al, “Development of a 4kx4k frame transfer electron multiplying CCD for scientific applications,” Proc SPIE 9154, (2014).

CCD sensors-3

CCD351

- Standard product, for commercial use
- L3Vision technology for sub-electron read-noise
- Video rate readout
- Backthinned spectral response
- In standard production



Package illustration (not final)

Typical Performance

Image section	**1024 x 1024**
Pixel size	10 µm × 10 µm
Active image area	10.24 × 10.24 mm
Package size	22.86 × 28.00 mm
Amplifier responsivity	3.5 µV/e–
Readout noise	< 1 e- (with EM gain)
Multiplication gain	100-1000 typical
Output data rate	37 MHz
Pixel charge storage	35 ke-/pixel
Dark signal (18°C)	100 e-/pixel/s

Contents-3

e2v develops sub-systems to complement its supply of sensors.

- **Bespoke systems are optimised for each application and use common modules where appropriate.**
- **Performance of sensors combined with system can be guaranteed.**

Precision System Assemblies-1

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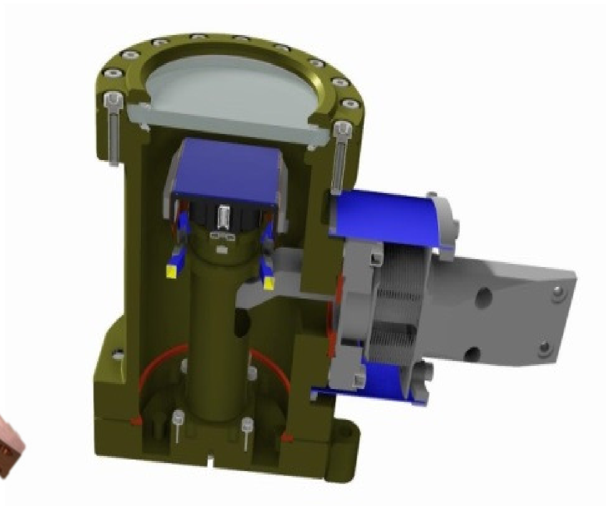
WUVS

World Space Observatory UV Spectrograph

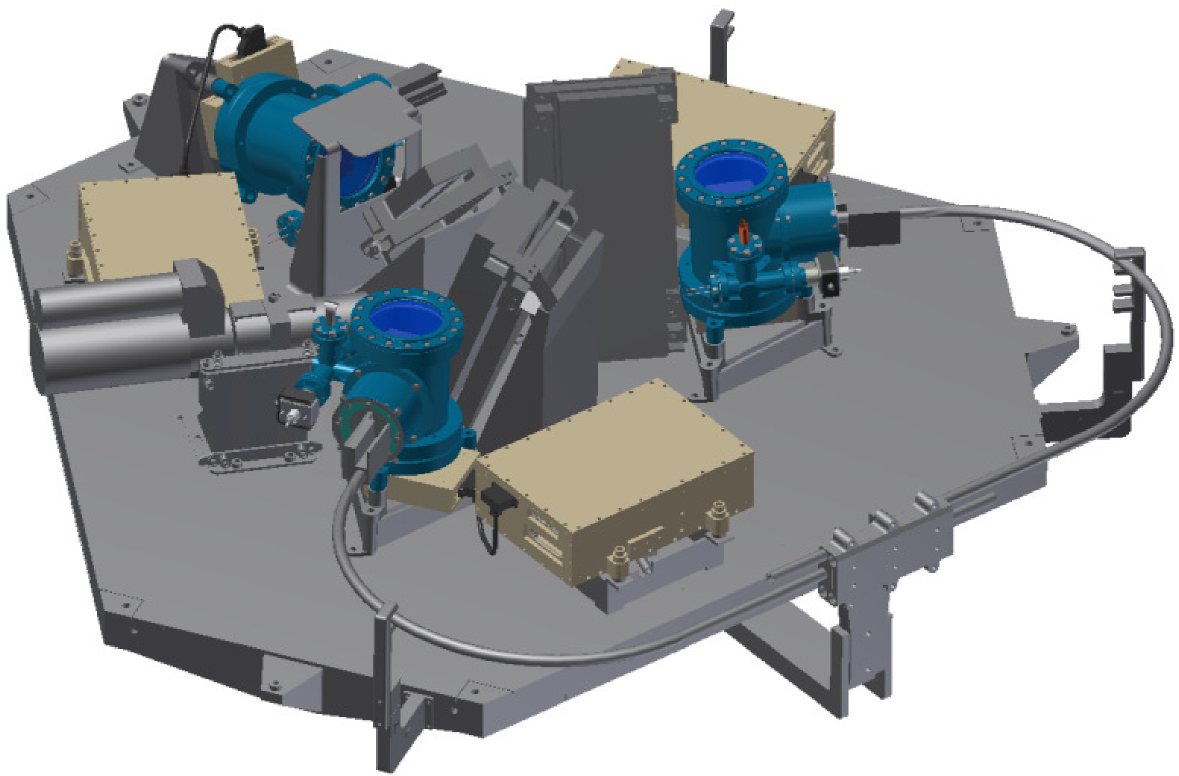
- 115-310 nm range covered by three sensor channels
- Custom sealed vacuum cryostat enclosures for 9 year life
- with flight electronics (associated with RAL Space)
- UV optimised custom CCD272 operated at -100°C
- Components maintain alignment after shock & vibration of launch
- Design and manufacture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



Precision System Assemblies-2

WUVS

Triple detector unit detector layout with camera electronics units



See Poster by Vladimir Panchuk, 9905, Sun pm

Precision System Assemblies-3

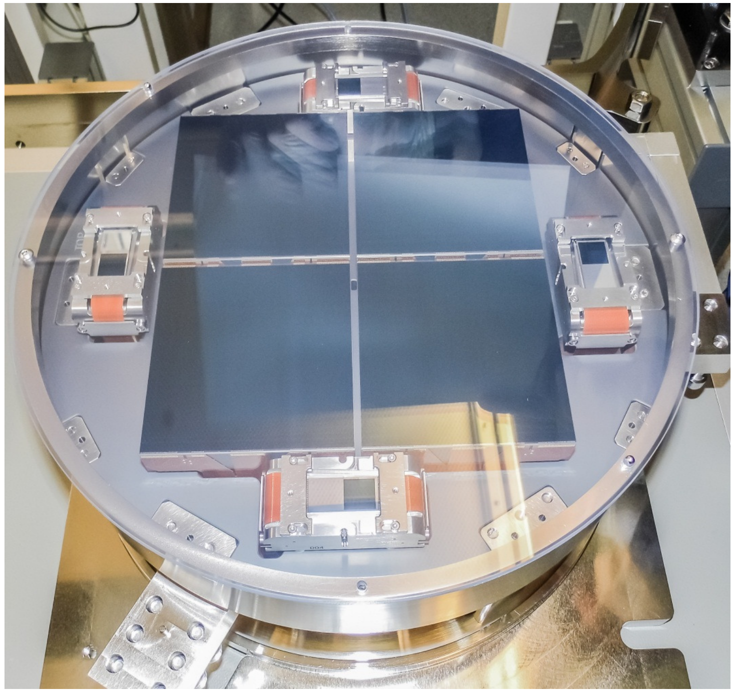
KMTNet focal planes

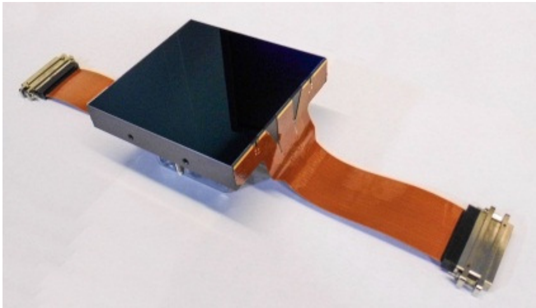
Korea Micro-lensing Telescope Network

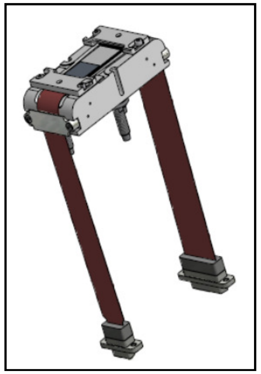
3 telescopes each with its own camera; 350 mm focal plane; 340 MegaPixel each

Each camera had four CCD290 science sensors and four guide sensors; < 30 µm flatness

Focal planes are complete (e2v) , operational and installed in cameras (by Ohio State University)







See Poster by Dae-Sik Moon, 9906, Mon pm. Also see previous paper Jorden et al, SPIE 2014

Precision System Assemblies-4

J-PAS Cryocam

A 1.2 Gigapixel cryocam for use on the 2.5m OAJ telescope for the J-PAS survey.

e2v has delivered (mid-2016) this important commercially-suppled astronomical camera

Precision System Assemblies-5

J-PAS Cryocam

Table of key features

450 mm focal plane diameter	-100ºC operating temperature	Stable to +/- 0.5ºC
27 µm peak-valley flatness	Measured at -100C	Stable against flexure
14 science CCD290-99 sensors:	1.2 Gig pixels	9K X 9K sensors
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 of science CCDs	Local frame stores
Complete LN2 cooling system	Integrated vacuum system	Post-delivery support
Cold light baffle	High Quantum Efficiency	minimum reflection AR coat

See paper by Mark Robbins, 9908, Tues 28 June 2016, am, S8

And K Taylor et al, JPCAM, JAI vol 3, 2014

Summary

- An increasing number of sensors are being developed using CMOS architectures

  Many of these are backthinned and offer low read-noise (comparable to CCDs)

- CCDs continue to be used in larger quantities and with greater heritage

- e2v offers custom system solutions including cryogenic cameras and electronic modules to complement its supply of sensors- and with guaranteed performance

Thank you for your attention

e2v Bringing life to technology

WE PARTNER WITH OUR CUSTOMERS TO IMPROVE,
SAVE AND PROTECT PEOPLE’S LIVES

OUR INNOVATIONS LEAD DEVELOPMENTS IN COMMUNICATIONS, AUTOMATION,
DISCOVERY, HEALTHCARE AND THE ENVIRONMENT