Synchrotron Radiation workshop

e2v image sensors for high end applications

Paul Jerram

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The e2v Group

11 Global locations

4 Production facilities

50+ Countries served

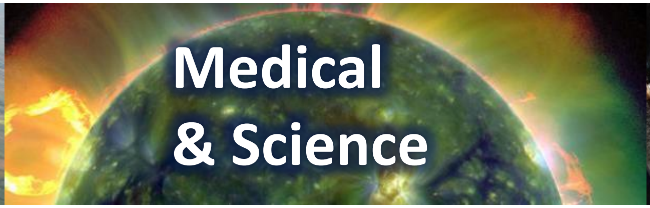
Founded in 1947

Annual sales of £225m

1700 employees

500+ engineers & scientists

Operational facilities in Europe, the US and Asia



Two Imaging Divisions

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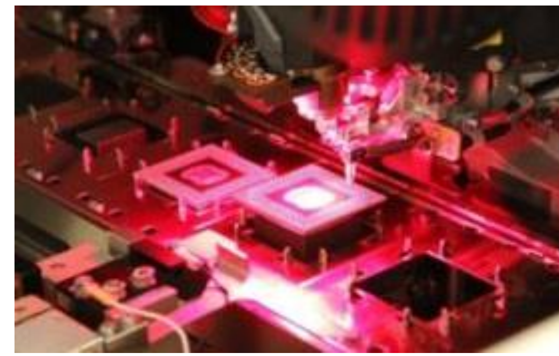
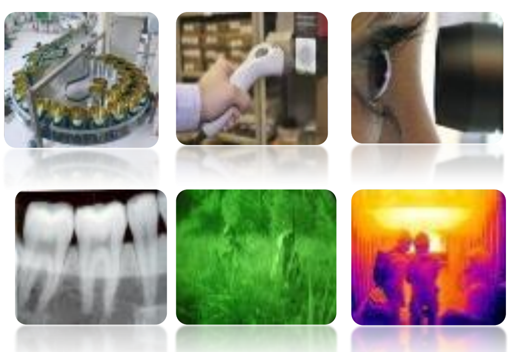
RF power

Imaging

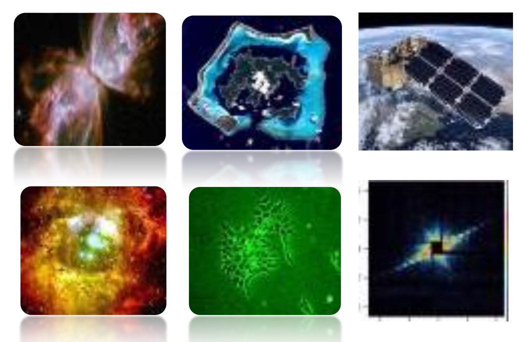
Semiconductors



Professional imaging



Space and physics imaging



Topics

- e2v Introduction
- Back-thinning summary
- Examples of detector technology for space, science and astronomy:
- Synchrotron radiation detectors
- CCDs for XFELs
- CMOS sensors for synchrotron radiation detection

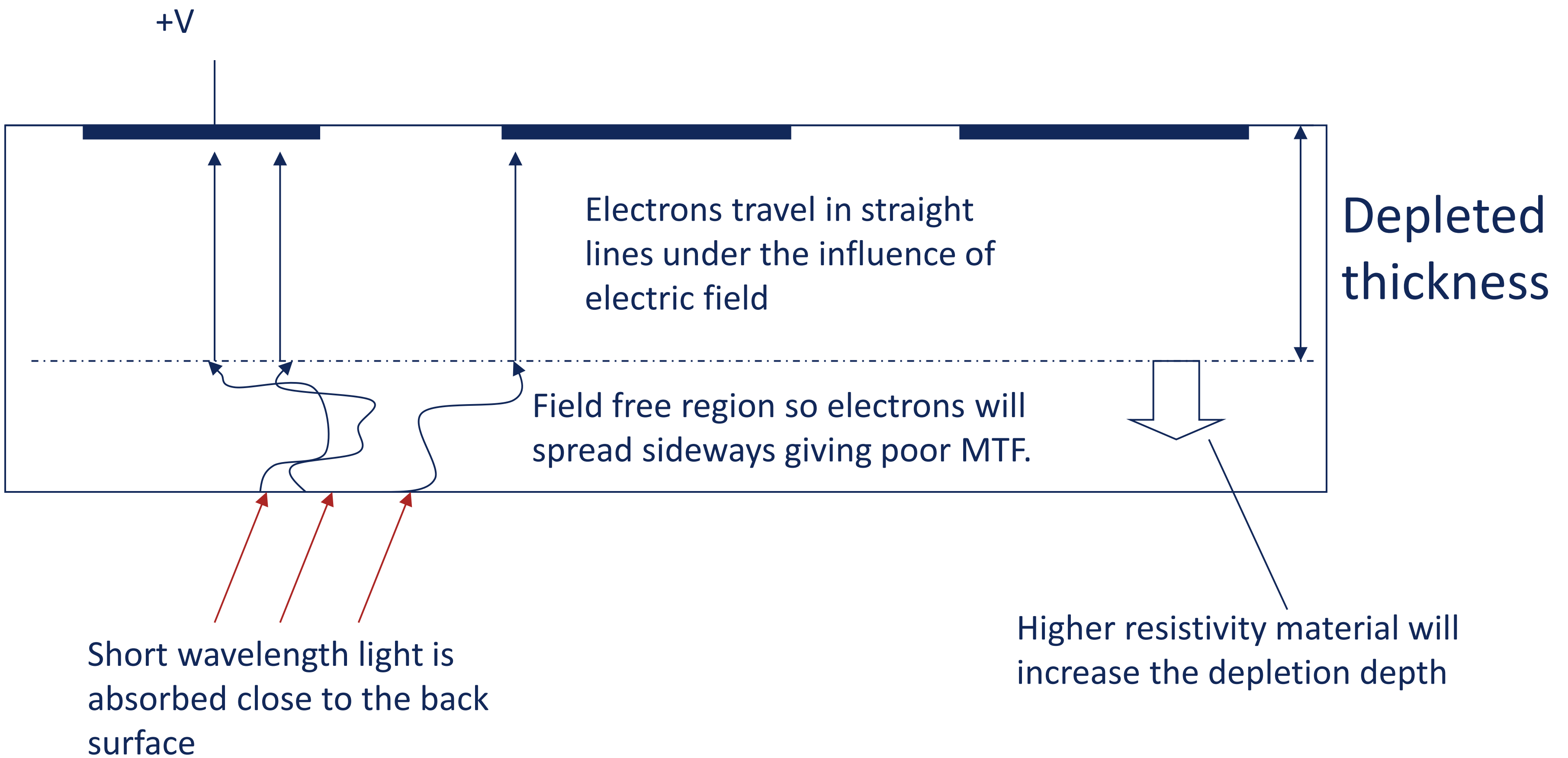
Backthinning

Quantum efficiency is critical for all of our applications – both for visible light and for extended spectral response to NIR or UV and soft x-rays

Standard devices have structure on the front that decreases this efficiency.

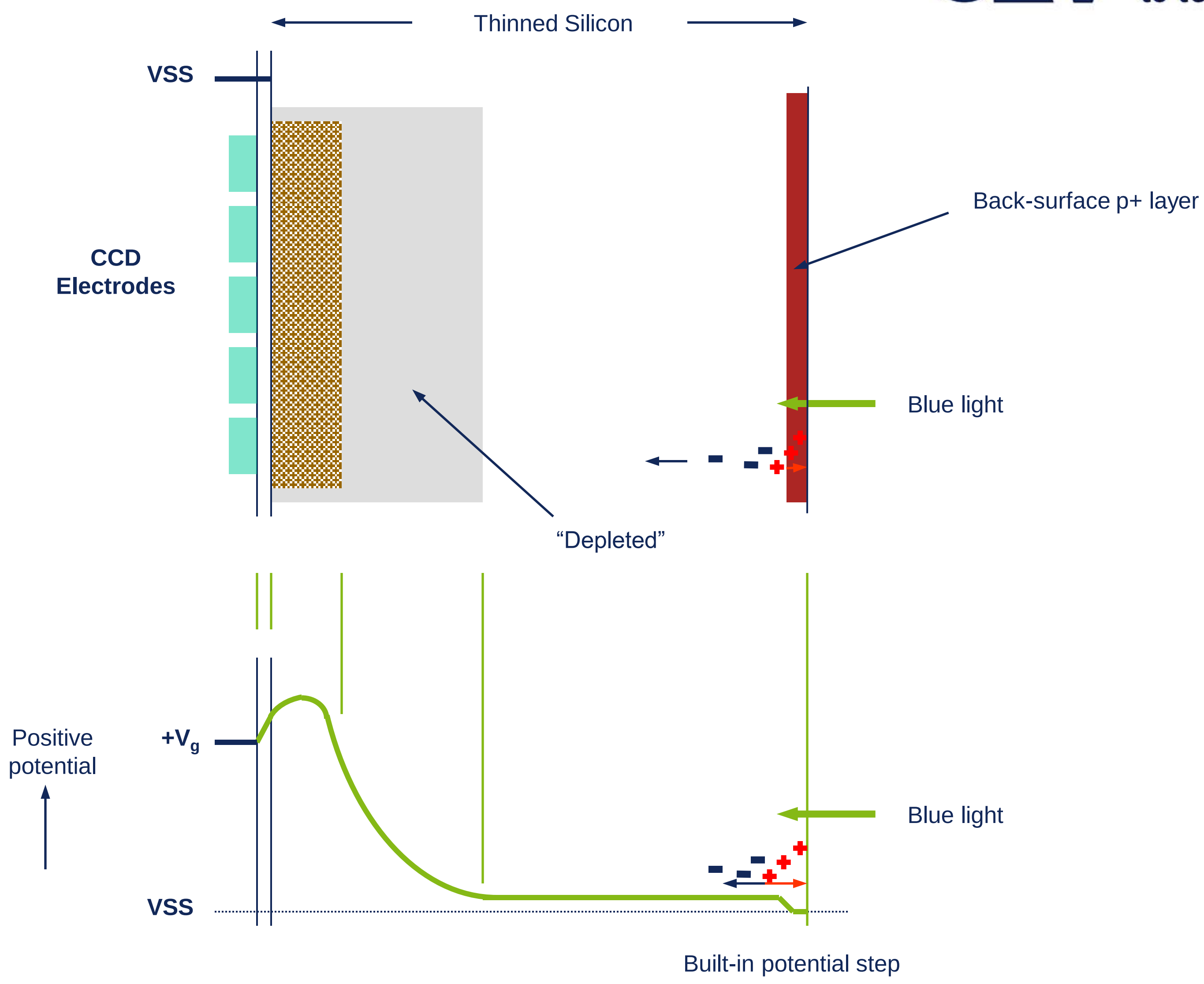
To maximise spectral response backthinning has been used for many years for high end applications

Requirements for backthinning



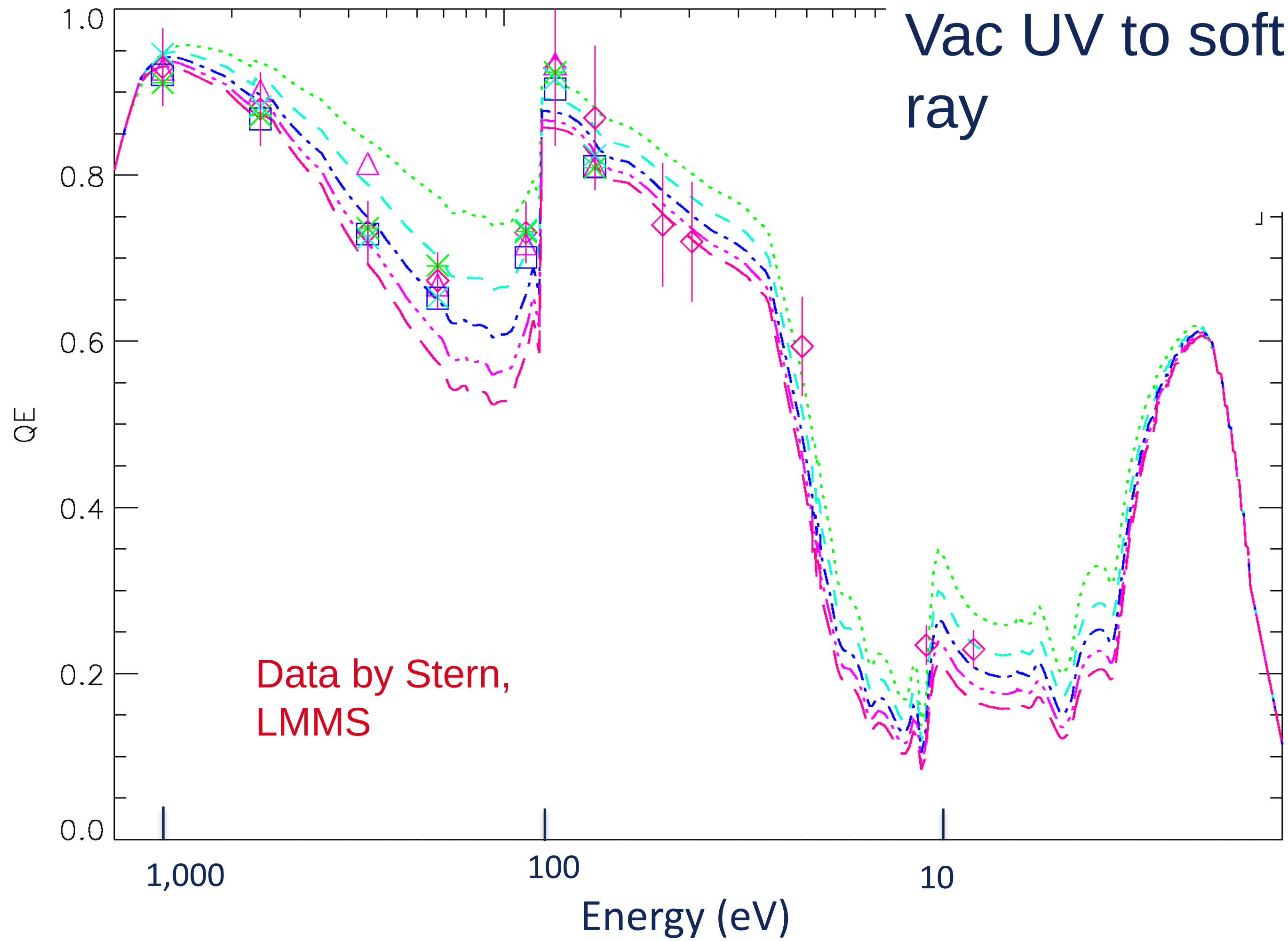
- MTF is determined by the ratio of the undepleted thickness to the pixel pitch
- Long wavelength QE is determined by the total thickness

Back-thinned structure



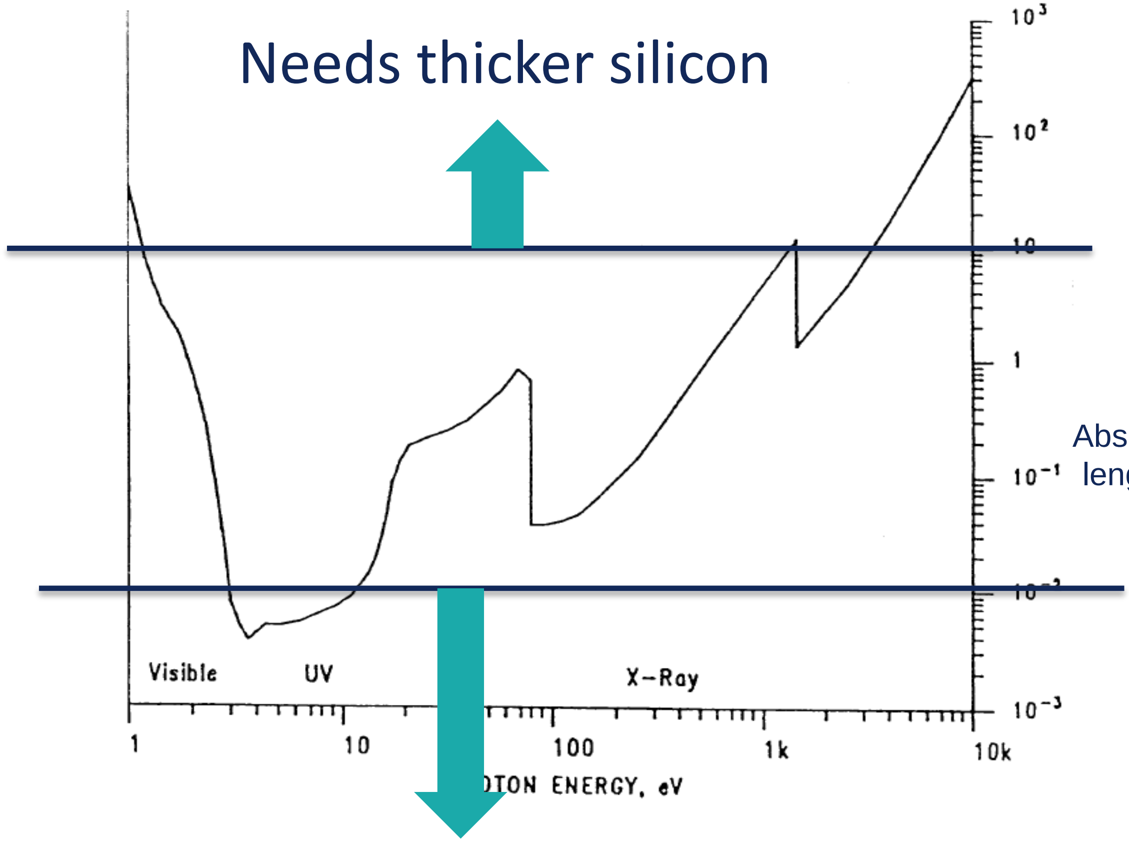
Standard silicon QE

Vac UV to soft X-ray



Absorption length

Needs thicker silicon



10 µm

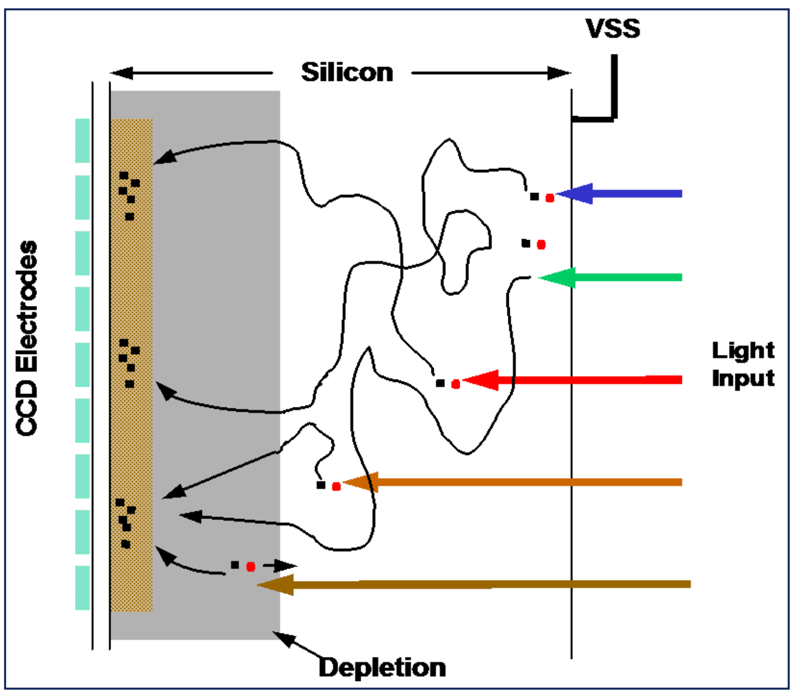
Absorption length µm

Back surface dead layer is critical

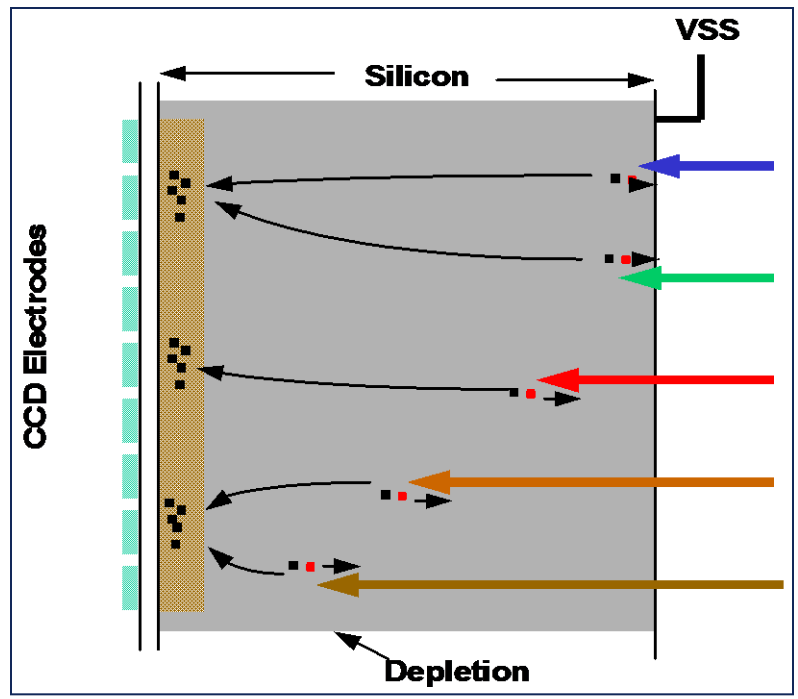
HiRho CCDs

Full depletion (minimum undepleted depth) is necessary for high MTF (good PSF)

Thick bulk silicon is used with low doping density (high resistivity), and an increased substrate voltage Vss (typically ~-70V) to extend the depth of depletion



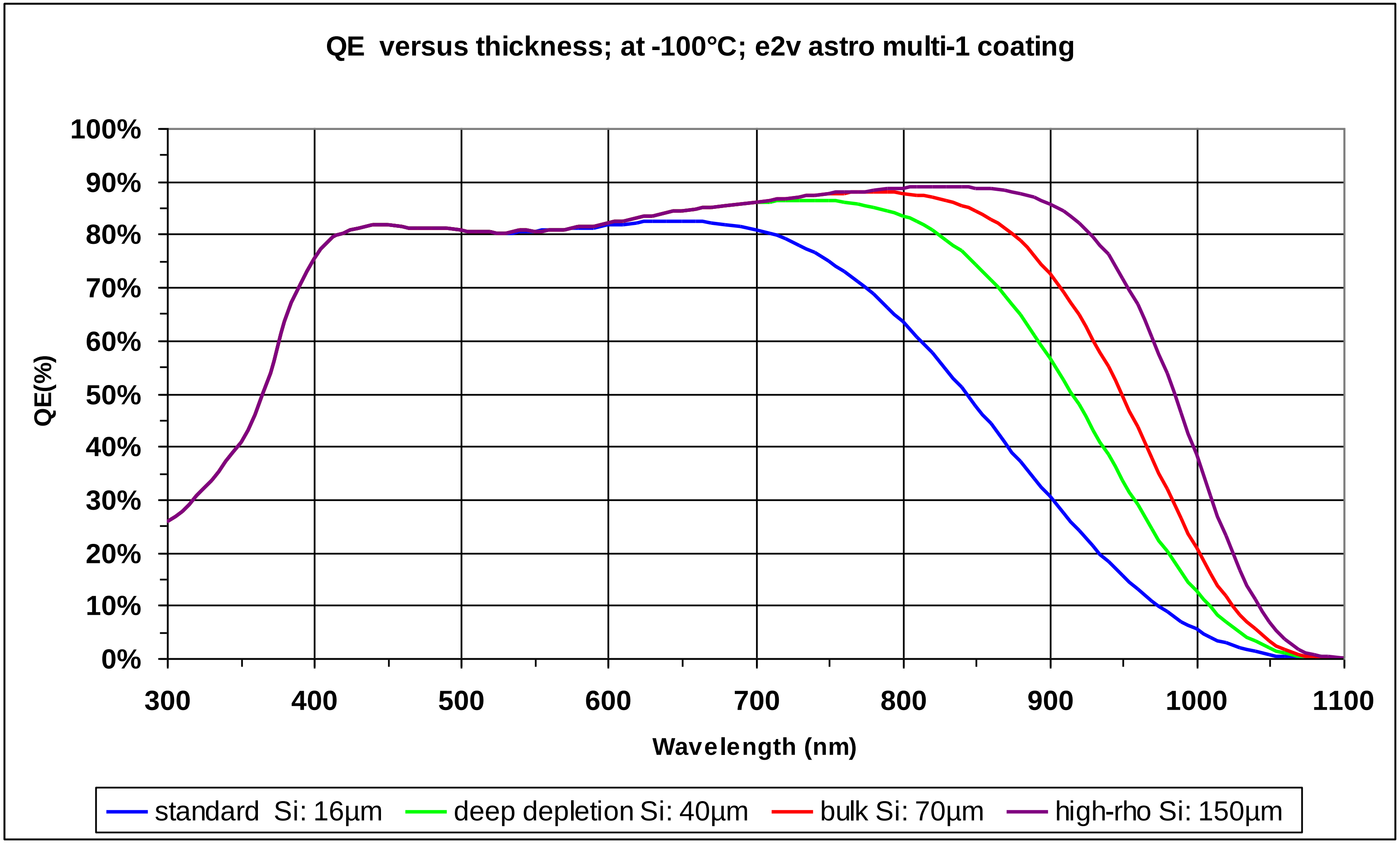
Low substrate voltage



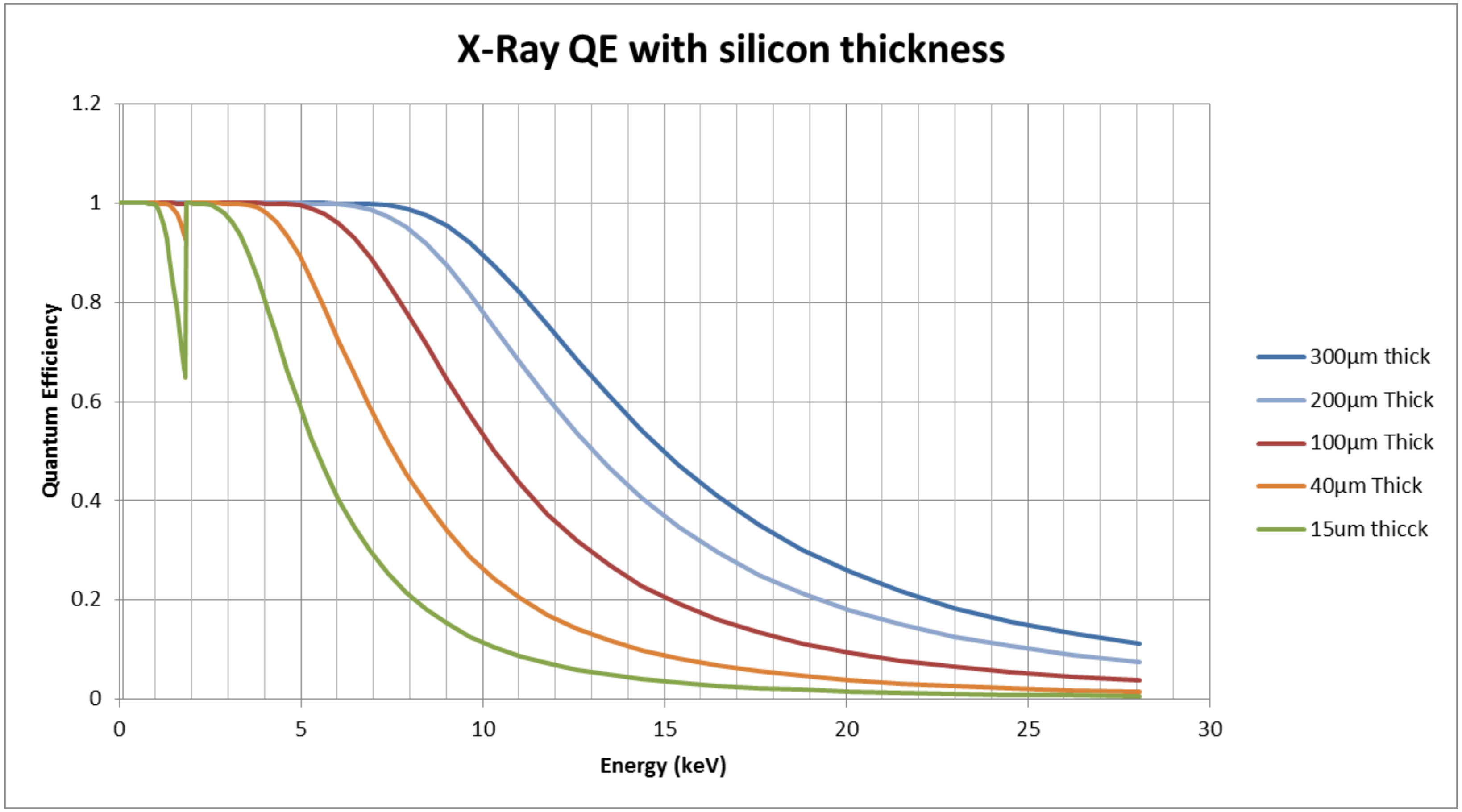
High substrate voltage

Improving red response

- Modelled change in QE with device thickness is as shown below



CCD Soft X-Ray QE



Variation of QE with silicon thickness – Model courtesy of Neil Murray, CEI, Open University, UK

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Space – Earth Observation

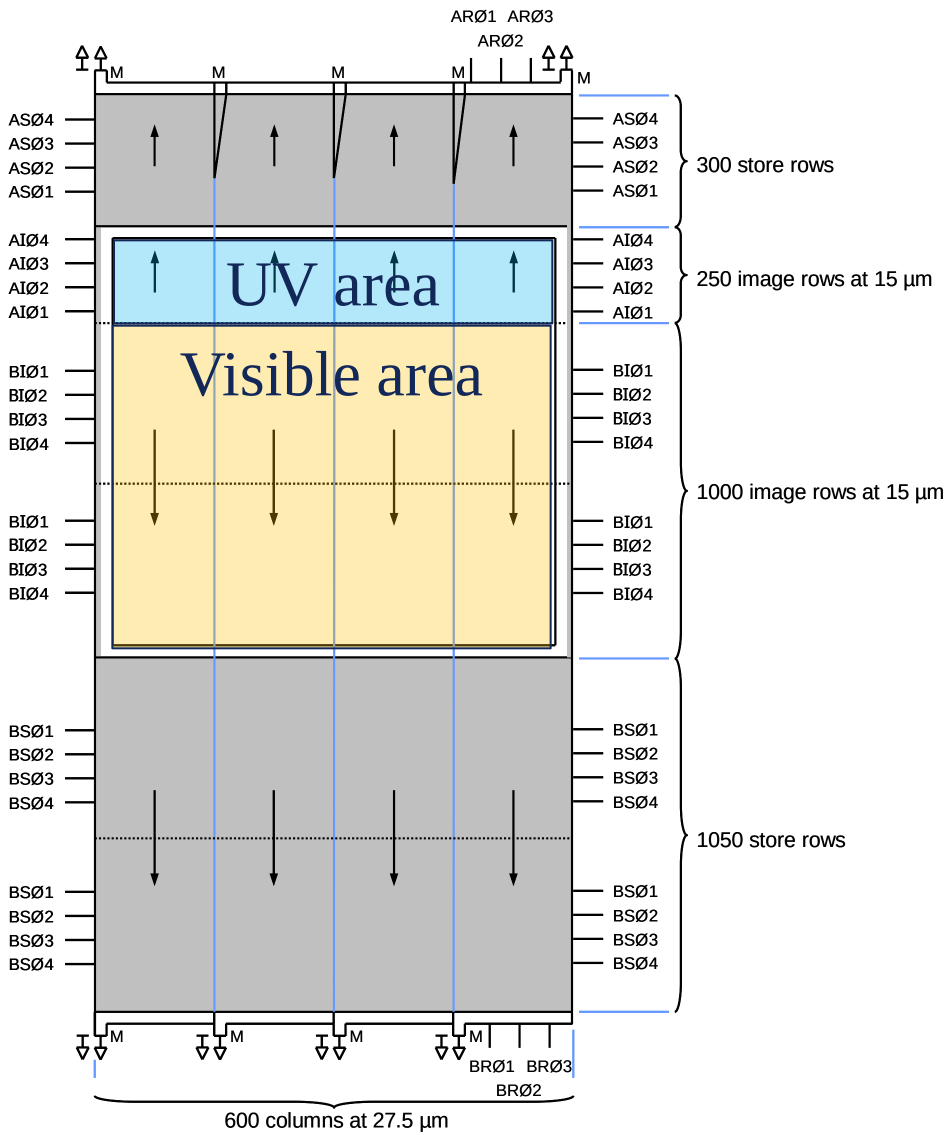
There are a number of existing and new hyperspectral programmes being run or currently in planning for ESA

- Sentinel 3
- Sentinel 4
- Tropomi
- Sentinel 5
- FLEX
- 3MI

The general trend with this devices is for larger pixel sizes and multiple readout ports to give higher speeds and increased peak signal (or dynamic range).

Most hyperspectral imagers still use CCDs but there is a trend towards CMOS as it allows higher frame rate and less crosstalk but at the expense of dynamic range

Sentinel 4

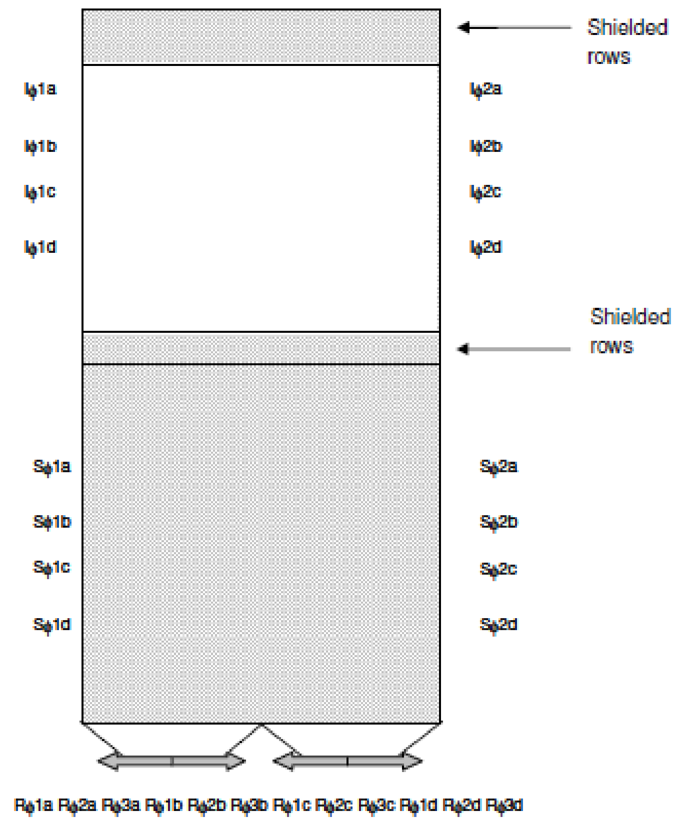


- Readout speed is 1.2MHz with a noise of approximately 20e at 1.4µv/e (using real and dummy outputs for common mode noise suppression)
- Frame transfer frequency 400kHz
- Peak Signal 1.4Me
- 97dB dynamic range

TropOMI – Sentinel 5 precursor

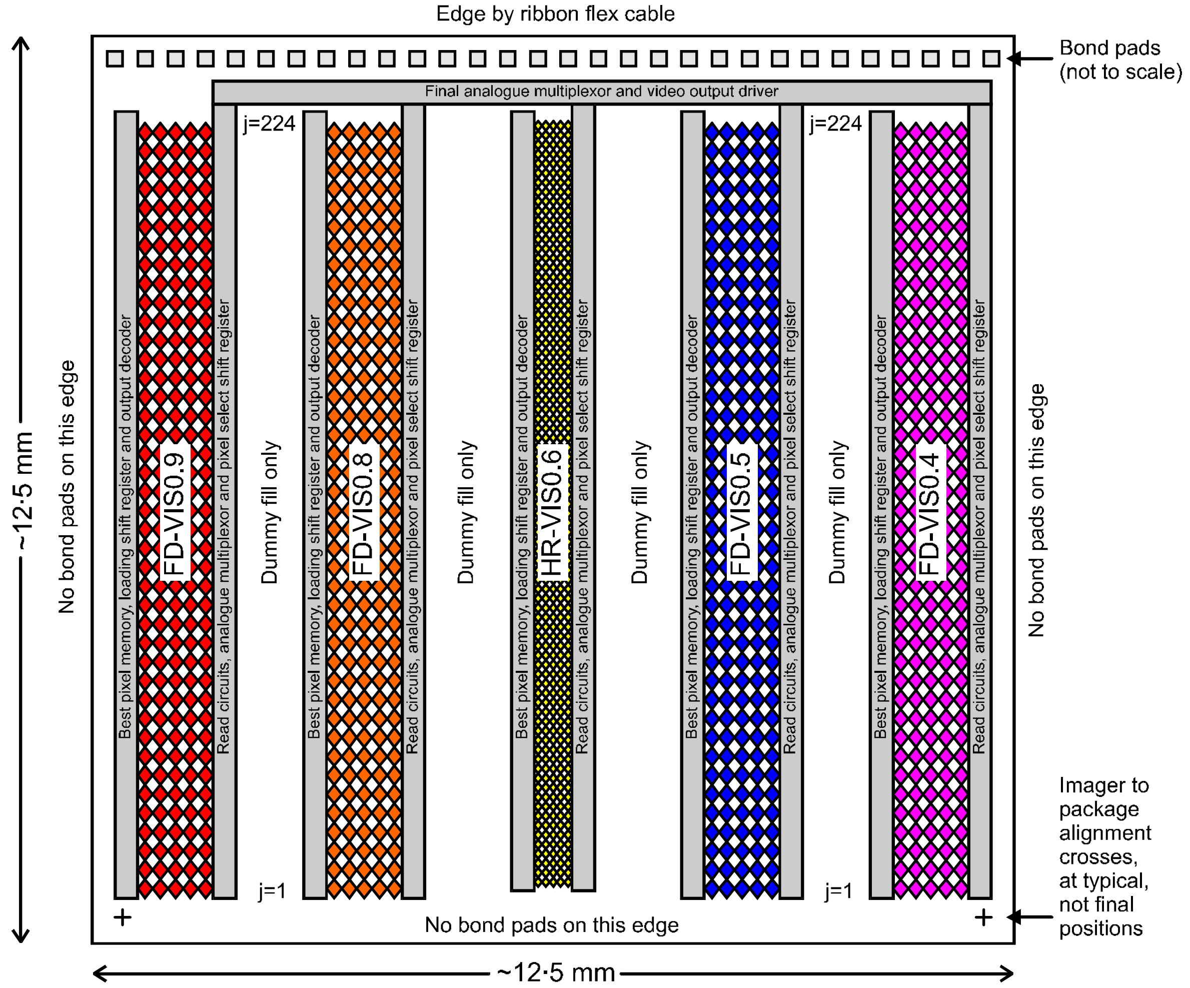
- TropOMI – Tropsheric Ozone Monitoring Instrument
- Aim to bridge the gap between Envisat / Aura and Sentinel 5 (2020)

- UV, VIS and NIR (40um thick epi) imagers
- CCD275
- 1024 x 1024 image area with 26 mm square pixels
- 2 phase image and store pixels with metalisation for fast line transfer
- 0.75µs per line
- 5MHz pixel frequency
- Peak signal >700ke with noise <50e
- Switchable gain amplifier



MTG FCI sensor

- The format of the sensor is shown below with 5 channels of rhombus shaped pixels operating at different wavelengths



MTG FCI Sensor 4T Pixel design

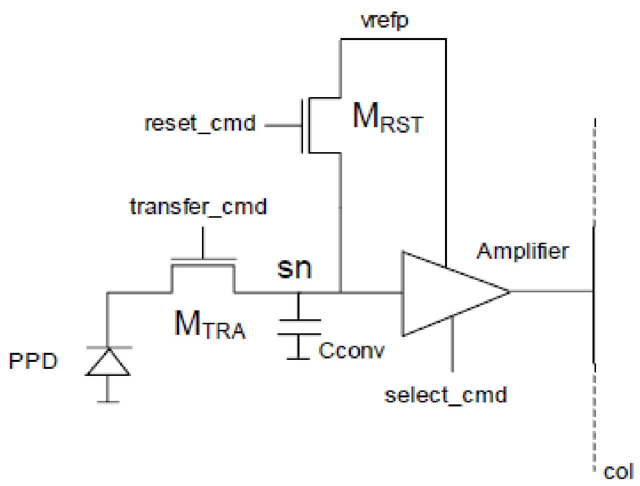


Figure 1: Schematic representation of a 4T pixel with photodiode.

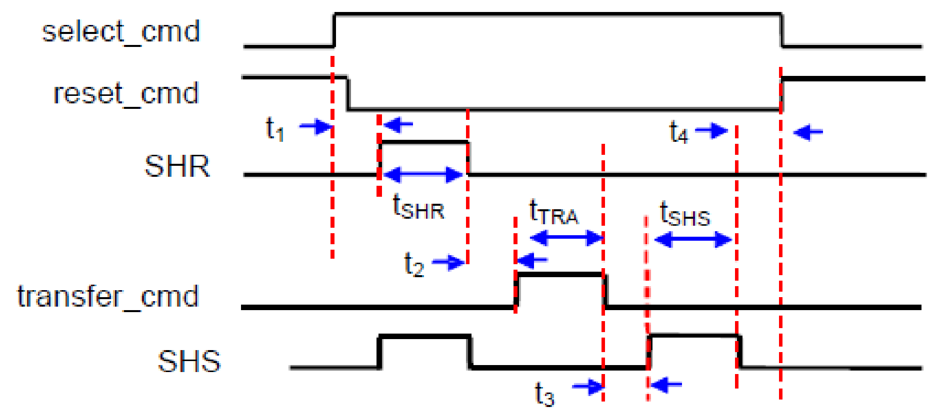
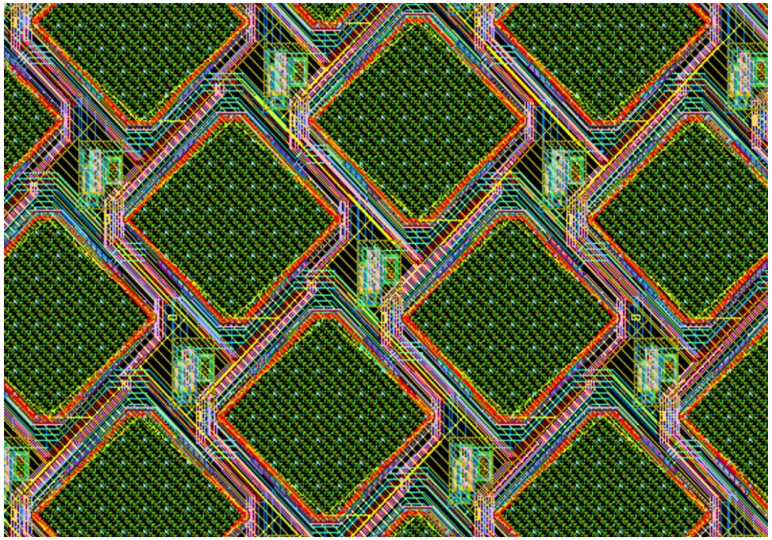


Figure 2: Pixel timing diagram.



FD: ~ 80 um photodiode
HR: ~40um photodiode

The array is composed of Rhombus pixels for MTF considerations (effective pixel pitch is smaller than photodiode pitch)

Sensor is full radiation hard

Special implantation shape for optimized transfer

Astronomy

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Significant trends in Astronomy are:

- Push for increased Red Quantum Efficiency (HiRho)
- Larger area devices and Larger area Focal planes
- Some use of CMOS detectors

Full wafer size CCD

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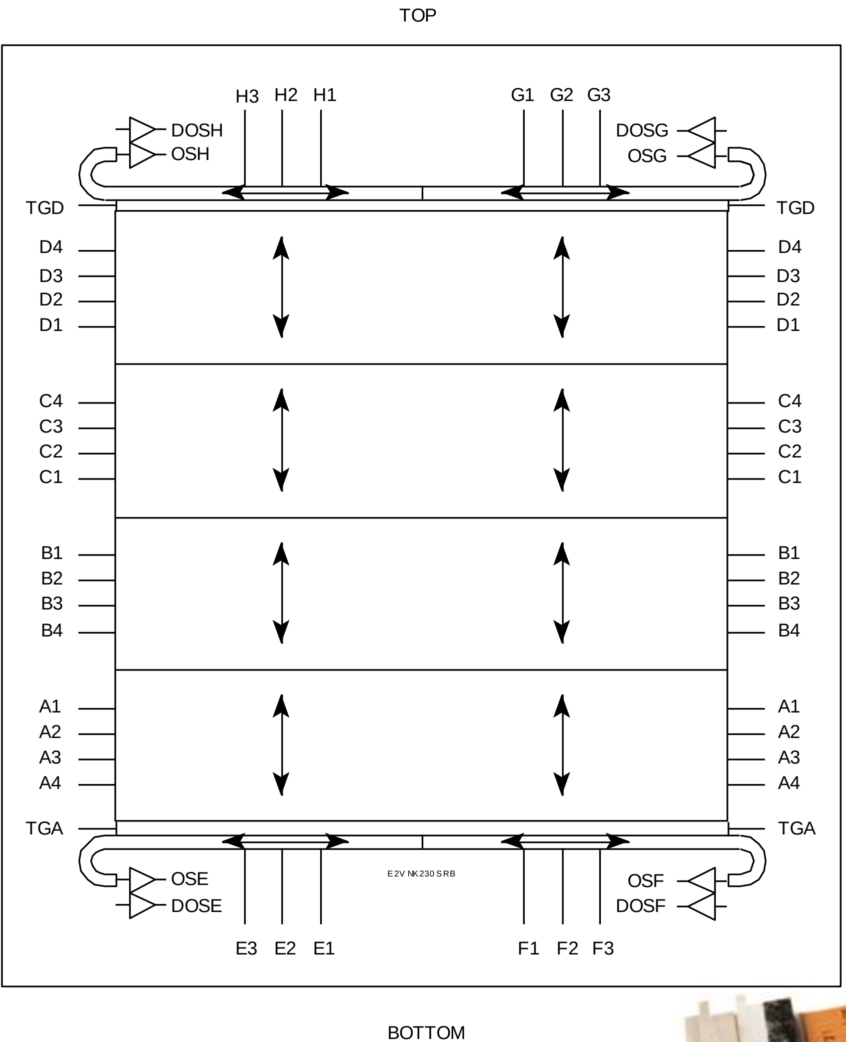
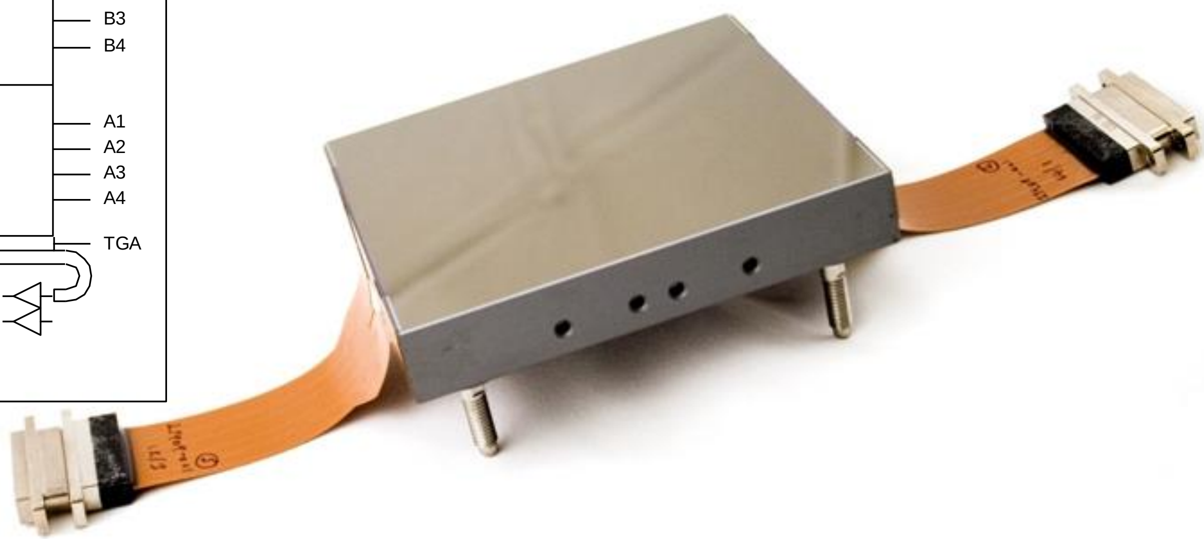


- Available as both 6k x 6k with 15µm pixels and 4 outputs or 9k x 9k with 10µm pixels and 16 outputs.

- Both devices are 9cm square and fill a complete 6” silicon wafer



CMOS imagers-1
TAOS-II CIS113 sensor

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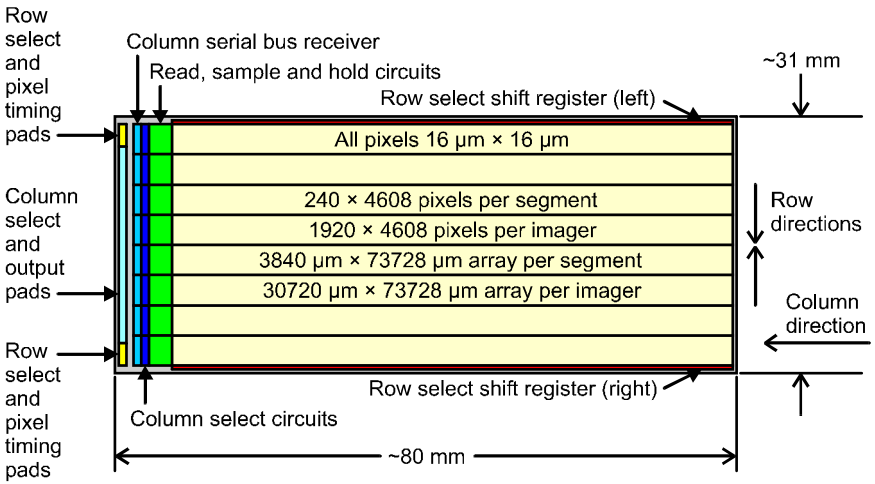


Trans-Neptunian Object detection by occultation

Sensor: 1920 x 4608 16 µm square pixels.

8 segments for parallel read-out

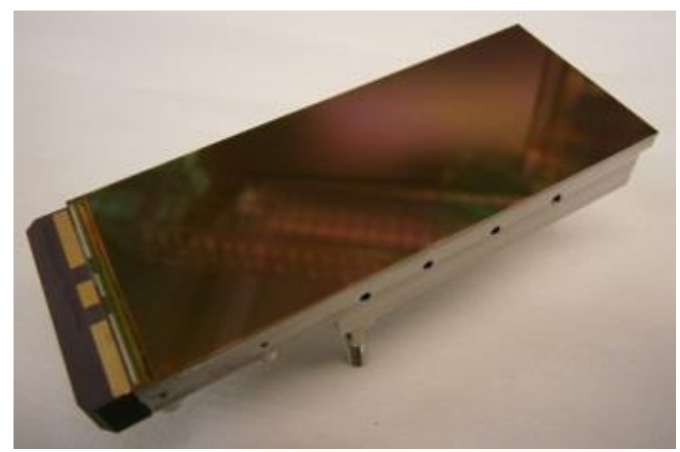
Independent access of left and right sides

Multiple ROI mode for 20 fps sampling rate

Noise floor ~3e^-_{RMS} and low dark current.

Backthinned for 90% QE

Saturation signal (node) ~ 18 ke-



WaveFront Sensor (NGSD) for AO system on E-ELT

Used to measure atmospheric turbulence and drive correcting mirror

Second samples early 2015

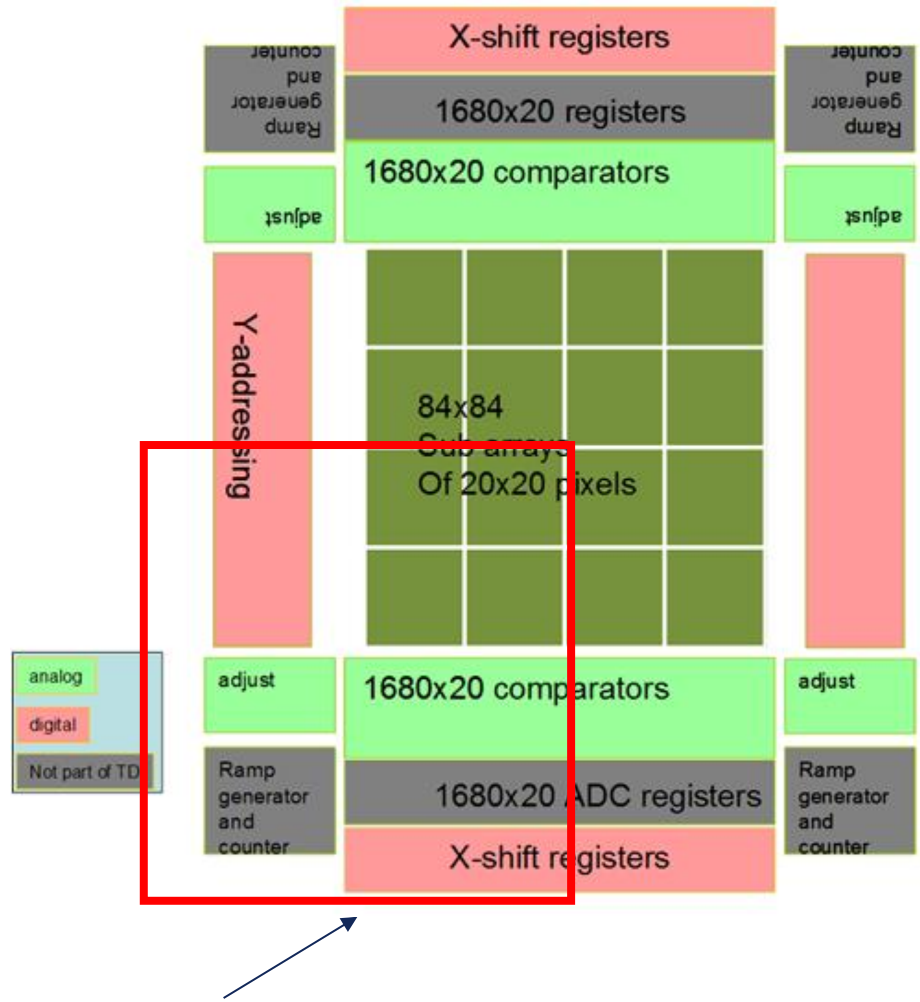
- Fully functional
- No data errors at 4·75 Gbps
- < 4 e^- total noise measured
- Lag < 1 e^- at low levels
- Many performance requirements met

But some problems found:

- Many hot pixels
- Interaction amongst the 17,600 ADC blocks
- Some digital to analogue feedback

Apart from solving these problems, customer also wants lower noise (< 3 e^-) for use with laser guide stars.

- This is expected to be possible



Natural guide star sensor

X-Ray detection in space

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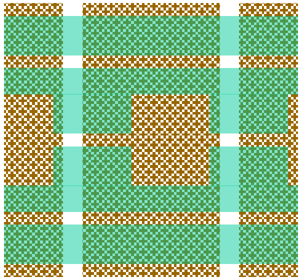
e2v provide sensors for detection of soft X-Rays in space using three different technologies

1 Backthinned sensors with no AR coating have been used for several solar observation projects including SDO, SXI (solar x-ray imager) and the X-Ray telescope on Hinode

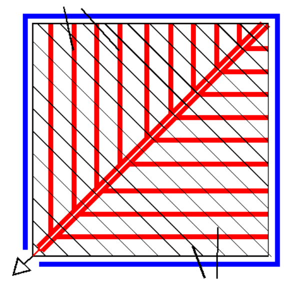
2 Open electrode CCDs have a gap in the electrode allowing photons to get directly into the silicon. This structure is used on XMM



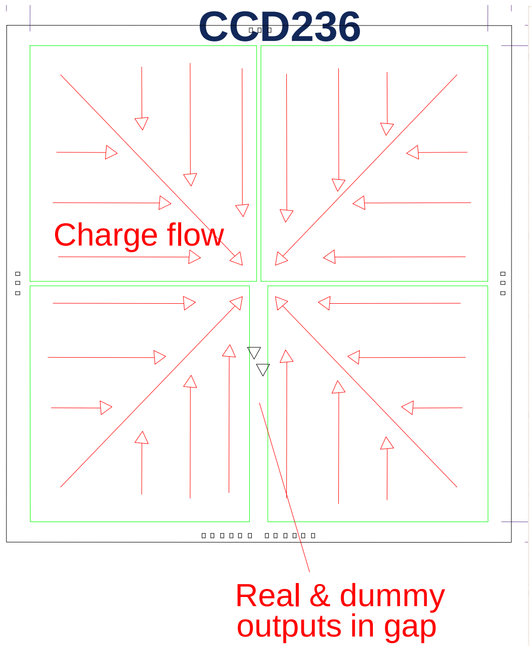
3 Swept charge CCDs are single pixel detectors that are used photodiode arrays – used on Chandryan and in HXMT

X-Ray Spectroscopy

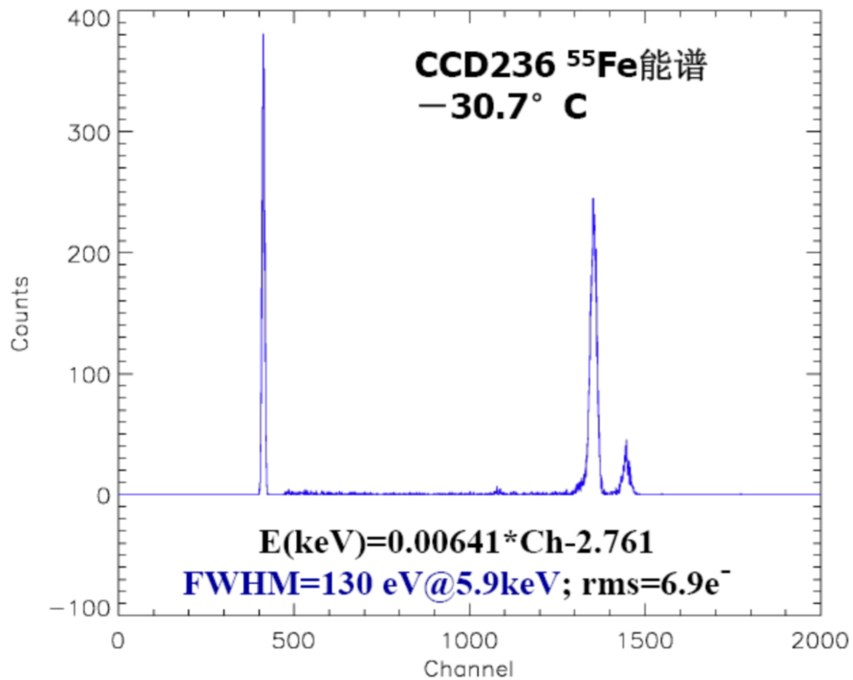
- HXMT uses CCD236 which is a larger version of the CCD54 used for lunar x-ray fluorescence measurements on Chandrayaan 1



CCD54: 1cm² with charge output from one corner

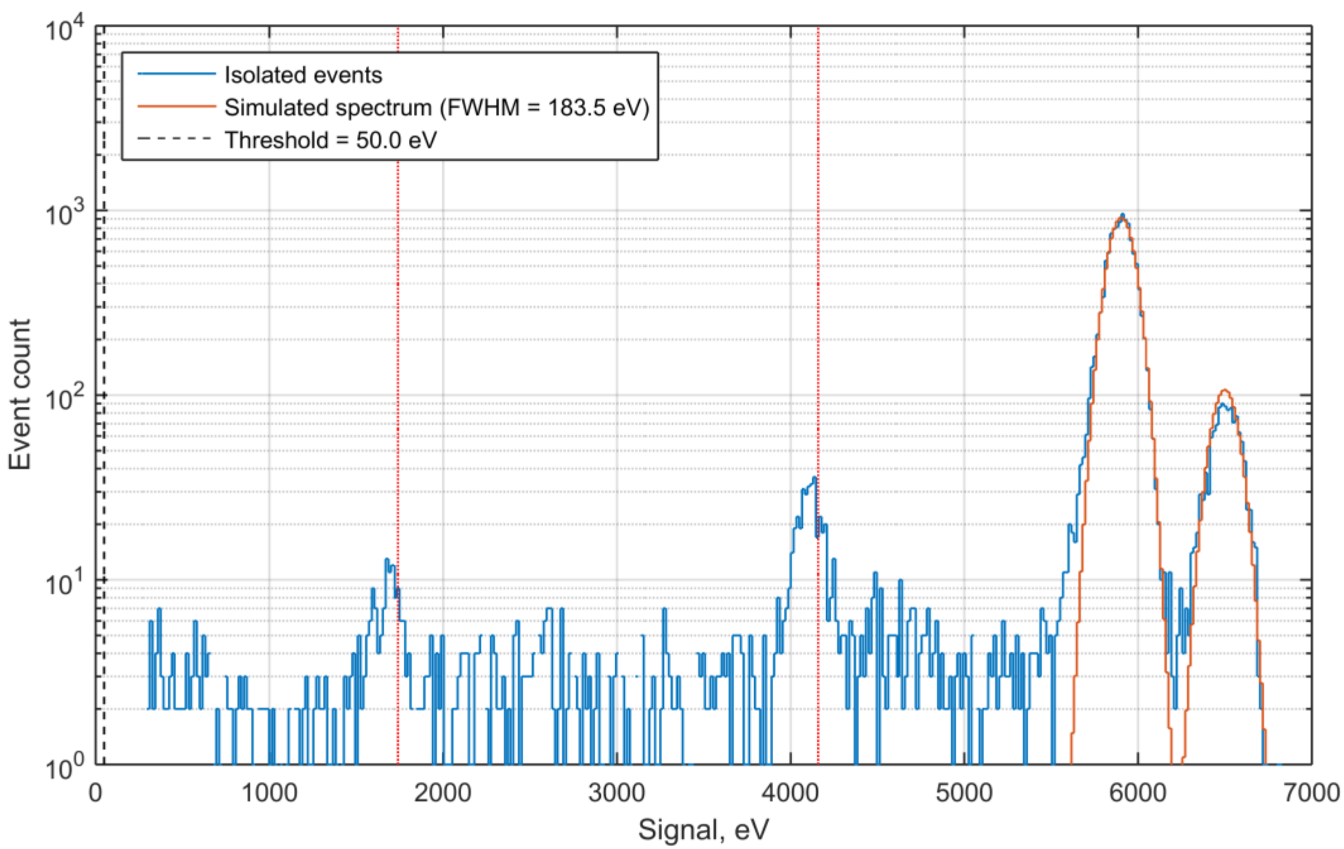


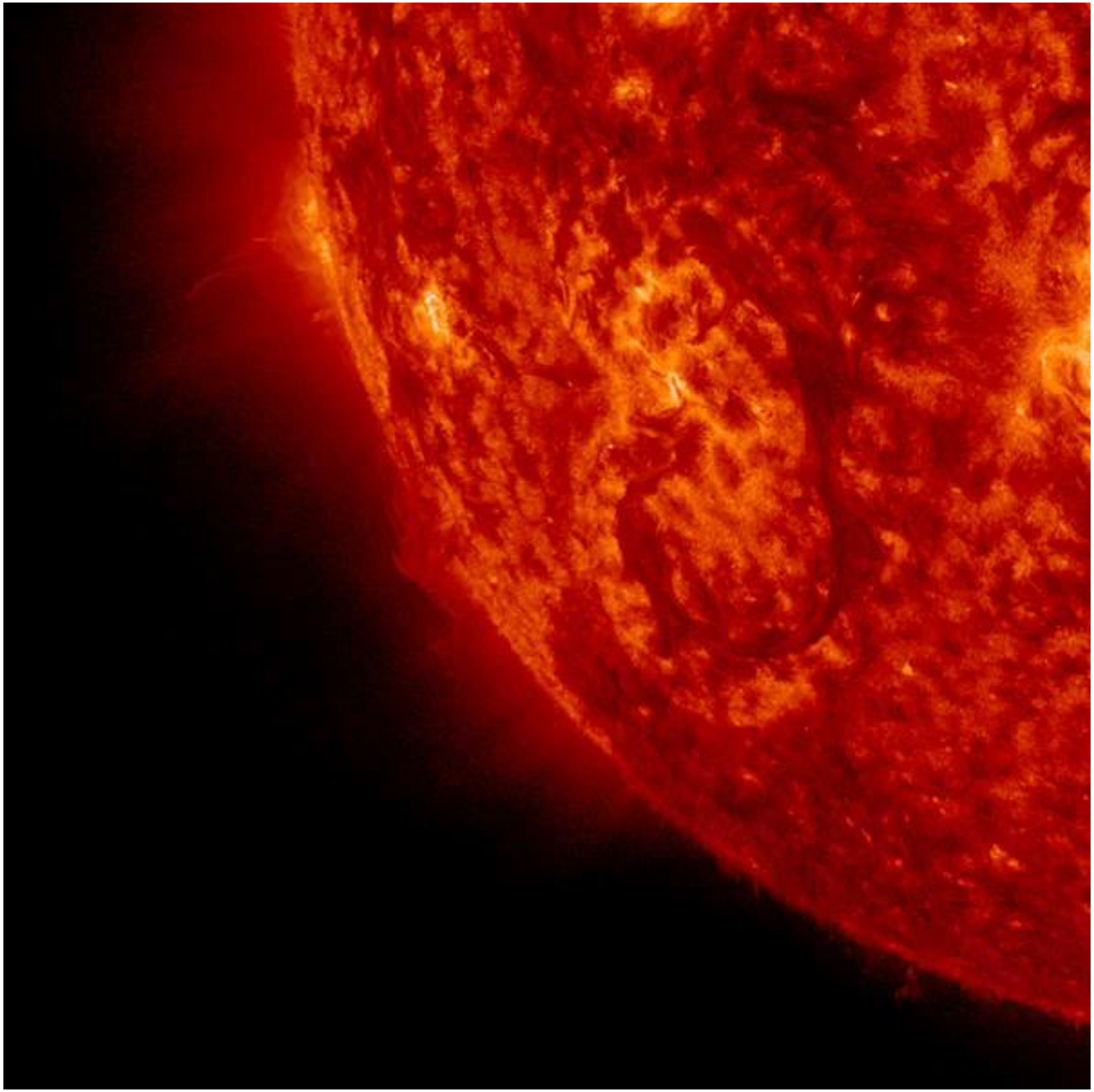
CCD236: 4cm² with charge output from the centre



X-ray spectroscopy with CMOS

- To date not as good as CCDs – latest results from the CEI (Open University) show good energy resolution from single events from Fe55





SDO VUV images

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Comparison to space detectors

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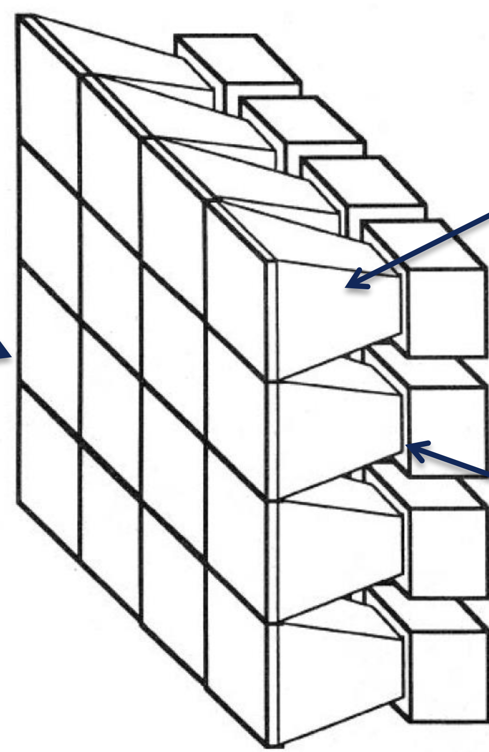
Requirement	Space detectors	Soft X-ray detectors
Rad Hardness	Critical but only up to ~40kRads ionising dose often much less. But significant proton and heavy ion requirements	Only ionising radiation but up to extreme doses – 100s of MRads
Quantum efficiency	Critical for all applications sometimes into deep UV or Near IR so requires backthinning and sometimes thick silicon	<5keV 40µm thick silicon is OK >5keV requires up to 300µm thick silicon
Dynamic range	Critical for many astronomy and EO applications	As high as possible – especially high peak signal required ~4Me
Noise	Critical for astronomy application (~2e) less so for EO	Less critical than dynamic range
Frame rates	Generally not high apart from adaptive optics and photon counting for x-ray astronomy	At least 60Hz for XFELs
Pixel size	Typically 10-30µm	Currently 50 µm for medium x-ray Trending to 10-30µm for soft x-ray

Synchrotron radiation detectors

Bringing life to technology

Indirect detection

- **Large area CCDs have been used on the back of fibre optic tapers for many years (eg M. Suzuki, M. Yamamoto, T. Kumasaka, K. Sato, H. Toyokawa, I. F. Aries, P. A. Jerram, D. Gullick and T. Ueki "A multiple-CCD X-ray detector and its basic characterization" *J. Synchrotron Rad.* (1999). 6, 6-18)**
- **These tend to use large area devices such as those used for Astronomy (CCD55-30 or CCD230-84)**

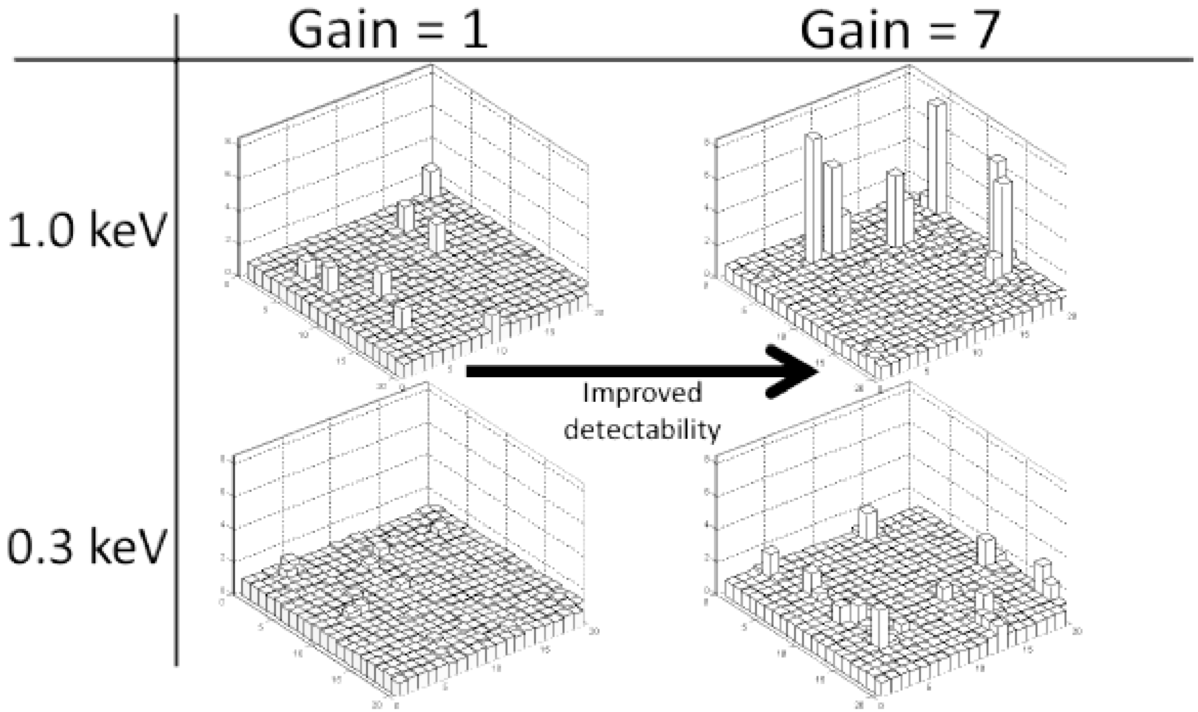


Back illuminate sensors are still often used to maximise the collection efficiency from the phosphor

Direct Detection: Soft X-rays

Electron multiplication in the charge domain

- The application of modest EM gain dramatically improves the detection of X-rays
- Here we see work done by the Open University demonstrating that a factor of x7 in gain significantly increases the signal to noise ratio



Ref: Electron-multiplying CCDs for future soft X-ray spectrometers
Tutt, J. H.; Holland, A. D.; Murray, N. J. ; Harriss, R. D.; Hall, D. J. and Soman, M. (2012). Journal of Instrumentation, 7(2) C02031.

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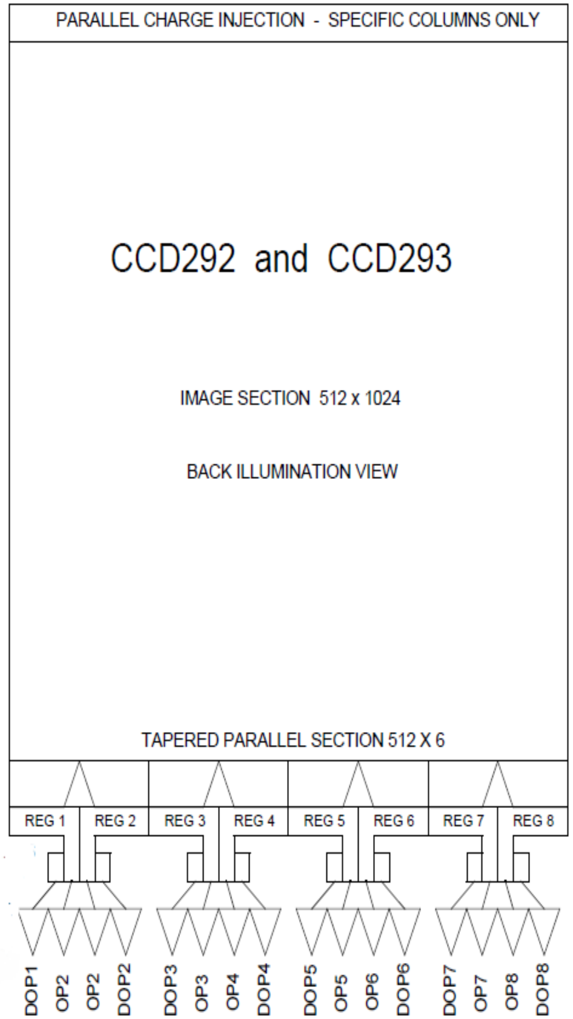
CCDs for XFELs

- The CCD 292 and CCD262 have been developed for Riken for x-ray detection in XFELs



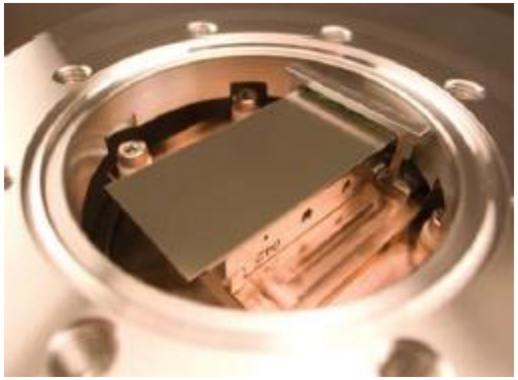
- CCD262 is standard deep depletion material front illuminated (40µm thick)
- CCD292 is HiRho back-illuminated (300µm thick)
- Pixel size is 50µm with 8 outputs with 2 phase image and store to provide a frame rate of up to 60Hz
- Up to 300µm thick to allow detection of soft x-rays up to 15keV

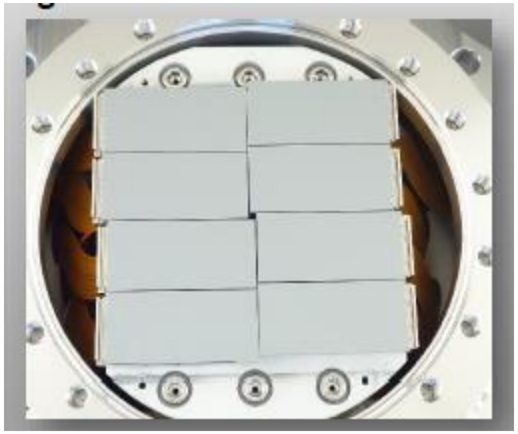
Sensors for Photon Science

e2v Bringing life to technology

XFEL Sensor portfolio

- CCD262-50, front illuminated deep depleted sensor capable of 60Hz frame rate operation.
- 512 x 1024 pixel format with 50 μm x 50 μm pixels
- Designed for assembly into a tiled array
- Peak X-ray QE of 90% at 4,000eV
- 80% QE at 6,000eV
- Peak signal 2.5 – 3.0 Me-
- System noise 100 – 250 e- rms @ 30Hz





The sensor was developed with direction and funding from RIKEN. The images are from RIKEN and performance figures are as tested by RIKEN

Sensors for Photon Science

XFEL Sensor portfolio

- The third sensor in the portfolio is the CCD293-50, a back illuminated sensor, which is a variant of the CCD292-50 with lower noise and lower peak signal.
- The three sensors compare as follows:

Description	CCD262-50	CCD292-50	CCD293-50
System noise [ph@6 keV]	0.06 – 0.15	0.12 -0.15	0.02 – 0.037
Peak signal [ph@6keV]	2500 - 3000	2100	970
Nominal QE [%@6 keV]	77	100	
Nominal QE [%@12keV]	19	73	
PSF*[μm r.m.s @12keV]	3.2 (150 phs)	9.4 (49 phs)	
	4.8 (910 phs)	14 (1030 phs)	
Comments	1st generation	Better QE Broader PSF Application SFX	Lower noise Lower peak signal App. XQO, XAFS

The performance figures are as tested by RIKEN. Acknowledgement to the team at SACLA and their great work

Systems for Photon Science

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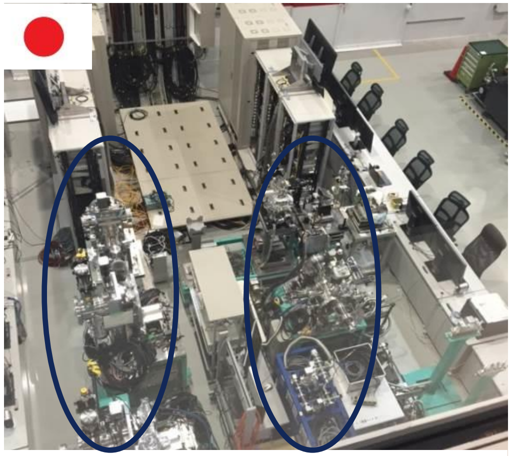
RIKEN developed the systems to run single, dual, octal sensor cameras with the Multi-Port 262, 292 and 293 CCDs, MPCCDs.

e2v has lead a contract to deliver single sensor and dual sensor cameras to the Pohang Accelerator Laboratory (PAL) X-ray Free Electron Laser (XFEL)

Pohang Accelerator Laboratory in South Korea are currently in the process of building a fourth generation XFEL and wish to use the MPCCD system. Majority of the work is conducted by Meisei wh
MPCCD sy

Deliveries :
2 single device systems : Aug/Sept 15
3 Dual device systems Oct/Nov/Dec15

In the case of the XFEL systems, re-use of RIKEN and Meisei's design minimised costs for PAL.
As a thin-prime e2v still brings a number of benefits to the customer and future customer.


MPCCD dual System @ Spring 8


PAL Experiment Hall

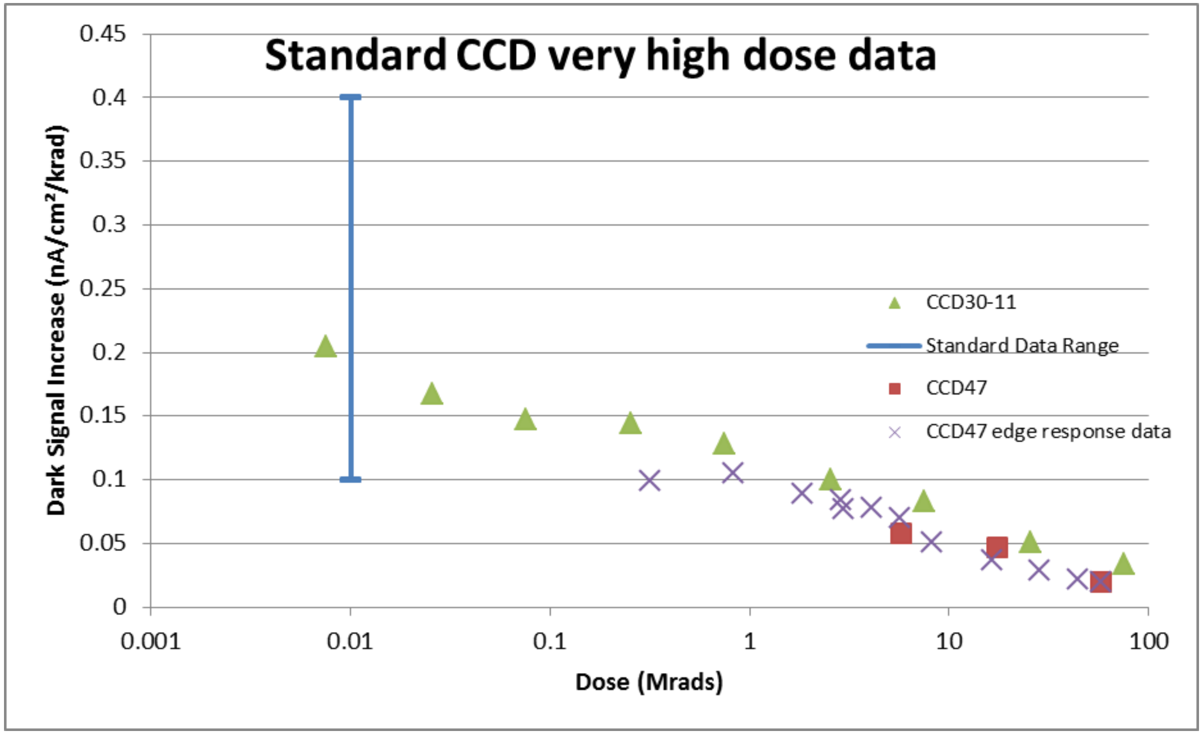
CCDs for XFELs

Ionising radiation causes two effects on image sensors (CCDs and CMOS)

- A build up of positive charge causes a threshold shift that varies with oxide thickness (approximately $\alpha\ t_{ox}^2$)
- The hydrogen anneal of the front surface is reversed giving an increase in dark signal ($\alpha\ t_{ox}$)
- Our science CCDs use a thick gate oxide and so both of the effects were a major concern, however it was found working with Riken and XCAM that both of these effects saturate
- For example threshold shift at low doses is ~0.2V/kRad so after the 60MRad dose reread by Riken this would have given 12,000V threshold shift!

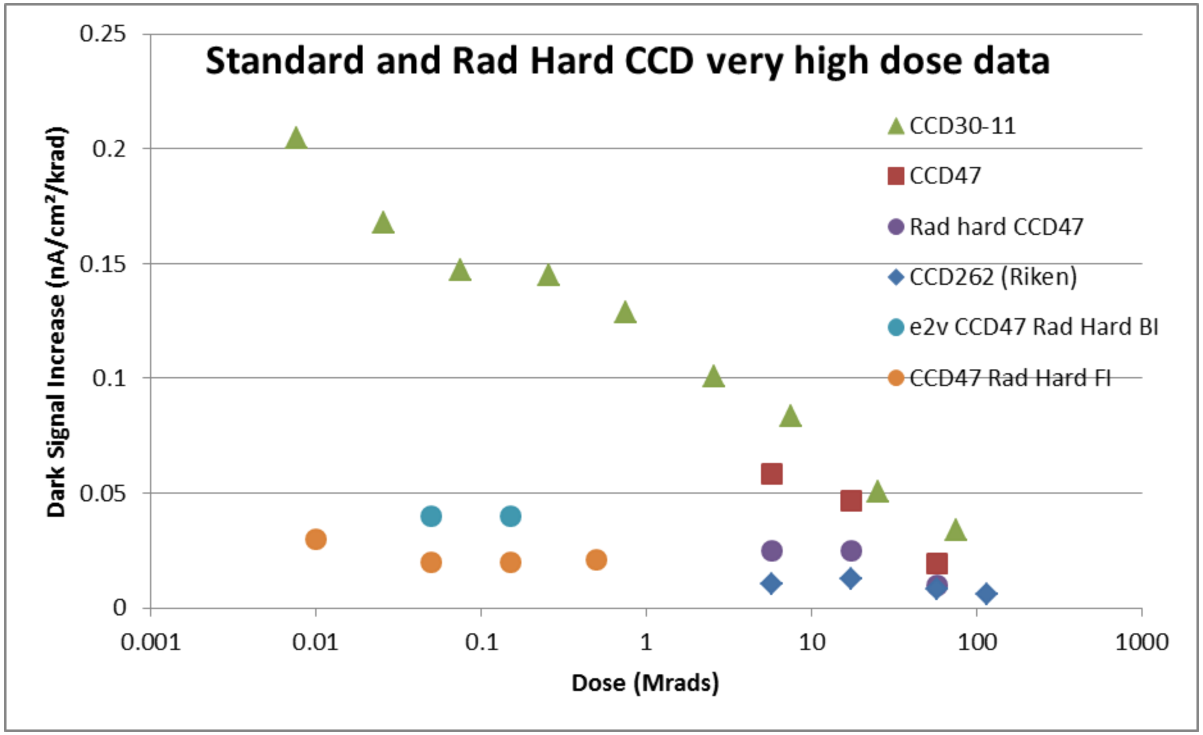
Rad hard Dark signal

- Adding the scanned beam data to the rad had and standard silicon gives the results shown on the next slides



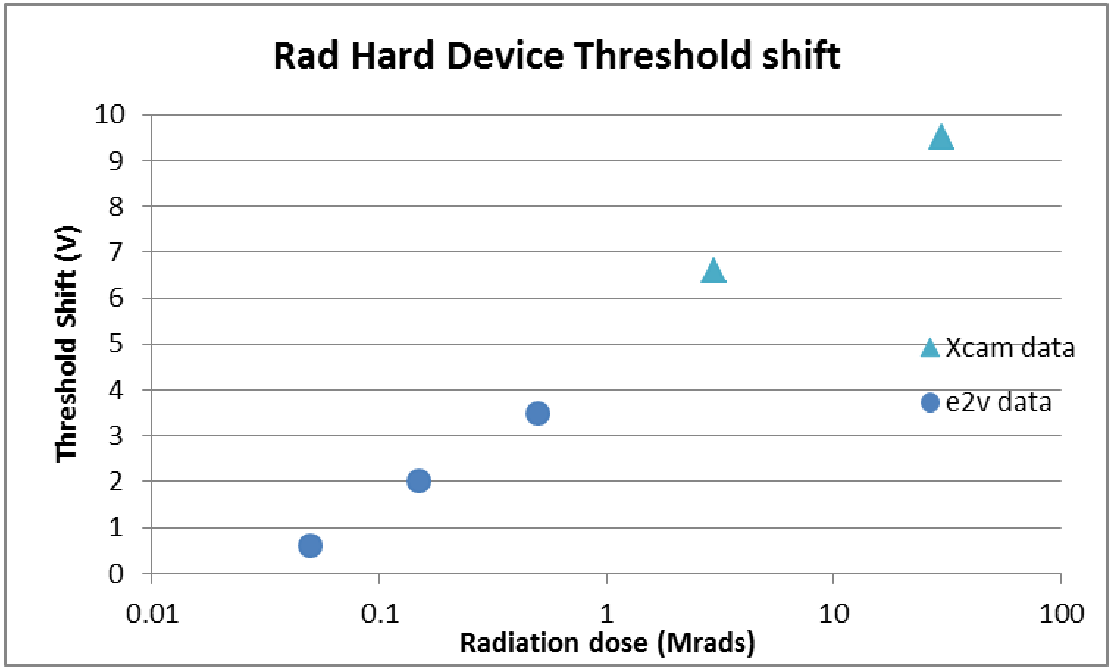
Dark Signal Variation

- The plot below includes data from Radiation Hard CCDs.
  - For the rad hard device that dark signal increase is significantly lower
  - Also varies much less with dose



Threshold shift

- Although plotted on a log-lin graph the data looks remarkably consistent – it would be good to have a physical explanation for this?
- Above ~50krads the there is an increased of threshold shift of 1V every time the radiation dose doubles



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CMOS requirements

Good radiation hardness

A significant advantage of standard commercial CMOS processes is that the very thin gates inherently give a good degree of radiation hardness

High dynamic range

Generally worse for CMOS than for CCDs but there are techniques available to improve dynamic range that are under investigation at e2v

Very high frame rate

A major advantage of CMOS over the existing detectors and a strong reason to move to CMOS technology

Thick silicon for good QE

This represents the major challenge for CMOS HiRho structures are more complex and it is also more of a challenge to get foundries to carry our non-standard processes. However the principles are the same as for CCDs in that a large negative voltage needs to be applied to the back surface – or use hybrids

Backthinning

Large area coverage – large devices 3 side buttable device + packaging. In principle easier than for CCDs