e2v

CCD Design for Space Applications

Paul Jerram and David Burt

Introduction

- Both the constraints and the requirements are somewhat different in designing imaging devices for Space when compared to ground based applications.

  - Generally the pixel pitch is not required to be below about 8µm
  - Design choices can be driven by the radiation environment
  - Optimisation of signal to noise becomes even more critical
  - High reliability is essential
  - Power consumption should be minimised

- CCDs optimised for space applications have been provided by small scale specialist facilities as the requirements generally diverge from those for consumer imaging.

Introduction

- This talk will cover the following topics
  - Effects of ionising irradiation
  - Effects of proton irradiation
  - Detection efficiency
  - Power Consumption
  - TDI Imaging

Radiation Damage

- Ionising Radiation – in reality is mostly Beta (high energy electrons), but testing generally uses a Gamma equivalent; the main impact is
  - MOS Threshold shift
  - Dark signal increase
- High energy particles – neutrons and protons - testing is generally carried out with protons, these cause displacement damage leading to;
  - Charge Transfer efficiency (CTE) degradation
  - Random Telegraph signals (RTS)
  - Bulk dark signal “spikes”

Traps

➲ A “trap” is a result of any imperfection within the silicon that reduces the bonding energy of an electron to below that of the regular lattice.

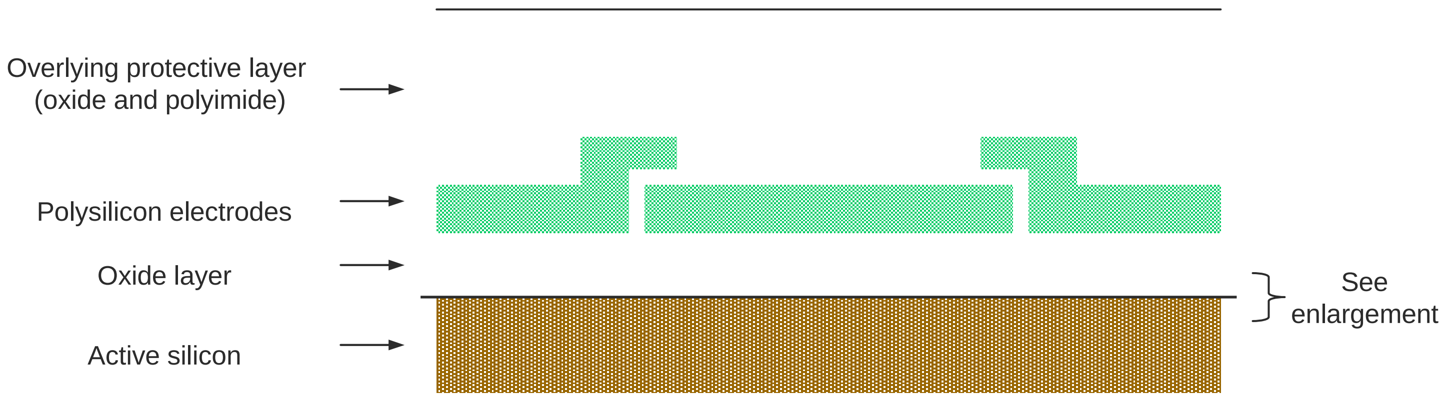
➲ Surface or interface traps are due to the inherent atomic mismatch between silicon and silicon dioxide. Bulk traps are largely due to crystal defects, often in conjunction with impurity atoms present in the silicon, e.g. oxygen, carbon, phosphorus, boron and metallic contamination.

➲ Traps have a major influence on parameters such as the dark signal, CTE, RTS etc, and the density of the traps generally increases with radiation dose.

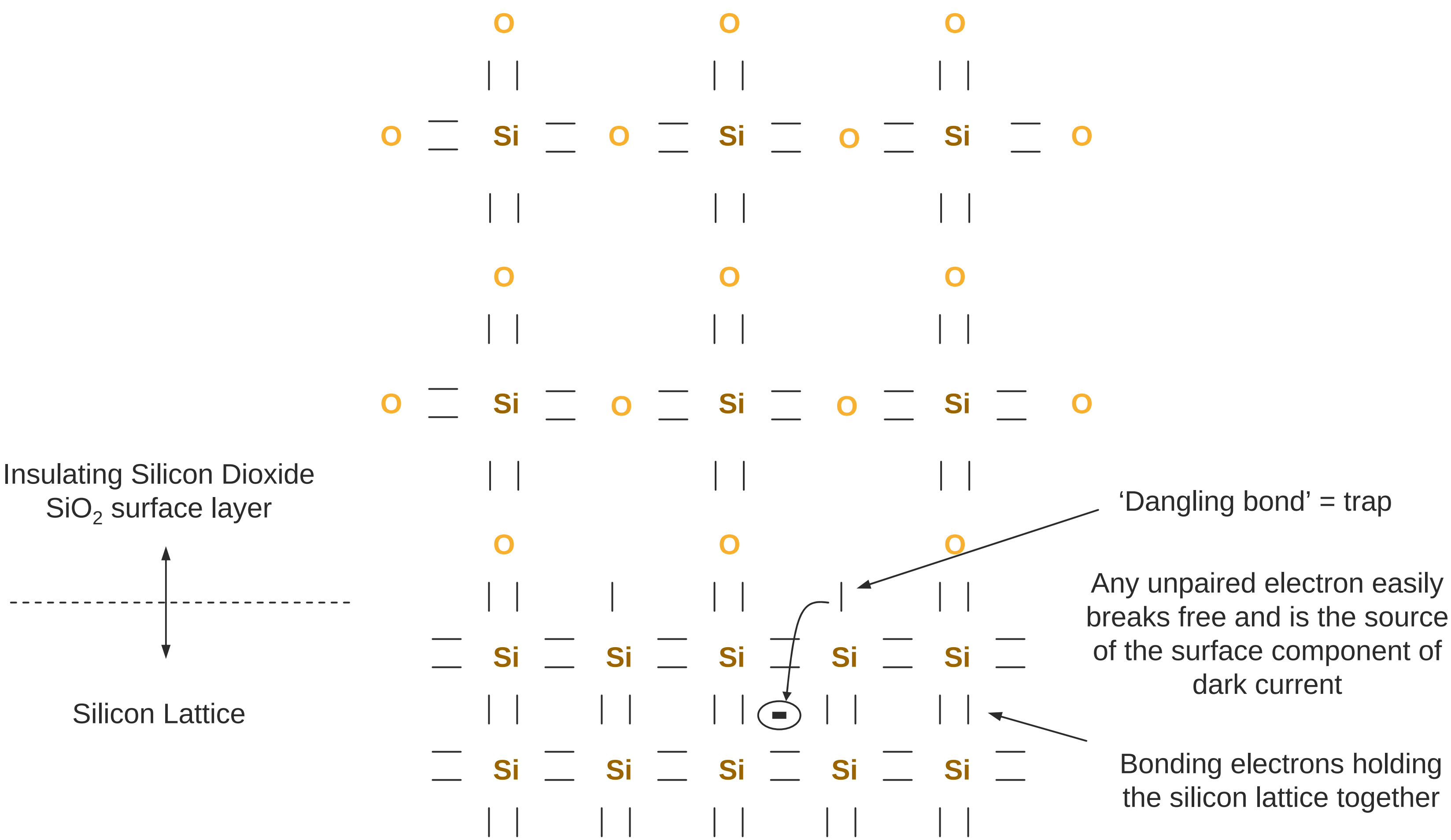
Ionising Radiation
Dark signal increase

➲ There is generally an increase in the dark signal with irradiation. In order to understand why, it is first necessary to discuss the process whereby the device is hydrogen annealed to reduce the dark signal.

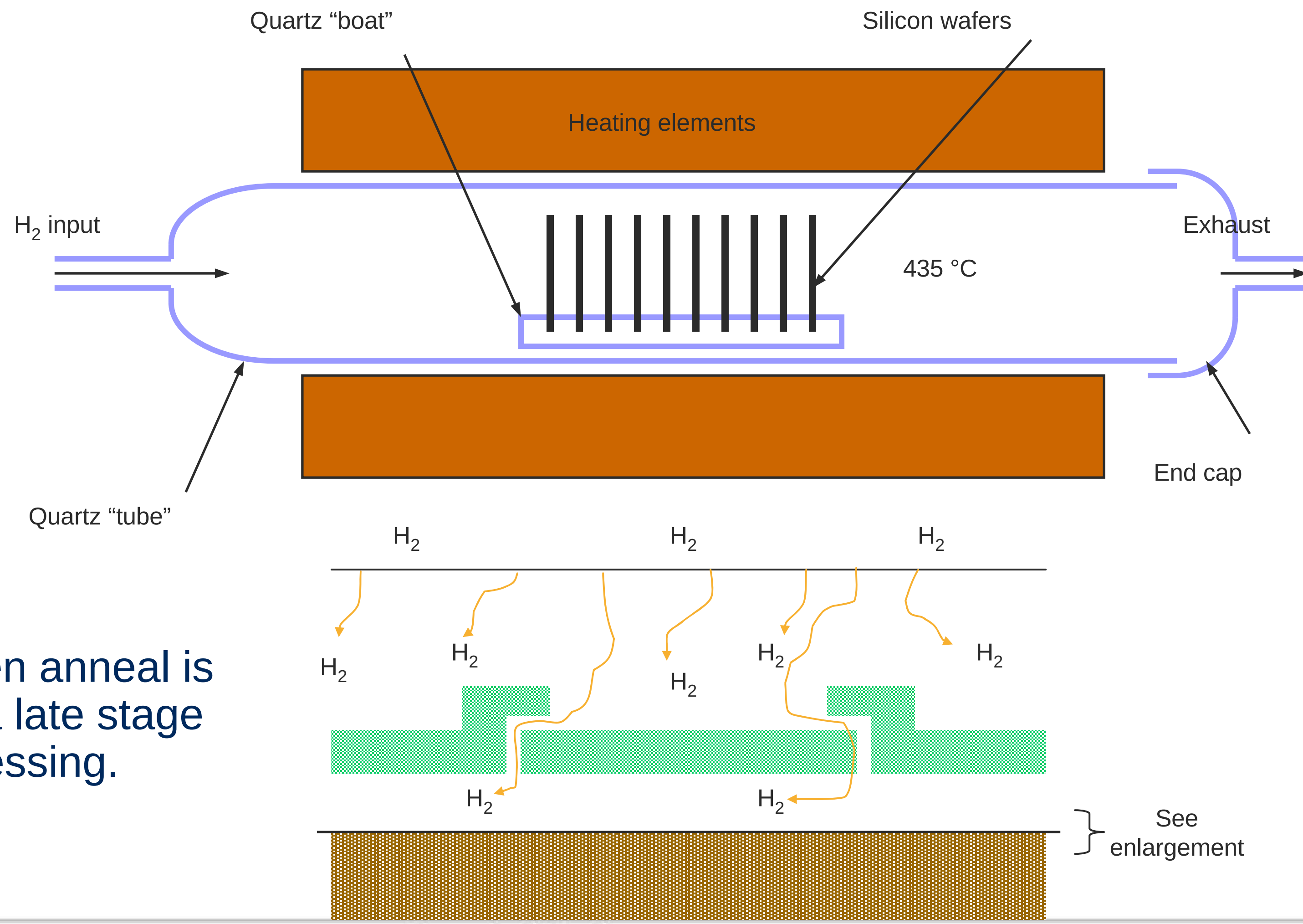
➲ At the interface between the silicon to silicon dioxide there are a number of dangling bonds – these can act as traps and dominate in the generation of dark signal.



Surface traps



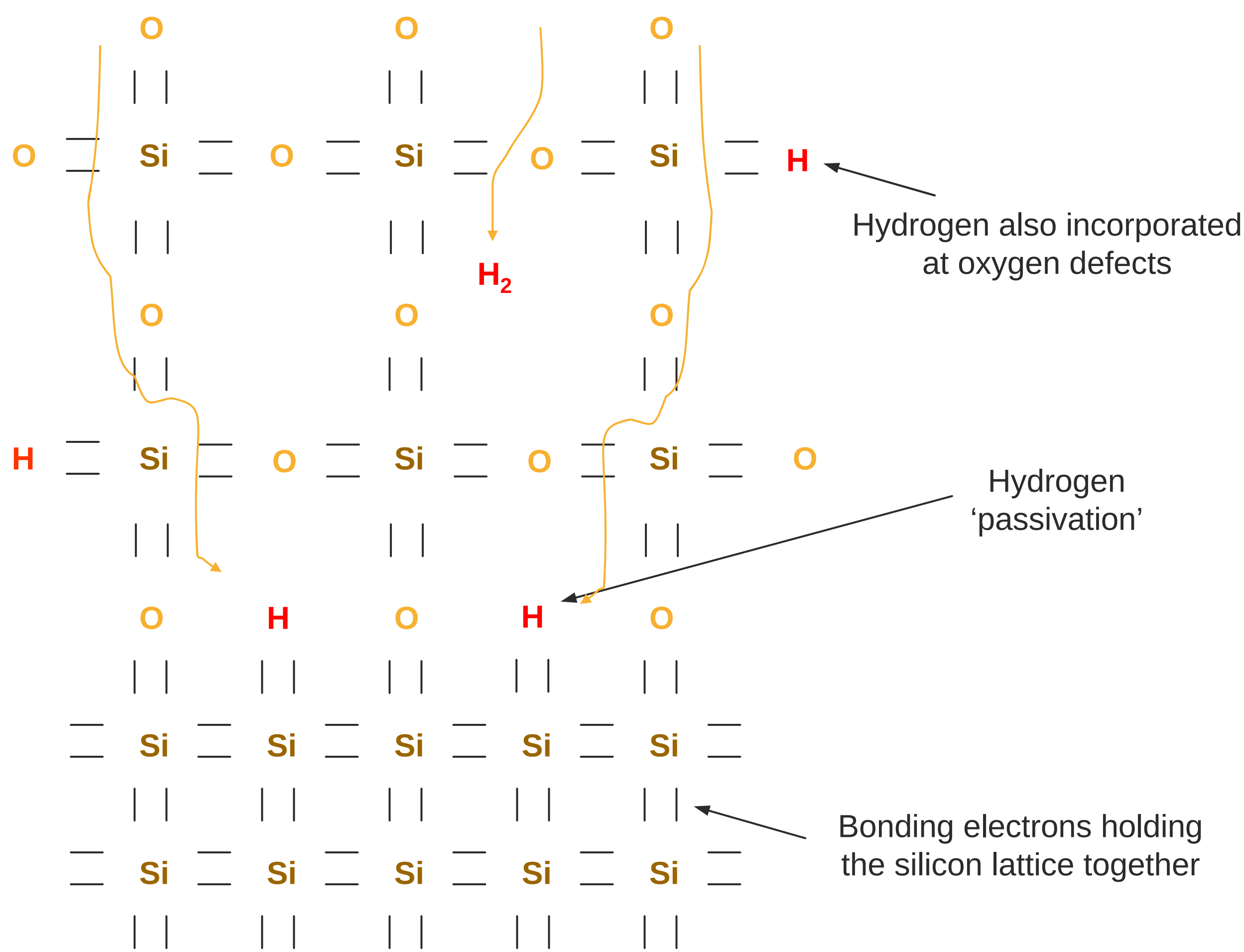
Hydrogen anneal



➲ The hydrogen anneal is carried out at a late stage in device processing.

Hydrogen passivation

- Hydrogen atoms attach to the dangling bonds and render them inactive.
- This significantly reduces dark signal.
- Note that hydrogen is also incorporated within the SiO_2



Ionising Radiation
Dark signal increase

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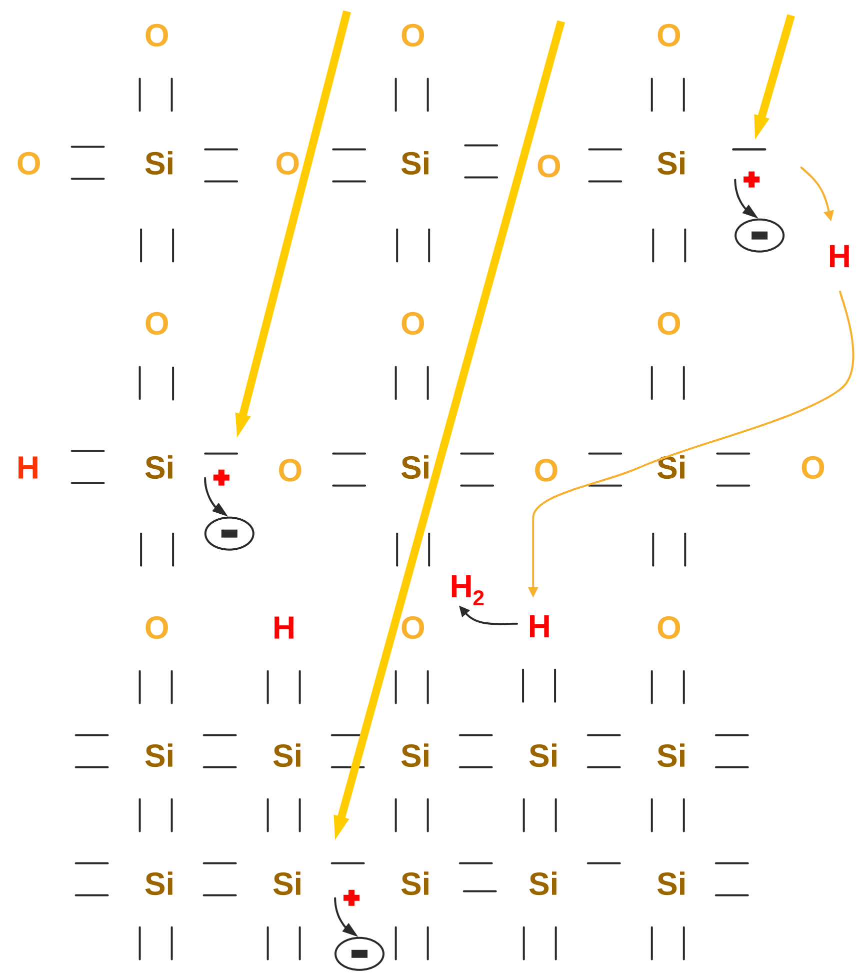
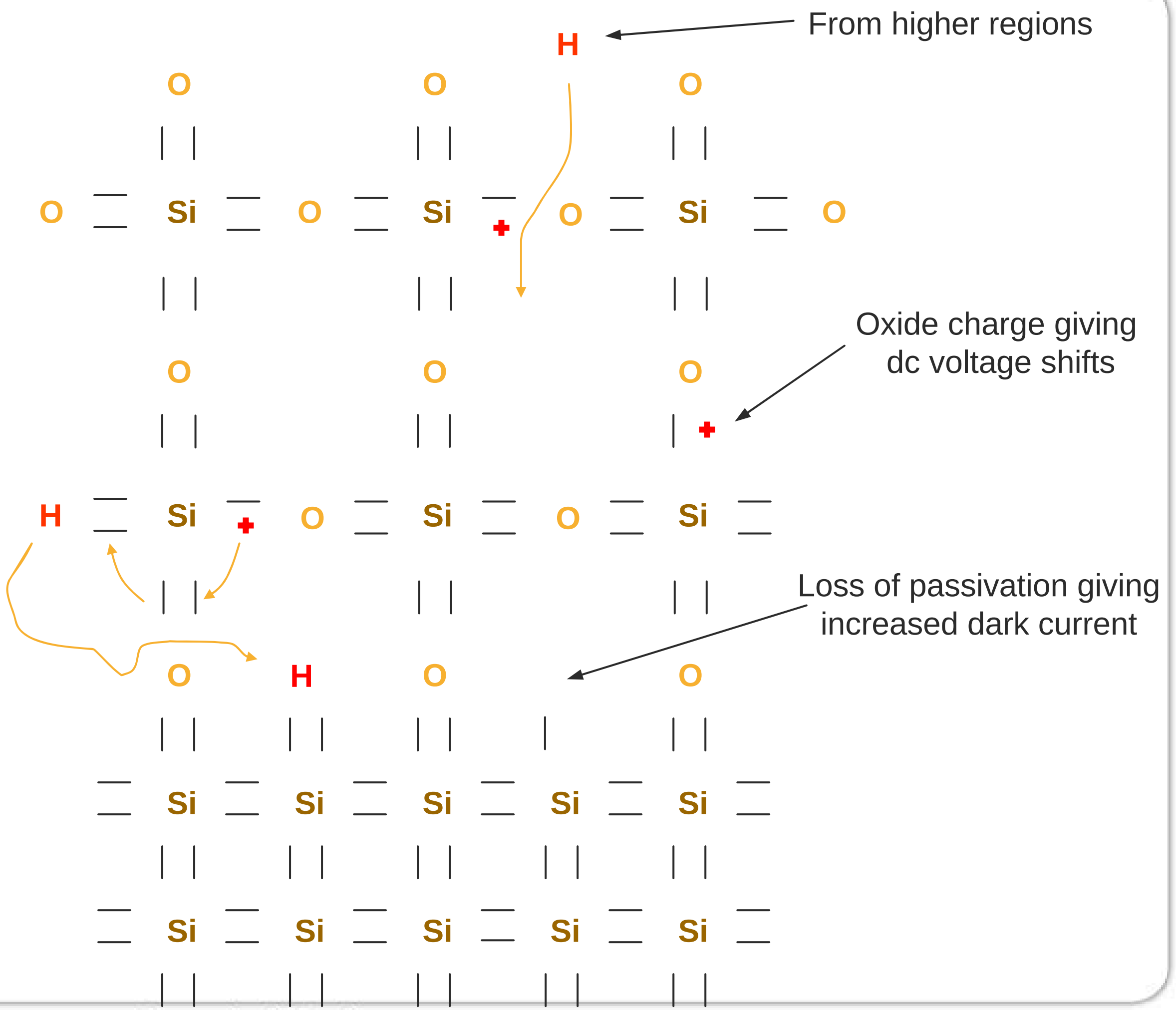
- Ionising radiation creates electron hole pairs in both the silicon and SiO_2 which will separate under bias
- The electrons will move rapidly but the holes move slowly and can cause the release of hydrogen, which can then diffuse to the interface and combine with the hydrogen atom that has attached to the dangling bond.
- This will reverse the anneal that had been carried out and thereby give a dark signal increase.
- In other words the surface returns to the pre-annealed state.



Ionising Radiation
Dark signal increase

- The dark signal can continue to increase after irradiation as the mobile holes can release more hydrogen from within the SiO_2
- Hydrogen can also diffuse from the regions above the electrodes.

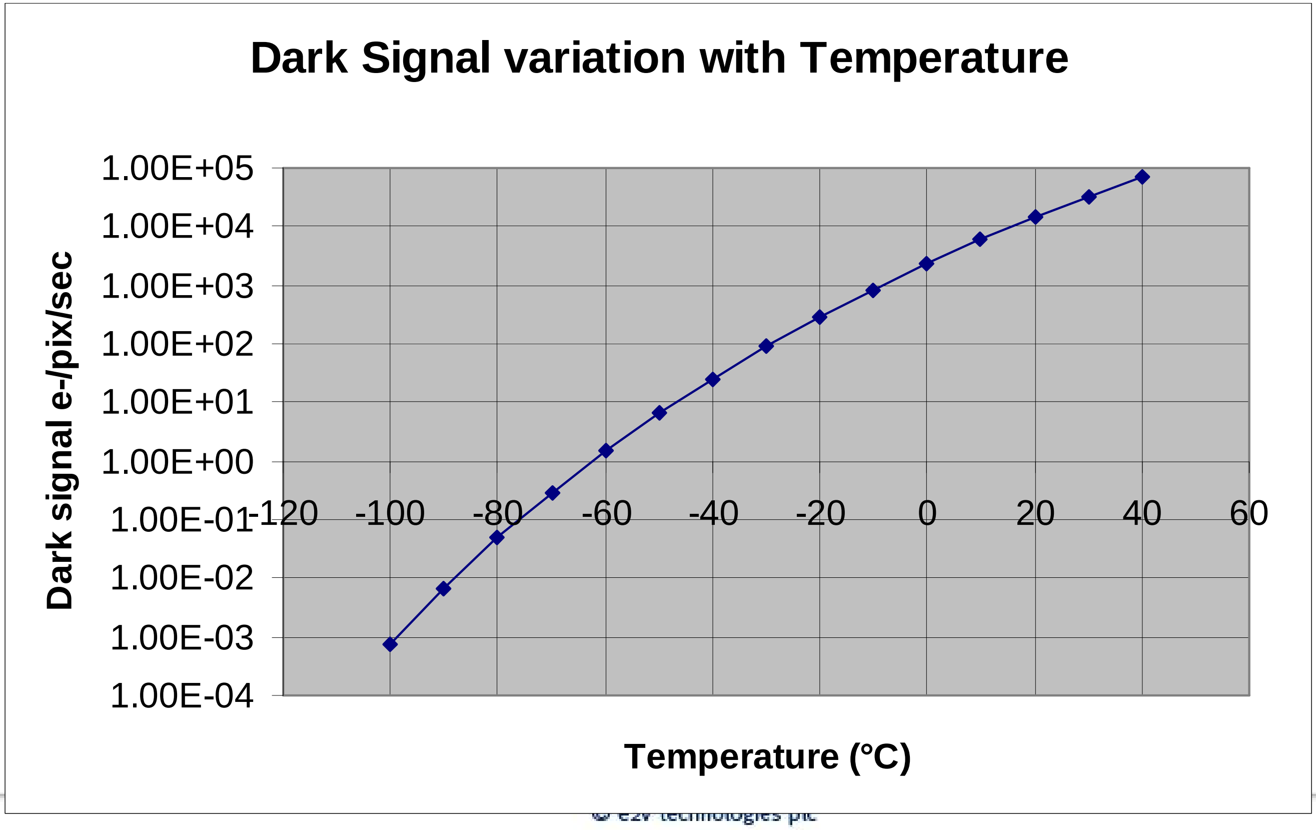


Ionising irradiation
Mitigating against dark signals increase

- As the dominant impact of radiation is the increase of surface dark signal, then one possible solution is to use a pinned or Inverted mode CCD. The surface is flooded with holes and the surface dark signal is suppressed. However such IMO CCDs are not always suitable:
  - Full well capacity will be reduced
  - Depletion depth is reduced and so MTF, or resolution is degraded
  - Clock capacitance is increased and so maximum clock rate is reduced
- The alternative used for many space programmes is to operate very cold to completely remove the dark signal, which typically varies as
- $I_d = I_{do}\ 122T^3 \exp(-6400/T)$, where I_{do} is the dark signal at T = 293K

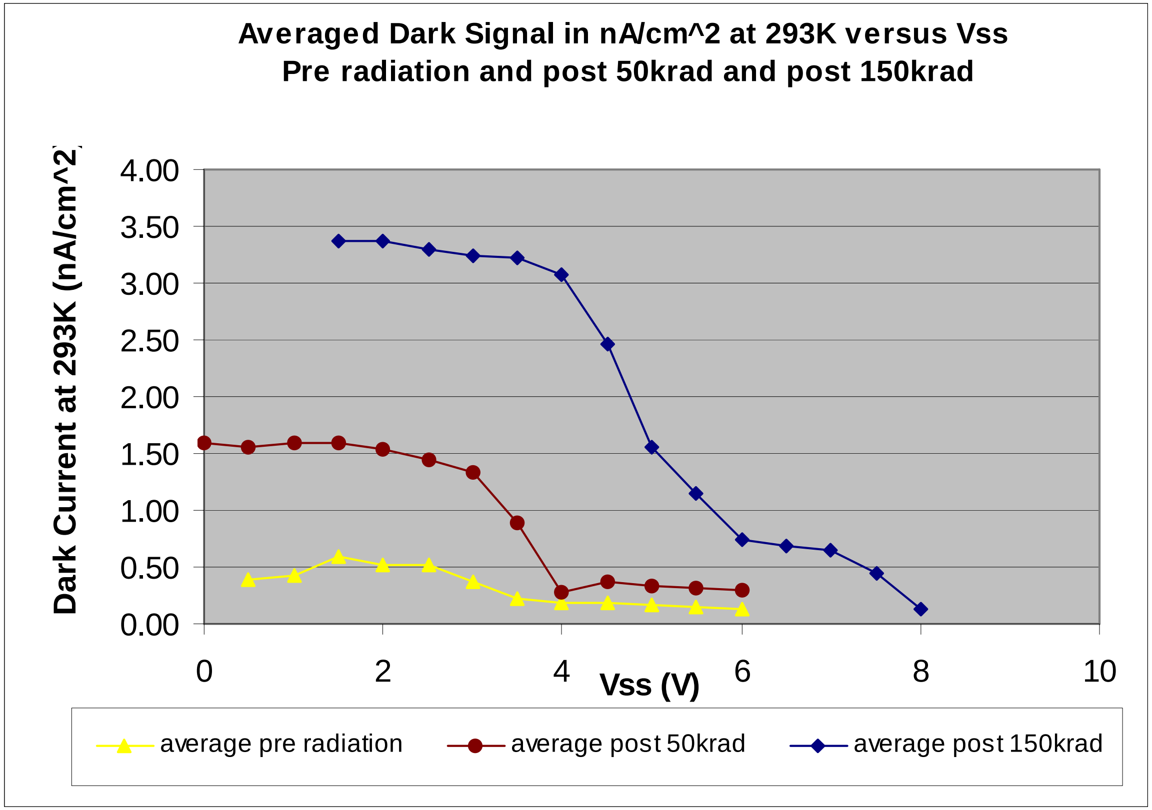
Ionising irradiation
Mitigating against dark signals increase

➲ For a 15µm pixel typically used for space science applications, cooling to -100°C gives 7 orders of magnitude of dark signal reduction from that at room temperature



Ionising irradiation
Mitigating against dark signals increase

➲ "Rad hard" devices with thinner gate dielectrics and an optimised device periphery can significant reduce the impact of ionising radiation.



➲ Pinning voltage drifts by approximately 10mV/kRad

Ionising Radiation
MOS Threshold Shift

- From the description given earlier it can be seen that under ionising radiation in the presence of a field the electron-hole pairs separate.

- Electrons move rapidly into the substrate but, for various reasons, holes accumulate and the fixed positive charge causes an MOS threshold shift.

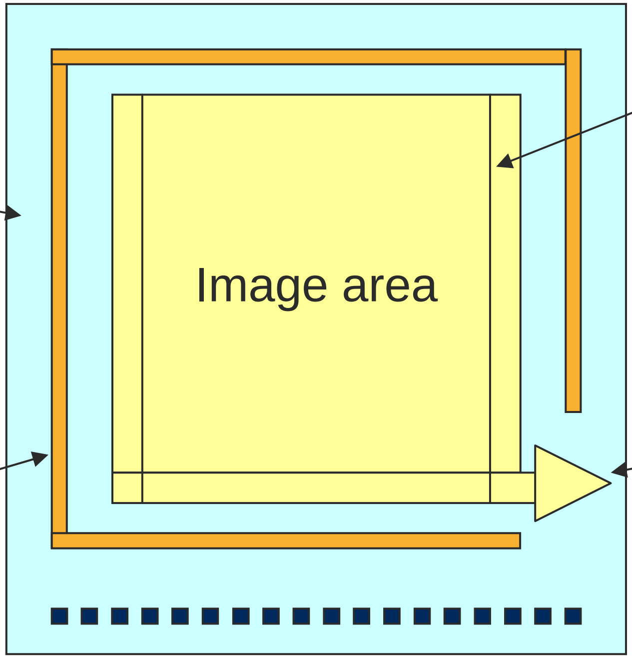
- The magnitude of the threshold shift varies as the square of the oxide thickness. Double layer oxide-nitride dielectrics are therefore often used.

- So whilst a standard scientific CCD may be only able to withstand ~10kRads before the shifts become excessive, e2v have manufactured rad hard devices that may be successfully operated after 1MRad.

- n.b. most CMOS sensors will use an oxide that is only a few nm thick and so the threshold shift should not be a significant consideration

Ionising radiation
Other considerations

The device periphery uses a thicker field oxide. This will generate very large levels of dark signal



Dump columns are incorporated to provide a clean edge to the image region

Amplifier

Drains must be included around the edge of the active region to remove charge generated in this region

The route through which hydrogen is able to enter and leave the structure is also critical when considering the impact of radiation on dark signal

Proton Irradiation
CTE Degradation

- ➲ High energy protons (or neutrons) cause displacement damage in the silicon lattice producing traps, especially the phosphorous-vacancy Si-E Centre.

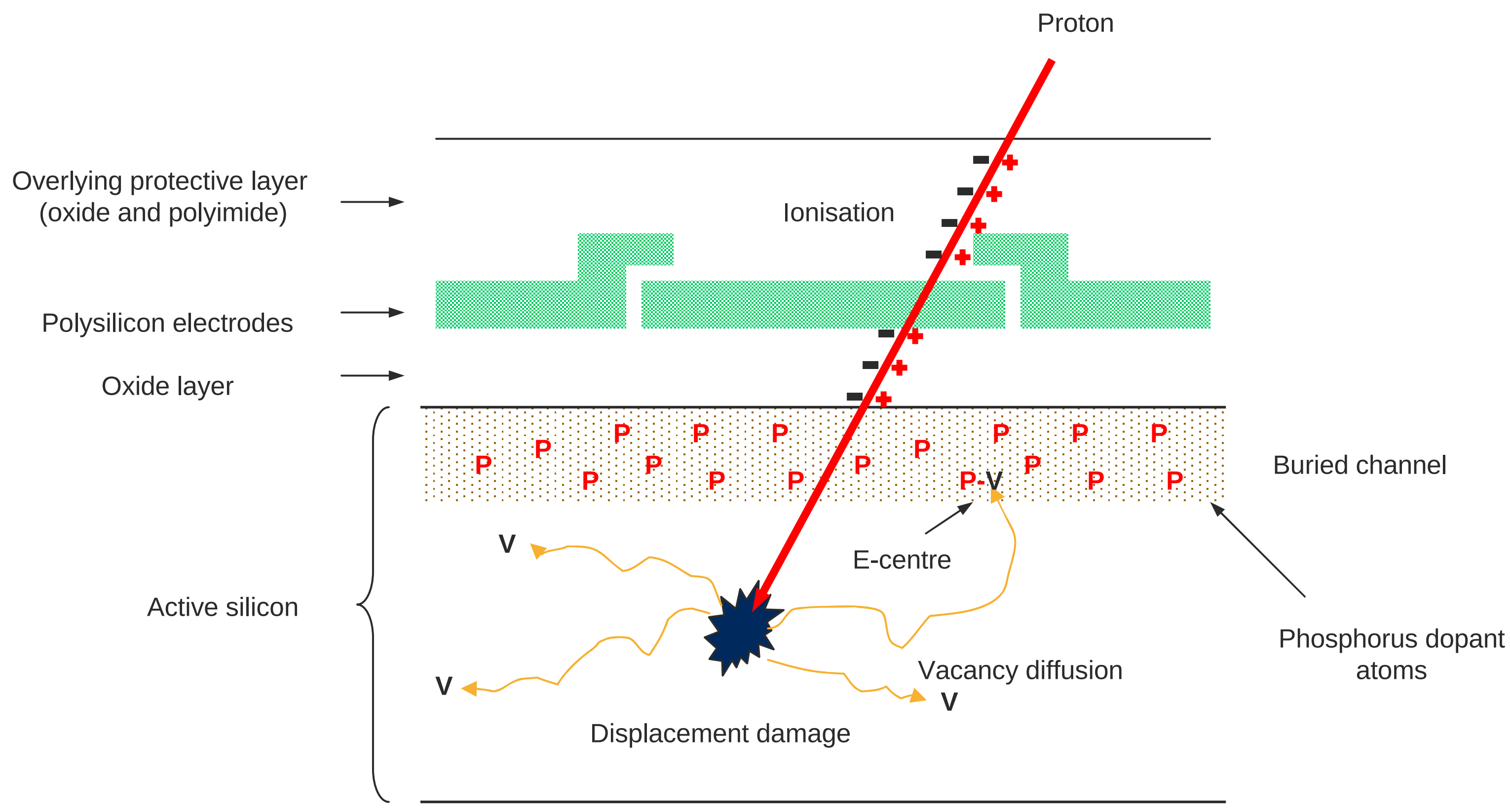
- ➲ If the trap is located in the buried channel, signal charge can be trapped during transfer, which is the origin of CTE.

- ➲ Although these traps capture only a single electron, after high levels of proton irradiation the numbers can be sufficient to cause serious CTE degradation.

- ➲ Mitigation against the impact of proton irradiation involves minimising the probability of a signal electron encountering a trap and/or ensuring that the trap is full before signal is passed through it.

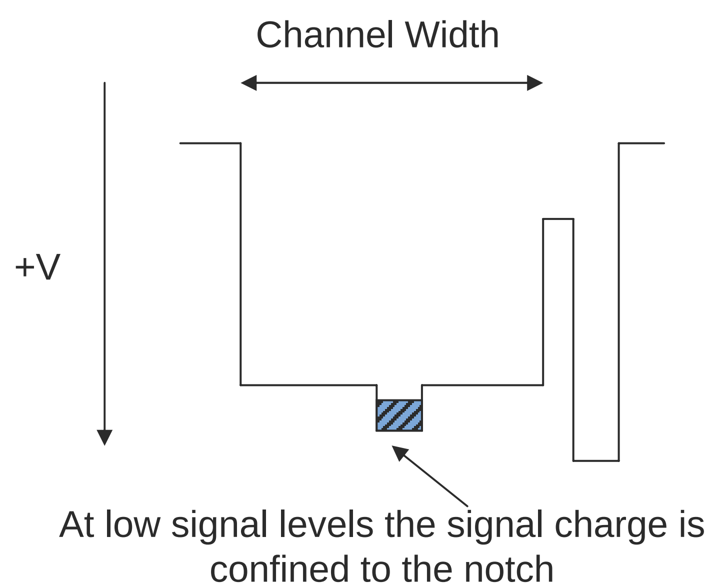
Proton Irradiation
CTE Degradation

➲ Schematic of the effects of proton irradiation



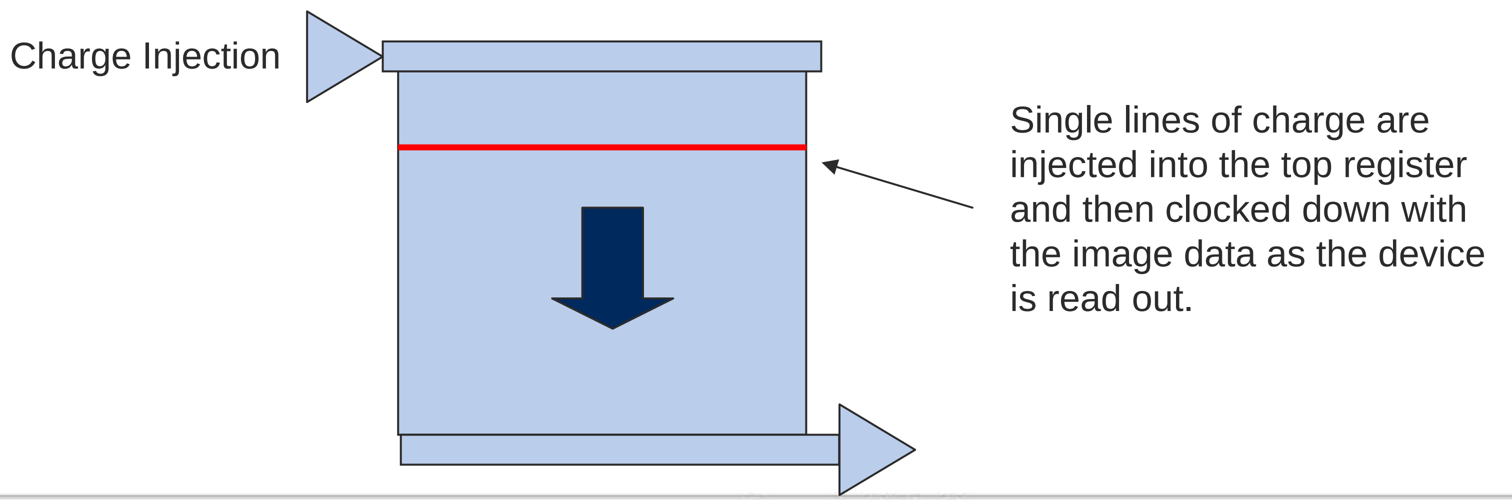
Proton Irradiation
CTE Degradation Mitigation

➲ In large sized pixels a supplementary channel or "notch" may be included to ensure that at low signal levels charge is contained within a small fraction of the pixel volume. This reduces the probability of the charge intercepting a trap.

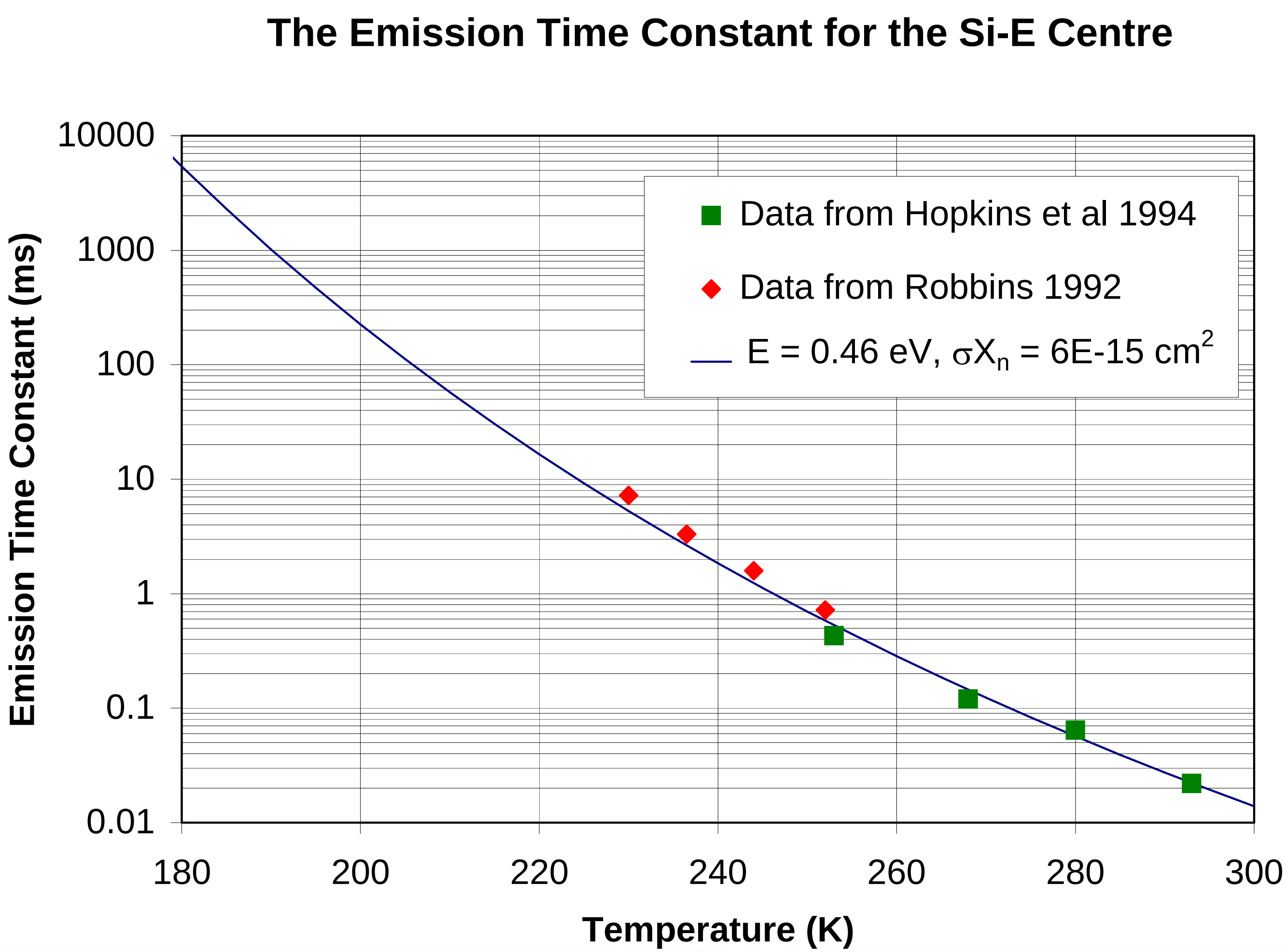


Proton Irradiation
CTE Degradation Mitigation

- An alternative/additional means of reducing CTE degradation, used for example on the CCD43 supplied for the Hubble space telescope upgrade and for the GAIA CCDs, is to sparsely inject rows of charge signals in at the top of a device to be clocked down the image area and fill any traps that are present. At low temperature the emission times of the traps are very long with the result that the traps remain full as following signal data is clocked through the device.
- In a TDI device such as GAIA, the frequency of the injected lines can be adjusted to match the emission times of the traps at the operating temperature.



Proton Irradiation
CTE degradation mitigation



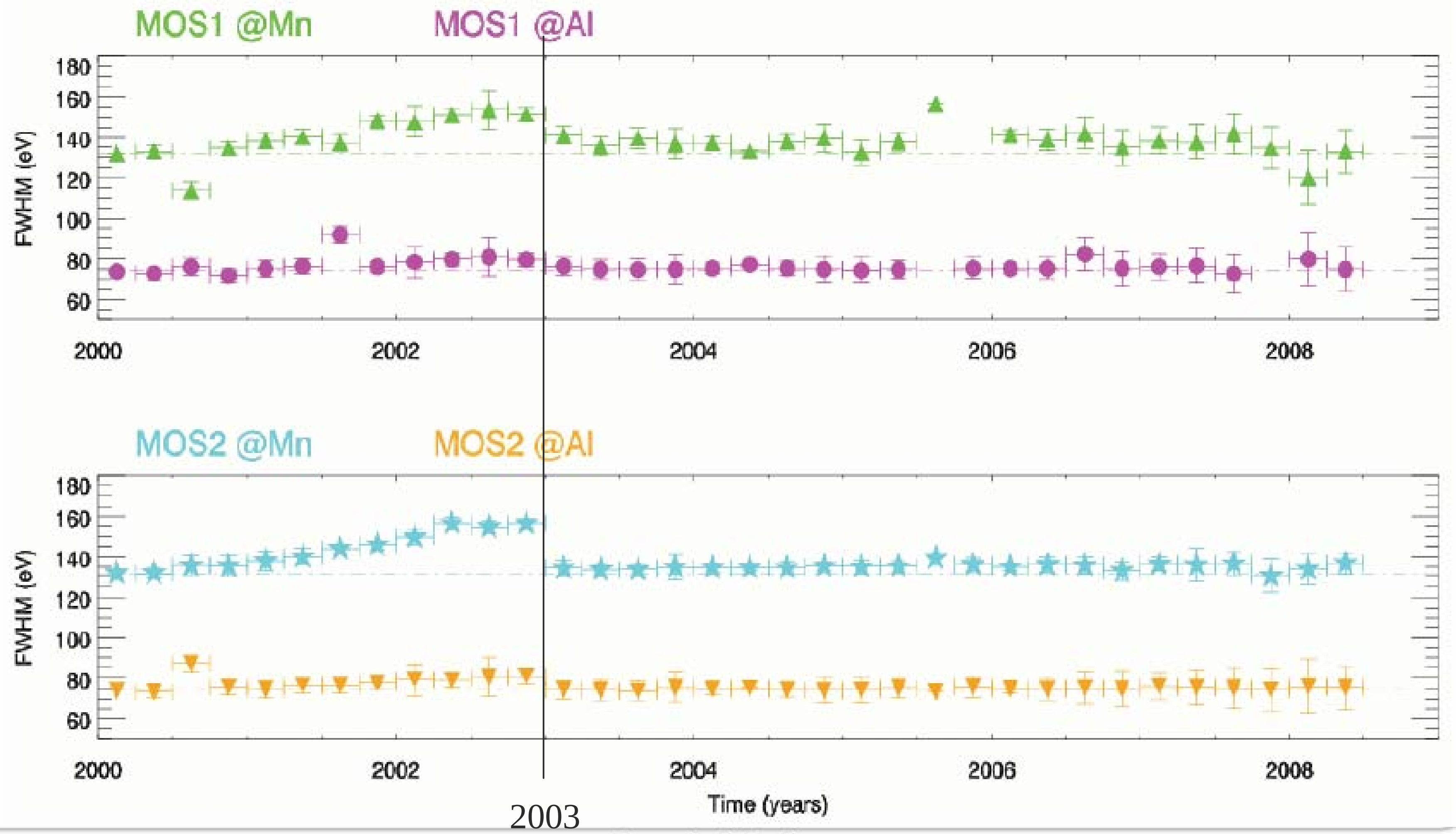
Proton Irradiation
CTE degradation mitigation

- The alternative approach is to provide a low level flash of light to provide a background signal to fill traps before an image is read out.
- This has the advantage that it can be used on any device.
- However, the background signal will give additional shot noise.

Proton Irradiation
XMM-EPIC results

- ➲ Whilst CTE degradation is undoubtedly a problem in CCDs, optimised devices can successfully operate in a space environment for many years. For example, XMM- EPIC is approaching 10 years of operation and has had a recent life extension. This is a very challenging application as both the energy and position of x-ray sources is measured and, if charge is lost, then the energy resolution is degraded. Virtually no degradation of energy resolution has been seen to date
- ➲The improvement seen in 2003 is when the operating temperature was dropped, causing the trap-filling to be more effective

Proton Irradiation
XMM-EPIC results

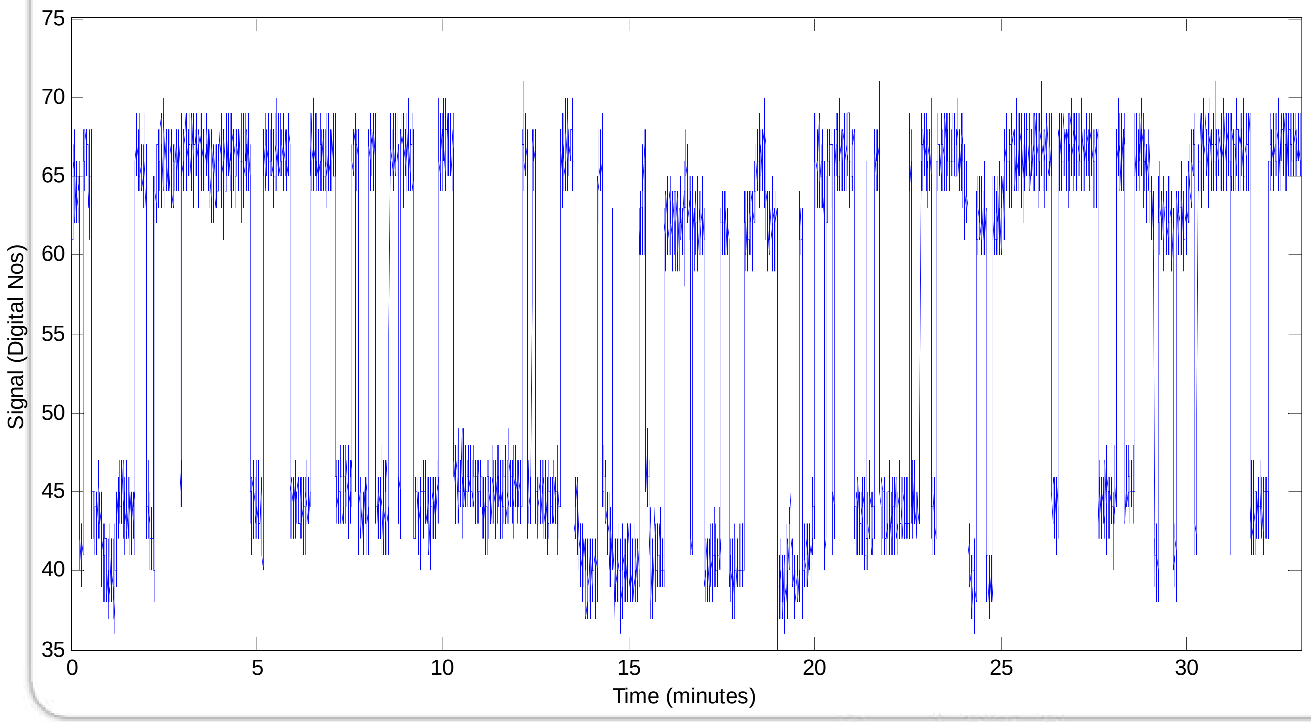


Random Telegraph Signals - RTS

- Certain traps can have two or more energy levels, meaning that a localised dark signal may switch between two or more levels. The resulting output waveform resembles a Random Telegraph Signal, hence the name.
- In CMOS sensors RTS signals can also result from the size of the source-follower transistor in the pixel being so small that the 1/f noise is dominated by a single surface trap.

Proton Irradiation
RTS

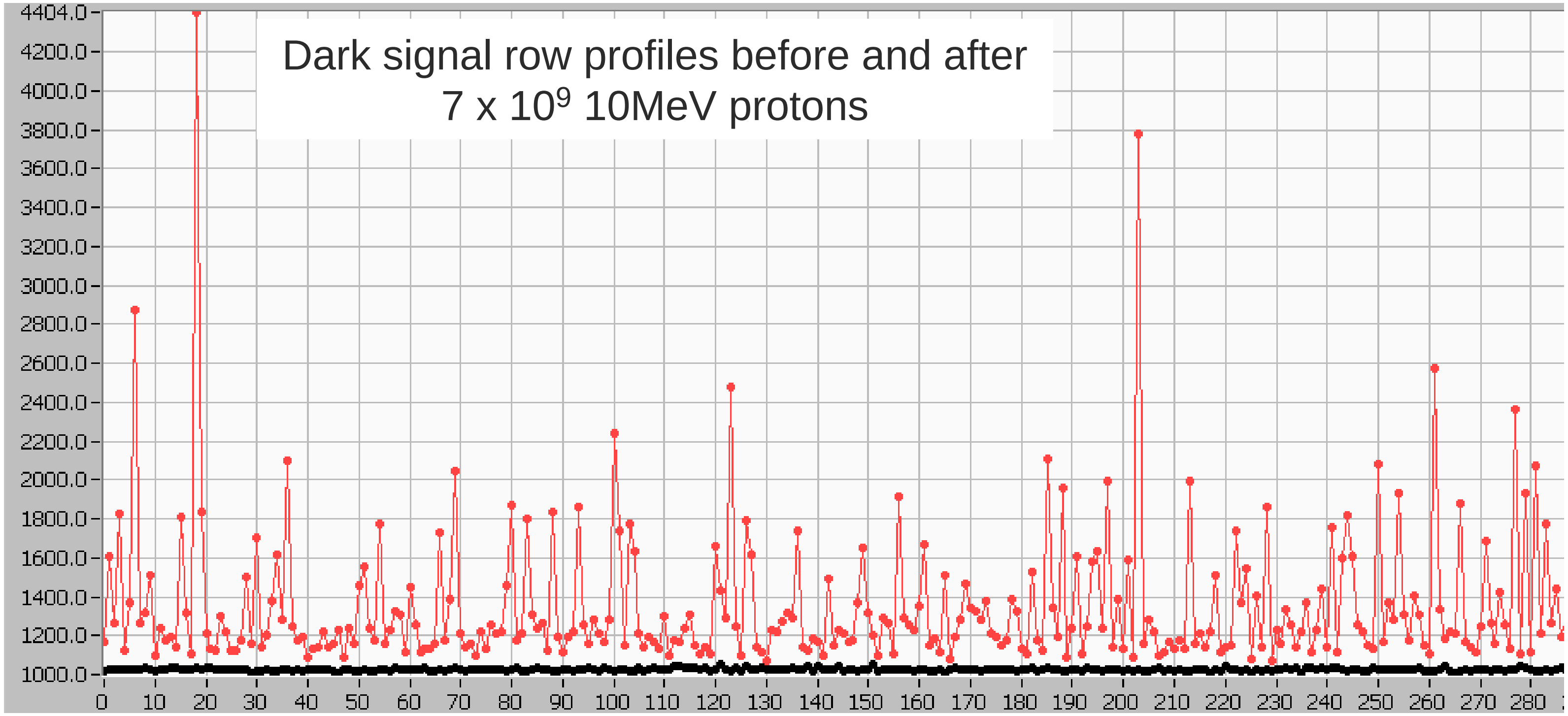
➲ RTS pixels are seen in both CCDs and CMOS sensors and make dark signal correction very difficult. The exact mechanisms are still uncertain, thus procedures for design optimisation are not yet established. The only mitigation is to operate devices at a low temperature where the dark signal generated is negligible and the time constant is also significantly increased.



➲ RTS dark signal image from a CMOS sensor after proton radiation. Thanks to Ben Dryer and Prof. Andrew Holland for the CEI, The Open University.

Proton Irradiation
Dark Signal Spikes

➲ In addition to the RTS generated from proton irradiation, there is an increase in the bulk dark signal which is non-uniform in nature. This is very significant for "pinned" devices, CCD or CMOS, at higher operating temperatures.



Post Irradiation Anneal

➲ The impact of a high temperature anneal on bulk damage from proton radiation is the opposite to gamma. The bulk damage tends to be repaired, thereby causing a reduction in the bulk dark signal.

➲ Note, however, that protons also cause ionisation damage giving an increase in the surface dark signal, so the overall situation is complicated.

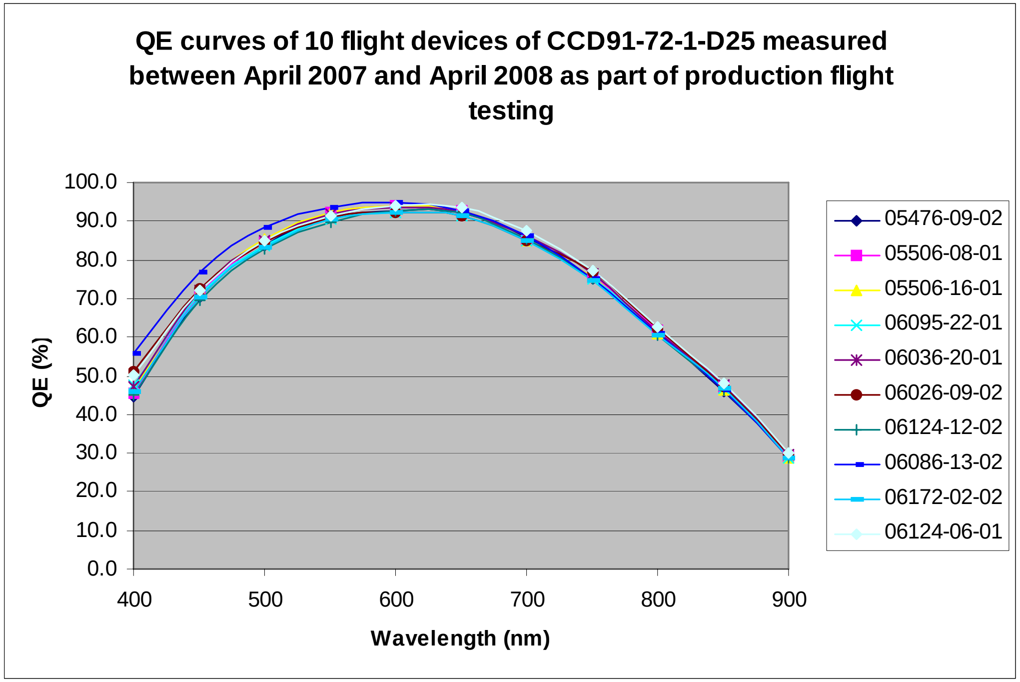
Detection efficiency
Quantum Efficiency

➲ Maximising detection efficiency involves obtaining the highest possible QE with the lowest possible noise.

➲ Back-thinned sensors can give over 90% peak QE with very repeatable performance, as seen for example in the samples below from deliveries for GAIA

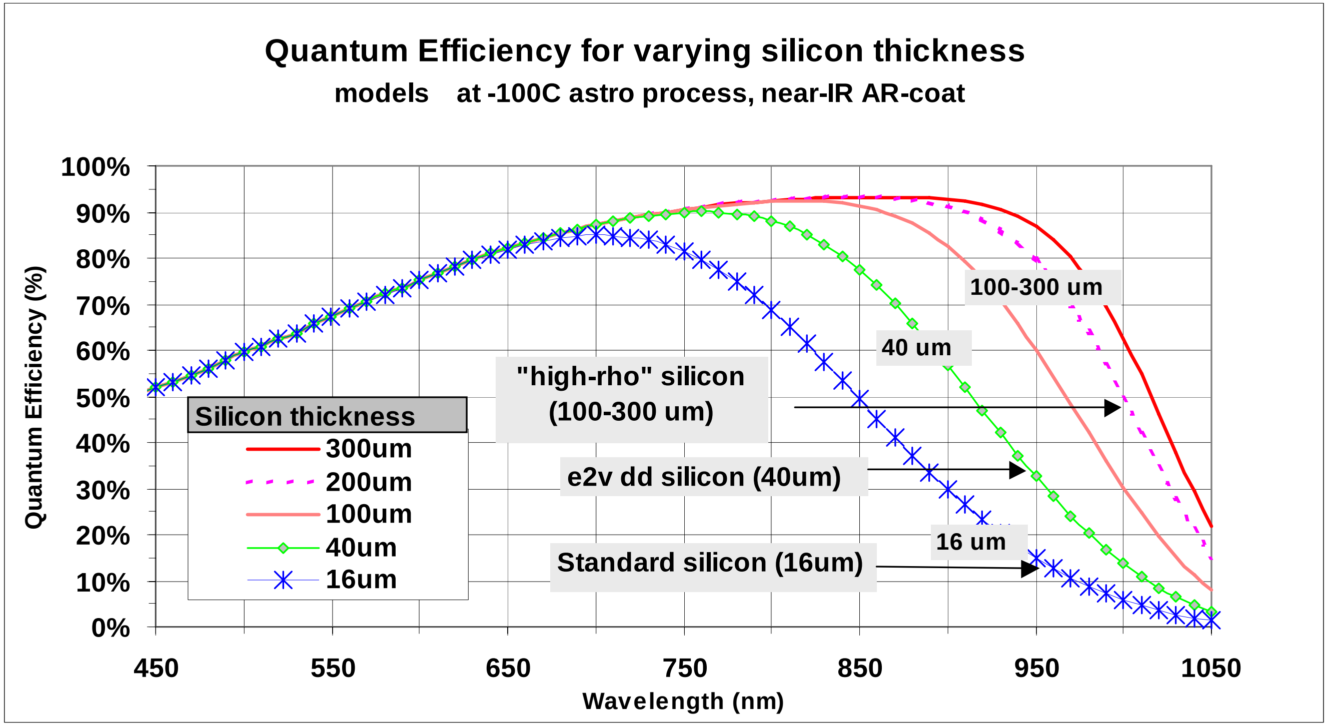
➲ QE is more related to the fabrication process than design, but for maximum QE with anti-blooming "shielded" drain structures must be used.

➲ The precise treatment of the back-surface is then critical for optimum performance.



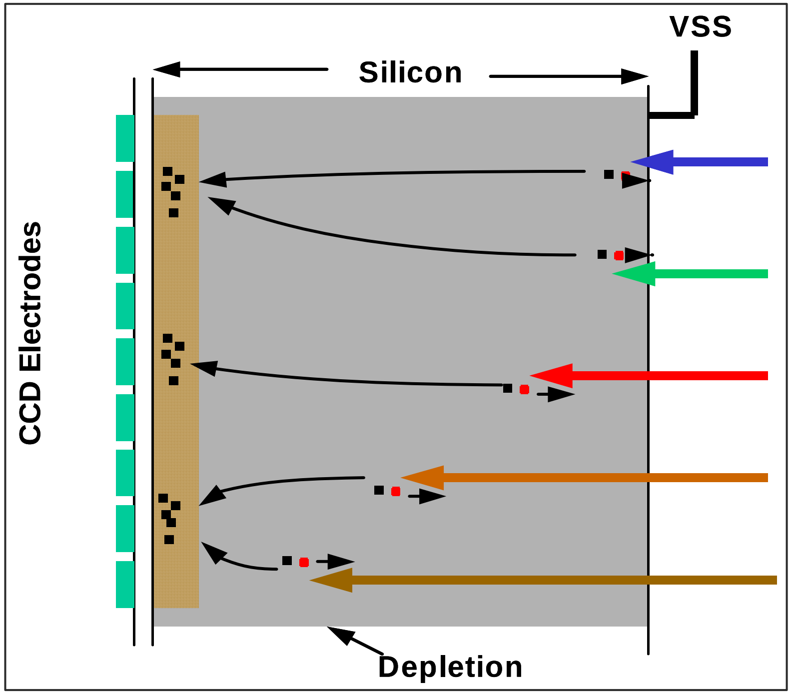
Detection efficiency
Quantum Efficiency

➲ Development continues at e2v to improve quantum efficiency. Recently, efforts have focussed on improving QE at wavelengths above about 700 nm by using thicker bulk silicon and means to achieve full depletion. The device technology is termed “HiRho”.



Detection efficiency
Quantum Efficiency

➲ The challenge for a HiRho CCD is to produce a voltage across the device large enough for the silicon to be fully depleted and thus give high resolution.



➲ Various modifications of the device structure are required to support the voltage (VSS) of up to -100V that is necessary at the back surface.

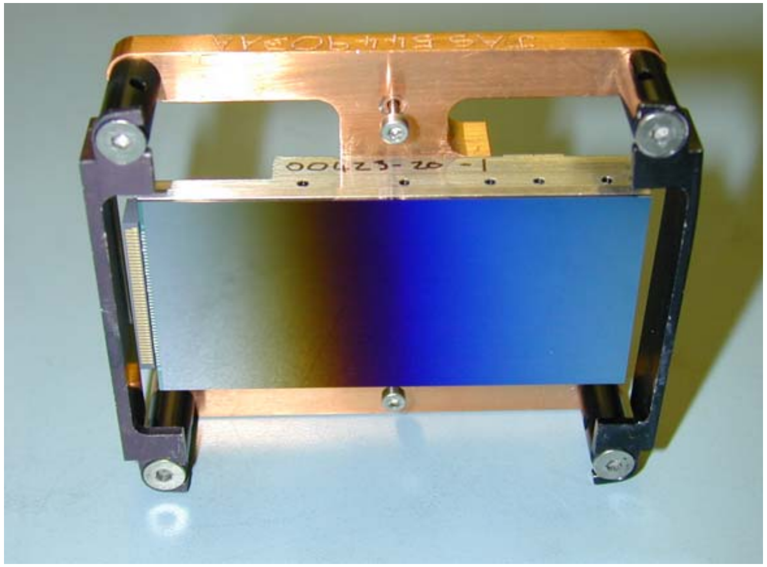
➲ Note that the scale is stretched – the device thickness is up to 200µm with a pixel pitch of ~10-15µm.

➲ HiRho devices have not yet used in space missions, but should be in the near future.

Detection efficiency
Graded AR coatings

➲ There are also different formats of AR coating available to optimise device performance at given wavelengths. The most extreme form is on Hyperspectral or spectroscopy type devices, where a graded coating can be provided to match the spectrum across the device.

CCD42-82 with graded coating

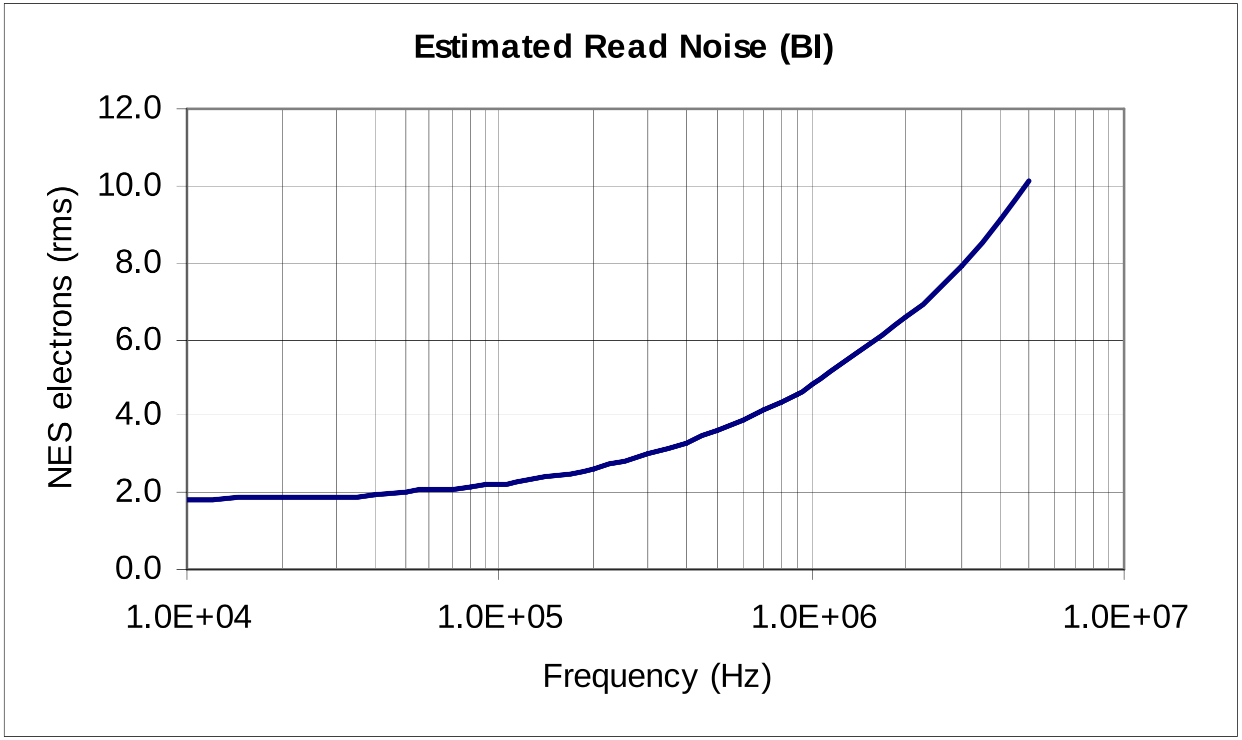


Blue-optimised end

Red-optimised end

Detection efficiency
Read-out noise

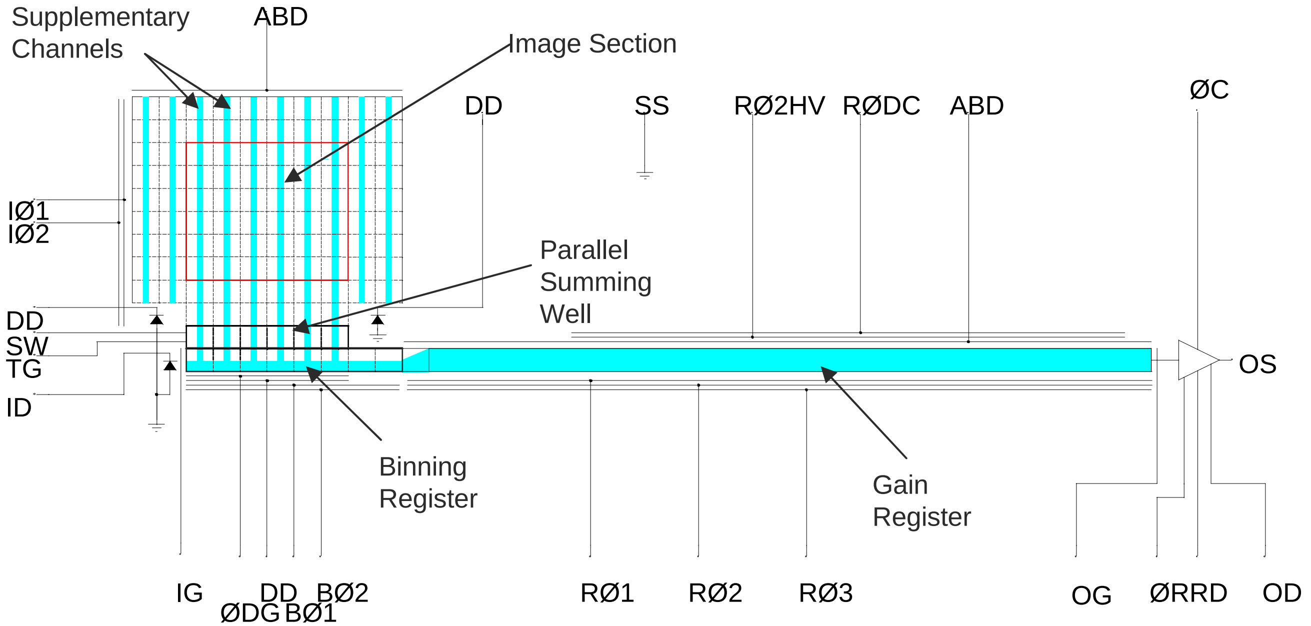
➲ For low signal level applications the other critical parameter is detection efficiency. At low frame rates CCDs with a high responsivity output circuit (~8 µV/e-) can give extremely low noise (below 2 e-), as shown below:



Detection efficiency
Read-out noise

➲ At higher read-out rates the CCD noise would normally increase, but with an electron multiplication “gain” register very low noise can still be obtained, e.g. sub-electron read-out noise at video frame rates.

➲To overcome concerns about the effect of radiation on gain registers, qualification for space application is now in progress, e.g. or LIDAR for ESA:



Power Dissipation

➲ For space applications power can sometimes be in short supply and so there is a strong incentive to reduce consumption.

➲ In order minimise power consumption:

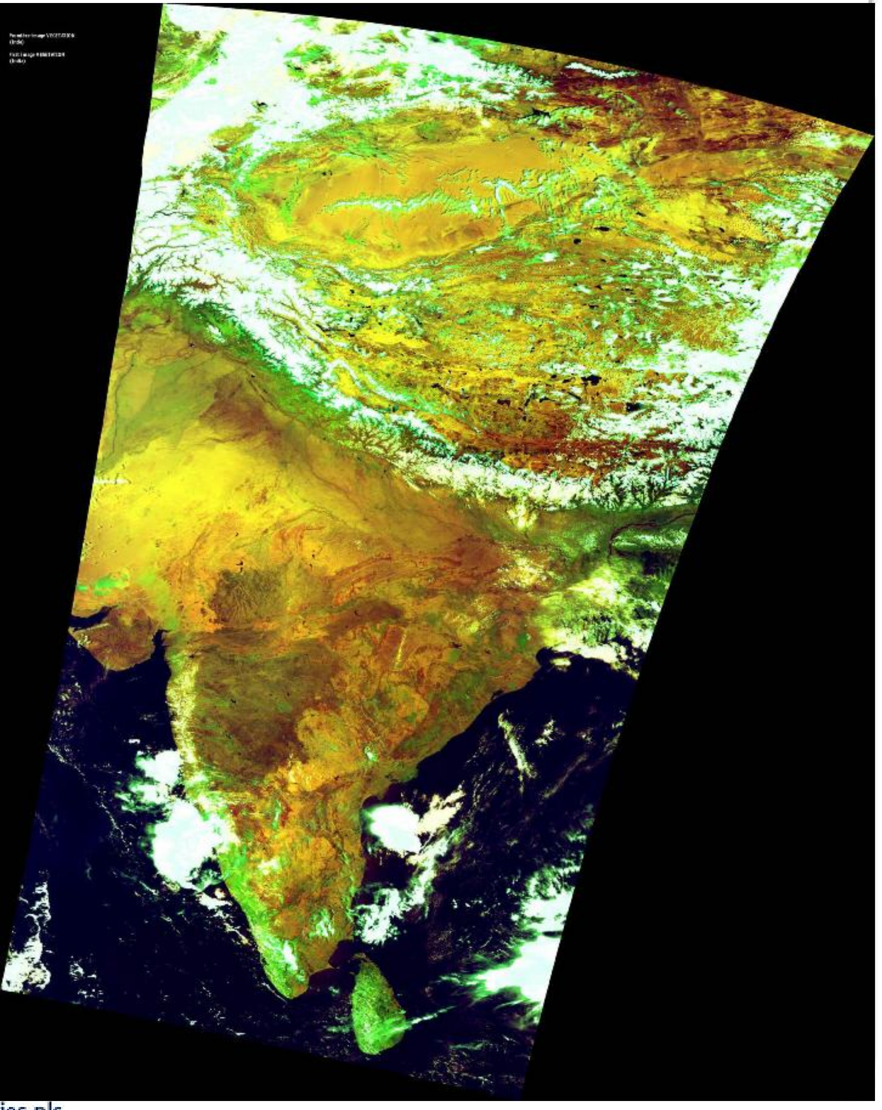
- ➲ Devices can be manufactured to operate with significantly lower clock voltages, 5-8V instead of the more standard 10-12V. This can give a very large saving in dynamic power dissipation (i.e. from $P=CV^2f$). The depth of depletion is however reduced, with possible consequences for resolution.
- ➲ Amplifiers can be operated at the minimum load current consistent with achieving acceptable settling performance at the required read-out frequency. The use of an external load minimise on-chip consumption but does not reduce the total power

TDI Imaging
Linear arrays

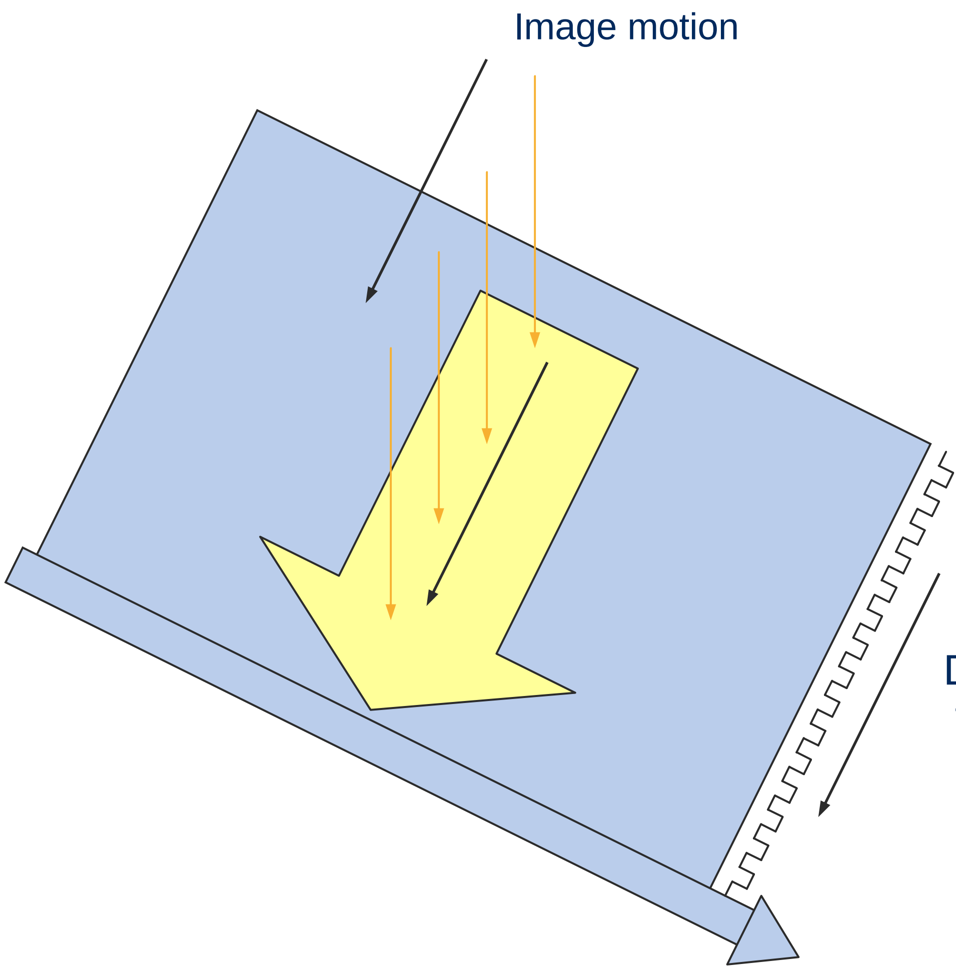
➲ Linear arrays are very well established and are used in many scanners

➲ Linear arrays in satellites have produced excellent images for many years – such as from the SPOT series of satellites

➲ However, the sensitivity of a linear array is limited by the pixel size and scan rate.



TDI devices

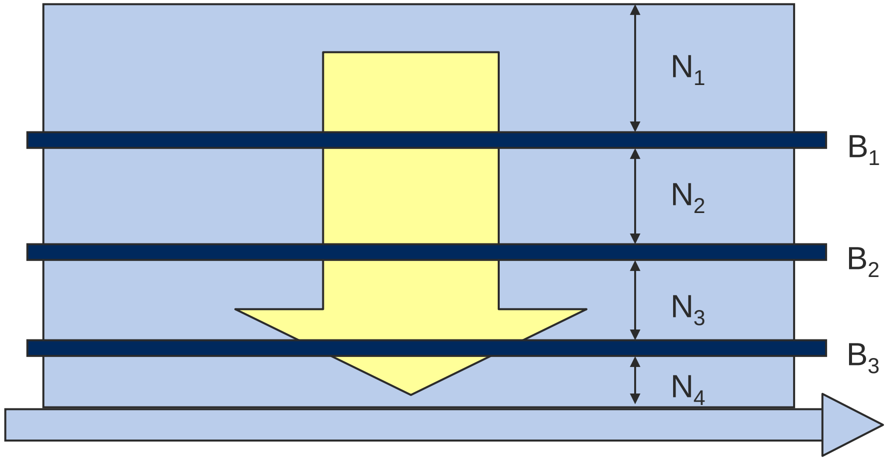


➲ More recent high sensitivity systems use TDI devices

Device clocked at such a rate as to transfer the potential wells to match the image motion.

TDI devices

➲ TDI sensors are frequently made with blocking phases, which may be used to vary the number of TDI stages and thus control the device sensitivity.

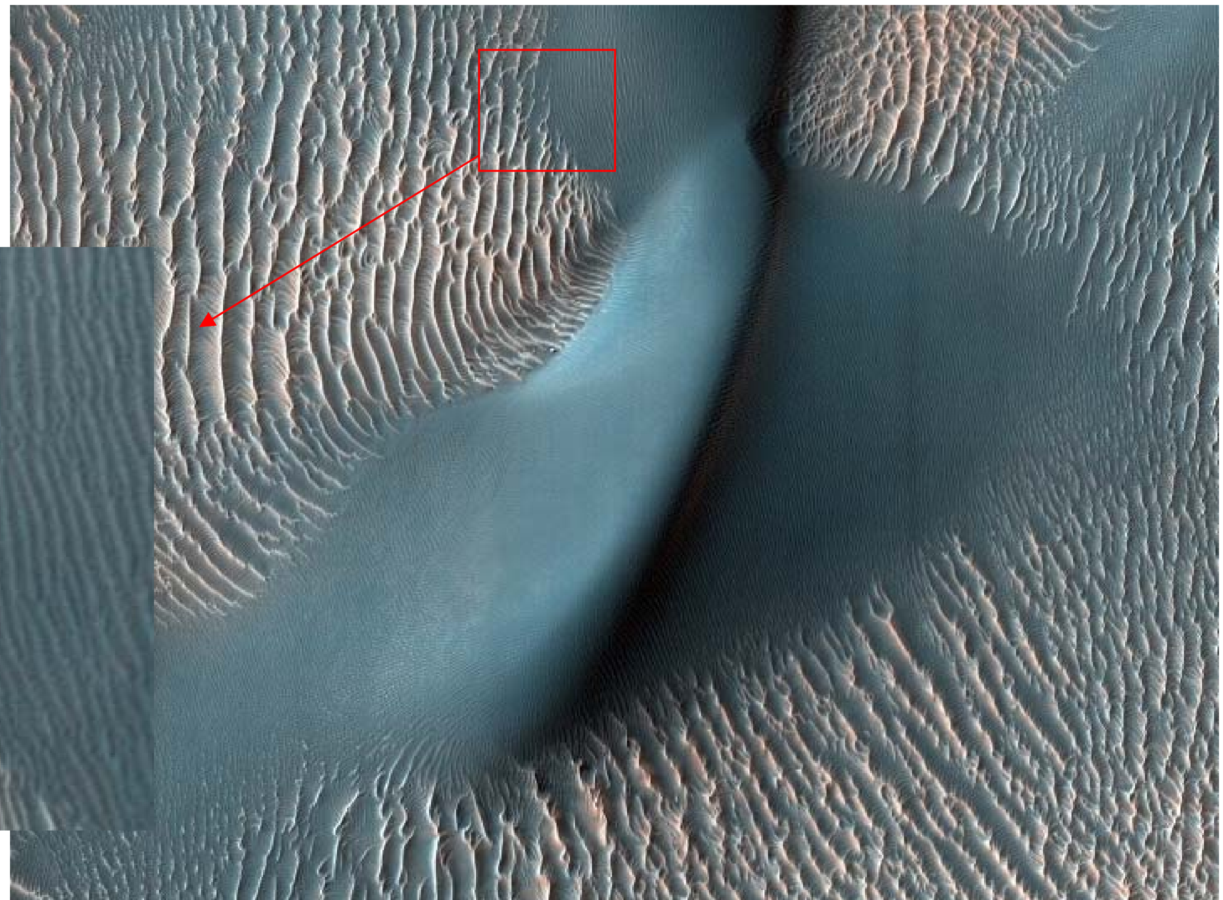


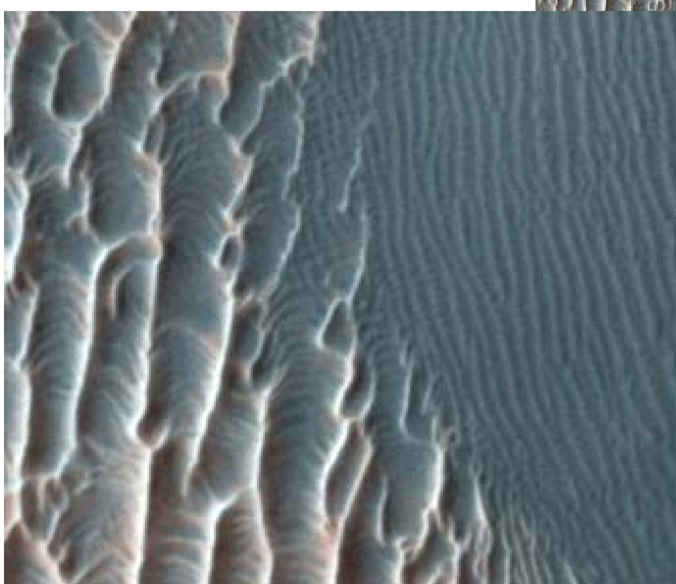
Tap selected	TDI Rows active
None	$N_1 + N_2 + N_3 + N_4$
B1	$N_2 + N_3 + N_4$
B2	$N_3 + N_4$
B3	N_4

TDI devices
Examples of images

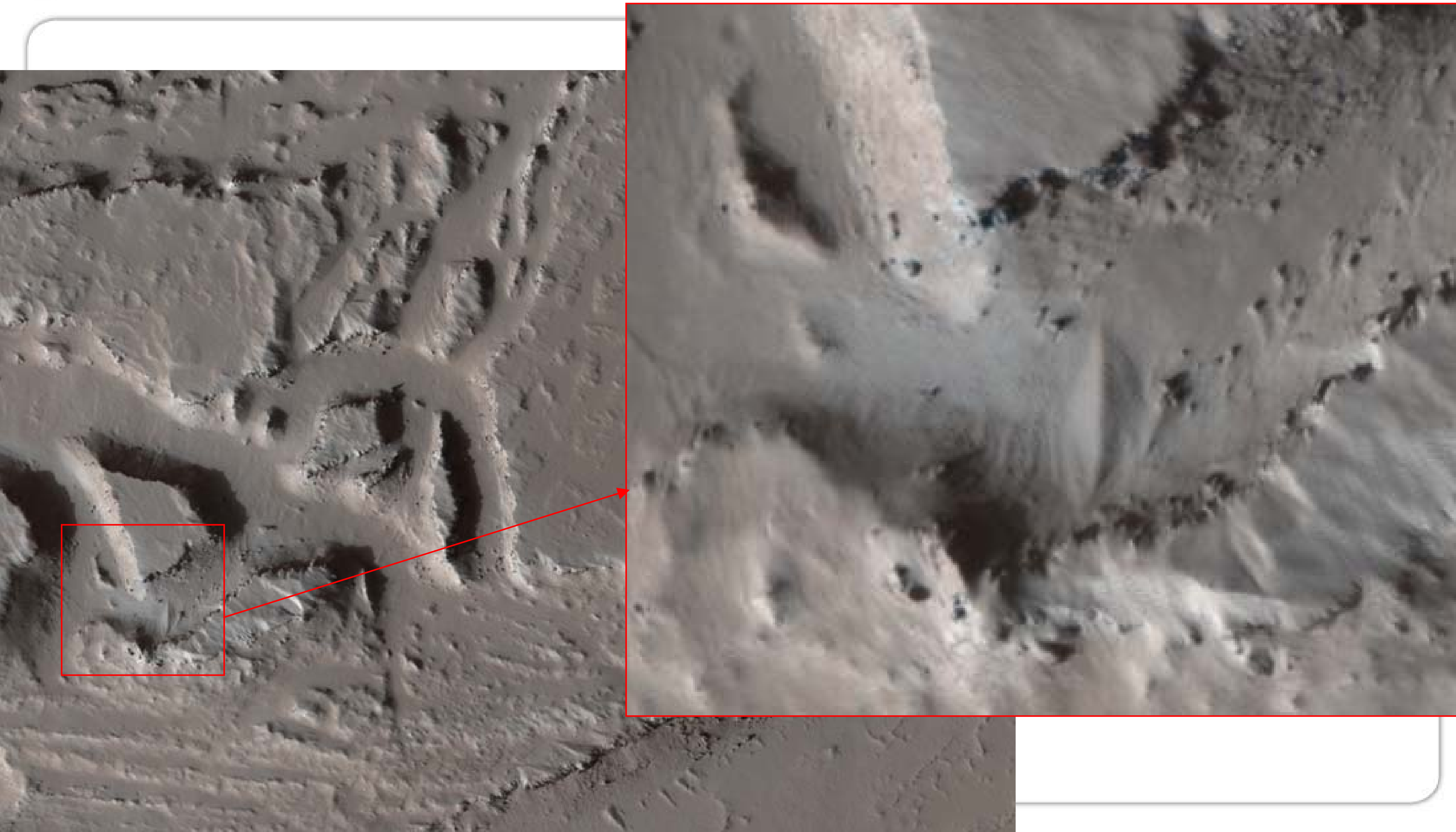
➲Recent images from HiRise over Mars (From University of Arizona Website)

Sand dunes and ripples in the proctor crater





TDI devices
Other examples of HiRise images – flood-carved rock



Future developments

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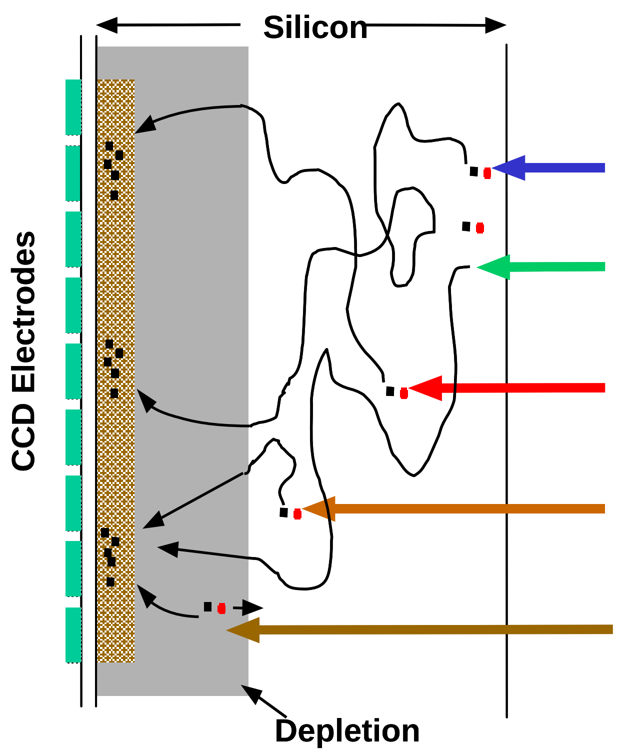
➲ For TDI applications with a back-thinned sensor, as the pixel size decreases obtaining good resolution becomes ever more difficult



➲ Pixel pitches in the future are likely to reduce to below 8µm, meaning that any significant thickness of undepleted silicon will give severe degradation of resolution.

➲ The silicon can be made correspondingly thinner, but this decreases red response

➲ A new technique is being developed to separately bias the back-surface to control depletion depth with high precision. This will also enable the front surface to be operated in the inverted mode, thereby reducing the dark signal before and after irradiation.

Conclusions

- ➲ Ionising radiation causes an increase in the surface dark current, which can be contained using inverted mode operation. There is also a shift in the MOS threshold voltage, which can be minimised using thinner gate oxides.
- ➲ Proton irradiation causes displacement damage leading to degradation of CTE, bulk dark signal non-uniformity and RTS effects. The CTE degradation can be minimised using “notches” and/or trap-filling techniques. The other effects appear to be fundamental to silicon and are present in both CCD and CMOS.
- ➲ Read-out noise can be minimised using high responsivity amplifiers or a gain register before charge detection.
- ➲ CCD power dissipation can be reduced using lower clock amplitudes and thin gate devices.
- ➲ The QE at longer wavelengths is being increased using HiRho devices with very thick silicon capable of full-depletion.
- ➲ TDI devices are being increasingly used for high-performance satellite-based ground-imaging applications.

Acknowledgements

- ➲ The authors would like to thank all those who have made inputs to this paper particularly;
  - ➲Peter Pool, David Morris and Mark Robbins from e2v technologies
  - ➲Ben Dryer and Prof. Andrew Holland from the Centre for Electronic Imaging at The Open University

➲Thank you for your attention