Detectors

The telescope captures light from astronomical objects and delivers it to the focal plane where it may be detected.

The delivered image will cover the full visible/IR or radio spectrum, as transmitted by the atmosphere, but it will generally be sampled by an instrument with a filter which selects a particular wavelength range and passes that to a detector.

Silicon CCD detectors are usually used in the visible (and at X-ray/UV wavelengths on satellites).

Hybrid infrared arrays with HgCdTe or InSb layers bonded to silicon multiplexers at near-Infrared wavelengths, or doped silicon detectors e.g. Si:As at mid-infrared wavelengths.

Radio receivers use custom-built SIS chips or superconducting transition edge sensors, Kinetic Induction Devices (KIDS), bolometers etc.

Semiconductors

Solid state detectors:
Photon absorption with E> band gap, promotes an electron to the conduction band.

The band gap in silicon is 1.1eV, requiring photons with $\lambda < 1.1\mu m$ for excitation.
The bandgap can be modified by doping with impurities, such as arsenic; Si:As bandgap ~0.05eV ($\lambda > 25\mu m$).

Devices are cooled to decrease the thermal population in the conduction band (reducing the dark current)

Impurities and defects affect the lattice structure

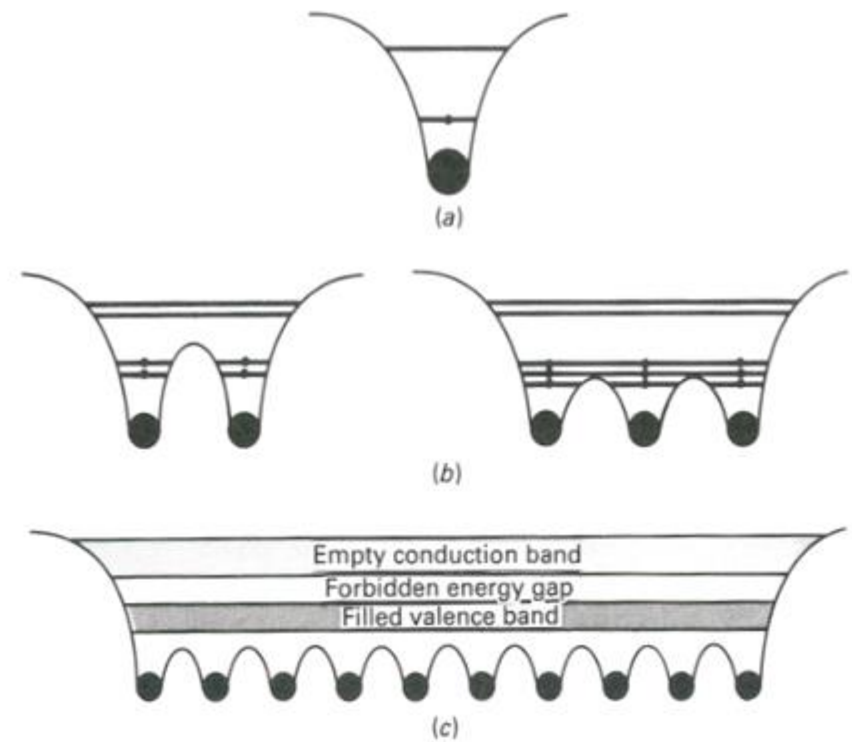
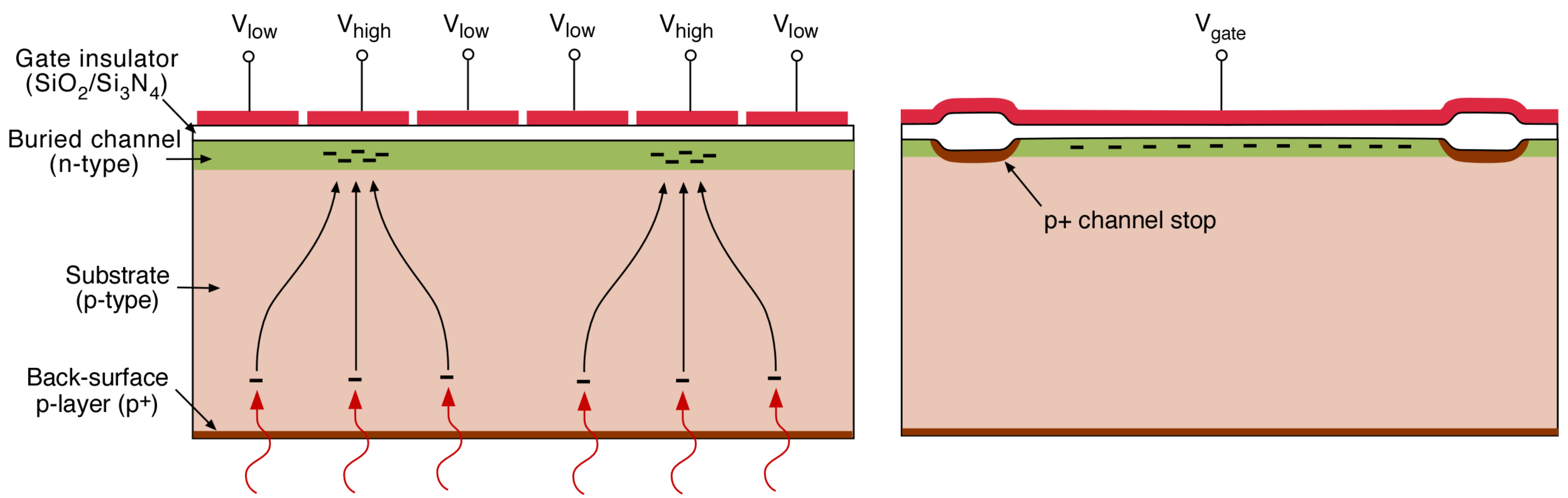


Fig. 6.3. The development of a conduction band and a valence band of electrons in a solid crystalline material such as silicon.

CCD (Charge Coupled Devices)

- Based on photo-electric effect
- Bucket-brigade concept for charge transfer (3 phase CCD)



View along charge-transfer direction

View across CCD channel

CCD pictures courtesy Paul Jorden (E2V)

Charge Coupled Devices

By implanting channel stops and electrodes into the silicon substrate, a set of cells can be defined within the silicon chip.

By clocking the electrodes, the charge accumulated in one cell can be moved across to the edge of the chip, where it can be read out. This is the basis of the CCD

The analogue signal is digitised by an ADC with a bias offset to ensure proper sampling

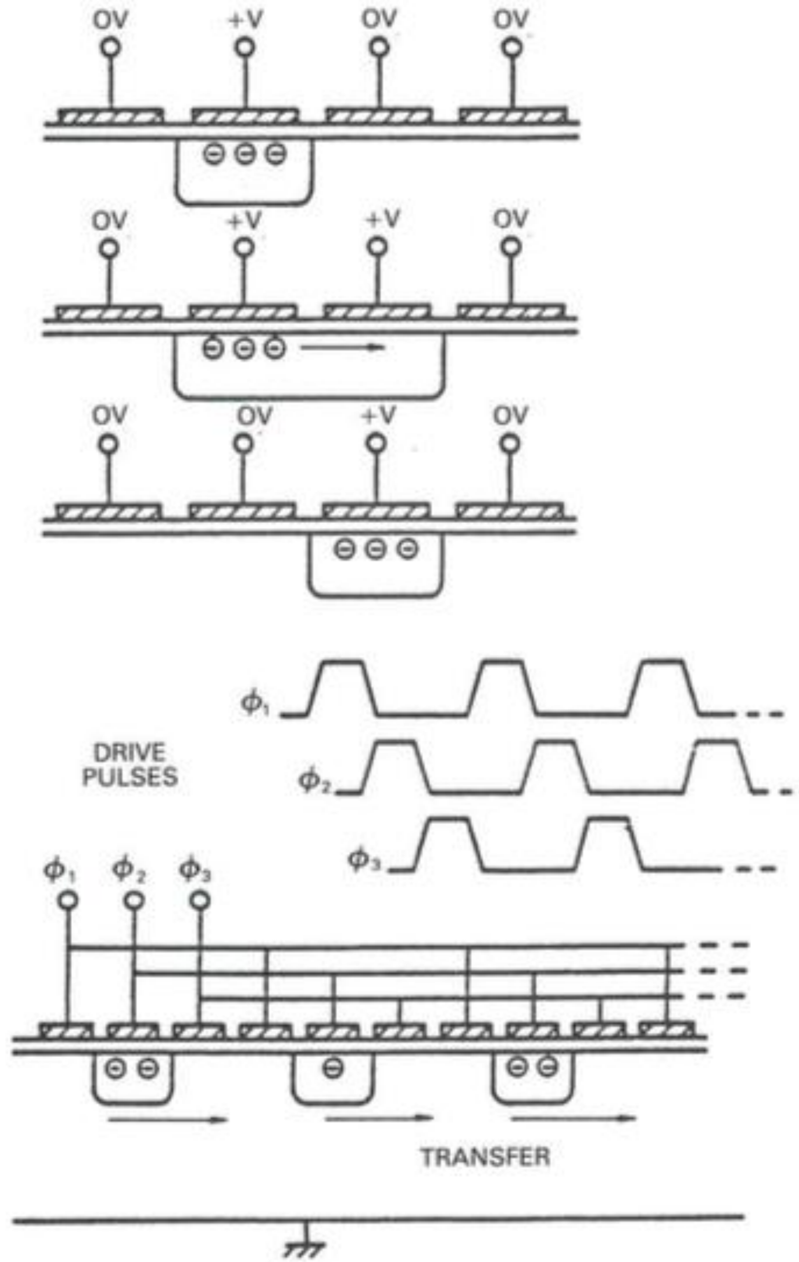
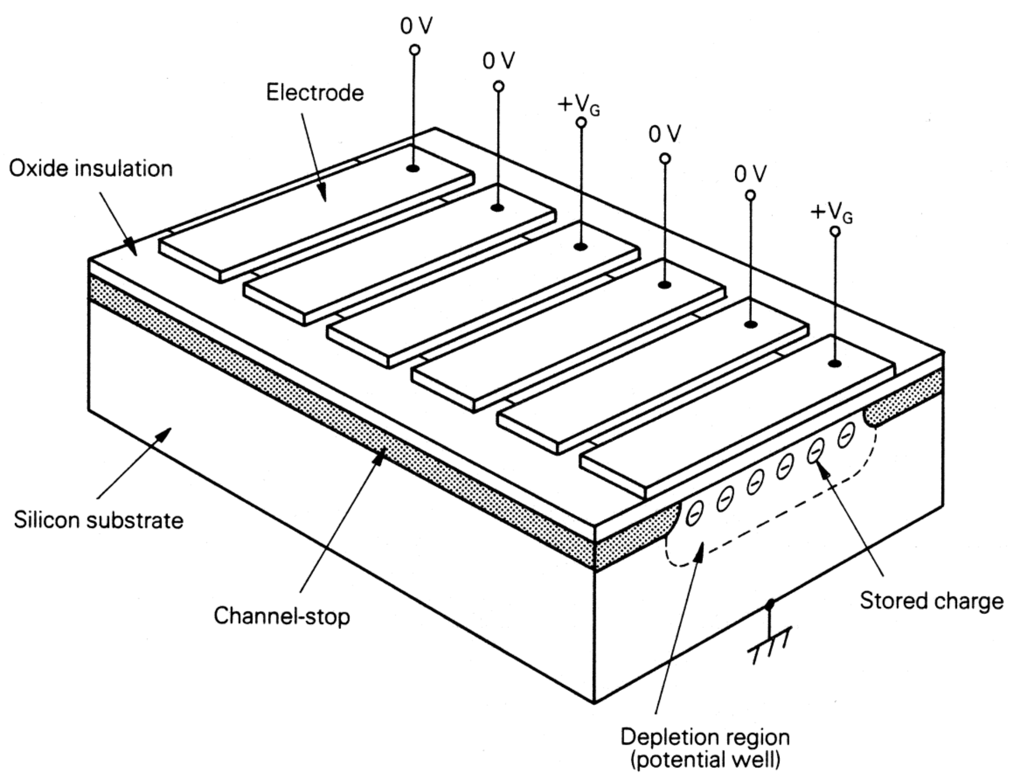


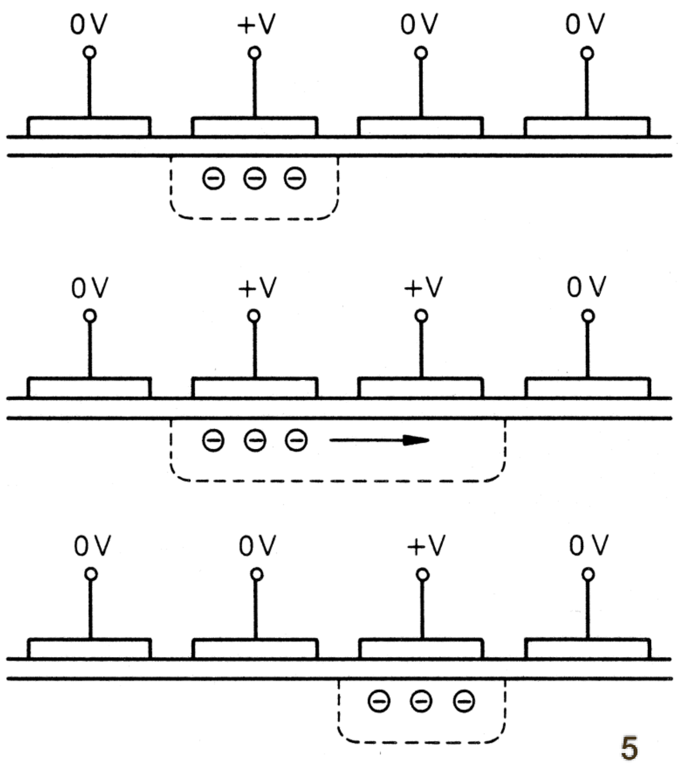
Fig. 6.9. Charge-coupling in a three-phase CCD and the associated timing waveform or clock pattern. In practice the degree of overlap between one electrode and the next depends on the CCD design.

(I S McLean 1997)

CCD (Charge Coupled Devices)

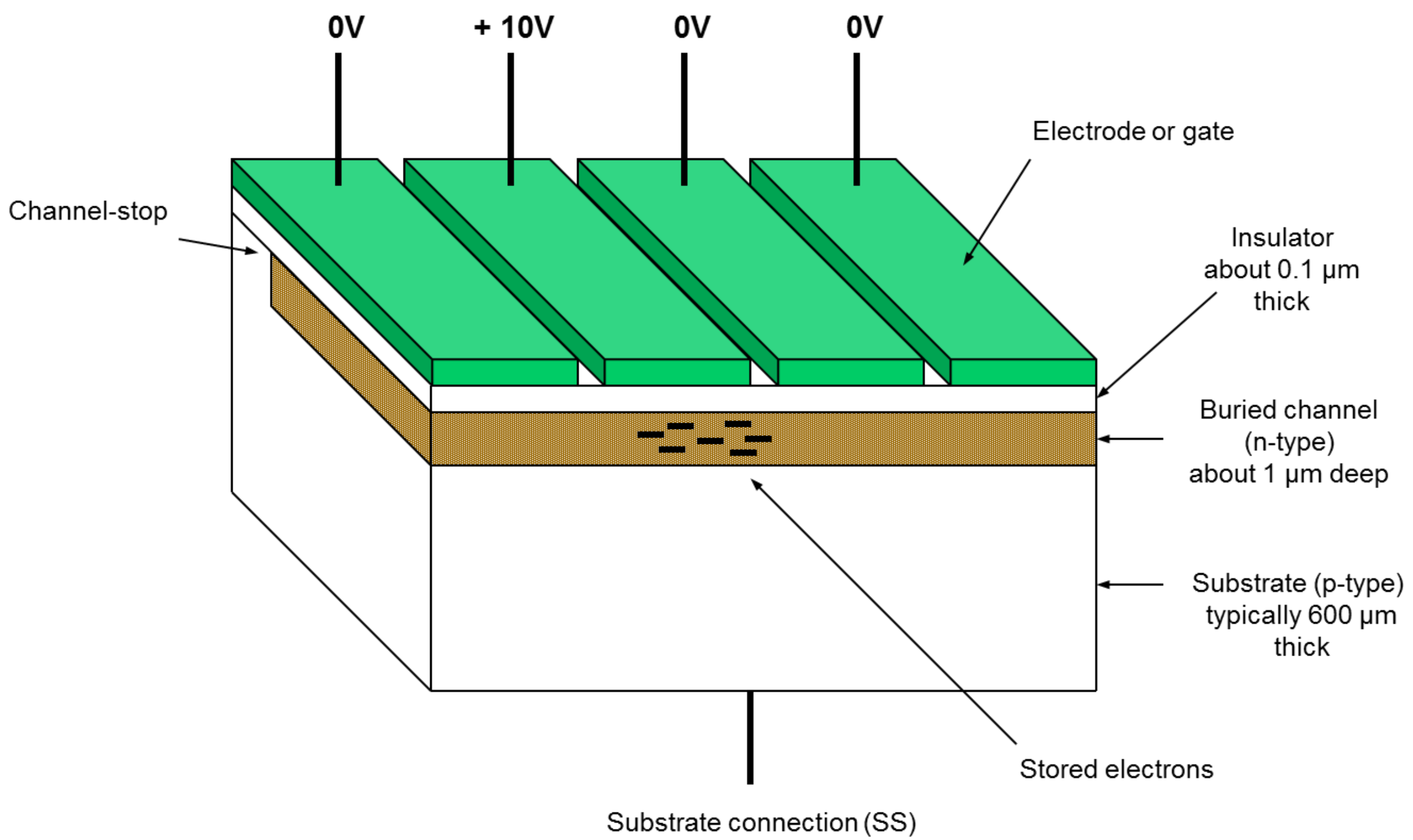
- This simplified structure has poor charge transfer efficiency
- Charge trapping in the $Si\text{-}SiO_2$ interface, and surface traps caused by polishing and implantation





CCD

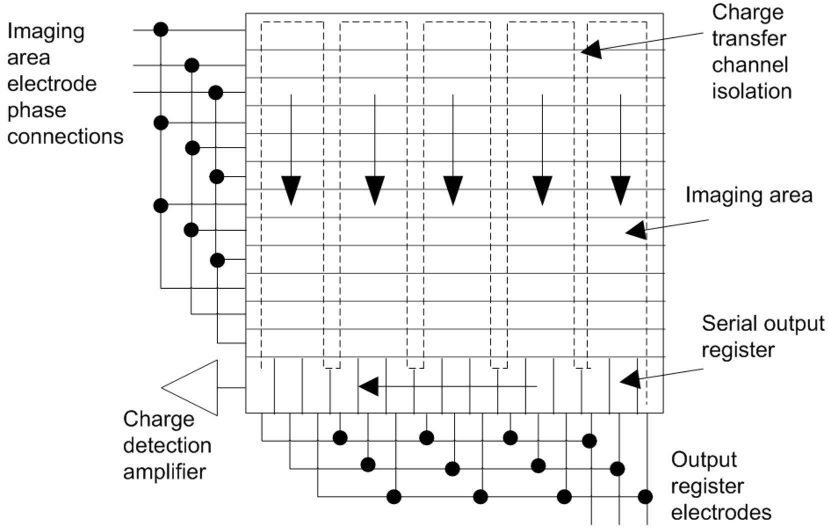
- Introduction of a buried-channel (n-type silicon) implant to improve charge transfer efficiency
- Charge transfer is now below the Si-SiO2 interface



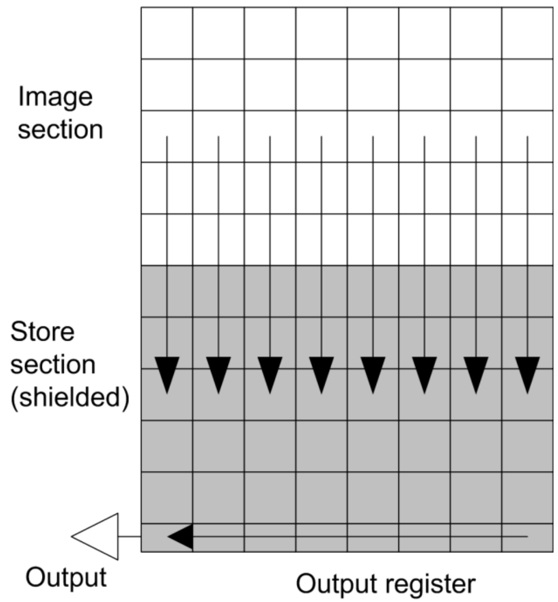
CCD pictures courtesy David Burt (e2v)

CCD Types

Full-Frame



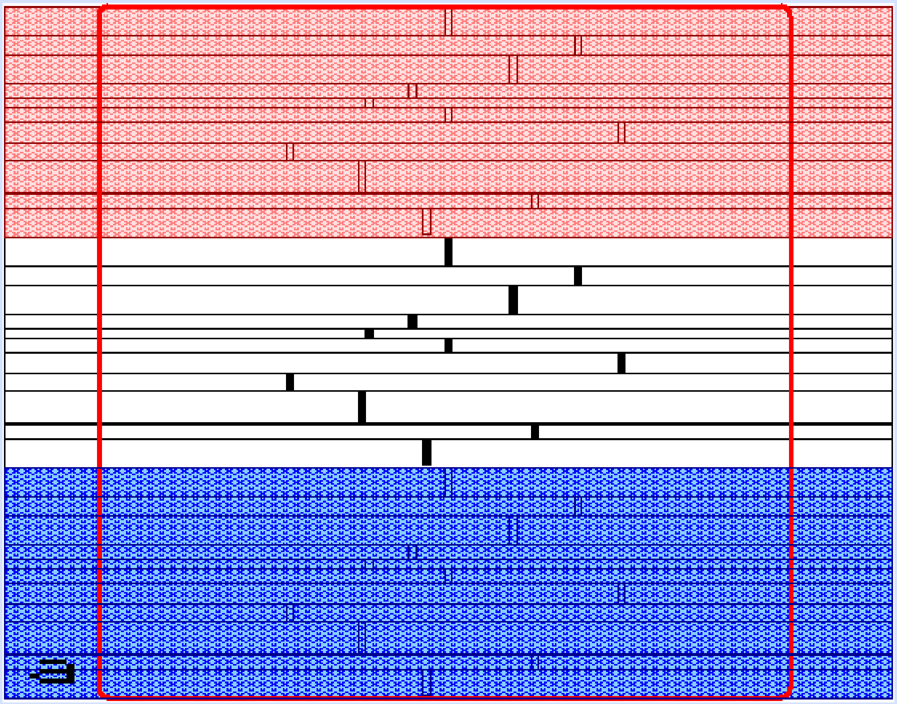
Frame-Transfer



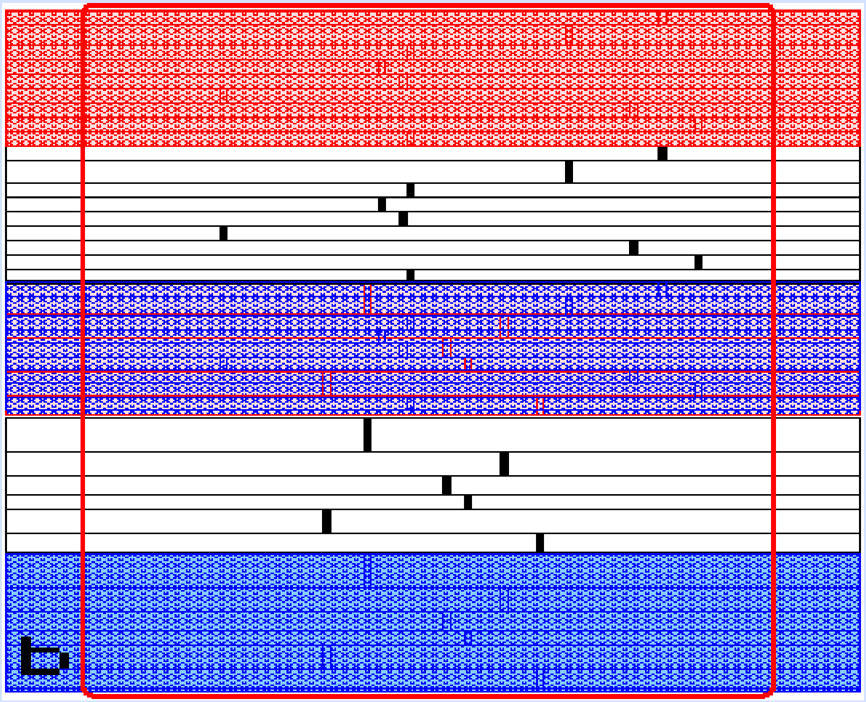
CCD read-out introduces a dead period when the detector is not integrating.

For high speed operation, can use a frame transfer device - the frame is shifted into an unilluminated part of the chip and then read out during the next exposure

Nod and shuffle a la GMOS



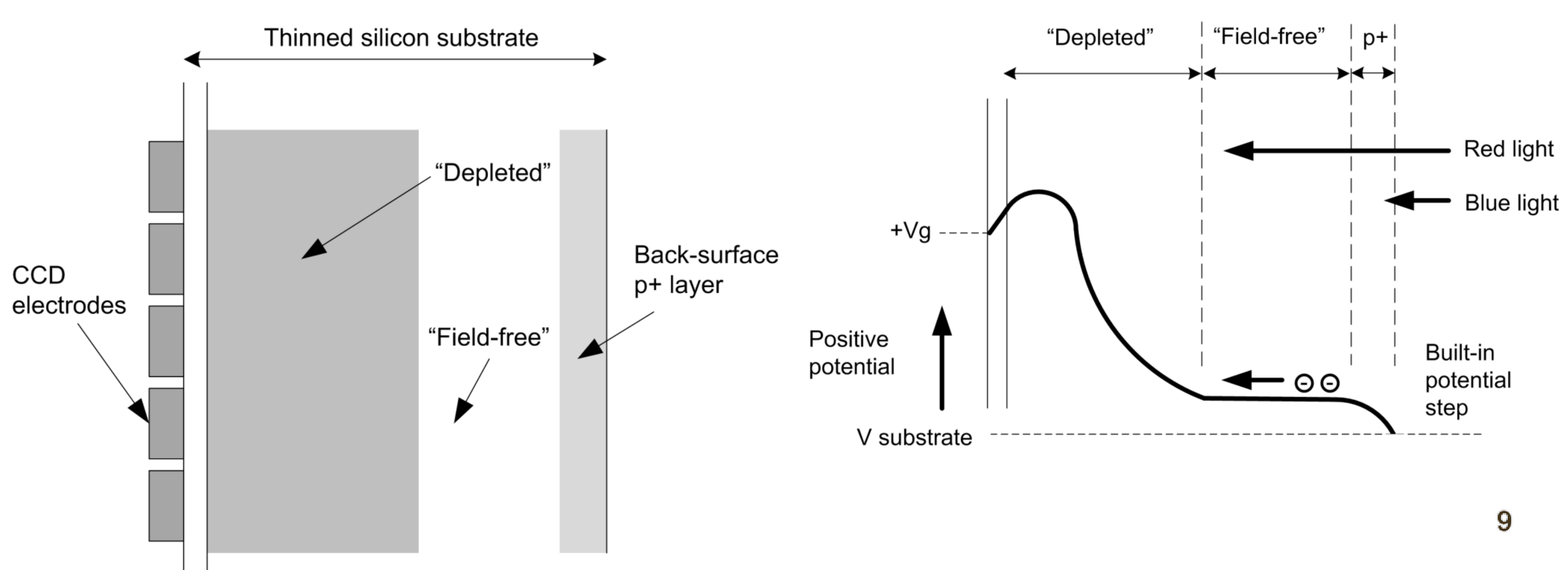
Band shuffling



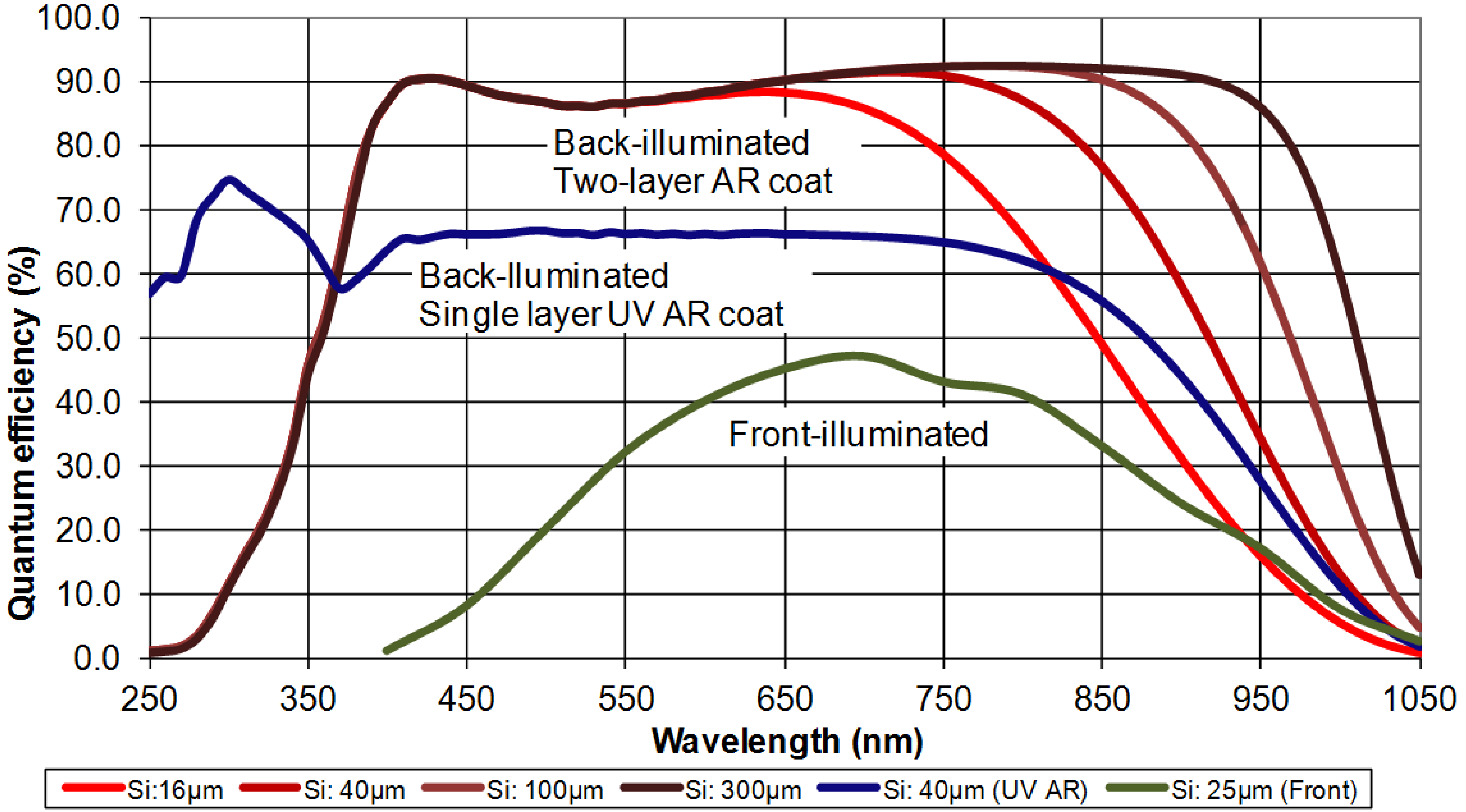
Micro shuffling

Back-illumination

- Back-illumination improves Q.E. – photons not blocked by electrodes etc
- Need to thin the silicon to maintain resolution
- Add anti-reflection coating to further reduce losses
- Very thin chips have poor red response – the path through silicon is below the mean absorption depth

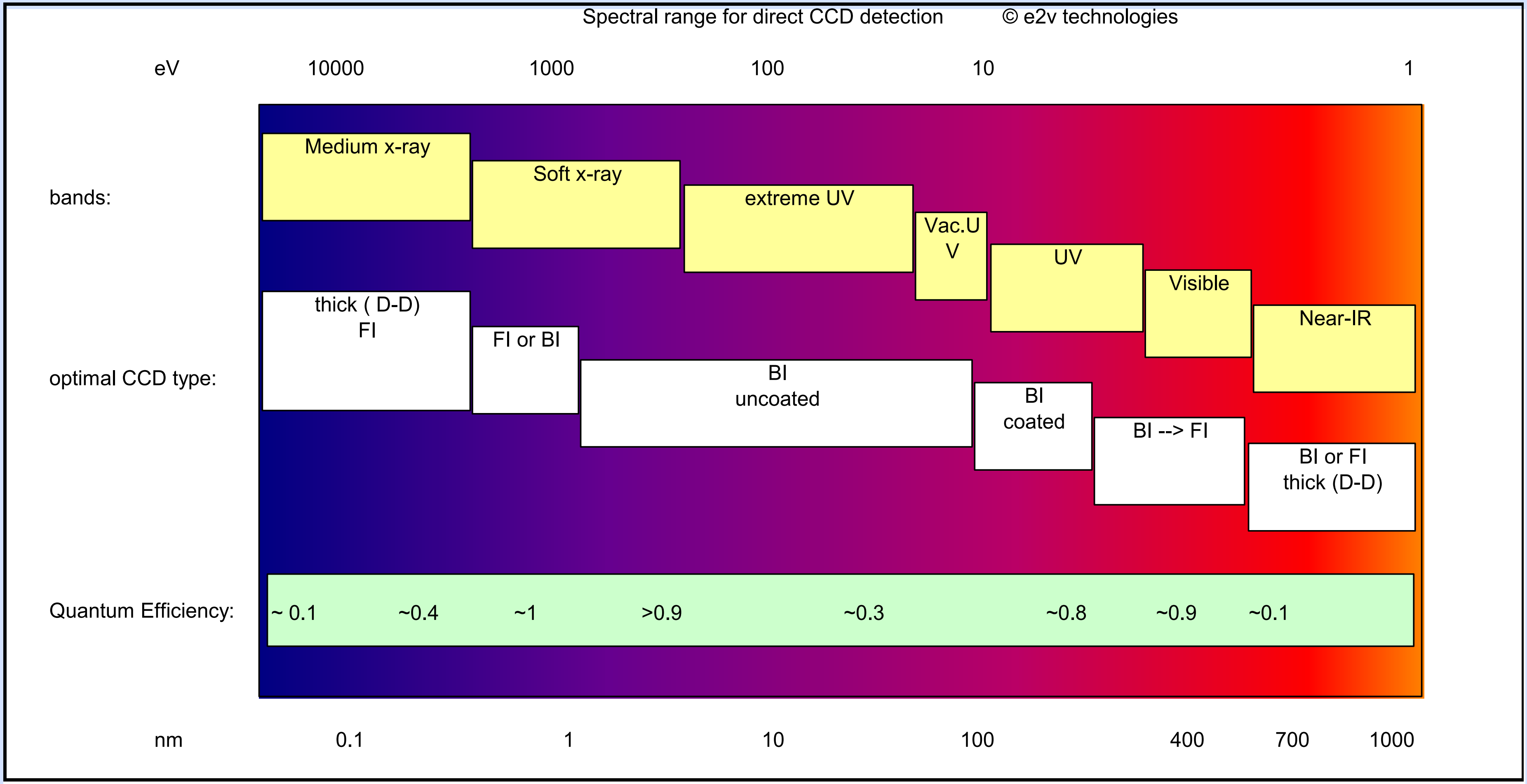


Quantum Efficiency



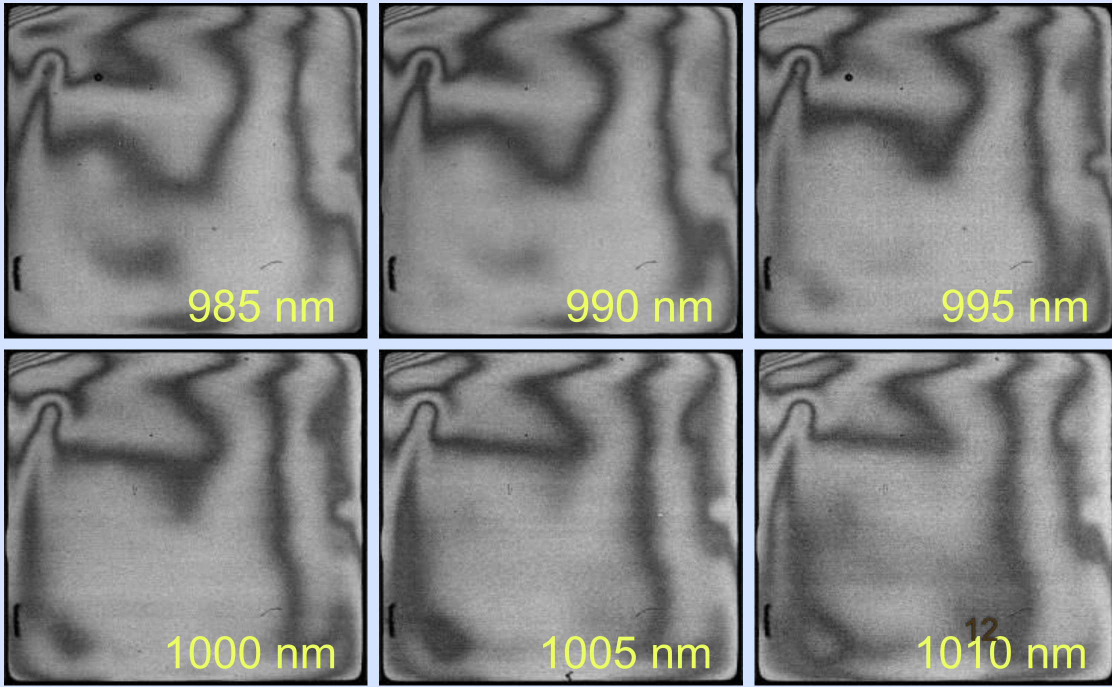
e2v technologies

Quantum Efficiency



Fringing

- Interference fringing occurs at long wavelengths – internal reflections within the device, which significantly affects narrow-band imaging and spectroscopy
- Typically ≥ 750-800 nm, rising in amplitude to ≈ 20%
- Pattern is wavelength dependent
- Fringing is decreased in thicker deep depletion devices
- AR coating at the fringing wavelengths minimises internal reflections.



CCD Performance

- Cosmetic issues – blocked or dead columns, defects, trapping sites

- Readout noise associated with charge measurement

- Dark current due to thermal effects

- Fixed pattern noise due to geometry variations

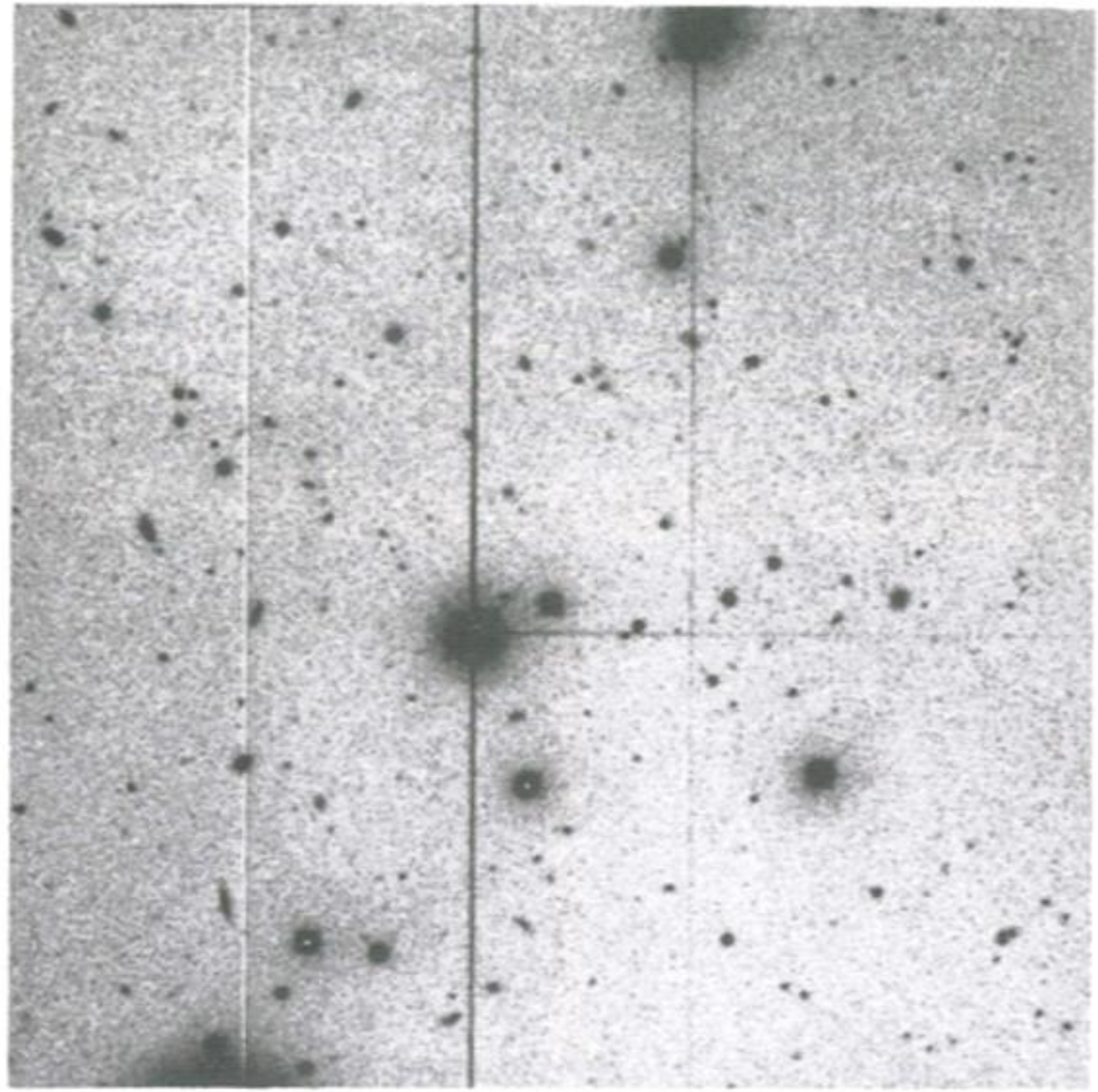


Fig. 7.8. An astronomical CCD image (displayed as a "negative") in which a bright star ha saturated in the exposure time needed to record the fainter objects. When the CCD pixel saturate it spills over and "bleeds" up and down the column. The horizontal trail is evidence of poor charg transfer efficiency in the serial register. The white line is a non-working or "dead" column Courtesy NOAO.

Dark Current

- Leakage current from electrons having sufficient thermal energy to break free from the lattice
- Surface traps at the silicon-silicon dioxide interface are largely responsible
- Typically 1 nA cm^{-2} at 20 ºC in standard CCDs
- Thermal noise decreases by a factor of two for roughly every 7-8 ºC reduction in operating temperature
- ≈ 2 electrons/pixel/hour at -100 ºC (10 µm pixel)
- CCDs typically operated at 77 K (LN2) to 150 K
- Dark current has associated shot noise and a relative statistical pixel-to-pixel non-uniformity of ~ 3-10 % RMS

Fixed Pattern Noise

•Fixed Pattern Noise : Variations in pixel responsivity due to geometry variations

• Typically in the range 1-2 % for a good CCD

• Removal by ‘flat-fielding’

• An exposure of a uniform field to remove local pixel-to-pixel sensitivity variations – some are intrinsic other may arise from dust on filters or other optics

• Global flat-field (often generated from twilight exposures) to remove large scale variations across the chip

CCD Dynamic Range

- Depends on full-well capacity and readout noise
- Linearity generally very good – 0.1% to >80% full well
- Well capacity driven by pixel design and size

  For a 12 × 12 μm pixel ≈ 100,000 e to 200,000 e

Readout noise is a function of readout rate

  ≈ 2 electrons RMS at 100 kHz, ≈ 5 electrons RMS at 1 MHz

- Instantaneous pixel dynamic range

  Could well be ≈ 100,000 (> 16 bits)

- e2v CCD231

  15 × 15 μm 4-phase pixel full-well capacity = 350,000 e

- And…

  24 × 24 μm 4-phase pixel can store 10^6 electrons!

Signal-to-Noise Ratio (SNR)

- Photon distribution obeys Poisson statistics (shot noise)
- Noise sources:
- Photon noise from **S**ource
- Photon noise from **B**ackground
- Photon-equivalent noise from detector **D**ark current
- **R**ead noise of detector

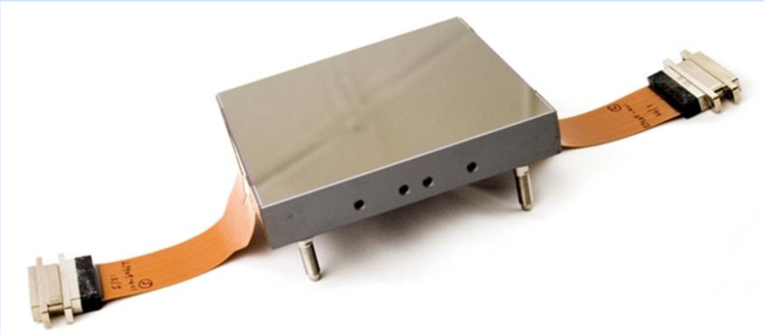
$$SNR = \frac{S \cdot t}{\sqrt{(S + B + D)t + R^2}} = \frac{S \cdot \sqrt{t}}{\sqrt{(S + B + D) + R^2 / t}}$$

Note: S and B in electrons, includes Q.E.

- Aim to be limited by the Background photon flux (unless the target is very bright) rather than by the detector noise

CCD Specification

e2v CCD231



SUMMARY PERFORMANCE (Typical)

Number of pixels	6144(H) x 6160(V)
Pixel size	15 µm square
Image area	92.2 mm x 92.4 mm
Outputs	4
Package size	98.5 x 93.7 mm
Package format	Silicon carbide with two flexi connectors
Focal plane height, above base	20.0 mm
Height tolerance	±15 µm
Connectors	Two 37-way micro-D
Flatness	<40 µm (peak to valley)
Amplifier sensitivity	7 $\mu V/e^-$
Readout noise	5 e^- at 1 MHz 2 e^- at 50 kHz
Maximum pixel data rate	3 MHz
Charge storage (pixel full well)	350,000 e^-
Dark signal	3 e^-/pixel/hour (at –100 °C)

Cosmic Rays

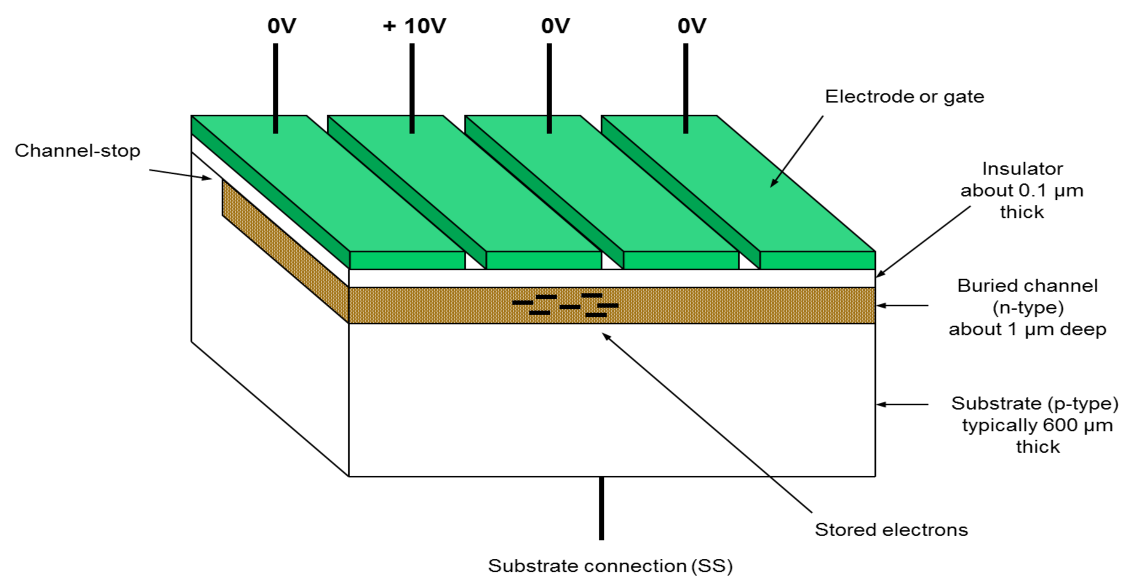
•Cosmic rays (or other energetic particles) can liberate a large number of electrons from the atoms hit

• Can be limited to single pixels - head-on strikes –or short or long track - glancing strikes

• Signal produced generally much bigger than from an astronomical target. Usually make several shorter exposures so that pixels suffering Cosmic Ray hits are only affected in a subset of the data.

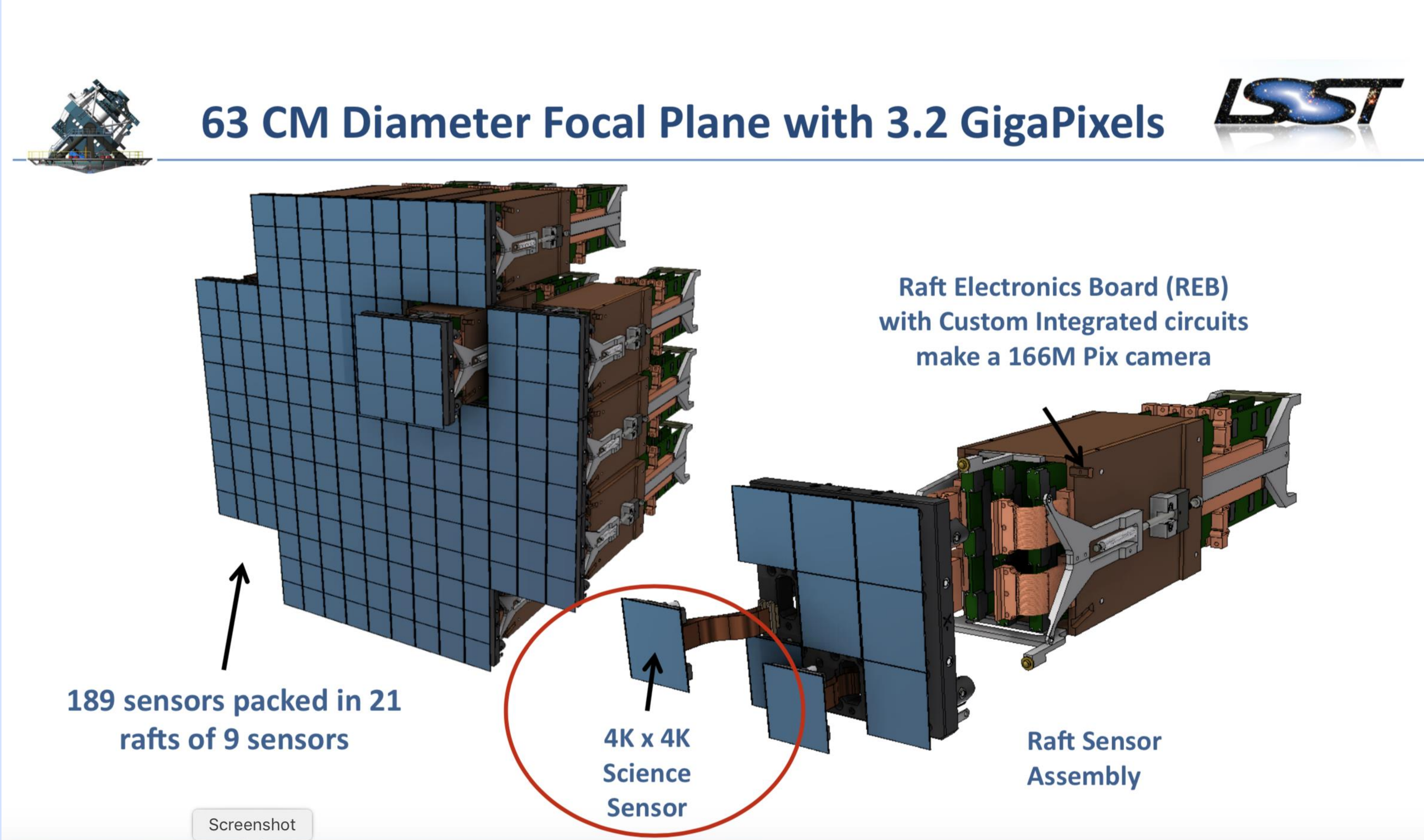
Image Retention or Persistence

- Image retention after saturation
- Charge gets trapped in the Si-SiO2 interface
- Long (many minutes) and temperature dependent release time
- Region of enhances signal or higher dark current at locations with high illumination levels



CCD pictures courtesy David Burt (e2v)

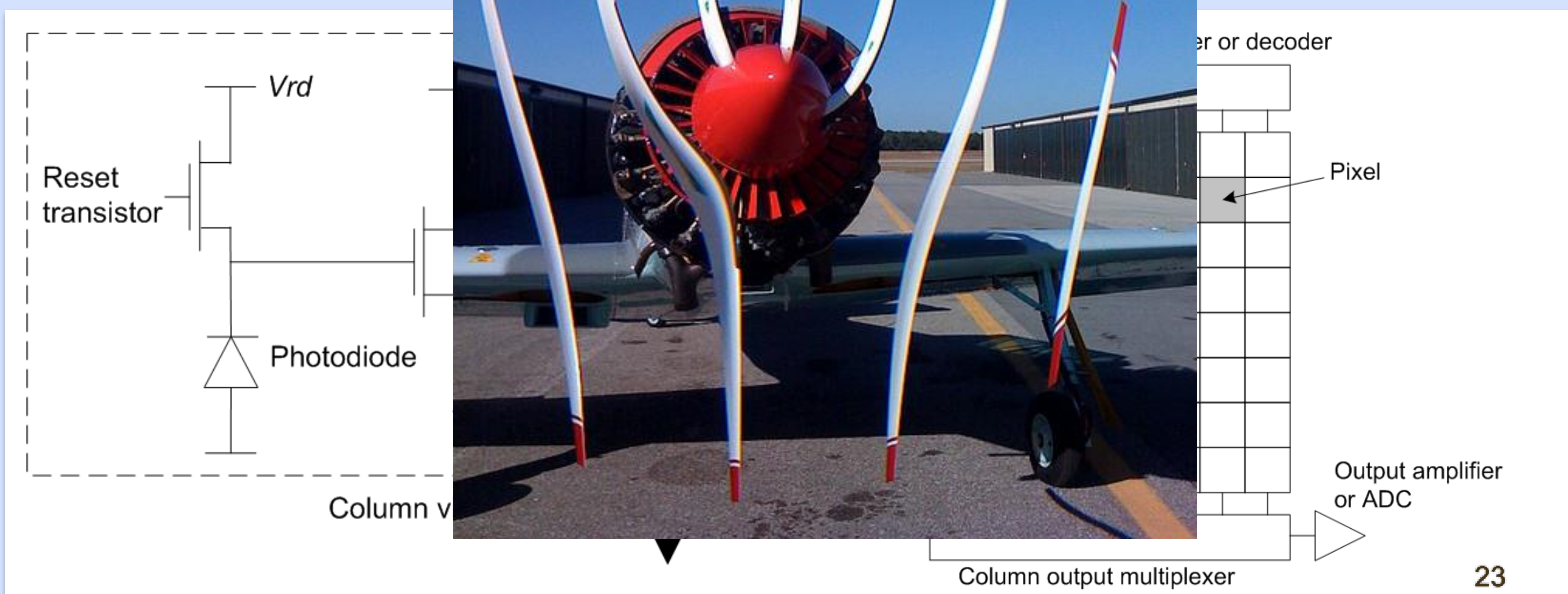
Buttable CCDS : Large Focal Planes



Completed 3.2 gigapixel LSST Camera

CMOS Sensors

- A new(ish) type of image sensor fabricated in CMOS
- Silicon chip tech … or systems
- Allows the integ … alongside all of the electronics … buffer the analogue video s…

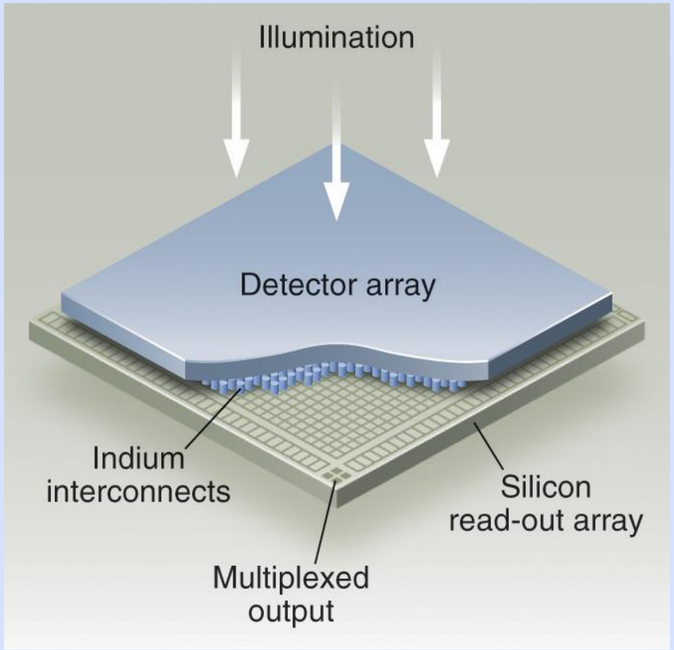


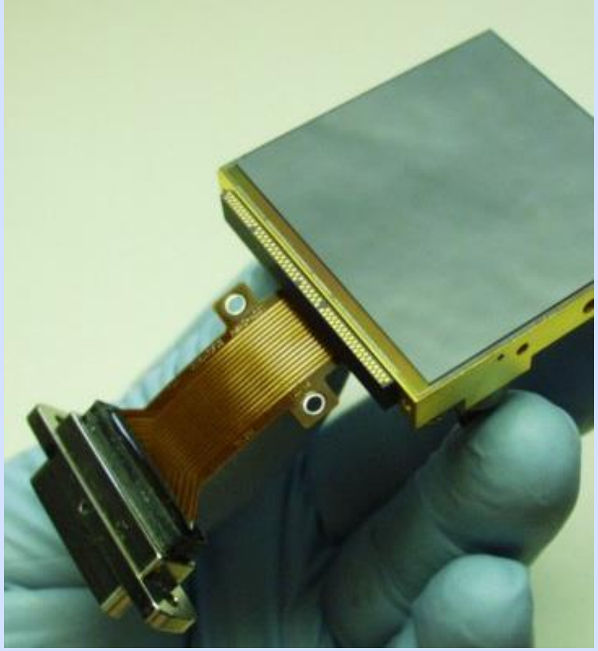
IR Sensors

- Broadly split into Photo-conductors and Bolometers
- NIR using intrinsic semi-conductors with smaller band-gaps such as HgCdTe or InSb in formats up to 4k x 4k pixels.
- HgCdTe operated at ~77K, InSb at ~40K
- MIR using BIB (blocked impurity band) to get high doping with low dark current – formats up to 1k x 1k. Si:As operated at ~7K
- FIR using extrinsic (doped) semi-conductors with added impurities

HgCdTe IR Sensors

- Mercury Cadmium Telluride - three key technologies:
  - Growth and processing of the HgCdTe detector layer
  - Design and fabrication of the CMOS ROIC
  - Hybridization of the detector layer to the CMOS ROIC

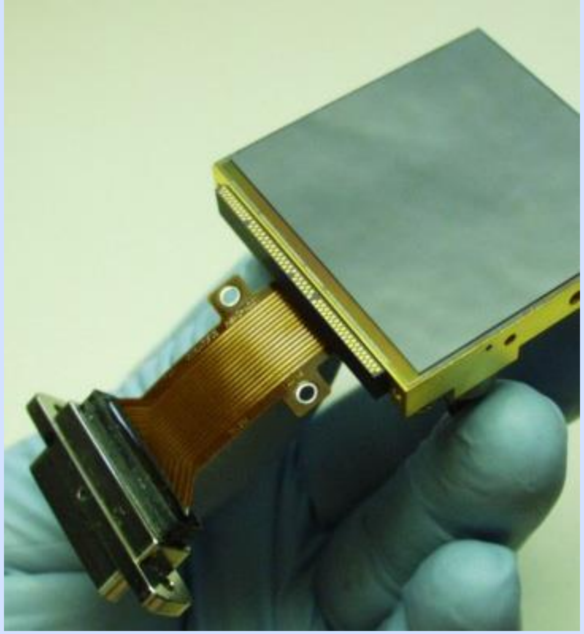




HgCdTe IR Sensors

• Bandgap can be "tuned" from 0.1 eV to 1.5 eV by varying the mixture of Hg and Cd

• Near-IR ≈ 1.7, 2.5 μm cutoff - defined as 50 % of peak QE



• Mid-wave IR ≈ 5 μm

• long-wave IR ≈ 10 μm

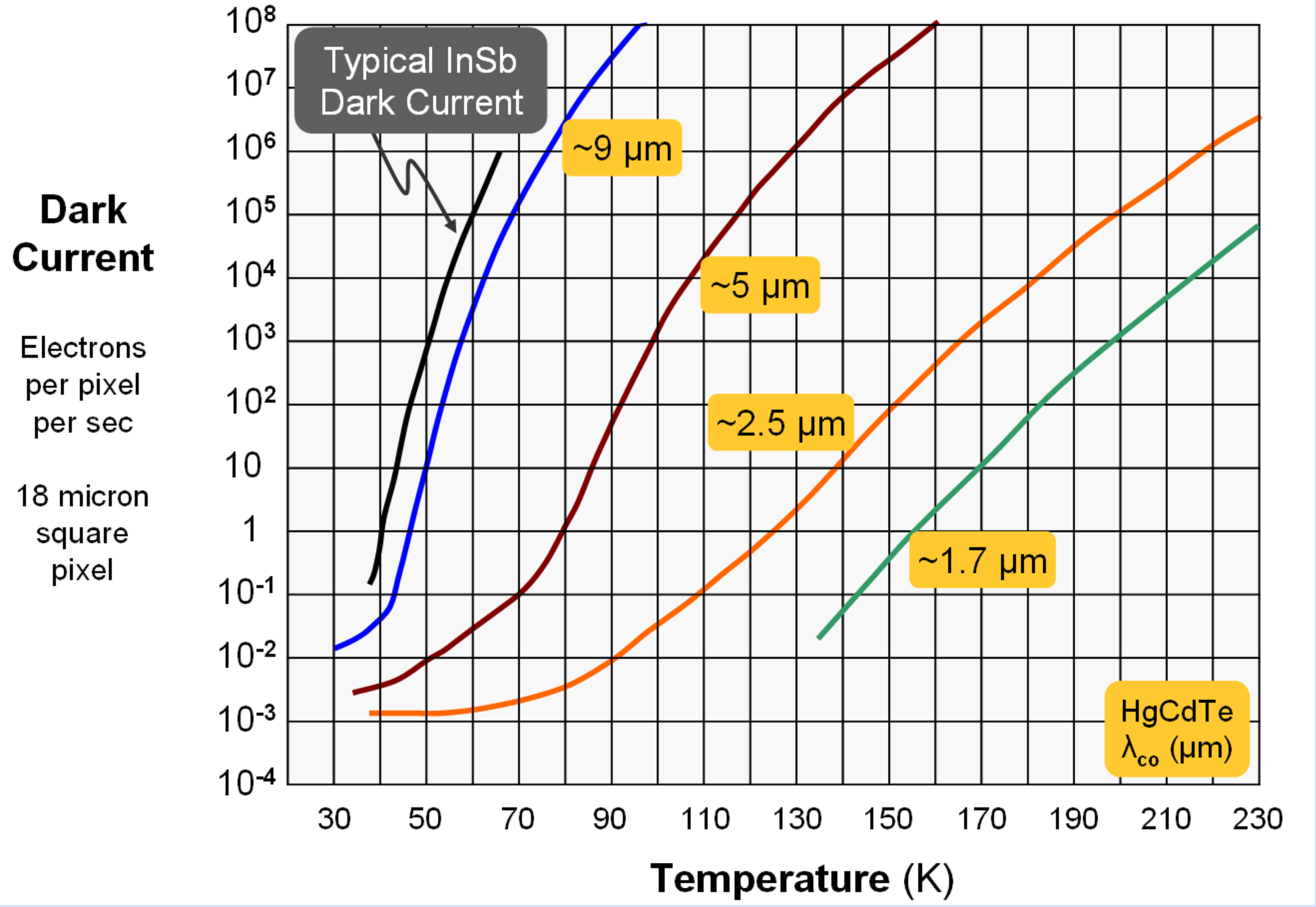
• Up to ≈ 15 μm is theoretically possible

• Best detectors are grown by MBE (Molecular Beam Epitaxy)

• HgCdTe grown on CdZnTe substrate

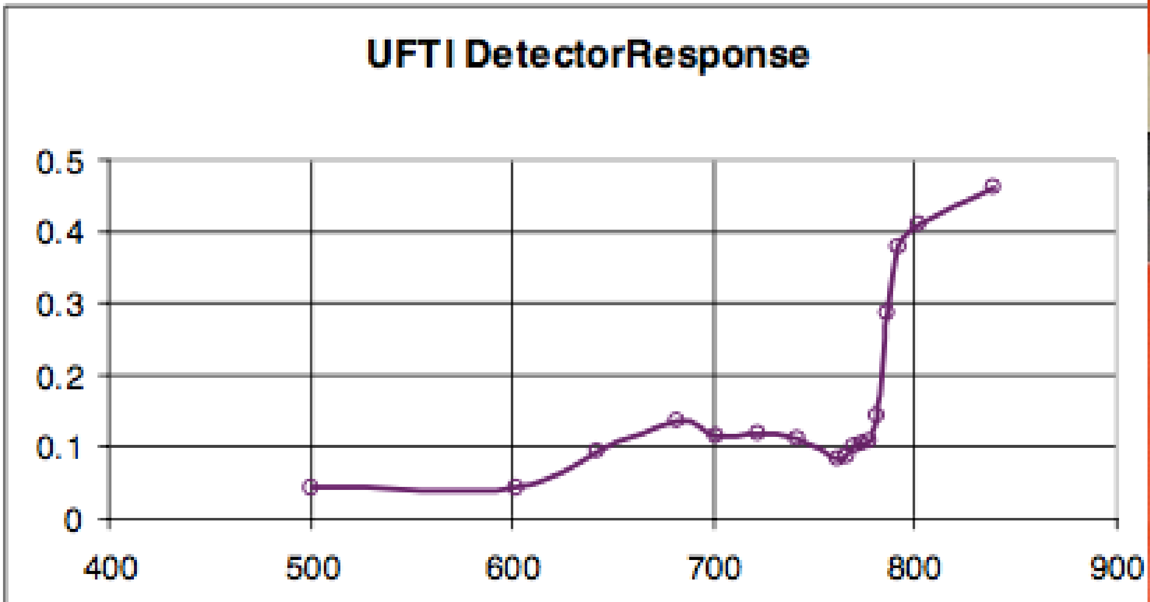
• Teledyne (formerly Rockwell Scientific) sensors are most widely used in astronomy, though the biggest IR camera uses 16 Raytheon 2k x 2k detectors on VISTA (P.I. Gavin Dalton)

Performance

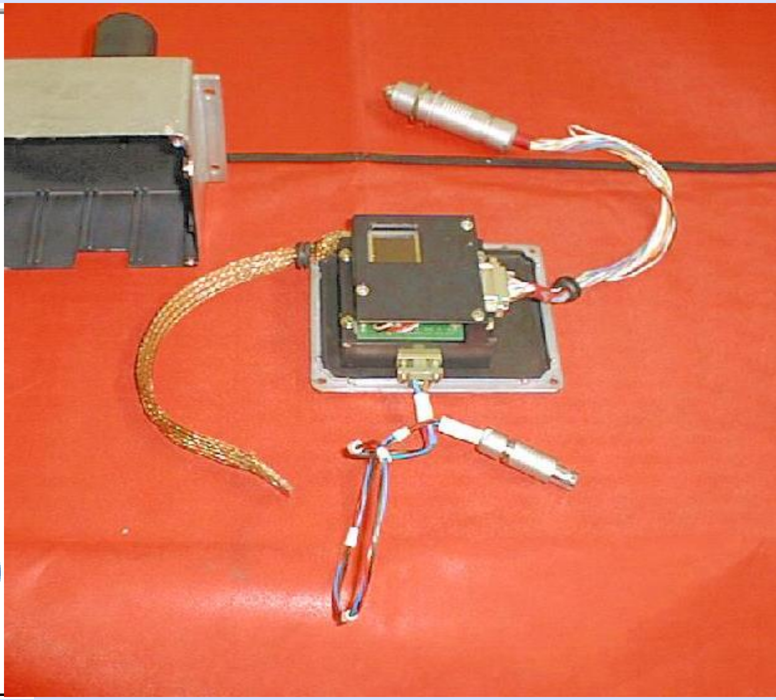


Lower temperature decreases dark current, but may also decrease QE

HgCdTe Response



(Roche et al 2002)



UFTI detector – Hawaii-I 1028 x 1028 Rockwell device
Near-IR camera on UKIRT with a fine (0.09 arcsec) pixel scale

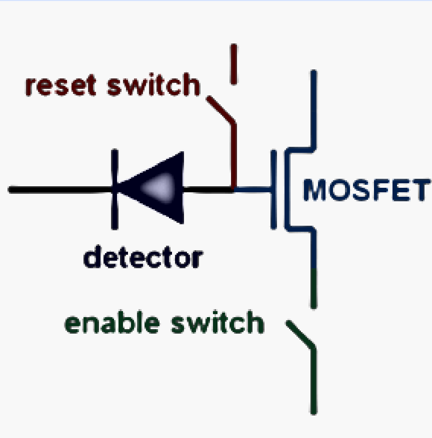
Short wave cut off at 0.78um but with residual sensitivity to 0.5um.
Dark current <1 e-/pix/min at 80 K
Read noise ~10e- with multiple NDR, 26e- with CDS, ~99.7% operable pixels

Hawaii-2RG (H2RG), 2K × 2K array with 18 μm pixel pitch, sensitive to 2.5um, QE~ 80-90%,

HgCdTe Readout

• Source-follower is the same as CCD/CMOS and subject to reset noise and removal by CDS

• Directly addressable pixels (rather than charge transfer in CCD) allows multiple, non-destructive reads to reduce Read noise



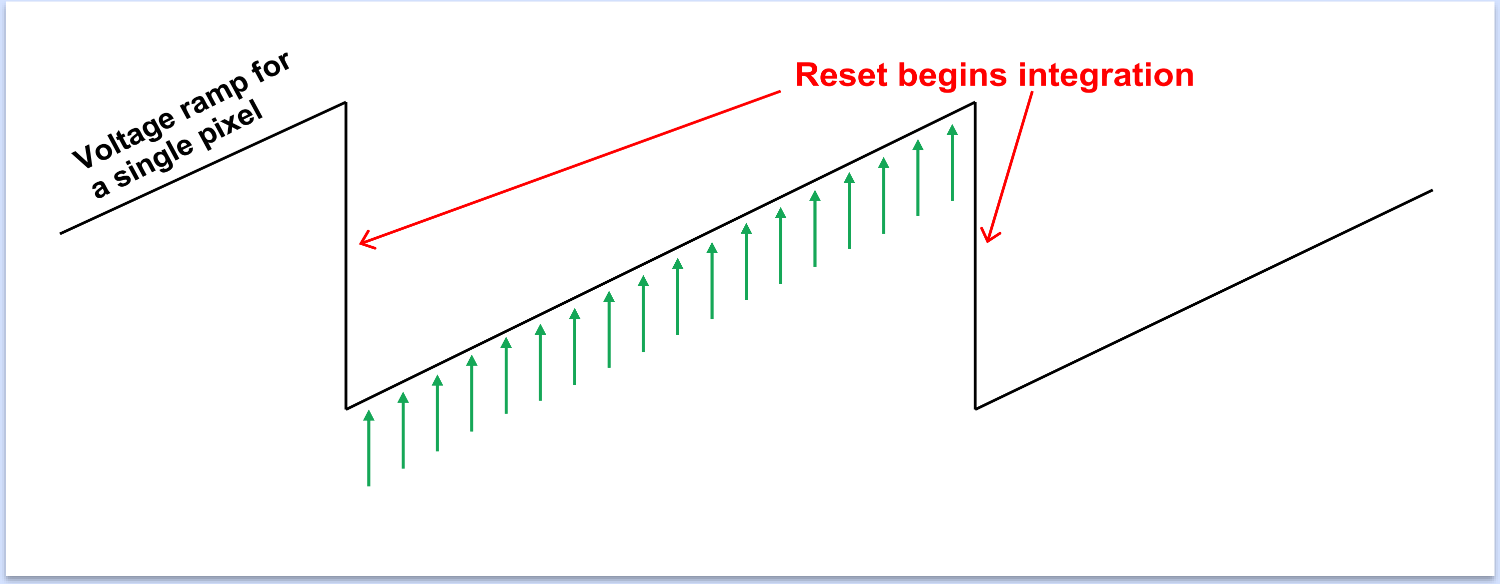
• Output amplifier noise 15 - 50e^- ,
full-well ≈ 10^5 to 10^6 e^-

• Noise reduction by:

• Averaging multiple samples at beginning and end of integration (Fowler & Gatley 1990). 4 reset samples and 4 signal samples reduces noise by $\sqrt{n} = 2$

• Or can perform continuous sampling during integration 'up the ramp' (R Glendinning et al 1990)

HgCdTe Readout



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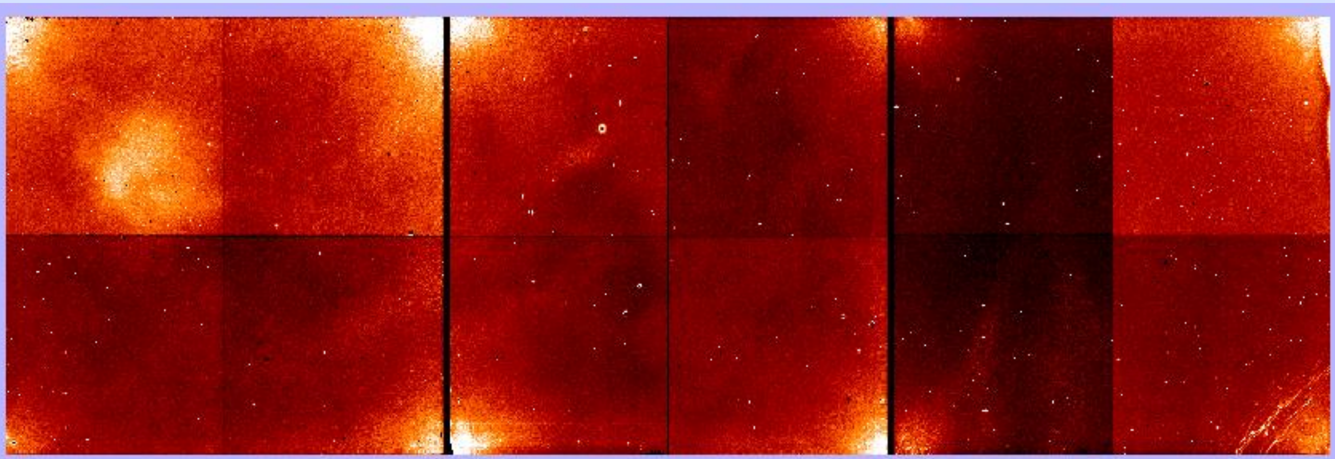
• Output amplifier noise 15 - 50e$^-$, full-well ≈ 10^5 to 10^6 e$^-$

• Noise reduction by:

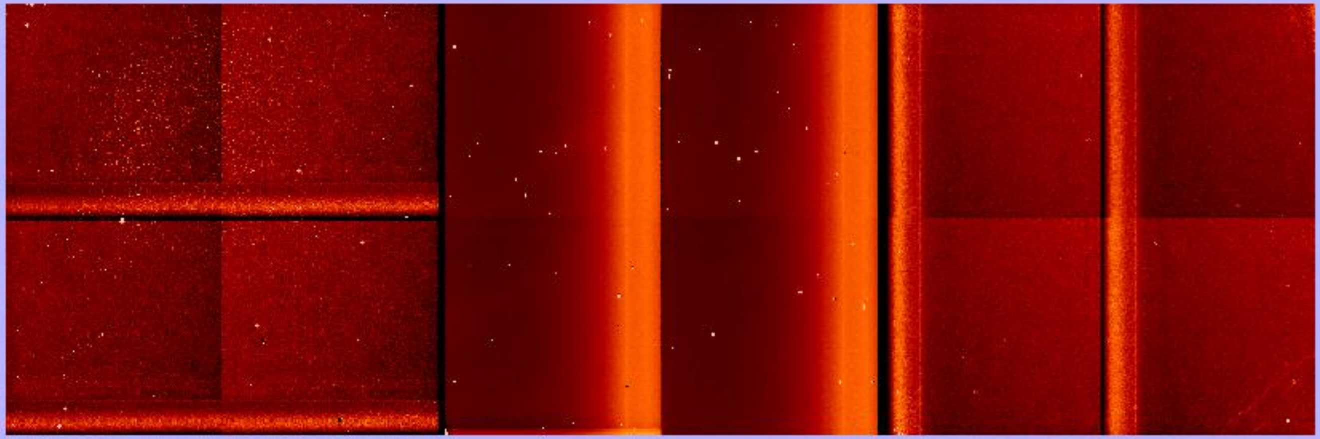
  • Averaging multiple samples at beginning and end of integration (Fowler & Gatley 1990). 4 reset samples and 4 signal samples reduces noise by $\sqrt{n}$ =2

  • Or continuously sample during exposure (R Glendinning et al 1990)

IR Sensors Issues

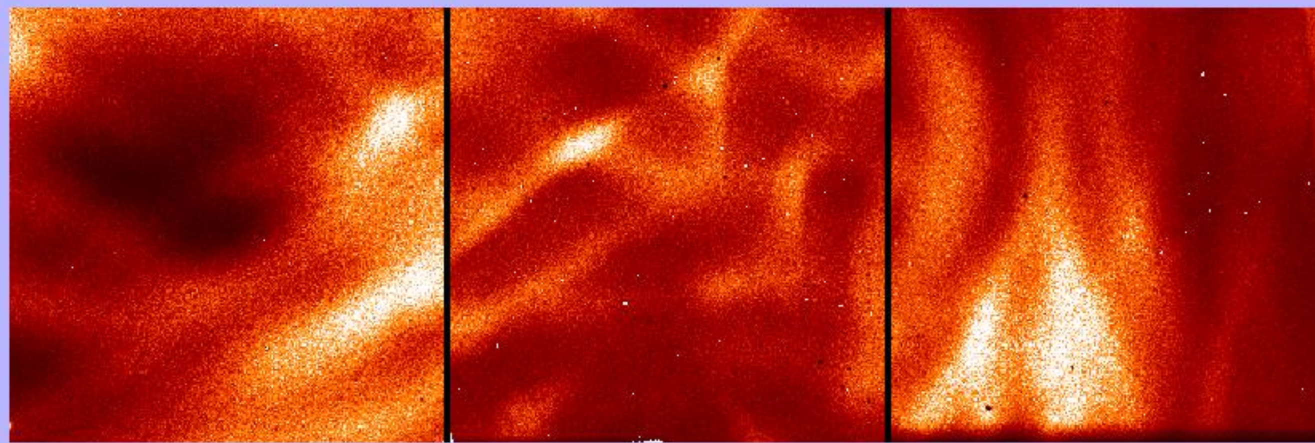


Dark Current

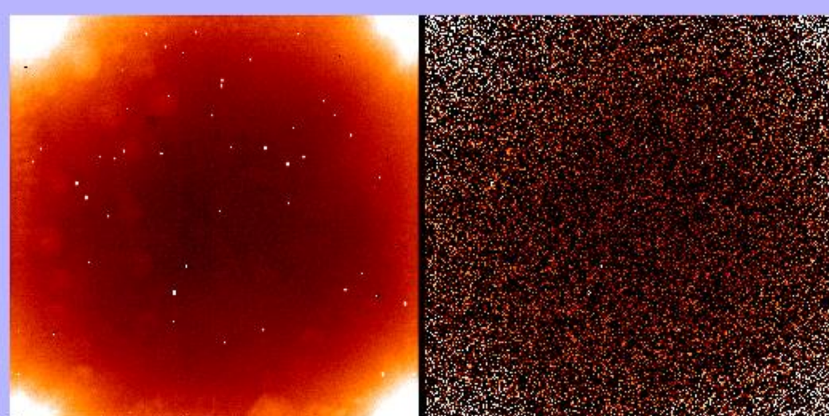


Spatially-dependent bias (“shading”)

IR Sensors Issues

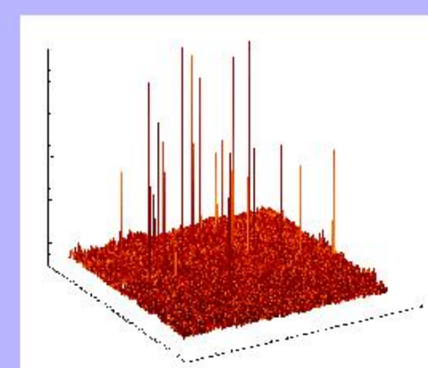


QE Spatial Variations



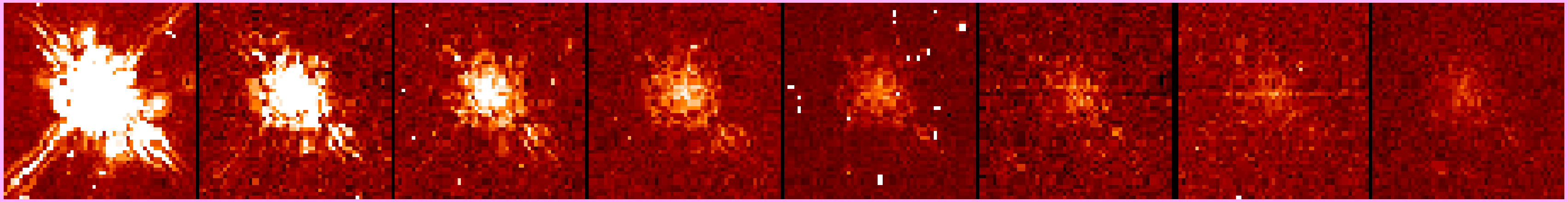
signal resulting noise

Amplifier (MUX) Glow



Bad Pixels

IR Sensors Issues



Latent Images ("persistence")

Bright objects can leave residual charge after pixel reset which appears as a 'ghost' in subsequent exposures.
The remnant typically fades after a minute or two.
To minimise the impact,
Avoid looking at faint things immediately after bright things, or at least not in the same part of the chip

Other Sensors

Intrinsic

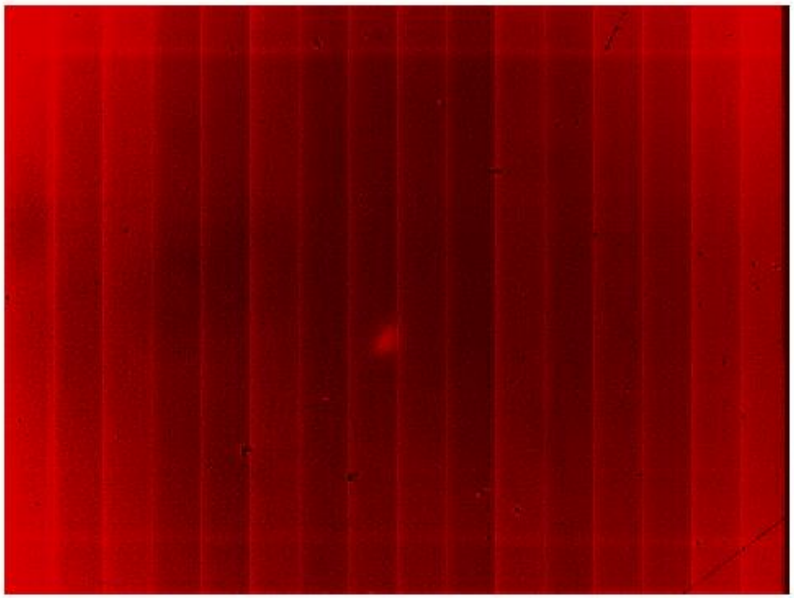
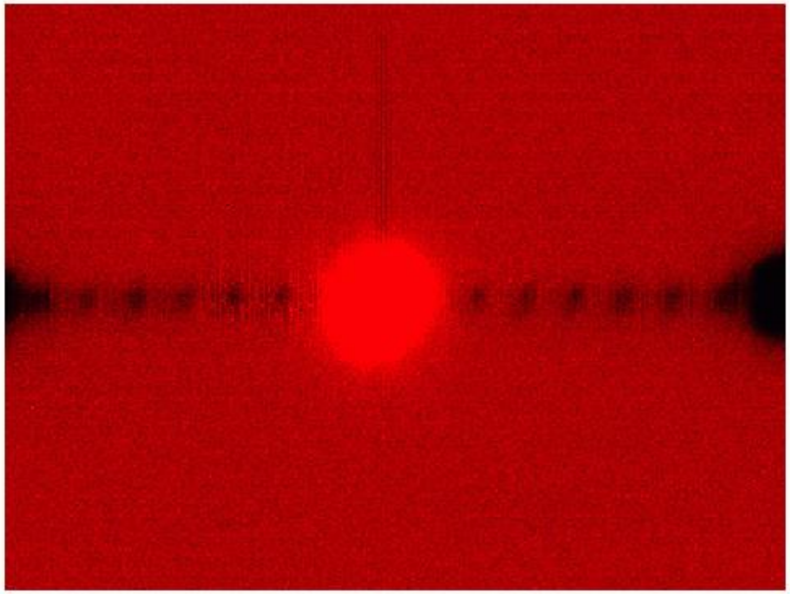
- **InSb** **Indium Antimonide 5.6 μm cut-off λ at 77 K used in instruments that cover JHKLM bands**

Extrinsic BIB (Blocked Impurity Band)

- **Si:As** **Silicon Arsenide 5-28 μm**
- **Si:Sb** **Silicon Antimonide 7-40 μm**

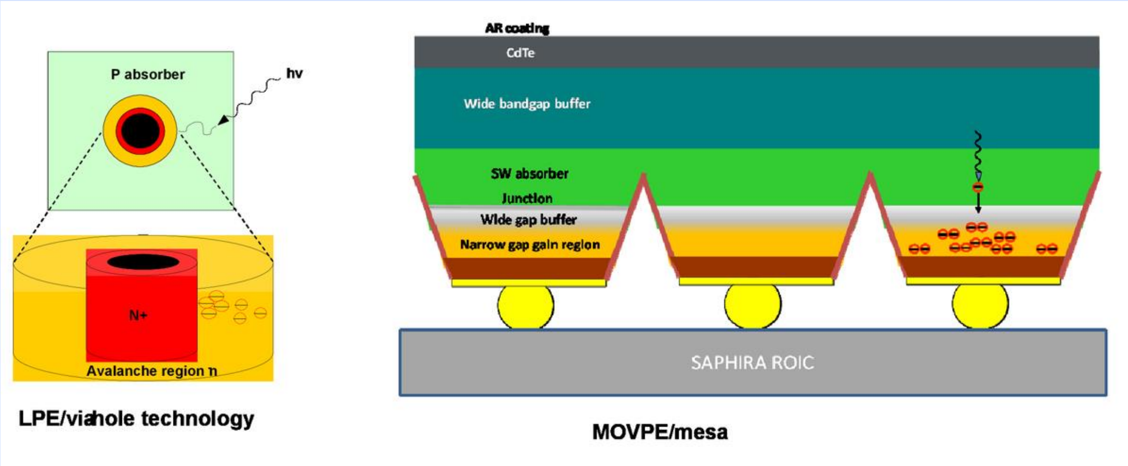
At thermal IR wavelengths, 3-30 μm, the large photon flux from the telescope and sky background requires rapid array read-out to avoid saturation. Higher dark currents can be tolerated in these conditions, as the detector is operated near full well capacity; frame times may be ~10 msec.

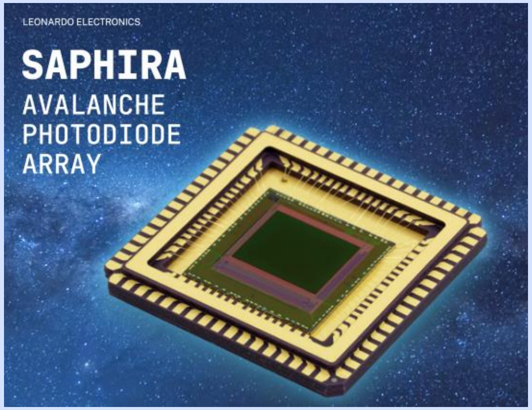
Si:As BIB detector array

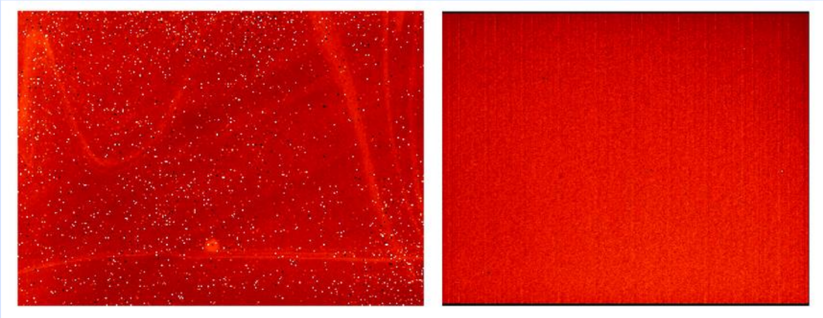
 

- Multi-channel readouts for fast frame rates, but they can suffer from discontinuities and cross-talk. 16 readout channels in this 320x240 Si:As Teledyne array
- Left: raw frame of a bright star obtained with TReCS/Gemini
- Right: image after chop & nod subtraction showing crosstalk

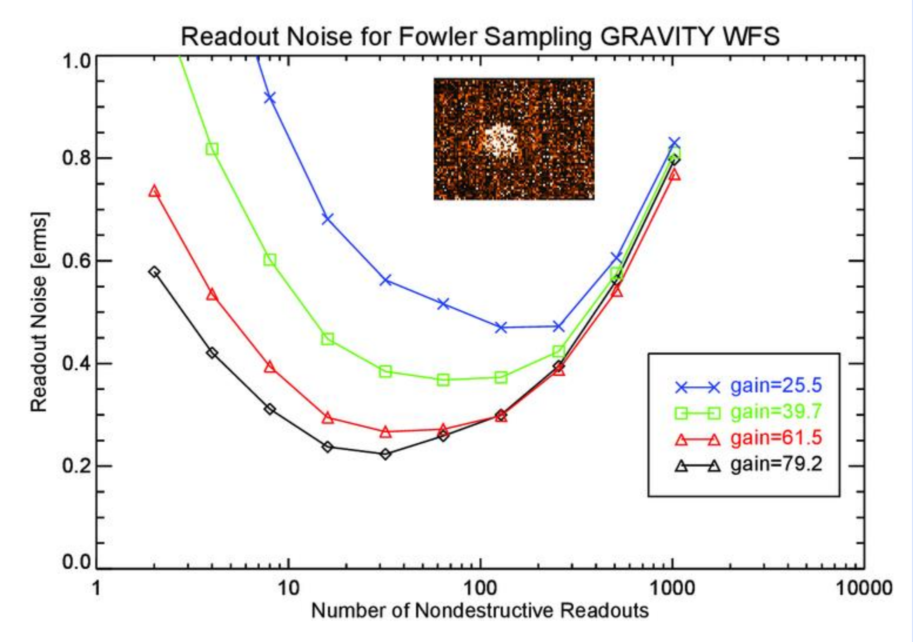
Avalanche PhotoDiode Arrays







LPE MOVPE



All figures courtesy Finger et al. 2014
https://doi.org/10.1117/12.2057078

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