

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 $\lambda < 1.1\mu\text{m}$ for excitation.

The bandgap can be modified by doping with impurities, such as arsenic; Si:AS bandgap $\sim 0.05\text{eV}$ ($\lambda > 25\mu\text{m}$).

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

Impurities and defects affect the lattice structure

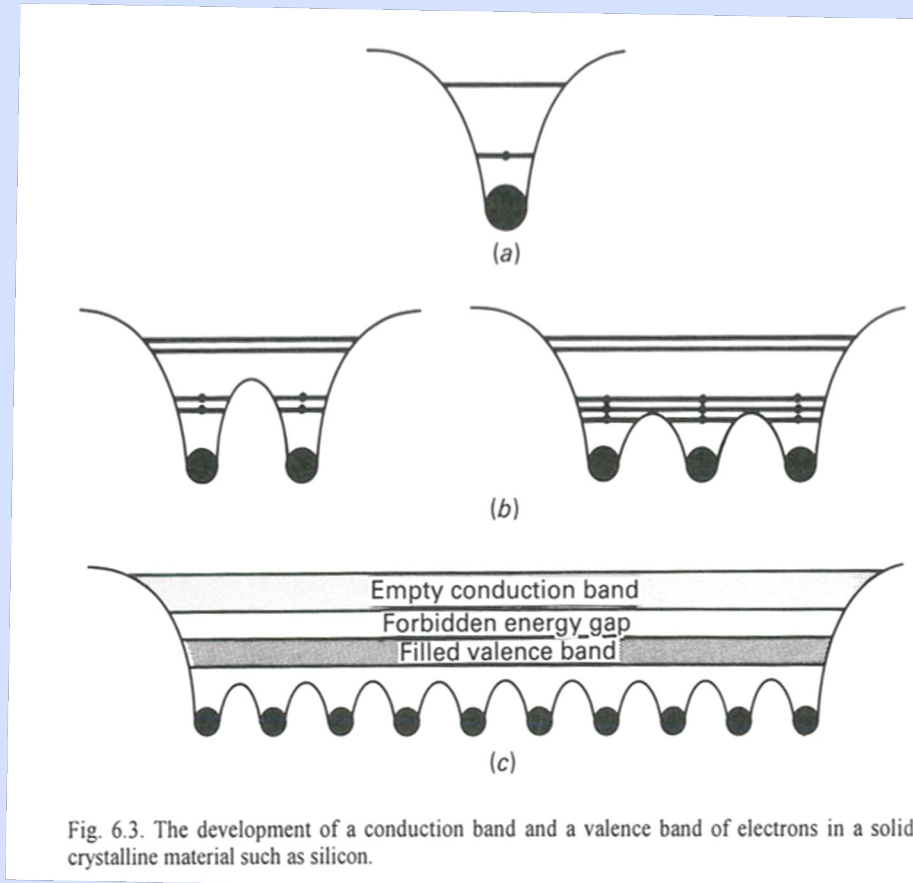


Fig. 6.3. The development of a conduction band and a valence band of electrons in a solid crystalline material such as silicon.

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

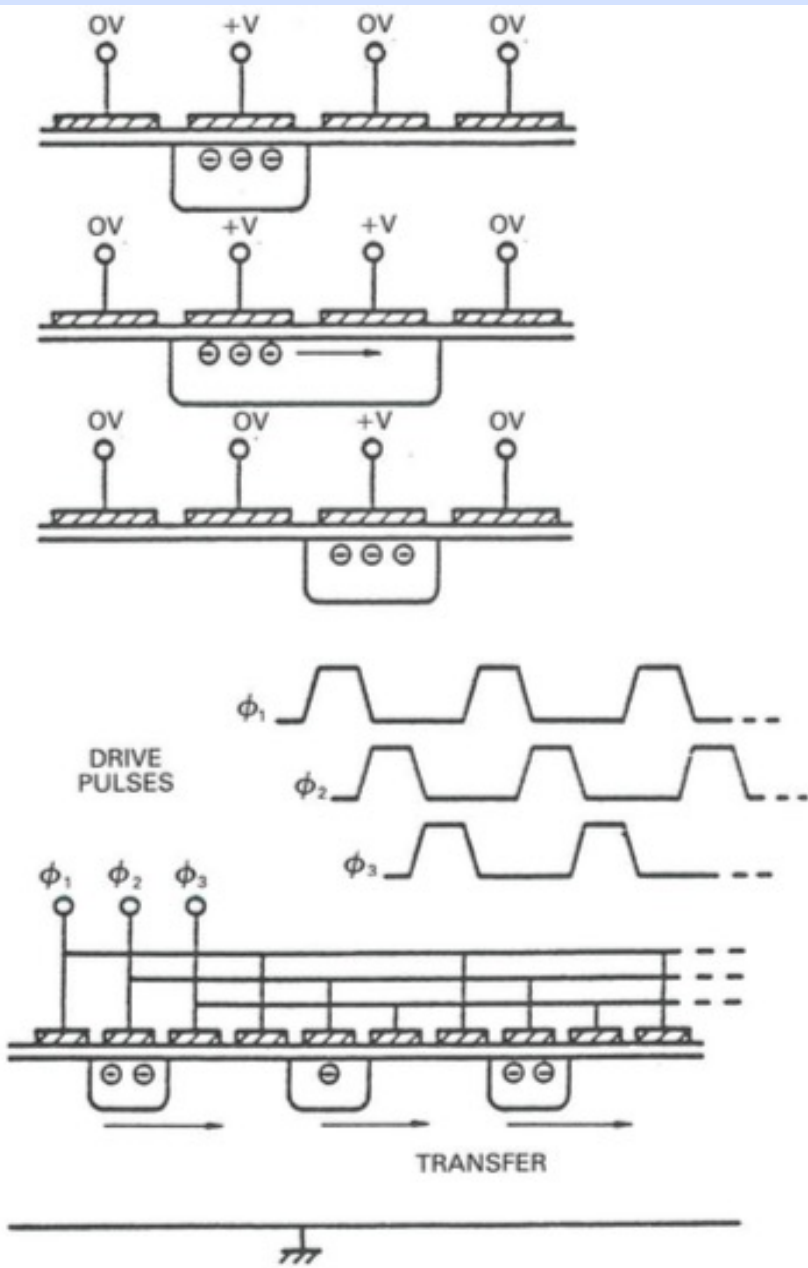
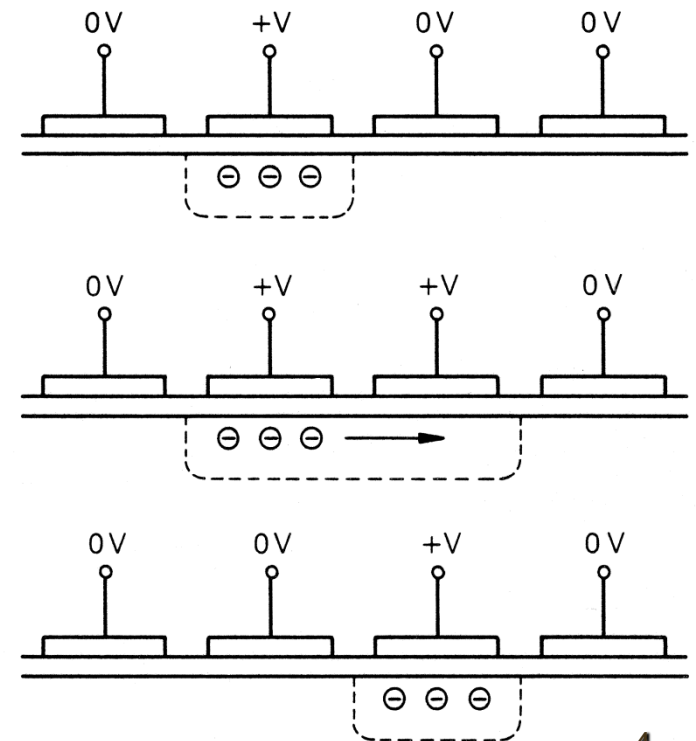
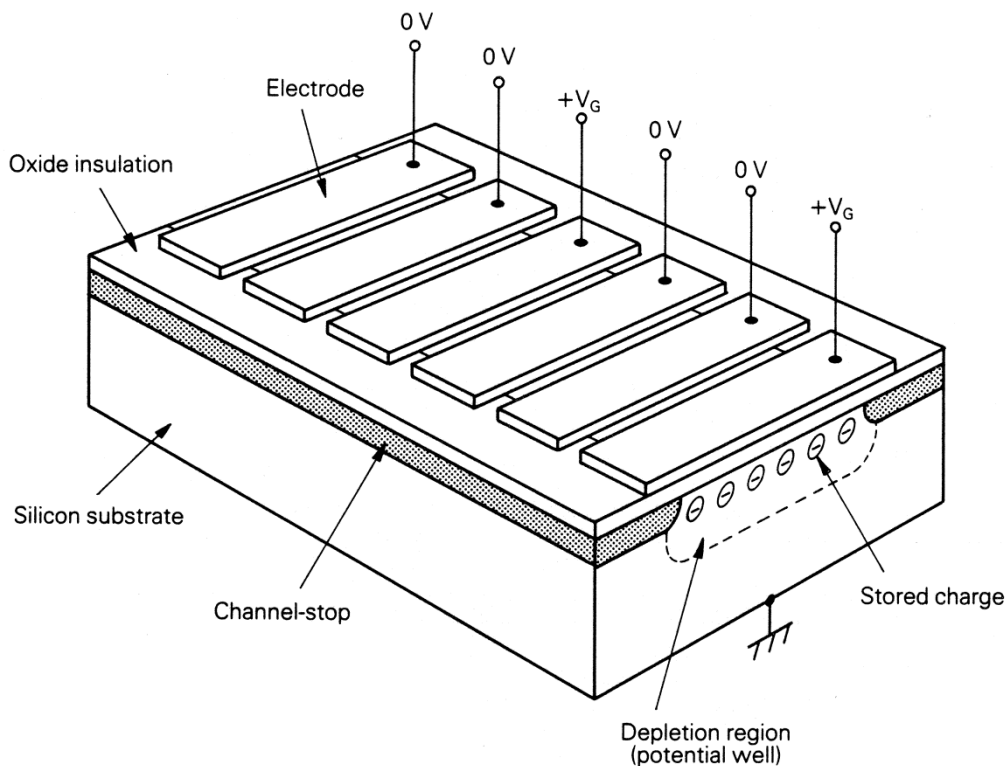


Fig. 6.9. Charge-coupling in a three-phase CCD and the associated timing waveform or clock pattern. In practice the degree of overlap between one electrode and the next depends on the CCD design. (I S McLean 1997)

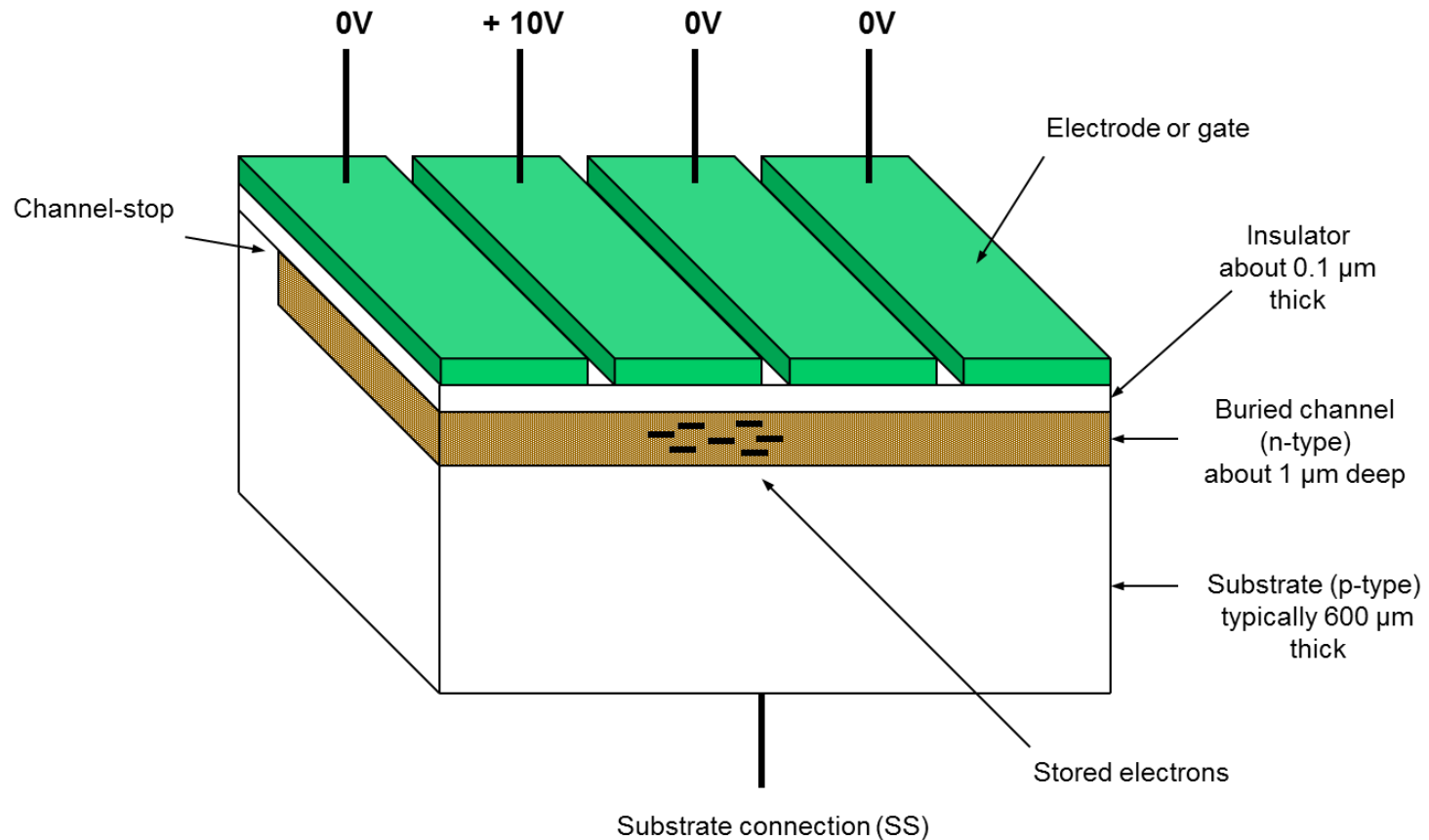
CCD (Charge Coupled Devices)

- This simplified structure has poor charge transfer efficiency
- Charge trapping in the Si-SiO₂ interface, and surface traps caused by polishing and implantation



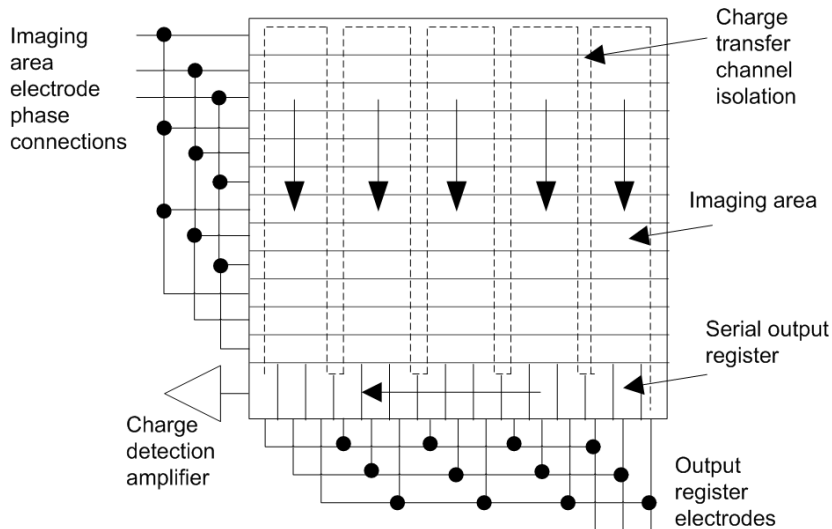
CCD (Charge Coupled Devices)

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

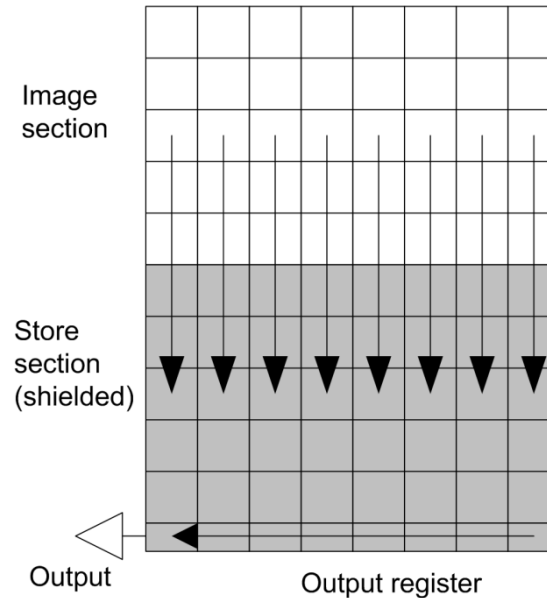


CCD Types

Full-Frame



Frame-Transfer

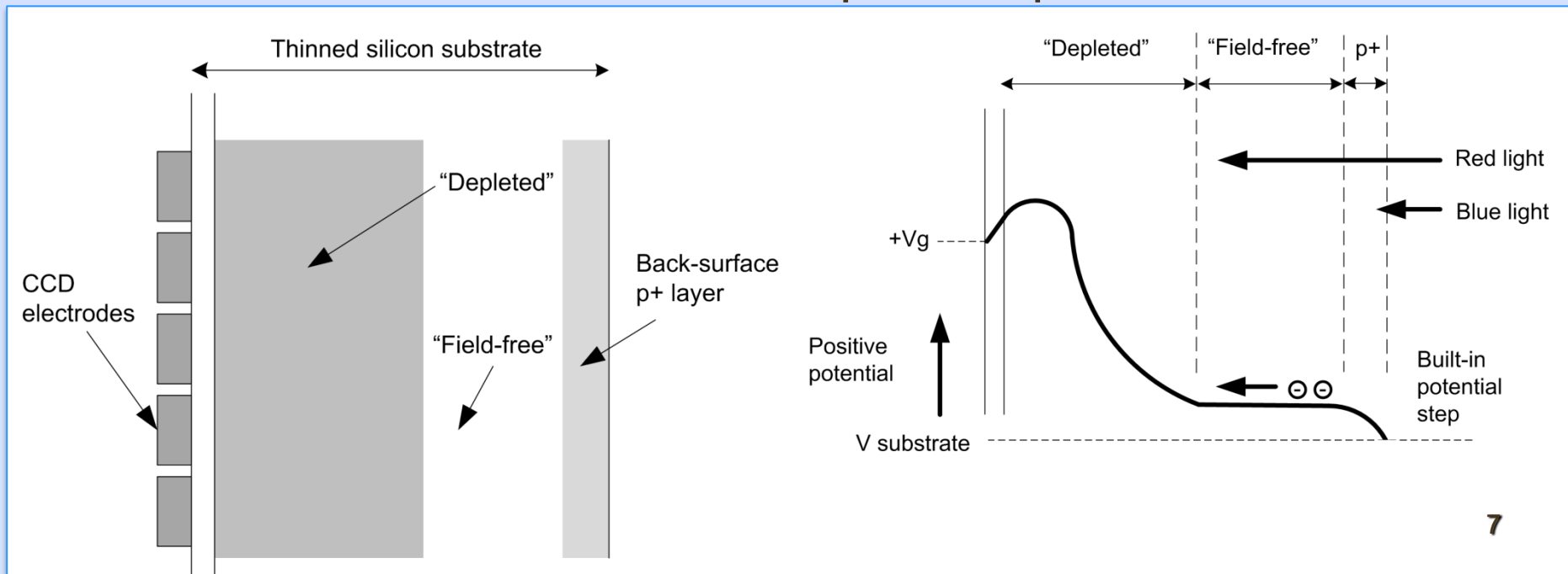


CCD read-out introduces a dead period when the detector is not integrating.

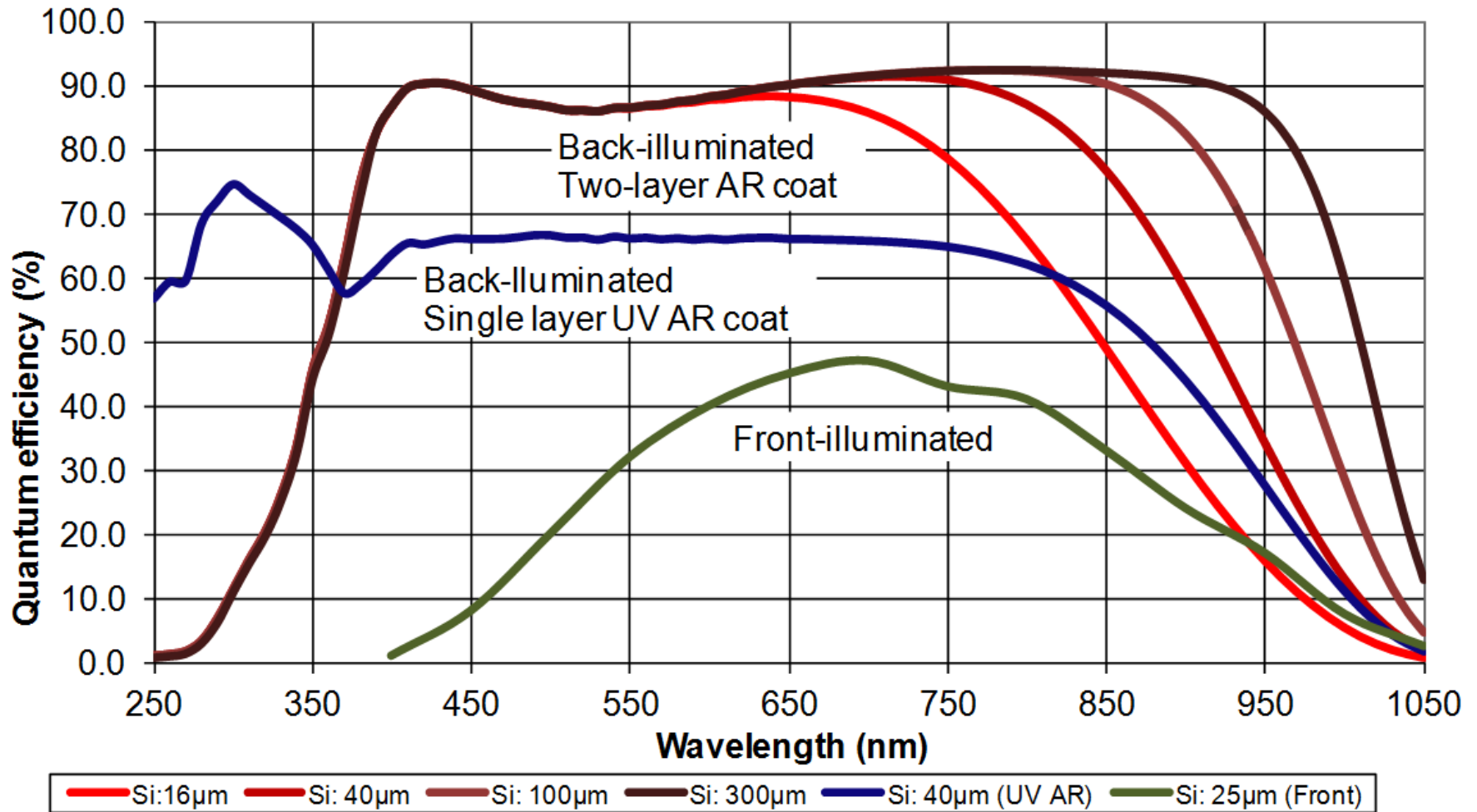
For high speed operation, can use a frame transfer device - the frame is shifted into an unilluminated part of the chip and then read out during the next exposure

Back-illumination

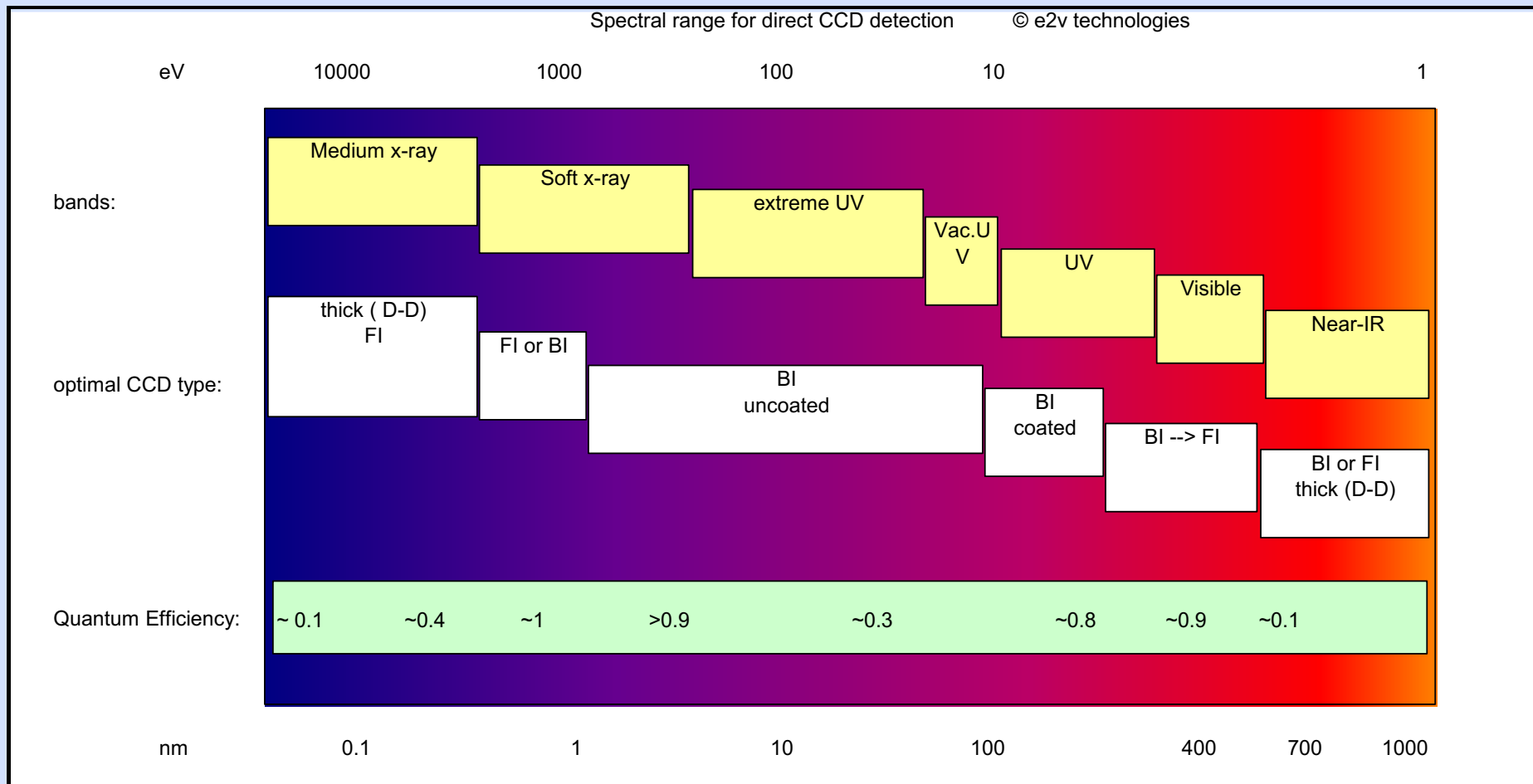
- Back-illumination improves Q.E. – photons not blocked by electrodes etc
- Need to thin the silicon to maintain resolution
- Add anti-reflection coating to further reduce losses
- Very thin chips have poor red response – the path through silicon is below the mean absorption depth



Quantum Efficiency

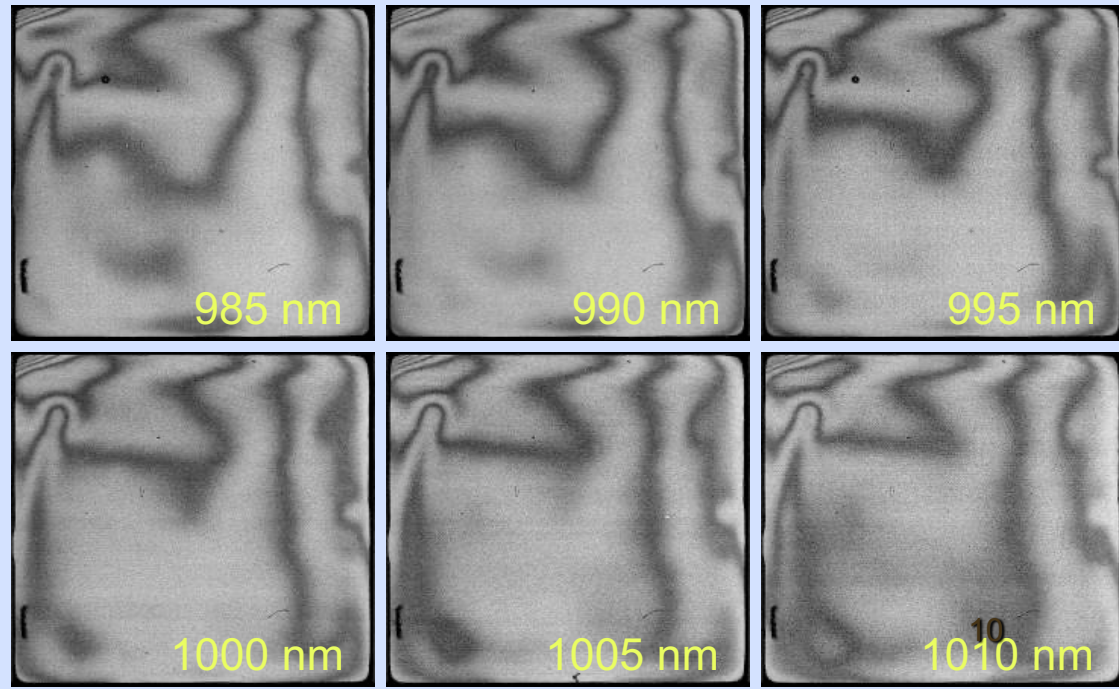


Quantum Efficiency



Fringing

- Interference fringing occurs at long wavelengths – internal reflections within the device, which significantly affects narrow-band imaging and spectroscopy
- Typically $\geq 750\text{-}800\text{ nm}$, rising in amplitude to $\approx 20\%$
- 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

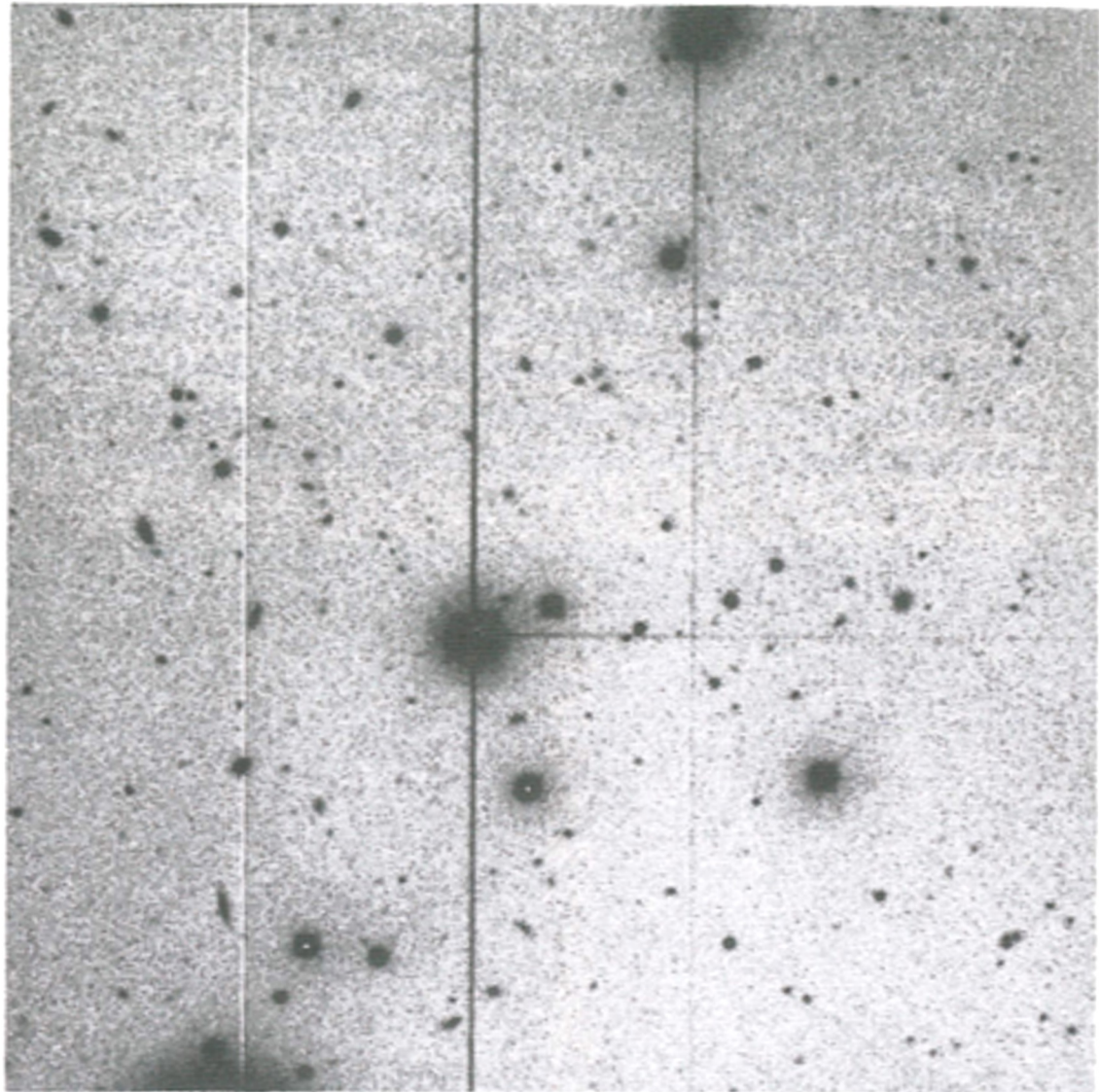


Fig. 7.8. An astronomical CCD image (displayed as a "negative") in which a bright star has saturated in the exposure time needed to record the fainter objects. When the CCD pixel saturates, it spills over and "bleeds" up and down the column. The horizontal trail is evidence of poor charge transfer efficiency 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 $20 \text{ }^\circ\text{C}$ in standard CCDs
- Thermal noise decreases by a factor of two for roughly every $7\text{-}8 \text{ }^\circ\text{C}$ reduction in operating temperature
- ≈ 2 electrons/pixel/hour at $-100 \text{ }^\circ\text{C}$ ($10 \text{ } \mu\text{m}$ 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 $\sim 3\text{-}10 \text{ \% RMS}$

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 $12 \times 12 \mu\text{m}$ pixel $\approx 100,000 \text{ e}$ to $200,000 \text{ e}$

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 $\approx 100,000$ (> 16 bits)
- e2v CCD231
 - $15 \times 15 \mu\text{m}$ 4-phase pixel full-well capacity = 350,000 e
- And...
 - $24 \times 24 \mu\text{m}$ 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 Source
- Photon noise from Background
- Photon-equivalent noise from detector Dark current
- Read noise of detector

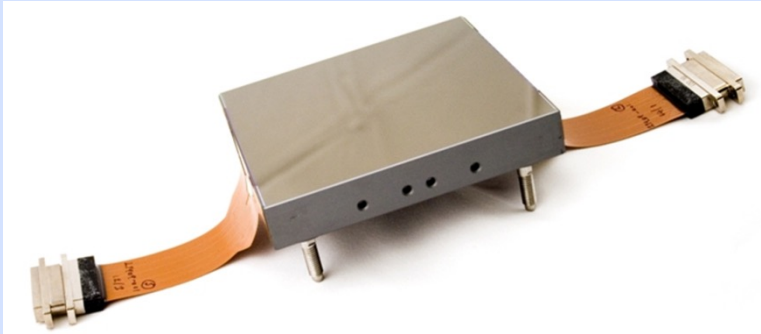
$$SNR = \frac{S \cdot t}{\sqrt{(S + B + D)t + R^2}} = \frac{S \cdot \sqrt{t}}{\sqrt{(S + B + D) + R^2 / t}}$$

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	$\pm 15 \mu\text{m}$
Connectors	Two 37-way micro-D
Flatness	$< 40 \mu\text{m}$ (peak to valley)
Amplifier sensitivity	7 $\mu\text{V}/e^-$
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 $e^-/\text{pixel}/\text{hour}$ (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.

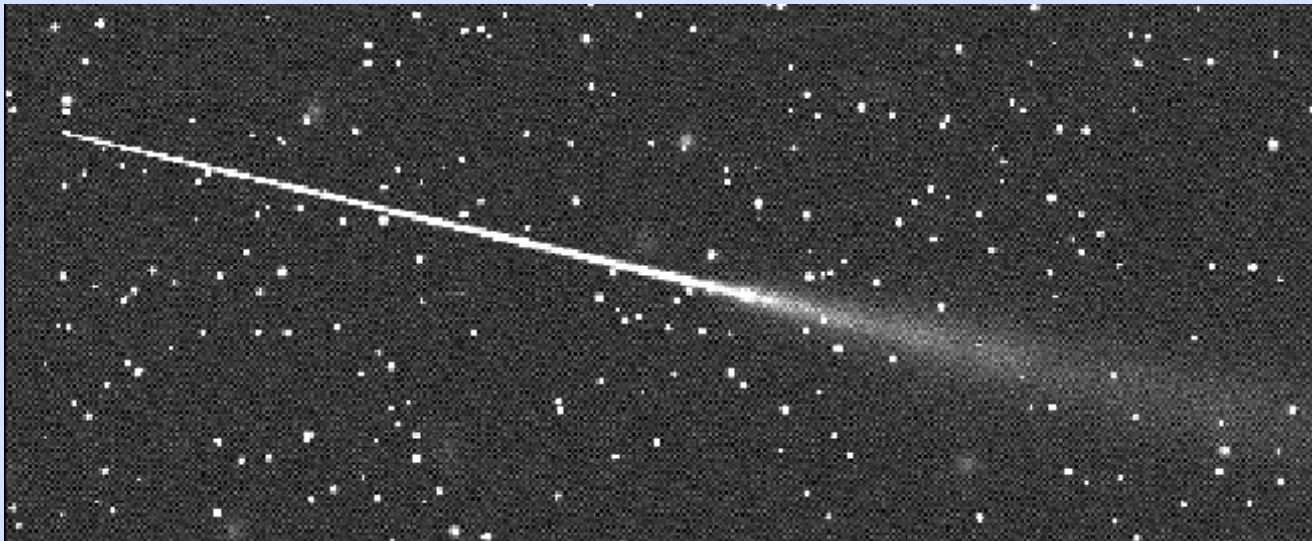
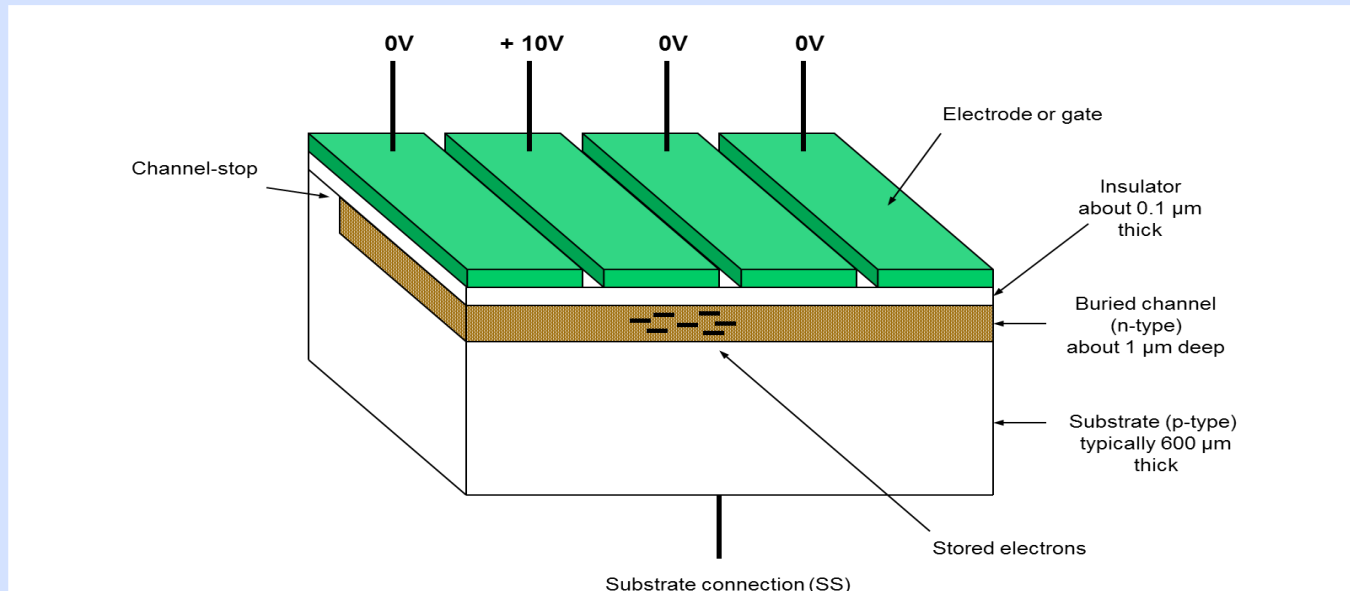


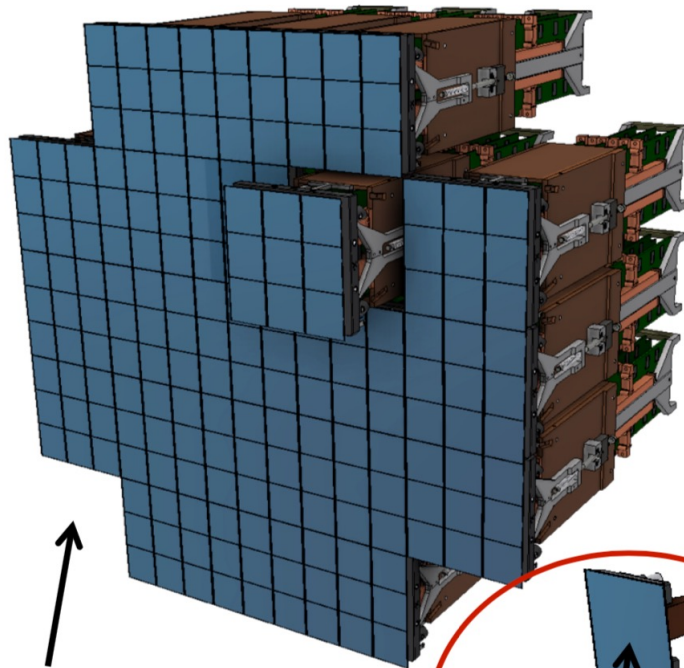
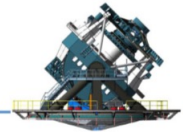
Image Retention or Persistence

- 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



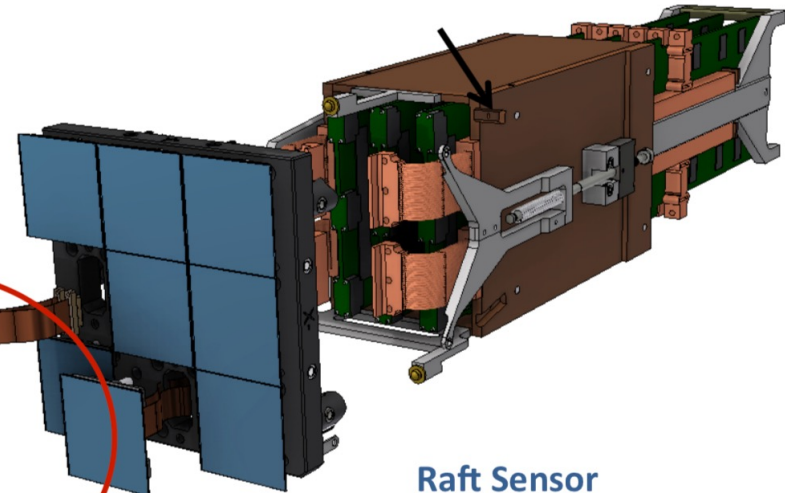
Buttable CCDS : Large Focal Planes

63 CM Diameter Focal Plane with 3.2 GigaPixels



189 sensors packed in 21 rafts of 9 sensors

Raft Electronics Board (REB) with Custom Integrated circuits make a 166M Pix camera



Raft Sensor Assembly

4K x 4K Science Sensor

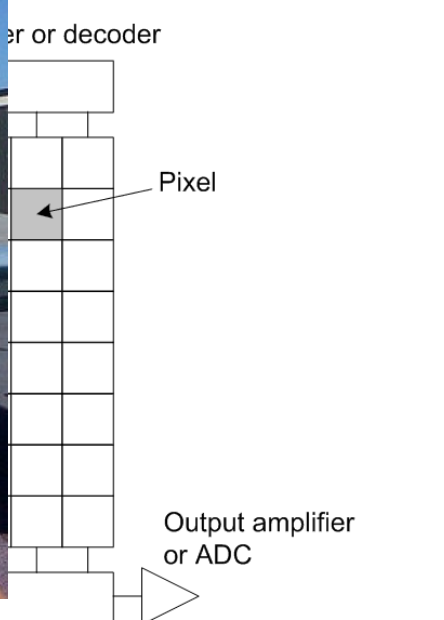
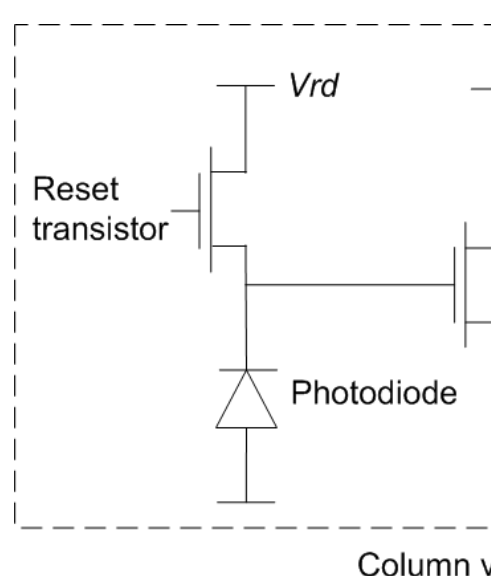
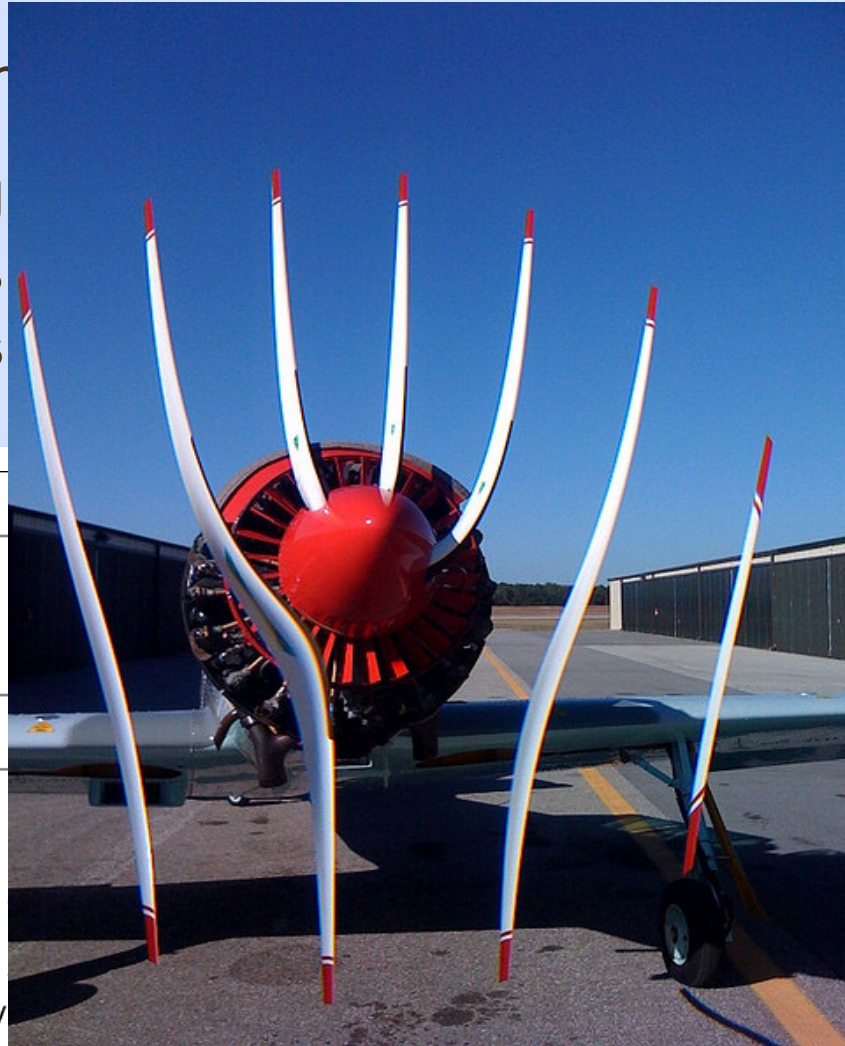
Screenshot

Completed 3.2 gigapixel LSST Camera



CMOS Sensors

- A new(ish) type of image sensor fabricated in CMOS
- Silicon chip technology for systems
- Allows the integration of the electronics alongside all analogue video signals to buffer the



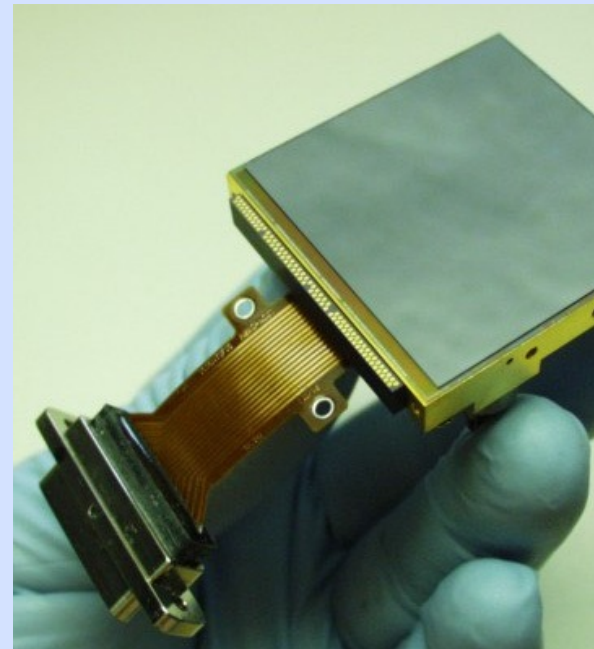
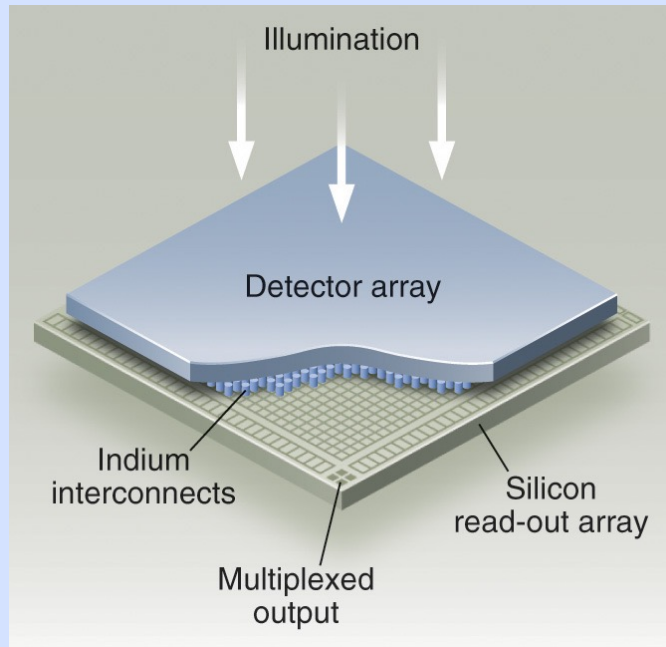
IR Sensors

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



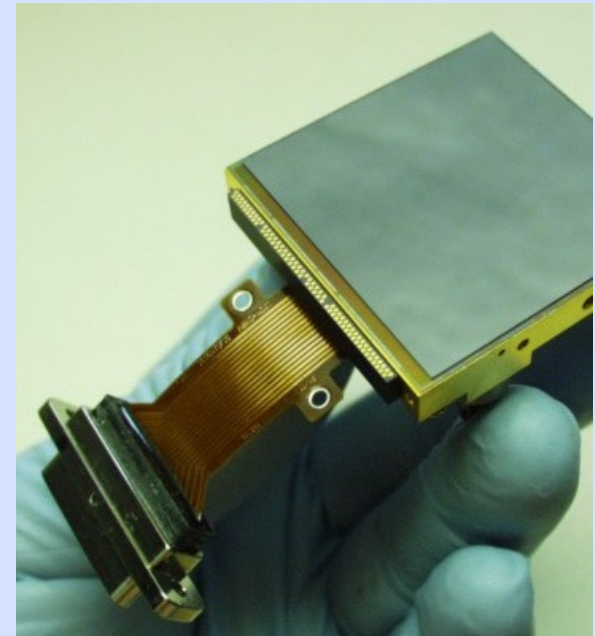
HgCdTe IR Sensors

- 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

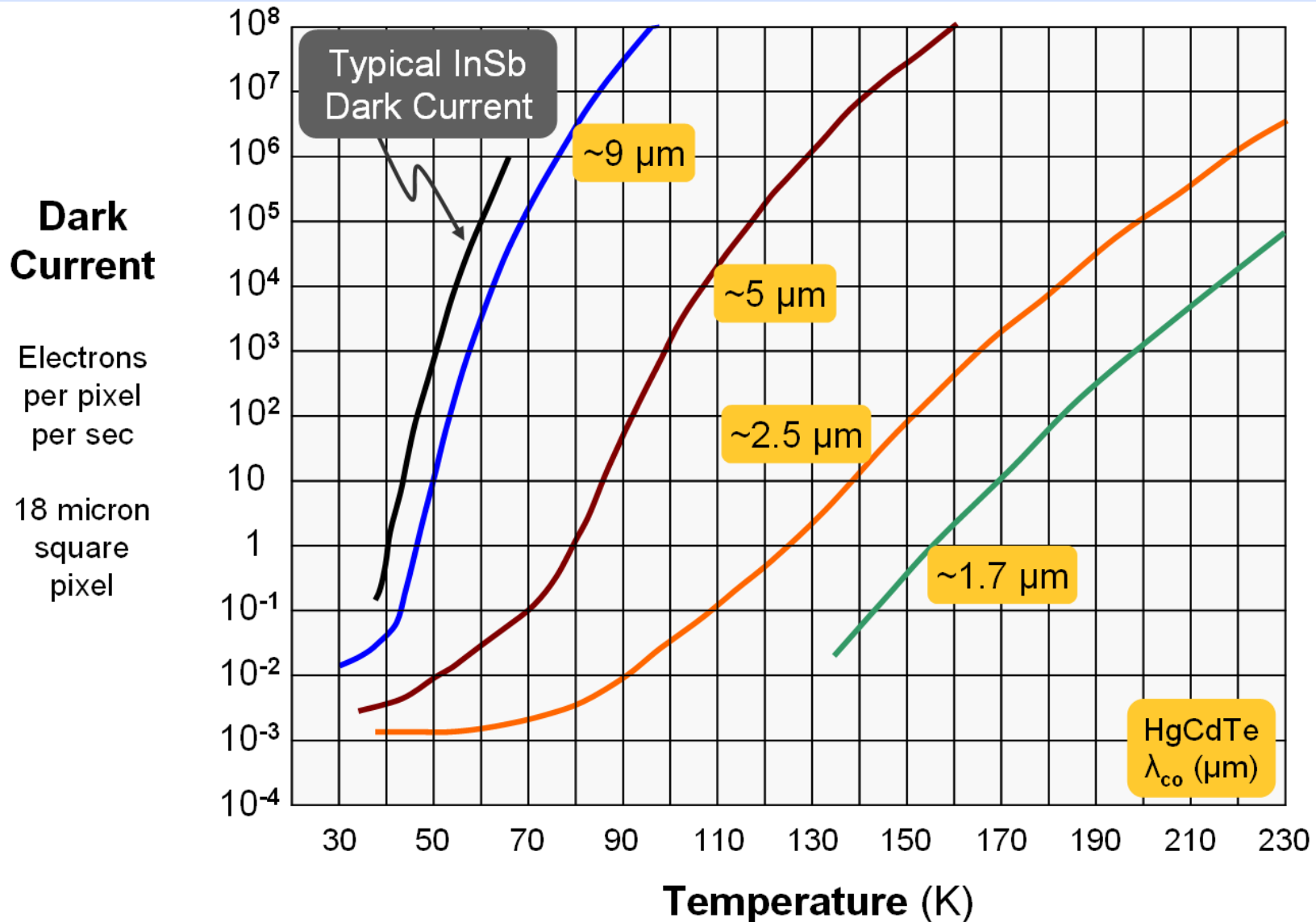


HgCdTe IR Sensors

- Bandgap can be “tuned” from 0.1 eV to 1.5 eV by varying the mixture of Hg and Cd
- Near-IR $\approx 1.7, 2.5 \mu\text{m}$ cutoff - defined as 50 % of peak QE
- Mid-wave IR $\approx 5 \mu\text{m}$
- long-wave IR $\approx 10 \mu\text{m}$
- Up to $\approx 15 \mu\text{m}$ 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)



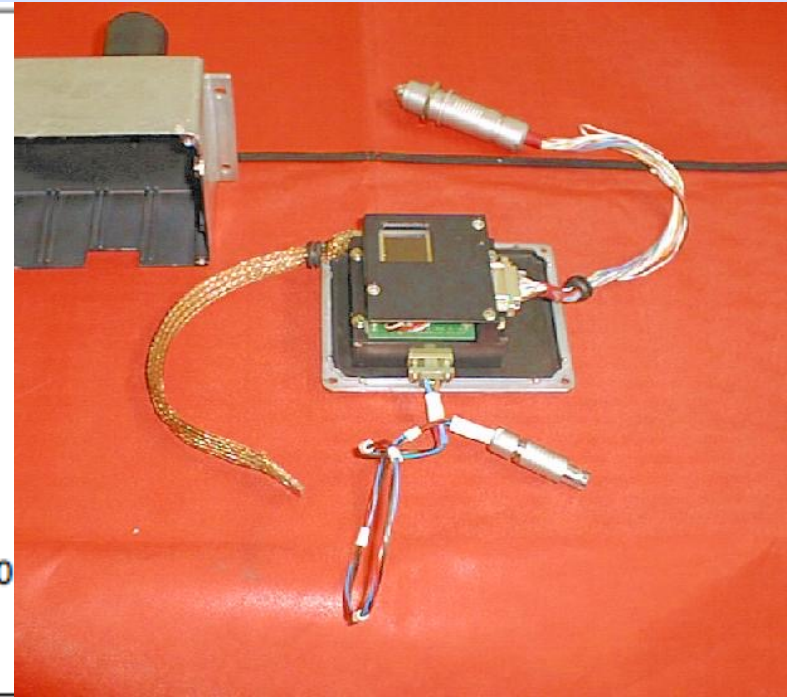
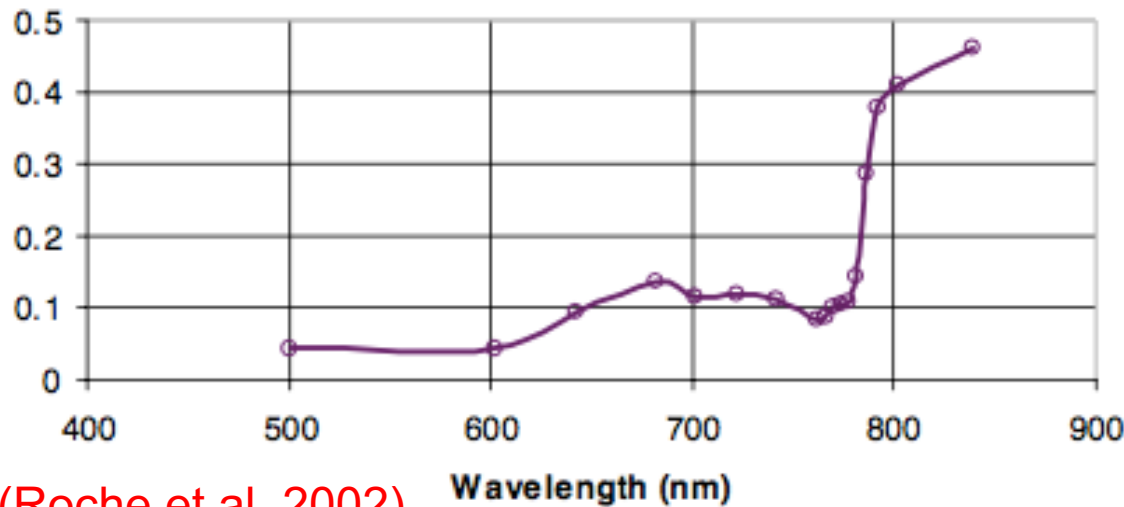
Performance



Lower temperature decreases dark current, but may also decrease QE_{25}

HgCdTe Response

UFTI Detector 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 0.78 μ m but with residual sensitivity to 0.5 μ m.

Dark current <1 e-/pix/min at 80 K

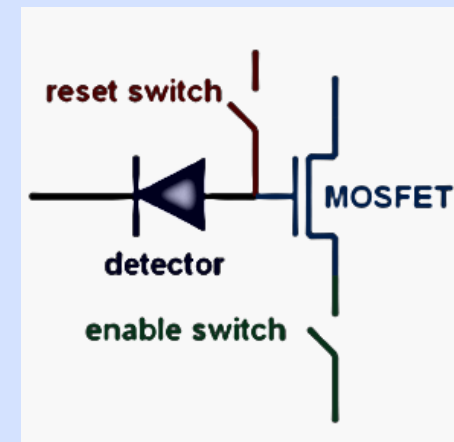
Read noise ~10e- with multiple NDR, 26e- with CDS, ~99.7% operable pixels

Hawaii-2RG (H2RG), 2K x 2K array with 18 μ m pixel pitch, sensitive to 2.5 μ m,

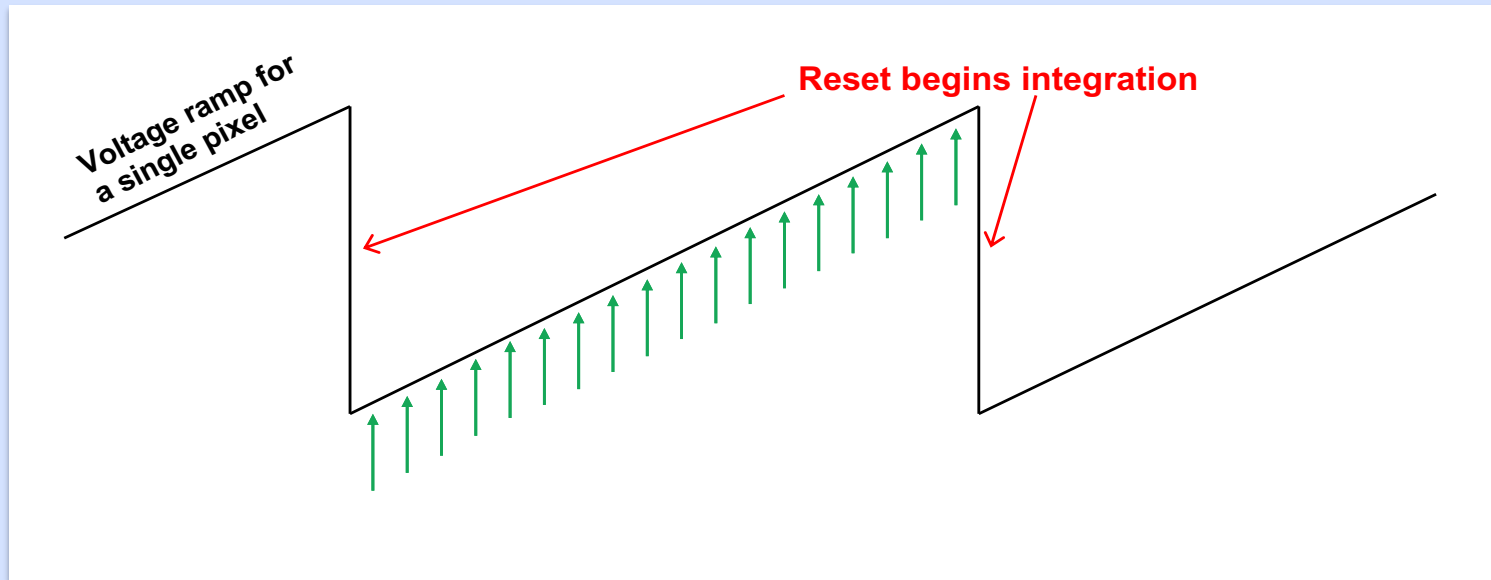
QE~ 80-90%,

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 $\approx 10^5$ 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)

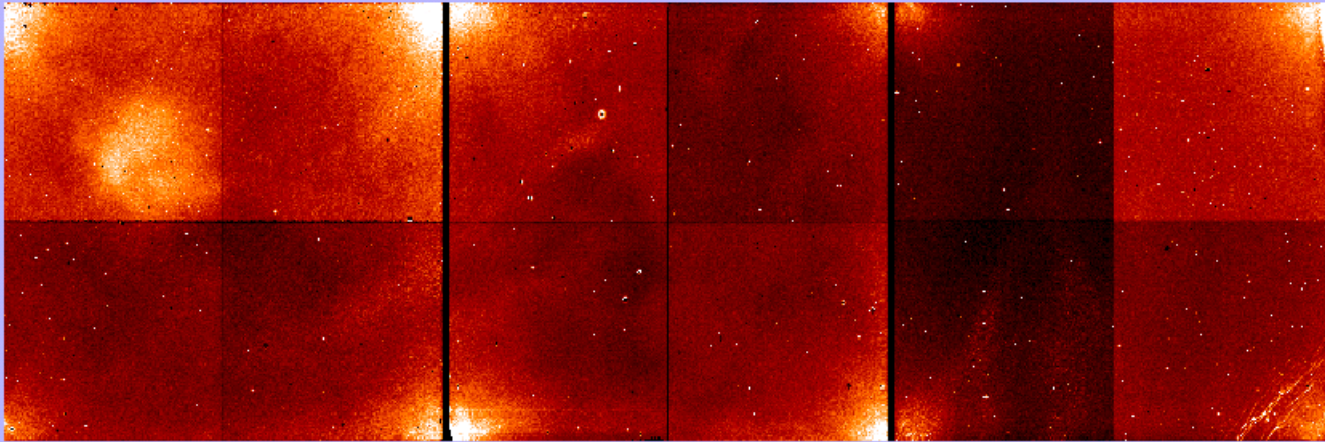


HgCdTe Readout

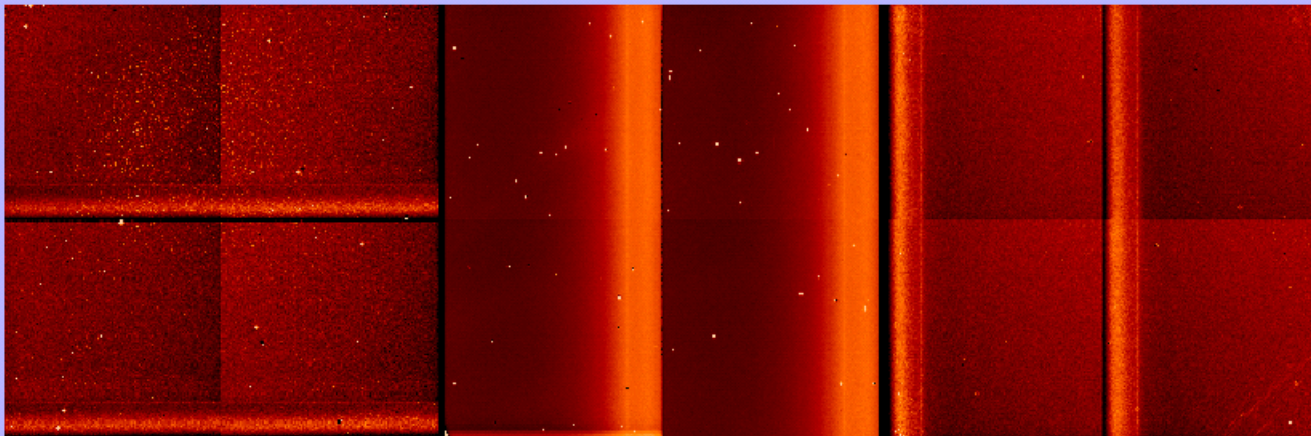


- Directly addressable pixels (rather than charge transfer in CCD) allows multiple, non-destructive reads to reduce Read Noise
- Output amplifier noise 15 - 50e⁻ , full-well $\approx 10^5$ to 10^6 e⁻
- Noise reduction by:
 - Averaging multiple samples at beginning and end of integration (Fowler & Gatley 1990). 4 reset samples and 4 signal samples reduces noise by $\sqrt{n} = 2$
 - Or continuously sample during (R Glendinning et al 1990)

IR Sensors Issues

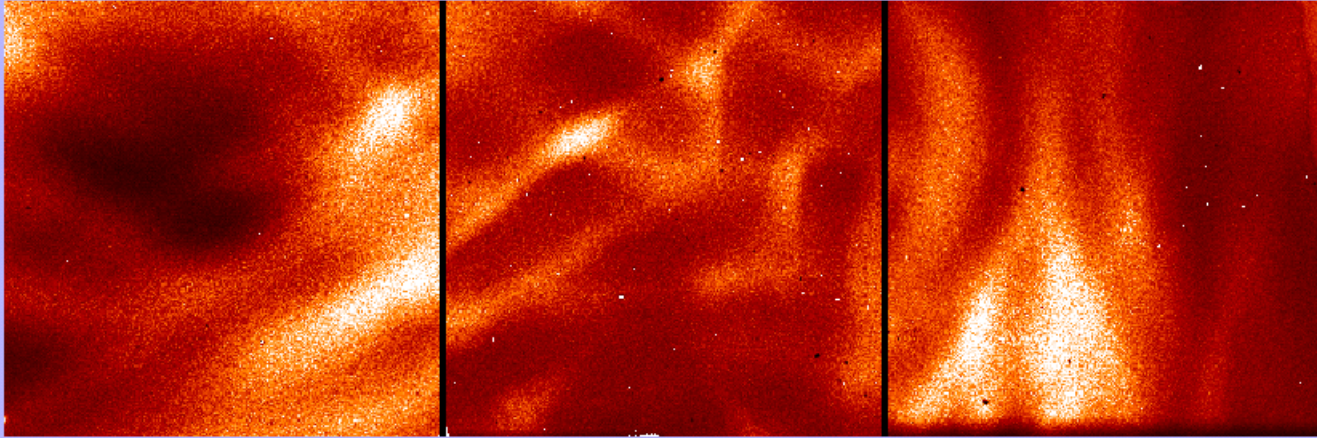


Dark Current

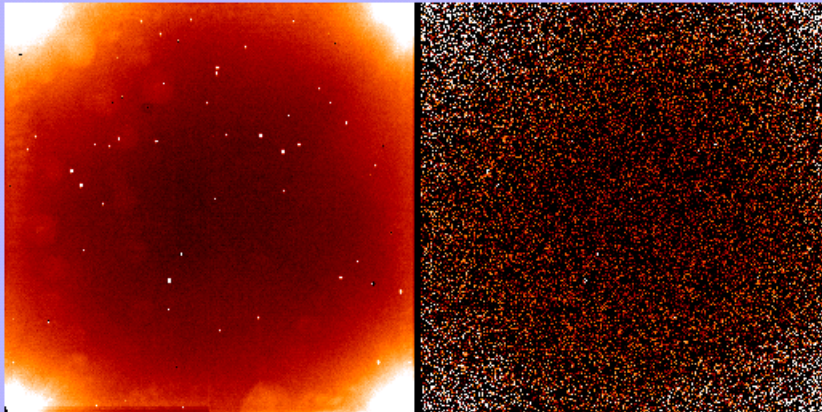


Spatially-dependent bias (“shading”)

IR Sensors Issues



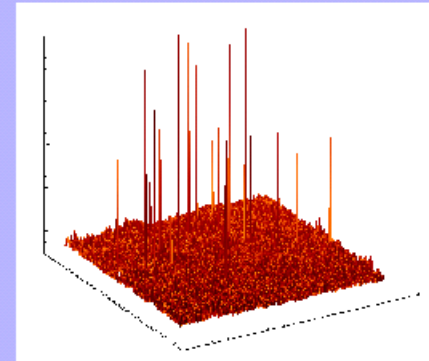
QE Spatial Variations



signal

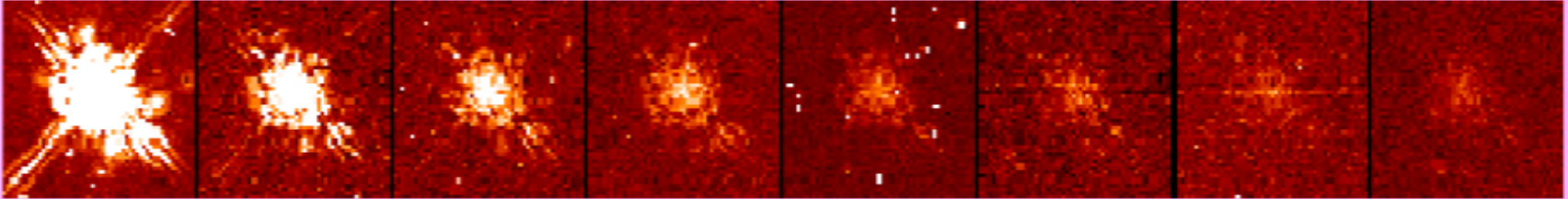
resulting noise

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

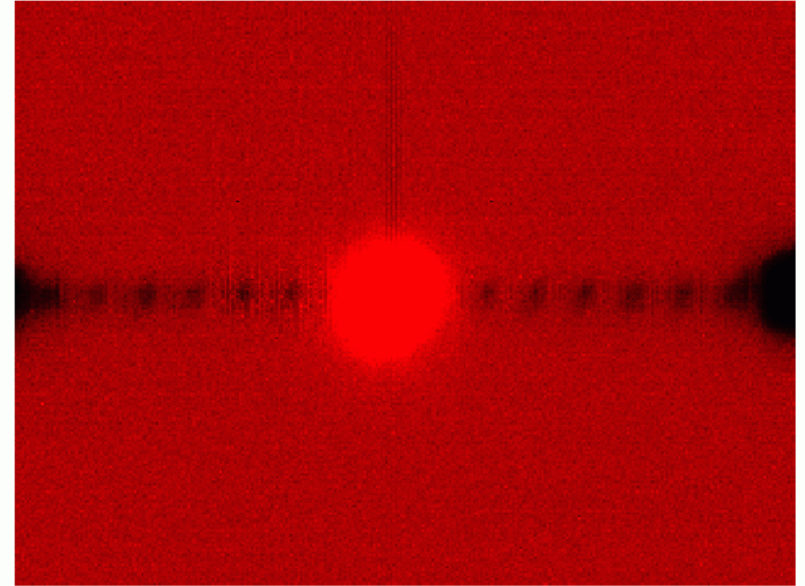
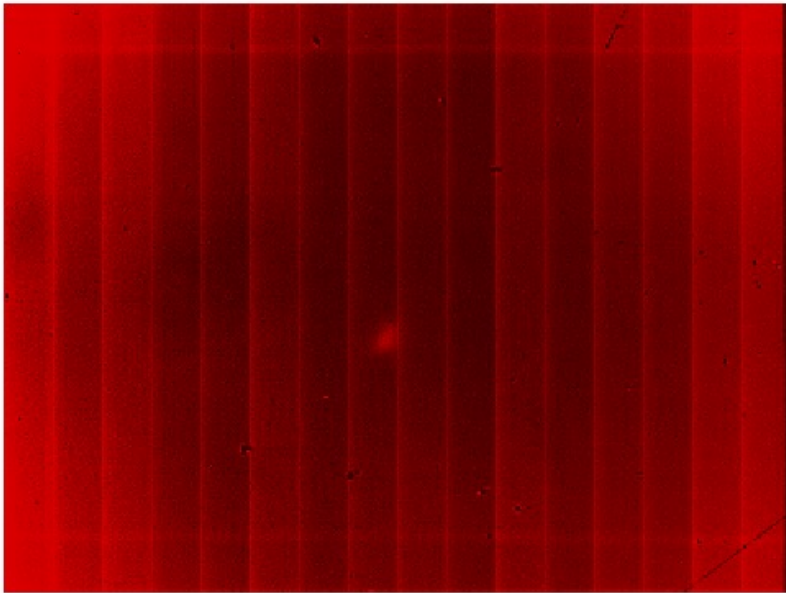
- **InSb** Indium Antimonide 5.6 μm cut-off λ at 77 K
used in instruments that cover JHKLM bands

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 crosstalk³³