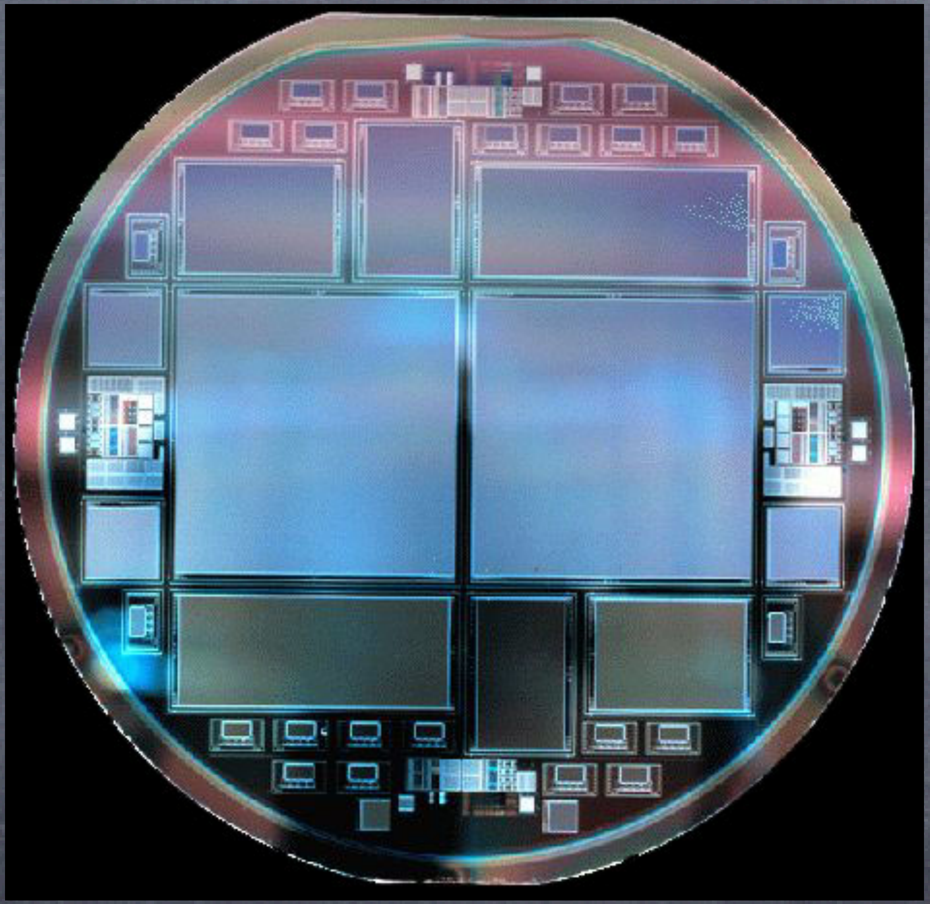
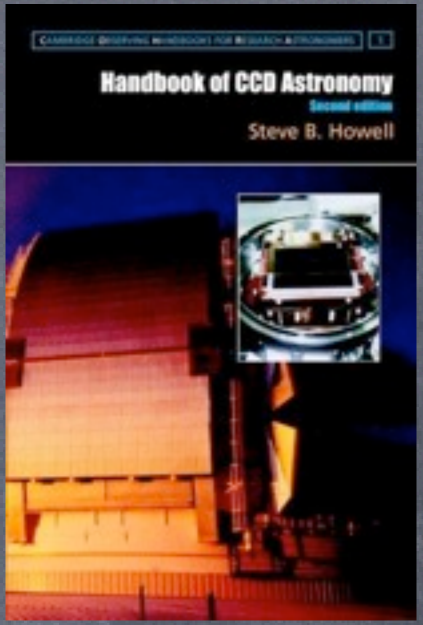
Charged-Coupled Devices



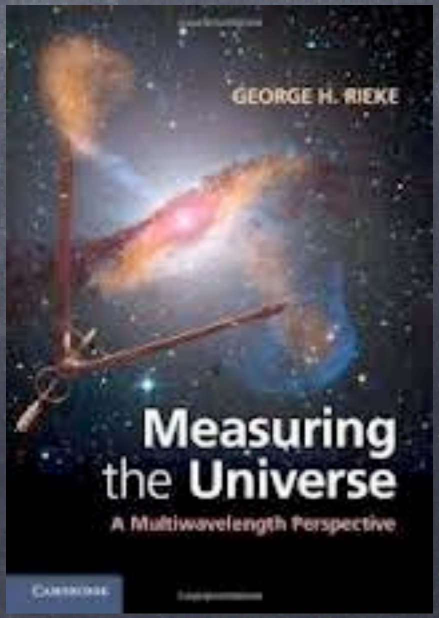
Charged-Coupled Devices

Useful texts:

Handbook of CCD Astronomy
Steve Howell- Chapters 2, 3, 4.4



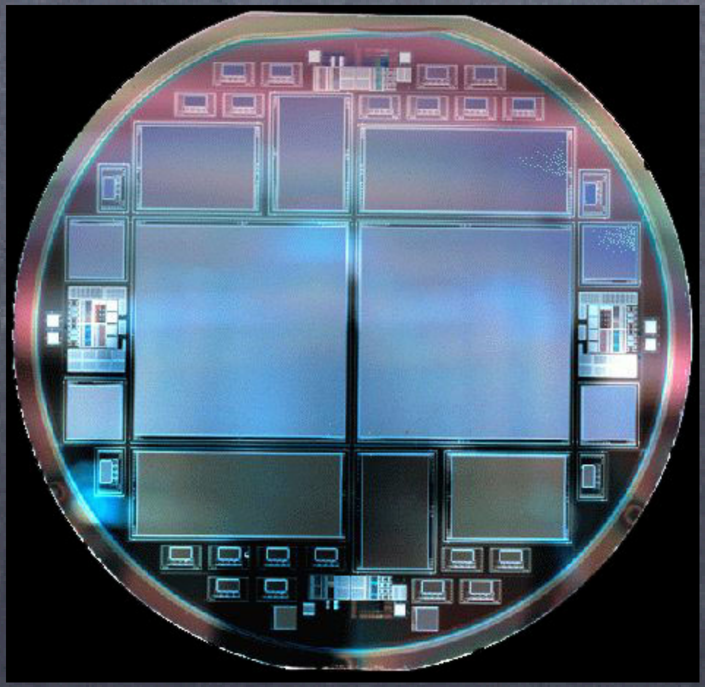
Measuring the Universe
George Rieke - 3.1-3.3, 3.6



CCDs

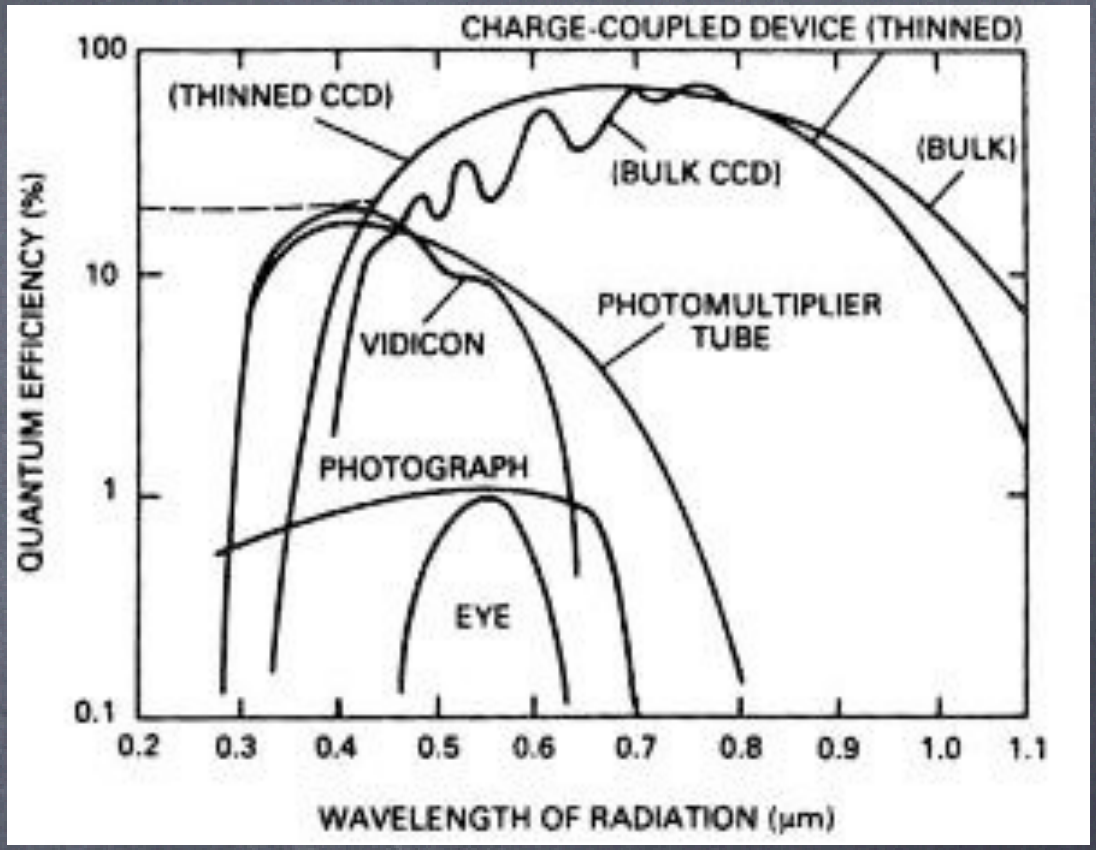
CCDs were invented in 1969 by Willard Boyle and George E. Smith at AT&T Bell Labs.

They were first used by astronomers in the late 1970's, and quickly took over as the preferred detector. CCDs are now the most common detector type over a wide wavelength range from the near-IR to X-rays.



Why We Like CCDs

- Very efficient at detecting photons! efficiencies of 80-90% compared to typically <5% for photographic plates --> leap in telescope sensitivity
- Relatively low noise (instrumental background)
- Wide wavelength response (photographic plates blue sensitive)
- Linear response giving improved flux calibration (1 count per photon)



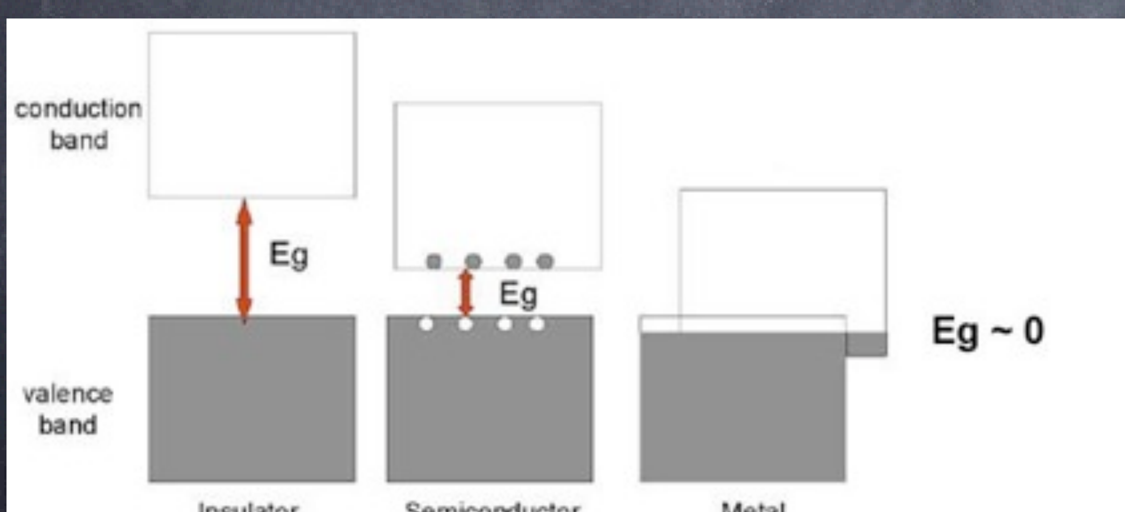
Handbook of CCD Astronomy, Howell

By the late 1980's, CCDs had replaced photographic plates for all but very large field imaging.

Basics of How They Work

CCDs are made of semiconducting silicon and use the photoelectric effect to detect photons. When a photon is absorbed by the silicon, a valence electron is bumped up to the conduction band.

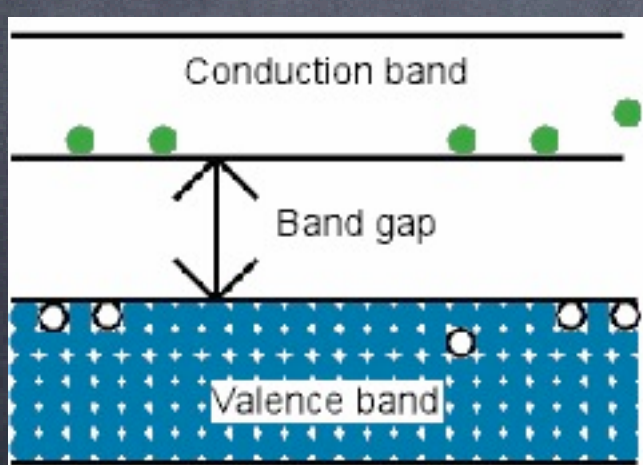
photon → | → e^-



Wavelength sensitivity depends on the band gap: the separation in energy between the valence band (lowermost, full, unexcited levels) and the conduction band (upper, mostly unoccupied levels, excitation to conduction band allows current to flow)

Basics of How They Work

photon $\rightarrow$ $\rightarrow$ e^-



There is a maximum wavelength/ minimum energy corresponding to the band gap:

$$\lambda_{max} = 1.24\ \mu m/E_g\,(eV)$$

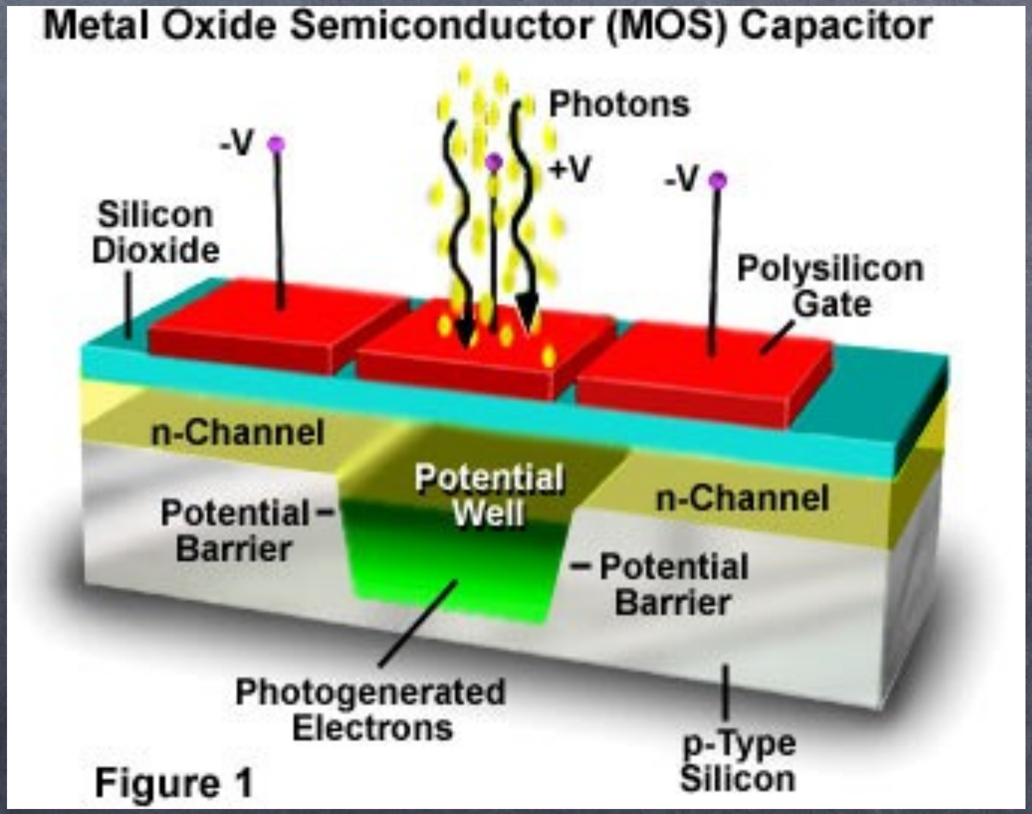
For Si, E_g = 1.11 eV and λ_{max} = 1.12 μm (note some e^- more tightly bound)

Infrared: detectors use materials with smaller bad gaps

X-ray: e^- from photoelectric absorption and Compton scattering

Basics of How They Work

CCDs are embedded with a system of electrodes called gates allowing applied voltages to be placed on each pixel. This creates localized potential wells where electrons are trapped after they are liberated by an incoming photon.



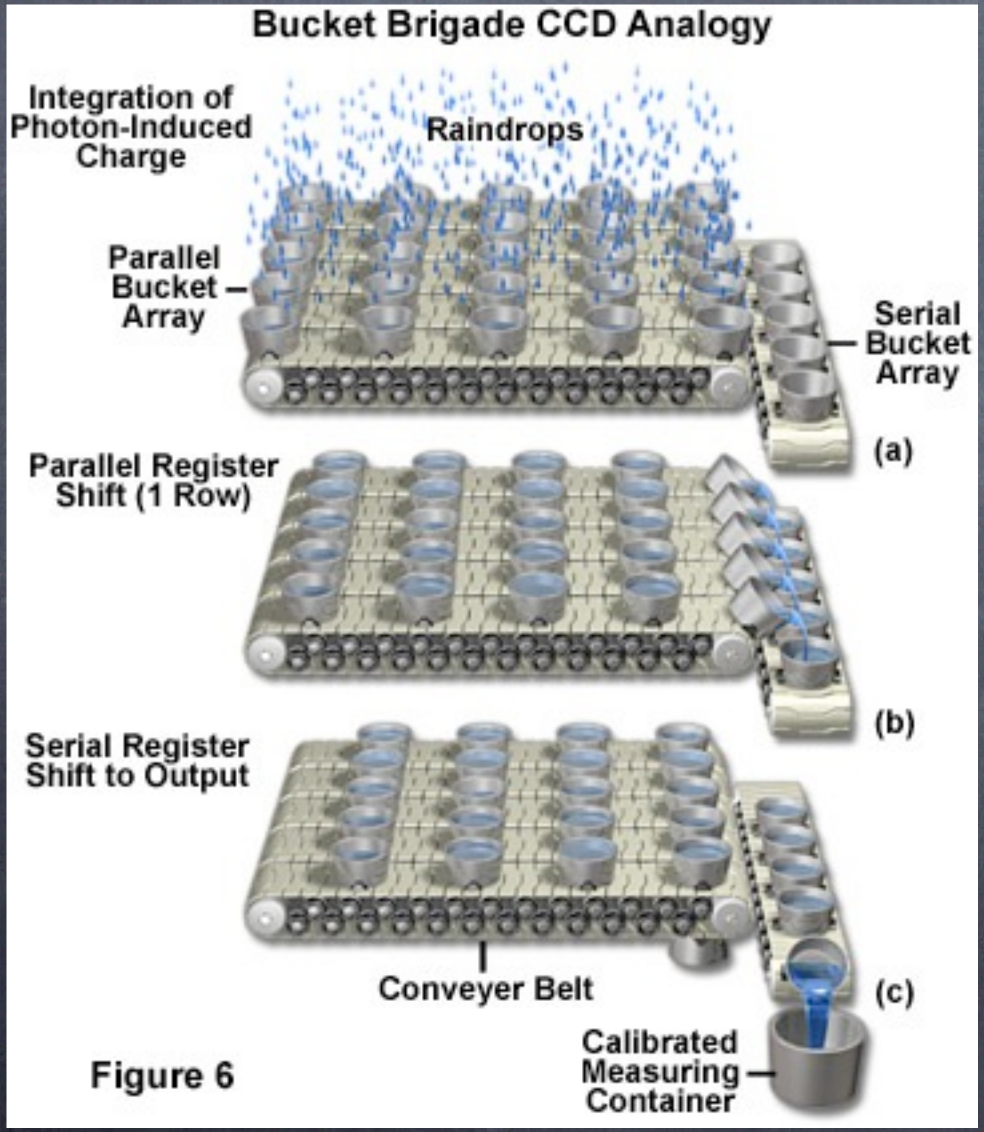
Basics of How They Work

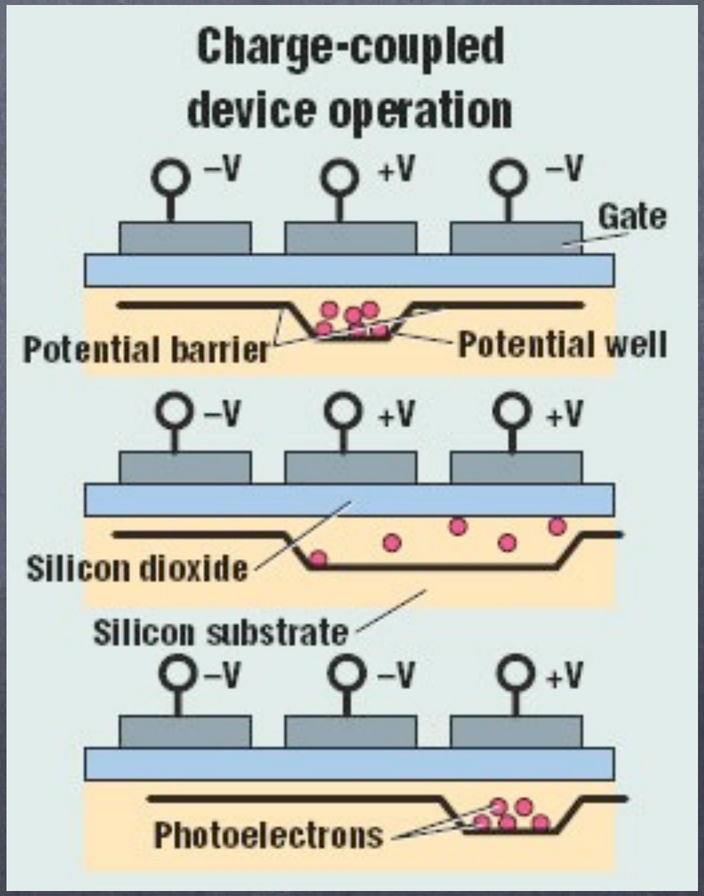
At the end of the exposure, the electrons collected in each pixel are "read out": they are shifted across the CCD, the collected charge is amplified and converted to a digital number (DN or ADU) with an analog-to-digital converter.

photons → e^- → read out and amplify → A/D convert to DN

Basics of How They Work

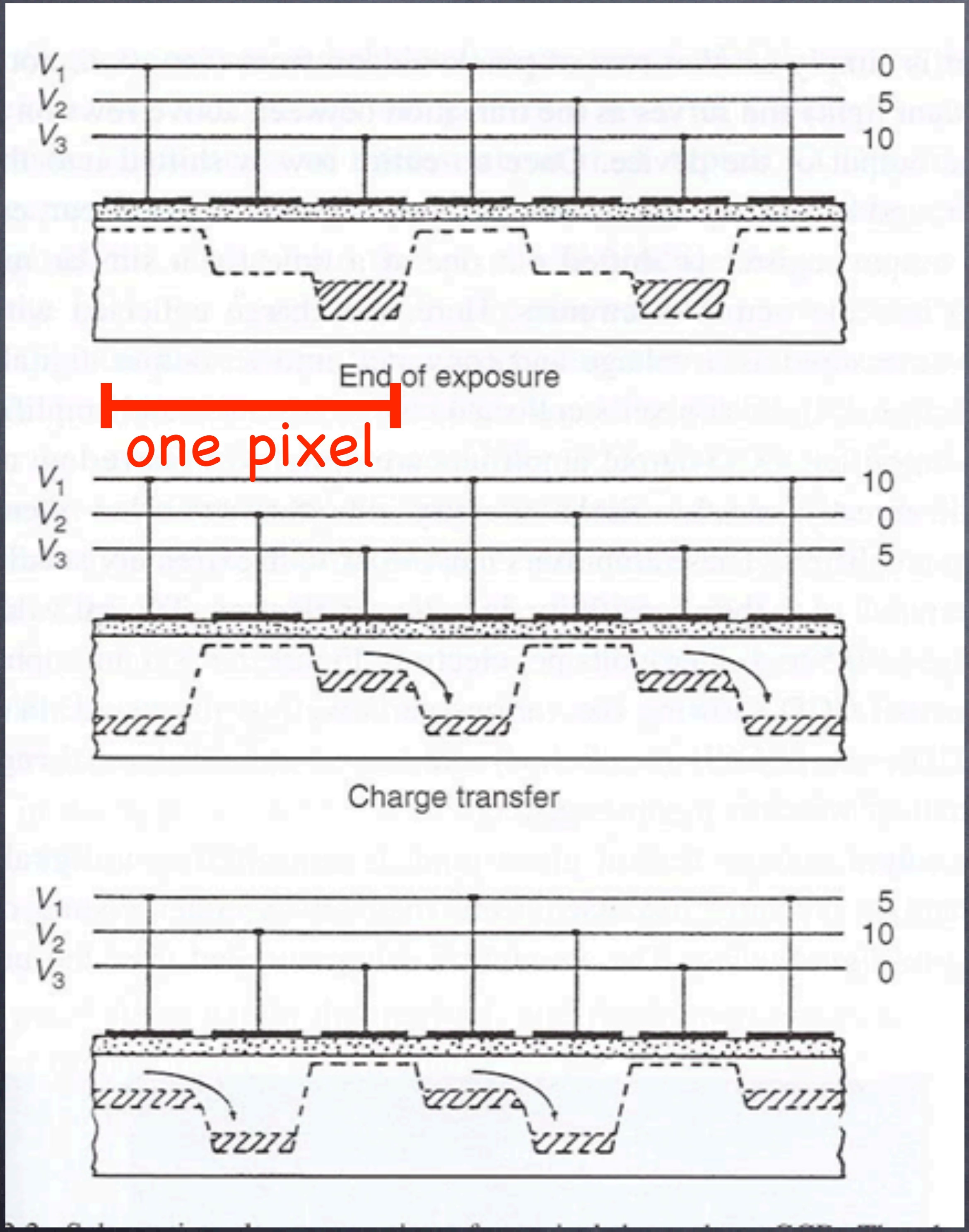
CCDs are readout through charge transfer. Rows are transferred across the chip and then a single row is clocked out pixel by pixel.





R. Repas, Machine Design, Nov. 2007

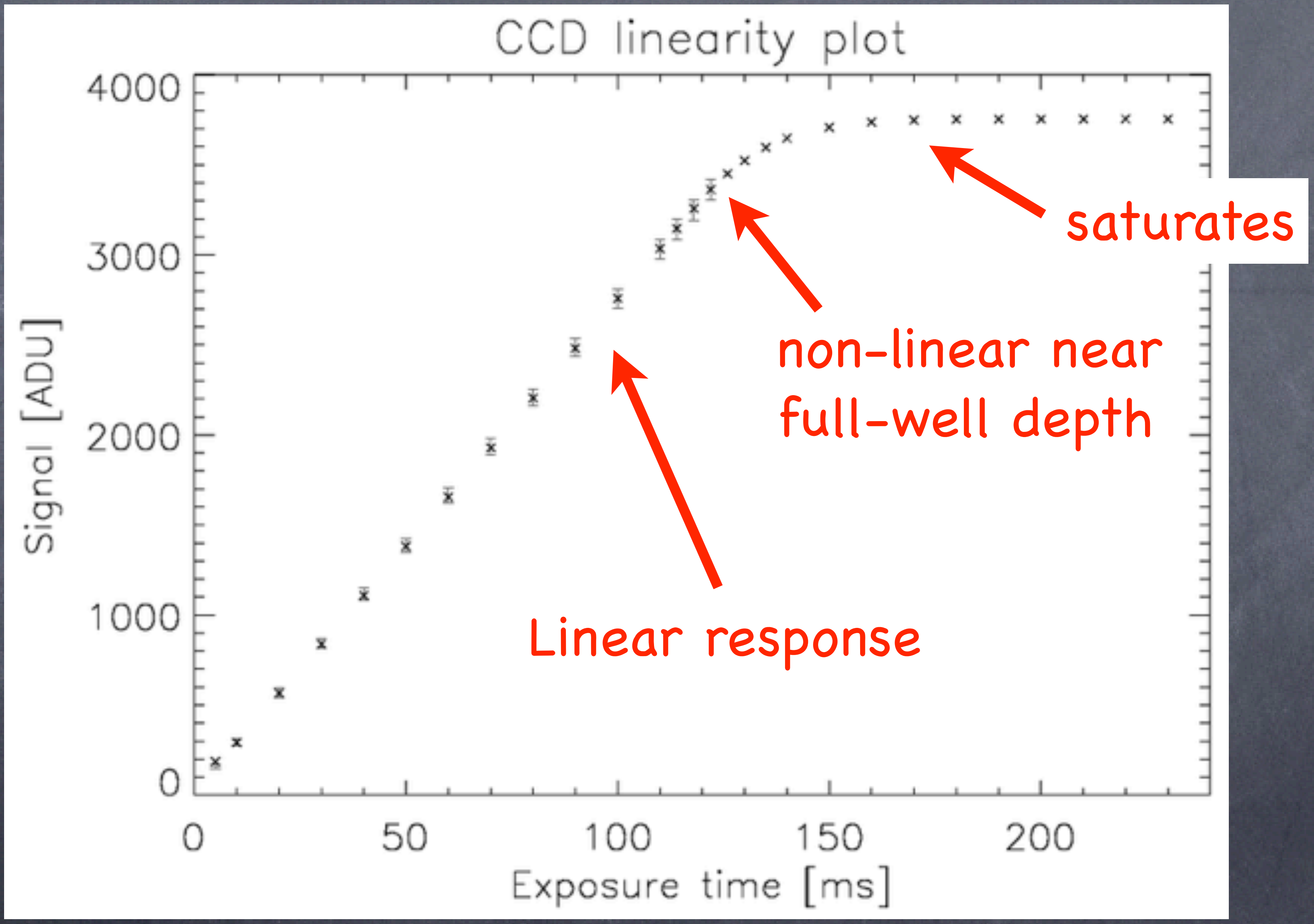
Basics of How They Work



Example of charge transfer in a three-phase CCD. The voltages on three gates are changed in sequence to migrate the charge.

Howell - Handbook of CCD Astronomy

CCD Linearity

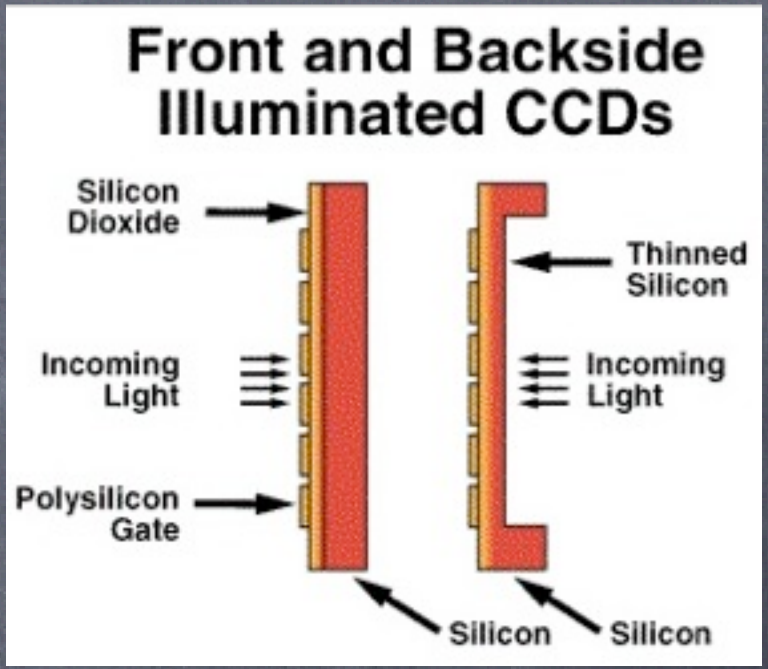


CCD Designs

There are a various CCD types, which can have advantages and disadvantages for astronomical observations.

Front illuminated: light hits gate structure first and then gets absorbed by silicon

- lower efficiency
- flatter imaging surface
- sensitive to cosmic rays

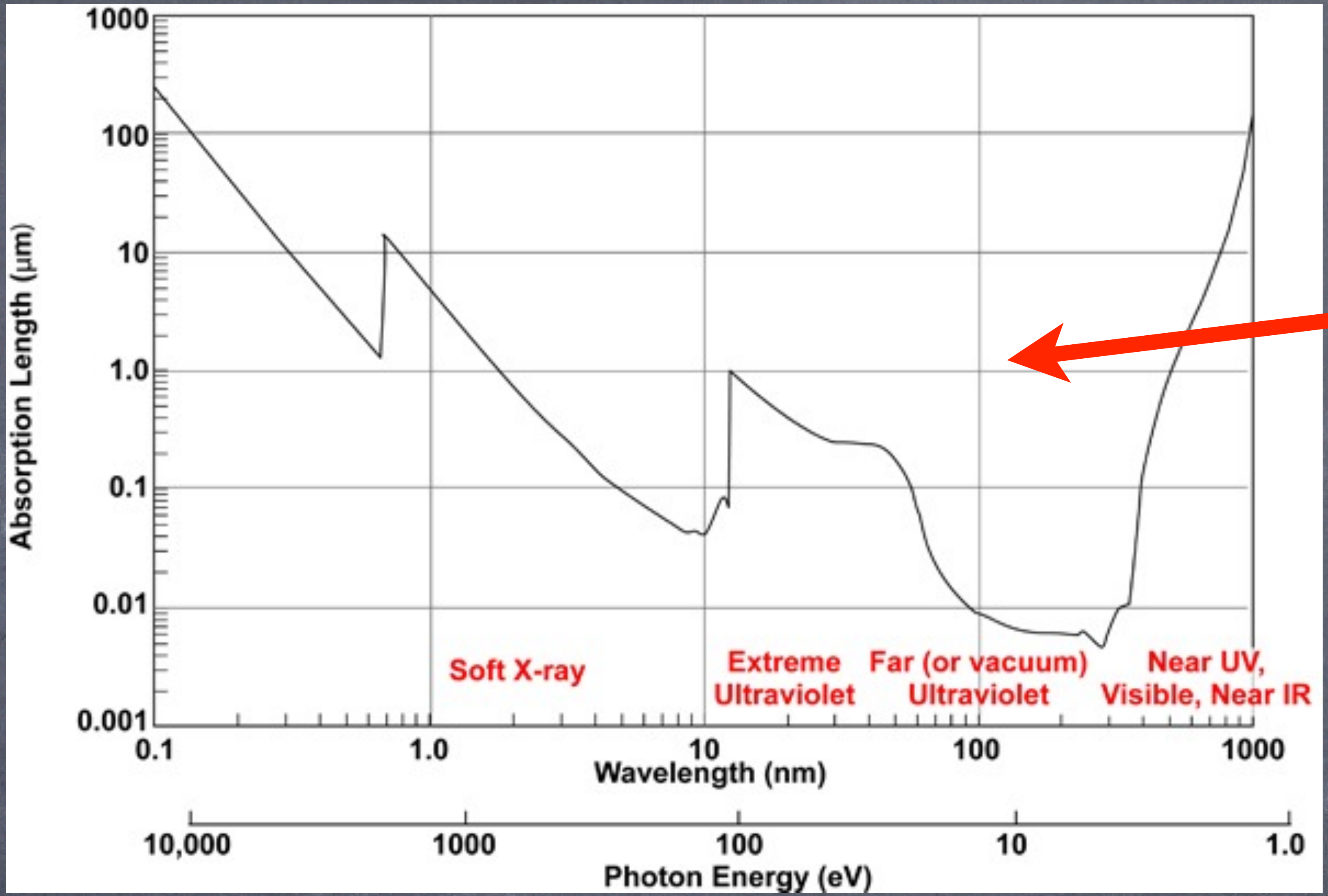


C. Tremonti

Back illuminated: light hits silicon layer first, which is thinned

- higher efficiency, response to blue light improved
- non-uniform thinning, fragile, shallower pixel well depth
- increased cost

Absorption length in Silicon



Use filters to select the energy band!!

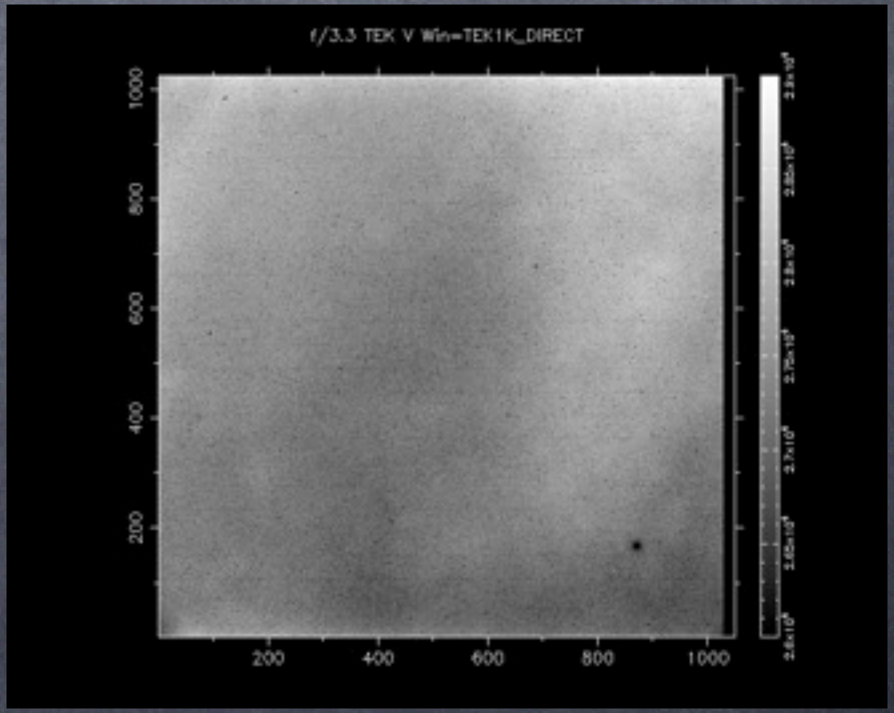
MIT Lincoln Lab

Depending on CCD thickness and wavelength photons may pass right through (to thin), get absorbed by the surface layer or gate structure, or reflect off the surface. Absorption length for red light much longer than blue.

Some Drawbacks to CCDs

- Small size
  --> mosaic
- Sensitive to things you don't want (cosmic rays, X-rays)
- Bright sources can saturate pixels leading to bleeding along columns
- Non-uniform response caused by small variations in manufacturing
- Cryogenically cooled to avoid dark current

CFHT Megacam



AAO flatfield

Some CCD Properties and Concepts

- Quantum Efficiency
- Charge Diffusion
- Charge Transfer Efficiency (CTE)
- Readout noise
- Dark current
- Gain