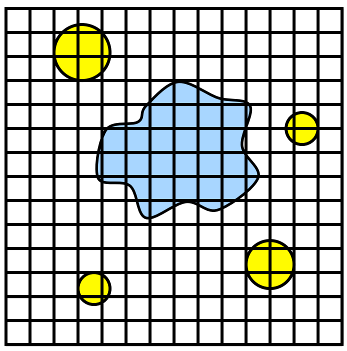
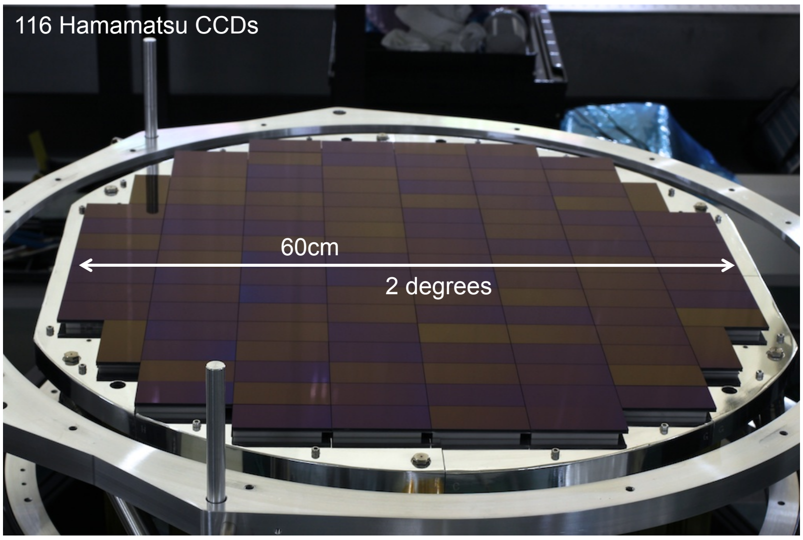
Charge Coupled Devices (CCD)

Charge Coupled Device

- Solid state detector
- Typically 1k x 1k light sensitive elements (pixels)
- Each pixel about 10-20mm square
- Pixels electrically insulated from each other
- Charge accumulates in each pixel
- Amount of charge proportional to intensity of light
- Charge distribution is the same as the light distribution



Hyper-Suprime-Cam

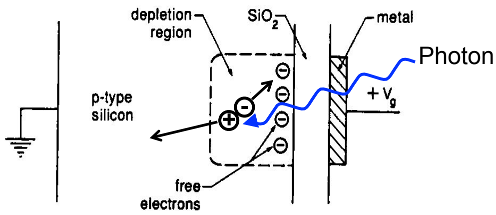


Overview of CCDs

1. Light (a stream of photons) is converted to a charge (electrons) by the photoelectric effect in a layer of silicon
2. The charge is accumulated in “wells” during the exposure
3. At the end of the exposure the CCD is “read out” – the charge is shifted to the readout register
4. Finally, the charge in each pixel is converted into a digital signal by the readout register

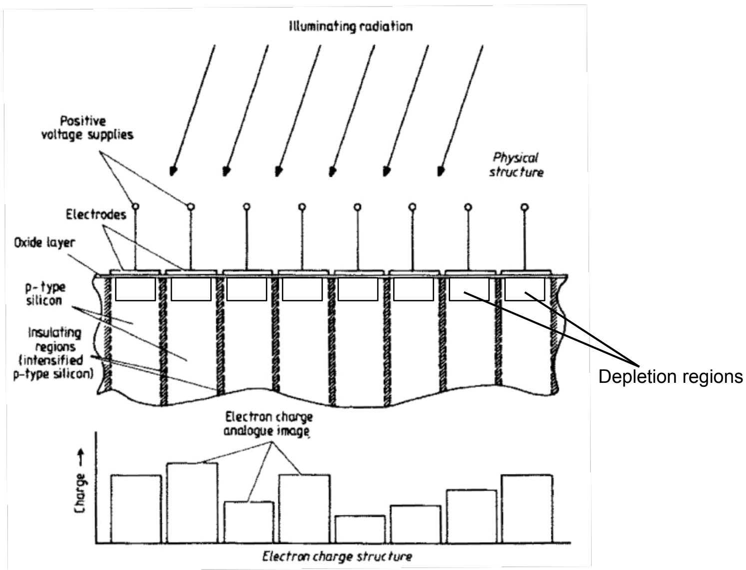
Structure of a CCD pixel

Metal Oxide Semi-conductor (MOS) Capacitor

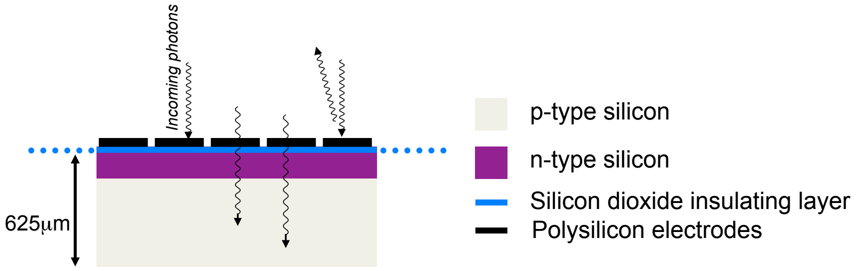


- Metal electrode:
  - V_g~+10V
  - Insulated from p-type Si substrate by layer of SiO_2 (~0.1um thick)
- Repels holes causing a –vely charged depletion region
- Incoming photons of energy <E_g create electron-hole pairs in Si substrate
- Holes diffuse away from metal electrode
- Electrons diffuse towards metal electrode and stored in depletion region

Structure of a CCD Array

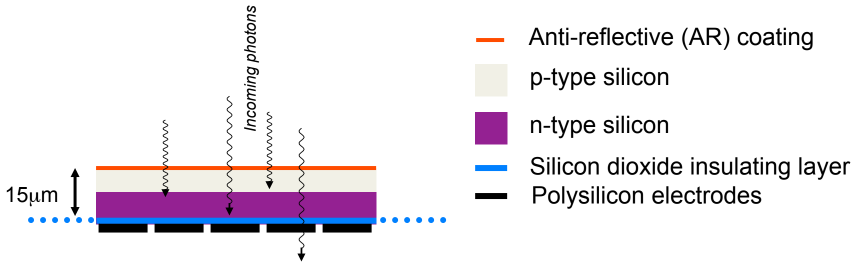


Thick front-side illuminated CCD



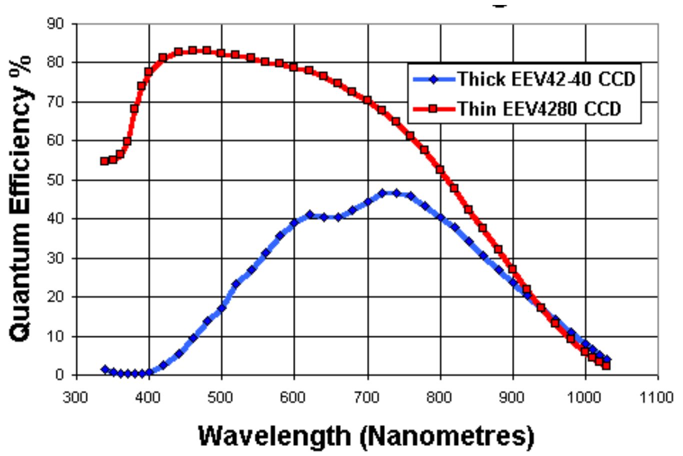
- Cheap to produce using conventional wafer fabrication techniques
- Poor QE due to the reflection/absorption of light by electrodes
- Transparent electrodes can be made from heavily doped Si
- Doped Si electrodes have large absorption coefficient at <0.4um
- Electrode structure prevents the use of anti-reflective coatings

Thinned Back-illuminated CCD

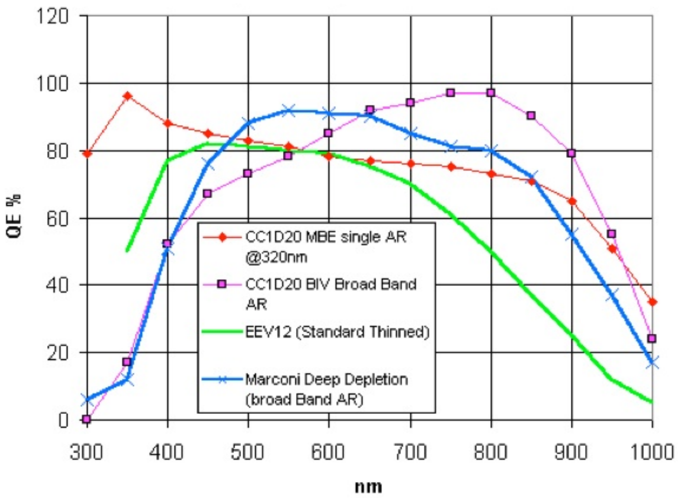


- Light is incident from the rear, so electrodes do not obstruct photons
- Electron-hole pairs produced far from depletion region
- Electrons therefore vulnerable to being caught in traps as they diffuse to depletion region
- Si is therefore thinned to ~15um to reduce path to depletion region
- However absorption length of Si at λ=1um is 80um, so thinned Si is transparent in the red
- Solution is "deep depletion" – the depth of the depletion region is increased, allowing the Si substrate to be ~40um thick

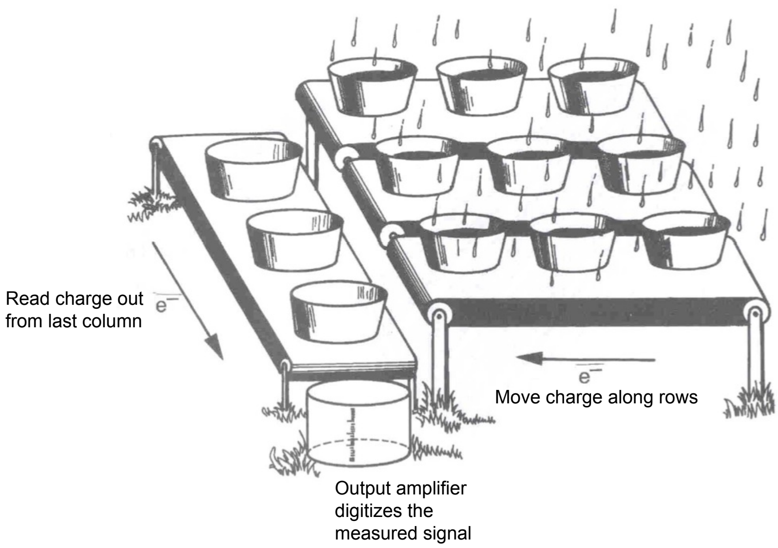
QE Improvement from thinning



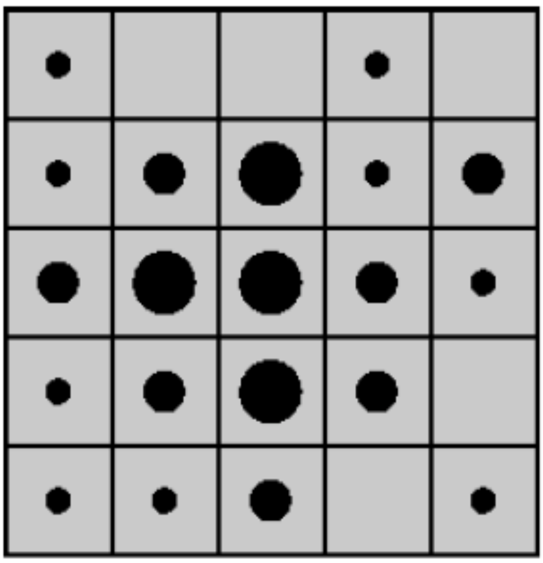
QE and deep depletion



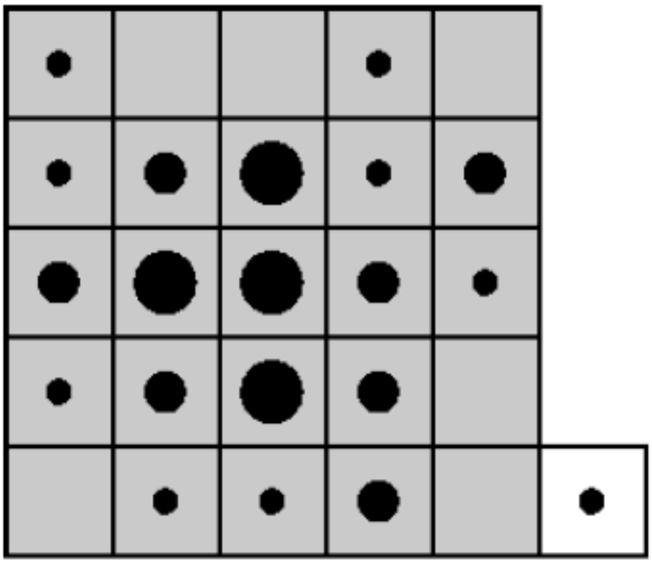
Reading out a CCD …



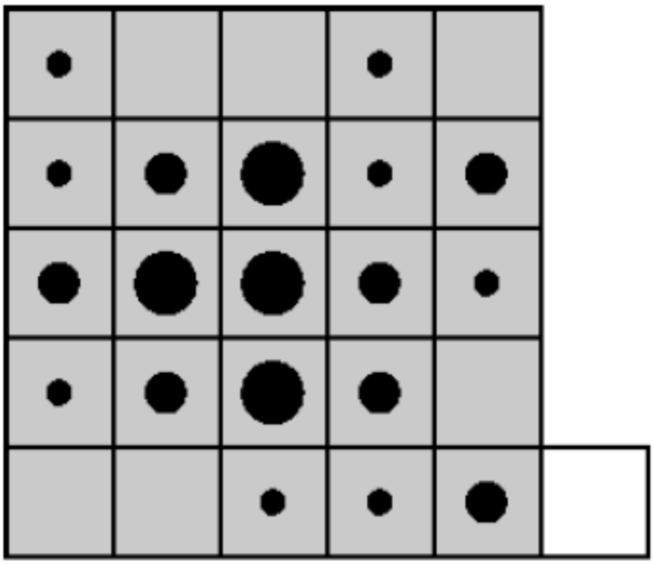
Reading out a CCD …



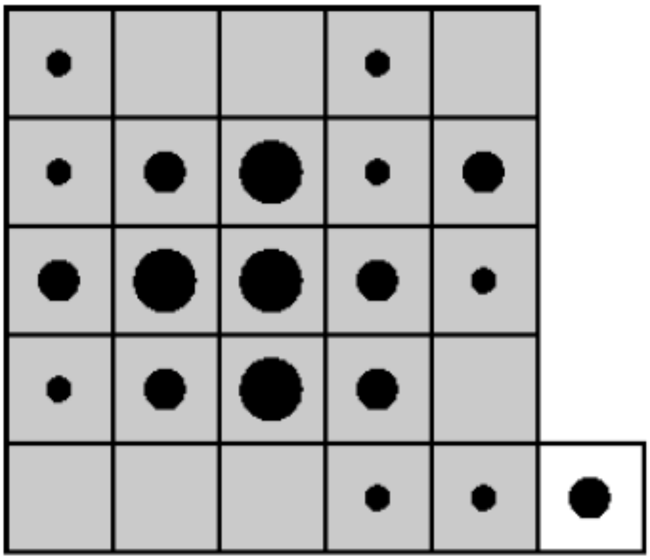
Reading out a CCD …



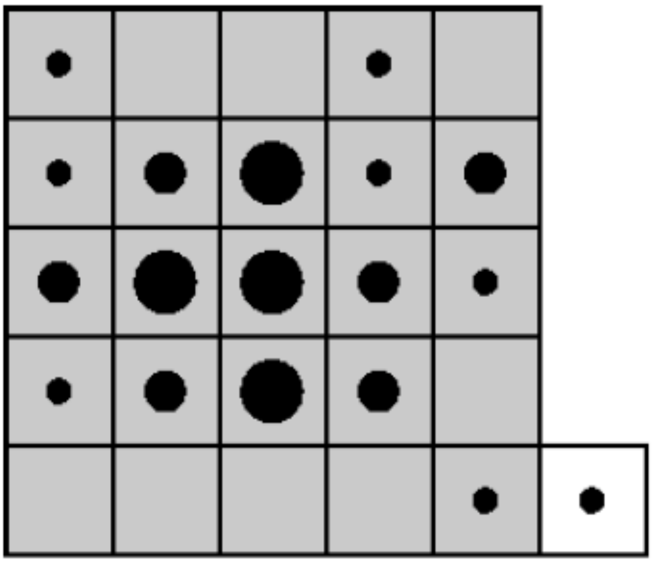
Reading out a CCD …



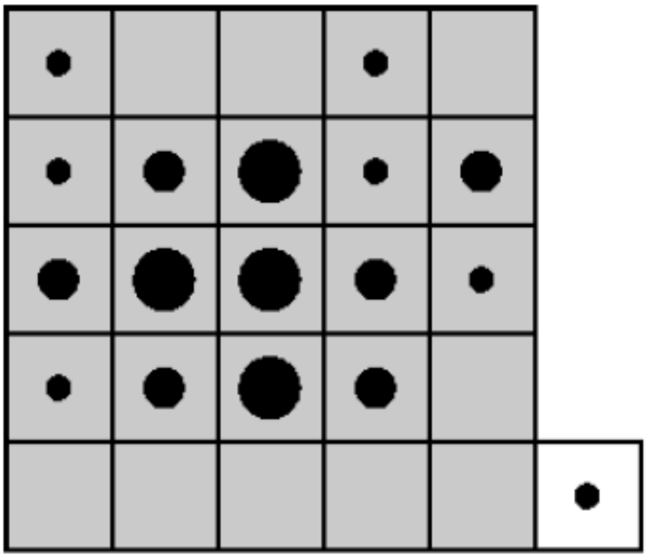
Reading out a CCD …



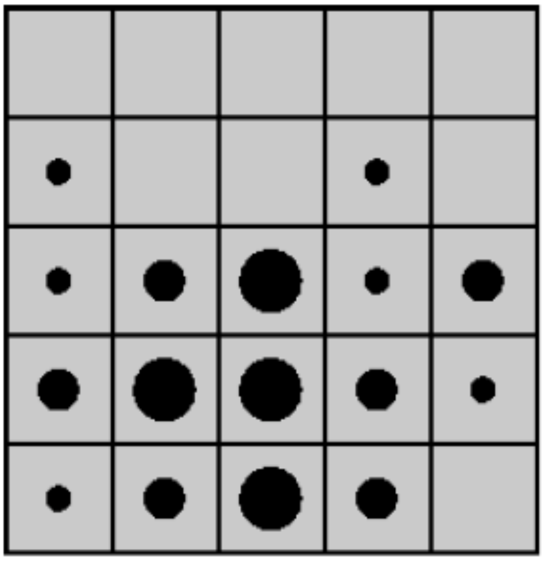
Reading out a CCD …



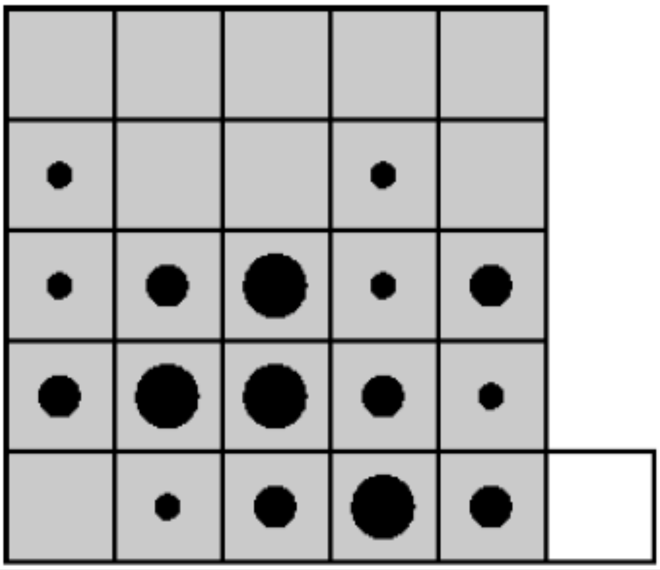
Reading out a CCD …



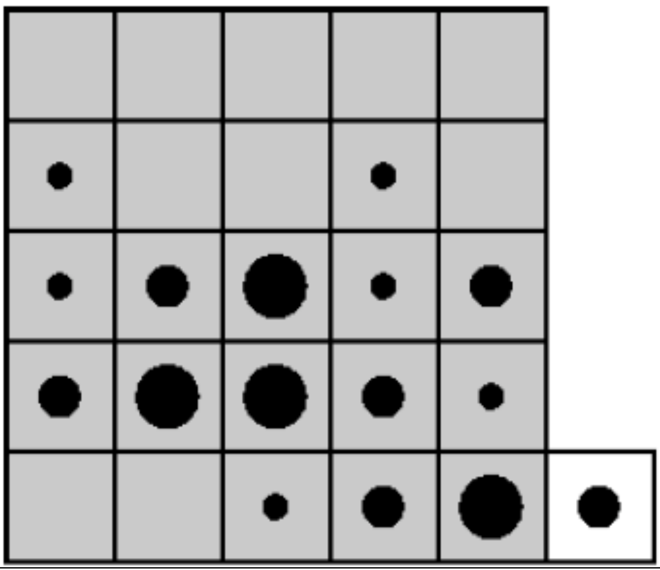
Reading out a CCD …



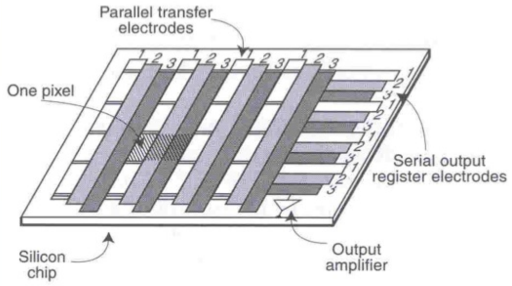
Reading out a CCD …



Reading out a CCD …

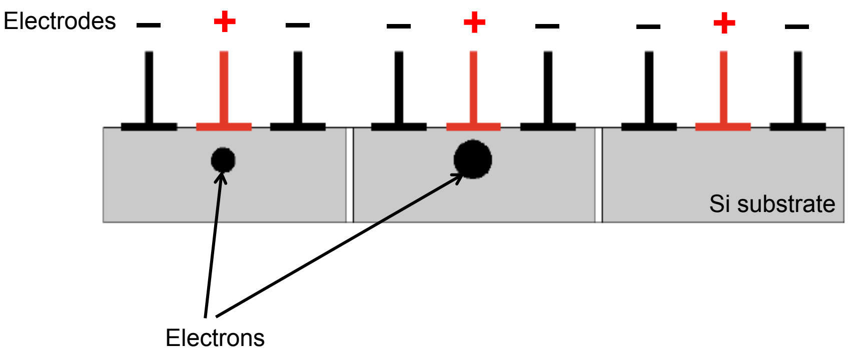


Three phase CCD read out

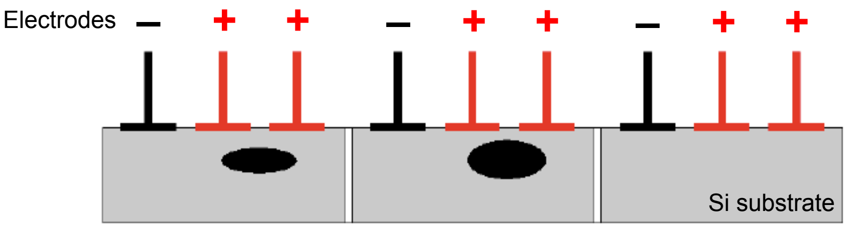


- Three electrodes per pixel:
  - One electrode at more +ve voltage than others to create depletion region
  - Voltages changed in a repeatable pattern (clocking) to move charge across rows of CCD
  - Heavy doping prevents charge from migrating along the electrodes

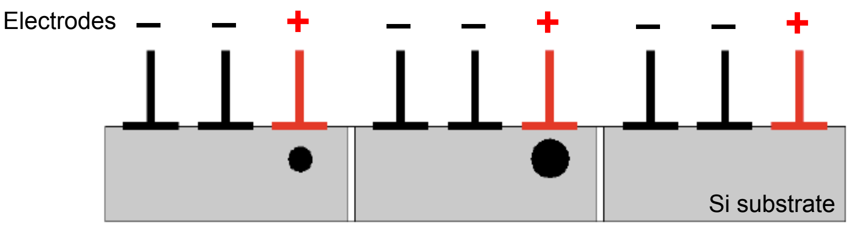
Three-phase CCD read out



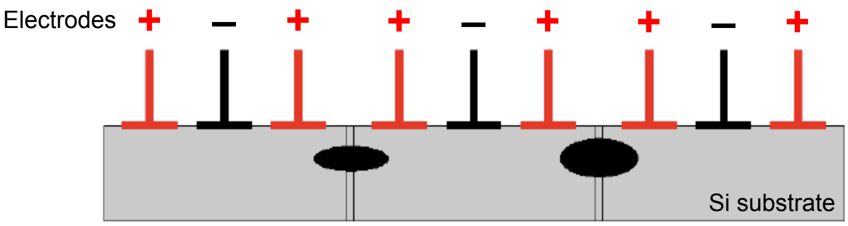
Three-phase CCD read out



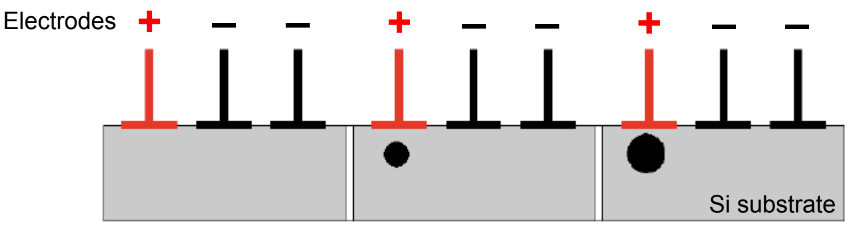
Three-phase CCD read out



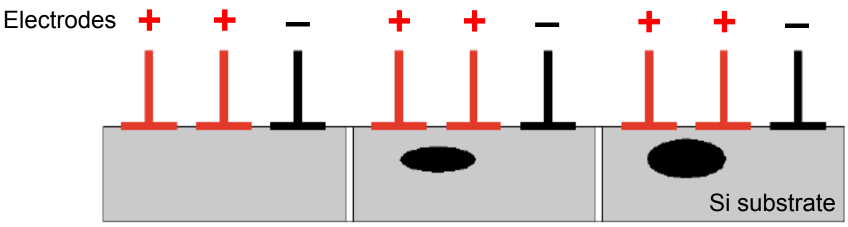
Three-phase CCD read out



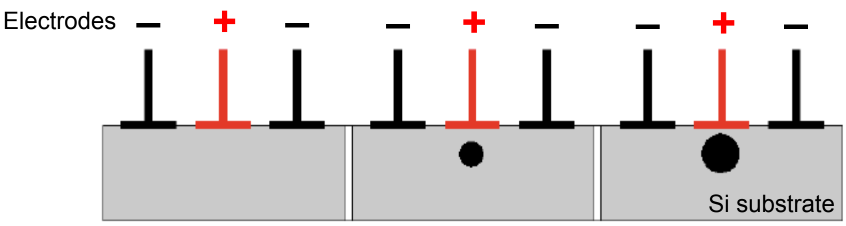
Three-phase CCD read out



Three-phase CCD read out



Three-phase CCD read out



Summary of CCD readout

- Charge carriers are moved along columns and rows by "clocking" the voltages applied to CCD pixels
- Charge in the final column is first read out to the readout register (amplifier) and digitized
- Charge is then shifted down vertically by one more pixel, the next column is shifted into the readout register
- Process is repeated until the entire image is read out
- For a 2048 x 2048 pixel CCD it takes several minutes to read out the whole chip

Overview of CCD performance

- Read out time
  - Compromise between short overhead (read out time) and inefficient charge transfer
- Gain, linearity and saturation
  - Match "digital capacity" of ADC (15 or 16 bit) with "electron capacity" of depletion regions
- Charge transfer efficiency
  - Scientific applications demand highly (99.9999%) efficient charge transfer during readout
- Cosmetic defects
  - Split integration time into separate dithered exposures to remove effects of bad columns/pix
- Variations in quantum efficiency
  - Illuminate CCD with a uniform light source to measure/correct pixel-to-pixel QE fluctuations
- Fringing
  - At red wavelengths illumination of CCD by sky emission causes interference fringes
- Dark current
  - Cool CCDs with liquid N_2 to reduce thermal excitation of charge carriers
- Bias and read noise
  - Readout electronics introduce bias and read noise into the measured (digitized signal)
- [Cosmic rays]
  - Split integration time into separate exposures to remove effect of cosmic rays from data

CCD Read-out Time

- Faster clocking reduces the time available for charge to travel from one depletion zone to the next
- High CTE requires clocking at a speed that is much slower than the thermal diffusion time constant
- Slow clocking speeds increase the readout time of a CCD, and thus increases unproductive time
- The compromise speed of CCD clocking is tens of thousands of cycles per second (~10^4Hz)
- How long does it take to read out a 1024x1024 CCD at a clocking speed of 10^4Hz?

Gain

- As CCD clocks out charges, an amplifier converts the electron packet net charge into a digital signal
- Gain = number of electrons combined to make one "count"
- "Counts" are called Analog-to-Digital Units or ADUs
- Typically Gain = several e-/ADU
  - For our Observatory CCD, G = 5 e-/ADU
- Dynamic range of the image output is limited by the Analog to Digital Converter (ADC)
- Typical limits are:
  - 15 bit = 2^{15} = 32768 distinct values
  - 16 bit = 2^{16} = 65536 distinct values

Linearity and Saturation

- As the number of electrons in the depletion region approaches capacity, the CCD response departs from linear
- Depletion region capacity depends on its physical size – larger pixels can hold more charge
- A full pixel is said to be "saturated"
- Saturation prevents reliable flux measurements – a BAD thing!
- Charge in saturated pixels tends to bleed along CCD columns
- The gain of a CCD is chosen to match the pixel capacity and the available number of bits

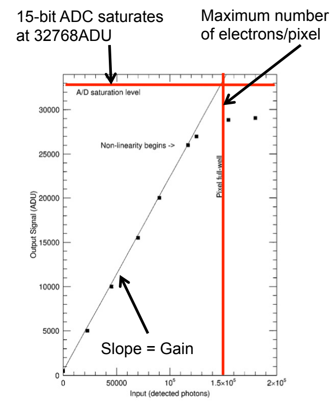
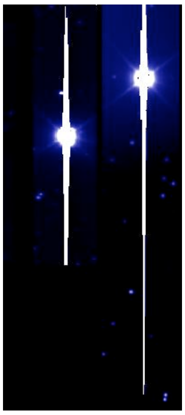


Fig. 3.6. CCD linearity curve for a typical three-phase CCD. We see that the device is linear over the output range from 500 ADU (the offset bias level of the CCD) to 26,000 ADU. The pixel full well capacity is 150,000 electrons and the A/D converter satuartion is at 32,767 ADU. In this example, the CCD nonlinearity is the limiting factor of the largest usable output ADU value. The slope of the linearity curve is equal to the gain of the device.

Charge bleed from saturated stars



Solution: break total "integration time" down into a series of shorter exposures

Charge Transfer Efficiency (CTE)

- Transfer of charge between pixels is <100% efficient
- Some electrons get left behind!
- Early CCDs had CTE~98%
- Today:
  - CTE>~99·995% in commercial devices
  - CTE>~99·9999% in scientific devices
- Consequences of poor CTE:
  - not all of the photons recorded by CCD will be counted
  - signal becomes blurred because charge that gets left behind is mixed with later packets
  - the further from the readout register the worse the effect

Charge Transfer Efficiency (CTE)

- Let:
  - N_0 = number of charges originally under gate
  - N_t = number of charges transferred to next gate
- CTE is defined as the fraction of charge that transferred from pixel to pixel:

$$CTE = \frac{N_t}{N_0}$$

- CTE of 99% means that 1 in every 100 electrons gets left behind every time charge is transferred on the CCD

Charge Transfer Efficiency (CTE)

- How good is 99% CTE?

- Start with 100 electrons stored in a pixel
- Transfer that charge packet from the original pixel to a pixel that is 100 pixels away – i.e. 100 pixel-to-pixel transfers
- How many electrons will arrive in the 100th pixel?

Charge Transfer Efficiency of Hubble's Advance Camera for Surveys

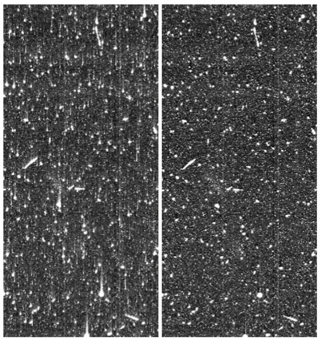


Figure 3. A typical _raw ACS/WFC science exposure from early 2010 (HST-GO-11689, PI: Renato Dupke) before (left) and after (right) CTI correction. The 380×820 pixel area selected is furthest on the detector from the readout register, and the logarithmic colour scale is chosen intentionally to highlight the CTI trails.

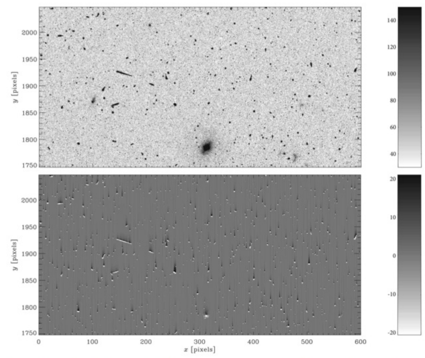


Figure 6. *Top*: The HST ACS/WFC image from figure 1, after CTI correction, in units of electrons. *Bottom*: Difference image.

- Charge transfer efficiency of ACS is degrading with time
- It is possible to correct for CTE using specialized software

Charge Transfer Efficiency of Hubble's Advance Camera for Surveys

- Radiation damage to Silicon lattice in ACS CCDs creates charge traps
- Electrons get stuck in these traps as the CCD is readout and then escape from the traps "several pixels" later

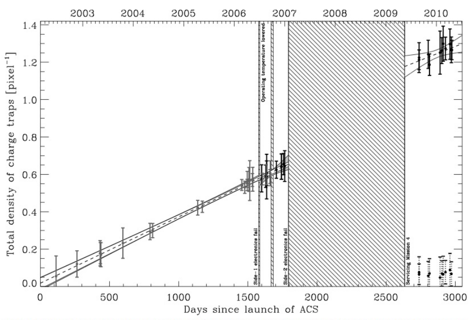


Figure 2. Measured density of charge traps in the ACS/WFC detectors, as they have accumulated over the lifetime of the camera. Measurements assume three trap species in a ratio of 1 : 3.38 : 2.85, with characteristic release times as described in the text. Grey (black) points indicate survey imaging acquired with a commanded gain setting of 1 (2), and all errors are 1σ. Separate fits are shown to data before and after shuttle Servicing Mission 4, plus (noisier) fits to shorter periods in grey. Hatched regions indicate times when ACS was offline. Points with dotted error bars show the total absolute density of traps after correction.

Charge Transfer Efficiency of Hubble's Advance Camera for Surveys

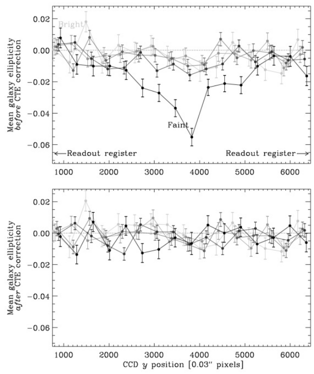


Figure 11. Component of mean galaxy ellipticities in the direction of the readout registers ($e \cos 2\theta$, where e is the ellipticity and θ is the angle between the major axis and the line joining opposite sides of the CCD) before and after CTI correction. Values are shown after correction for convolution with the PSF, whose shape is imprinted on the galaxies', but this correction increases the scatter. Solid lines connect subsamples of galaxies within magnitude limits of $F814W$ = 22–23, 23–24, 24–25, 25–26 and 26–27. Points show mean values in bins and 68% confidence limits.

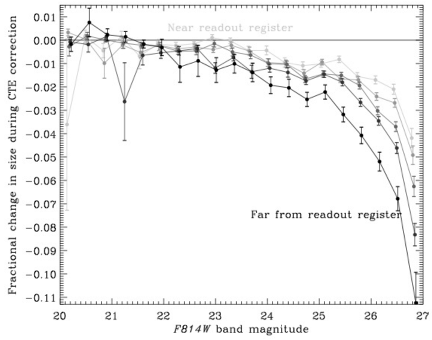
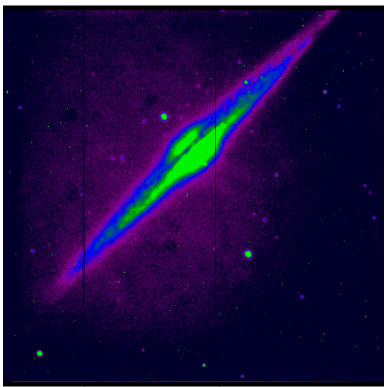


Figure 10. Change in galaxy FWHM size during CTI correction. Solid lines connect the same samples as in figure 8. Points show mean values within bins and 68% confidence limits.

Bad columns and pixels

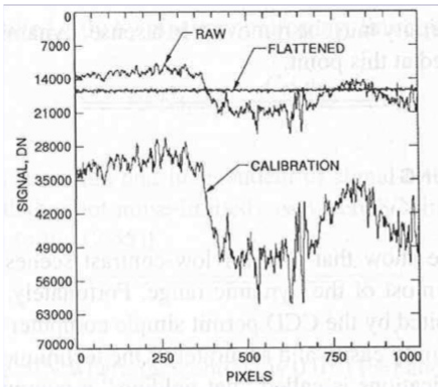


Bad columns

- Not all pixels in a CCD work properly!
- Problems can arise from short-circuits and a variety of manufacturing faults
- Bad pixels can be "dead", "hot", "flickering"
- **Solutions**:
  - replace bad pixel with average value of the pixel's neighbors
  - dithering telescope: take a series of images, move telescope slightly to ensure image falls on good pixels

Pixel-to-pixel Variations in QE

- Quantum efficiency is not uniform across a CCD
- Variations can be as large as 10%
- Important to remove these variations to ensure reliability of flux measurements
- **<u>Solution</u>**:
  - Illuminate CCD uniformly (light reflected off dome, or twilight sky): f_i
  - Calculate mean pixel value of the flat field observation: $\mu_f = \langle f_i \rangle$
  - Divide flat field by mean value to measure QE of each pixel: f_i/μ_f
  - Divide raw science observation (r_i) by this normalized flat field to obtain corrected observation, c_i:



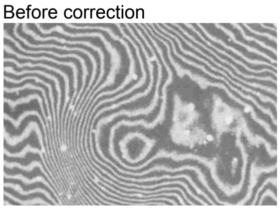
$$c_i = r_i \left(\frac{\langle f_i \rangle}{f_i} \right)$$

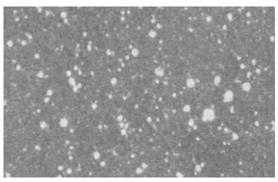
Fringing

- Light reflects off surfaces of detector material, creating overlapping coherent beams that can interfere
- Phase shift between input and reflected beams at wavelength λ is: $\phi = \frac{2nx}{\lambda}\pi$

  n=refractive index, x=thickness of substrate
- Consider a silicon substrate of thickness x=20um; at λ=0.9um n=3.7; at λ=0.4um n=4.7
- ϕ(0.9um)=164π; ϕ(0.5um)=470π
- Variations in substrate thickness of ~1% (~0.1um) can change interference from constructive to destructive
- This is an issue at λ>~0.7um due to uniform monochromatic illumination of CCD by the sky background (mainly airglow)

Before correction

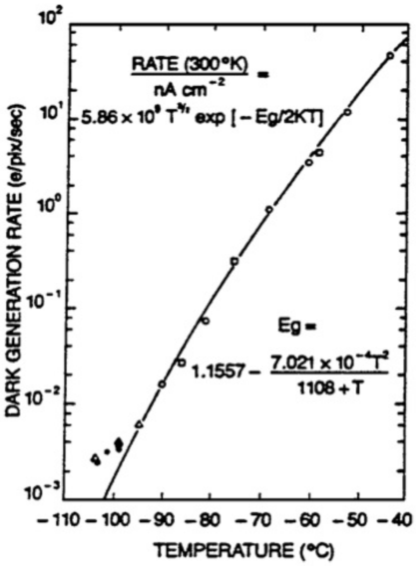




After correction

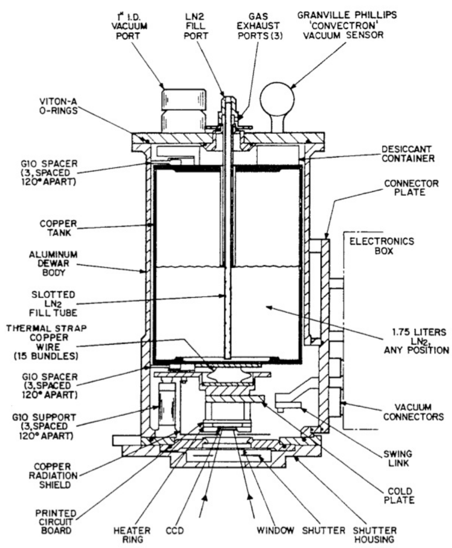
Dark Current

- Valence and donor electrons thermally excited into conduction band and thus depletion region
- "Dark current" indistinguishable from photo-excited electrons
- **Solution**:
  - – Cool the CCD with liquid Nitrogen
  - – Measure residual dark current
    - Expose CCD to zero light signal for time equal to that of science observations
    - Subtract the "dark frames" from the science frames



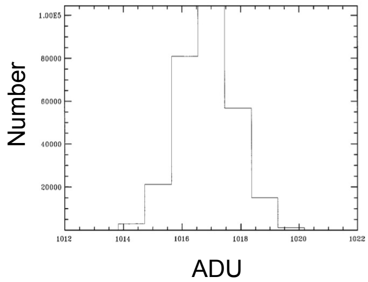
Cooling

- T~300K:
  - – Dark current ~10^4 electrons/pixel/sec
  - – Typical exposure time ~100–1000 sec
  - – Implies large dark current and Poisson noise on dark subtraction
- T<~170K:
  - – Dark current <~1 electron/pix/sec
- Temperature stability is crucial
- CCDs typically kept at constant temperature (+/-0.1K)
- Re-filling dewar with liquid N_2 is a daily task at an observatory



Bias and Read Noise

- Noise in the readout electronics causes dispersion in measured digitized signal
- To avoid negative signal in the digitized signal, the readout electronics therefore add a positive bias
- Bias and read noise is measured (for example) by taking some exposures of length zero seconds
- The distribution of bias levels measured from many such exposures is then analyzed



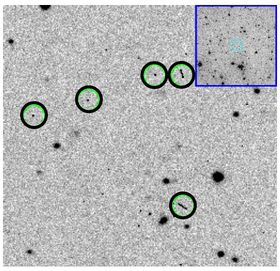
Bias~1017ADU(~3000electrons)

Read noise~3ADU(~9electrons)

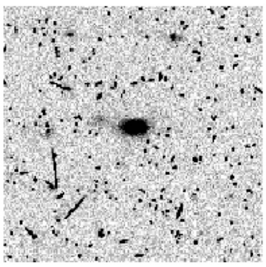
[assuming Gain~3e/ADU]

Cosmic Rays (CRs)

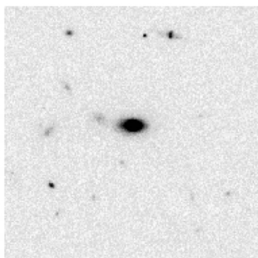
Ground-based data



HST data - before



HST data - after



- Ground-based CCDs are efficient at detecting the secondary particles of cosmic rays
  - Typically muons are absorbed by the Si lattice
  - Energy released from e/hole pair production ~80ē/pixel/μm
  - Typical 20μm depth, a CR generates ~1000electrons
  - Appears as a ‘spike’ well above the background – distinctive shape
- Problem more acute in space – see HST example
- Solution:
  - Split total integration time into several exposures

Summary of CCDs

- Advantages:
  - Negligible intrinsic noise
  - Very high quantum efficiency (>90%)
  - Large spectral window (optical/near-IR)
  - Large variations in the signal strength (dynamic range~10^5)
  - High photometric precision (sub-% precision achievable)
  - Very good linearity
- Disadvantage:
  - Limited number of detector elements (pixels), but this is changing fast

CCD Example

- Light from a source of flux 1 photon/ second is incident on the center of a CCD
- The CCD comprises 2048x2048 pixels, has QE=80%, CTE=99.9% and Gain=3
- How many electrons are stored in the CCD pixels after a 2-hour exposure?
- How many ADU are recorded from this source at readout?