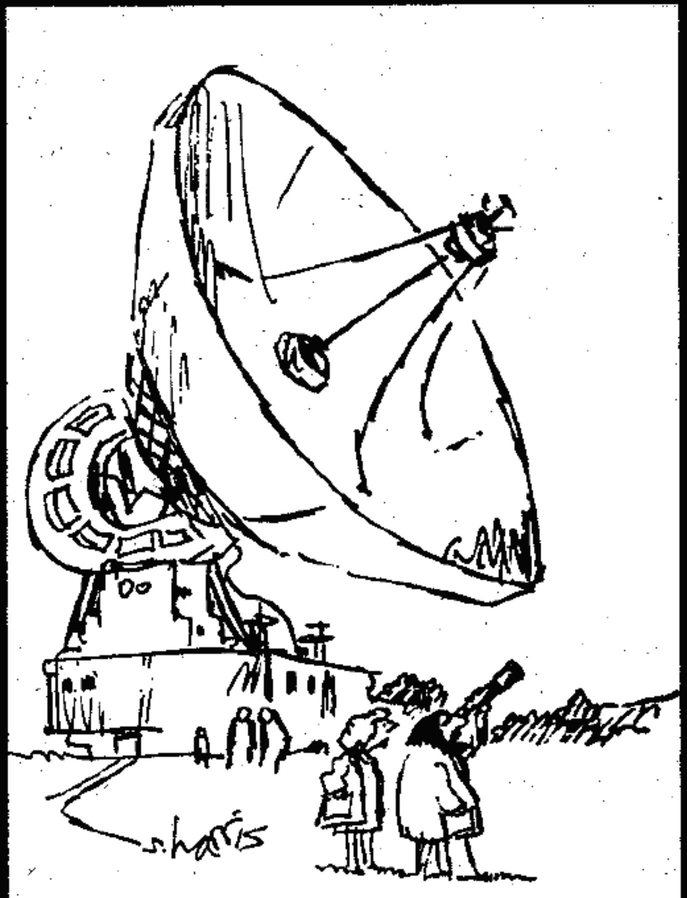
Optical/IR Observational Astronomy

Detectors II

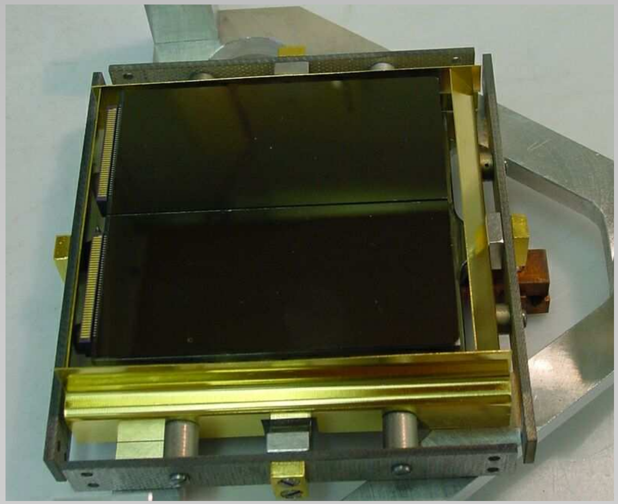


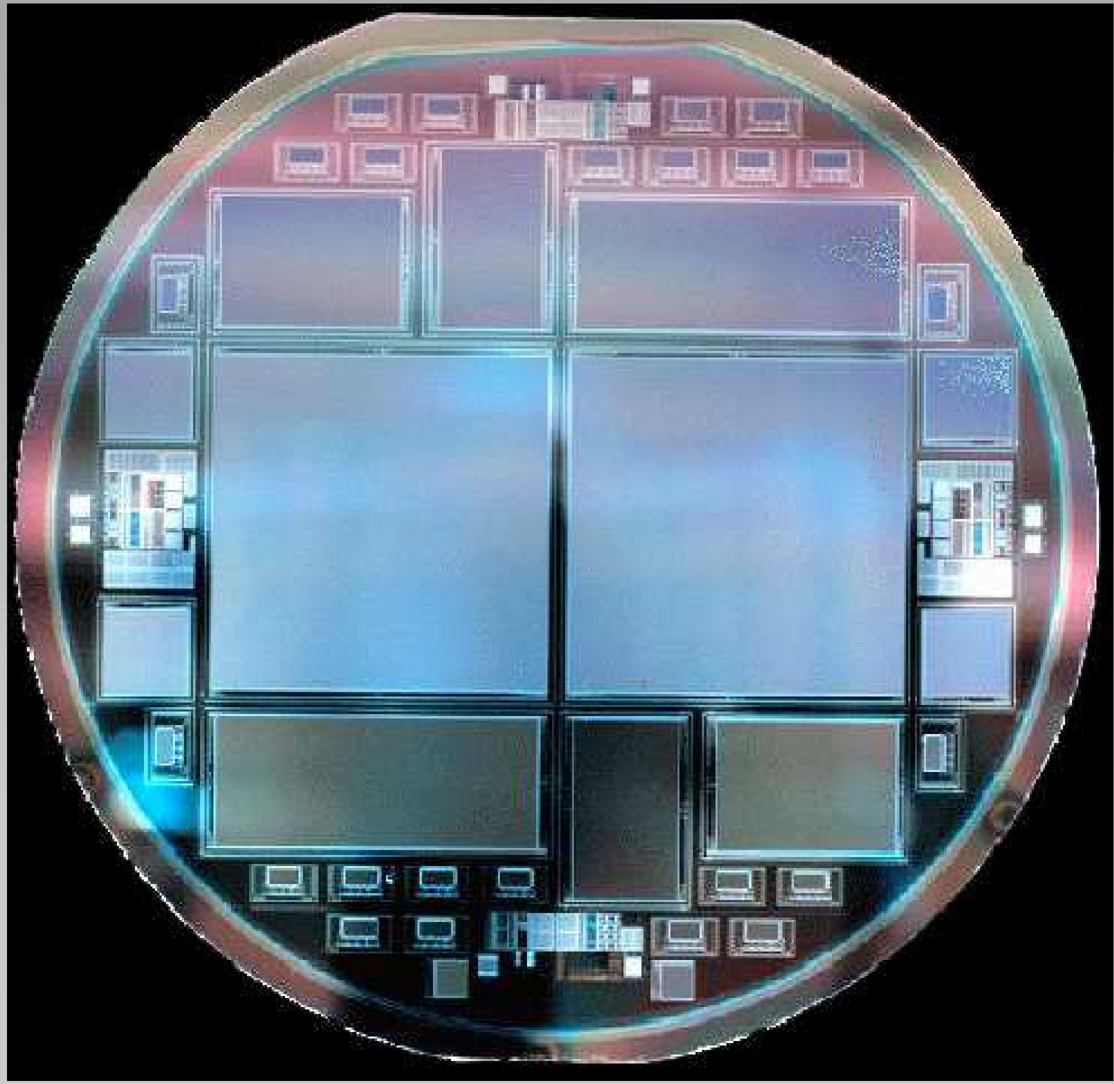
"Just checking."

David Buckley, SAAO

Detectors II

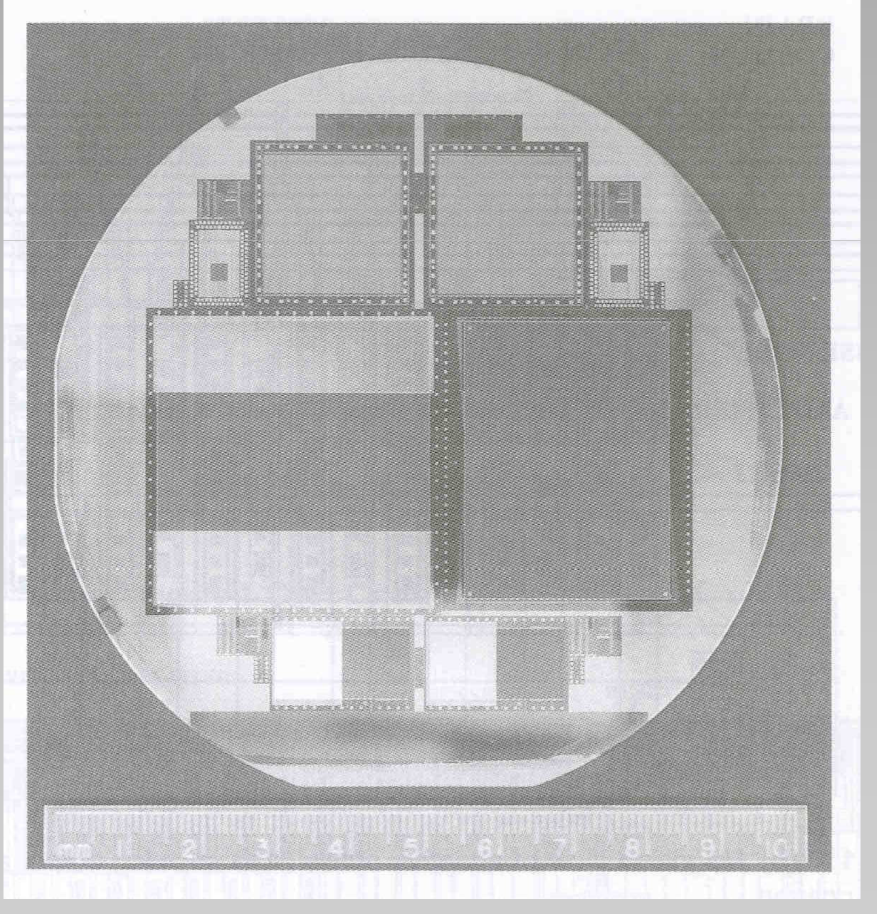
The Next Revolution: Charge Couple Device Detectors (CCDs)

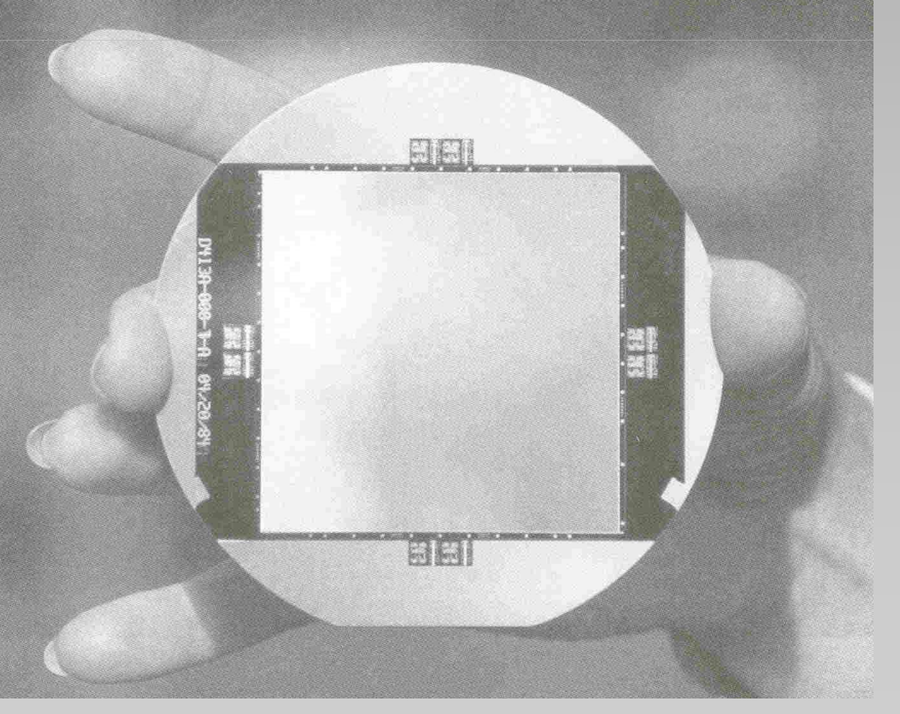




CCDs

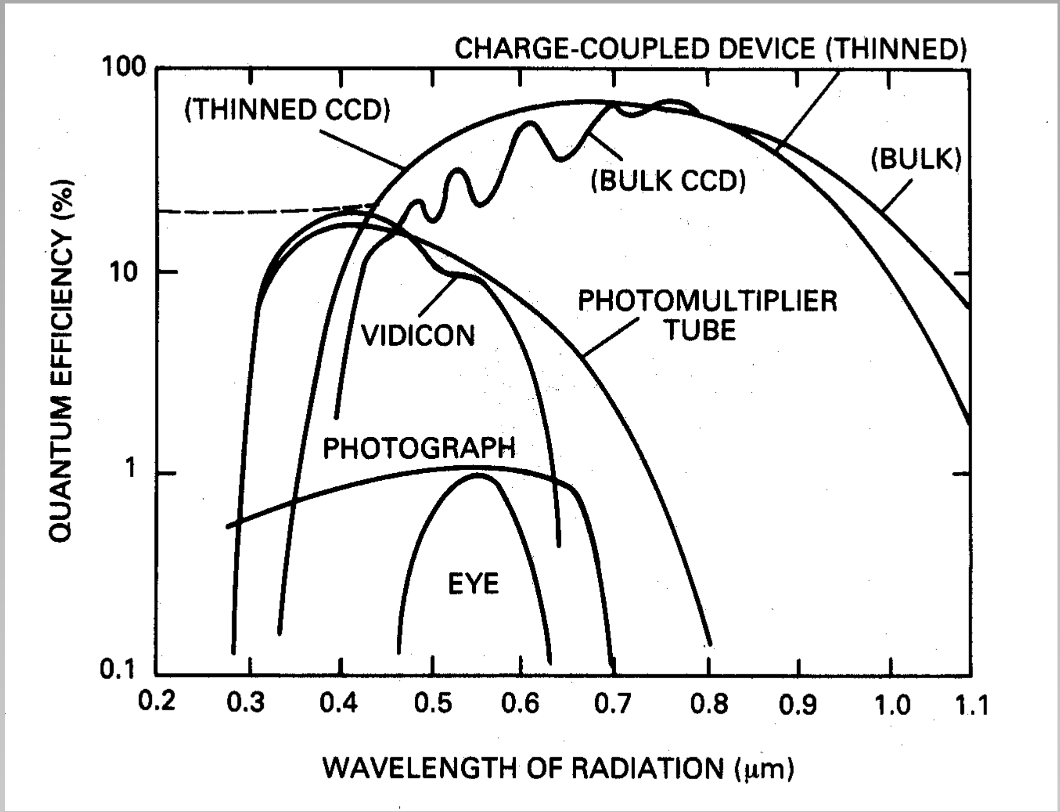
- **Integrated semi-conductor detector**
  - **From photon detection (pair production) to final digitization of signal**
- **Manufactured from a Si wafer, as in ICs**





Major advantages of CCDs

- **Some of the many advantages of CCDs over conventional electronic and photographic imaging mentioned include:**
  1. Compact, rugged, stable, durable, low-power (using 10's instead of 1000's of volts)
  2. Excellent stability and linearity
  3. No image distortion (direct image onto a Si array fixed in fabrication process
  4. Relative ease of operation, and reasonable cost due to mass production
  5. Unprecedented sensitivity (i.e. quantum efficiency) over wide λ range



History of the invention of CCDs

- **The CCD was invented by Willard S. Boyle and George E. Smith of Bell Labs (where the transistor was invented) in 1969**

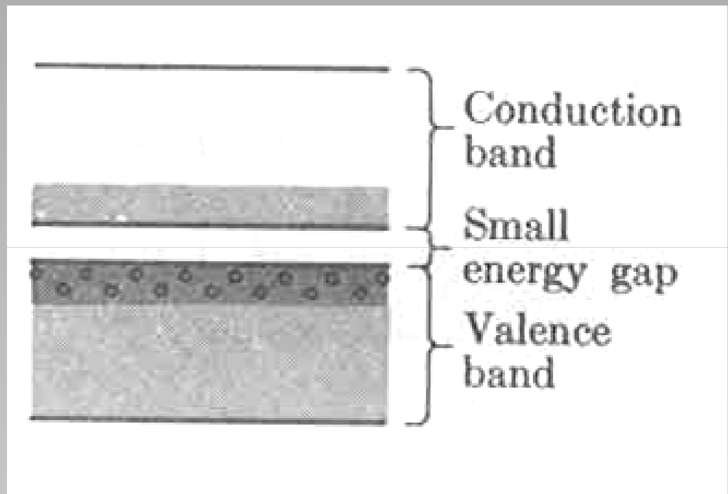
They were jointly awarded the Nobel Prize for Physics in 2009

History of the invention of CCDs

- **It was already known that charge could be stored by insulating a small metal plate placed on the surface of a Si crystal.**
  - **Stringing these 'storage sites' together and using voltage differences between them to pass the charge along constituted the innovative idea**
  - **It took just few weeks to produce a proto-type 8-element device, and the first paper on a 'CCD' (for *<u>charge-coupled device</u>*, a name coined by Boyle) was published in April 1970 (*Bell System Technical Journal*, Vol. 49, 1970)**
  - **Wording from that paper reads:**
    - » *"A new semiconductor device concept has been devised which shows promise of having wide application" Boyle & Smith*
  - **Within a few months many types of applications were listed – some actually of relevance to a phone company!**

Semiconductors

- **Semiconductors**
  - If valence levels and higher *don't* overlap, but have small E-separation, thermal excitation can be sufficient to raise some electrons energy from valence band to higher conduction bands. These are referred to as *semi-conductors.*



- **Band-gap (E_G) between valence and conduction bands:**
  - In a metal, $E_G = 0$, hence excellent conduction
  - Insulator has large E_G, resulting in no appreciable conduction
  - Semi-conductors have $0 < E_G < 3.5$ eV, resulting in significant numbers of either thermally or radiatively excited electrons available for conduction. Thus semi-conductors are intermediate in conductivity between conductors and insulators.

Energy level diagrams

- **Insulators and semiconductors**

Insulators	**Band gap (eV)**	**Semiconductors**	**Band gap (eV)**
Carbon (diamond)	5.33	Silicon	1.16
Zinc oxide	3.2	Germanium	0.67
Silver chloride	3.2	Tellurium	0.33
Cadmium suphide	2.42	Indium Antimonide (InSb)	0.23

Thermal excitation might allow electrons to jump the band-gap (only ~0.5 eV)

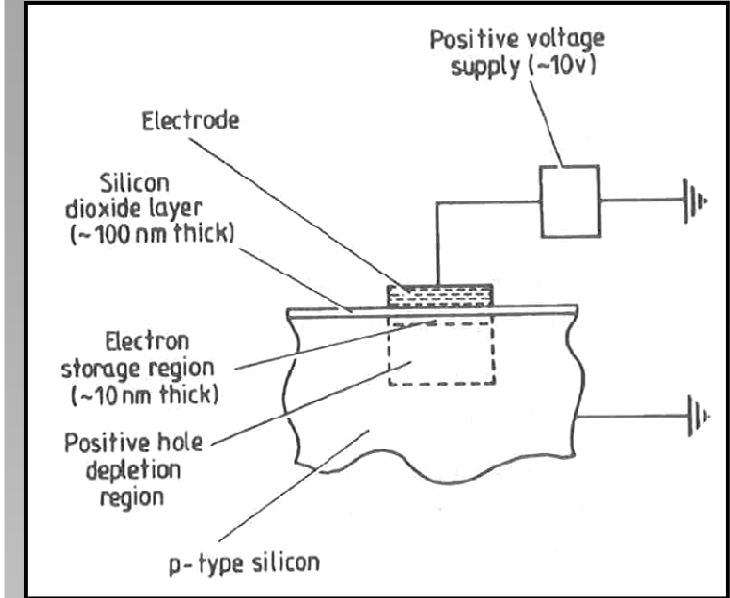
***Also*, photoabsorption of photons of $E > E_G$ can (e.g. in Si).**

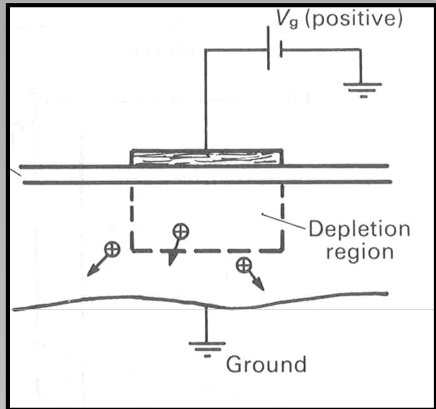
p/n junctions and diodes

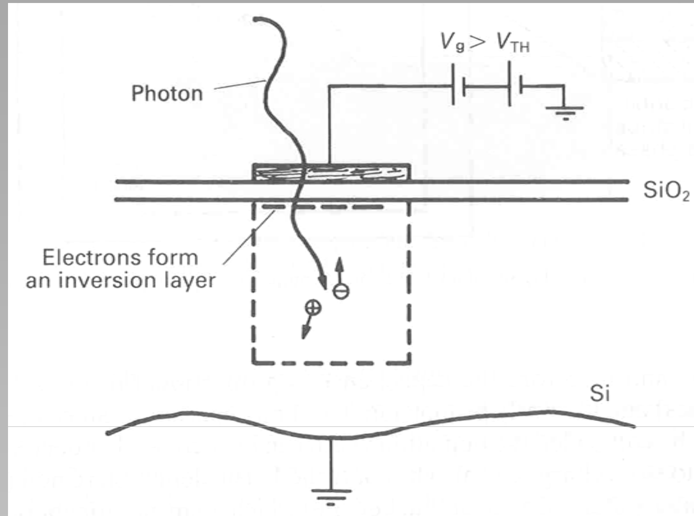
Energy Gaps and Cutoff Wavelengths for semiconductors

Name	Temp (K)	E_G (eV)	λ_C (μm)
CdS	295	2.4	0.5
CdSe	295	1.8	0.7
GaAs	295	1.35	0.92
Si	295	1.12	1.11
Ge	295	0.67	1.85
PbS	295	0.42	2.95
InSb	77	0.23	5.4
HgCdTe	77	0.10	12.4

Basic definition of a CCD

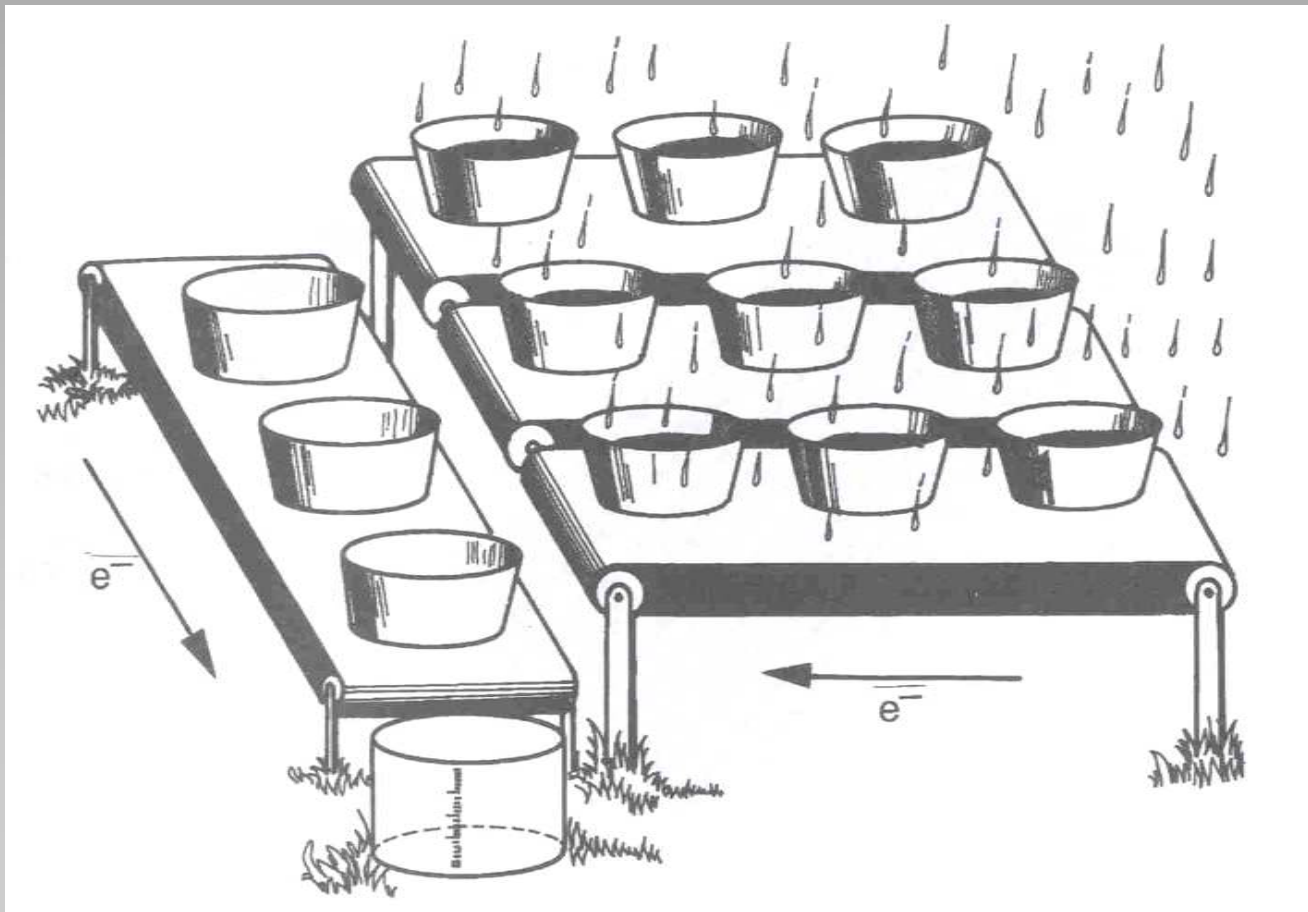




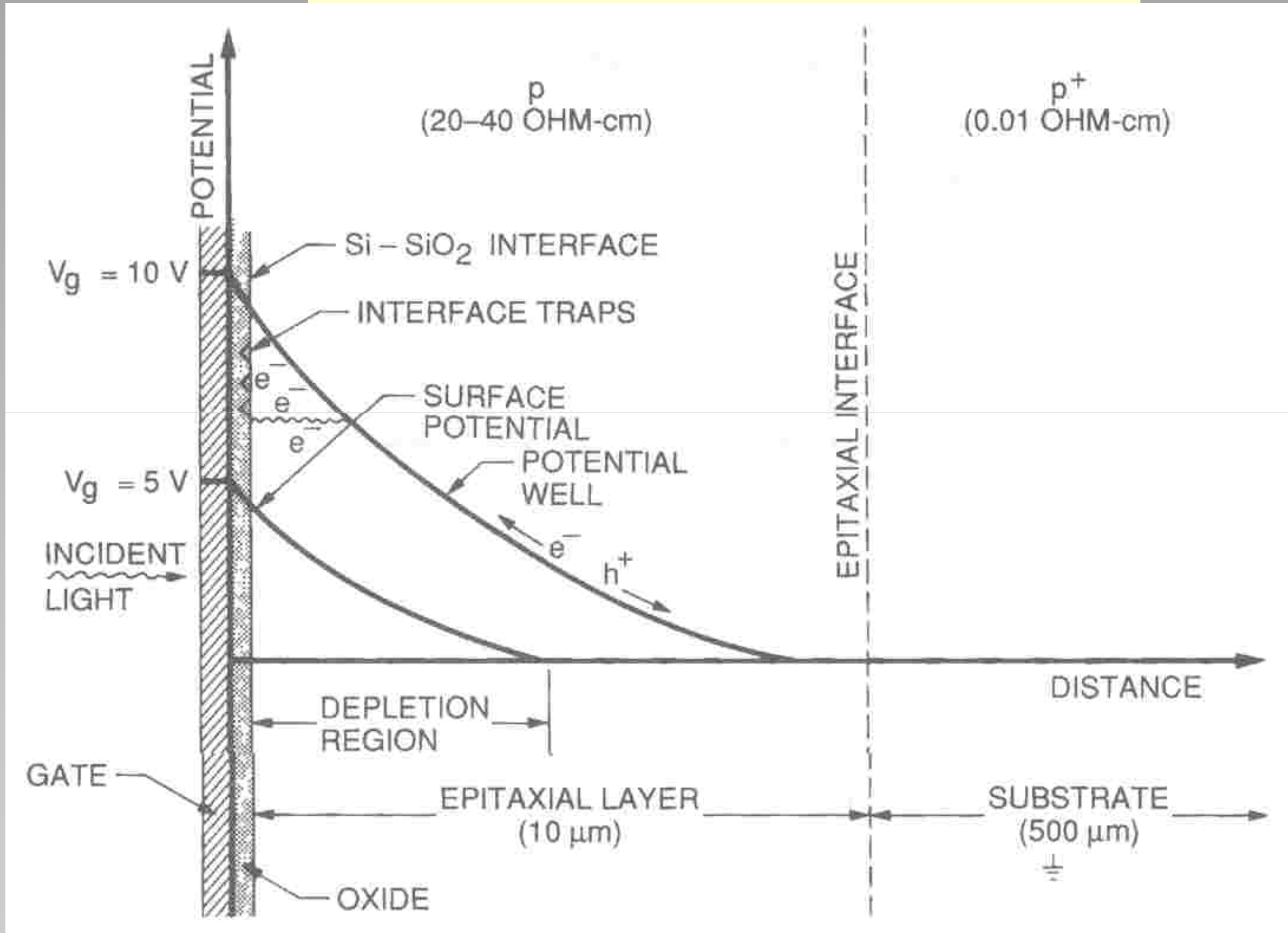


- **CCD is a *metal oxide structure* (MOS), consisting of a transparent metal electrode separated by a ~0.1µm of SiO_2 insulator from a layer of p-type Si. Thus it is a simple capacitor, capable of storing electrical charge.**
- **CCD behaves as a two dimensional array of Si p/n junctions. The whole array is essentially a giant p/n junction, but individual 'picture elements', or *pixels*, are created using insulating 'channel stops' and electrodes.**
- **Individual 'rows' of pixels are isolated by channel stops (stopping charges being able to diffuse vertically)**
- **Individual 'columns' of pixels are created by voltages applied to control electrodes.**
- **Charges are accumulated in pixels during exposure to light and remain there due to applied voltages.**

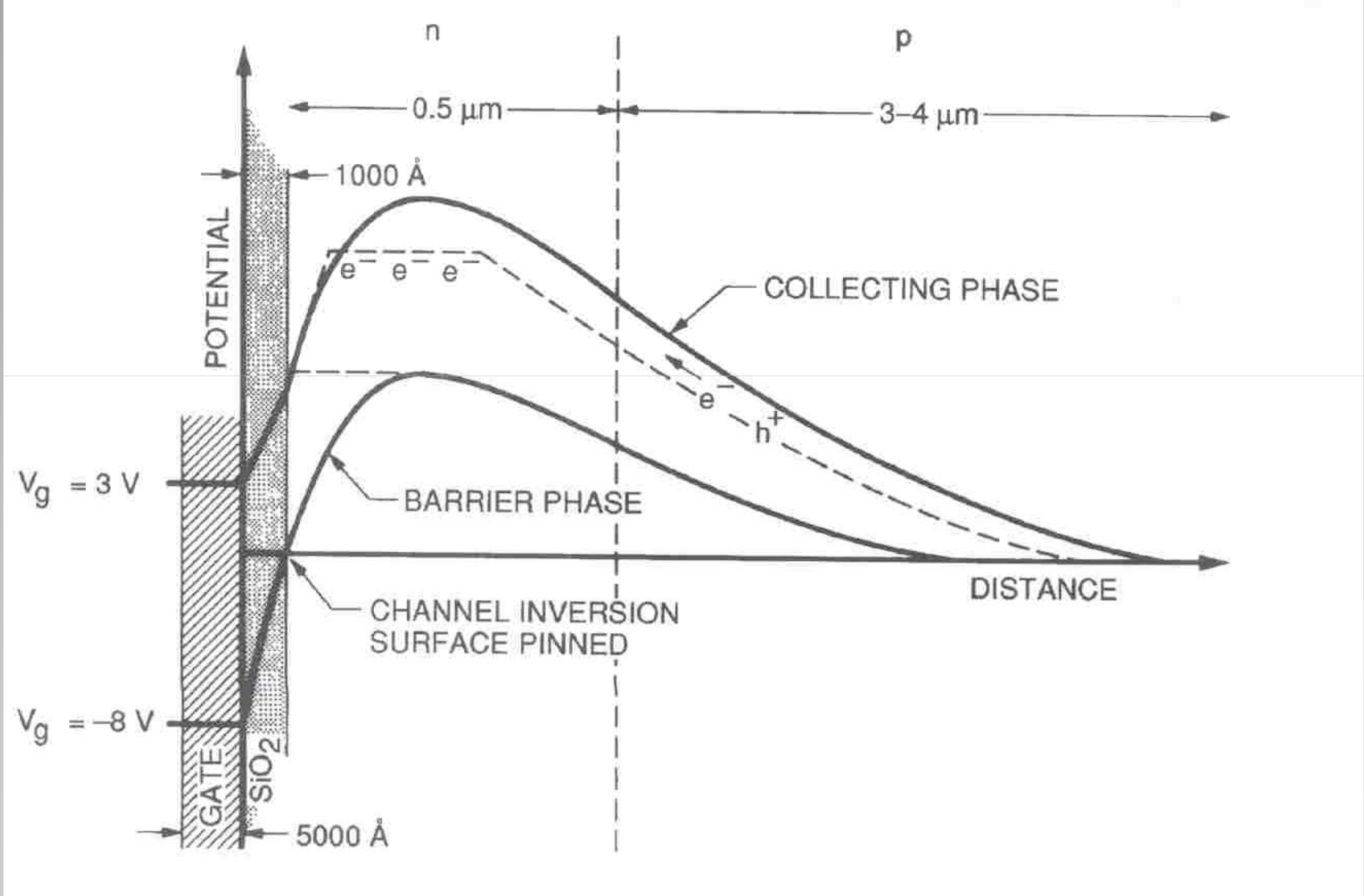
"Bucket brigade" analogy for a CCD



Surface Channel CCDs

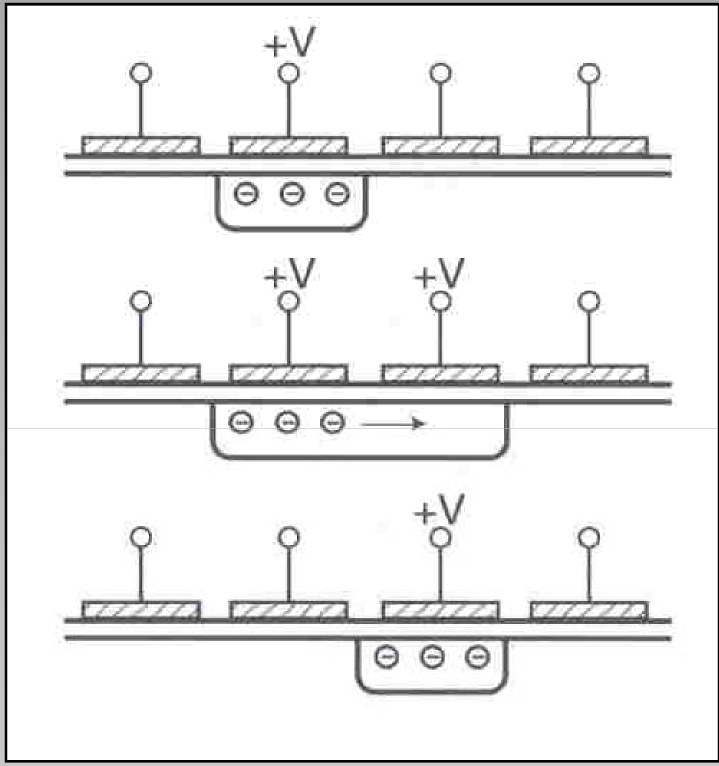


Buried Channel CCDs



Principle of a CCD

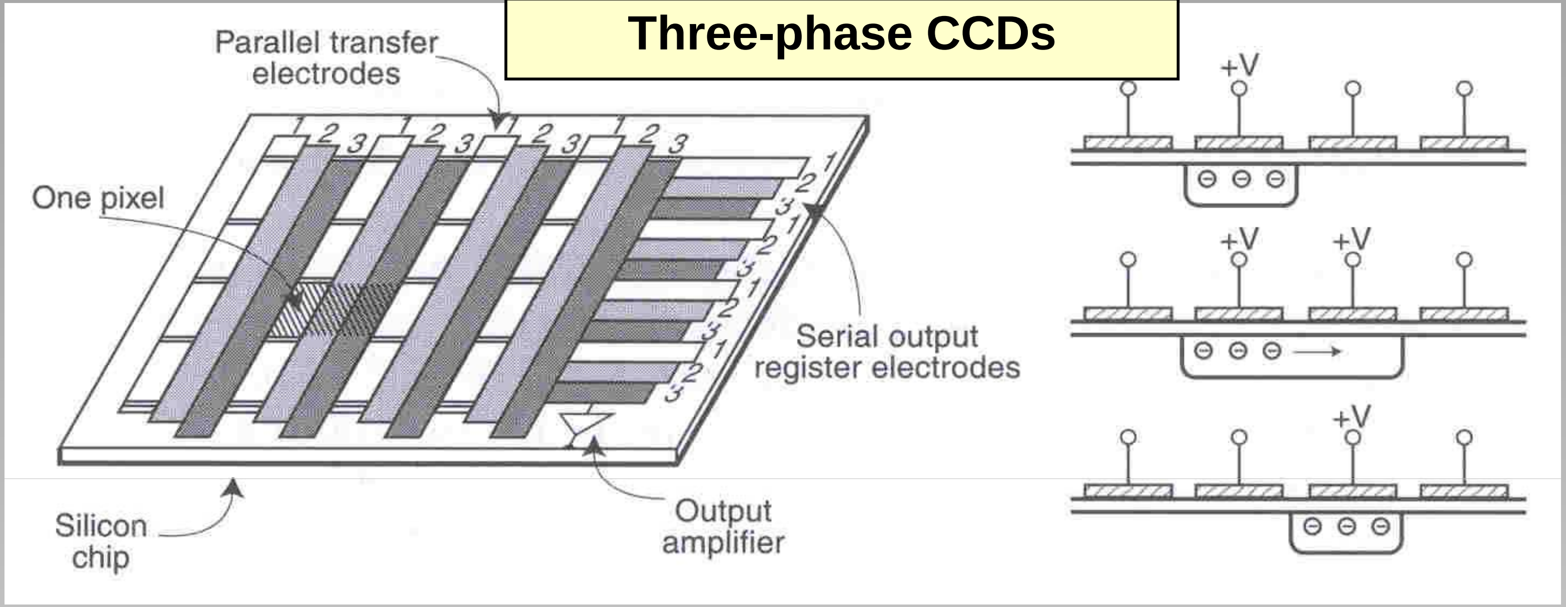
- **Positive voltage applied to the electrodes *sweep* the majority charge carriers i.e. holes, forming a *depletion region* under the electrode.**
- **Effectively a CCD is a radiation-driven capacitor.**
- **Photoabsorption creates ē-hole pairs, with the ē's attracted into the depletion region, because of the +ve charge. Size of voltage control depth of depletion zone and the total capacity to store charge.**
- **Depletion region is an electrostatic 'potential well' or 'bucket', in which photo-generated charge can accumulate.**
- **Amount of accumulated charge is directly proportional to the intensity of the light.**
- **At completion of exposure, charge is 'shuffled around' the 2-D detector by changing the control voltages on the electrodes.**
- **Thus 'reading out' consists of first 'clocking' the voltages horizontally until they reach a vertical register of 1-D pixels. These are readout vertically, one at a time.**



CCD stands for "Charge Coupled Device". Why ?

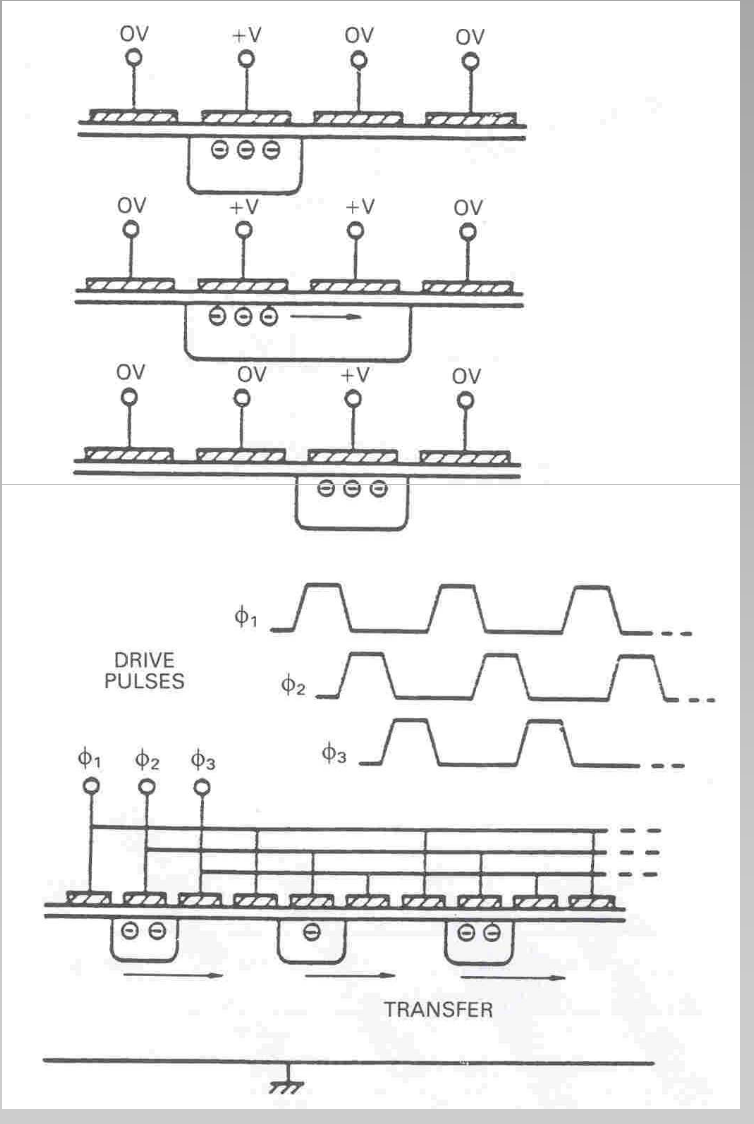
- **charges are coupled to electrodes**
- **'clocking' electrode voltages allows charge to be moved, but integrity of charge packets is kept.**

Three-phase CCDs

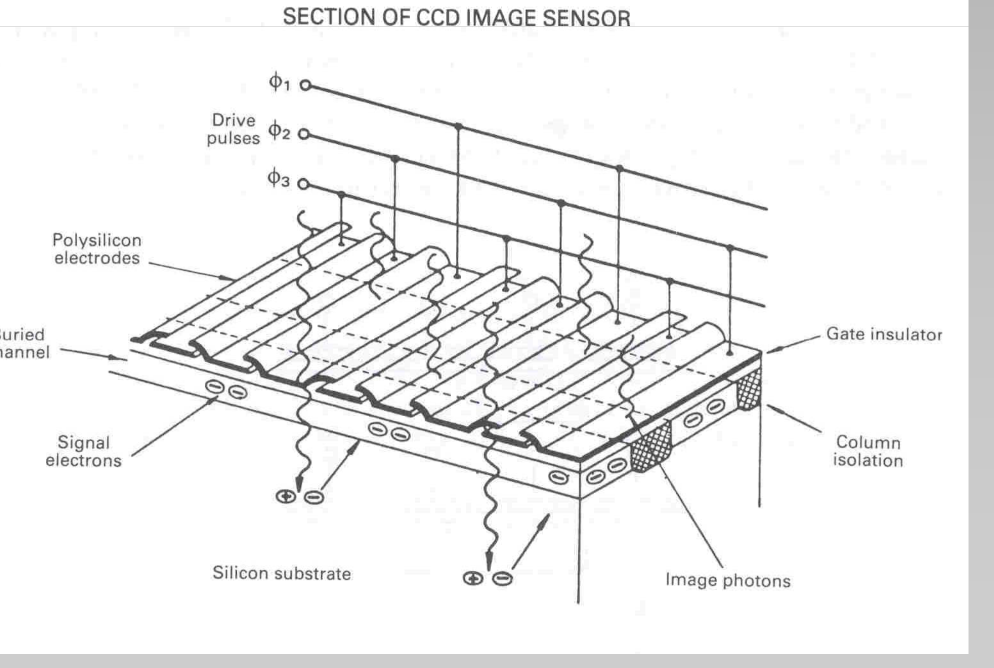


- Apart from the initial efficient conversion of photon → ē, and 'trapping' at a specific place in the Si array, the CCD needs to '***read out***' the resulting charge.
- One of the basic initial CCD designs was the so-called '***three phase***' CCD consisting of 3 separate electrodes per pixel.
  - Changing the voltages in a repeatable pattern (i.e. 'clocking'), causes charge to shuffle along rows of the CCD until they reach a serial output register.
  - One of the electrodes is set to a more +ve voltage which causes the depletion region to form under it.
  - Heavy doping of the Si crystal structure creates a narrow channel stop, preventing charge from migrating along the length of the electrode.

Three-phase clocking

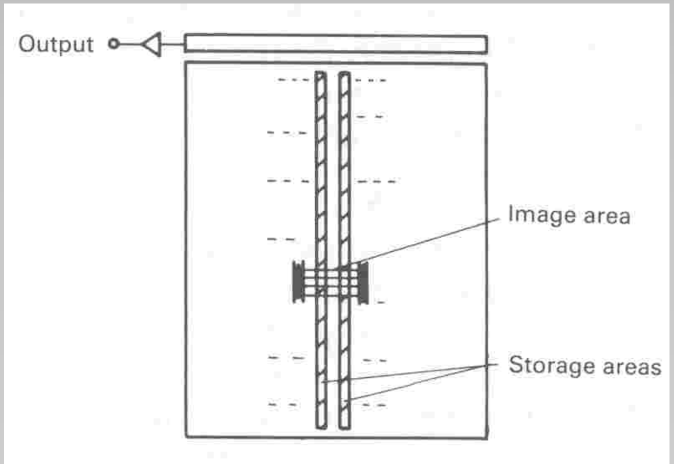


- **Control electronics provide for fast clocking of voltages, up to a frequency of a *few hundred MHz.***
- **Waveform frequency and shape determines how fast and efficient the charge is transferred (latter is called *Charge Transfer Efficiency*, or CTE).**
- **The clock, or drive, pulses for the electrodes are described by the timing waveform.**

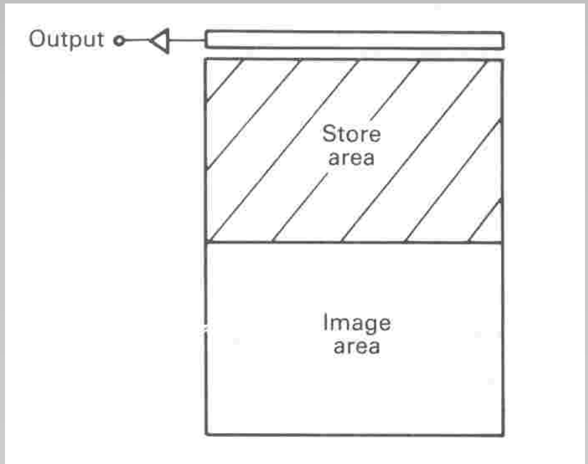


Interline and Frame Transfer CCDs

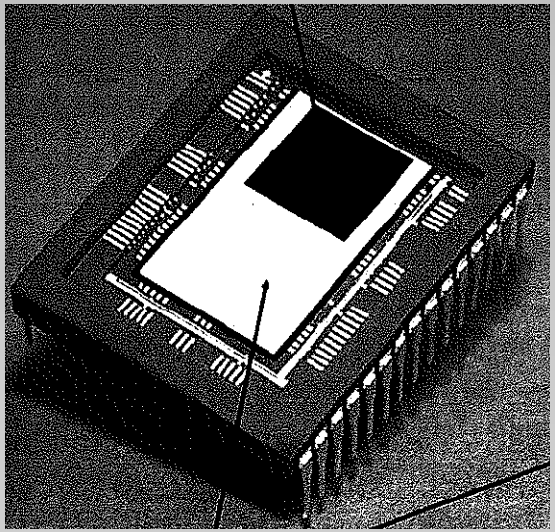
- **Clocking takes finite time to transfer the pixels (in parallel) to the serial readout register(s), which also has to transfer it's charge packets to the readout amplifier(s).**
- **For fast rates applicable to video camera (e.g. >25 frames per second), then the simple three-phase readout is too slow. Two different architectures were developed for this use, where speed rather than efficiency is important**
  - **Interline transfer CCDs**
    - » **These consist of adjacent opaquely shielded columns (i.e. blocked from light). Only ~50% of area is sensitive to light, but this is OK for all but the lowest light levels (i.e. astronomy!). Can operate at TV rates (e.g. 5 MHz).**
    - » **Charge is only moved by one pixel, then the shielded columns are readout while new charge accumulates on the exposed pixels**
  - **Frame transfer CCDs:** **imaging and store areas (latter blocked from light)**



(b) Interline transfer



(a) Frame transfer

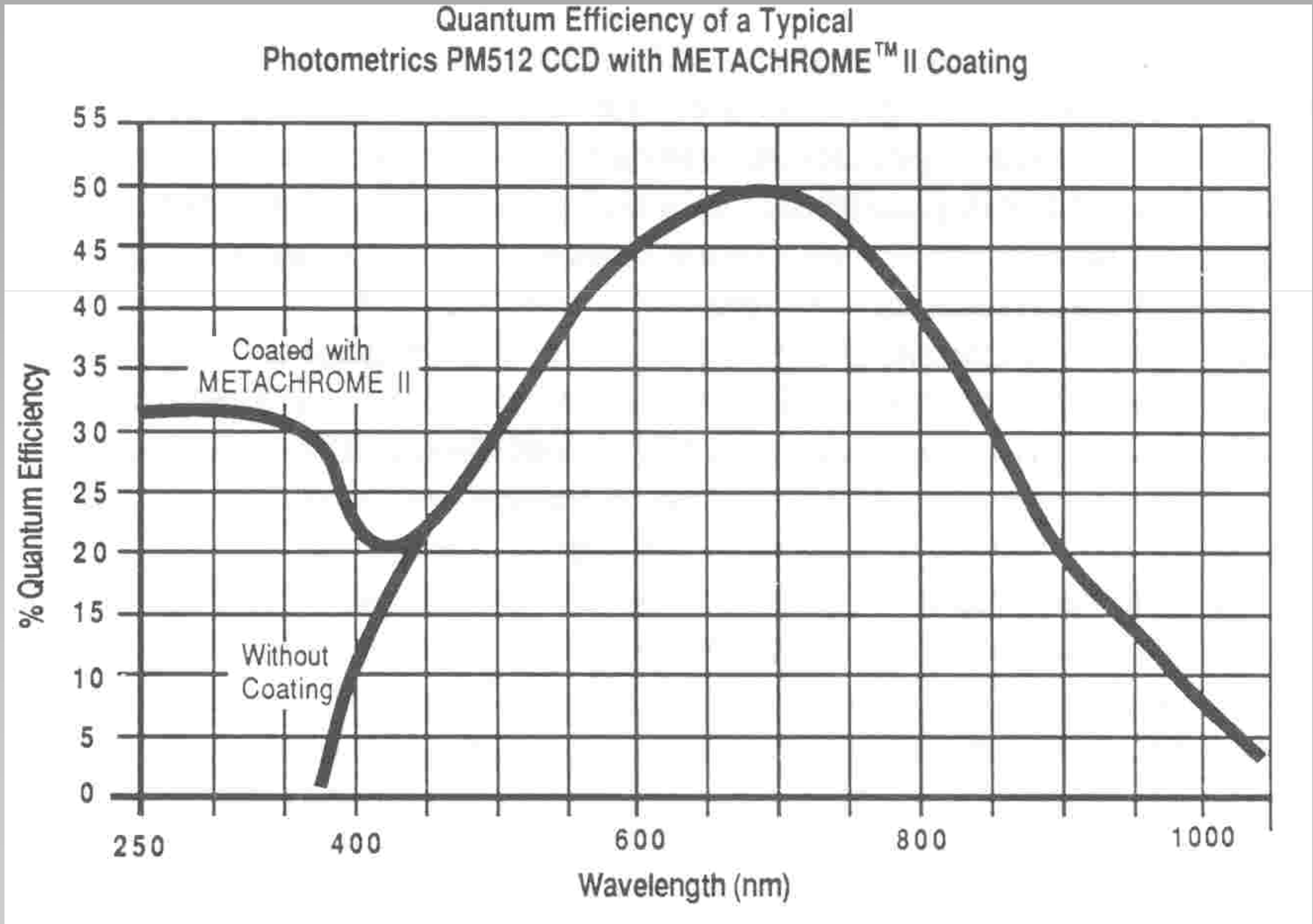


Backside Illumination of CCDs

- **Frontside illumination, through a semi-transparent electrode structure, was first devised for CCDs**
  - Ensures that the electron-hole pairs are created close to the depletion region, where the charges can be separated before recombination
  - Problems with overall sensitivity, particularly with the shorter wavelength, which are easily absorbed in the electrode and metal oxide layer without producing a detectable photoelectron
  - By illuminating the CCD from the back, the blue response can be improved. The problem is that the photo absorption in a normal 'thick' device causes electron-hole pair to form and recombine to quickly – before they are influenced by the electrical potential of the device
  - Overcome the above by "thinning" a process of mechanically or chemically removing the Si so that it is only ~10μm thick – thin enough for photoelectrons from blue photons to be accumulated in the depletion zone.
  - Now the problem becomes a lack of response in the far red, because these photons can now pass right through the device!

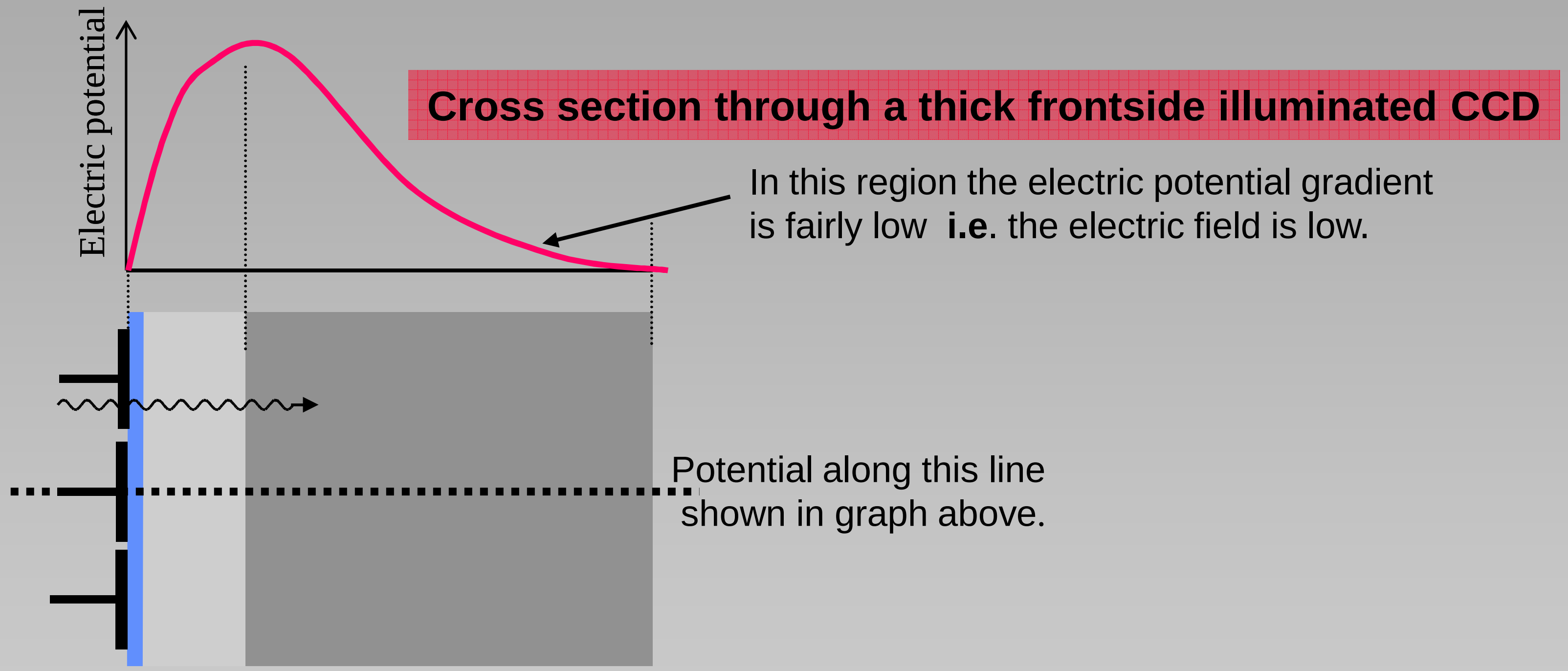
Other ways to increase CCD blue response

- **Apply a chemical coating to the front which converts blue photons into red photons, which can penetrate to the depletion region.**



Front-illuminated CCDs

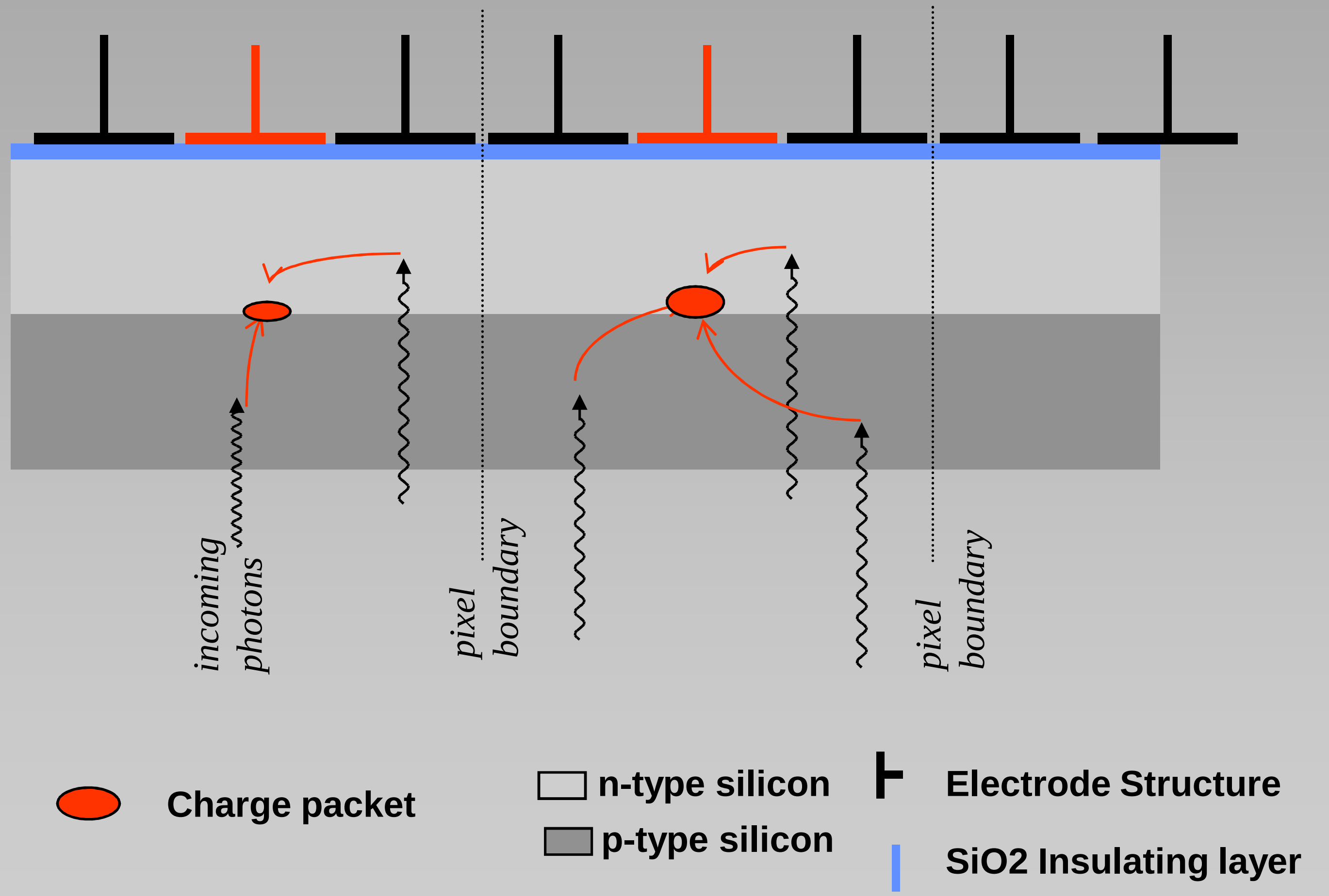
The electric field structure in a CCD defines to a large degree its Quantum Efficiency (QE). Consider first a thick frontside illuminated CCD, which has a poor QE.



Any photo-electrons created in the region of low electric field stand a much higher chance of recombination and loss. There is only a weak external field to sweep apart the photo-electron and the hole it leaves behind.

Charge Collection in a CCD

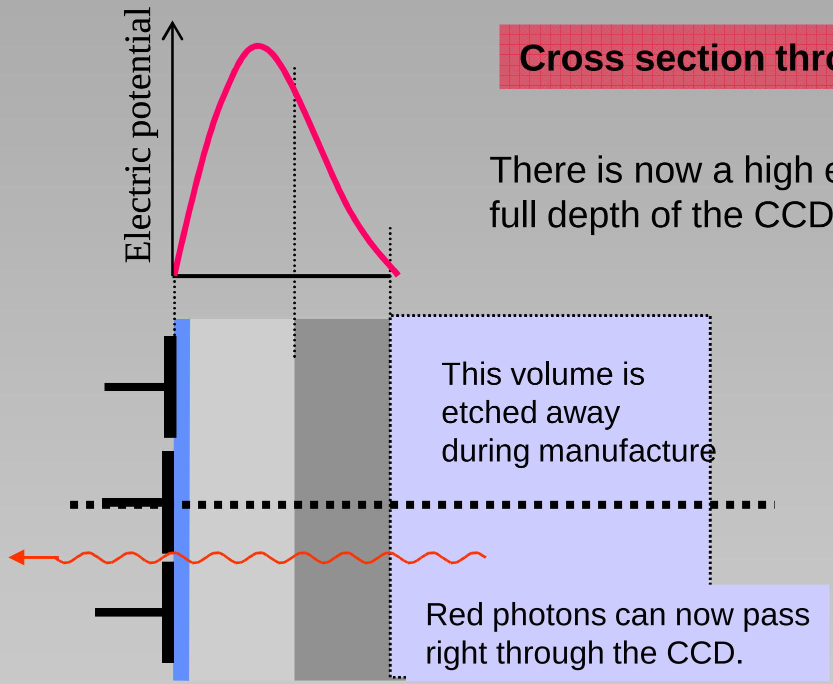
Photons entering the CCD create electron-hole pairs. The electrons are then attracted towards the most positive potential in the device where they create 'charge packets'. Each packet corresponds to one pixel



Back-illuminated CCDs

In a thinned CCD , the field free region is simply etched away.

Cross section through a thinned CCD



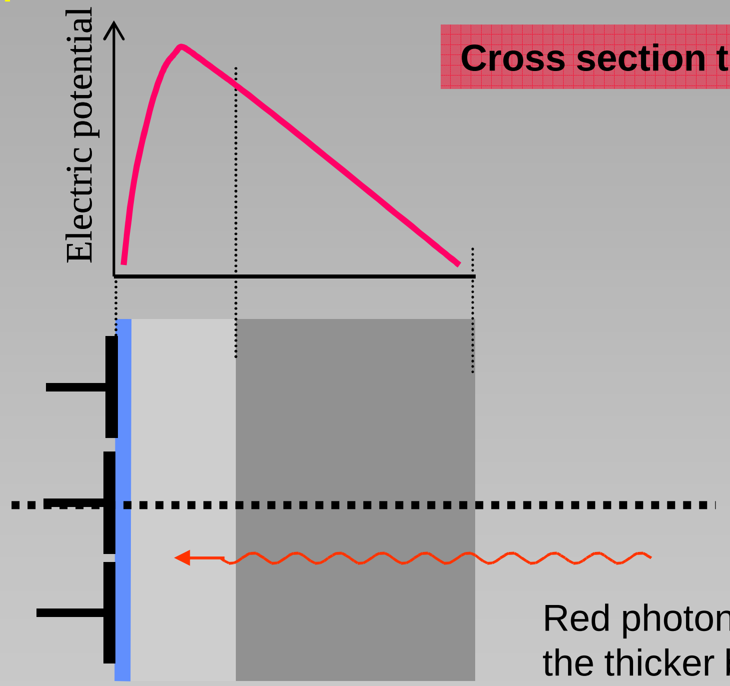
There is now a high electric field throughout the full depth of the CCD.

Problem : Thinned CCDs may have good blue response but they become transparent at longer wavelengths; the red response suffers.

Photo-electrons created anywhere throughout the depth of the device will now be detected. Thinning is normally essential with backside illuminated CCDs if good blue response is required. Most blue photo-electrons are created within a few nanometers of the surface and if this region is field free, there will be no blue response.

Deep Depletion CCDs

Ideally we require all the benefits of a thinned CCD plus an improved red response. The solution is to use a CCD with an intermediate thickness of about 40μm constructed from Hi-Resistivity silicon. The increased thickness makes the device opaque to red photons. The use of Hi-Resistivity silicon means that there are no field free regions despite the greater thickness.



Red photons are now absorbed in the thicker bulk of the device.

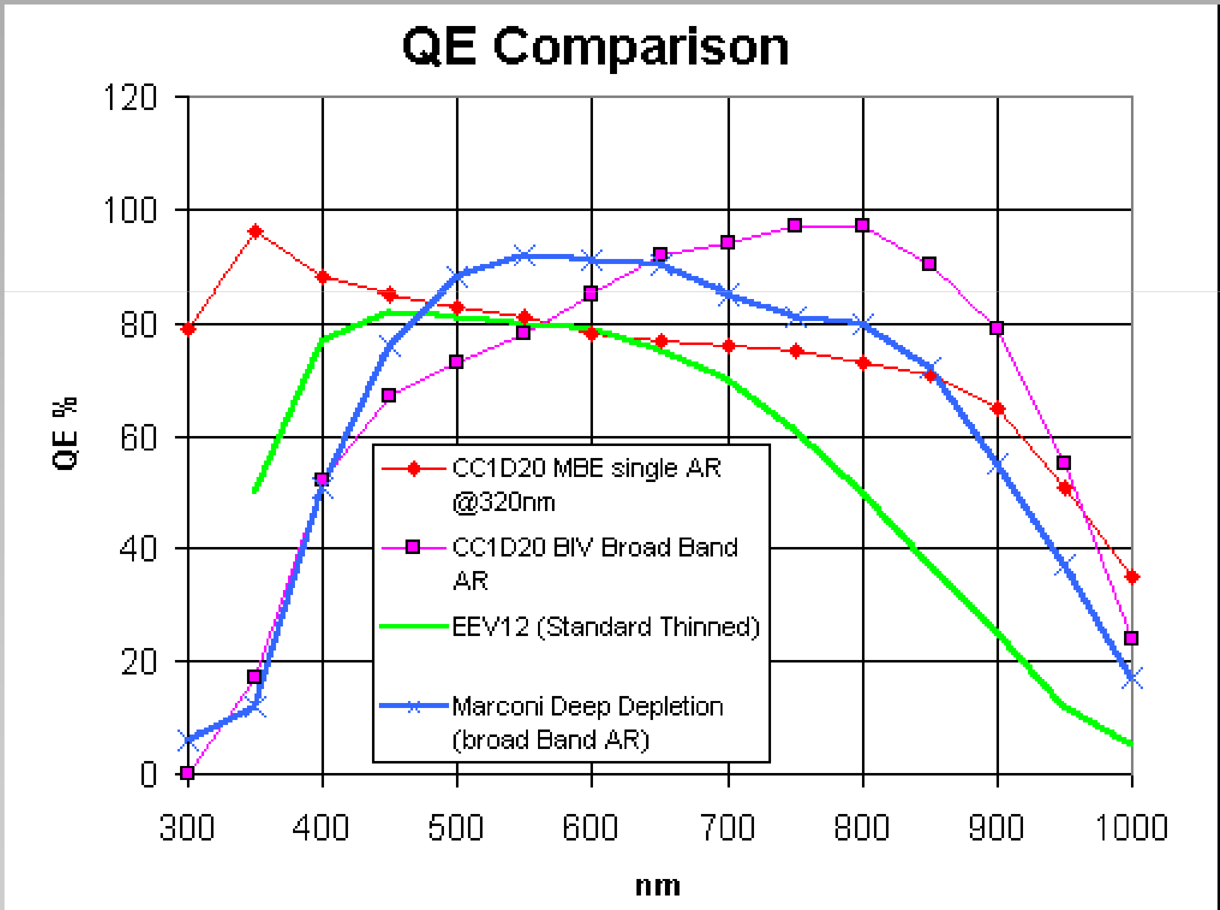
Problem :

Hi resistivity silicon contains much lower impurity levels than normal. Very few wafer fabrication factories commonly use this material and deep depletion CCDs have to be designed and made to order.

There is now a high electric field throughout the full depth of the CCD. CCDs manufactured in this way are known as *Deep Depletion* CCDs. The name implies that the region of high electric field, also known as the 'depletion zone' extends deeply into the device.

CCD sensitivites

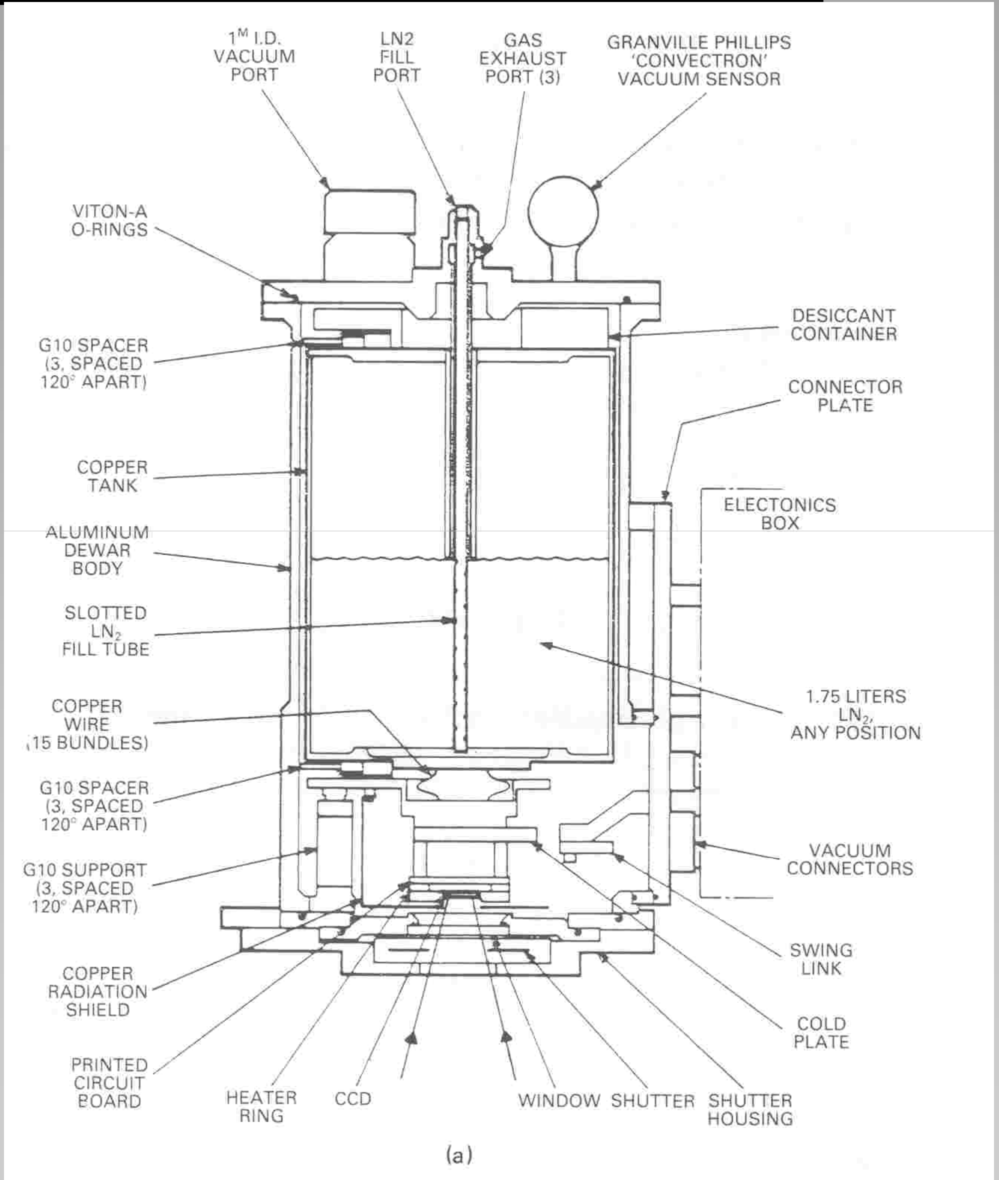
- **Quantum Efficiencies (QEs) are one of the most important parameters of a CCD. What are the properties of modern CCDs (e.g. buried channel, back-illuminated, thinned, doped, deep-depletion, etc)**



Detectors II

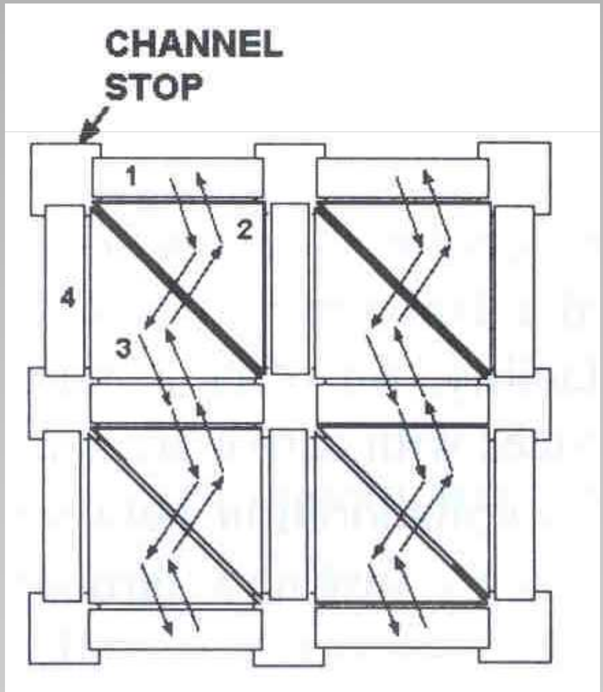
'CCD Cameras

- **CCD design has evolved considerably**
  - **Better noise characteristics**
    - » **R.N. of 2e now instead of 80e in 80s**
- **CCD "controller" is just as important as the CCD detector in terms of overall performance (e.g. noise) and versatility.**
- **This is what controls the "clock" voltages, i.e. readouts**
- **CCDs need cooling (reduce 'dark current'), i.e. thermal effects**
  - **At 20ºC, a CCD can generate 100,000 ē/sec/pixel thermally**
  - **Reducing T to –90 to –140ºC (i.e. 135 to 180K) reduces dark current to 10's of ē/*pixels per hour***
- **CCDs used in "camera" consisting of dewar, cryostat, pre-amp, signal proc. electronics, filters, etc.**

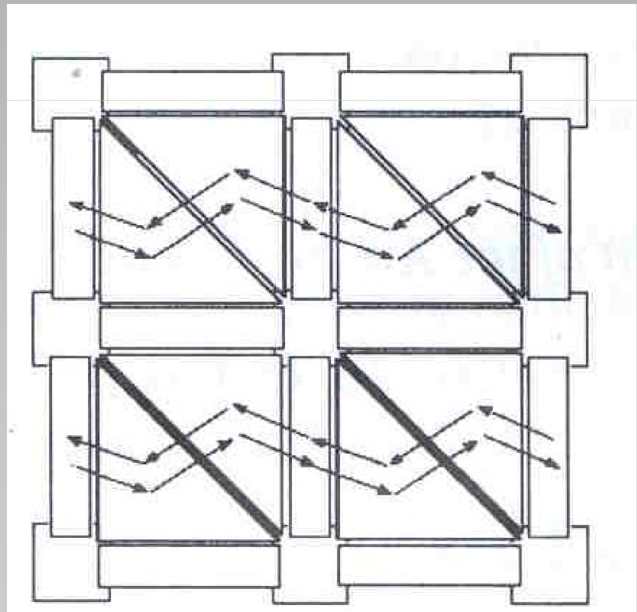


New developments in CCDs

- **Orthogonal transfer CCD (OTC)**
  - **4-phase CCD, but allowing charge shuffling both vertically and horizontally *during* exposure**
  - **Half of CCD readout semi-continuously (storage half of frame-transfer type)**
  - **Motion of a bright star in this half is used to 'clock' the voltages on the OTC side**



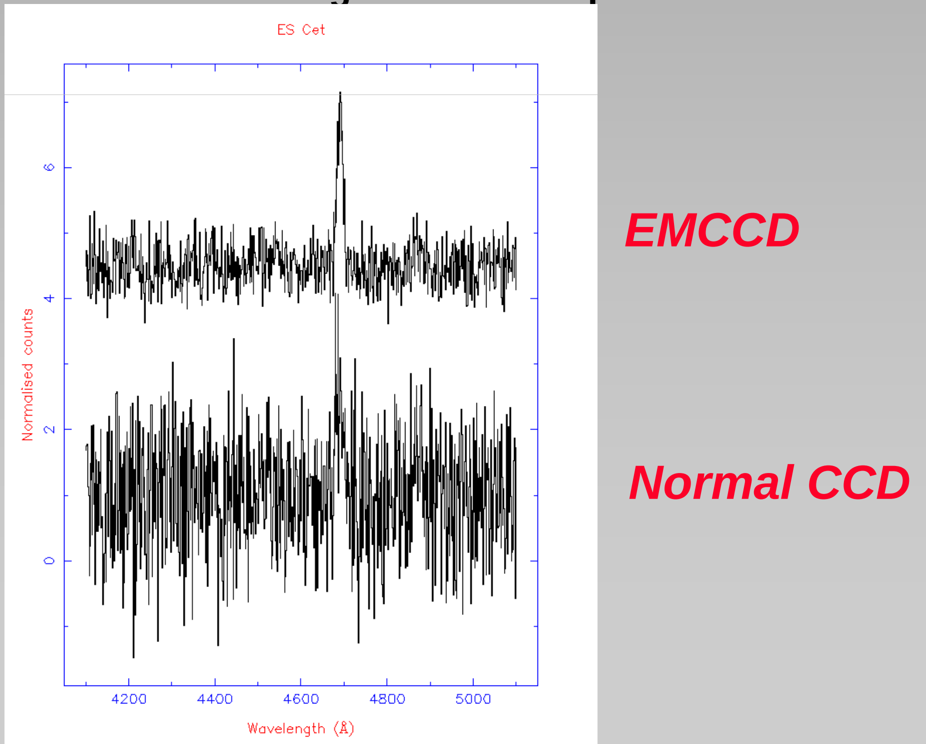
Vertical transfers

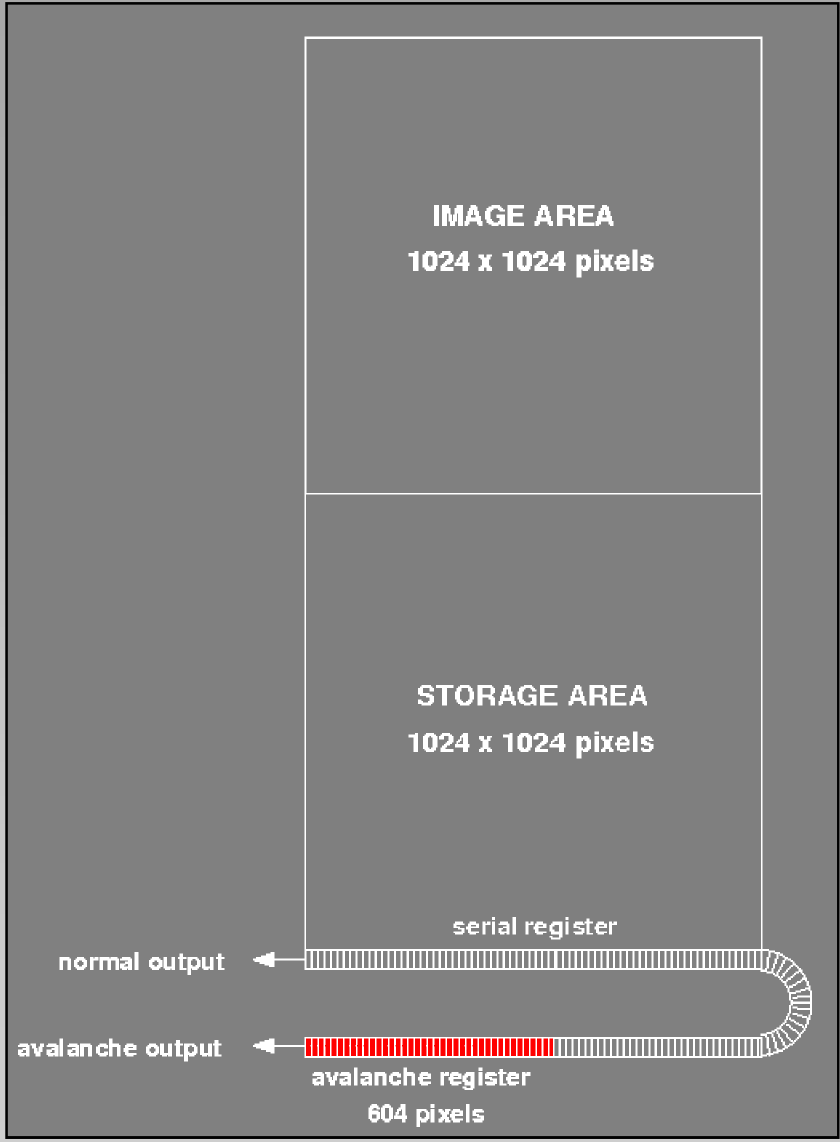


Horizontal transfers

New developments in CCDs

- **Electron Multiplication CCDs (EMCCDs)**
  - Amplify signal in the serial readout register
  - Avalanche gain
  - Effectively a photon counting device
  - Readout noise is insignificant
  - Advantage for short exposures





Drift-scanning with CCDs

Detectors II

- Clock charge along CCD rows at the same rate an object moves
- Good survey mode (e.g. Sloan Digital Sky Survey)

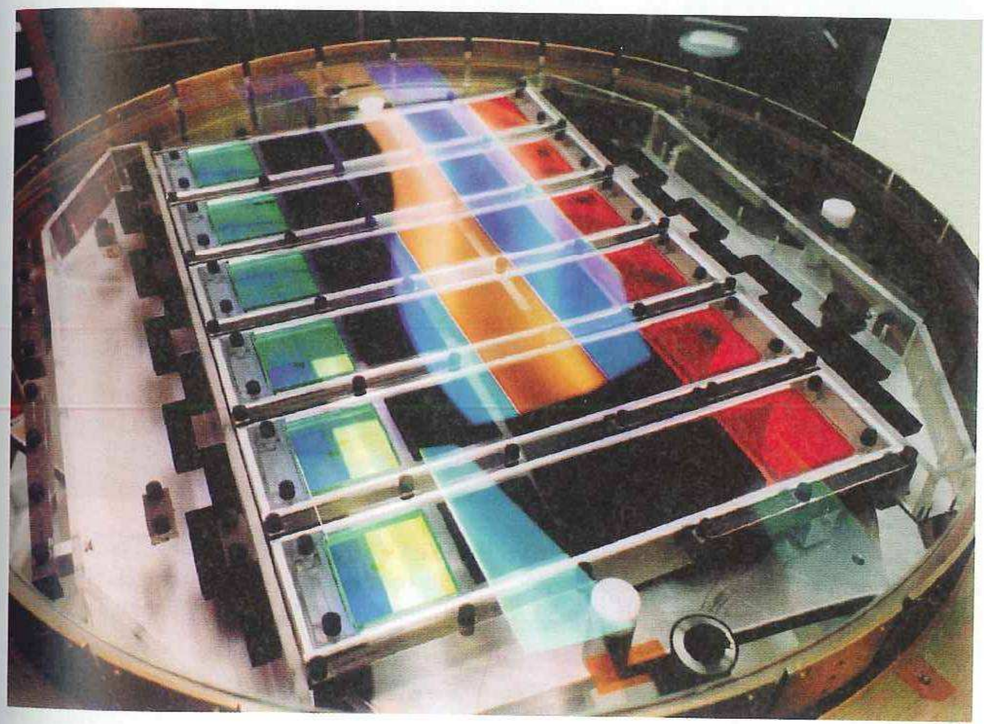
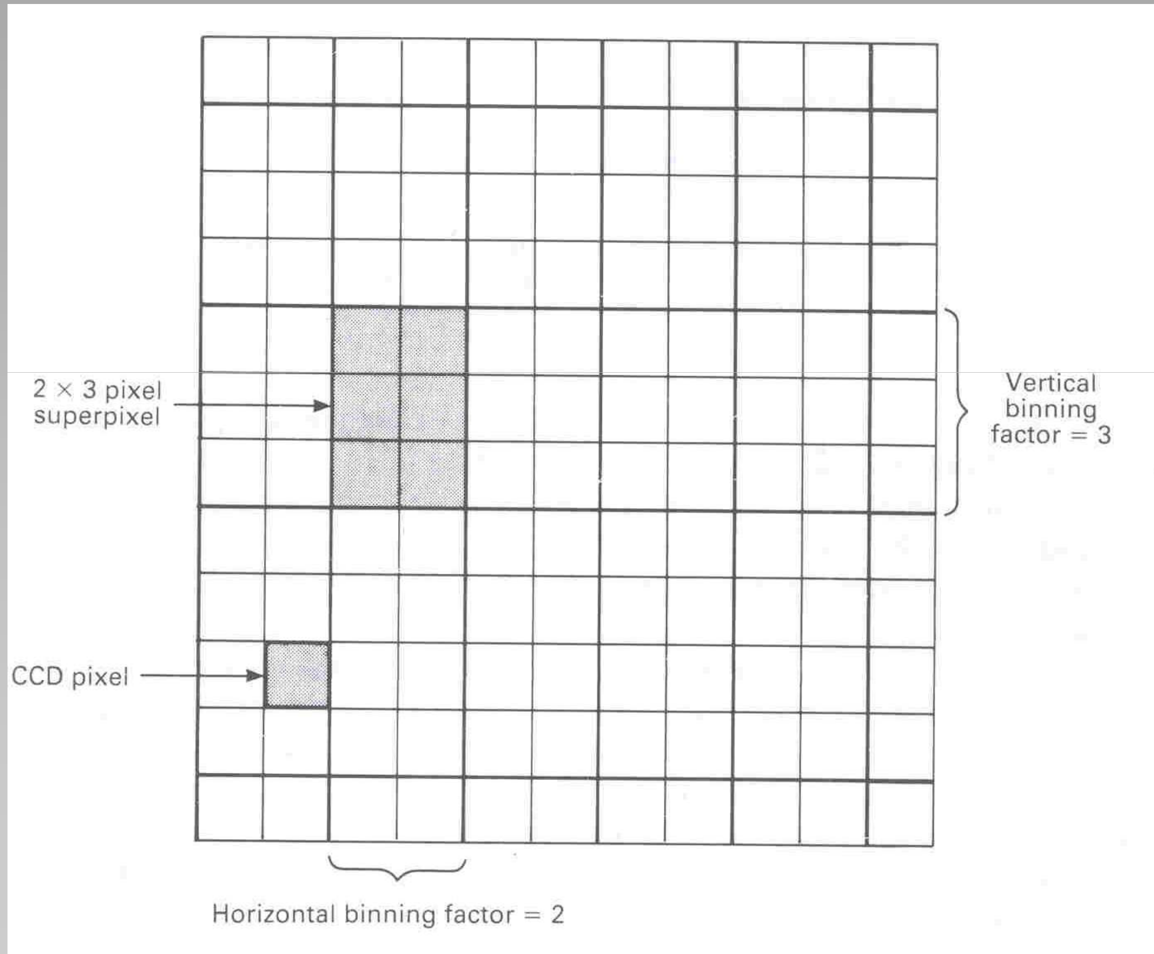


Plate 15. In this color picture of the photometric camera for the Sloan Digital Sky Survey (SDSS) the layout of the 30 CCDs can be seen below the corrector plate. Each of the six rows has five CCDs, and each CCD in a row is covered by a different filter (from left to right they are g', z', u', i', and r'). Credits: Sloan Digital Sky Survey team/Jim Gunn.

On-Chip Binning

- **Add or combine charge packets at the output node capacitor**
- **These groupings become ‘super-pixels**
- **Combined by either**

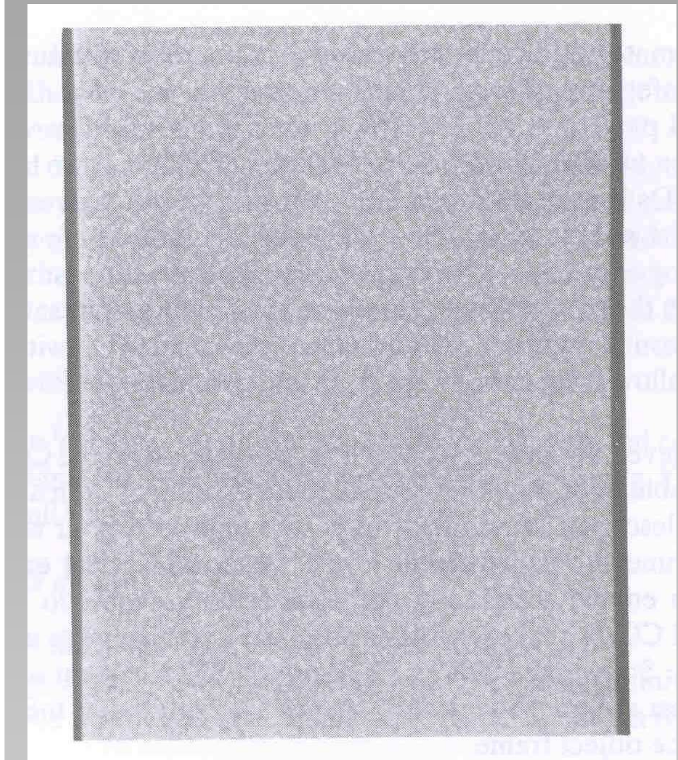
1. **delaying the serial register shift after a parallel shift, or**
2. **not resetting the output capacitor after a serial transfer**



Readout Noise in CCDs

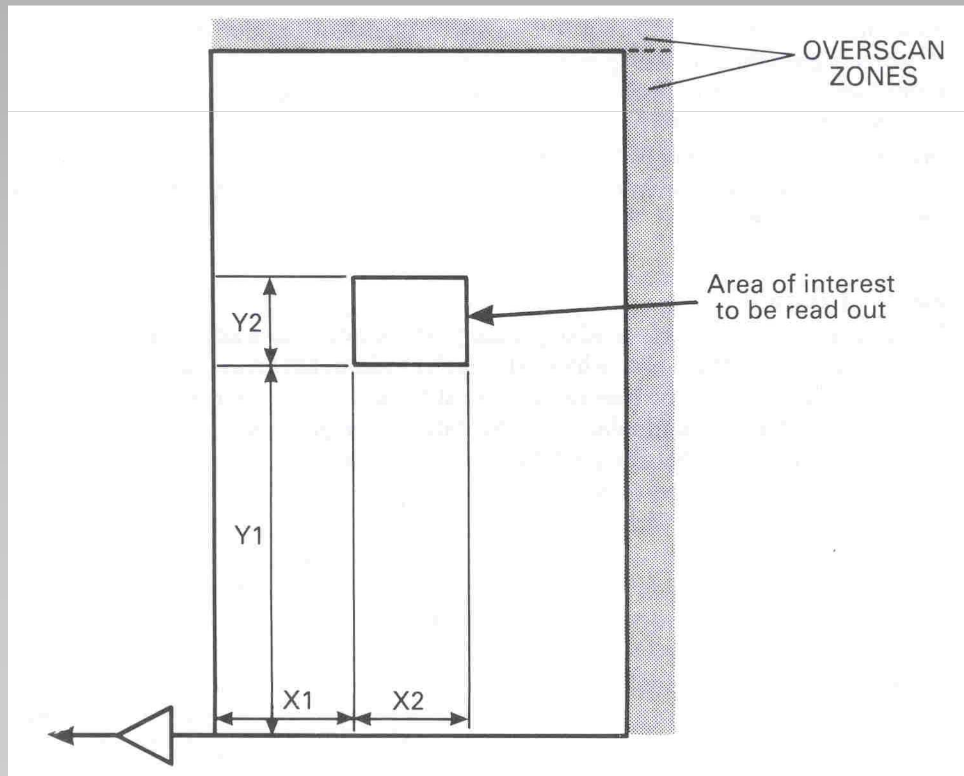
- Ideally only associated with the output transistor (on-chip)
- Other noise sources arise from electronics affecting the weak signals (typically few 10's of microvolts)
  - Background charge associated with DC offsets
  - Charge transfer fluctuations
  - Reset ('kTC') noise (resetting node output capacitance). Can be eliminated (e.g. correlated double sampling)
  - MOSFET noise (transistor)
- Originally CCDs had readout noises of ~80ē
- Modern CCDs have 1 or 2ē readout noise
- Readout noise is constant signal added every time a CCD is readout
  - Not proportional to the exposure time

Bias and Overscan



Typical bias frame

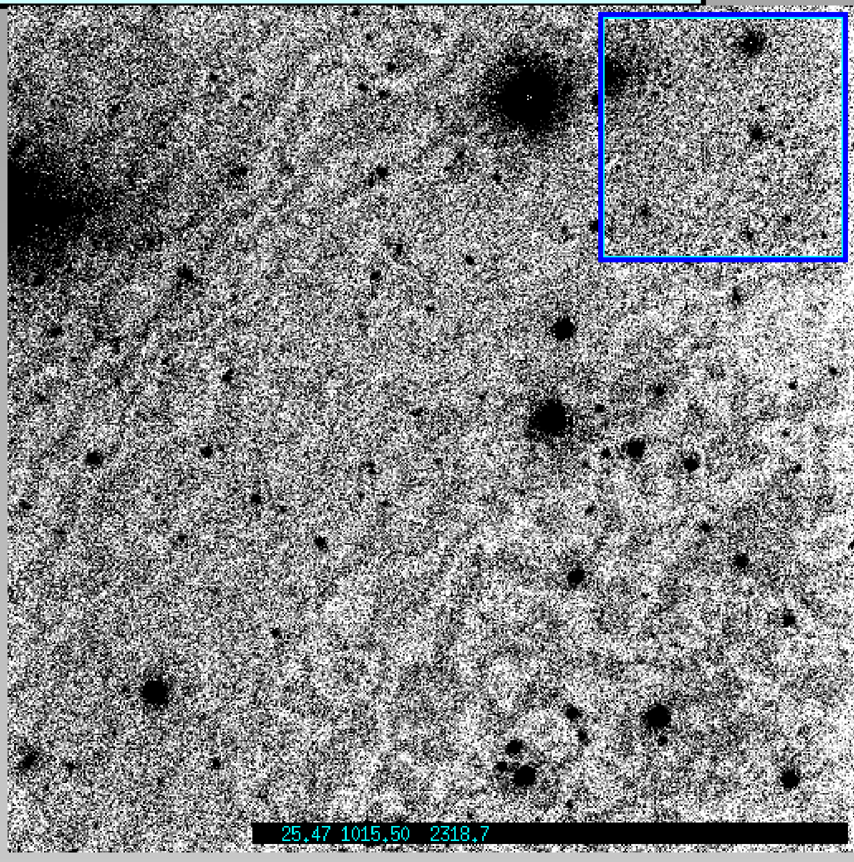
- **Purposely 'bias' the CCD video signal, so that readout noise never drives A/D input into the negative.**
- **Essentially it is a 'pedestal' or 'DC offset' signal which is ideally *uniform* and *constant*.**

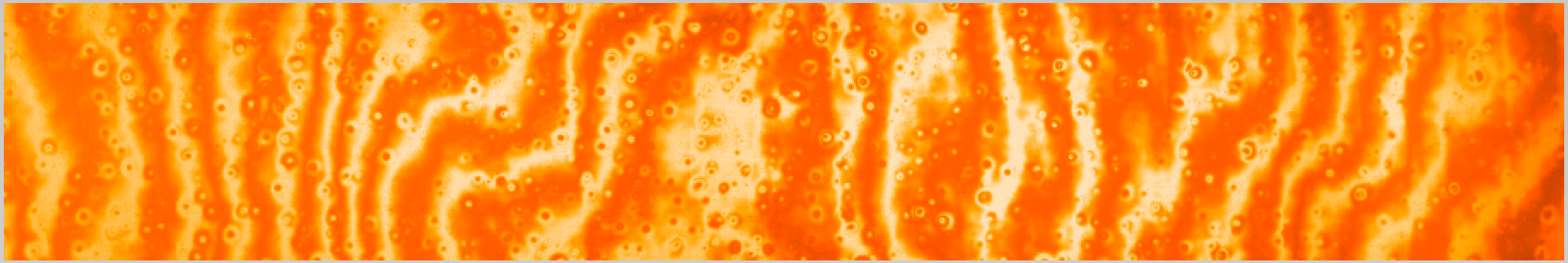


Modern CCDs have good bias (i.e. both constant in time and position).
So rather than take bias frames (wasting time), just use part of the unilluminated portion of CCD (overscan).

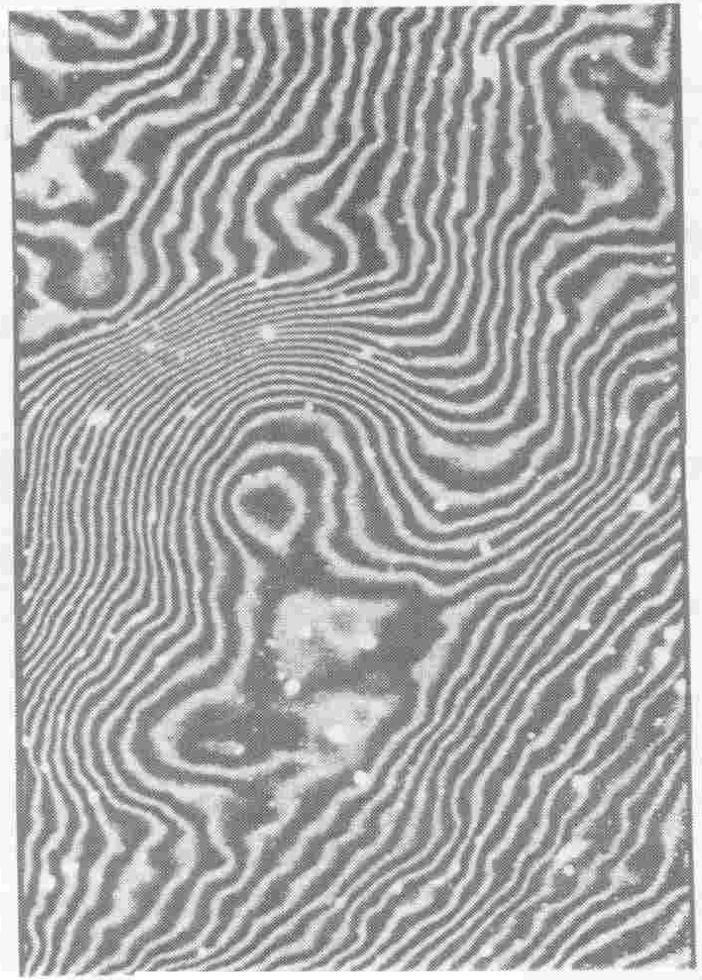
Fringing

- Interference pattern (e.g. Newton's rings) produced from night-sky emission lines (I.e. 'monochromatic' sources)
- Particularly prevalent in thinned CCDs and at longer wavelengths
- Potentially highly variable (in position and time) – up to 20%!

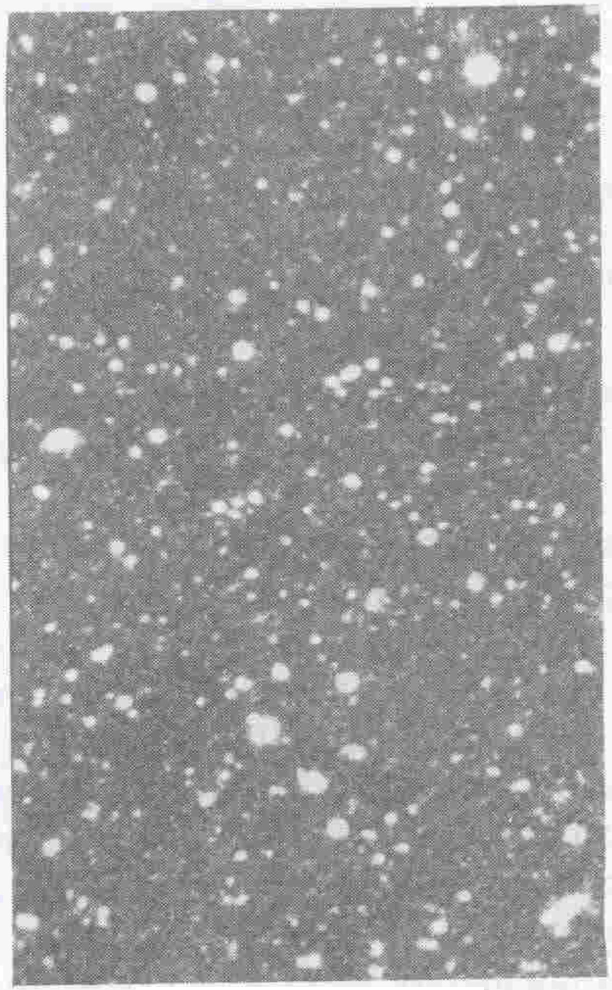




Removal of Fringing

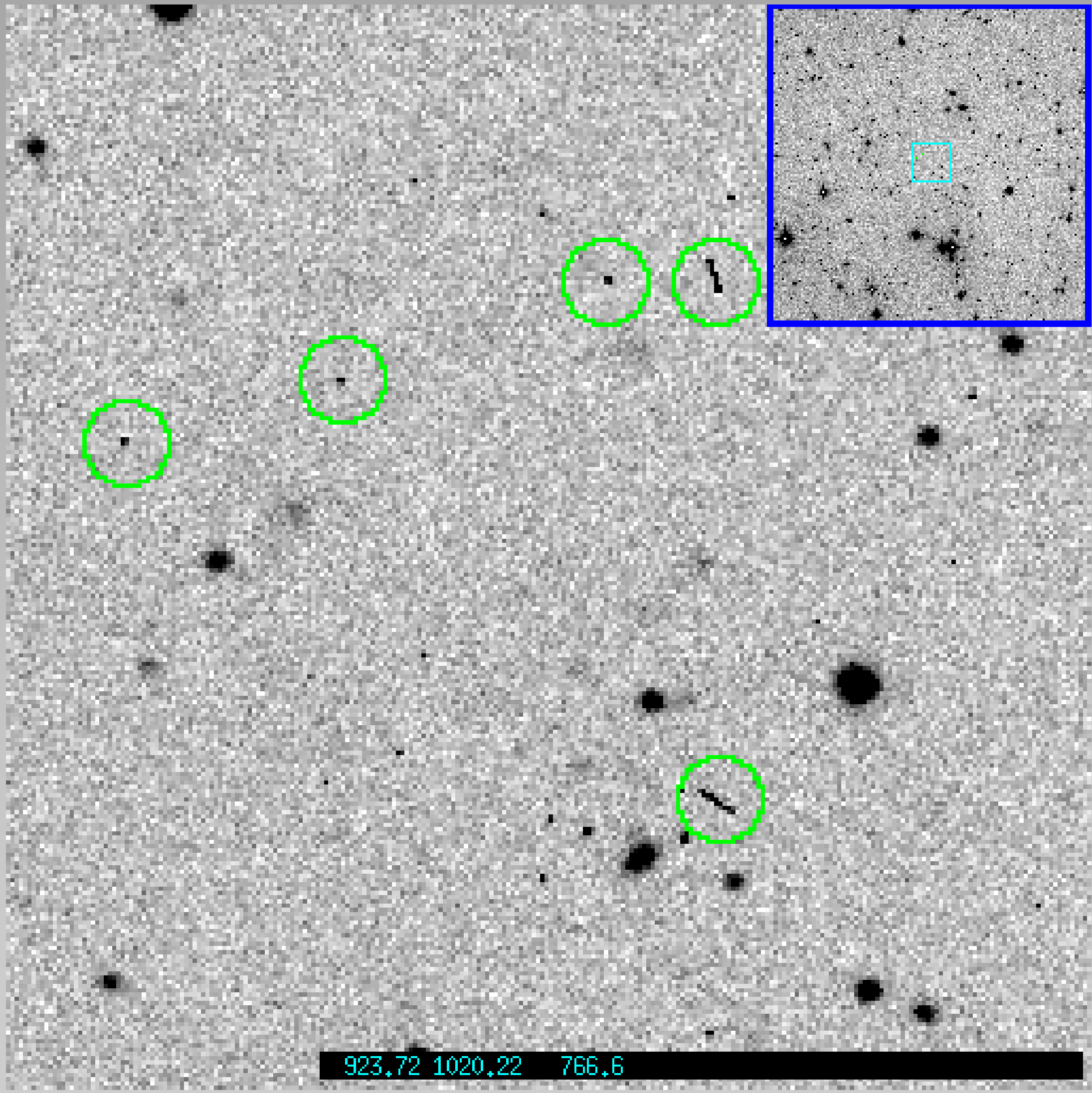


Before removal



After removal

Cosmic Rays

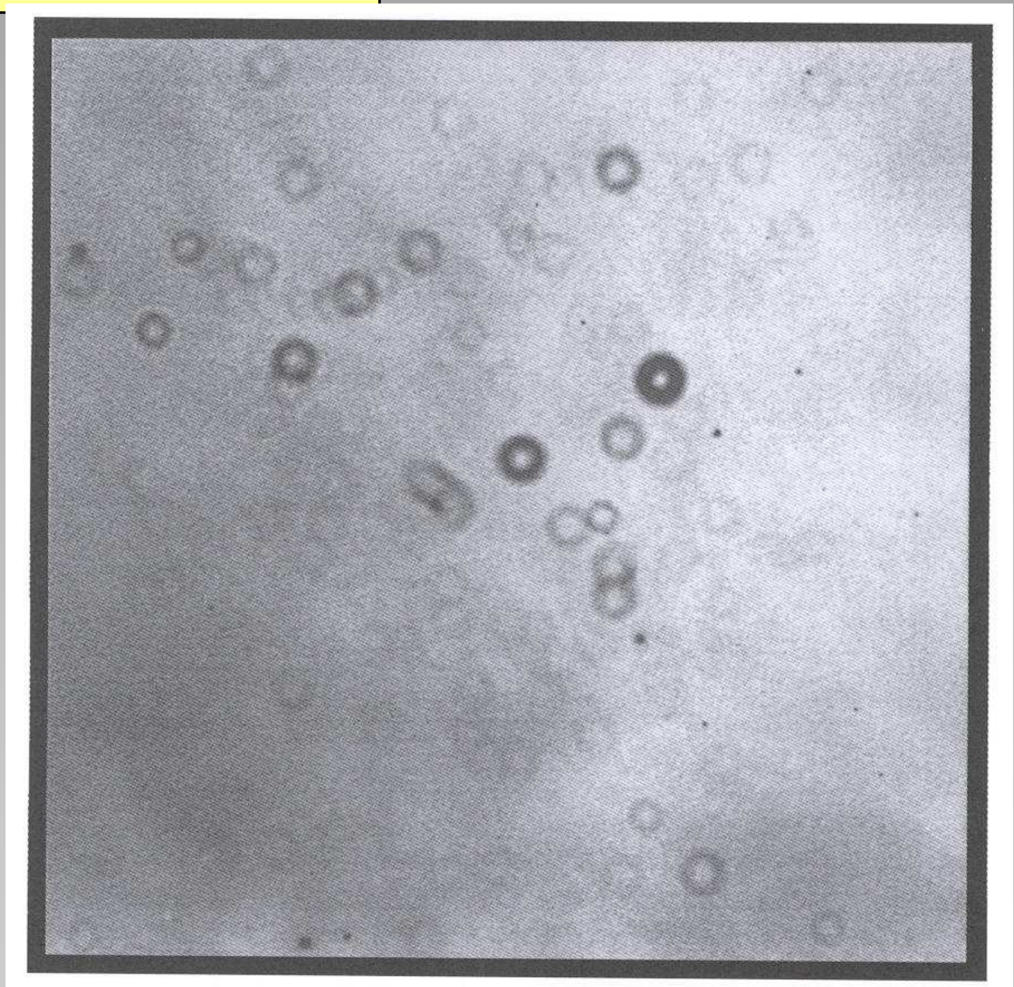


- **CCDs are efficient at detecting the secondary particles of *cosmic rays.***
- **These are typical *muons* which are absorbed in the Si lattice of the CCD**
- **Energy released from pair production leads to ~80ē/pixel/μm**
  - **For a typical 20μm depth, a cosmic ray can generate ~1000ē**
  - **Appears as a 'spike' well above the background (many sigma of mean pixel values)**
  - **Shape non-star like**
  - **Easily removeable in software (replace with mean of surrounding pixels)**

Detectors II

Dust & dirt (!)

- Optical elements in the light path (e.g. filters, windows) can accumulate small dust spot
- These are 'imaged' as out-of-focus spots ('doughnuts')
- Generally stable over timescale of a night (unless in a dust storm)
- Will appear on every CCD frame
- Remove using 'flat field' techniques



Flat Fielding

The excellent linear response of CCDs permits the technique of 'flat fielding'.

$$c_i = \mu_s \frac{r_i}{f_i}$$

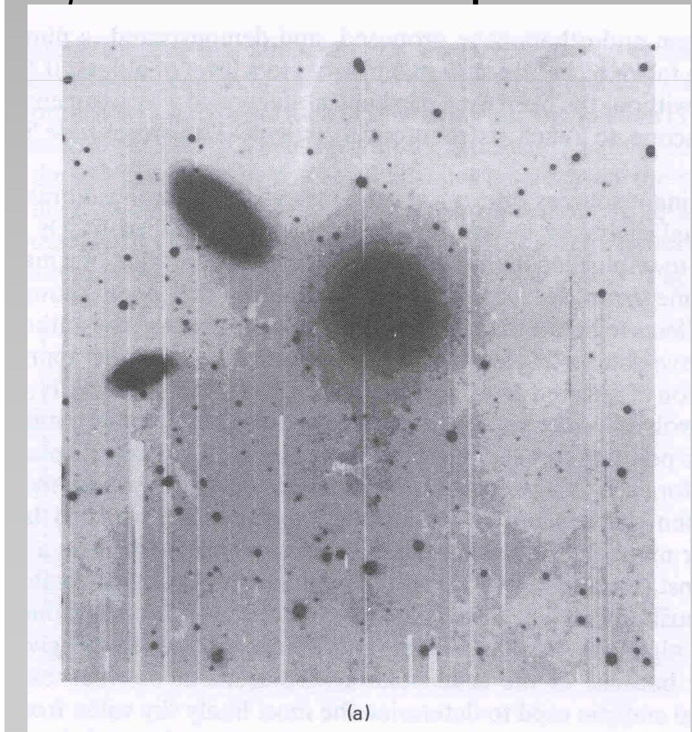
Where:

μ_s **is the mean pixel value of a** $n \times n$ **sub-array of the flat field CCD frame**

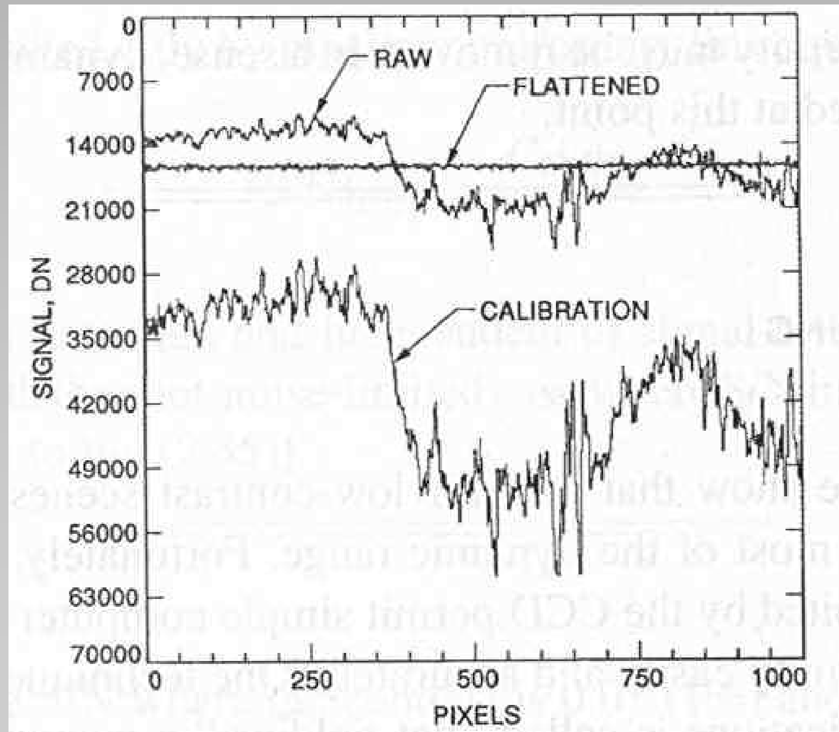
r_i **is the value of the** i^{th} **pixel in the raw CCD frame**

f_i **is the value of the** i^{th} **pixel in the flat field CCD frame**

c_i **is the value of the** i^{th} **pixel in the corrected CCD frame**



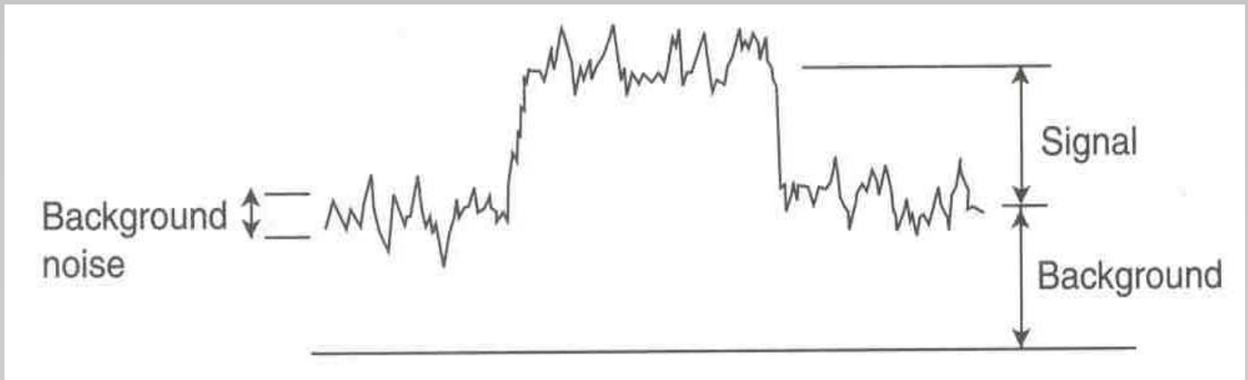
(a)



Signal-to-Noise

- A fundamental measurement with a CCD is the signal-to-noise ratio (S/N or SNR)
  - Background signal (e.g. from 'sky') can be subtracted from *total* (i.e. source + background) signal, even if the actual value of the background is >> source.
  - What is important in defining how faint a source is detectable is the *fluctuations* of background (analogous to detecting a weak radio signal on a transistor radio in the presence of strong static).
  - Noise processes are a result of independent events (i.*e. photon arrivals*) occurring at a (nearly) constant rate, described by Poisson statistics.
    - » Standard deviation (rms of the fluctuations) is given by the simple formula:

$\sigma = (S\ t)^{1/2}$, where S is the intensity (e.g. ē/sec) and t is the time interval



Signal-to-Noise

- **Poisson distribution implies that the errors inherent in a measurement have a Gaussian distribution.**
  - **A S/N of unity is also called a "1-σ" detection, and implies that there is a probability of 0.68 that the detection was real rather than a random 'fluke' (i.e. 68% confidence).**
  - **A S/N = 3 ("3-σ" detection) has a probability of 0.997 being 'real' (often used as a criterion for believing a result).**
- **Taking into account common noise sources and assuming Poisson statistics, the S/N ratio for a source of intensity *S* (photoelectrons/sec), observed for a time, *t*, whose photons fall into n_{pix} pixels on the CCD detector, can be expressed as:**

$$\mathrm{S/N} = \frac{S\,t}{\sqrt{(S + Bn_{\mathrm{pix}} + I_d\,n_{\mathrm{pix}})\,t + R_{\mathrm{n}}^2\,n_{\mathrm{pix}} + \mathrm{var}(B_t n_{\mathrm{pix}}\,t)}}\,,$$

Where *B* is the number of photoelectrons received from the *background* (per pixel per second), R_n is the readout noise of the CCD, I_d is the dark current of the detector, expressed in # of ē's/pixel/sec) and *var( )* is the variance of the estimate of the *total* background, $B_t = (B + I_d)t + R_n$ (again, per pixel per sec). The latter reflects uncertainty in estimating the background which does *not* arise from photon stats (i.e. from *true* variations in background level and inadequacies in the method of estimation).

Signal-to-Noise

- Usually the total background is estimated over many pixels (>> just source pixels) and sometimes over longer time interval (e.g. when the source is uniform, and little changing sky background)
  - $\Rightarrow$ var($B_t\, n_{pix}\, t$) term is often negligible
- Depending on the relative importance of various terms in the S/N equation, can define three main ***regimes:***

1. Source photon-noise limited

When source is bright and its photon noise dominates all other fluctuation

$S/N = \sqrt{(S\,t)}$

2. Detector-noise limited

When both source and background are faint, and detector noise dominates

$S/N = S\,t\,/\,\sqrt{(I_d\,n_{pix}\,t) + (R_n^2\,n_{pix})}$

This is the case where usually S/N increases linearly with time (when read noise dominates dark current). Can't take this to the extreme, however, due to cosmic ray hits.

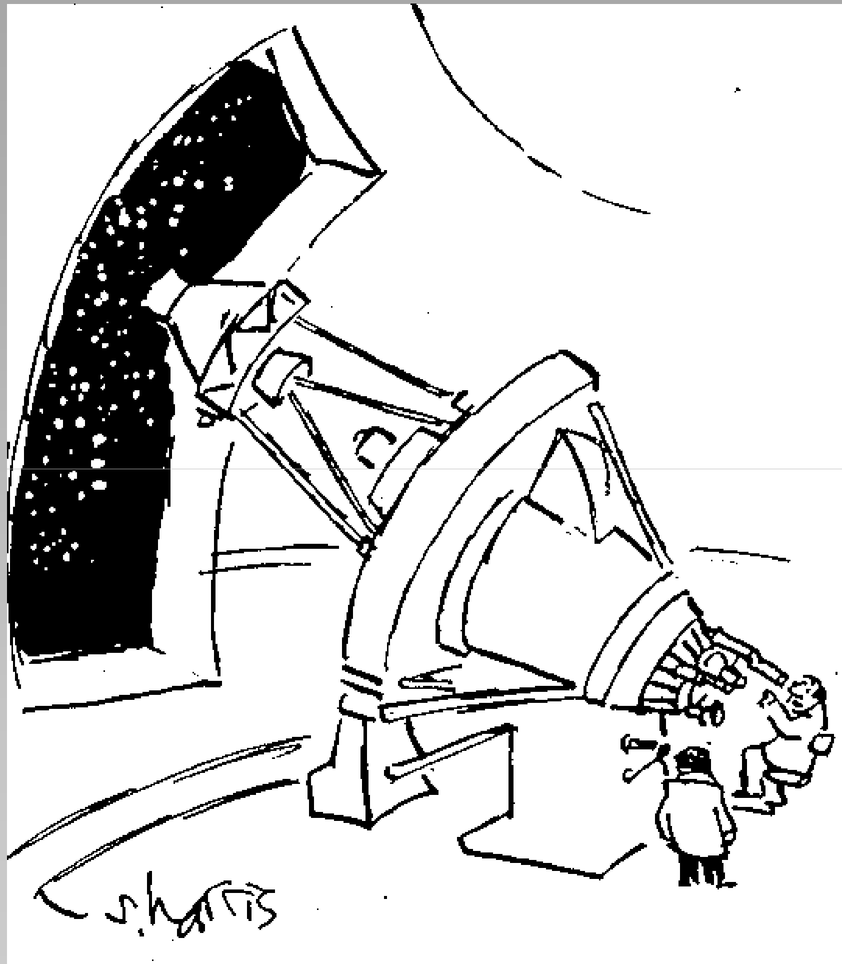
– Background limited

Also called 'sky limited', when source is faint and signal is dominated by the sky (e.g. sky glow, zodiacal light, background emission from other sources)

$S/N = S\,\sqrt{t}\,/\,(B\,n_{pix})$

This is the case where all instrumental noise is minimized, and the only option for increasing S/N is to observe longer ($t^{1/2}$), or with a larger telescope ($S \propto D^2$) or better image quality (reduce n_{pix}) or reduced background.

Detectors II



"Actually they all look alike to me."