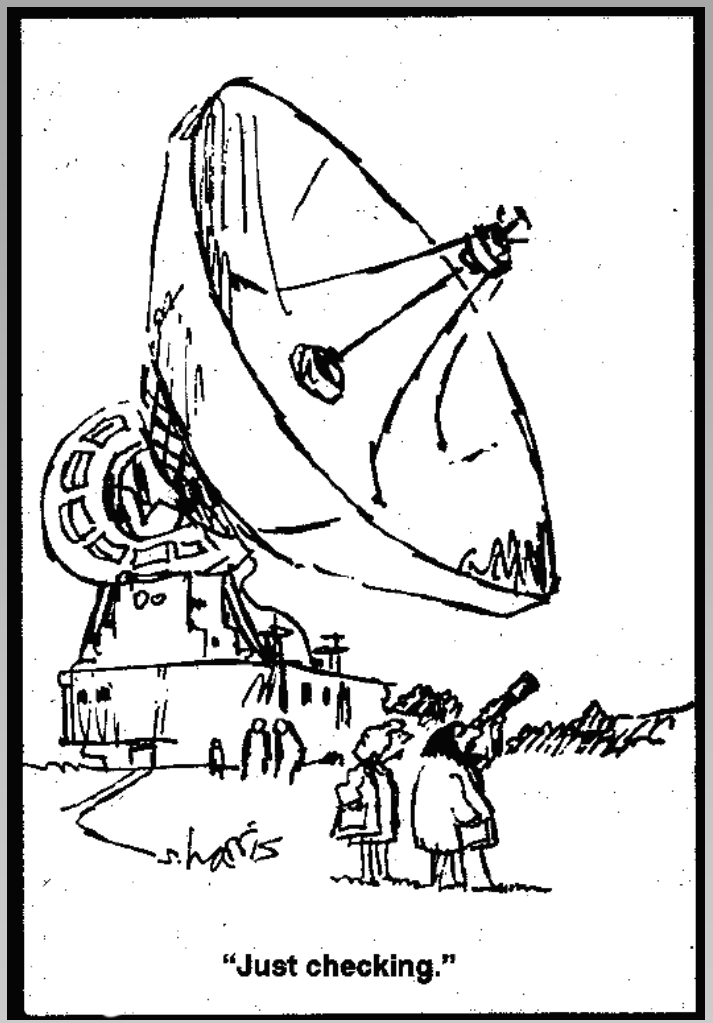
Optical/IR Observational Astronomy

Detectors II



David Buckley, SALT

Optical/IR Observational Astronomy

Detectors II

Charge Couple Device (CCD) Detectors

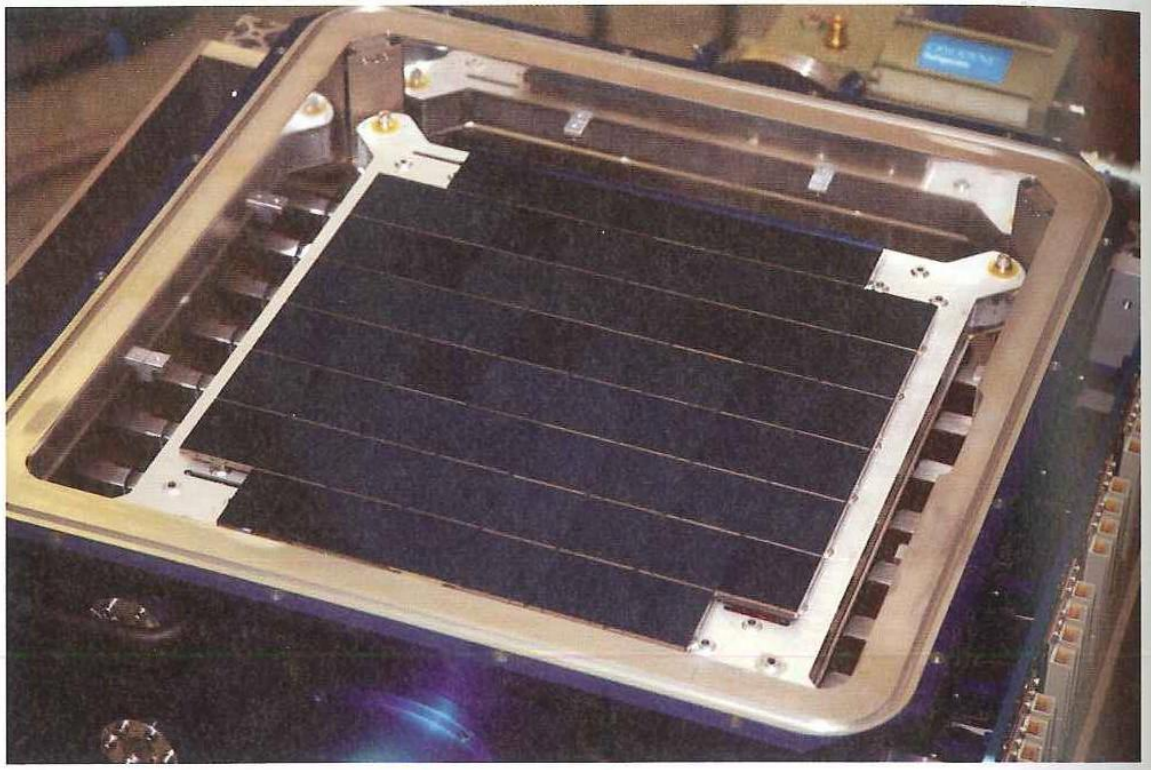
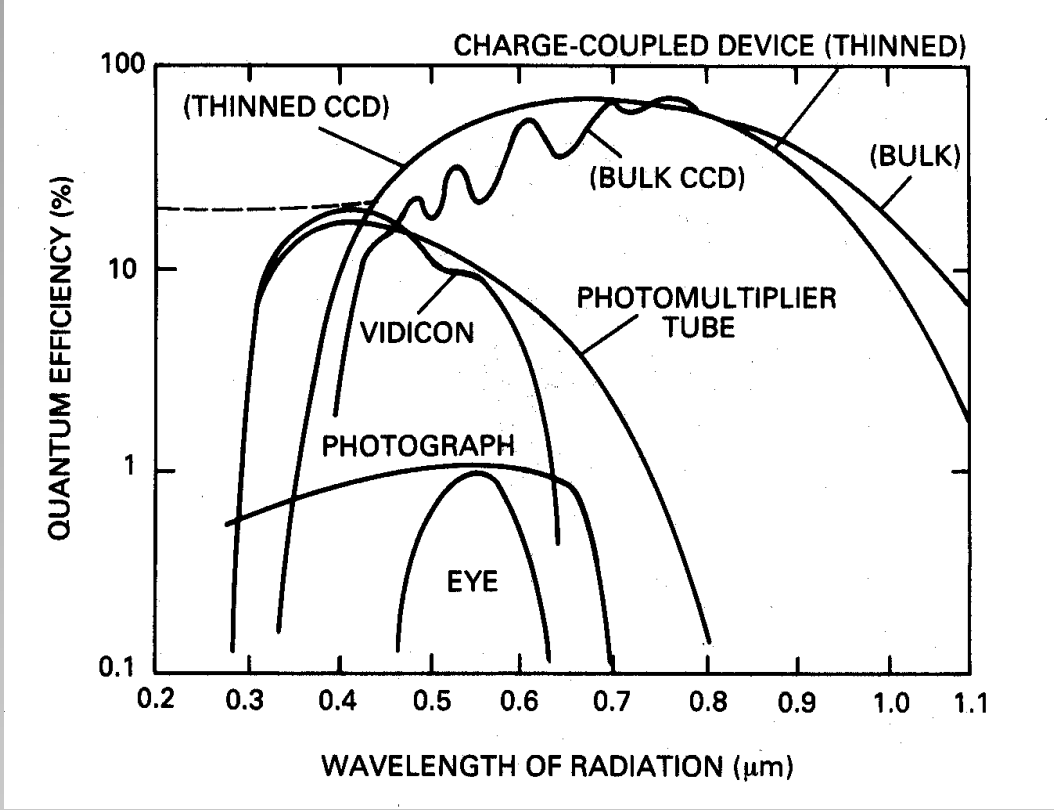


Plate 16. This picture shows the 1.4-gigapixel Pan-STARRS CCD camera which is composed of 60 orthogonal transfer arrays, each of which contains 64 devices of 600 × 600 pixels. The focal plane is about 40 cm square. Credit: Pan-STARRS Team/University of Hawaii/John Tonry and Peter Onaka.

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**

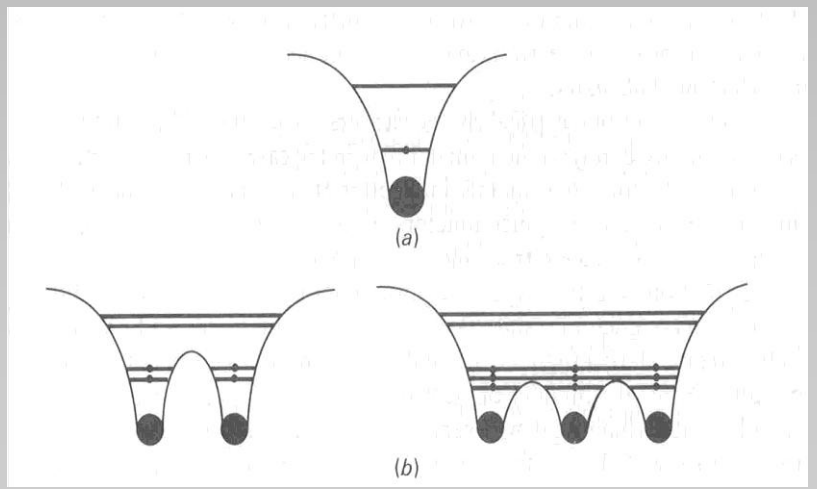


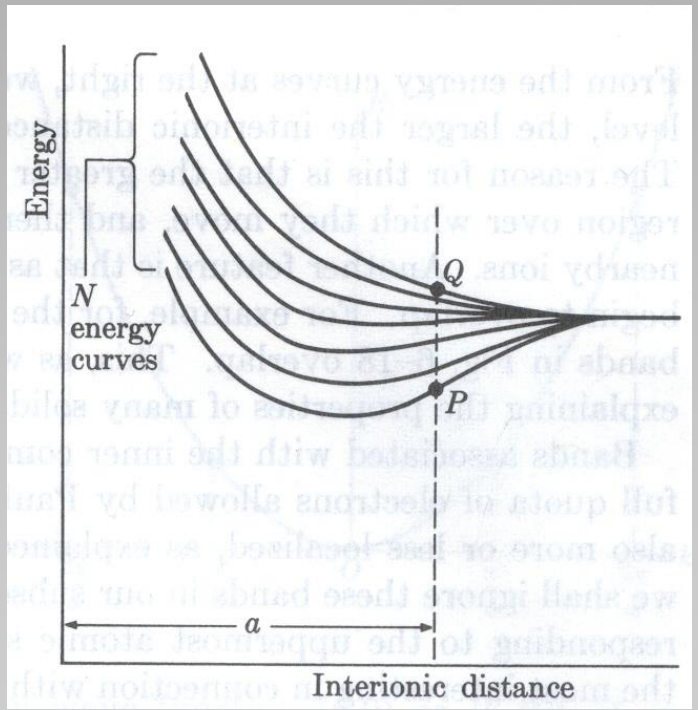
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Detectors II

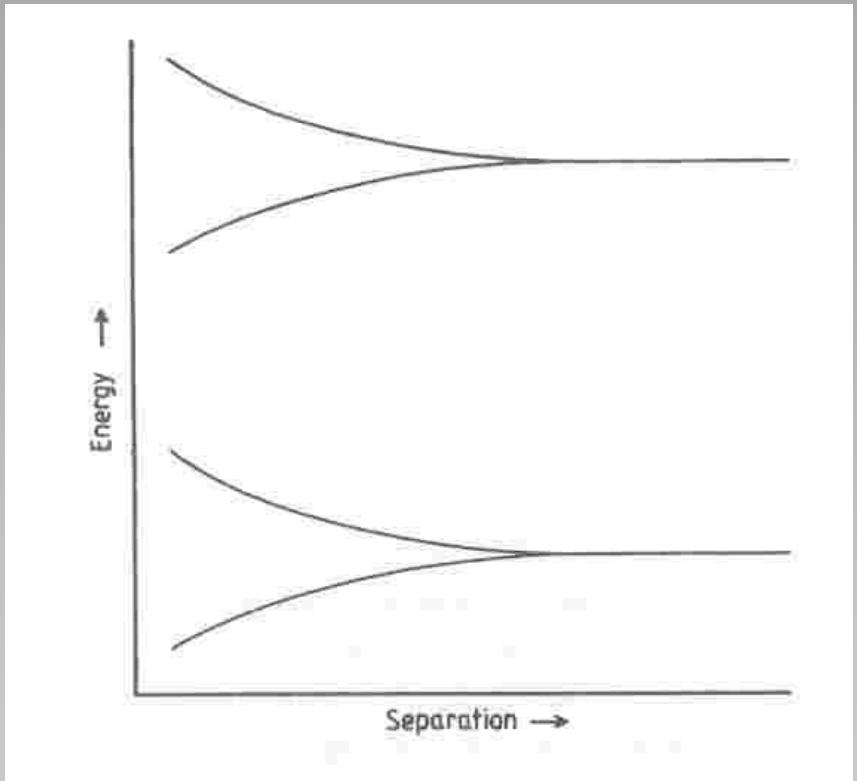
Principles of conductors, semi-conductors, insulators

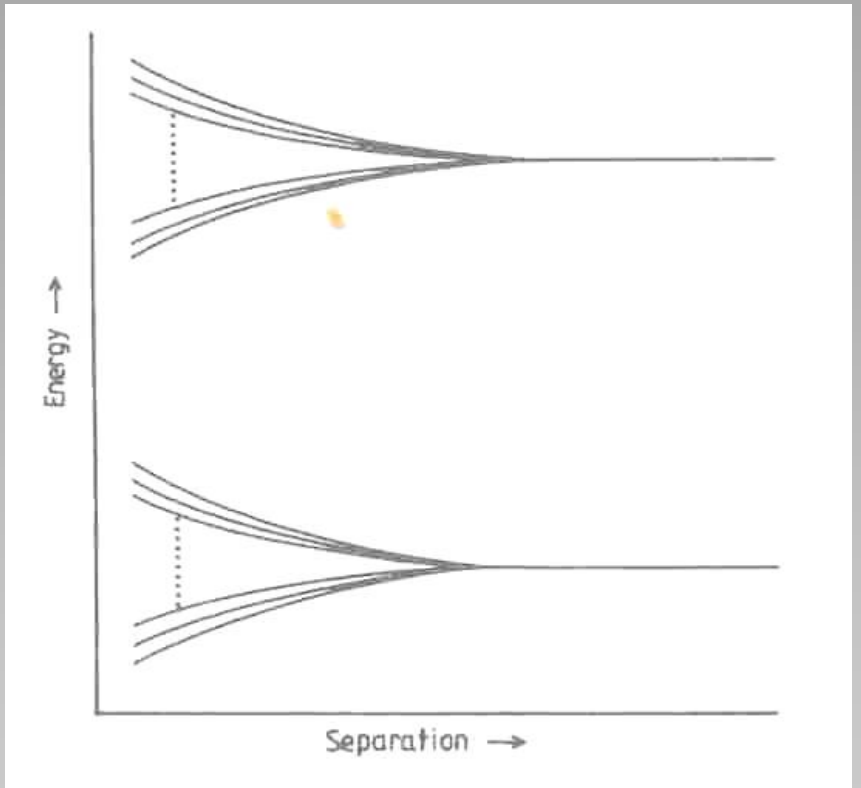
- **Consider the electron energy levels of a solid**
- **Single (unperturbed) E-levels of an atom → split when approached by neighbour**
- **→ for *N* atoms in close proximity (e.g. solid lattice) → *N* degree of splitting**
- **→ a pseudo-continuous band of energies**





Splitting of energy levels: for 2 atoms (left) and N atoms (right)

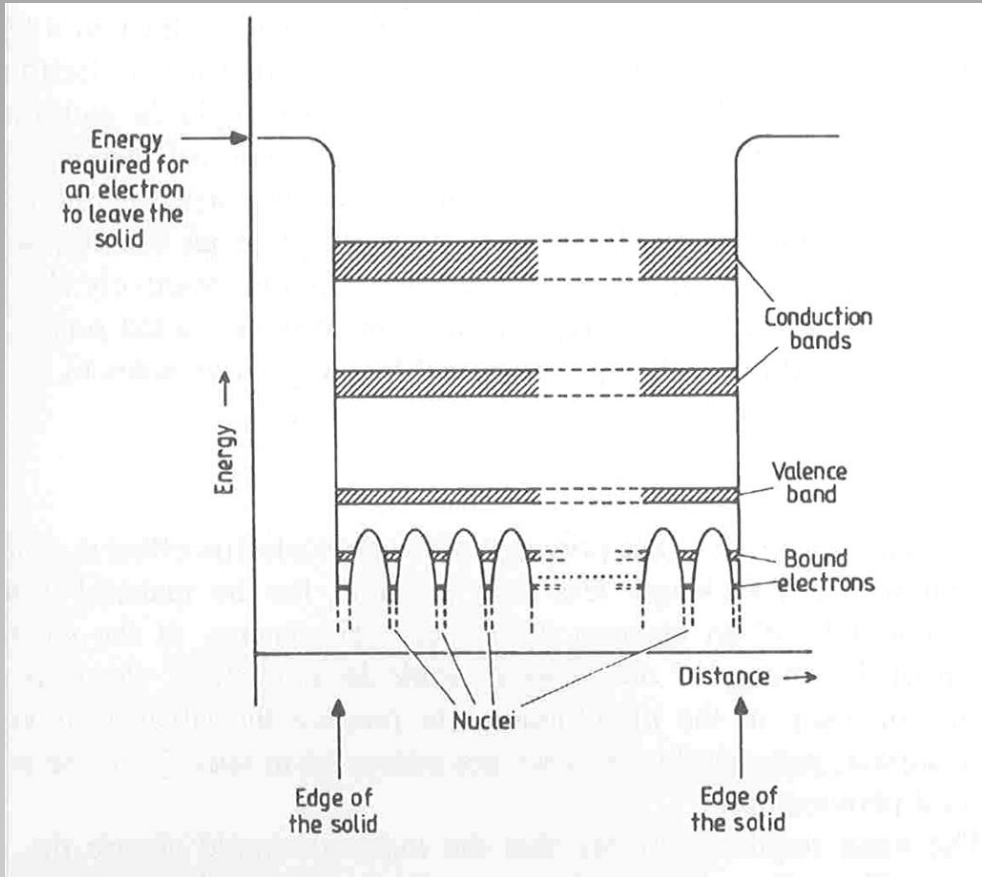




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Detectors II

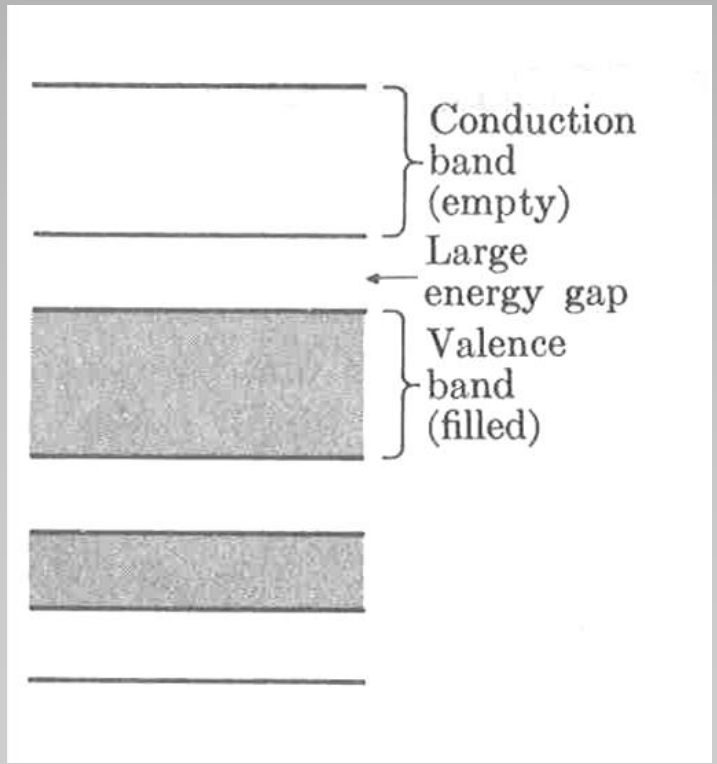
Principles of semi-conductors



- **All but the valence electrons are bound to the individual atoms. They occupy the *valence band*, which binds the solid together.**
- **For electrical *conduction*, individual electrons must be free to move. Conduction can only occur if there is a suitable E level, above that of the conducting electron.**
- **If valence band is occupied, implies lower E levels filled.**

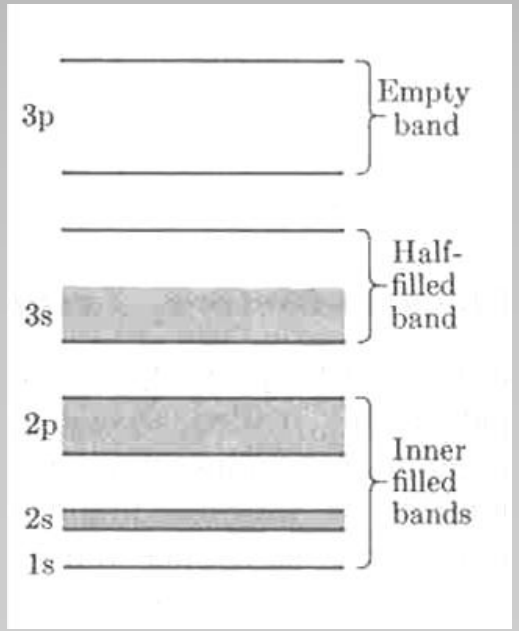
Some physics background: conduction

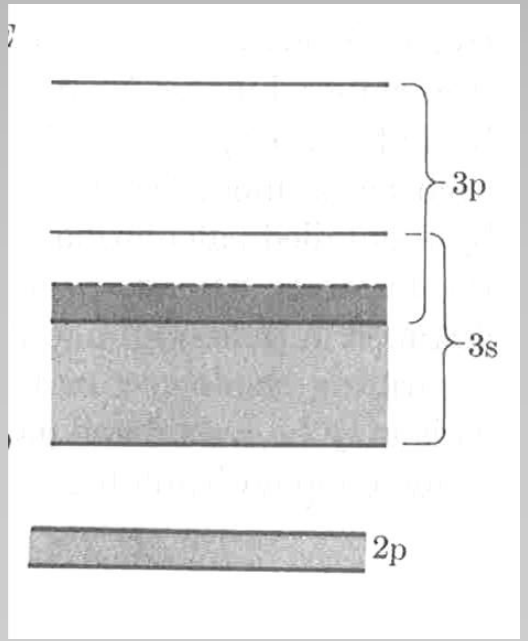
- An empty sublevel has to be available for the valence electron to enter and be ‘conducted’.
- If valance band is fully occupied, then electrons can’t increase their energy, hence solid does not conduct: it is then an *electrical insulator.*



Conduction

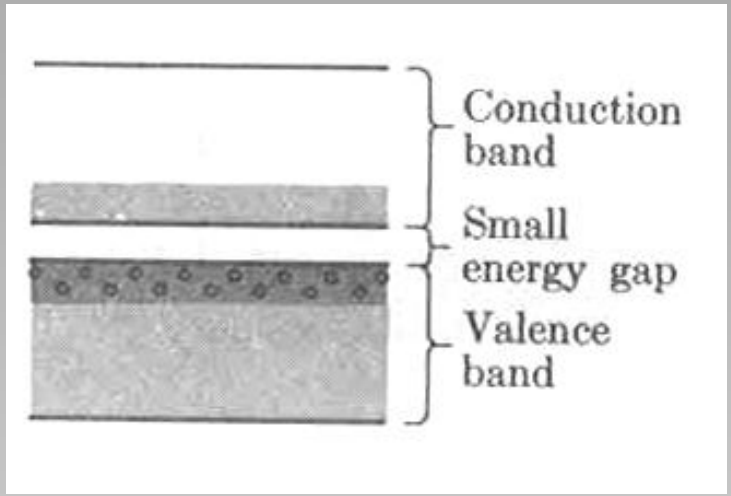
- **Valence band unfilled**
  - **Either only a single S-shell electron**
  - **Or higher E levels sufficiently broadened to overlap valence band**
    - » **At T = 0K, all sublevels filled up to the Fermi level, with higher sub-levels unoccupied**
    - » **At higher T, some ē's will move into these levels, as there will still be ones unoccupied and available for conduction**
    - » **In situation where overlap occurs between valence and conduction bands, then material is a good *electrical conductor,* as in a metal.**





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.**

Solid state physics: refresher

- ***Momentum of ē***: $p = m_e v = \hbar k$

- ***Wave function of ē***: $\psi = e^{ik.r}$ ***(where k is electron wavenumber = $2\pi/\lambda$)***

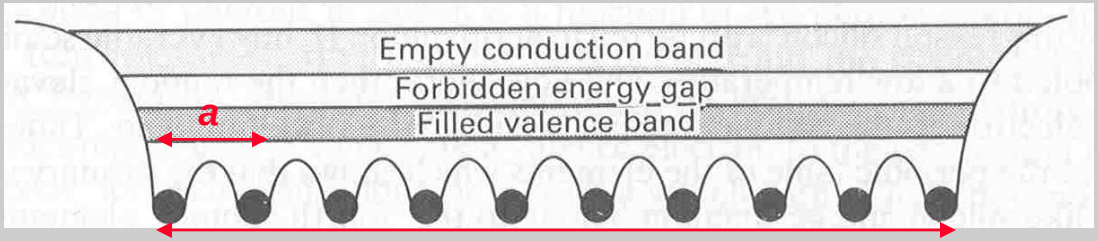
For now assume free-ē model (not quite correct, since ē's expected to be near +-ve ions in lattice). The E of ē in a constant potential is given as:

$E = p^2/2m_e = \hbar^2k^2/2m_e$ **(so $E \propto k^2$)**

Corresponding to K.E. of ē with momentum $p = \hbar k$. This formulation implies all values of E are allowed, therefore does not reflect true width of the conduction band. Estimate as follows:

Consider a lattice of length *L* consisting of *N* ions each a distance *a* from their nearest neighbours:

$L = N a$



Energy of levels in free-electron model

$E = \hbar^2 k^2 / 2 m_e$ (i.e. quadratic function)

Discrete energy level for each quantized wavenumber

For an ē standing wave to exist, then $L = n (\lambda/2)$, ($n = 1, 2, 3 \ldots N$),

$\Rightarrow \lambda = 2L/n$

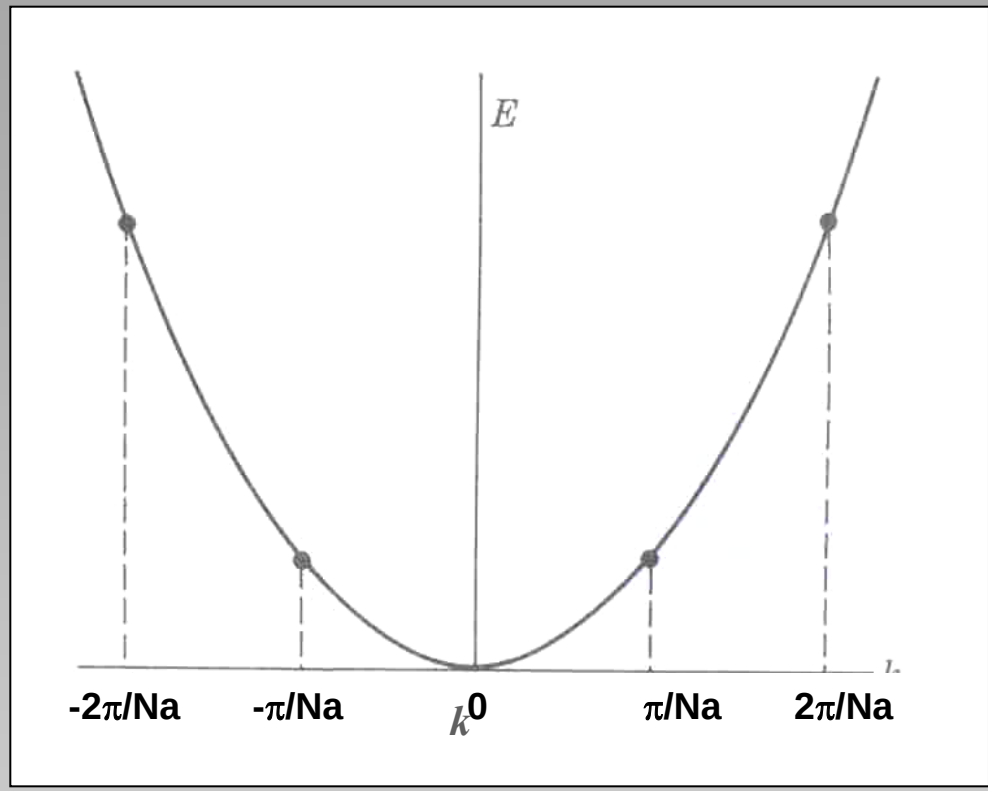
So,

$k = 2\pi/\lambda = n\pi/L = n\pi/Na$

The difference between successive wave numbers, *k*, is π/Na (very small, since *N* is large, hence can treat *k* as a continuous variable).

$k_{max} = \pm \pi/a$

for a given band



Energy states in a solid

- **Maximum energy is therefore:**

$$E_{max} = \hbar^2 \pi^2 / 2m_e a^2$$

Independent of *N* (adding more ions adds more states, but does not change the basic periodicity of the lattice, and hence not k_{max}).

Recall (?) from quantum mechanics that the solution of a 'particle in a box' for the density of energy states as a function of energy is given as:

$$dn = 8 \pi (2 m_e^3)^{1/2} h^{-3} E^{1/2} dE, \text{ i.e. } dn \propto E^{1/2}$$

If all ē's are in *ground state* (when at 0ºK), they occupy all of the lowest E levels, compatible with Pauli exclusion principle (i.e. each level is occupied by 2ē of opposite spins).

If total number of ē's, n_0, < total number of E levels, then at T = 0K, all ē's occupy E levels up to the *Fermi energy*, ε_F.

Energy states in a solid

Fermi energy is:

$$\varepsilon_F = h^2 / 8m_e \, (3 n_0 / \pi)^{2/3}$$

When Fermi energy is equal to energy band width ⇒ band is fully occupied

If band is not completely full, ē's can be excited by thermal energy (*kT* ~ 0.025 eV at T = 20ºC) into higher states. Electrons gain as much as ~20kT ~0.5eV.

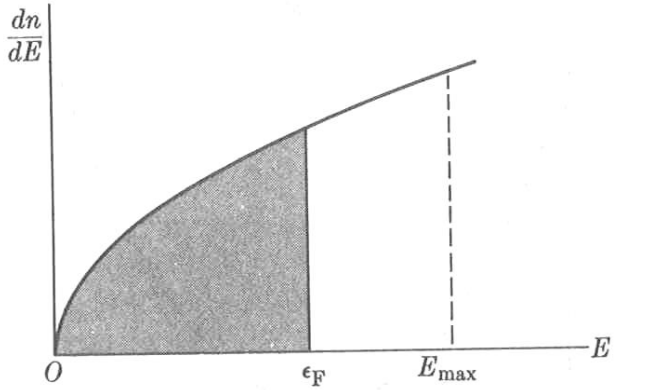
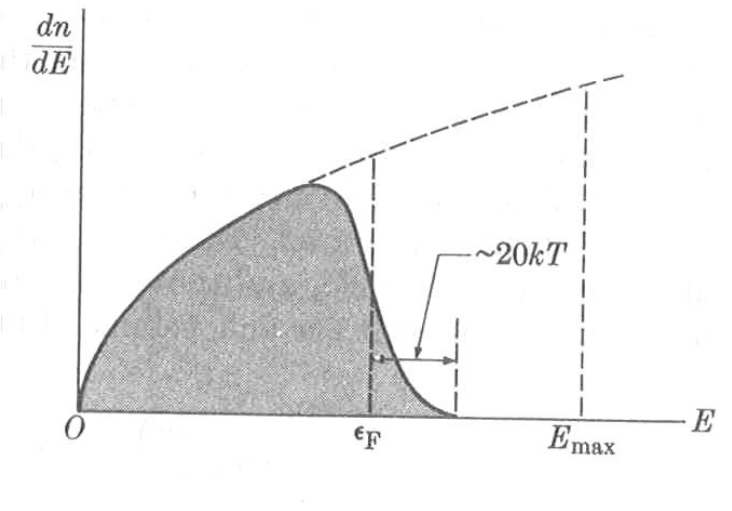
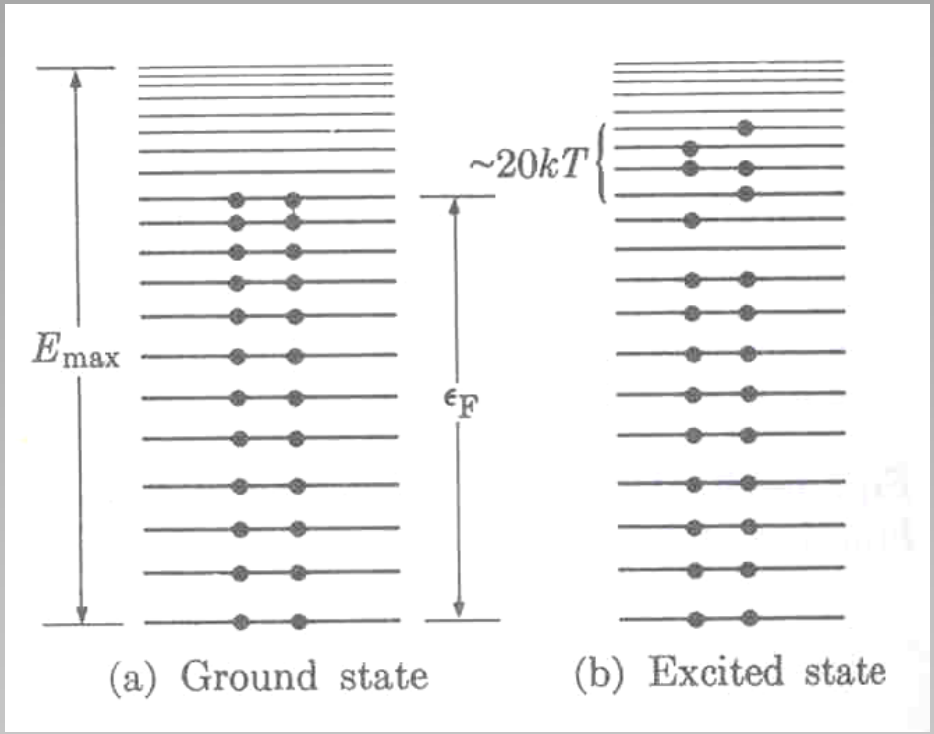


Fig. 6–20. Density of energy states of free electrons in a solid.



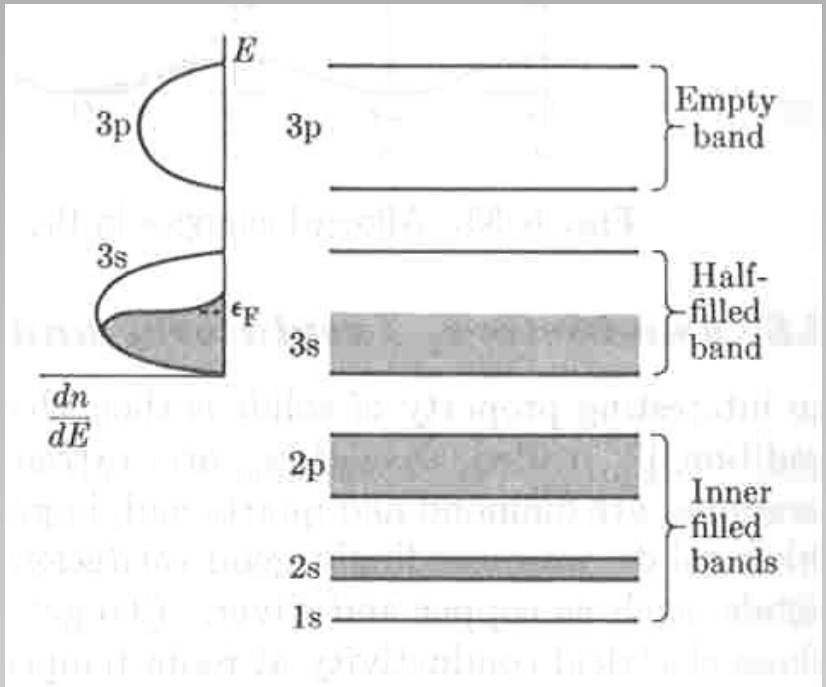
Energy states in a solid

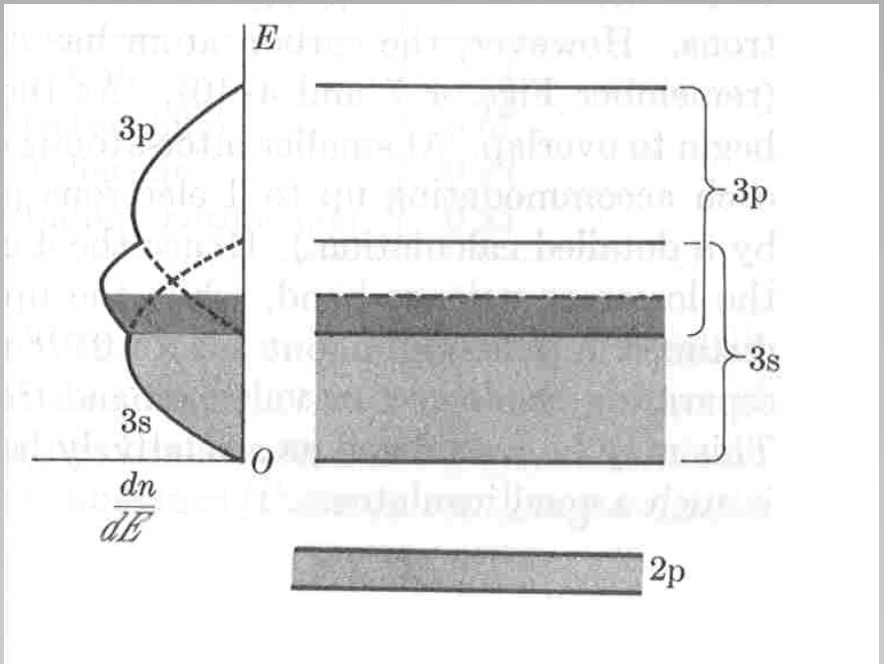


- At T = 0K, all ē's are in their lowest energy states, and obeying the Pauli exclusion principle, filling the states maximally.
- Fermi energy (ε_F) is the max energy of the last occupied states
- In a conductor (metal), there's enough thermal E to excite the uppermost ē's into higher E levels

Energy level diagrams

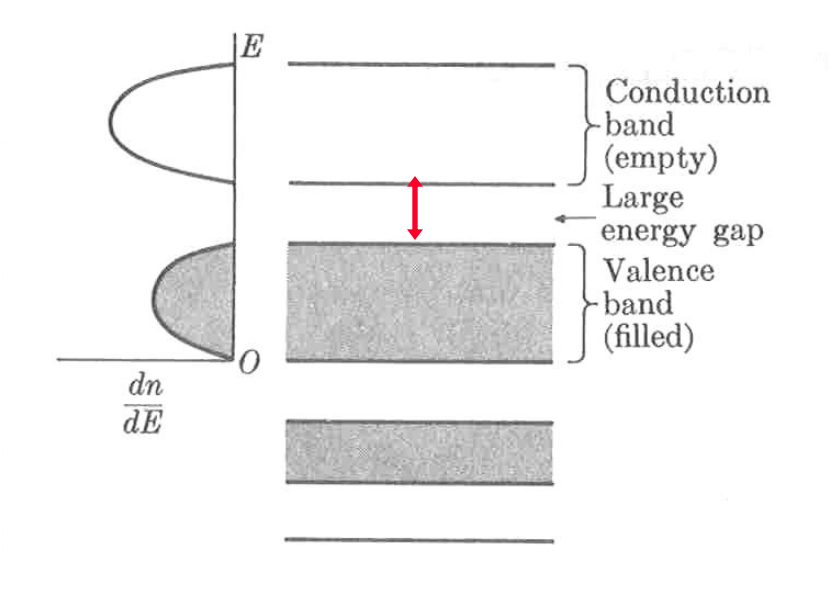
- **Conductors and Insulators**
  - **e.g. a metal like Cu is 10^{20} times more conductive than an insulator like quartz.**
  - **Semi-conductors are intermediate**



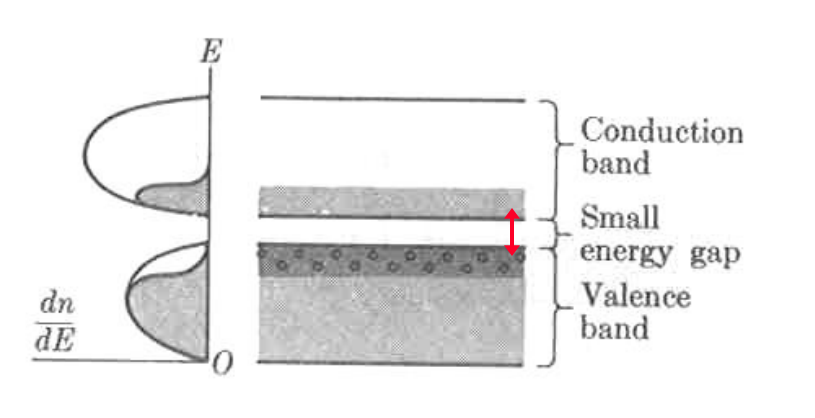


Energy level diagrams

- **Insulators and semiconductors**



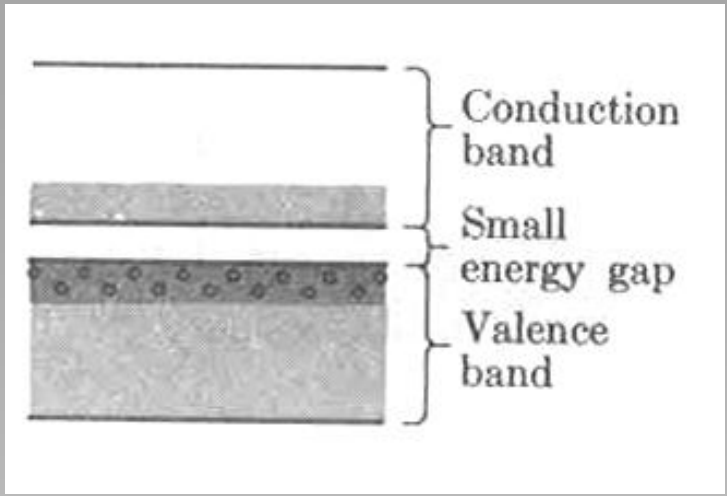
Insulator (non-conductor)



Semiconductor

Detectors II

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

Photoelectric effect: absorption

IIB	IIIA	IVA	VA	VIA
Z Symbol	13 Al	14 Si	15 P	16 S
30 Zn	31 Ga	32 Ge	33 As	34 Se
48 Cd	49 In	50 Sn	51 Sb	52 Te
80 Hg	81 Tl	82 Pb	83 Bi	

The Group number gives # of valence electrons available for conduction

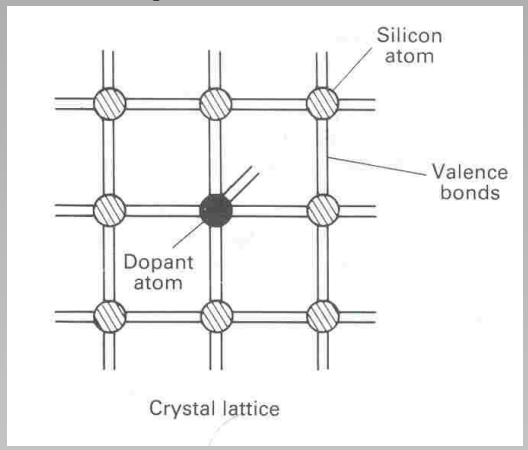
- Semi-conductors used as photoemitters, with Fermi levels close to valence band.
  - Reduce thermionic noise by have Fermi levels in valence band and by cooling.
- Semi-conductors are typically silicon based or germanium based.
- These are Group IV elements in the periodic table, each having 4 valence electrons per atom.
  - Si and Ge form diamond-like crystal lattices, with each atom sharing ē's with four neighbours.
- Compounds including elements from neighbouring columns of periodic table (I.e. Group III and V) can also be used.
  - Examples include HgCdTe, InSb, and these alloys have semi-conductor properties.

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Detectors II

Intrinsic/extrinsic photoconductors

- **Intrinsic photoconductors comprise all Si, Ge, HgCdTe and InSb type semi-conductors where single optical-IR photons are sufficient to promote electrons into conduction.**
- **Photon wavelengths are given by: $\lambda = h\,c\,/E_g$ and the lower limits for photon energies apply to visible/near IR region.**



- **Semiconductors working at lower E / longer wavelengths are referred to as *extrinsic photoconductors*. These have *dopants* – impurities added to the semi-conductor.**
- **Conduction then occurs when valence electrons from the dopant, rather than the semi-conductor, are promoted into the conduction band. These have a lower E_G**

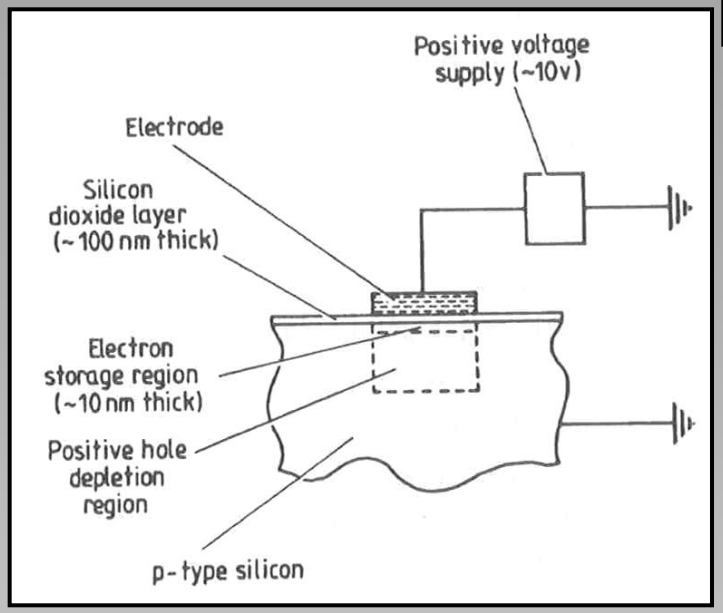
–Such devices designated by the notation *semiconductor: dopant, e.g. Si:As* (which is preferred technology for mid-IR [5-30μm] detectors).

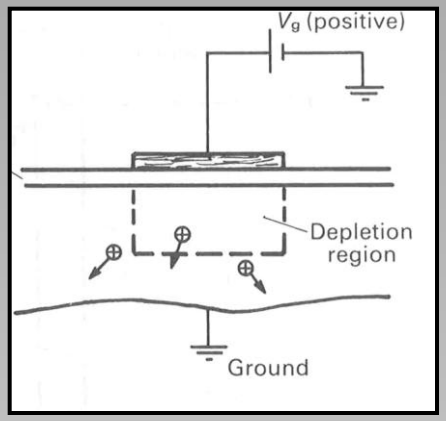
- **Less radical doping is used to alter semi-conductor properties (e.g. n-type and p-type, for on-average more or less valence electrons that the bulk semi-conductor). Importance of these in Si devices discussed shortly.**

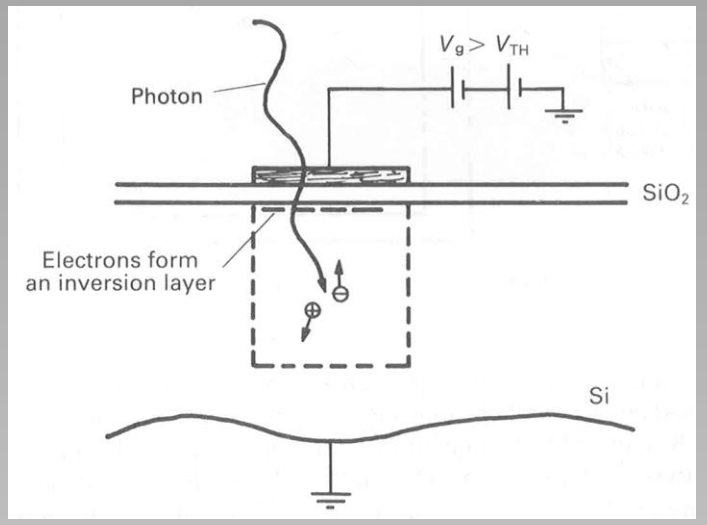
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Detectors II

Basic definition of a CCD





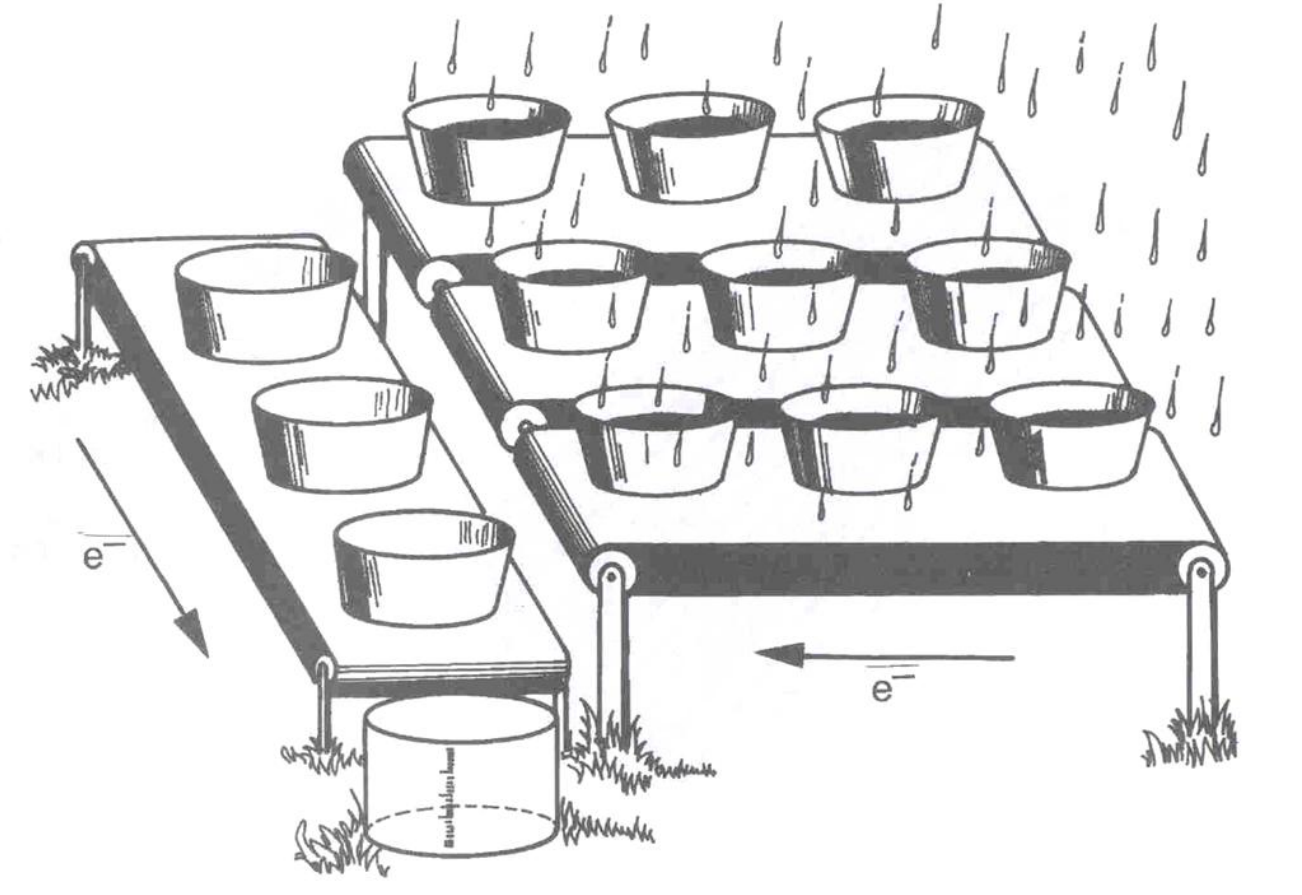


- CCD is a *metal oxide structure* (MOS), consisting of a transparent metal electrode separated by a ~0.1μm of SiO_2 insulator from a layer of p-type Si. Thus it is a simple capacitor, capable of storing electrical charge.
- CCD behaves as a two dimensional array of Si p/n junctions. The whole array 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.

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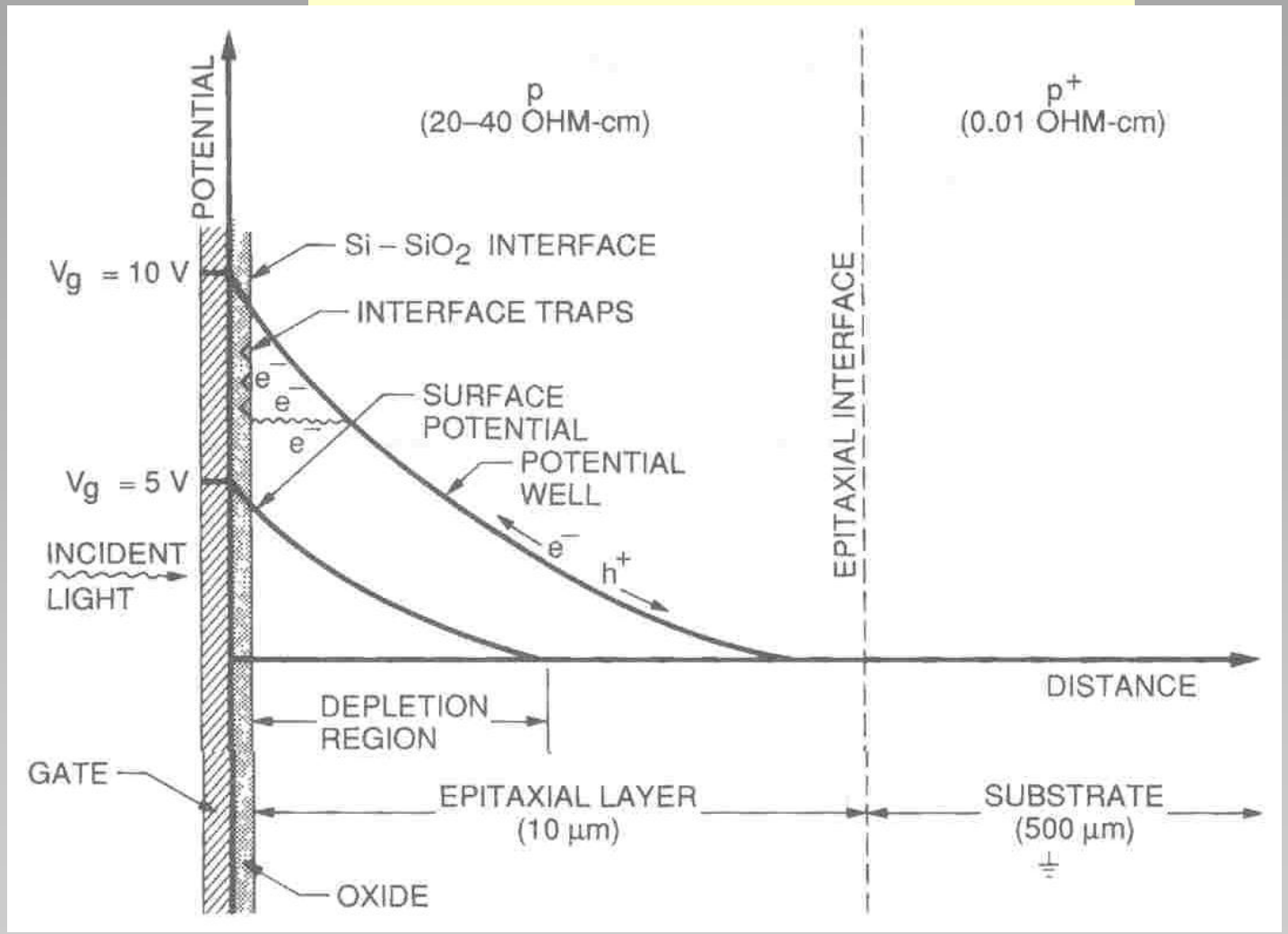
Detectors II

"Bucket brigade" analogy for a CCD

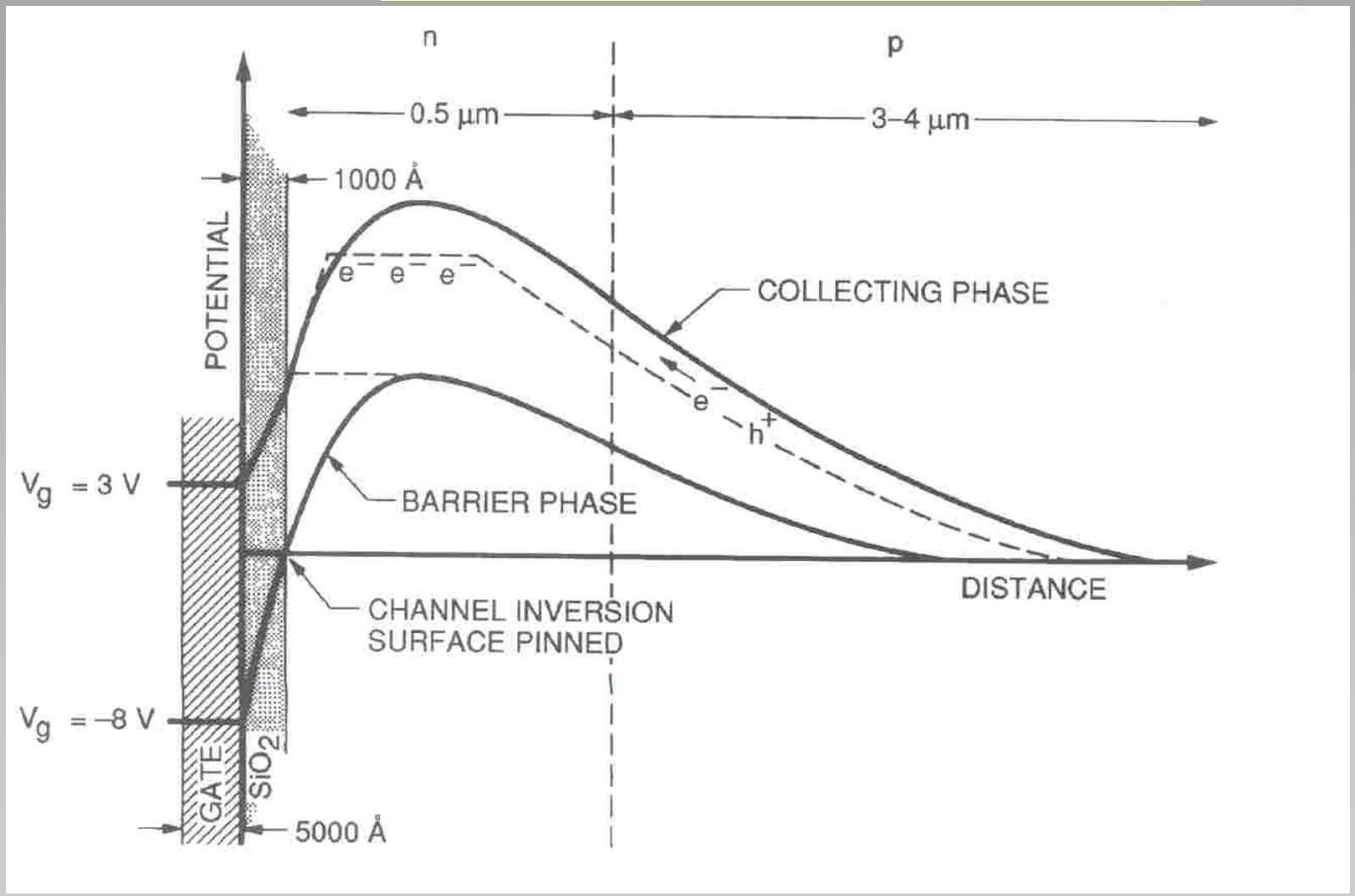


Detectors II

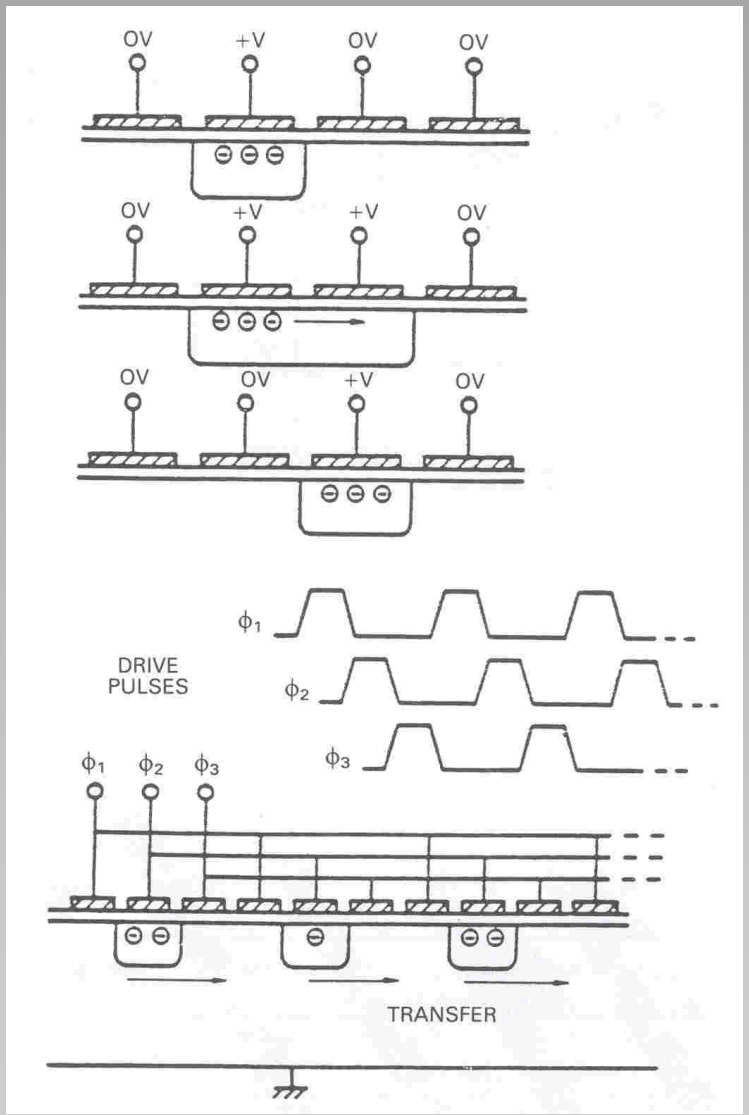
Surface Channel CCDs



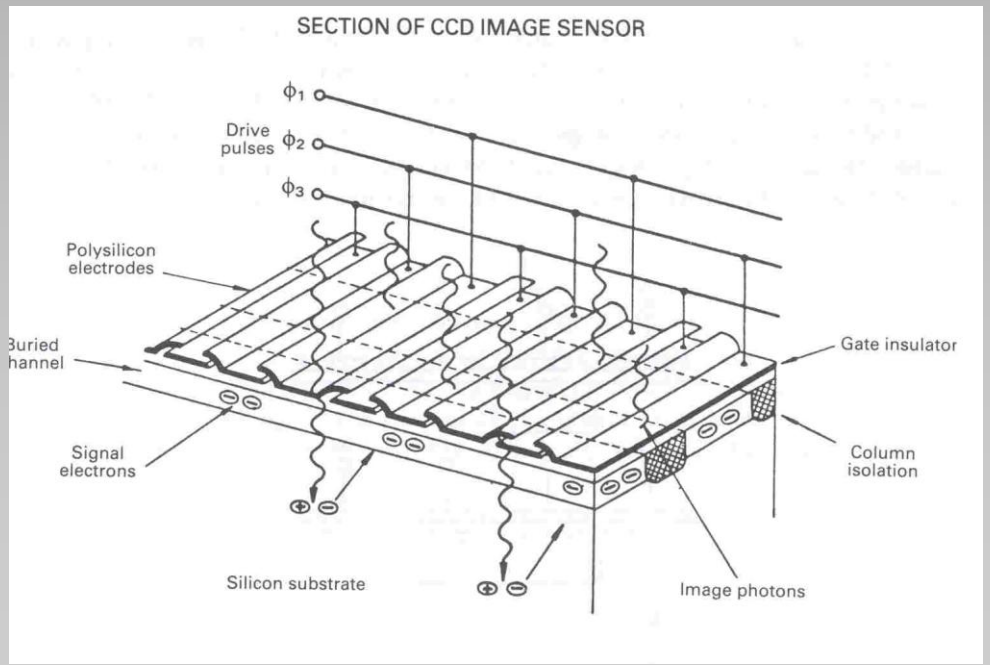
Buried Channel CCDs



Three-phase clocking



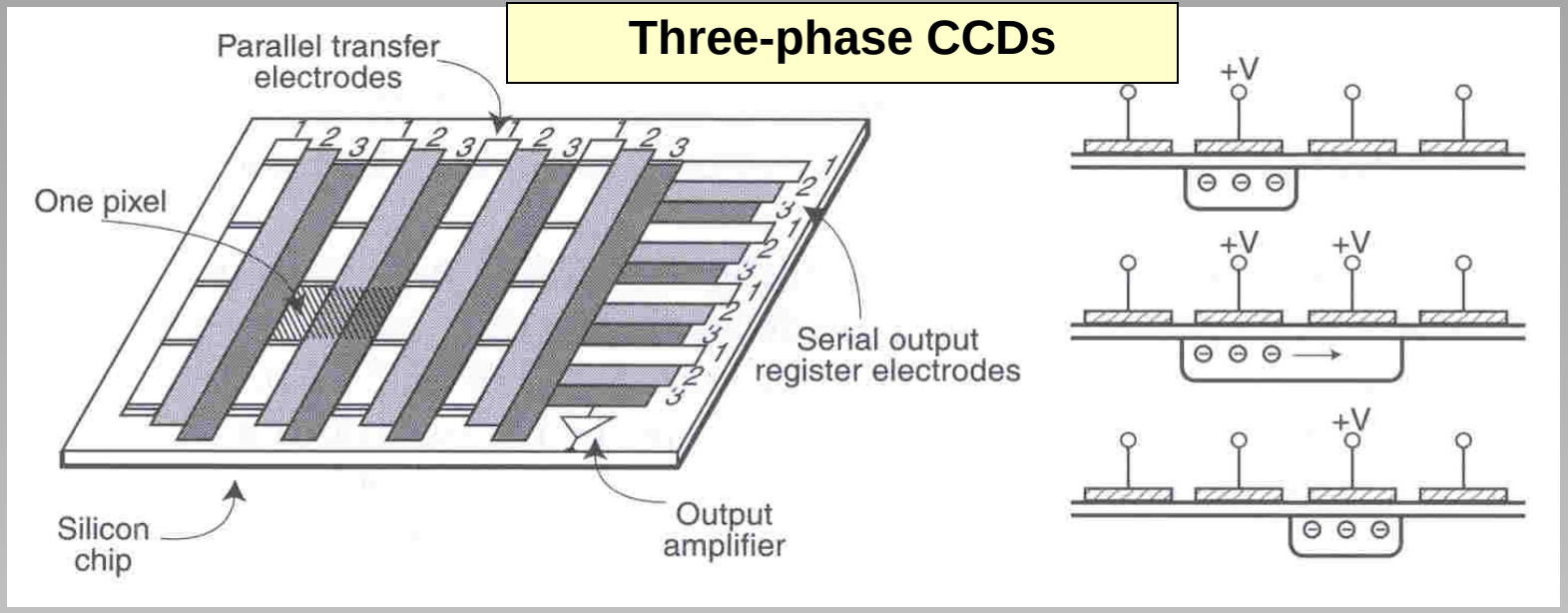
- Control electronics provide for fast clocking of voltages, up to a frequency of a *few hundred MHz.*
- Waveform frequency and shape determines how fast and efficient the charge is transferred (latter is called ***Charge Transfer Efficiency***, or CTE).
- The clock, or drive, pulses for the electrodes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



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Three-phase CCDs



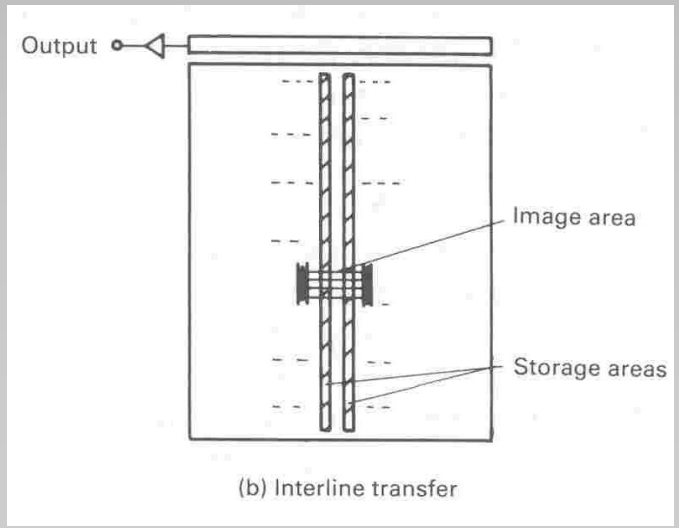
- **Apart from the initial efficient conversion of photon → ē, and 'trapping' at a specific place in the Si array, the CCD needs to '*read out*' the resulting charge.**
- **One of the basic initial CCD designs was the so-called '*three phase*' CCD consisting of 3 separate electrodes per pixel.**
  - **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.**

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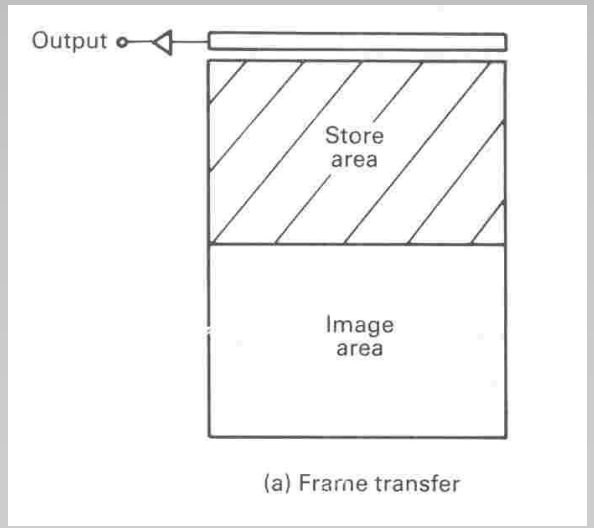
Detectors II

Interline and Frame Transfer CCDs

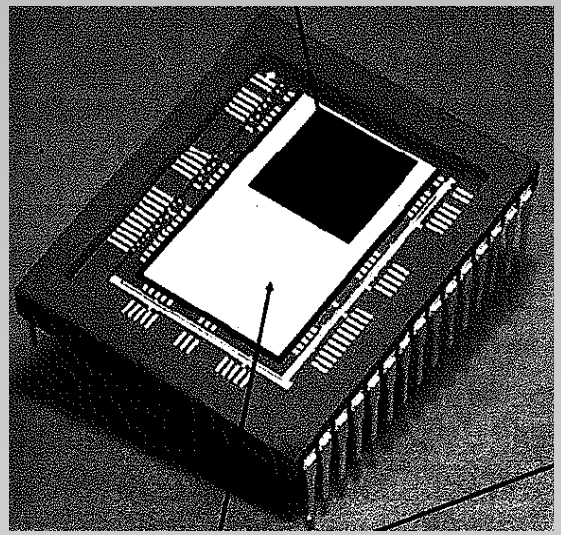
- Clocking takes finite time to transfer the pixels (in parallel) to the serial readout register(s), which also has to transfer it's charge packets to the readout amplifier(s).
- For fast rates applicable to video camera (e.g. >25 frames per second), then the simple three-phase readout is too slow. Two 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

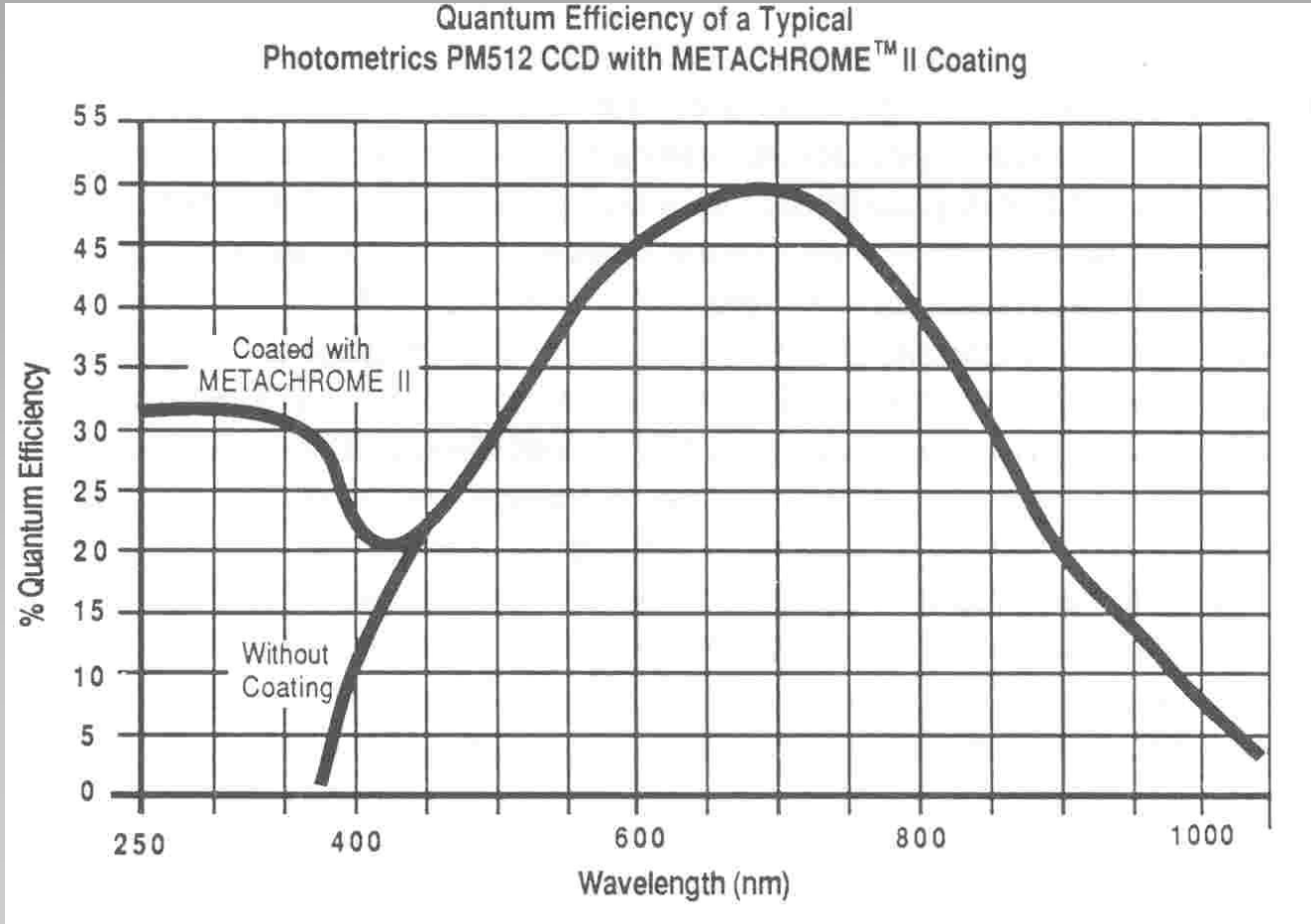


Backside Illumination of CCDs

- **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!**

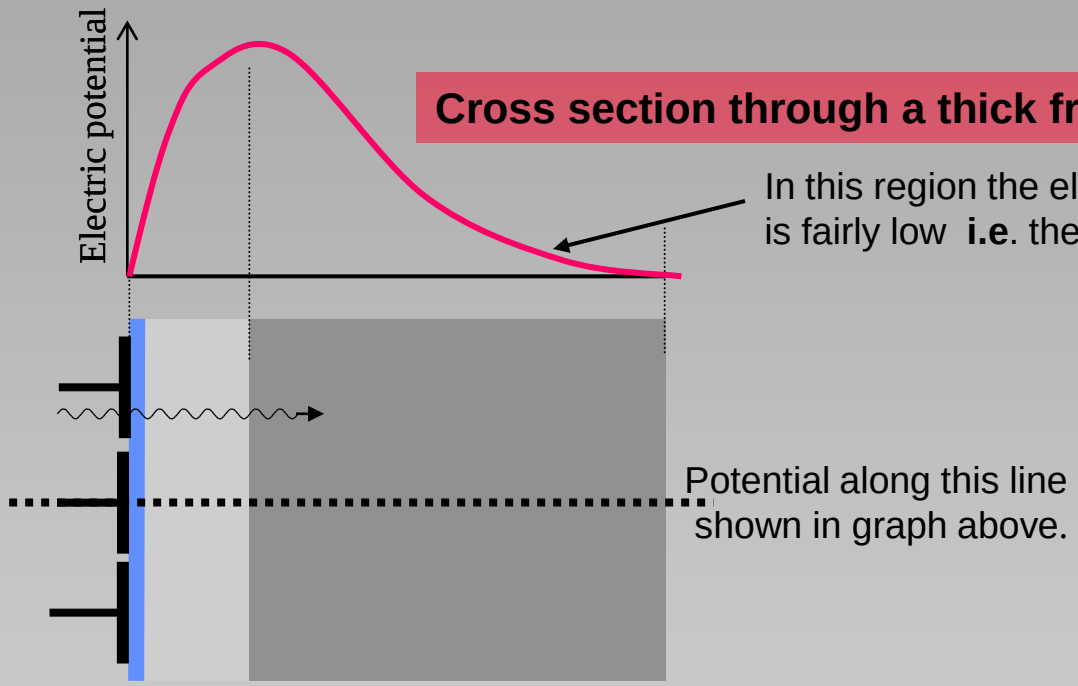
Other ways to increase CCD blue response

- 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.

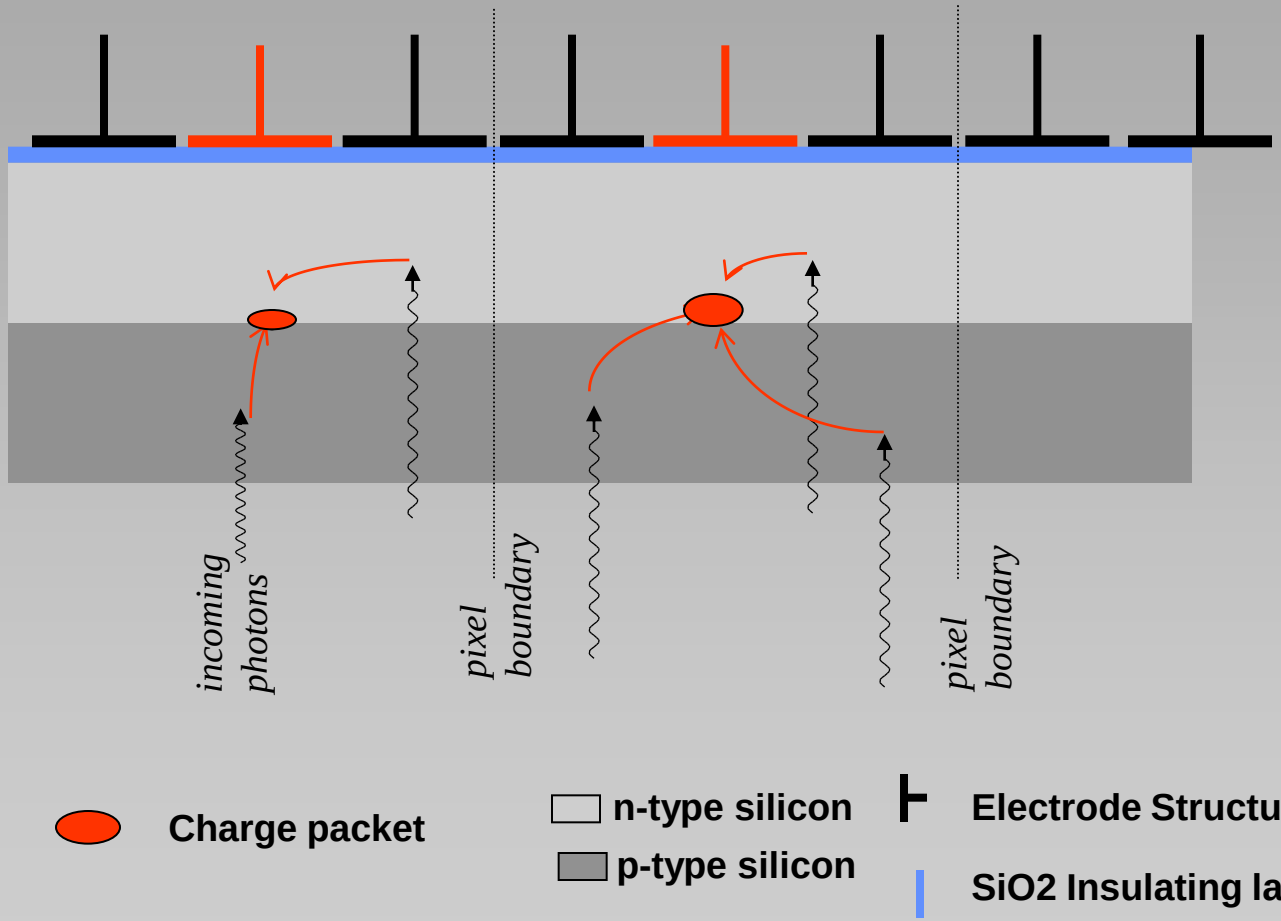


Any photo-electrons created in the region of low electric field stand a much higher chance of recombination and loss. There is only a weak external field to sweep apart the photo-electron and the hole it leaves behind.

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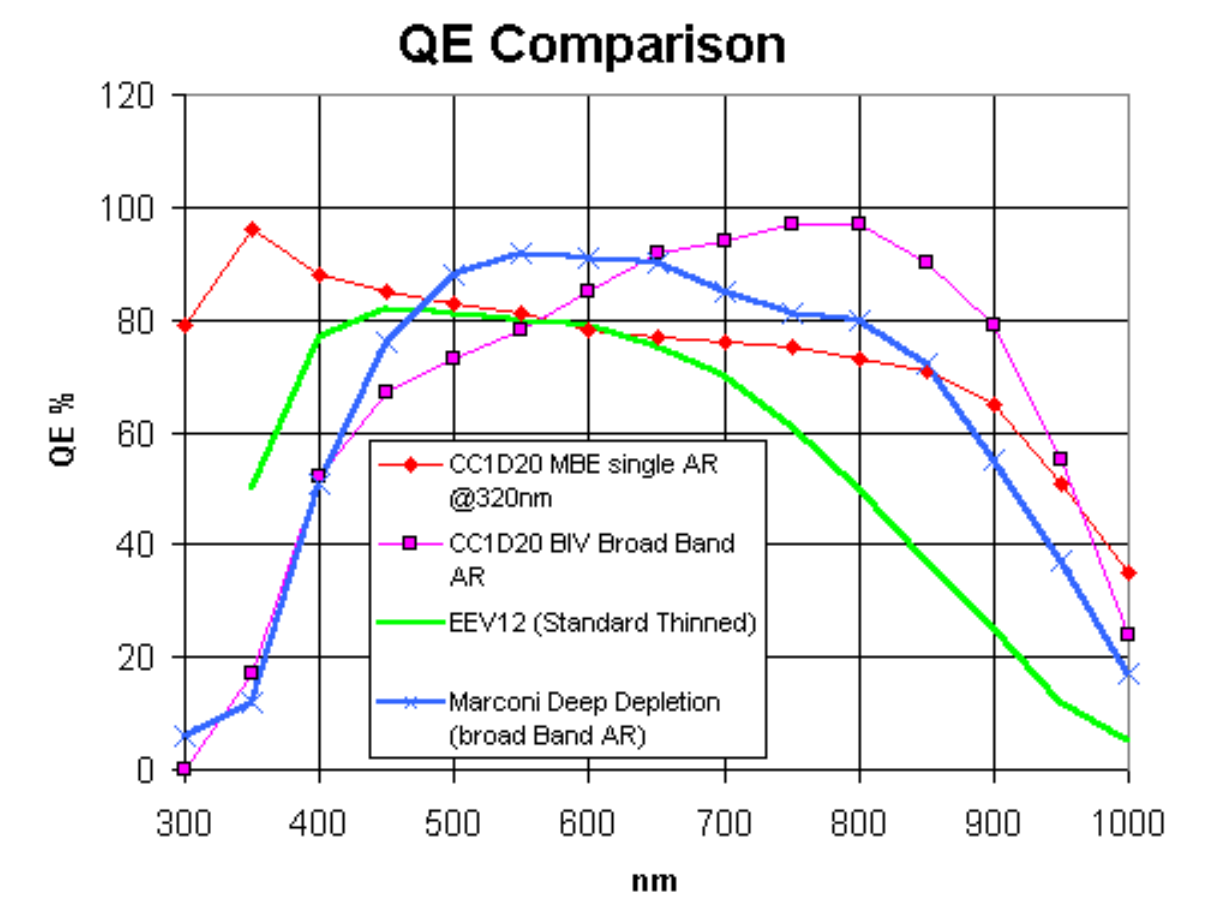
Charge Collection in a CCD

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



CCD sensitivites

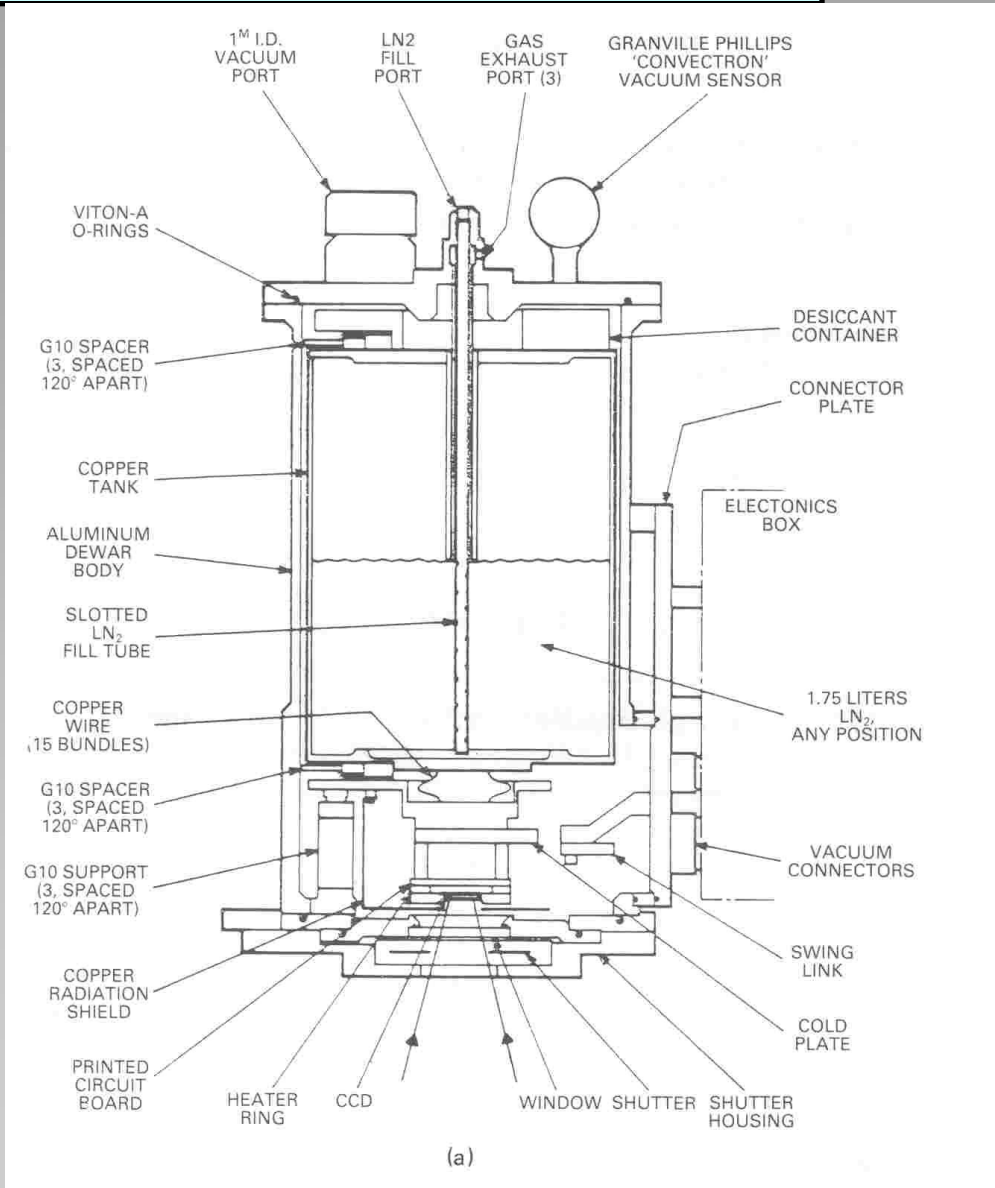
- **Quantum Efficiencies (QEs) are one of the most important parameters of a CCD. What are the properties of modern CCDs (e.g. buried channel, back-illuminated, thinned, doped, deep-depletion, etc)**



Detectors II

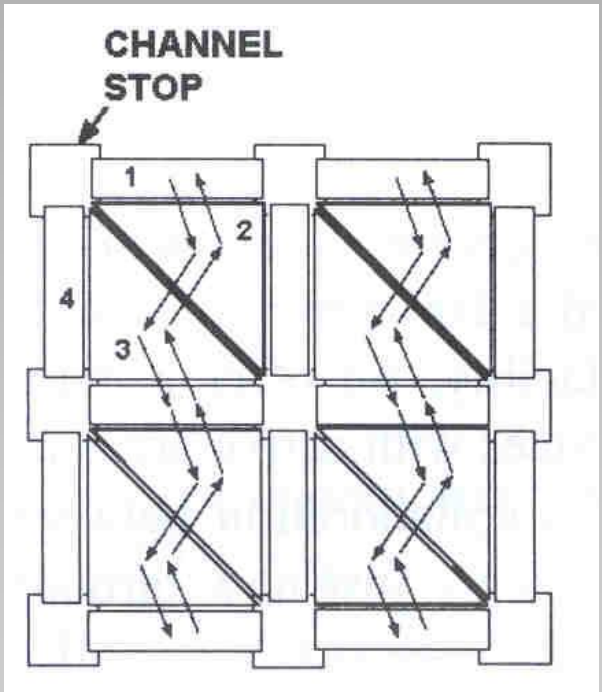
'CCD Cameras

- 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.

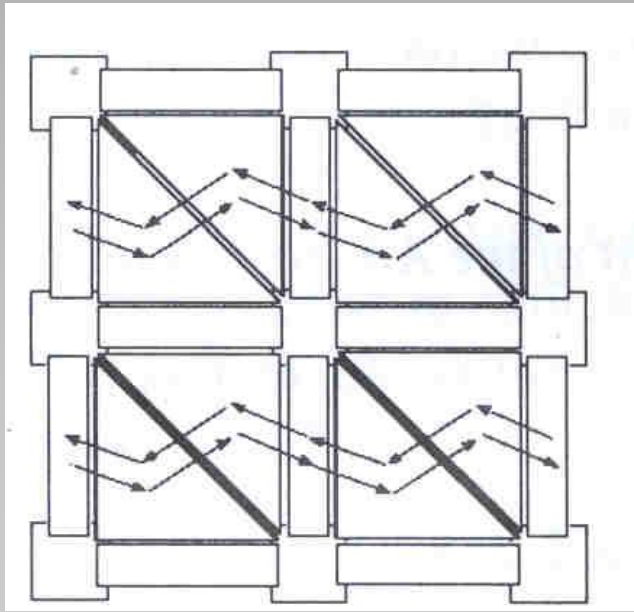


New developments in CCDs

- **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

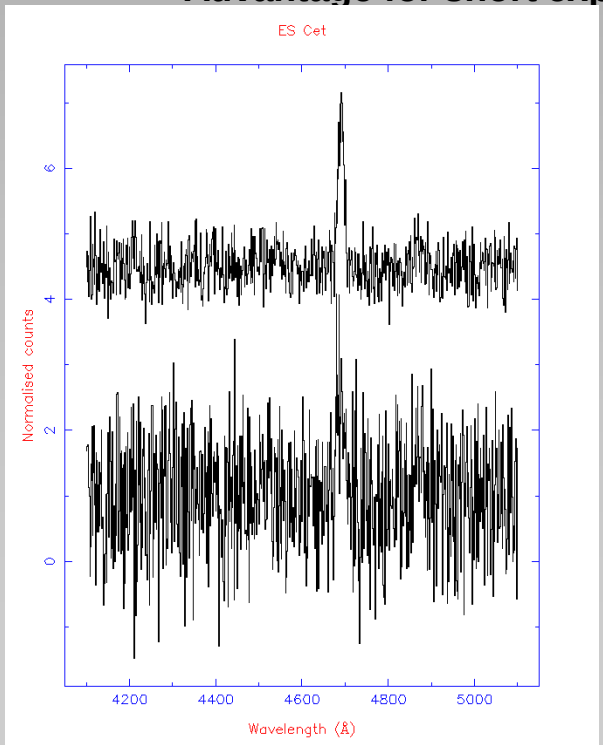


Horizontal transfers

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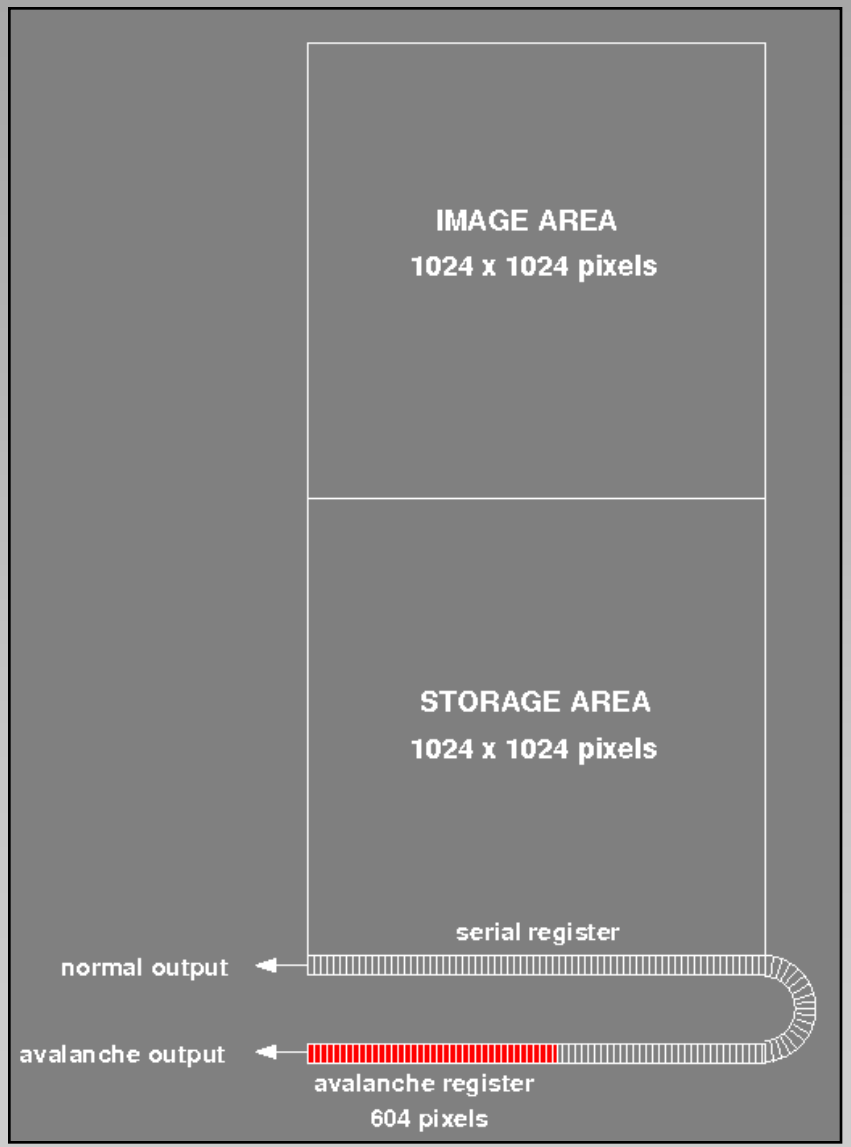
New developments in CCDs

- **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



EMCCD

Normal CCD



~~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.

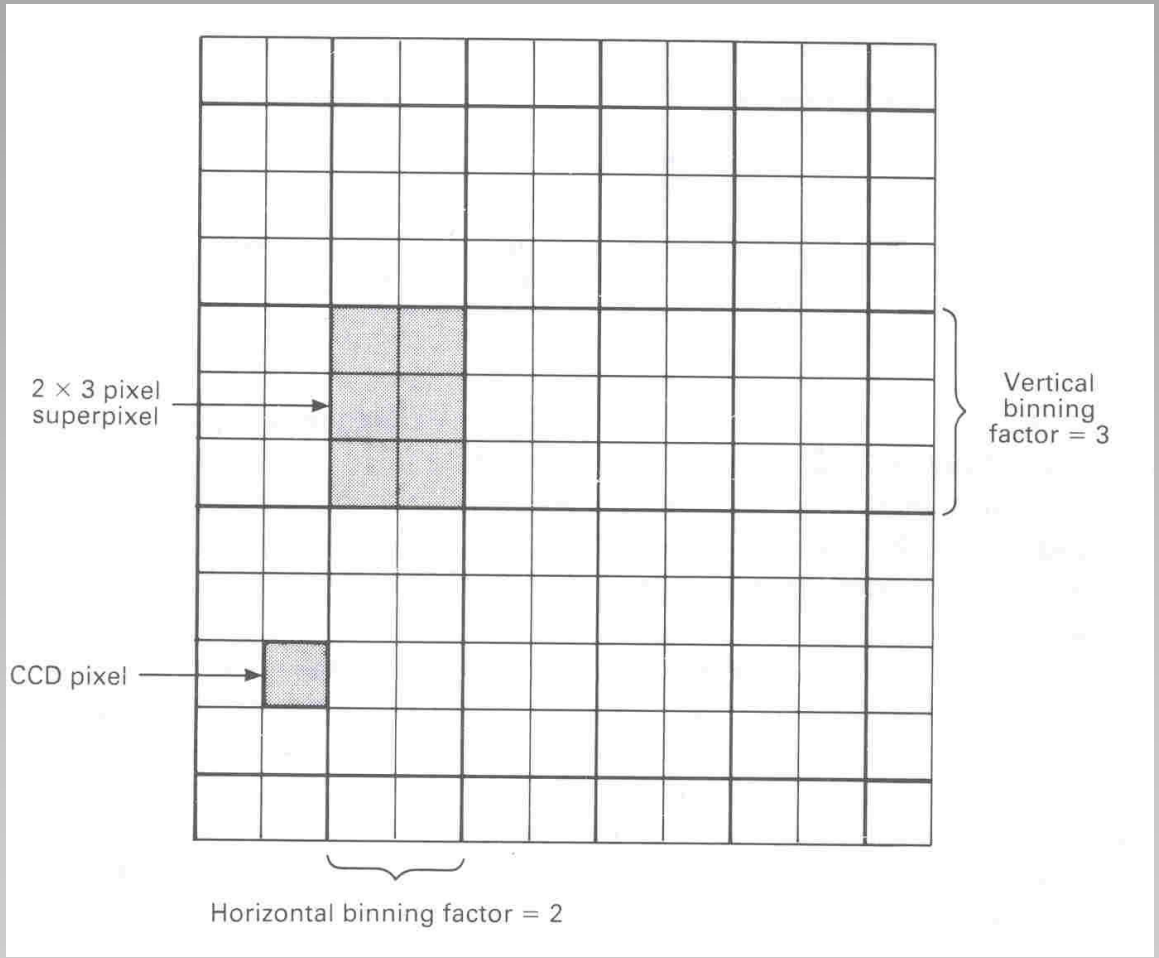
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Detectors II

On-Chip Binning

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

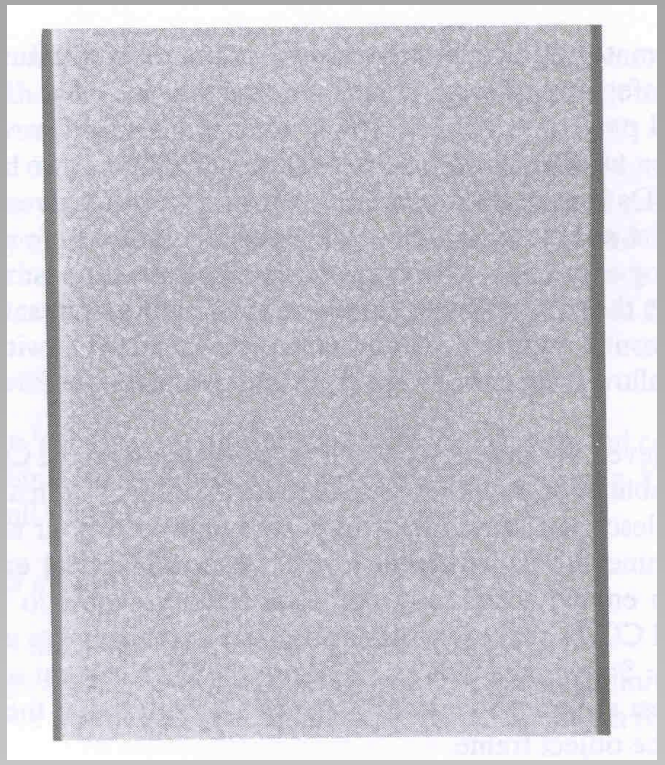
1. delaying the serial register shift after a parallel shift, or
2. not resetting the output capacitor after a serial transfer



Readout Noise in CCDs

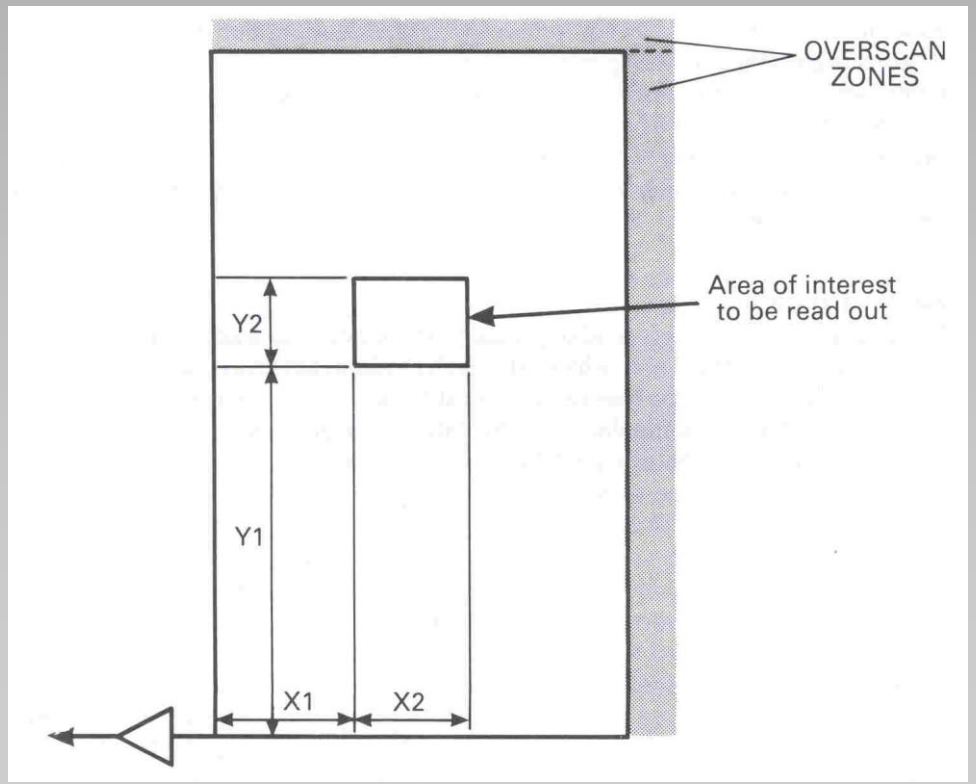
- Ideally only associated with the output transistor (on-chip)
- Other noise sources arise from electronics affecting the weak signals (typically few 10's of microvolts)
  - Background charge associated with DC offsets
  - Charge transfer fluctuations
  - Reset ('kTC') noise (resetting node output capacitance). 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*.**

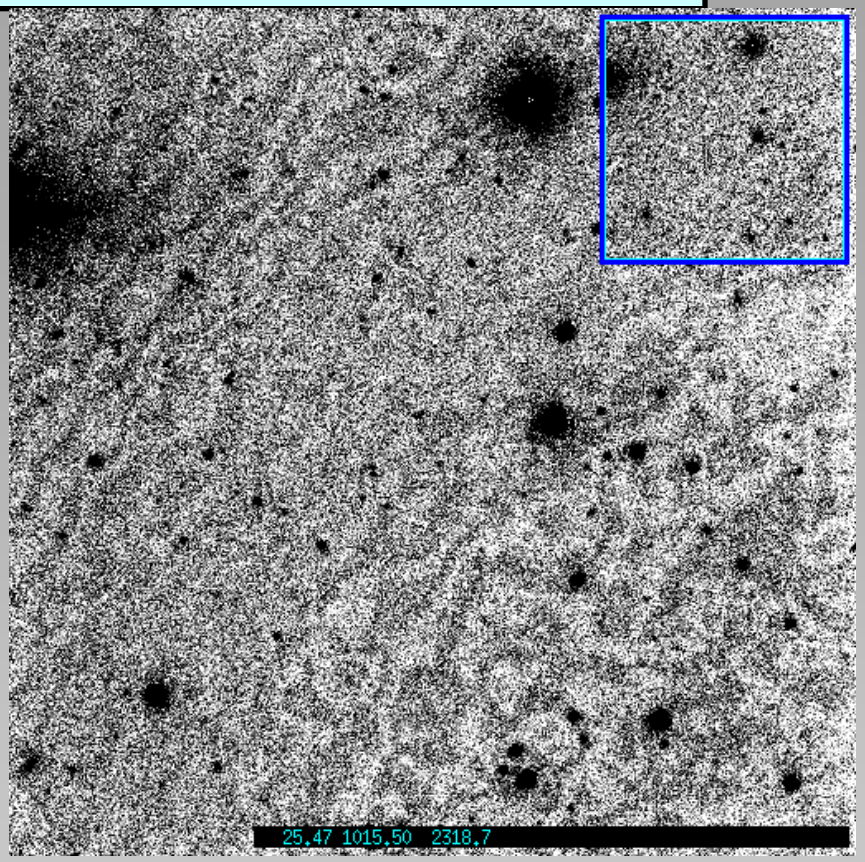


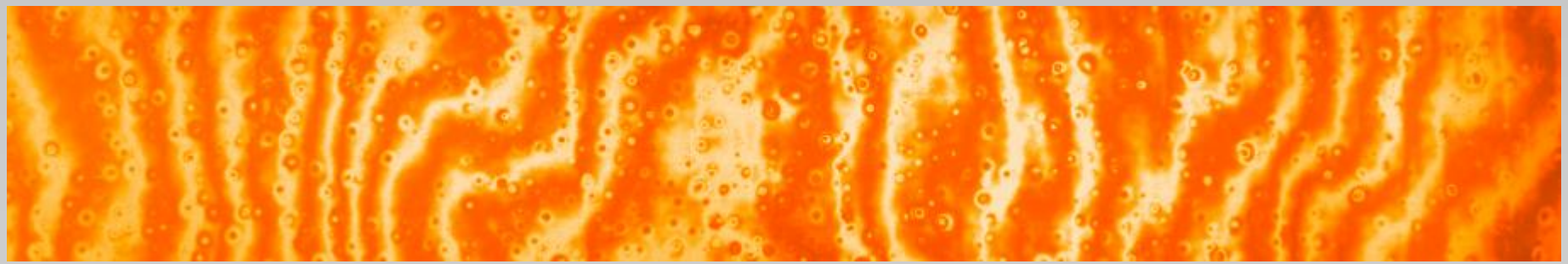
Modern CCDs have good bias (i.e. both constant in time and position).
So rather than take bias frames (wasting time), just use part of the unilluminated portion of CCD (overscan).

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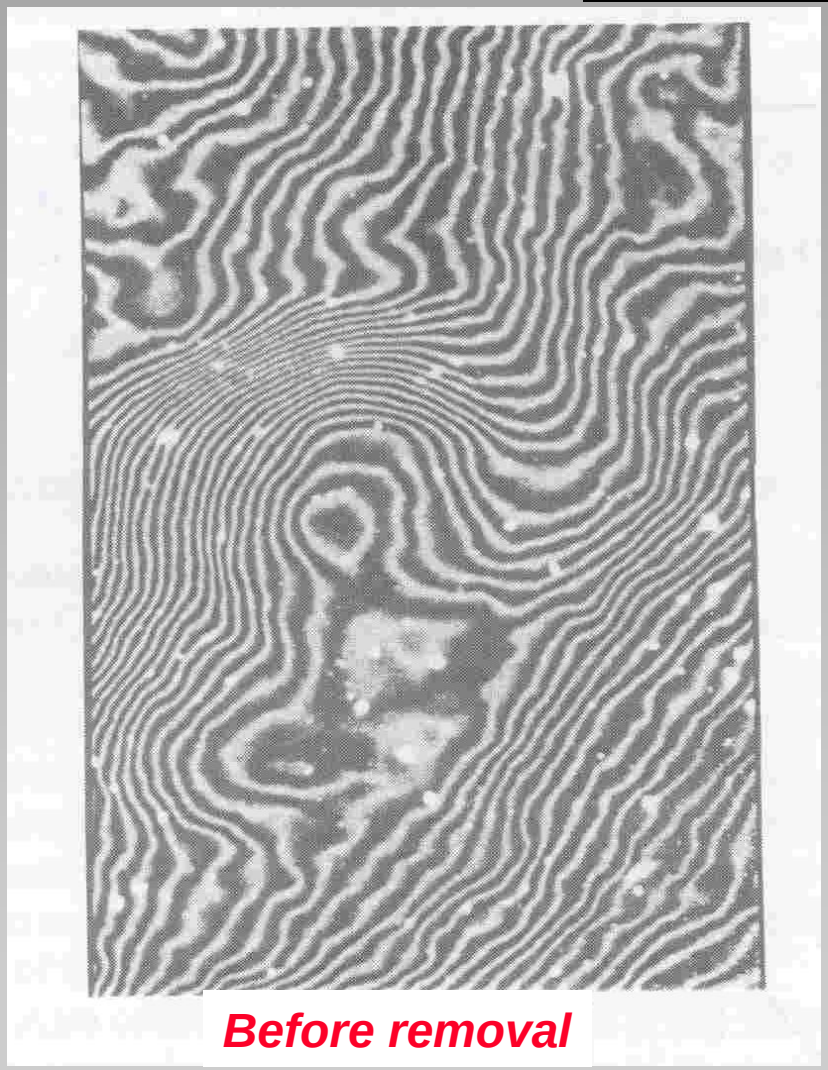
Fringing

- 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%!

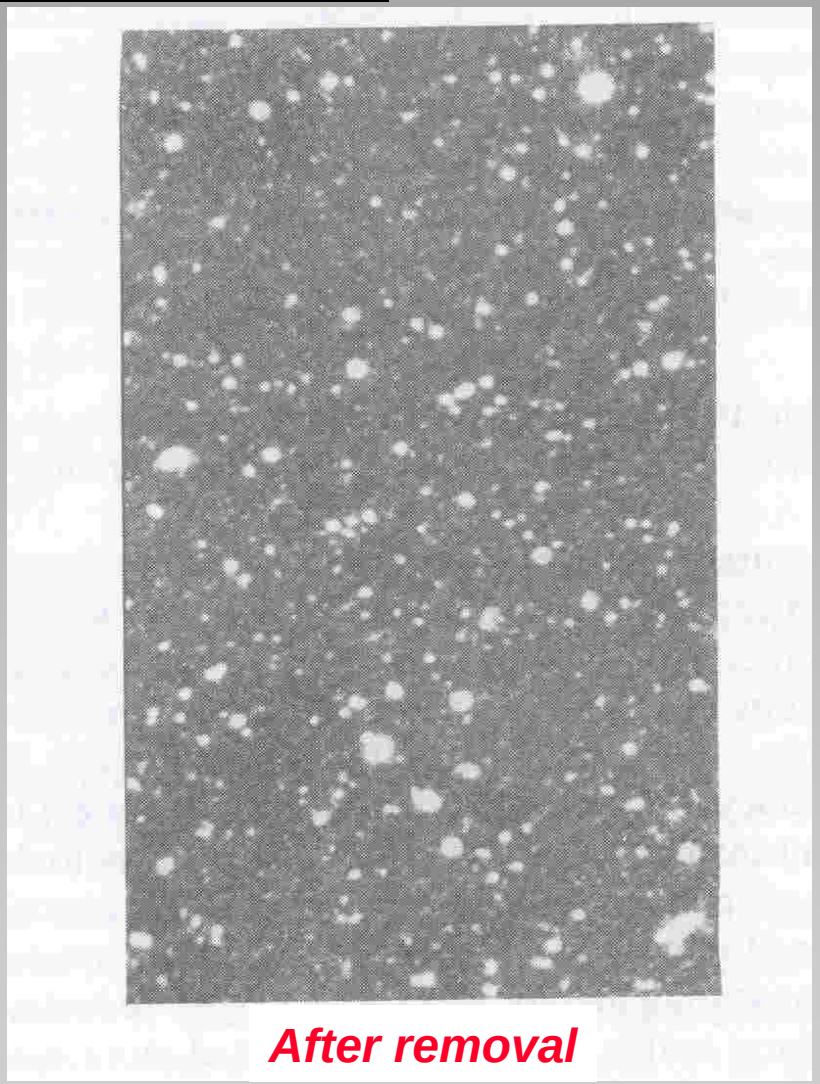




Removal of Fringing

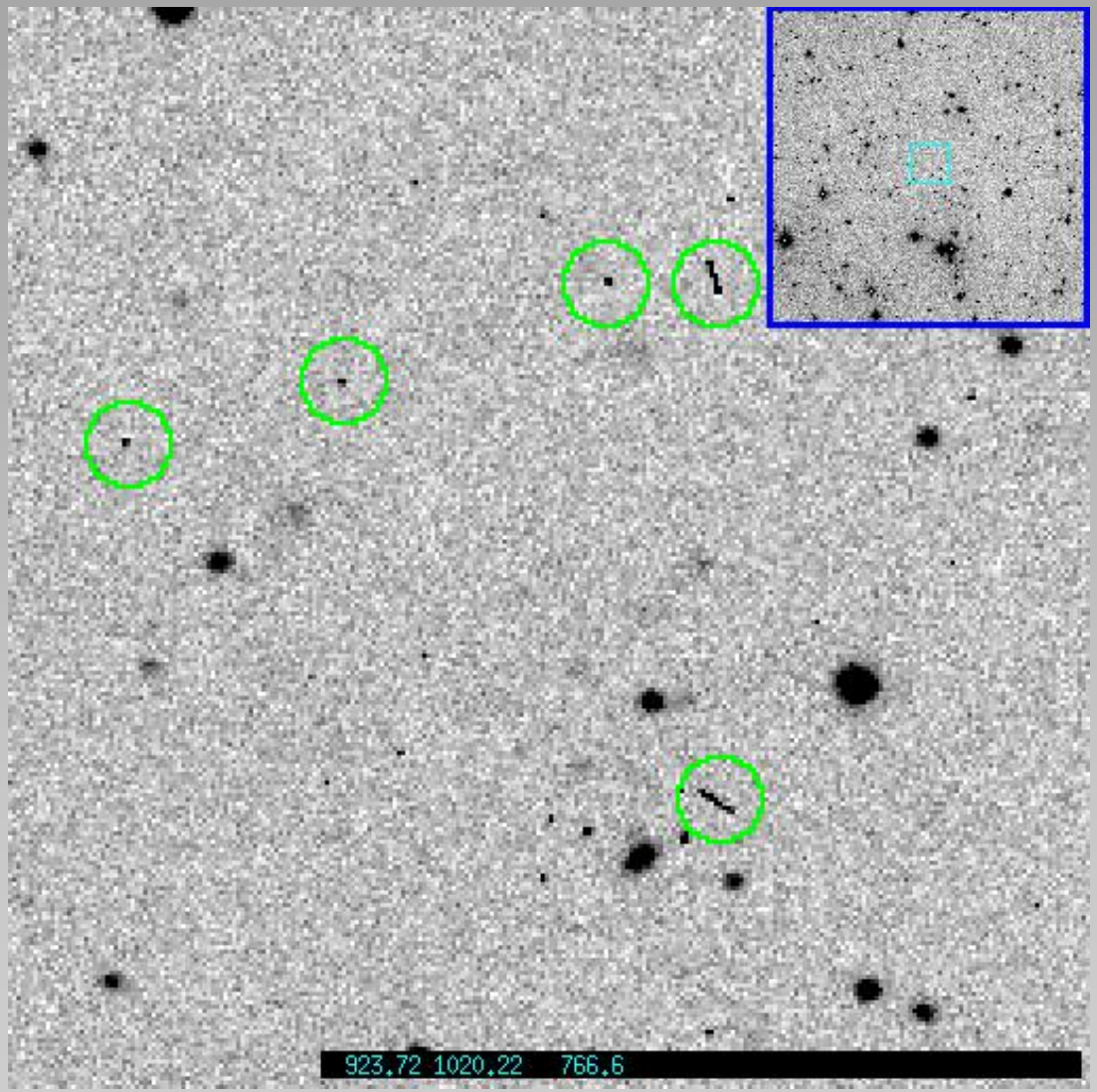


Before removal



After removal

Cosmic Rays

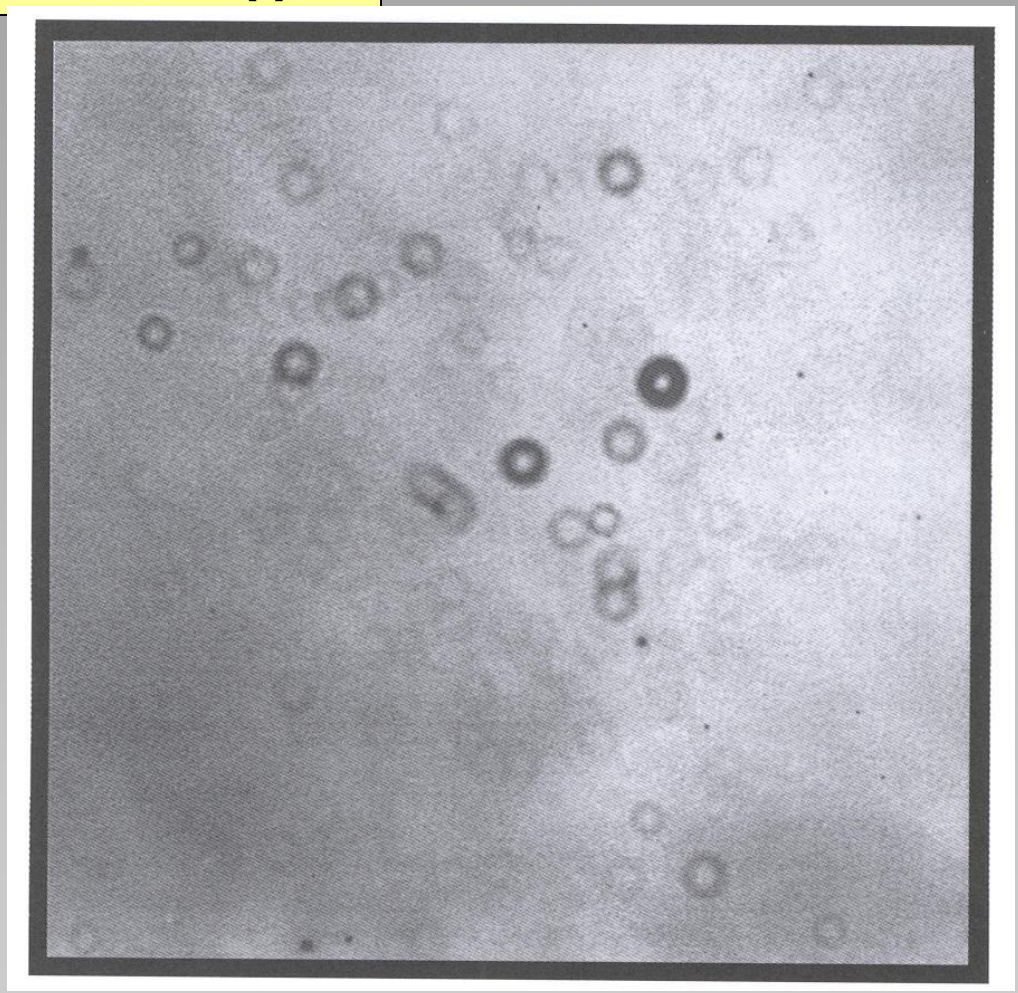


- CCDs are efficient at detecting the secondary particles of *cosmic rays.*
- These are typical *muons* which are absorbed in the Si lattice of the CCD
- Energy released from pair production leads to ~80ē/pixel/μm
  - For a typical 20μm depth, a cosmic ray can generate ~1000ē
  - Appears as a ‘spike’ 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'.

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

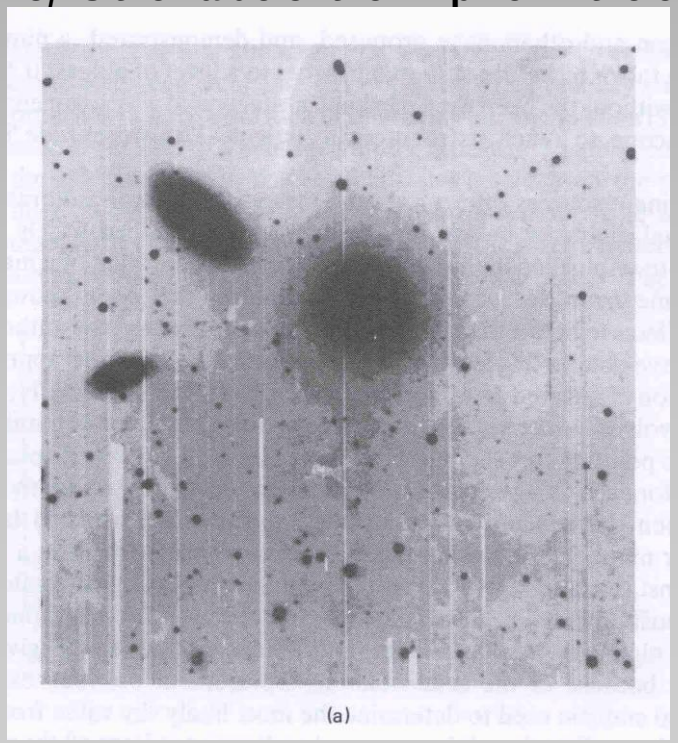
Where:

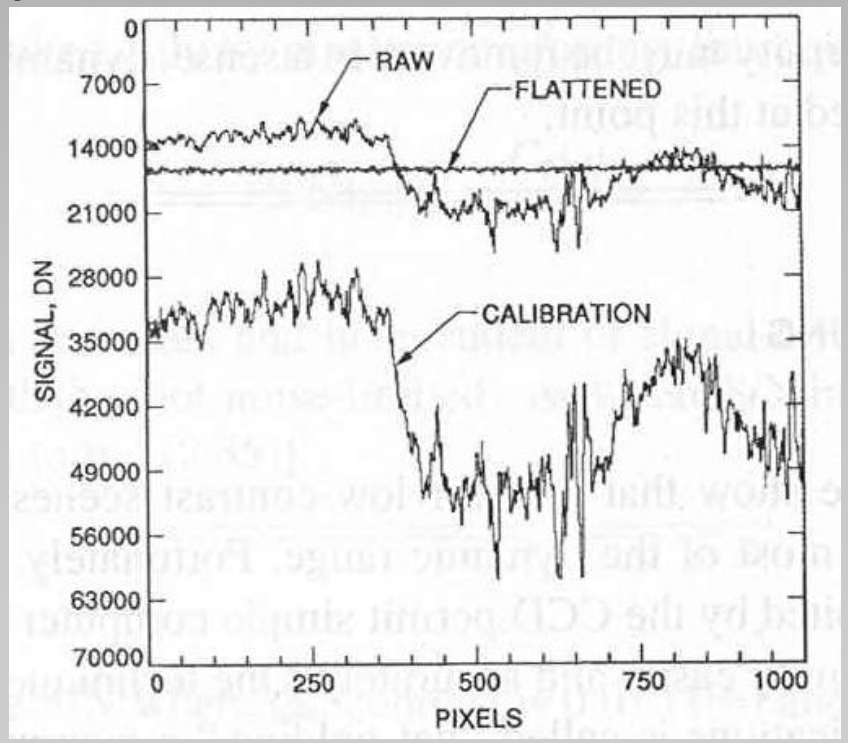
μ_s is the mean pixel value of a $n \times n$ sub-array of the flat field CCD frame

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

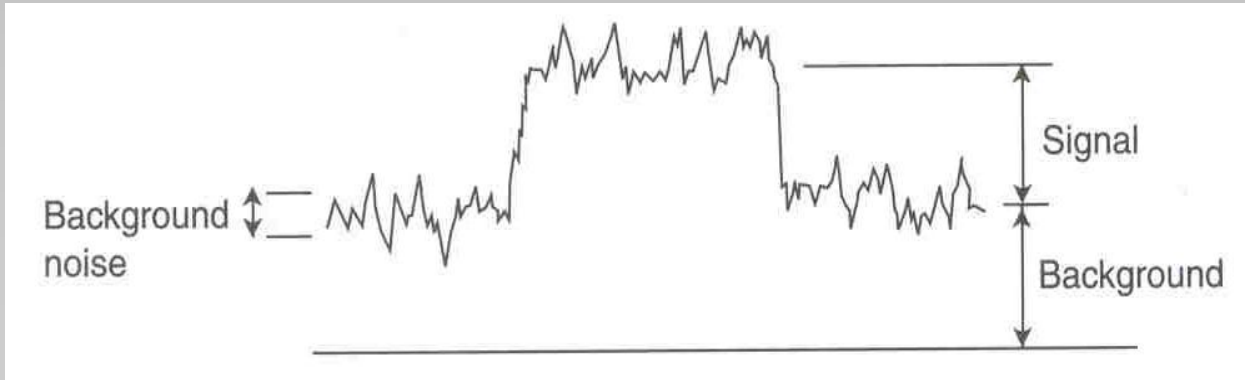




Signal-to-Noise

- **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:**

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

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.

Optical/IR Observational Astronomy

Detectors II



"Actually they all look alike to me."