NASSP LECTURE NOTES:

THEORY AND APPLICATION OF CCDS IN ASTRONOMY

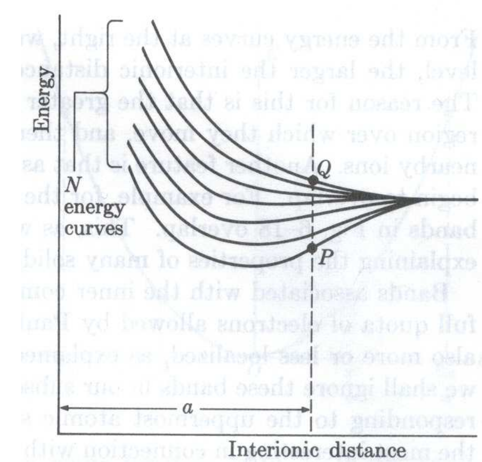
David Buckley
SALT/SAAO
Email: dibnob@saao.ac.za
Phone: 4606286

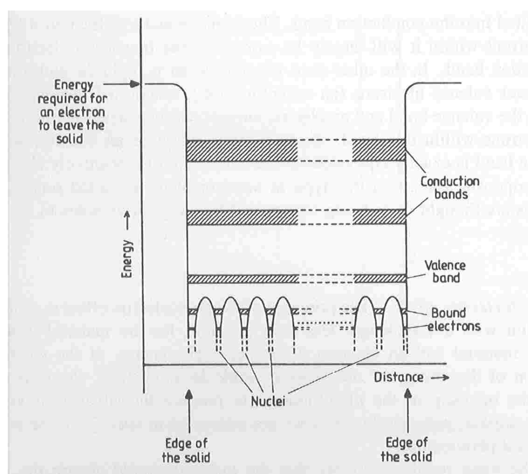
PRECURSORS: PHOTOMULTIPLIERS

•Based on the photoelectric effect
•Low noise photon counting devices
•But only *single* channel
–No "multiplex advantage"
–Like a single cell in the retina
•Need for efficient, low noise "panoramic" detector better than a photographic plate
•Attempts using TV tube-based technologies
–Combine efficiency of a PMT with extended field of a TV camera
•TV imaging devices scan an e-beam across a target previously exposed to light. Amount of current used to 'reset' the target provides intensity information.
•All such devices (including CCDs) derive their properties from the behaviour of *semi-conductors*

PRINCIPLE OF SEMI-CONDUCTORS, ETC

•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



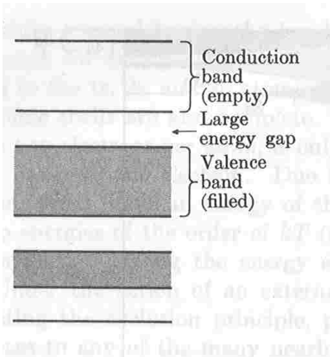


•All but the valence electrons are bound to the individual atoms. They occupy the *valence band*, which binds the solid together.
•For electrical *conduction*, individual electrons must be free to move. Conduction can only occur if there is a suitable E level, above that of the conducting electron.
•If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

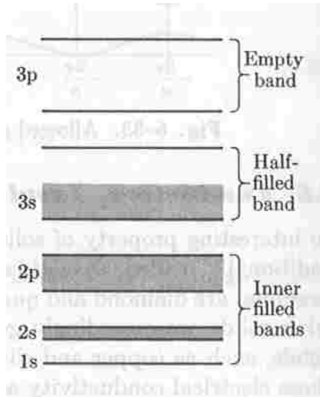
CONDUCTION

•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.*
•Valence band unfilled
–Either only a single S-shell electron

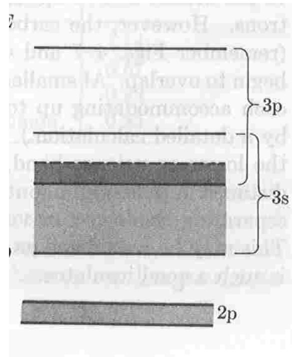
–Or higher E levels sufficiently broadened to overlap valence band
»At T = 0K, all sublevels filled up to the Fermi level, with higher sub-levels unoccupied
»At higher T, some ē's will move into these levels, but there will still be ones unoccupied and available for conduction
»In situation where overlap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



A CONDUCTOR



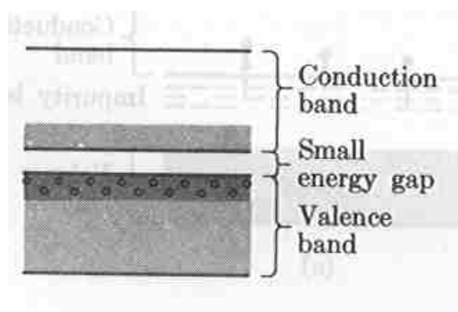
A CONDUCTOR WITH UNFILLED VALENCE LEVELS



A CONDUCTOR WITH OVERLAPPING VALENCE & CONDUCTION LEVELS

•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:

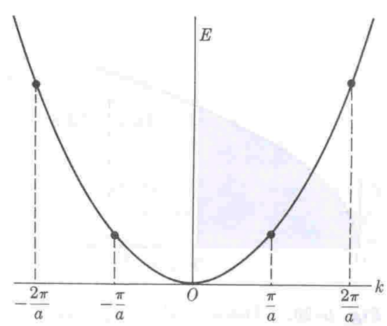
–In a metal, $E_G = 0$, hence excellent conduction
–Insulator has large E_G, resulting in no appreciable conduction
–Semi-conductors have $0 < E_G < 3.5$ eV, resulting in significant numbers of either thermally or radiatively excited electrons available for conduction. Thus semi-conductors are intermediate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

SOLID STATE PHYSICS: REFRESHER

• ***Wavenumber of ē:*** $k = 2\pi/\lambda$
• ***Momentum of ē*:** $p = m_e v = \hbar k$
• ***Wave function of ē*:** $\psi = e^{ik.r}$

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:

$$E = p^2/2m_e = \hbar^2 k^2/2m_e$$



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:

$$L = N a$$

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

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

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

$k_{max} = \pm \pi / a$ for a given band

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:

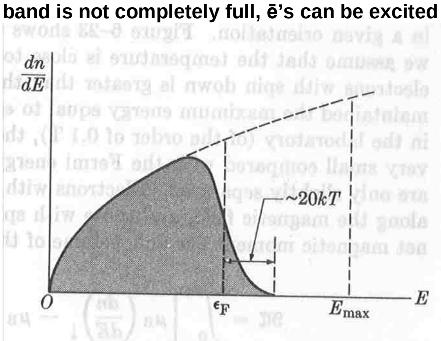
$$dn = 8 \pi (2 m_e^3)^{1/2} h^{-3} E^{1/2} dE, \quad \text{i.e. } dn \propto E^{1/2}$$

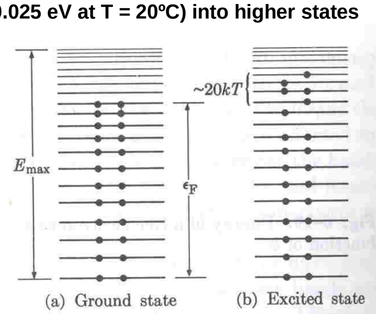
If all ē's are in *ground state* (when at 0ºK), they occupy all of the lowest E levels, compatible with Pauli exclusion principle (i.e. each level is occupied by 2ē of opposite spins).
If total number of ē's, n_0, < total number of E levels, then at T > 0K, all ē's occupy E levels up the *Fermi energy,* ε_F.

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

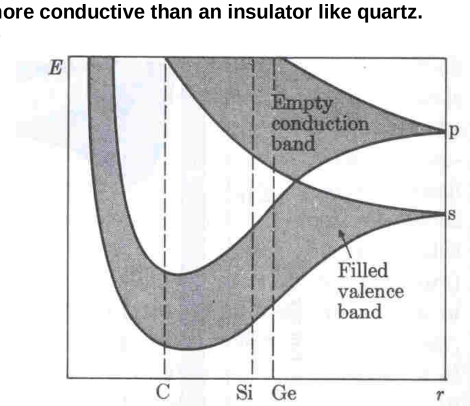




ENERGY LEVEL DIAGRAMS

•Conductors and Insulators

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

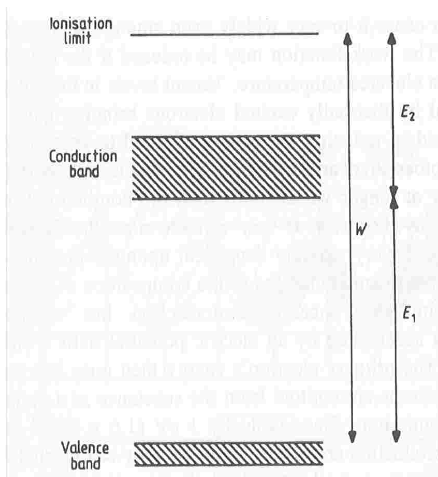


Above: **Example for insulator (carbon; diamond) and two semiconductors (silicon and germanium).**

In former, the 2s and 2p levels (allowing, respectively, 2 and 6 electrons) overlap, forming two levels. At the typical inter-atomic distance for diamond, the two bands can accommodate 4ē each, but are separated by 5eV, preventing ē's from easily moving into the upper conduction band, explaining why diamond is such a good insulator.

PHOTOELECTRIC EFFECT

• Photoemission occurs if the E_{photon} > "work function" of the photoemitter.
• Work function is the difference between ionization (¥) level and the top of the valence band.
• Value can be increased by effects of pair production
– Particularly for photons E above the minimum.
– Can reduce expected flux of photoelectrons at shorter wavelengths (higher E)
• Work function is also dependent on surface properties (e.g. defects, oxidation, impurities)
• Work function can be reduced if photoemitter at elevated T.
– Vacancies in upper valence levels filled by thermally excited electrons from lower levels. Thus closer to ionization limit and easier to release.



• In PMTs once photoelectron is released from photoemitter, it is accelerated by electrical potential.
• P-type 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.

PHOTON DETECTION IN SEMI-CONDUCTORS

Good photoemitters should have low E loss mechanisms for released photoelectrons
- collisional losses minimized by employing insulators or semi-conductors

Collisional de-excitation of photoelectron by a valence electron is difficult because there are no vacant valance levels for photoelectrons to occupy.
Semiconductors have a relatively low population of conduction band electrons to collisionally de-excite the photoelectrons
- main E loss mechanisms for photoelectrons in such materials are:

1. Pair production (ē – hole pairs in conduction – valence bands)

2. Phonon production by collisions between photoelectrons and atoms in crystal lattice, particularly at discontinuities (i.e. sound production). Only few % of electrons E is lost in this way, but mean free path is small (few nm), thus can be significant loss mechanism. Reduce effect by cooling material, thereby reducing number of quantised vibrational excitation states.

(Electron-Hole pair production is the important mechanism in a CCD)

• Intrinsic photoconductors comprise all Si, Ge, HgCdTe and InSb type semi-conductors and 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.

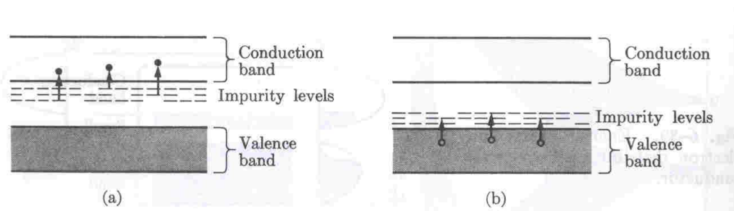
•Semiconductors working at lower E / longer wavelengths are referred to as *extrinsic photoconductors*. These have *dopants* – impurities added to the semi-conductor. Conduction then occurs when valence electrons from the dopant, rather than the semi-conductor, are promoted into the conduction band.
–Such devices designated by the notation *semiconductor: dopant, e.g. Si:As* (which is preferred technology for mid-IR [5-30mm] 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.

•A pure (intrinsic) semi-conductor will, statistically, have equal numbers of electrons available in the conduction bands as there are 'empty spaces' in the valence bands.
–For Si, there are 4 valence ē's available, distributed in the overlapping 2S and 2P energy levels (which can accommodate 8ē).
•Imbalances can be induced by 'doping': the addition of other atomic species.

• N-type
– If doping atom has higher number of valence electrons, and these occupy new energy levels between the valence and conduction bands.
– From there they are more easily excited into the conduction band and current is carried by the (negative) electrons in this band.
– This type of semi-conductor is referred to as 'n-type'.
– These are "donor atoms" – making available their ē's for conduction

• P-type
– If doping atom has fewer valence electrons, then more 'spaces' become available in the valence band
– Hence the current will be carried by electrons in the valence band.
– Since the movement of an ē in the valence band is equivalent to the motion of a positive 'hole' in opposite direction, this type of semi-conductor is referred to a 'p-type'.
– These a "acceptor atoms" - taking up ē's from conduction band



• Photoelectric effect: photon absorption by a photoemitter
– Photon of wavelength < certain limit is absorbed and an electron emitted. E of ē is function of E of photon, while *number* of electrons emitted is dependent on photon flux.– Main requirements for good photoemitter:
» should absorb radiation efficiently (i.e. not reflect it, like a metal)
» mean free path of ē's emitted > photon mean free path
• e.g. in a metal conductor there are many vacant sub-levels near their Fermi levels. After a photon absorption, emitted ē is moving energetically and looses E due to collisions, thereby preventing escape from surface of metal
– Mean free path of ē is ~1nm while photon's is 10 nm. Little chance of emitted electron escaping and therefore conducting.

P-N JUNCTIONS
• When n-type semi-conductor is butted with p-type, create a p-n junction or diode.
• On average, more conducting ē's in n-type than p-type, so set up of an E-field between them.
• Diffusion results (ē's migrate to the p-type, holes to the n-type in the 'depletion region'). Sets up equivalent of a capacitor.
• If a +-ve voltage is applied to n-type and –ve voltage to the p-type, diffusion can be halted (reverse biasing). Diode will only conduct when the *difference* is strong enough to overcome voltage established by charge diffusion. In case when –ve voltage is applied to n-type and +-ve to p-type (forward biased), then even more ē's pile up in p-type and more holes in n-type.

• 'Reverse biased' diodes are the basic photo-sensitive elements of modern CCDs (and IR arrays)
• Light entering diode creates ē – hole pair (i.e. valence ē in conduction band, leaving a hole)
• Because charge is mobile, it can migrate to depletion region of the p-n junction, and ē goes to p-type side, hole to n-type side, eliminating a unit of charge from capacitor.
• These photo-excited charges 'bleeding off' the bias is the physical method of charge collection.
• Absorption of photons is energy dependent, with higher E (shorter wavelength) photons absorbed more readily. Longer wavelength photons penetrate deeper into the crystal, and once energy < E_G, then no longer absorbed (cutoff wavelength).
• This happens at 1.12eV, or a wavelength of 1.1µm ($\lambda_c = hc/E_G$)

•At p-n junction, ē's from n-region diffuse into p region, filling up some of the 'holes' in the valence band, ē's cause a negative charge to build up in the p-region near the boundary. A potential is therefore set up.
•Narrow depletion region is formed where the majority charge carriers (ē's for n-type; +ve holes for p-type) are 'depleted' relative to concentrations well away from the junction.
•Eventually the diffusion process leads to electrostatic potential barrier, tending to repel further diffusion.

•Magnitude of potential barrier, V_0, depends on the impurity (i.e. dopant) concentrations, or the number of donor electrons at the junction which transfer into nearby acceptor levels.
• This is shift of E-bands needed to ensure Fermi level is constant throughout the crystal.

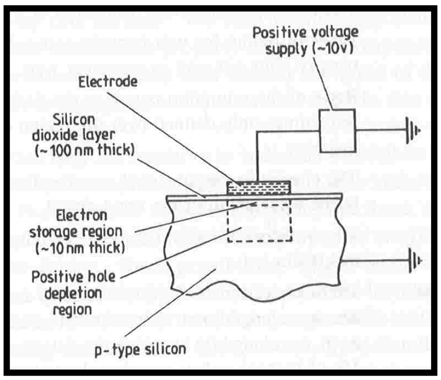
BASIC CCDs

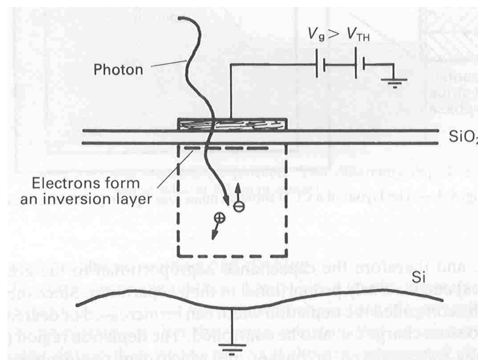
Invented by Boyle & Smith at Bell Labs in 1969

Charge Coupled Device:

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

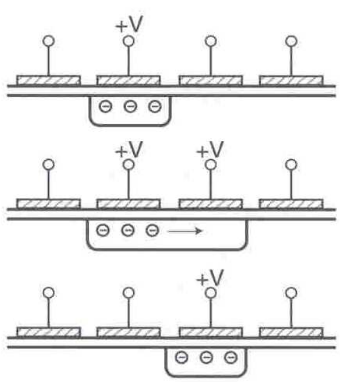
CCD is a *metal oxide structure* (MOS), consisting of a transparent metal electrode separated by a ~0.1µm of SiO_2 insulator from a layer of p-type Si. Thus it is a simple capacitor, capable of storing electrical charge.•CCD behaves as a two dimensional array of Si p/n junctions. The whole array is essentially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





CCD PRINCIPLE

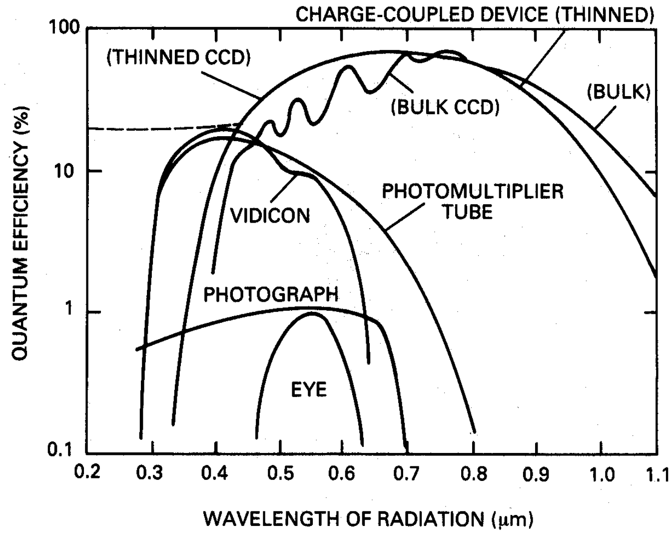
• Positive voltage applied to the electrodes *sweep* the majority charge carriers i.e. holes, forming a *depletion region* under the electrode.
• Effectively a CCD is a radiation-driven capacitor.
• Photoabsorption creates ē-hole pairs, with the ē's attracted into the depletion region, because of the +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.



ADVANTAGES OF CCDs

•Some of the many advantages of CCDs over conventional electronic and photographic imaging mentioned included:

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 I range
6. Can mosaic many devices to build up a larger detector area



FRONT-ILLUMINATED CCDs

• Semi-transparent electrodes are deposited on Si layer, with insulating layer between.
• Photons rapidly absorbed in the Si layer (particularly higher E / lower λ photons). For efficiency in detection, the released photoelectrons should be released in or near the depletion zone, and this should be as close as possible to the insulated electrode structure.
• During exposure, electrodes are raised to some positive voltage, which attracts the minority charge carriers (electrons) released by photoabsorption.

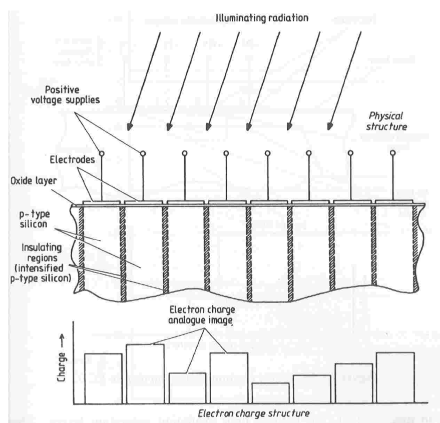
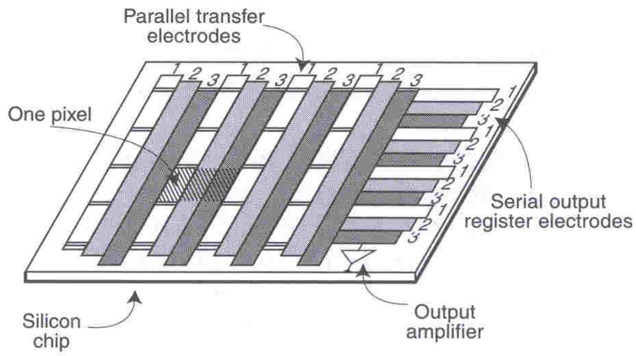


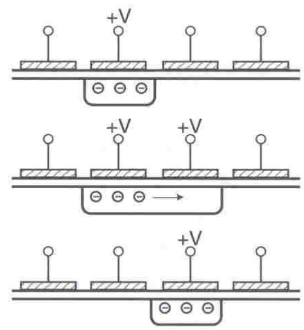
Figure 1.1.12. Array of CCD basic units.

THREE-PHASE CCDs

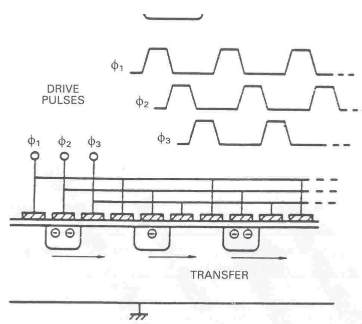
• Apart from the initial efficient conversion of photon -> ē, and 'trapping' at a specific place in the Si array, the CCD needs to '*<u>read out</u>*' the resulting charge.•One of the basic initial CCD designs was the so-called 'three phase' CCD consisting of 3 separate electrodes per pixel.

–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.





• 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.

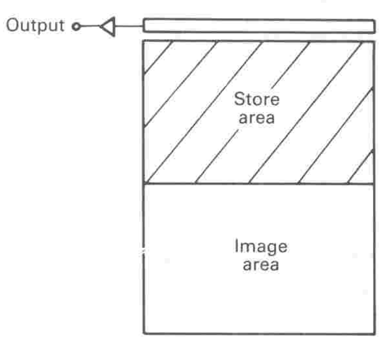


INTER-LINE AND FRAME TRANSFER CCDs

• 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)**



(a) Frame transfer

BURIED CHANNEL CCDs

• The three-phase CCD made from p-type Si is also known as a surface-channel CCD, since the electrons are stored and transferred at the *surface* of the p-type Si lattice.

• There are disadvantages with this approach, due to surface imperfections

–Defects in the crystal structure can lead to charge traps, inhibiting the efficient transfer of charge from pixel to pixel

–Thus the CTE of a surface-channel CCD is poor

–Leads to inaccurate rendering and smearing of images

• To avoid surface trapping phenomena, a 'buried channel' is preferable, where the depletion region is substantially buried in the bulk Si.

• How can this be accomplished ? ***Using a p-n junction***

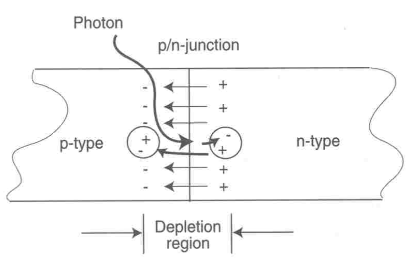
• Photoelectrons produced in ē-hole pair will be repelled by the +ve charge of the p-type Si and attracted to the –ve charge of the n-type, particularly where the E-field is strongest.

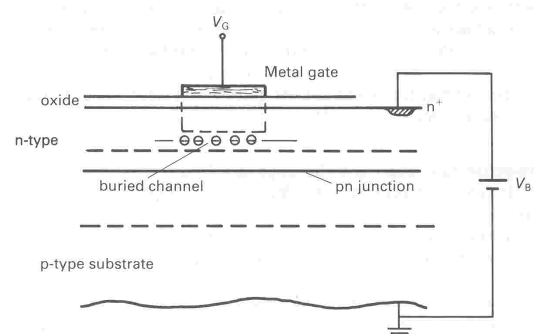
• In the depletion region, the absence of repelling electrons in the n-type Si provides a good place for photoelectrons to accumulate.

• In fact there are two depletion regions: the p-n junction and under the gate. Electrons accumulate between the two.

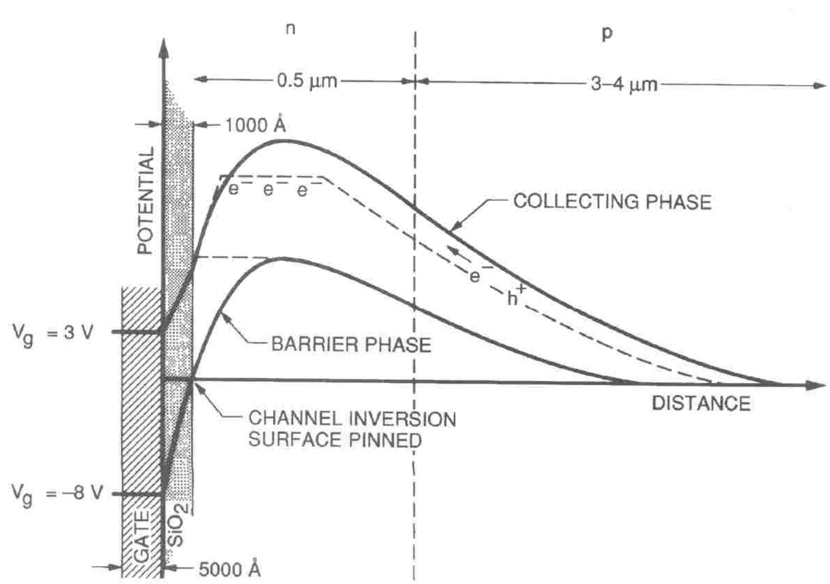
• This p-n junction is applied to a CCD, and is what constitutes a '*buried channel'* CCD, free of surface defect effects.

•*All modern CCDs adopt this architecture*.





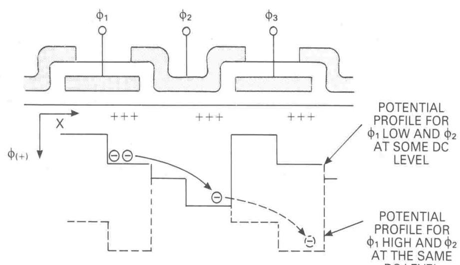
Photoelectrons will accumulate in a region free of holes (avoiding recombination) and of high potential. In a surface channel CCD, this region is close to the surface, whereas in a buried channel it is some distance into the n-layer of the CCD.



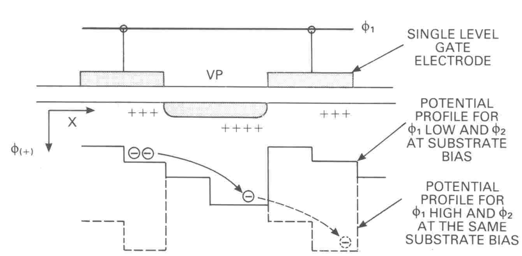
TWO-PHASE AND VIRTUAL PHASE CCDs

- **Alternatives also exist for the electrode structures in CCDs, other than the 3-phase system.**
- **Two-phase CCDs has one of the electrodes buried in the oxide layer**

–This electrode is at a higher potential than its neighbouring surface electrode
–In addition, implants in the p-layer are added under each half of an electrode, resulting in a varying depletion region
–Two clock voltages, out of phase, gives a “stair-case” form to the potential, resulting in charge motion in the direction of the lowest potential
–Thus charge only moves omni-directionally



Two-phase operation.



Virtual Phase electode

BACK-ILLUMINATION

- **Frontside illumination, through a semi-transparent electrode structure, was first devised for CCDs**

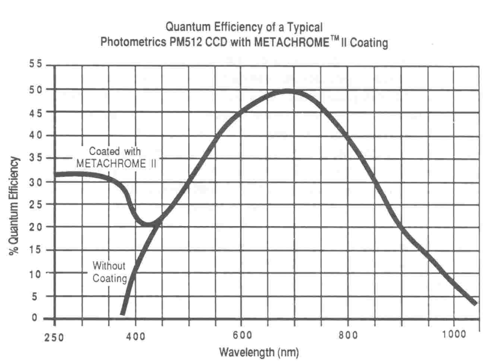
–Ensures that the electron-hole pairs are created close to the depletion region, where the charges can be separated before recombination
–Problems with overall sensitivity, particularly with the shorter wavelength, which are easily absorbed in the electrode and metal oxide layer without producing a detectable 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

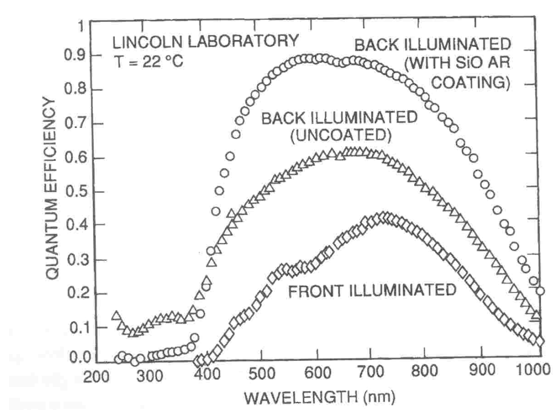
–Overcome the above by “thinning” a process of mechanically or chemically removing the Si so that it is only ~10μm thick – thin enough for photoelectrons from blue photons to be accumulated in the depletion zone.

– Now the problem becomes a lack of response in the far red, because these photons can now pass right through the device!

Solve using high resistivity Si in ‘deep depletion’ CCDs:
They are back illuminated to improve QE in the UV-blue, but they are thicker than standard thinned Si devices. The nature of the Si is such that the E potential is higher near the back surface than would otherwise be the case for ‘normal’ Si. This means that once a photon is absorbed, charge separation occurs, even for higher E (blue) photons nearer the back surface. The increase thickness is good for avoiding transparency to red photons, and minimizing fringing (interference effects). passing rpough

SENSITIVITY IMPROVEMENTS





'REAL' CCDs: as used in astronomical instruments:

• CCD design has evolved considerably

• 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*• Other typical hardware required:**

– **CCD driver (i.e. clocks) and signal processors**

– **Motors, encoders, actuators (e.g. for filters, masks, etc)**

– **Shutter**

– **Temperature controller: keep CCD at constant low (but not *too* low)**

– **preamplifiers**

– **A/D units**

• Some electronics (e.g. pre-amp) needs to be in close proximity to the CCD chip (avoid long cable lengths and consequent noise).

• Clock drivers are key feature of control, and complexity of CCD system revolves around the *timing diagrams.*

– **Preparing and 'flushing'**

– **Open/close shutter**

– **Readout CCD in precise pattern (parallel and serial register shifts, prebinning, etc)**

– **Digitize signal**

– **Store data**

BINNING

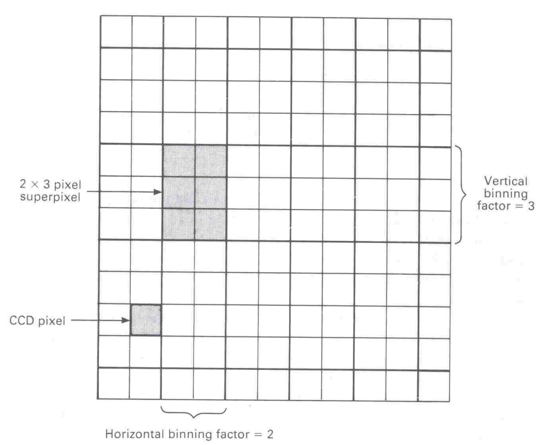
• Add or combine charge packets at the output node capacitor

• 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



NOISE SOURCES

• **An ideal detector would be capable of detecting *any* source, however faint, given a long observation. Noise, from a number of sources, limits the detection threshold.**

• Noise from thermal effects (dark current: generally very low in CCDs). Also called Nyquist (or Johnson) noise

• Noise associated with imperfect CCD charge transfer

–**CTE (Charge Transfer Efficiency)**

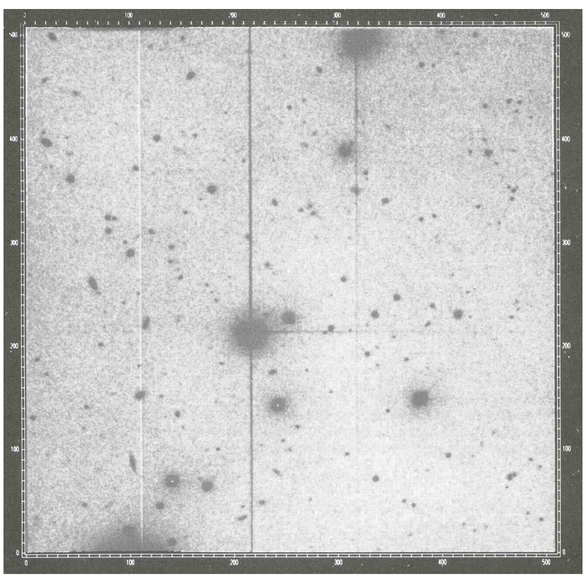
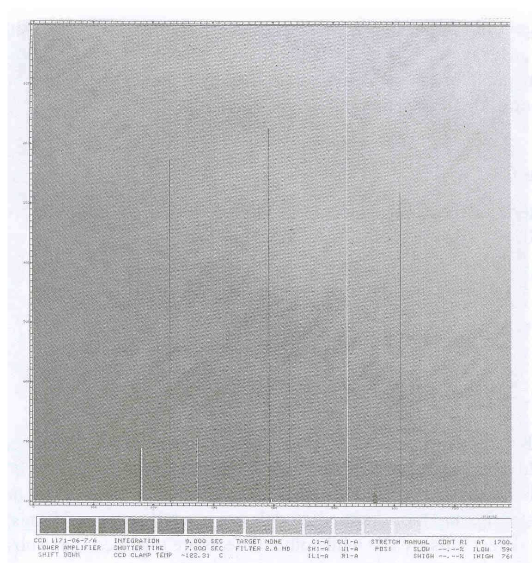
–**Surface channel CCDs prone to poor CTE, affecting faint object (few ē/pixel)**

»***<u>Example:</u>*** **If, say, 1000x1000 device, with parallel and serial CTE of 0.99999, then total minimum efficiency for a pixel transfer is: 99.999^{2000} = 98%. The remaining 2% of the signal from that pixel will be spread into neighbouring pixels (and vice versa)**

– **Poor CTE can be alleviated by "pre-flashing", i.e. evenly illuminating the CCD briefly before an exposure to 'deposit' a pedestal, or base level, of a few 100ē (removed later).**
»**This means that the CTE is better (e.g. 103ē are moved more efficiently than 3ē)**
– **Modern devices (buried channel) have better CTEs (99.9999% efficiencies), which usually precludes needing to pre-flash.**
–**Saturation, blooming or '*charge bleeding'*, results when the well capacity of a pixel is exceeded, and charge 'leaks' into nearby pixels along the parallel register**
– ***Blockages* of columns can also result from broken electrodes during manufacture, which prevents charge being conveyed past a certain point.**
– **Electrode short circuits cause high leakage currents: *bright column* blemishes**

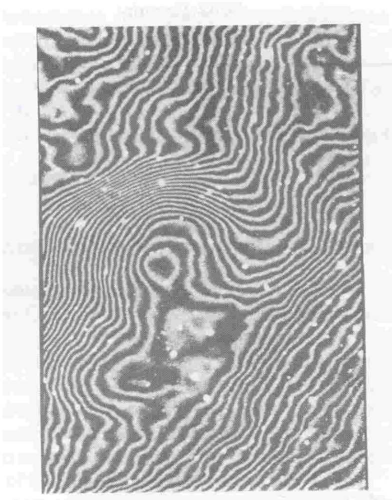
• **Ideally only associated with the output transistor (on-chip)**
• **Other noise sources arise from electronics affecting the weak signals (typically few 10's of microvolts)**
–**Background charge associated with DC offsets**
–**Charge transfer fluctuations**
–**Reset ('kTC') noise (resetting node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

COSMETICS
• **Traps (due to imputities) result in 'local' (pixel scale) CTE changes**
– **Poor CTE and consequent image smear**
– **"lost' charge is generally just**
delayed and released in the over
the remaining pixels
–**Called 'deferred charge'**

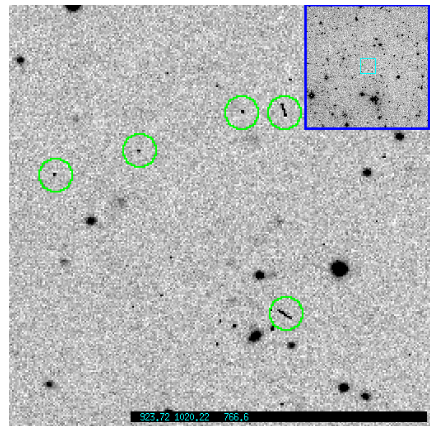



BIAS AND OVERSCAN
• **Purposely 'bias' the CCD video signal, so that readout noise never drives A/D input into the negative.**
• **Essentially it is a 'pedestal' or 'DC offset' signal which is ideally *uniform* and *constant*.**
Unexposed rows or columns of pixels on the CCD are used to calculate bias levels.

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%!**



(a)



Example of cosmic rays in CCD frame

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)

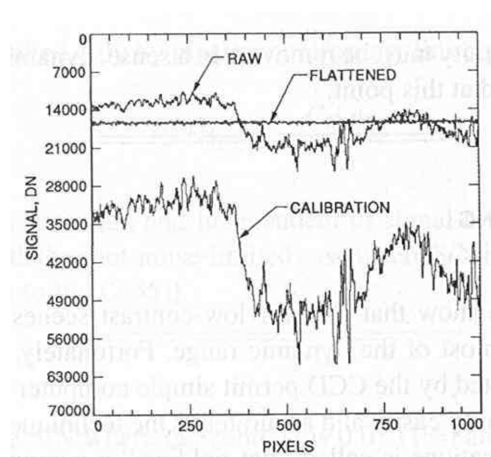
FLAT-FIELDING

- **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**

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 ´ 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

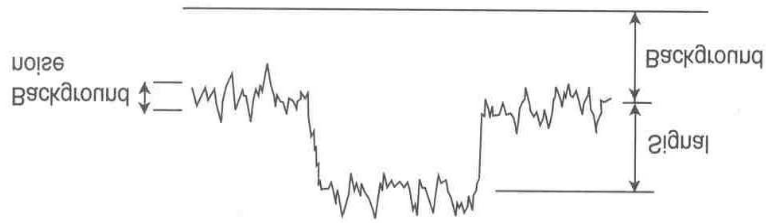


SIGNAL-TO-NOISE

- **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, there described by Poisson statistics.

» **Standard deviation (rms of the fluctuations) is given by the simple formula:**
$\sigma = (N\,t)^{1/2}$, where N is the intensity (e.g. ē/sec) and t is the time interval



• 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)
***var( )* is the variance of the estimate of the *total* background, $B_t = B + I_d + R_n\,t$ (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).**

• 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)
– 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. <u>Source photon-noise limited</u>
When source is bright and its photon noise dominates all other fluctuation

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

2. <u>Detector-noise limited</u>
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.
3. <u>Background limited</u>
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)

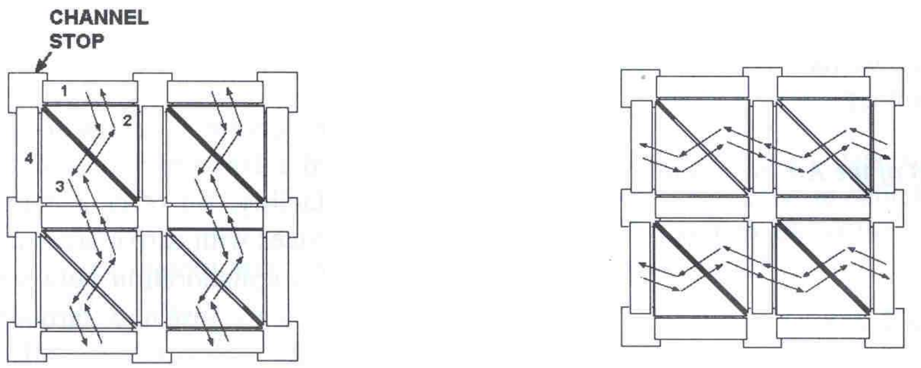
$S/N = S\,\sqrt{t} / (B\, n_{pix})$

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.

NEW CCD DEVELOPMENTS

- **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**



- **Electron Multiplication CCDs (EMCCD) or L3CCD (Low Light Level)**
-
    - **These devices apply higher voltages on the serial readout register**
    - **Results in an amplification of the signal, or "gain" (g)**
    - **Makes the readout noise insignificant**
        - **Noise reduced by factor R_n/g, where g = 100-1000**
    - **so acts as a photon counting device**
    - **better for short exposures**