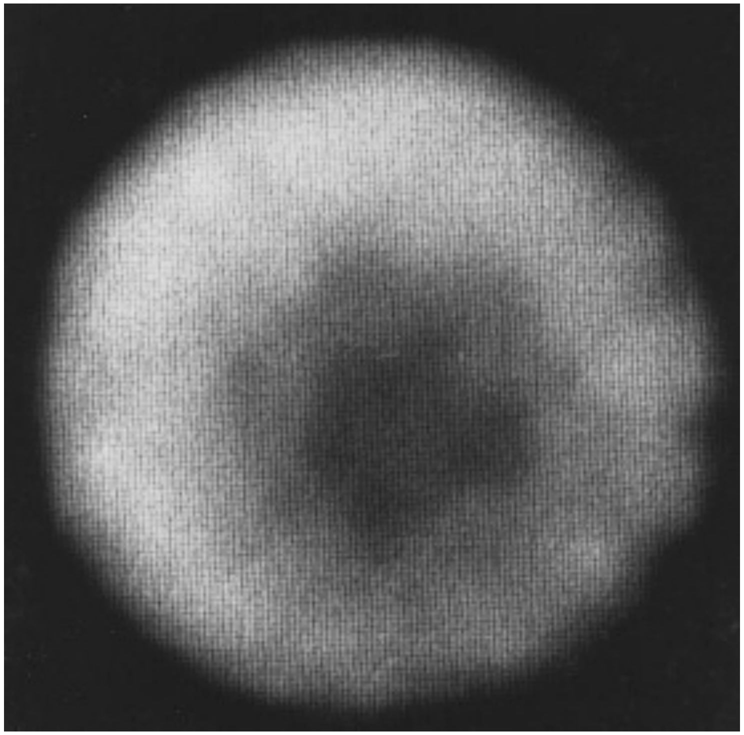
Ay 122a - Fall 2012

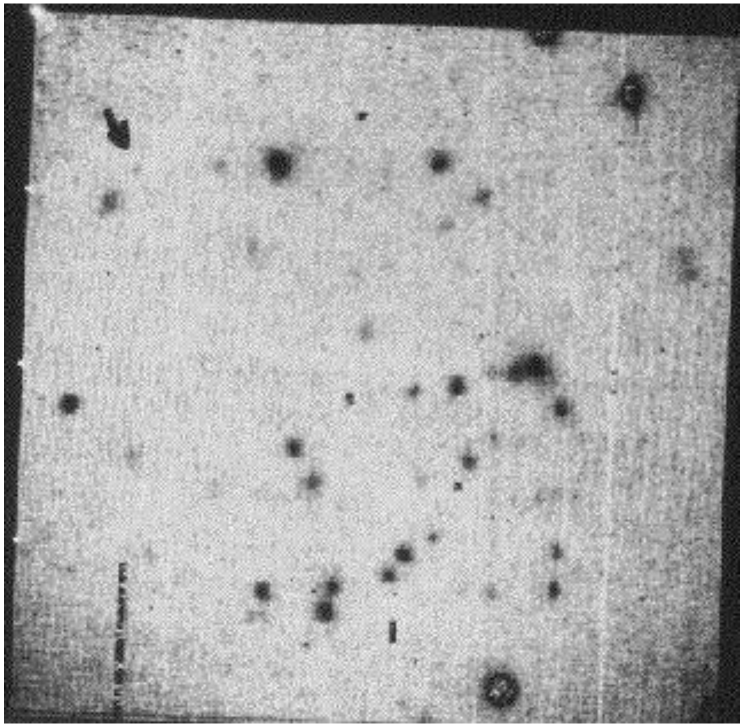
Detectors (UV/Opt/IR)

S. G. Djorgovski

Some of the earliest astronomical CCD images, obtained in the early 1970's at P200 (and Mt. Lemon?), by Westphall, Gunn, et al.



Uranus

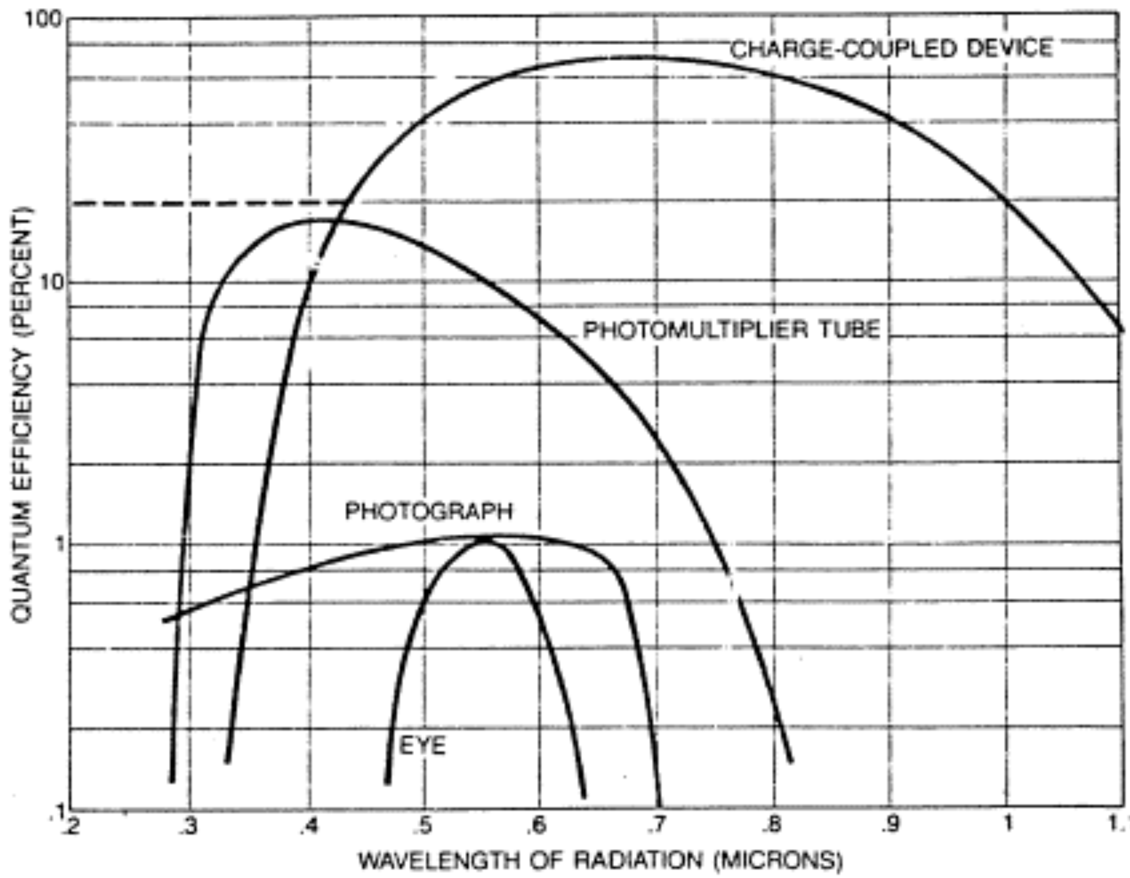


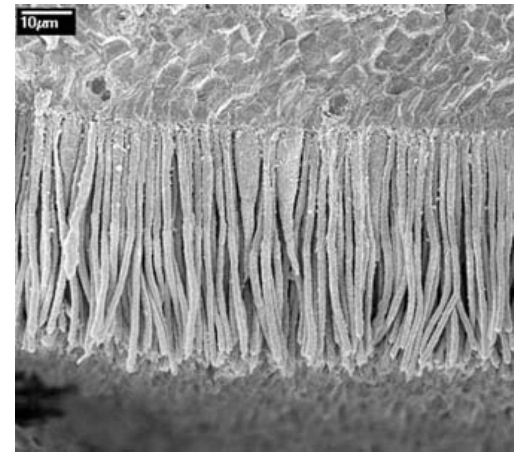
A distant cluster; $R_{lim} \approx 24.5$ mag

General Considerations and Concepts

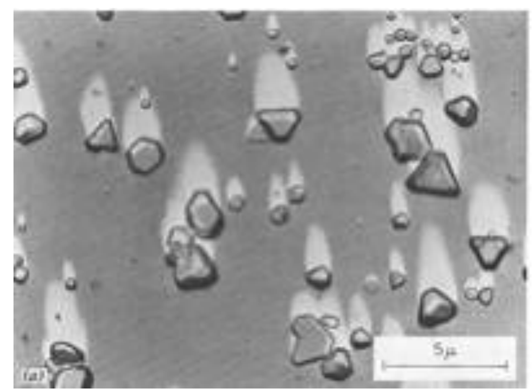
- **Historical evolution:** Eye ➞ Photography ➞ Photoelectic (single-channel) devices ➞ Plate scanners ➞ TV-type imagers ➞ Semiconductor-based devices (CCDs, IR arrays, APDs, bolometers, …) ➞ Energy-resolution arrays (STJ, ETS)
- Astronomical detectors today are applications of solid state physics
- **Detector characteristics:** Sensitivity as a f(λ), size, number of pixels, noise characteristics, stability, cost
- **Types of noise:** Poissonian (quantum), thermal (dark current, readout), sensitivity pattern
- **Quantum efficiency:** QE = N(detected photons)/N(input photons)
- **Detective Quantum Efficiency:** DQE = $(S/N)_{out}/(S/N)_{in}$

The Evolving Quantum Efficiency





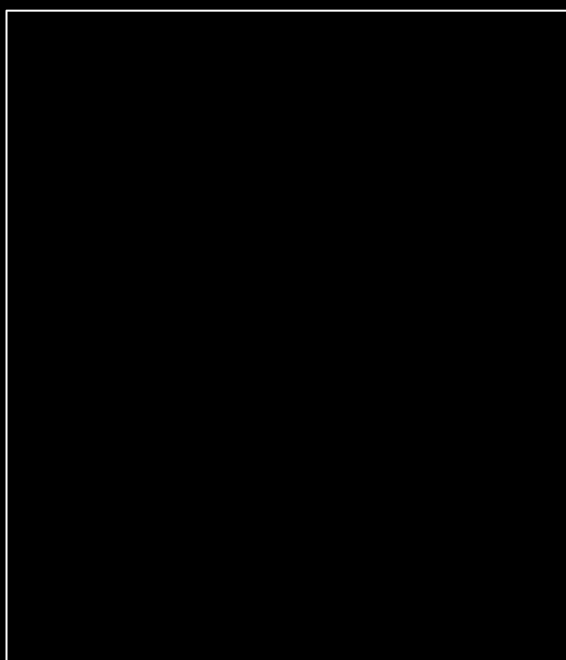
Rods and cones in the human retina



Photographic emulsion grains

Hubble Extreme Deep Field

Naked Eye (~ 1 pixel)

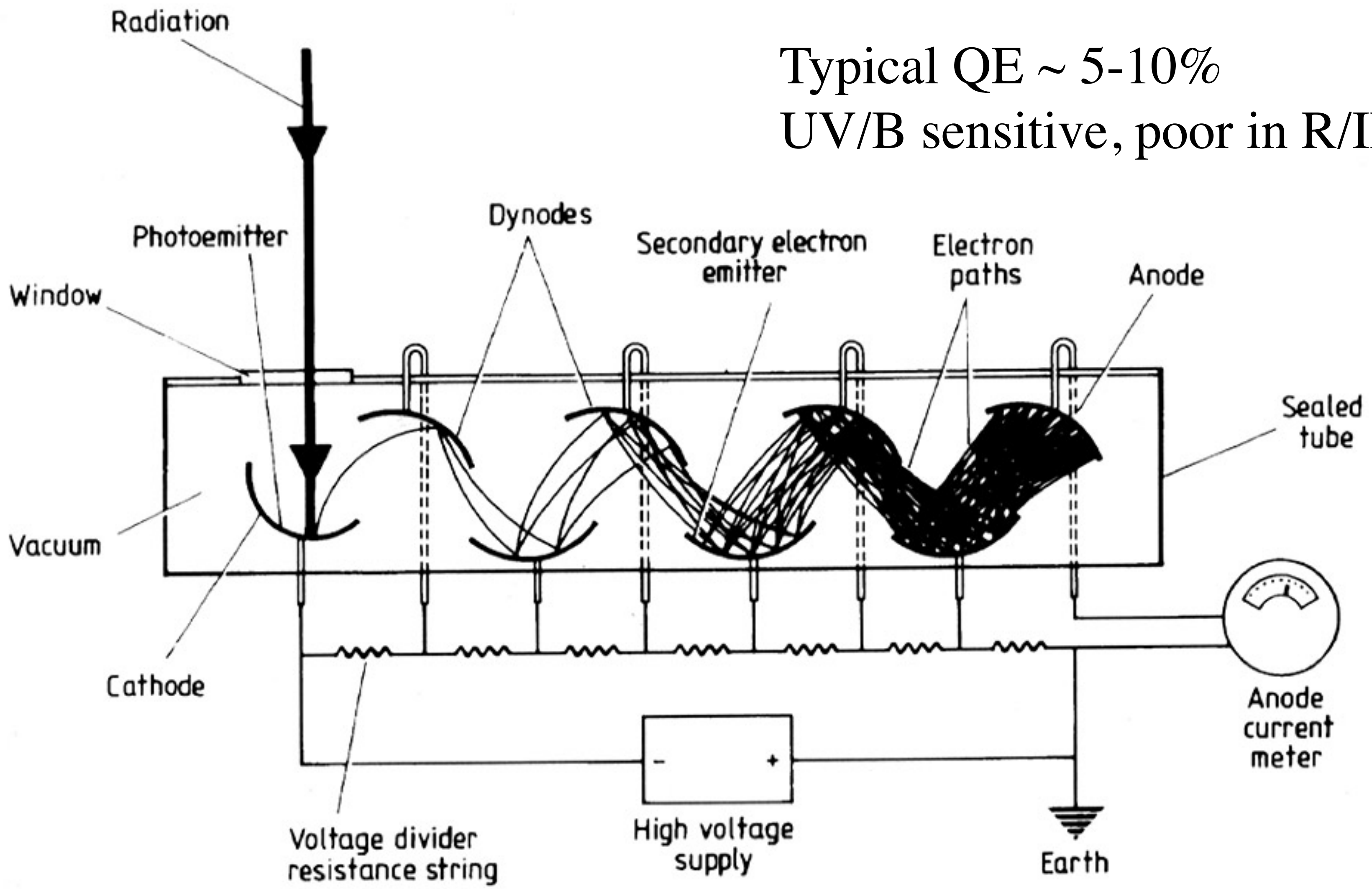


DSS plate scan

HST CCD coadd

Classical Photomultiplier Tubes

Typical QE ~ 5-10%
UV/B sensitive, poor in R/IR



Semiconductor equivalent: Avalanche Photodiodes (APD)

Image Intensifiers

Still used for some night vision applications

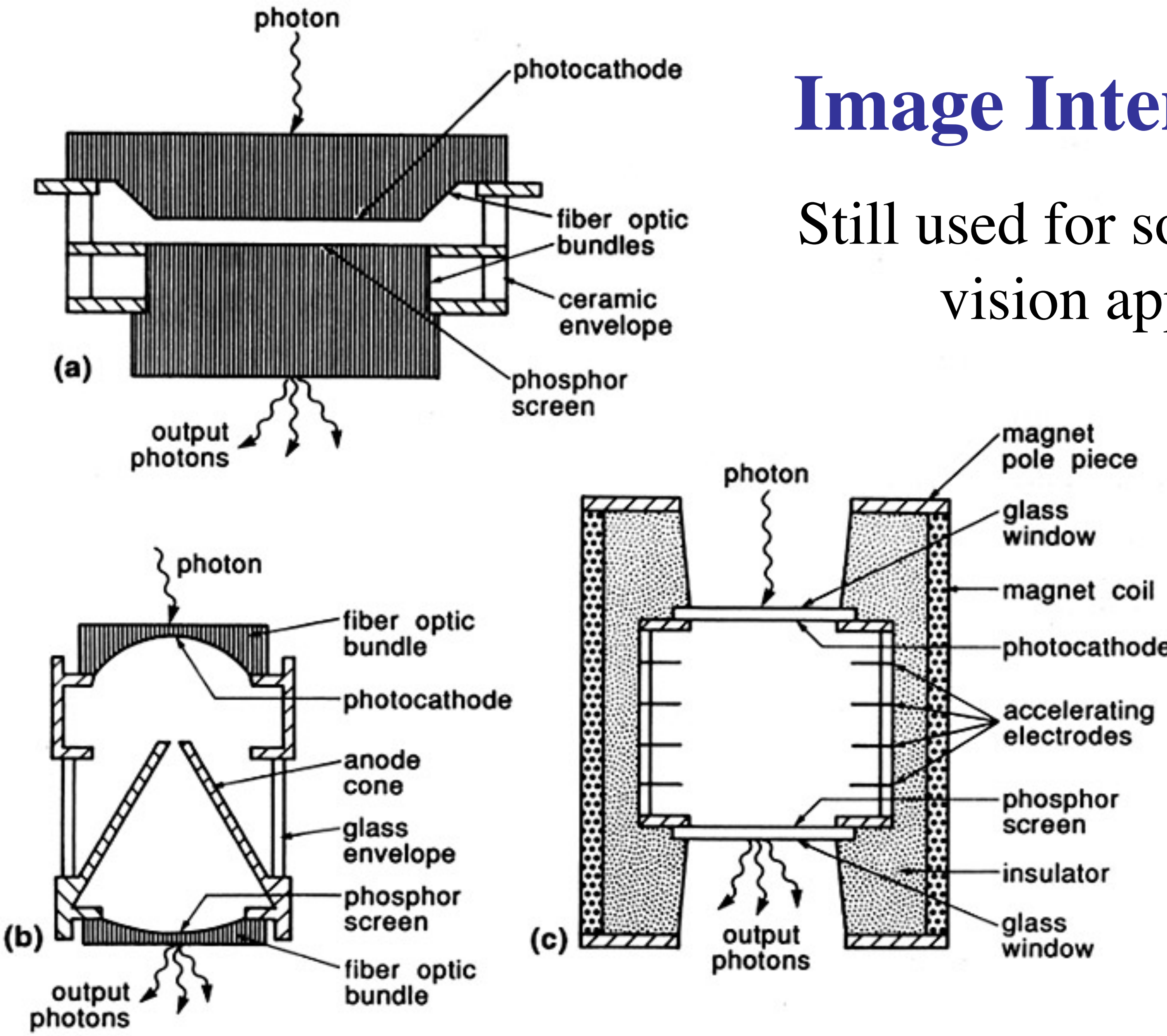


Figure 7.10. Cross-sectional diagrams of a variety of image intensifier types: (a) proximity focused; (b) electrostatically focused; and (c) magnetically focused. After Csorba (1985).

Image Intensifiers

- An image intensifier amplifies light signals by:
  - converting photons to electrons via the photoelectric effect ,
  - accelerating the electrons them via electrostatic forces,
  - focusing the electron beam, electrostatically or magnetically,
  - having them impact on an output phosphor releasing a shower of photons,
  - recording the output photons using a photographic emulsion or some more modern detector (or indeed the human eye).
- The gain = N(output photons) / N(input photons); multi-stage image intensifiers can reach total gains up to $\sim 10^6$
- Image intensifiers are now used very little in the optical, where CCDs dominate, but are still used in the UV

Microchannel Plates:

Effectively arrays of PMTs

Still used in UV (e.g., in *GALEX*)

Also for some night vision applications

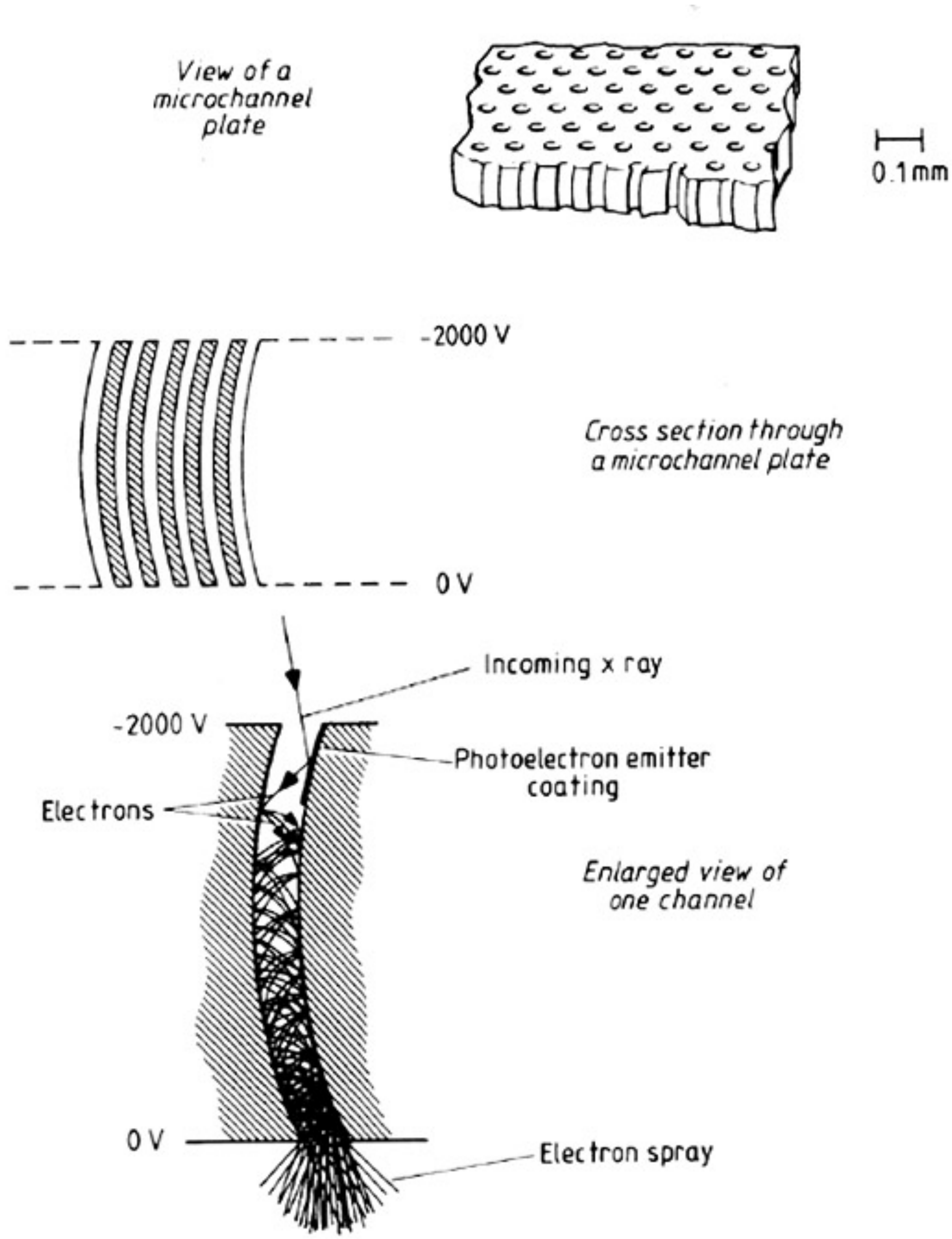


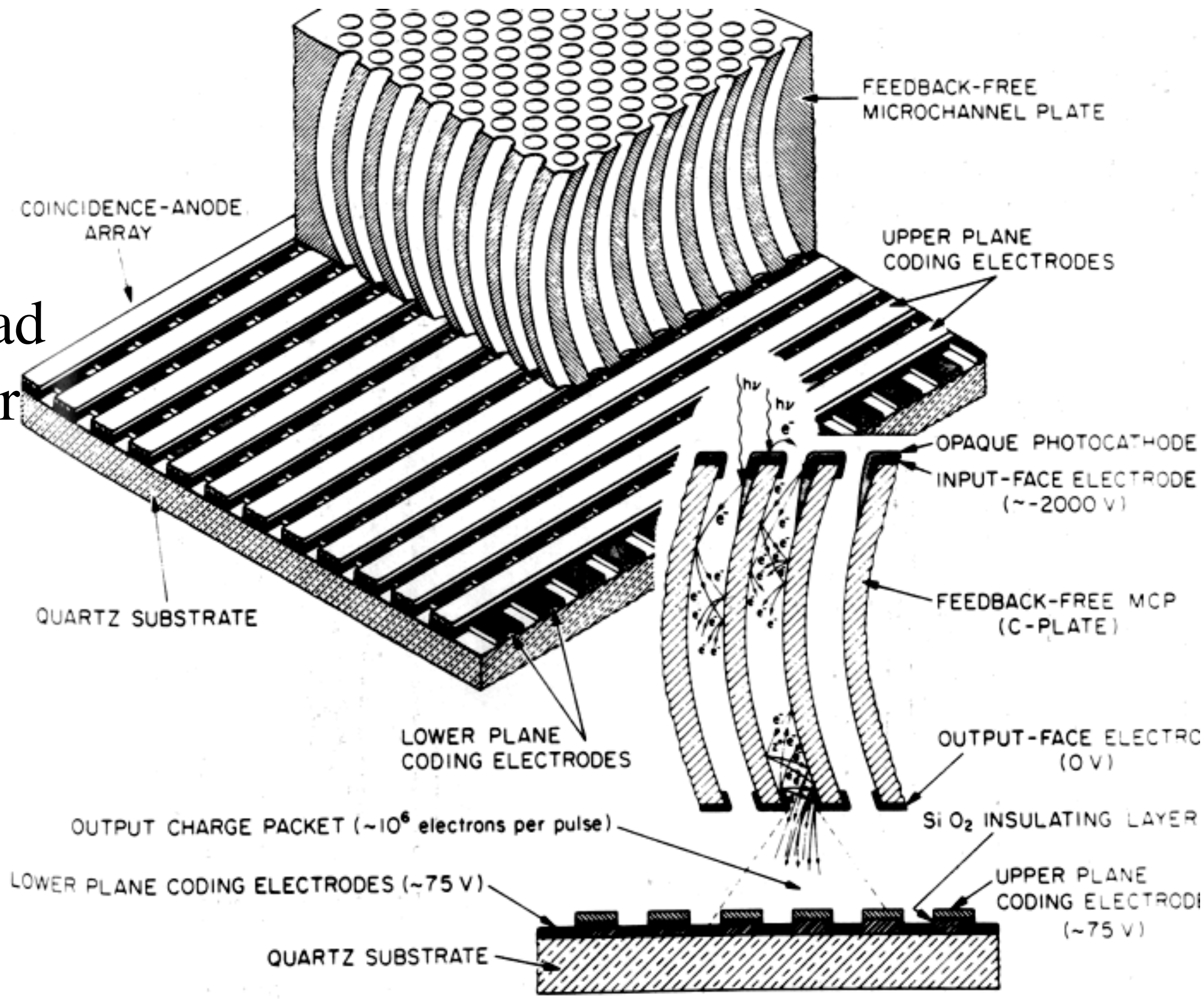
Figure 1.3.4. Schematic view of the operation of a microchannel plate.

Microchannel Plate Intensifiers

- A microchannel plate is a modern image intensifier:
  - A thin disk of Pb oxide glass with many microscopic channels/pores running parallel to each other from one face to the other
  - Pores are either slanted or curved, to allow the electrons to hit the walls to provide the gain, and to absorb positive ions produced from residual gas before they generate a cascade
  - A potential of a small number of kiloVolts is applied between one face and the other
  - Each channel acts like a tiny image intensifier: electrons hitting the walls eject additional electrons resulting in a cascade of electrons
  - It still needs a photocathode and an output phosphor
- Advantages over conventional image intensifiers:
  - Channels confine the electron shower → better resolution
  - Voltages are lower (~2 kV instead of ~30 kV for gain of $10^{6)}$

The Multi-Anode Microchannel Array (MAMA)

- Developed for space app's (mainly UV)
- Uses a position sensitive anode instead of an output phosphor and light sensitive detector
- Anode has two perpendicular sets of coding electrodes



Classical (pre-CCD) TV-type Detectors

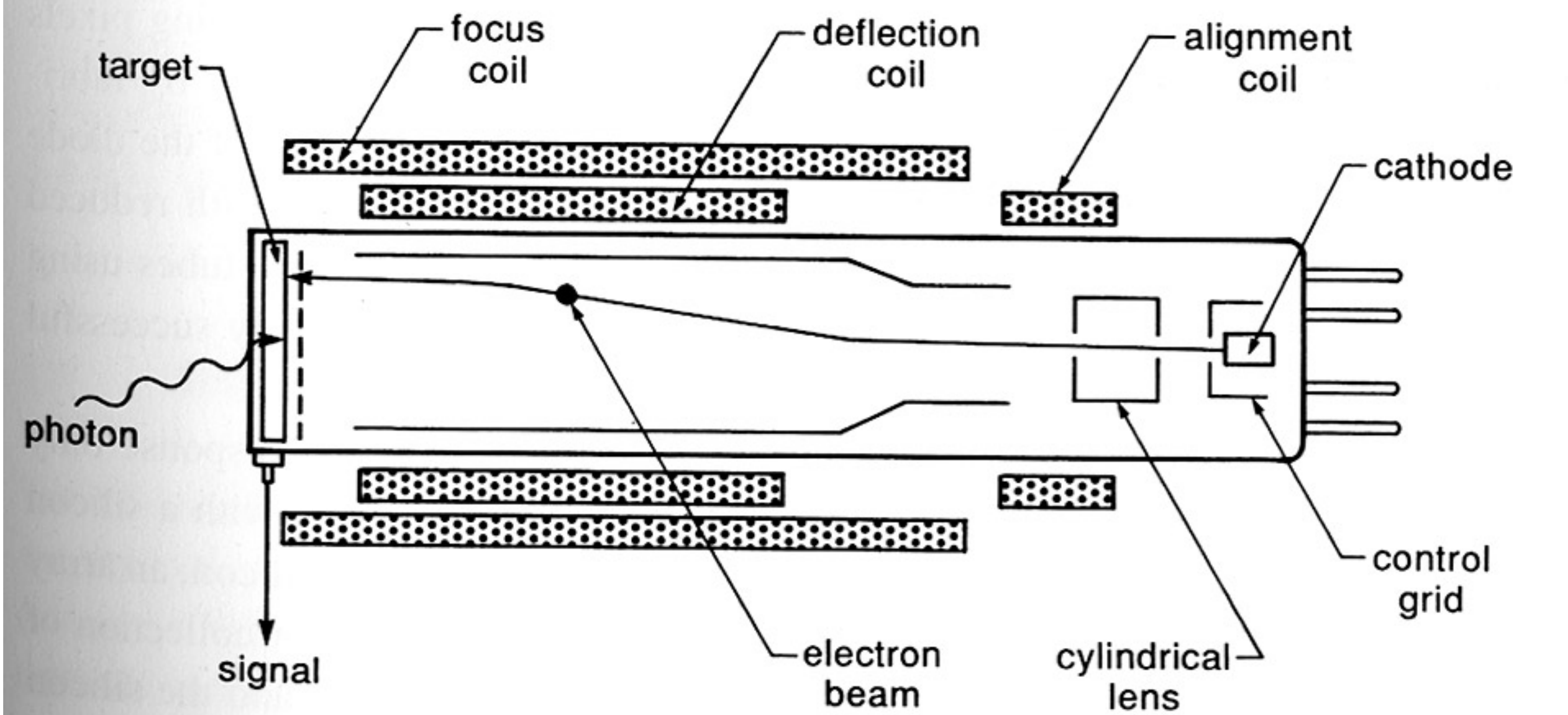


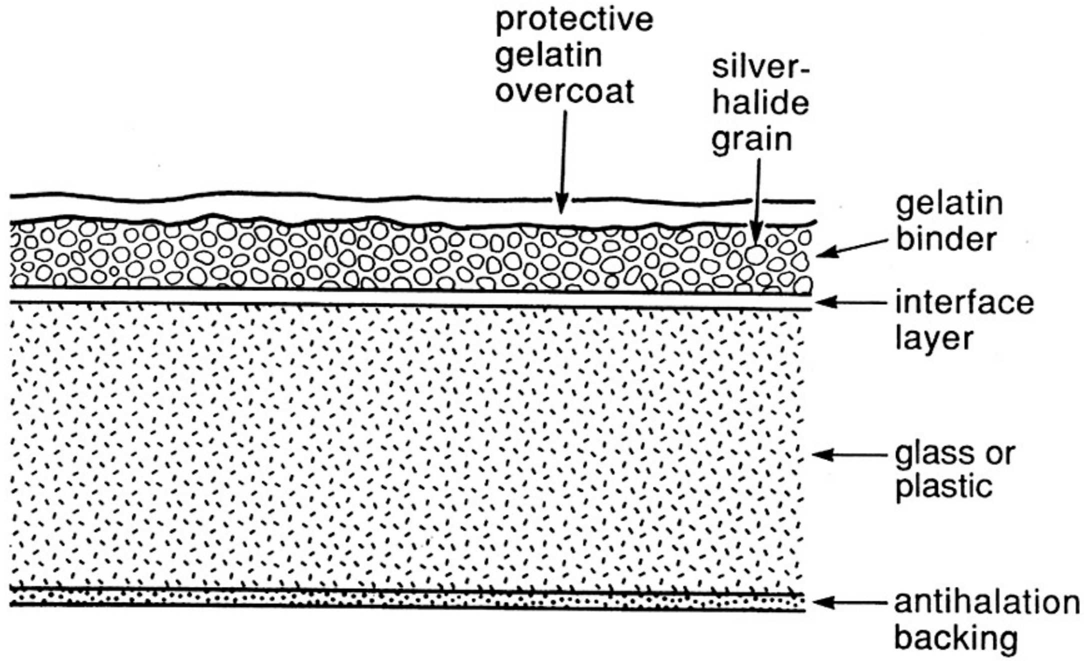
Figure 7.12. Cross-section of a conventional vidicon.

Photon Counting Detectors

- Run an image intensifier at high gain ($\sim10^6$), and image the output phosphor onto a CCD or similar detector
  - For each photon incident at the photocathode there is a large splash of photons at the detector.
  - Read this out and centroid, record {x,y,t}
  - Build up *time-resolved image* photon by photon
  - If more than one photon arrives in a particular location within the frame time of the detector then one or both will be lost
    - ✧There is a limit to the count rate (per pixel and per frame)
    - ✧You cannot remove saturation by taking short exposures
    - ✧Useful in the UV/Xray, where photon rates are low
- Photon counting detectors have *no readout noise* and thus a potential advantage for all ultra-low light level app's

Classical Photography

Typical QE ~ 2-3%, but large formats available; can be digitized



Cross-section of a typical photographic plate.

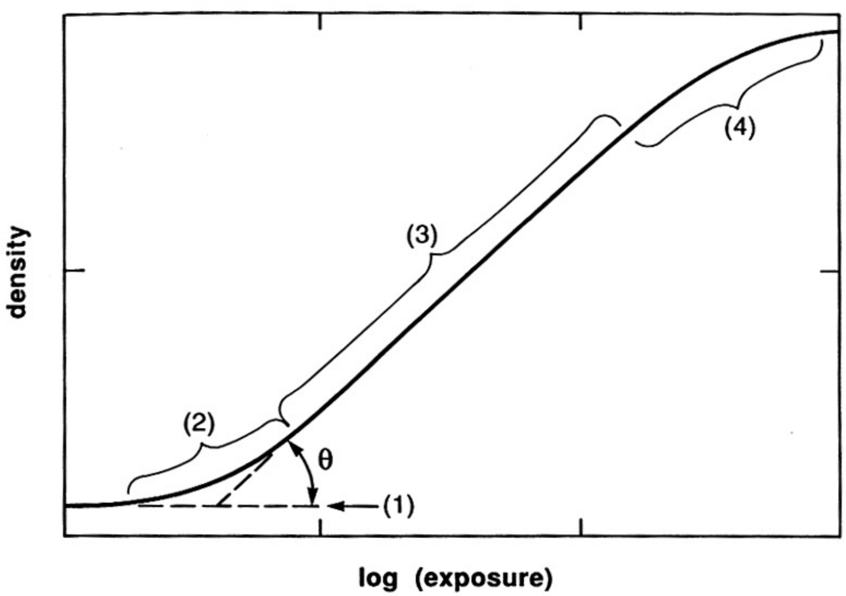


Figure 8.5. Characteristic curve. Zones of the curve include (1) level of gross fog; (2) toe; (3) straight-line portion; (4) shoulder. The contrast parameter γ ($= \tan\theta$) is discussed in Section 8.4.2.

A problem: non-linear response! (H-D curve)

Also: non-uniform

And messy …

Plate Digitization: Still used for sky surveys (DPOSS, DSS, etc.)

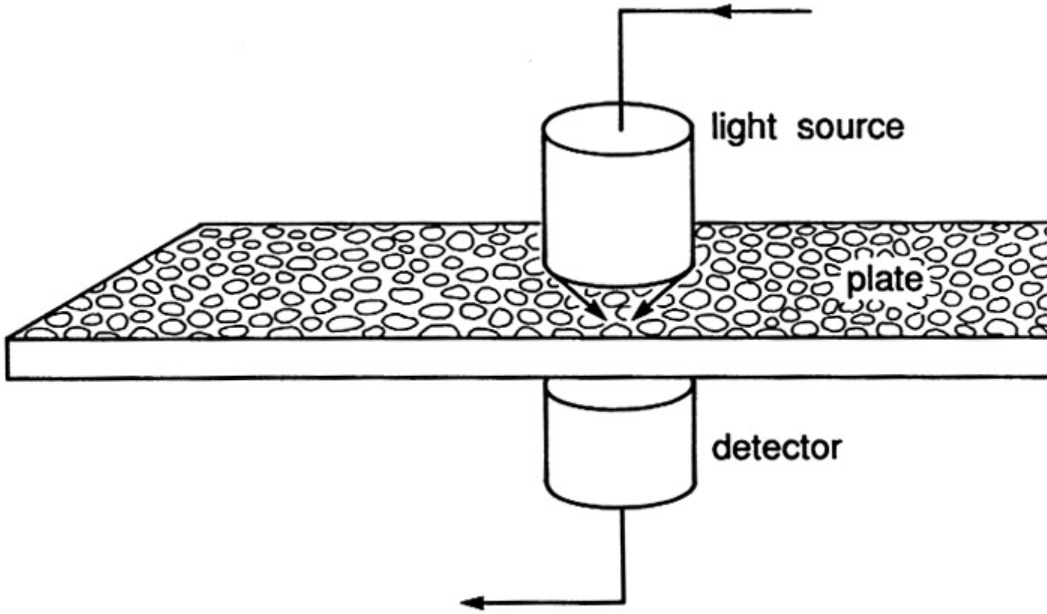
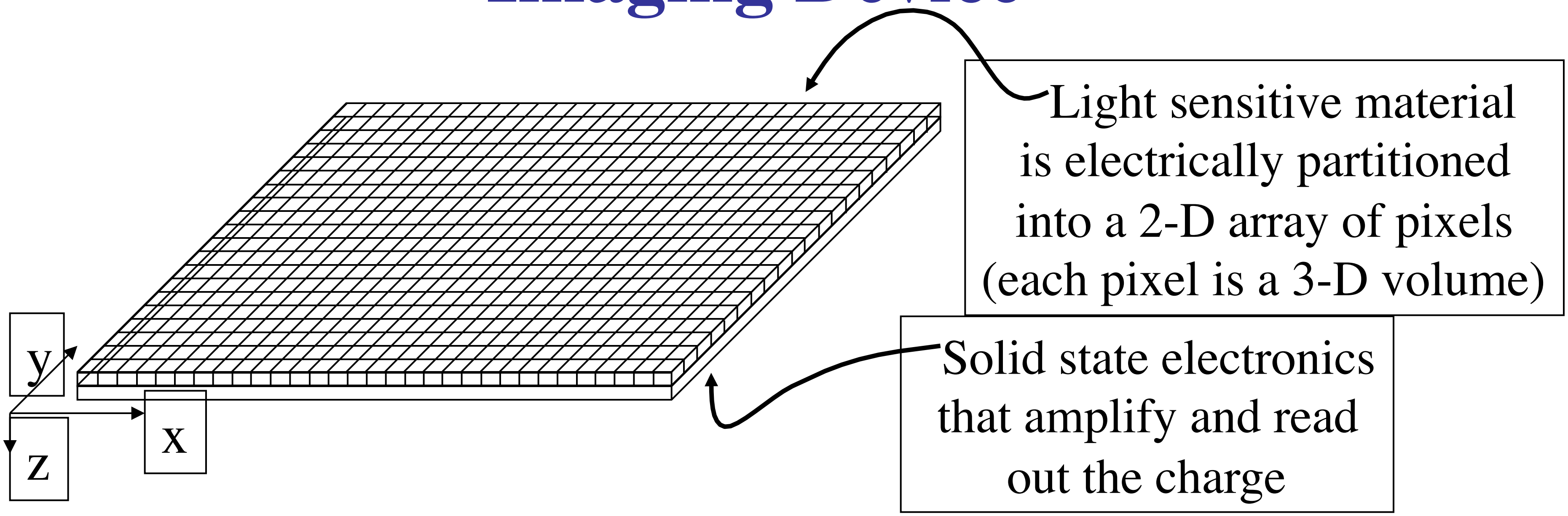


Figure 8.4. Electronic measurement of a photographic image.

Problems and challenges: Scattered light, calibration …
Limited to a pixel size of a few microns, due to the grains

Basic Operation of a Solid-State Imaging Device



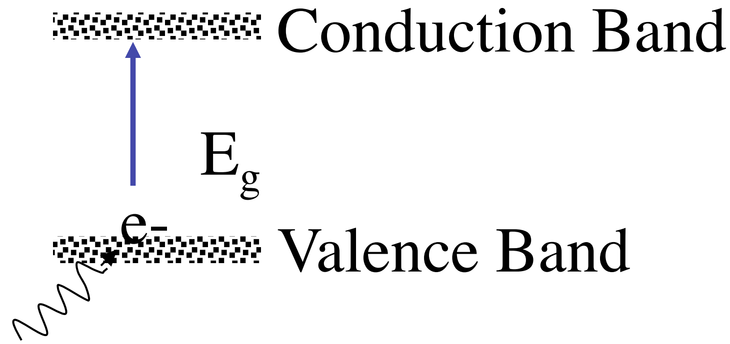
- Intensity image is generated by collecting photoelectrons generated in 3-D volume into 2-D array of pixels.
- Optical and IR focal plane arrays both collect charges via electric fields.
- In the z-direction, optical and IR use a p-n junction to "sweep" charge toward pixel collection nodes.

Five Basic Steps of Optical/IR Photon Detection

1. **Get light into the detector :** need anti-reflection coatings
2. **Charge generation :** popular materials include Si, HgCdTe, InSb
3. **Charge collection :** electrical fields within the material collect photoelectrons into pixels.
4. **Charge transfer :** in IR, no charge transfer required. For CCD, move photoelectrons to the edge where amplifiers are located.
5. **Charge amplification & digitization :** This process is noisy. In general, CCDs have lowest noise, CMOS and IR detectors have higher noise.

Charge Generation via Photoelectric Effect

An incoming photon excites an electron from the conduction band to the valence band: $h\nu > E_g$, E_g = energy gap of material



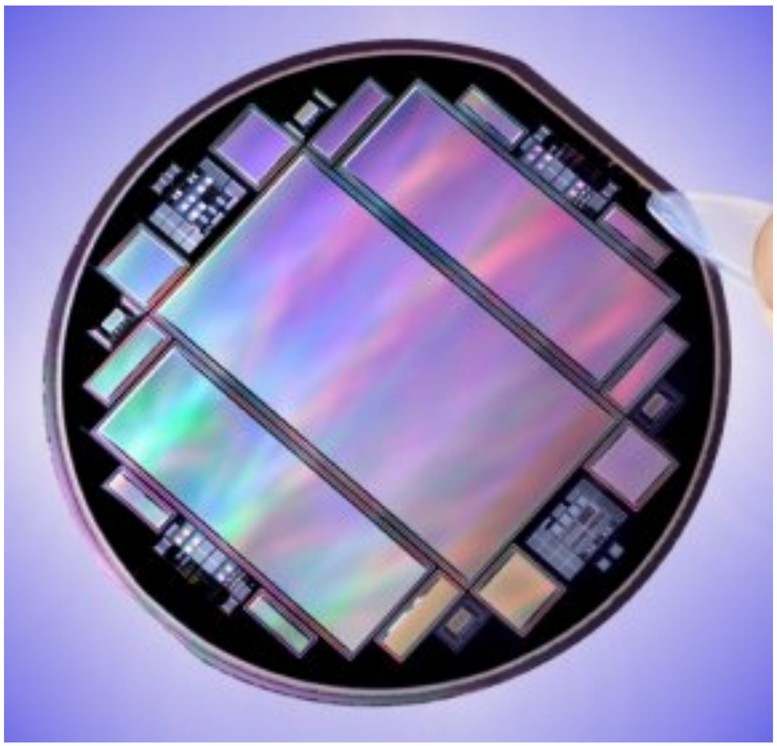
Critical wavelength: λ_c (μm) = 1.238 / E_g (eV)

	Material	E_g (eV)	λ_c (μm)	Op. Temp. (K)
	Si	1.12	1.1	163 - 300
	HgCdTe	1.00 – 0.09	1.24 – 14	20 - 80
	InSb	0.23	5.5	30
	Si:As	0.05	25	4

(Must keep them cold, to avoid thermal electrons = dark current)

But Nowadays, Charge Coupled Devices (CCDs) Are The Detectors of Choice

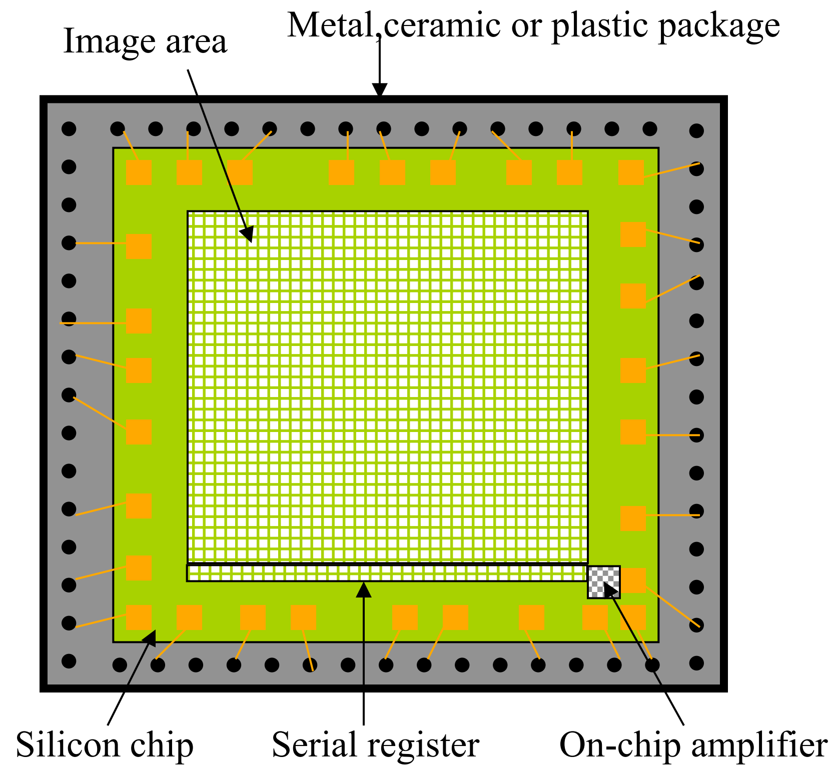
(in visible, UV, and X-ray)



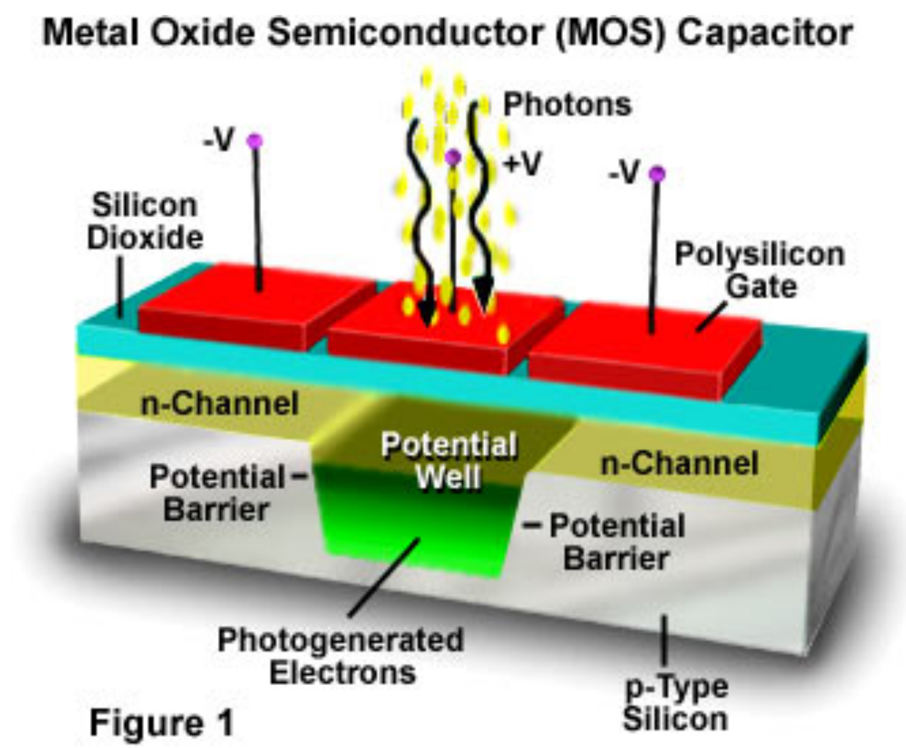
A whole bunch of CCDs on a wafer

Nearly ideal detectors in many ways

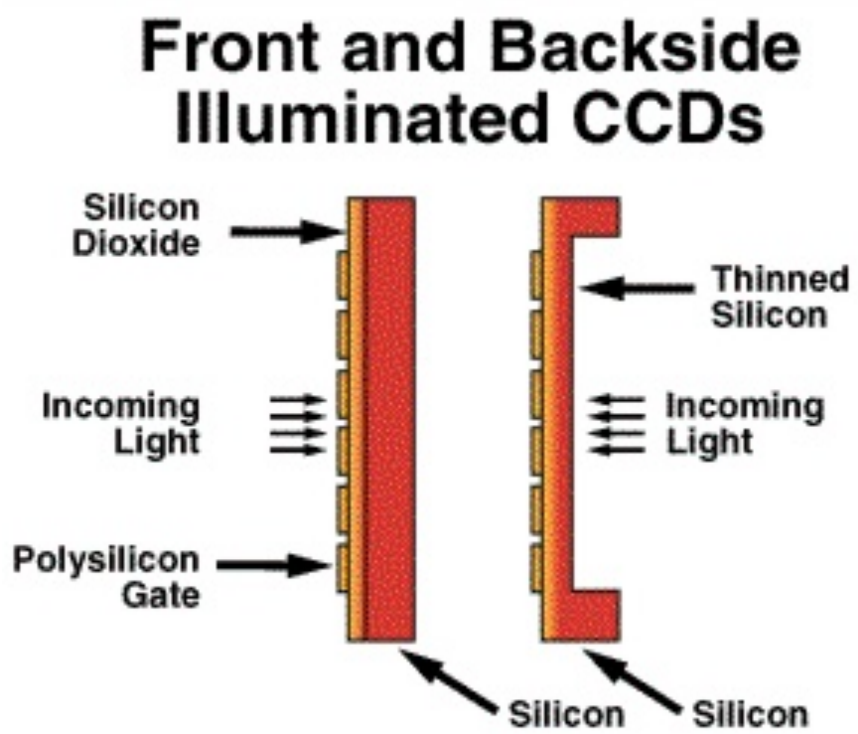
Counting photons in a pixel array

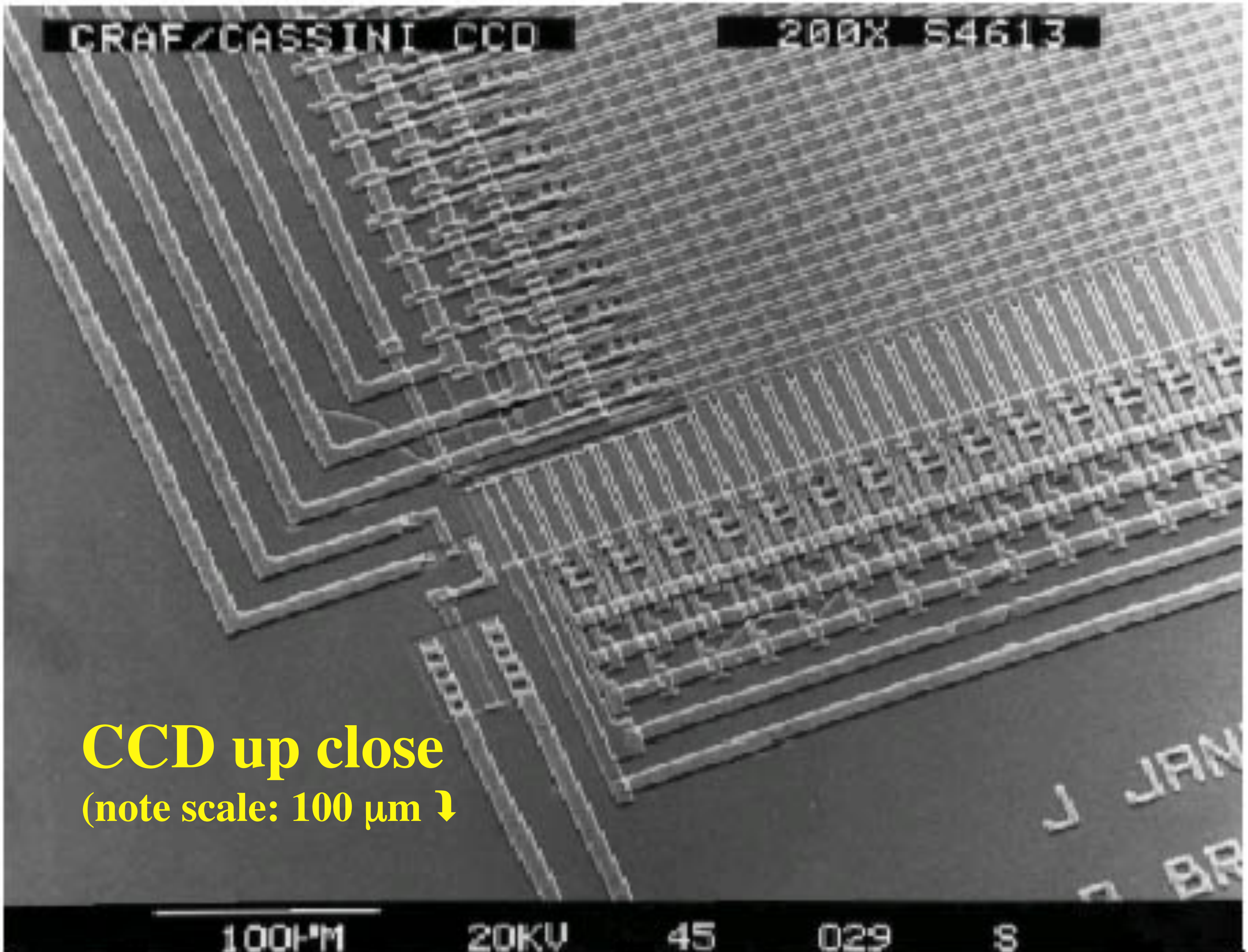


The structure of a single CCD pixel:



Two modes of CCD use:

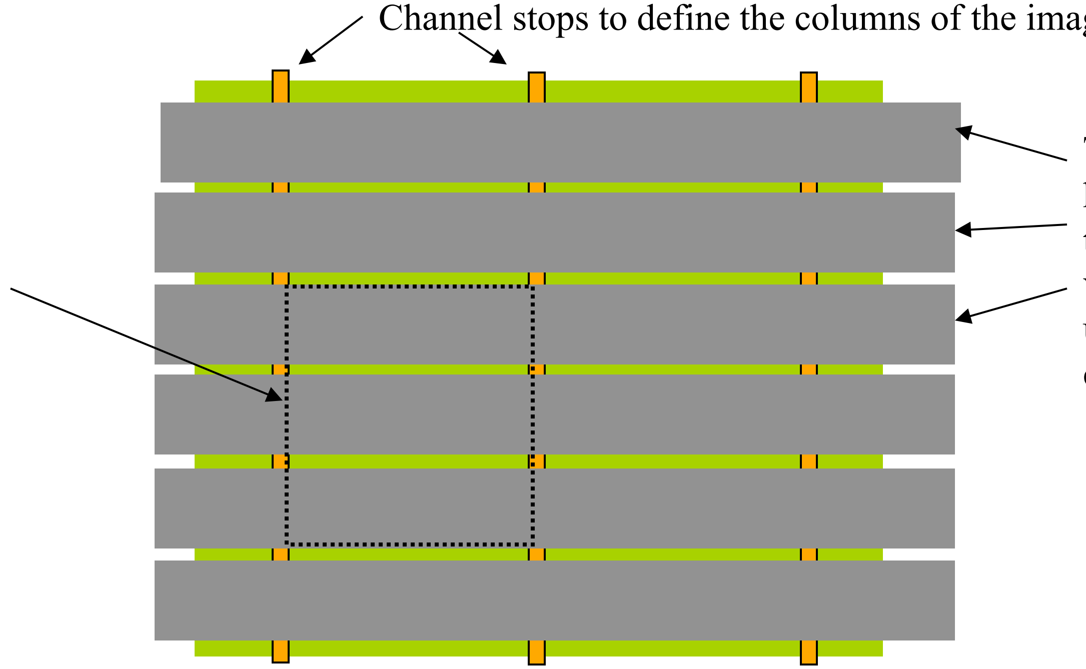



CRAF/CASSINI CCD
200X S4613
CCD up close
(note scale: 100 µm ➘
100µM 20KV 45 029 S

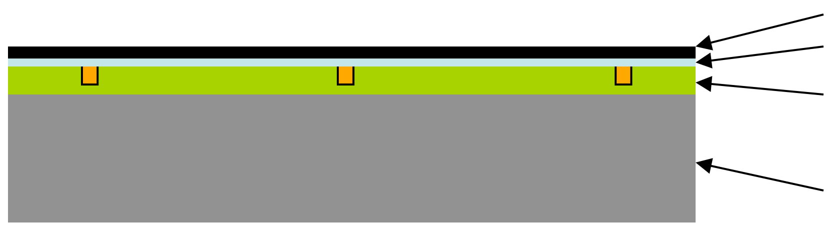
Structure of a CCD

The diagram shows a small section (a few pixels) of the image area of a CCD. This pattern is reapeated.

Plan View



Cross section

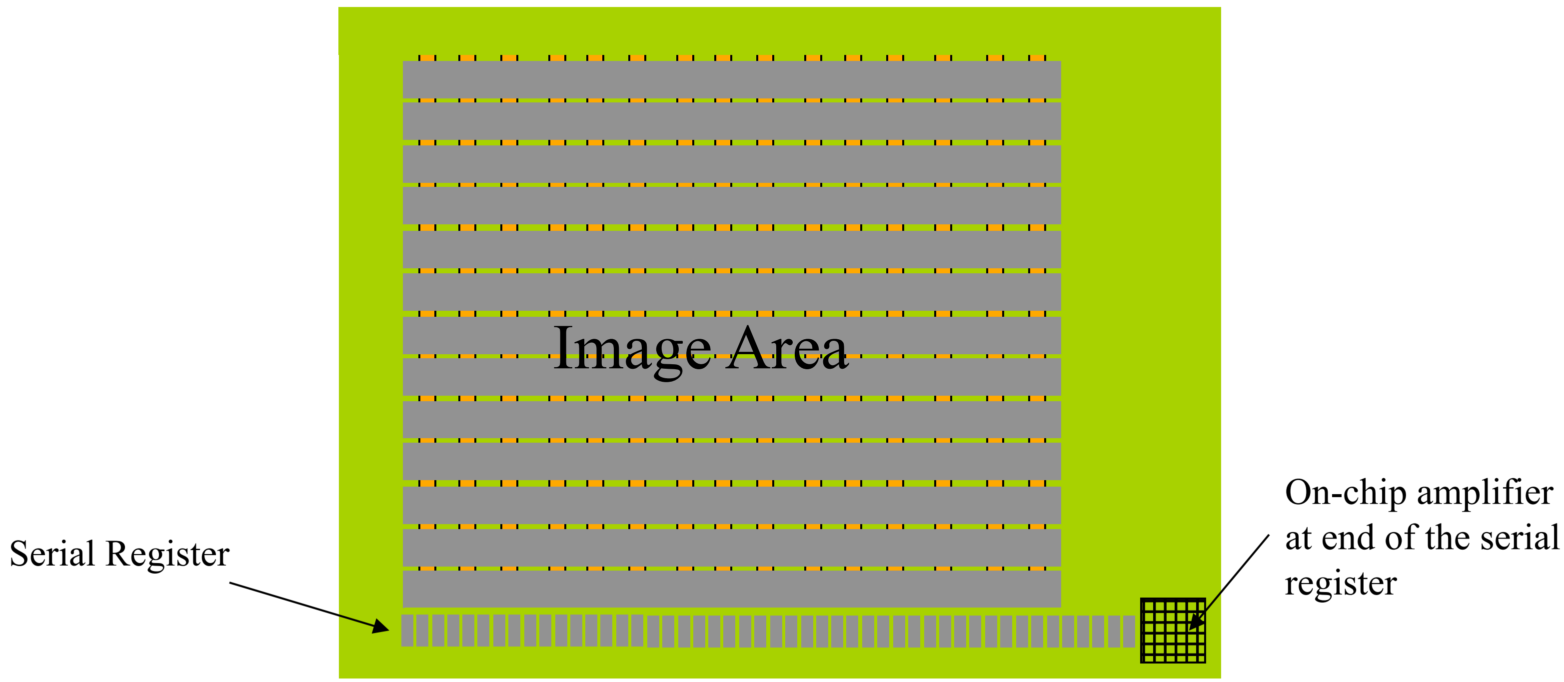


Every third electrode is connected together. Bus wires running down the edge of the chip make the connection. The channel stops are formed from high concentrations of Boron in the silicon.

(This slide and many others from S. Tulloch)

Structure of a CCD

Below the image area (the area containing the horizontal electrodes) is the 'Serial register' . This also consists of a group of small surface electrodes. There are three electrodes for every column of the image area



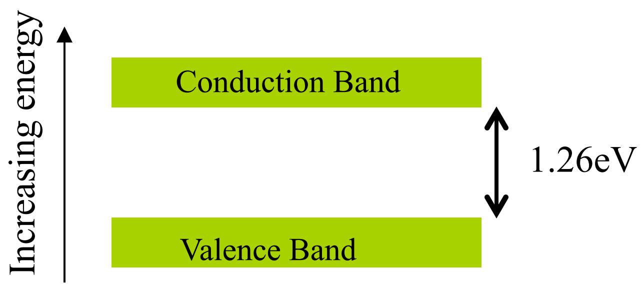
Cross section of serial register

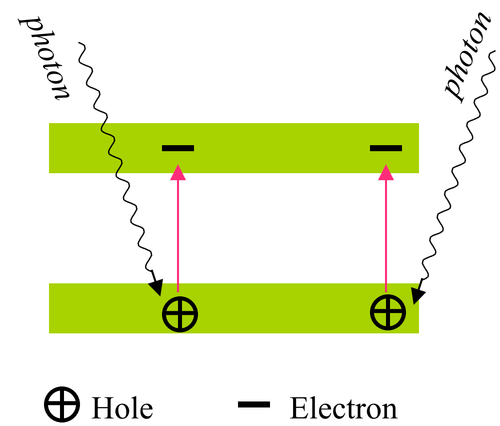
Once again every third electrode is in the serial register connected together.

How Does A CCD Work?

Internal Photoelectric Effect in Doped Silicon

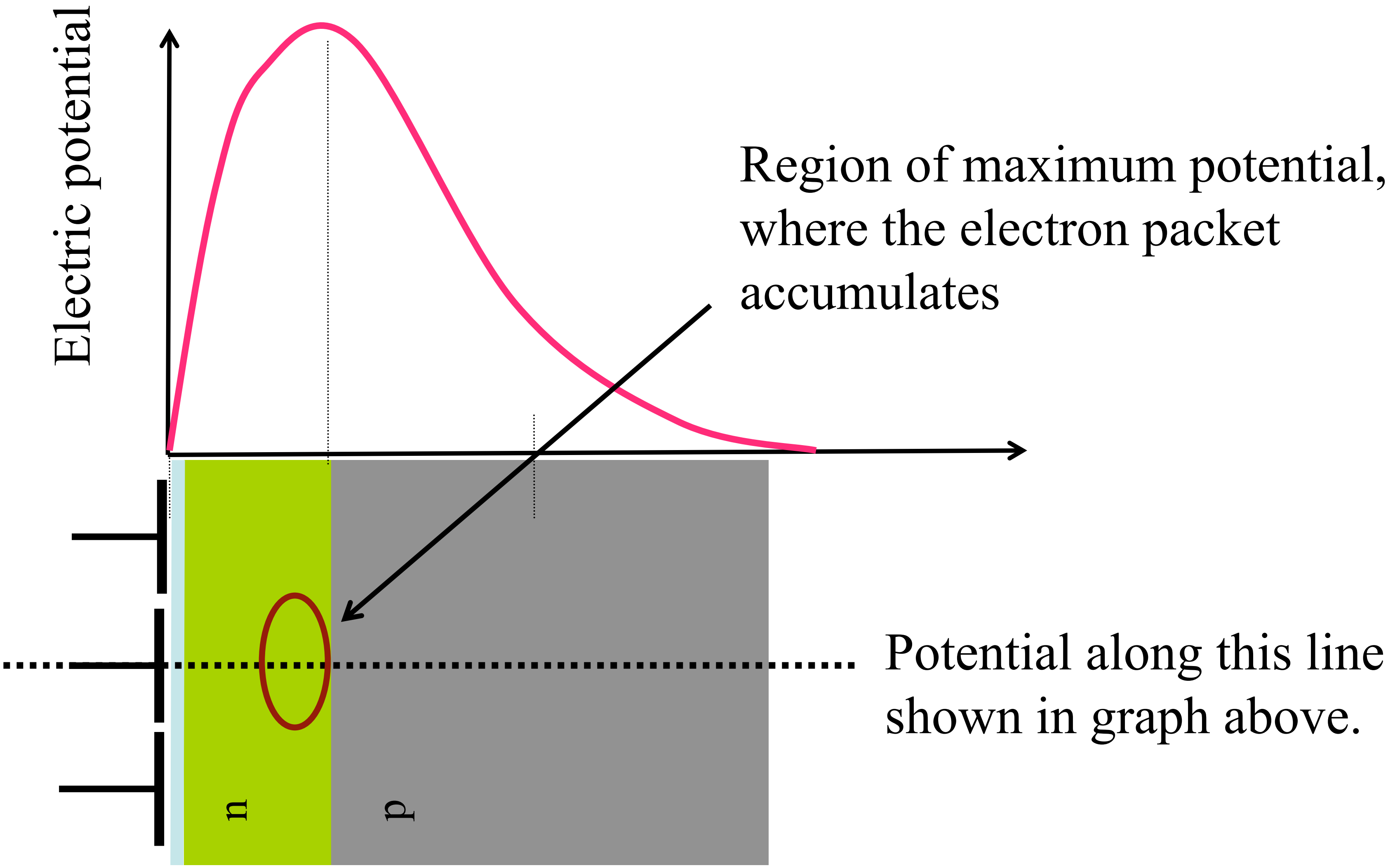
- Incoming photons generate electron-hole pairs
- That charge is collected in potential wells applied on the surface





- Thermally generated electrons are indistinguishable from photo-generated electrons → Dark Current → keep the CCD cold!
- Silicon is transparent to photons with $E < 1.26$eV ($\lambda \approx 1.05$ μm) → Red Cutoff! Need a different type of detector for IR …

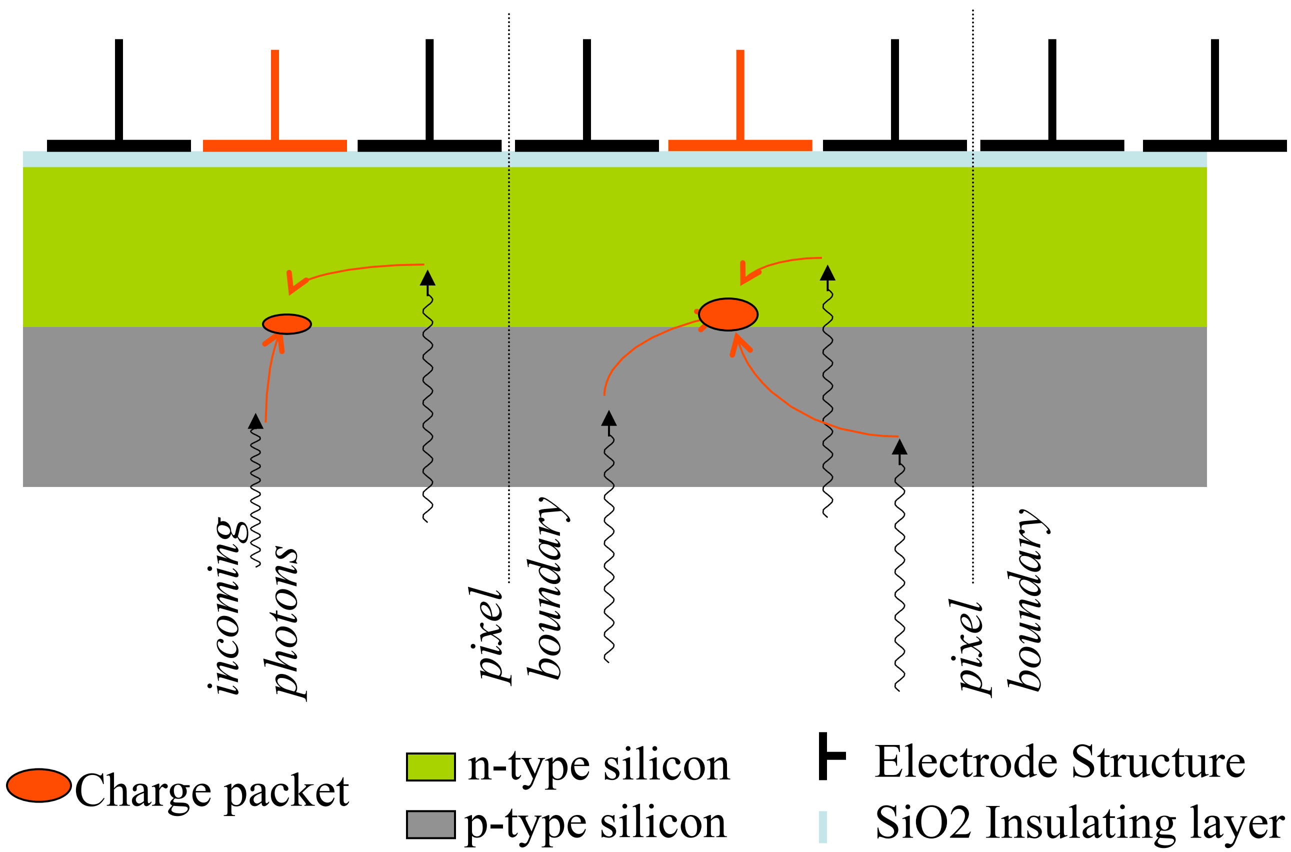
Electric Field in a CCD



Cross section through the thickness of the CCD

How Does A CCD Work?

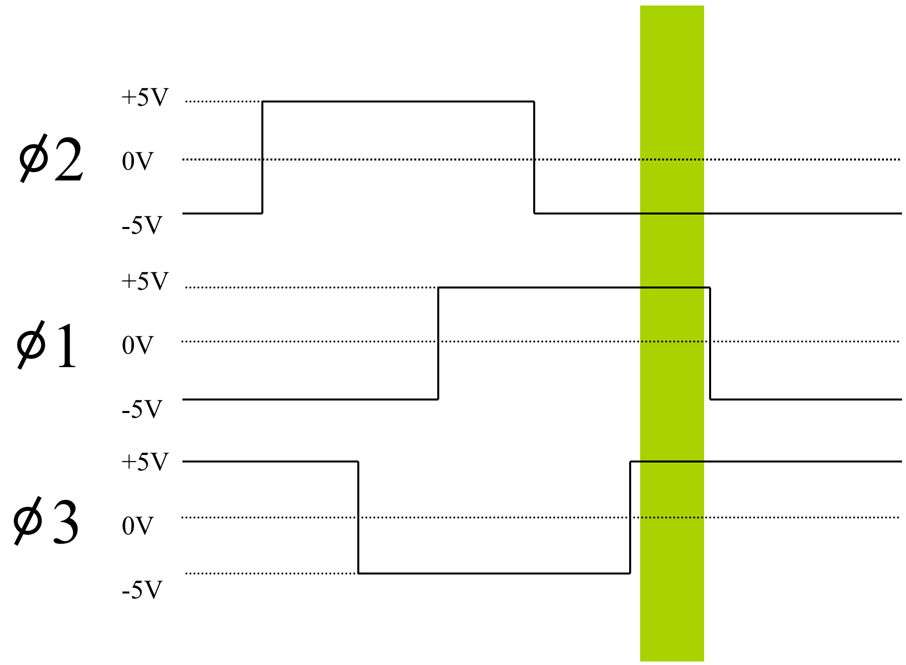
A grid of electrodes establishes a pixel grid pattern of electric potential wells, where photoelectrons are collected in “charge packets”

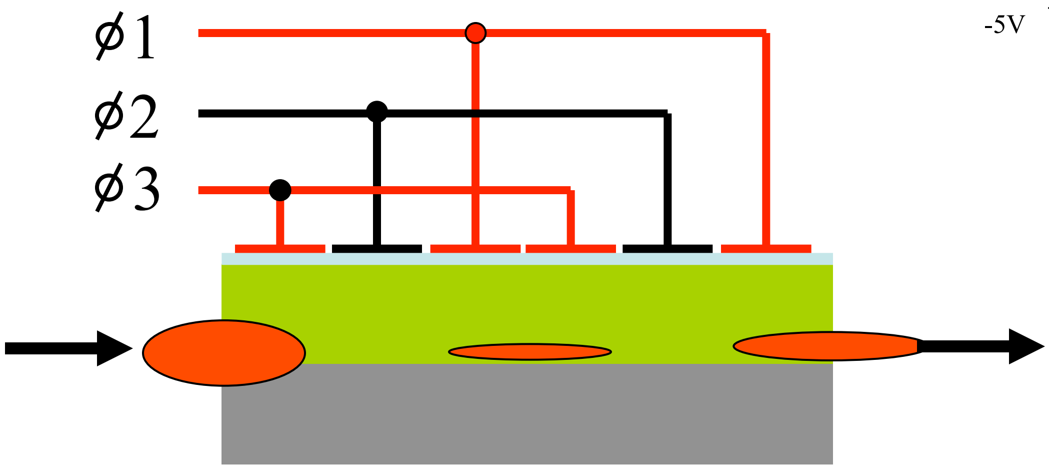


Typical well (pixel) capacity: a few $\times 10^5$ e^- . Beyond that, the charge “bleeds” along the electrodes.

Reading Out A CCD: Shift the electric potential pattern by clocking the voltages - pixel positions shift

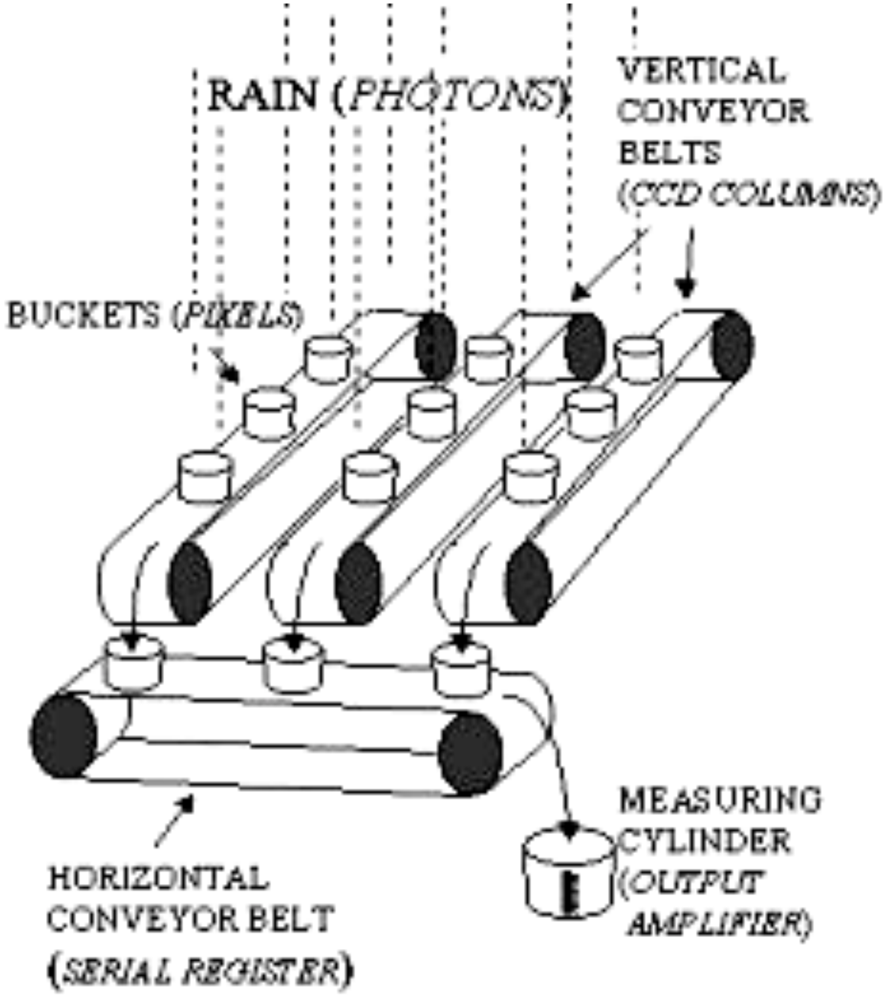
Charge packet from subsequent pixel enters from left as first pixel exits to the right.



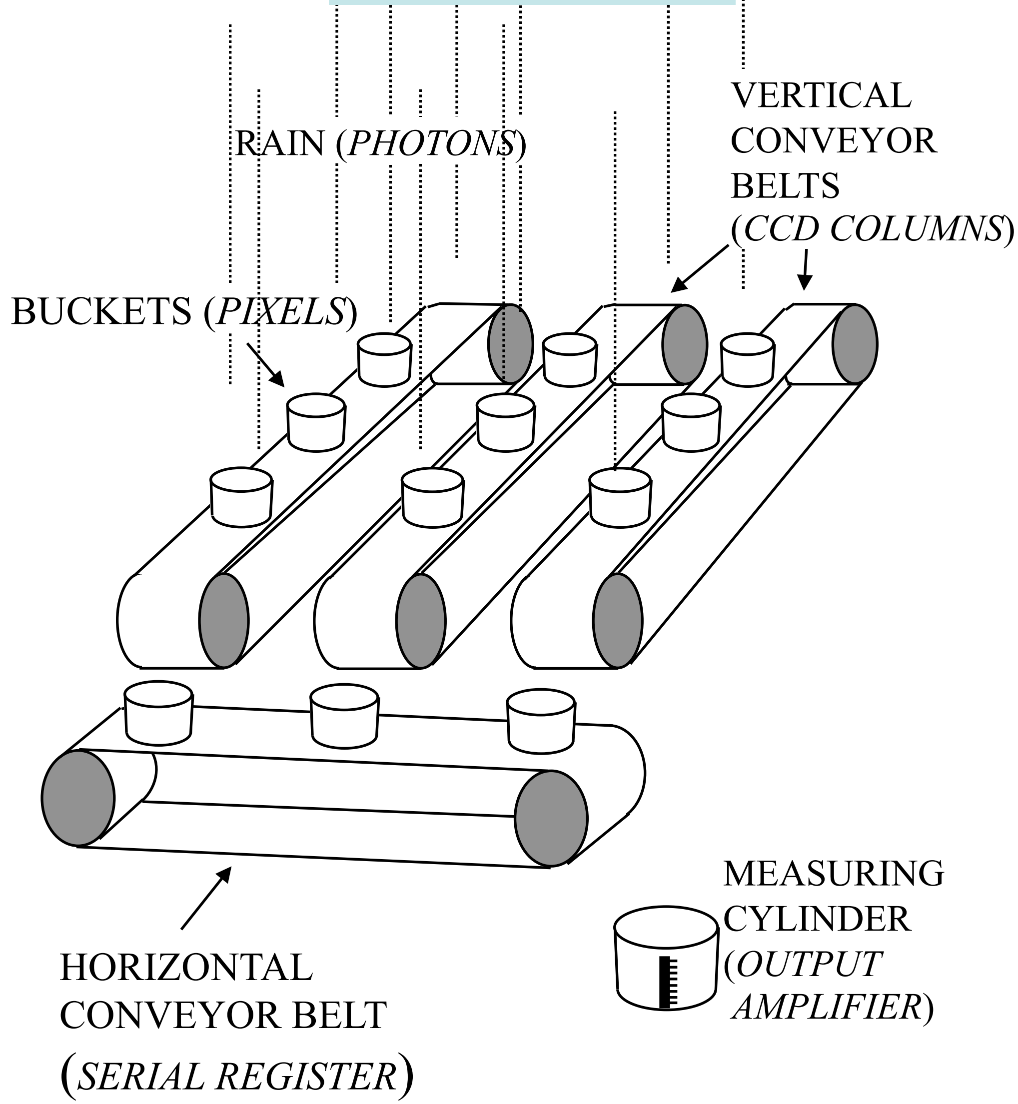


Pattern of collected electrons (= an image) moves with the voltage pattern, and is read out

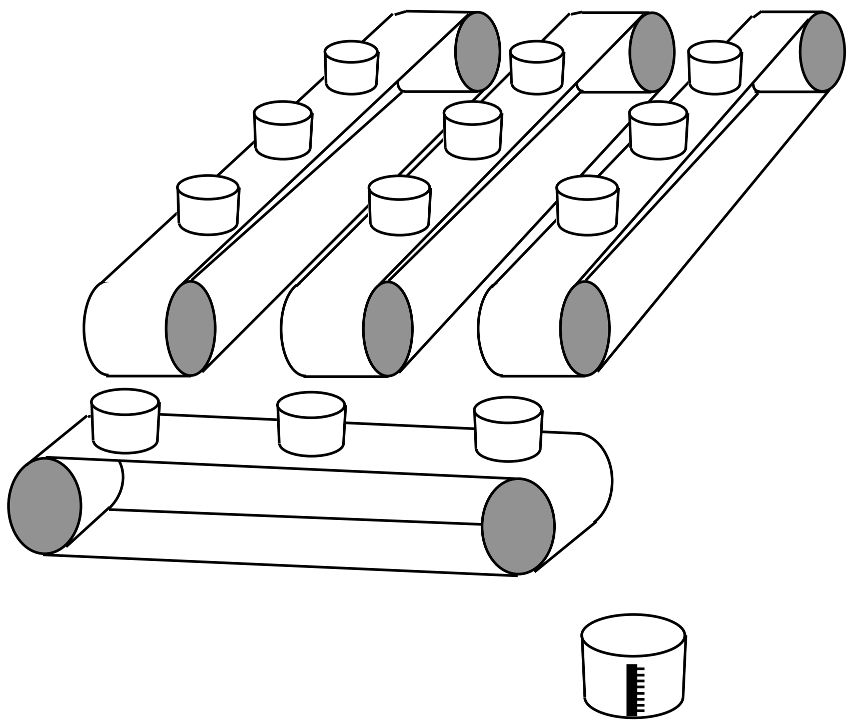
Reading Out A CCD: The Buckets-on-a-Conveyor Metaphor



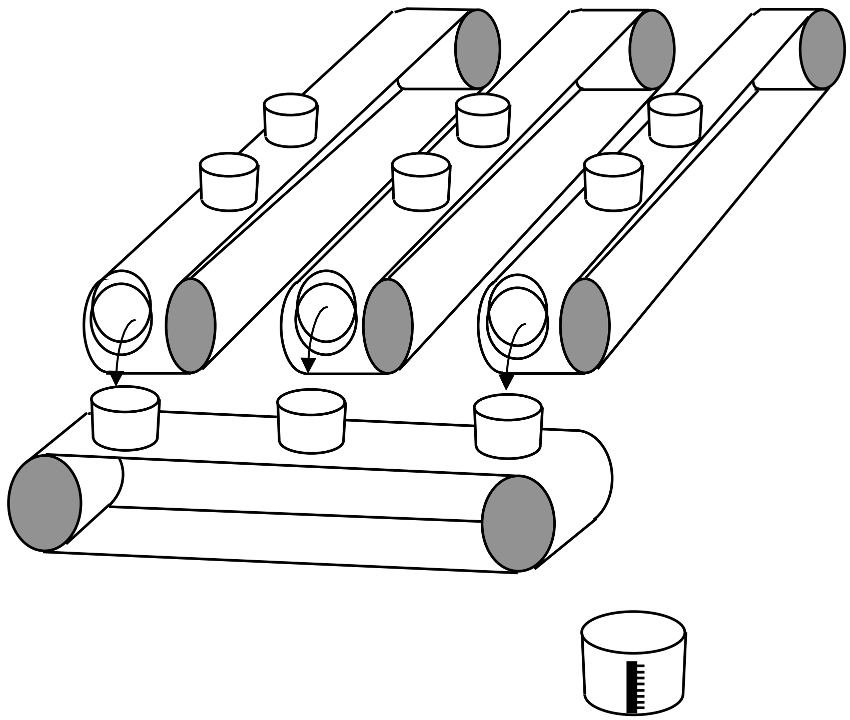
CCD Analogy


RAIN (*PHOTONS*)
VERTICAL CONVEYOR BELTS (*CCD COLUMNS*)
BUCKETS (*PIXELS*)
HORIZONTAL CONVEYOR BELT (*SERIAL REGISTER*)
MEASURING CYLINDER (*OUTPUT AMPLIFIER*)

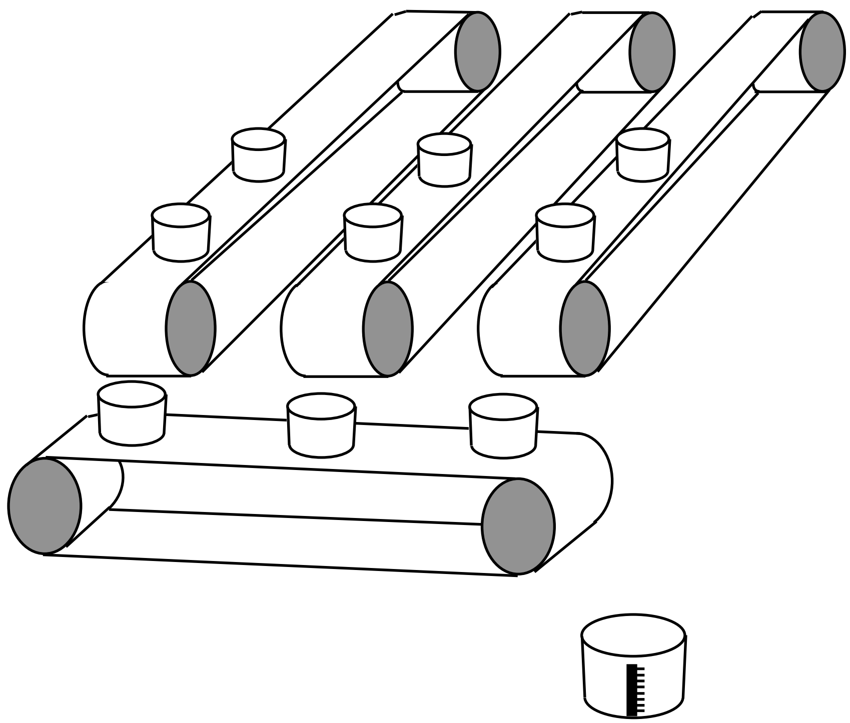
Exposure finished, buckets now contain samples of rain.



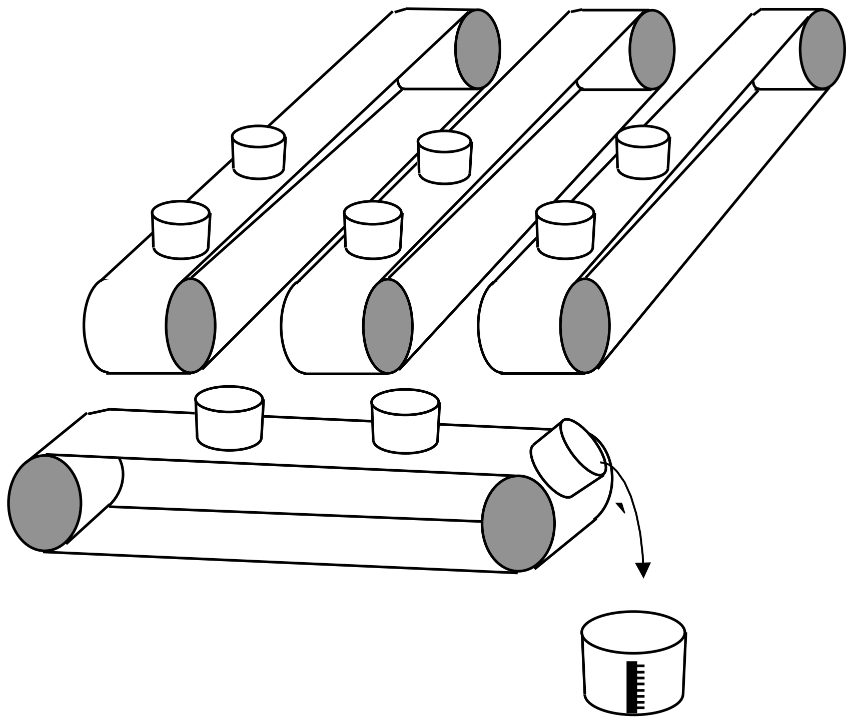
Conveyor belt starts turning and transfers buckets. Rain collected on the vertical conveyor is tipped into buckets on the horizontal conveyor.

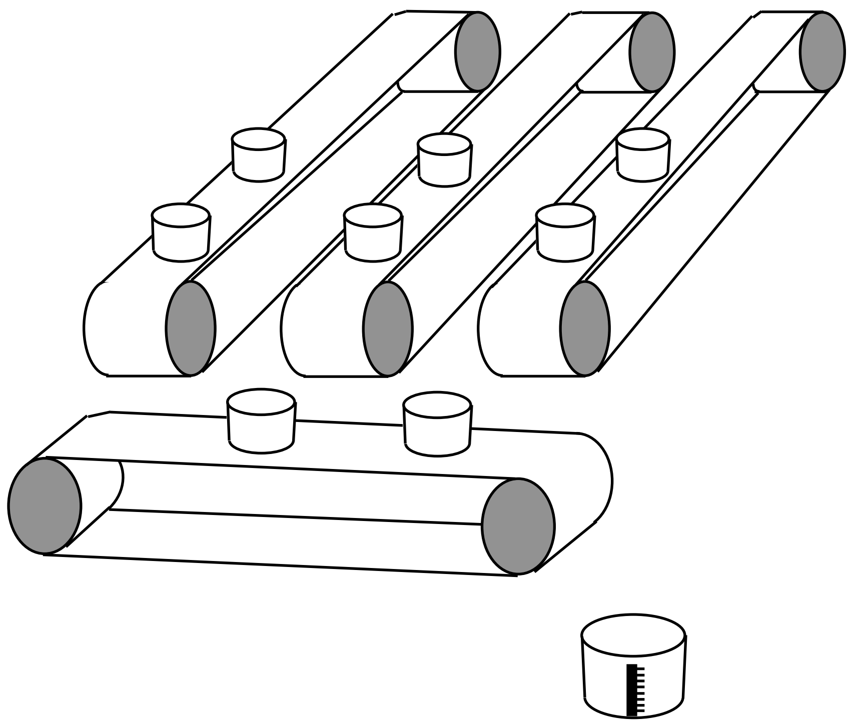


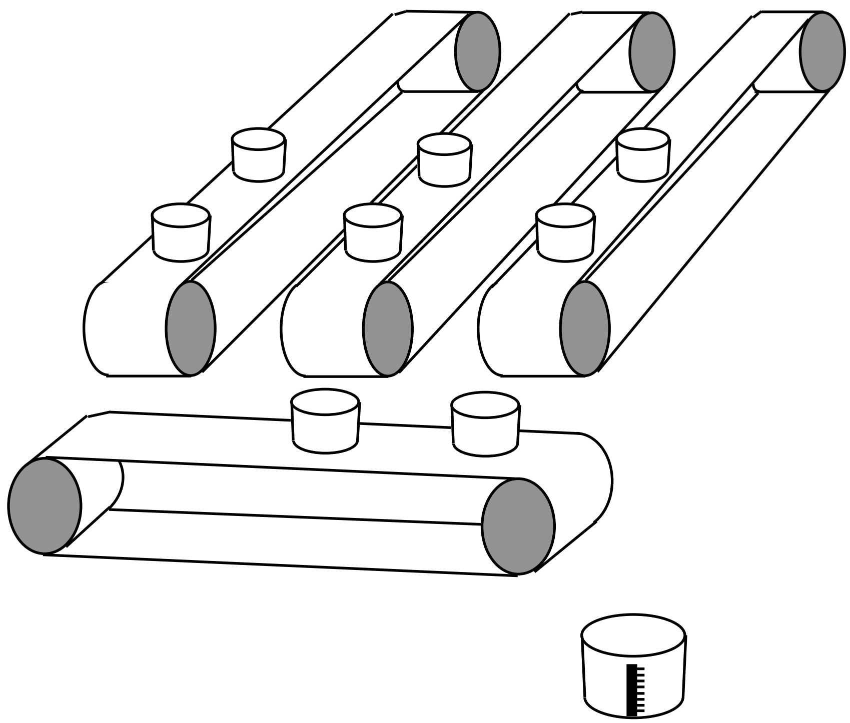
Vertical conveyor stops. Horizontal conveyor starts up and tips each bucket in turn into the measuring cylinder .

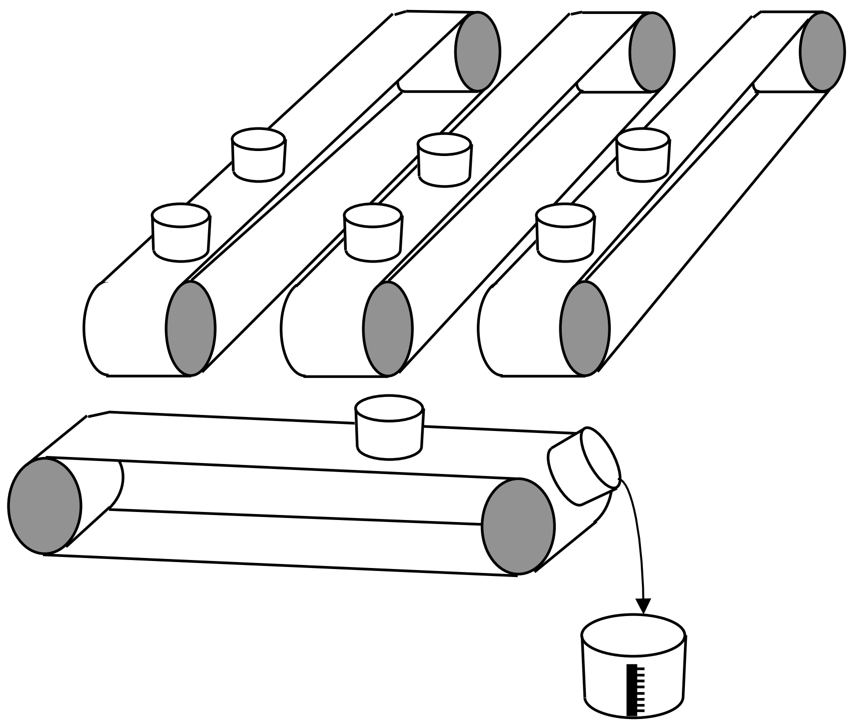


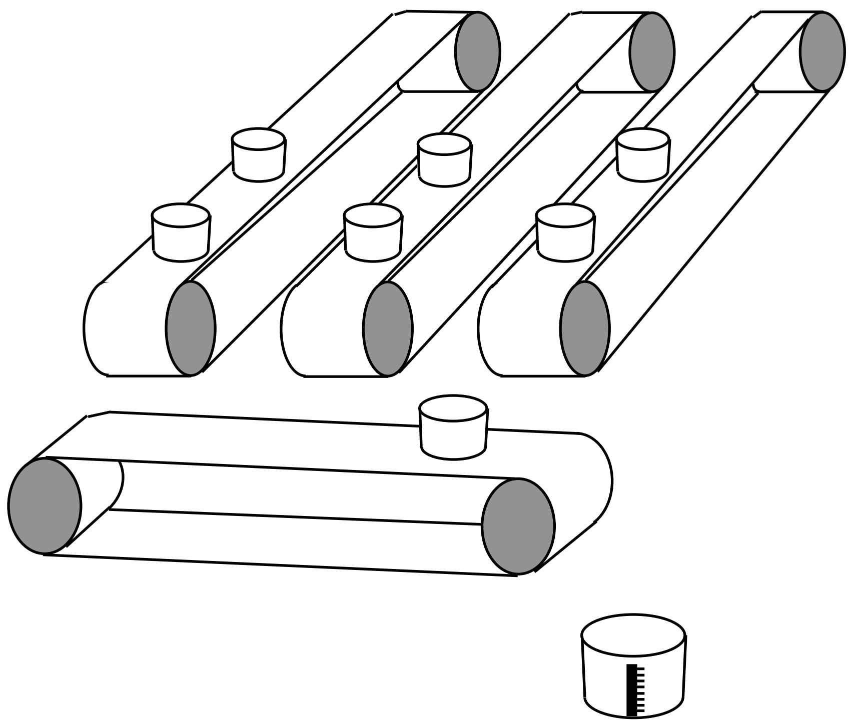
After each bucket has been measured, the measuring cylinder is emptied , ready for the next bucket load.







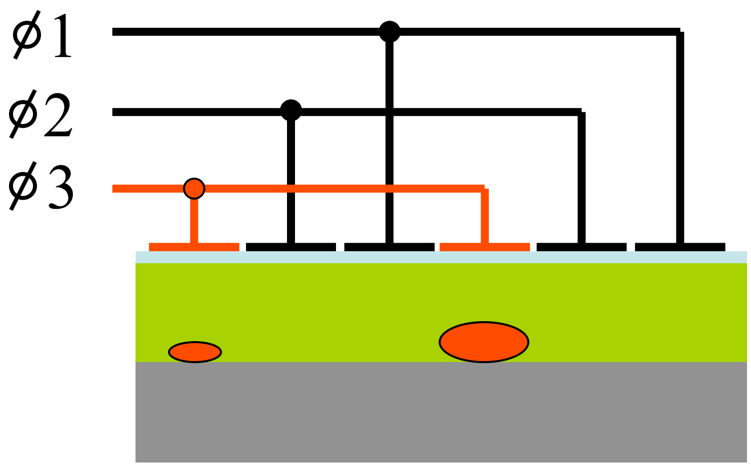




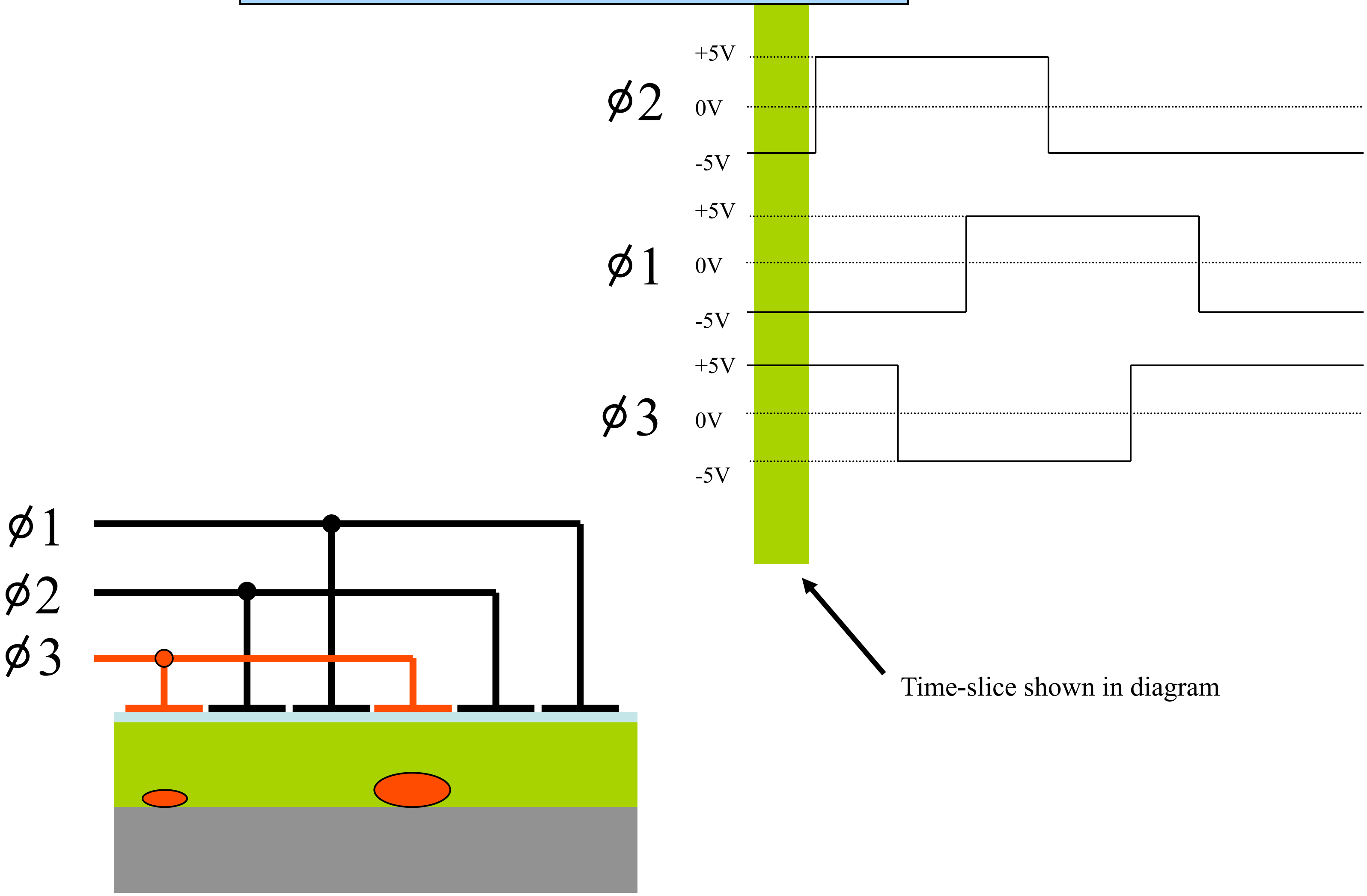
Charge Transfer in a CCD 1.

In the following few slides, the implementation of the ‘conveyor belts’ as actual electronic structures is explained.

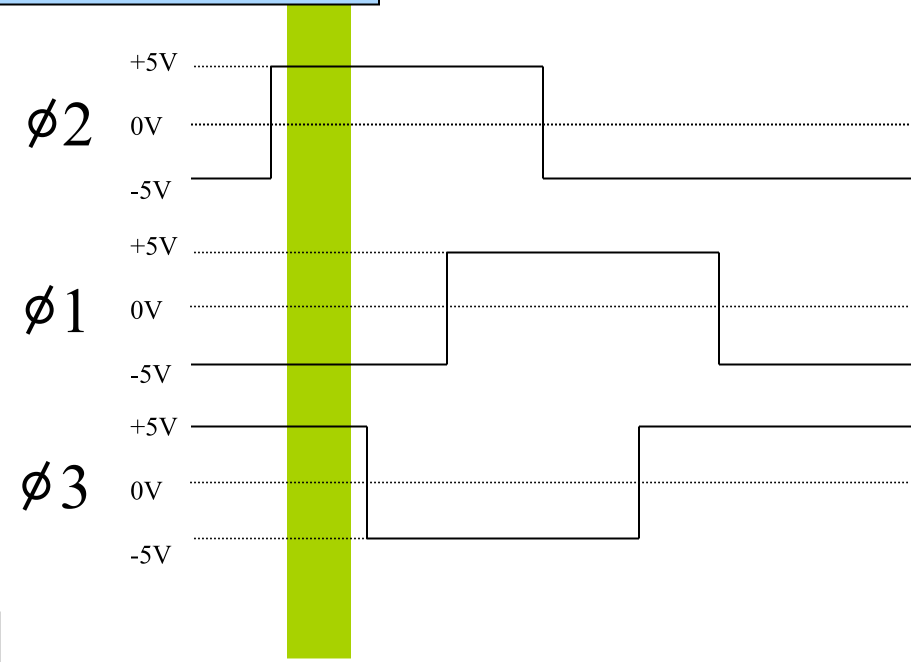
The charge is moved along these conveyor belts by modulating the voltages on the electrodes positioned on the surface of the CCD. In the following illustrations, electrodes colour coded red are held at a positive potential, those coloured black are held at a negative potential.

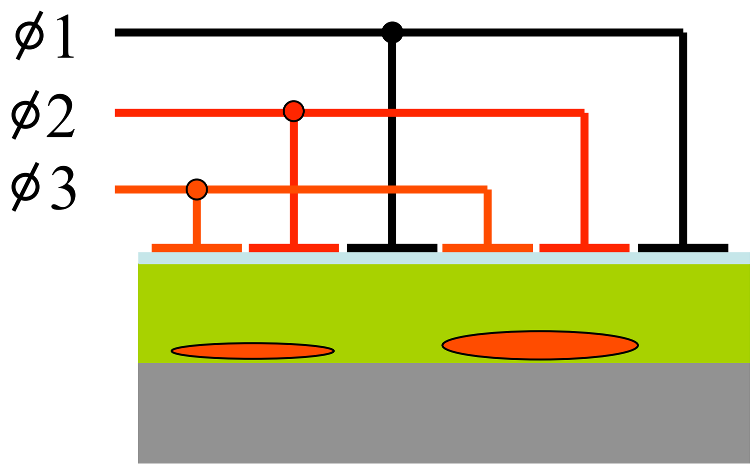


Charge Transfer in a CCD 2.

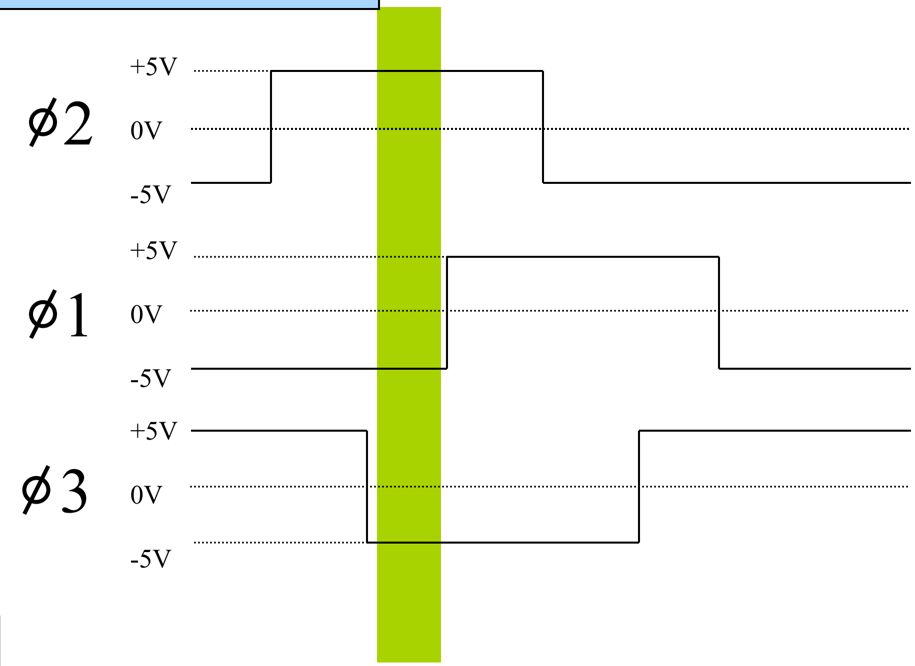


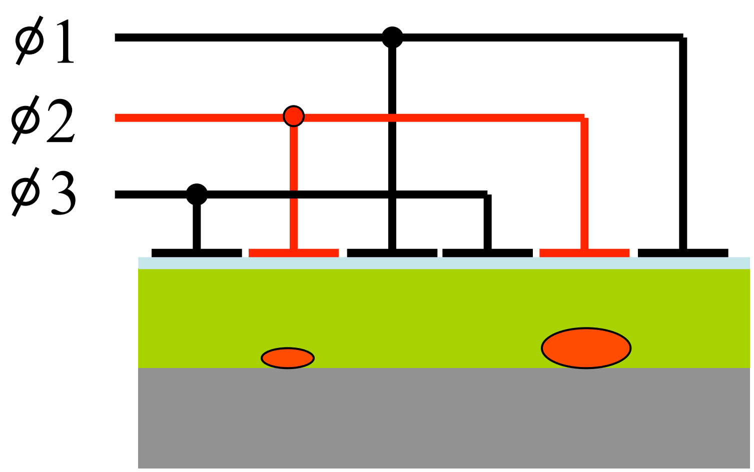
Charge Transfer in a CCD 3.



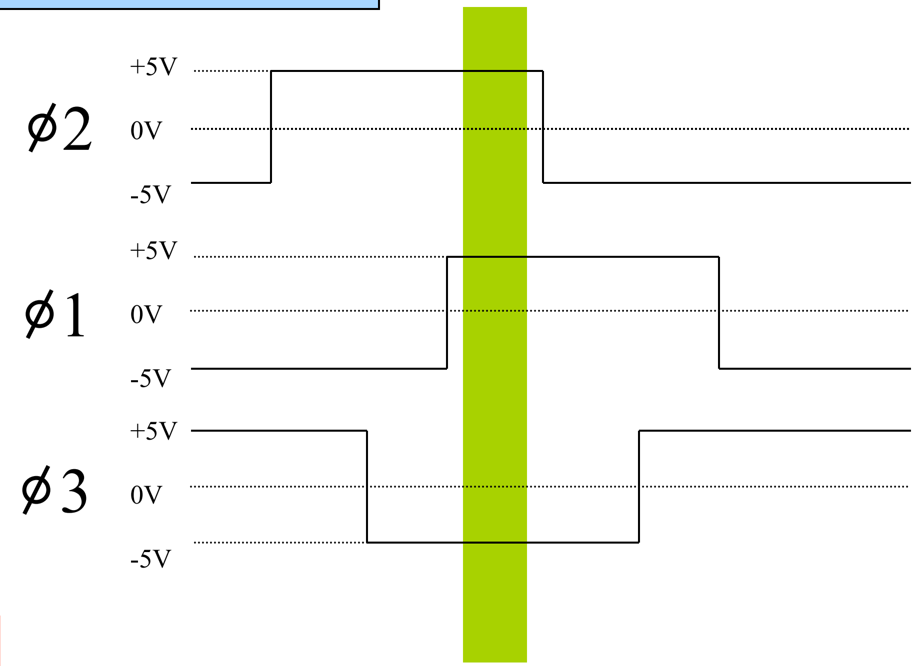


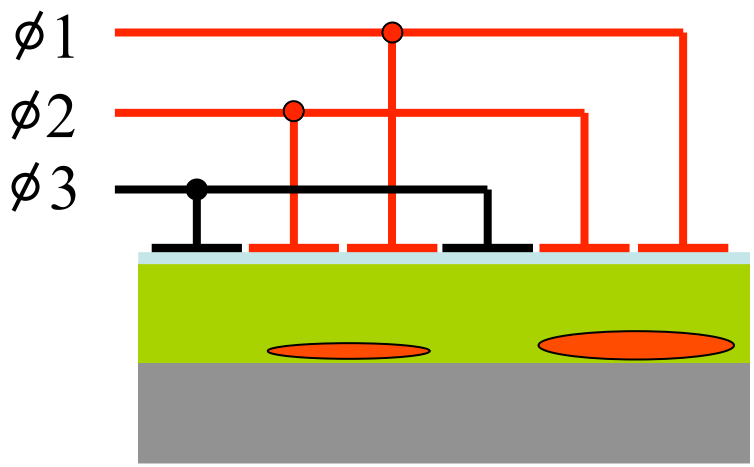
Charge Transfer in a CCD 4.



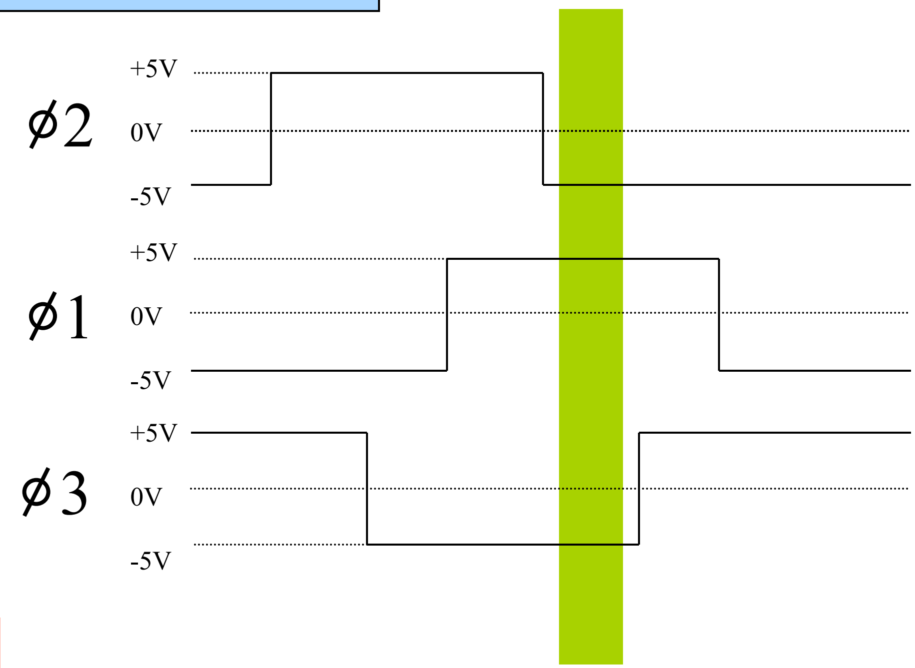


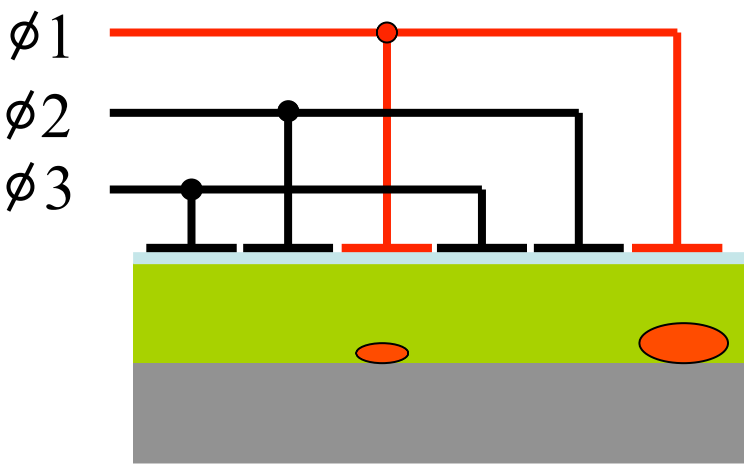
Charge Transfer in a CCD 5.





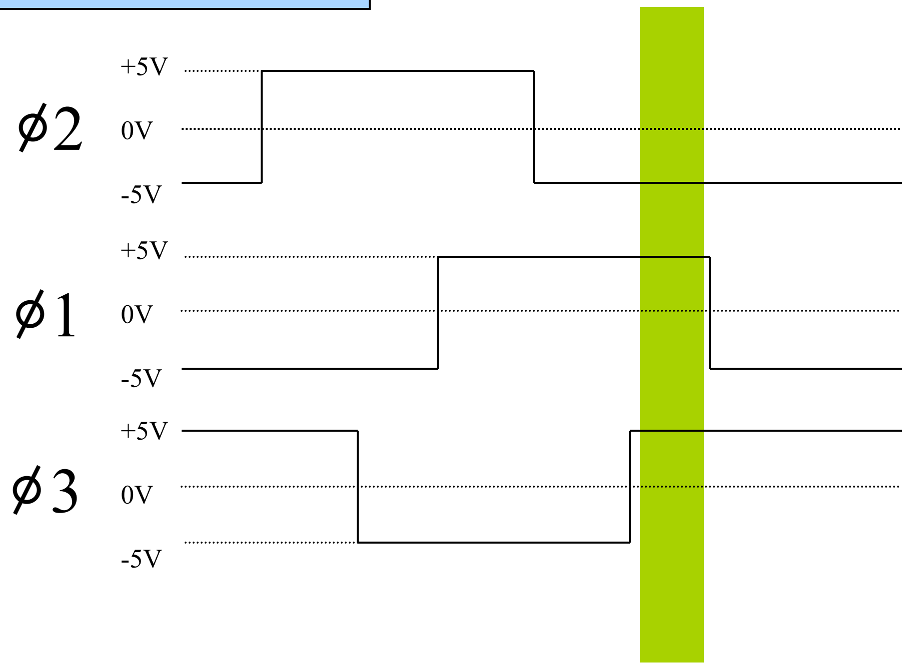
Charge Transfer in a CCD 6.

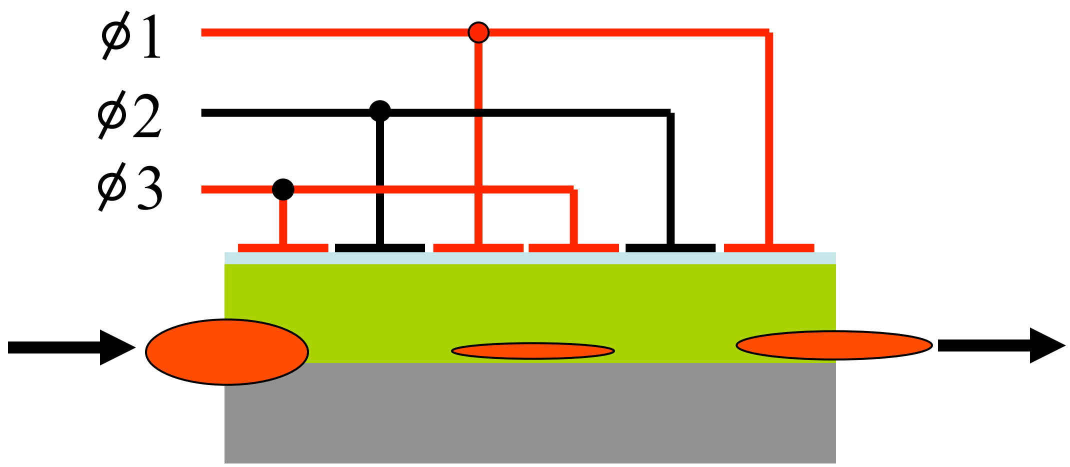




Charge Transfer in a CCD 7.

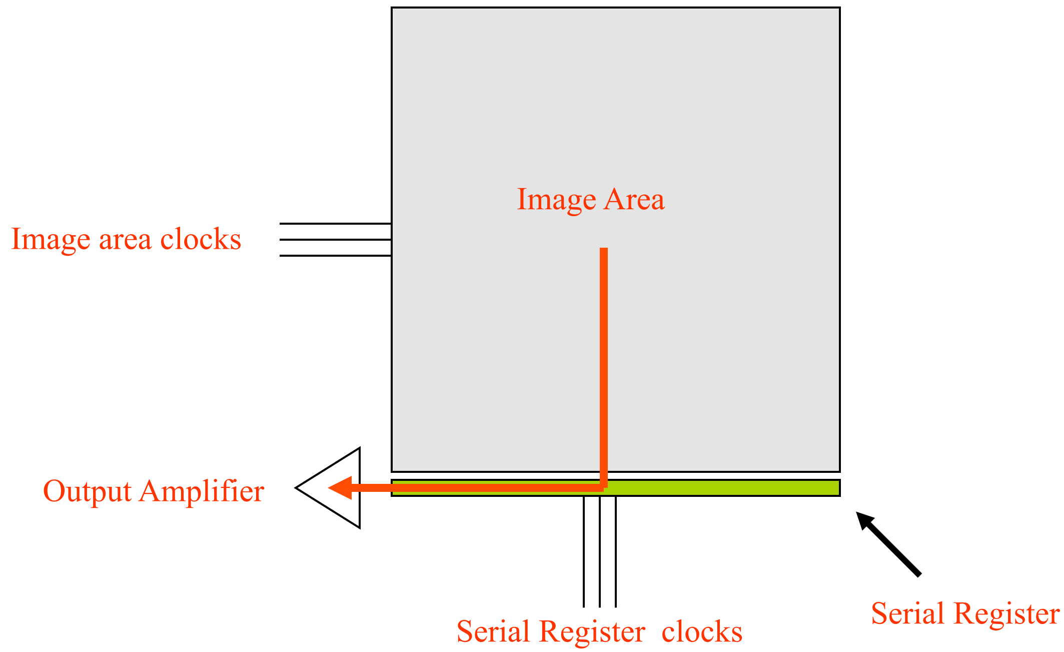
Charge packet from subsequent pixel enters from left as first pixel exits to the right.





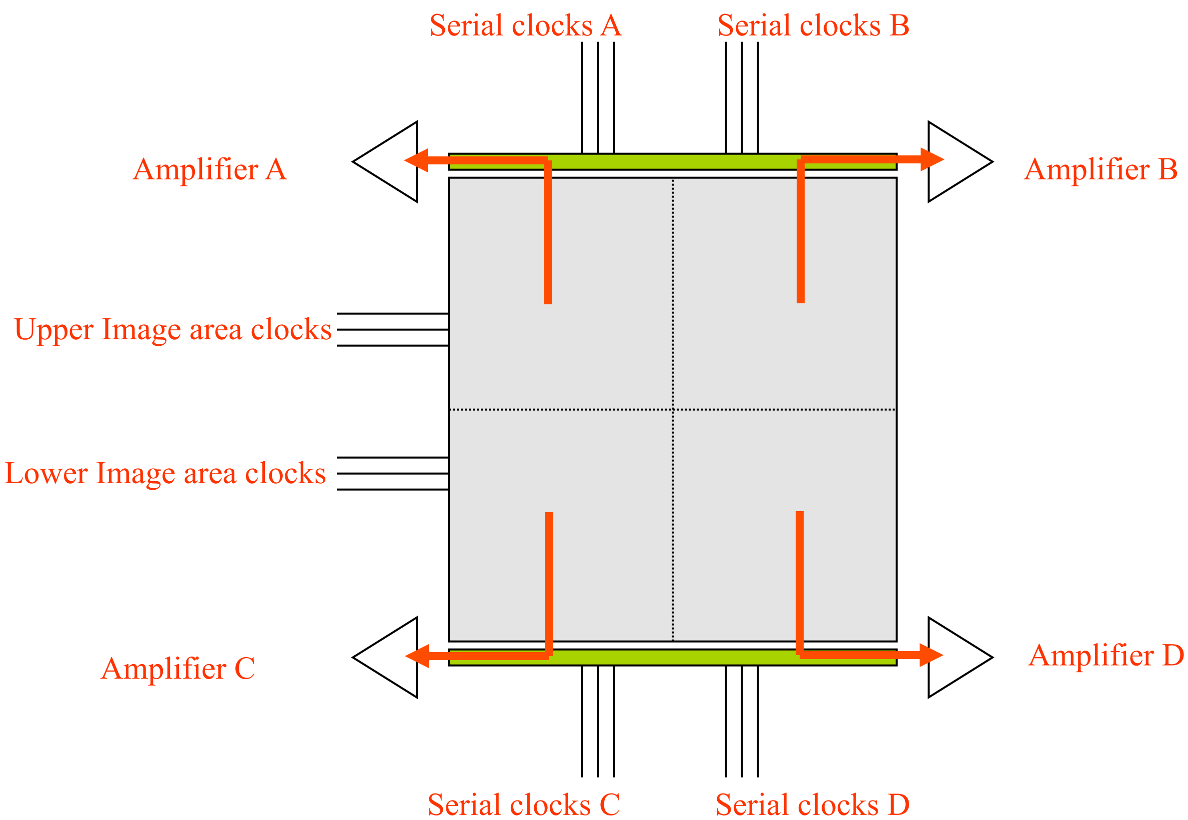
Slow Scan CCDs 1.

The most basic geometry of a Slow-Scan CCD is shown below. Three clock lines control the three phases of electrodes in the image area, another three control those in the serial register. A single amplifier is located at the end of the serial register. The full image area is available for imaging. Because all the pixels are read through a single output, the readout speed is relatively low. The red line shows the flow of charge out of the CCD.



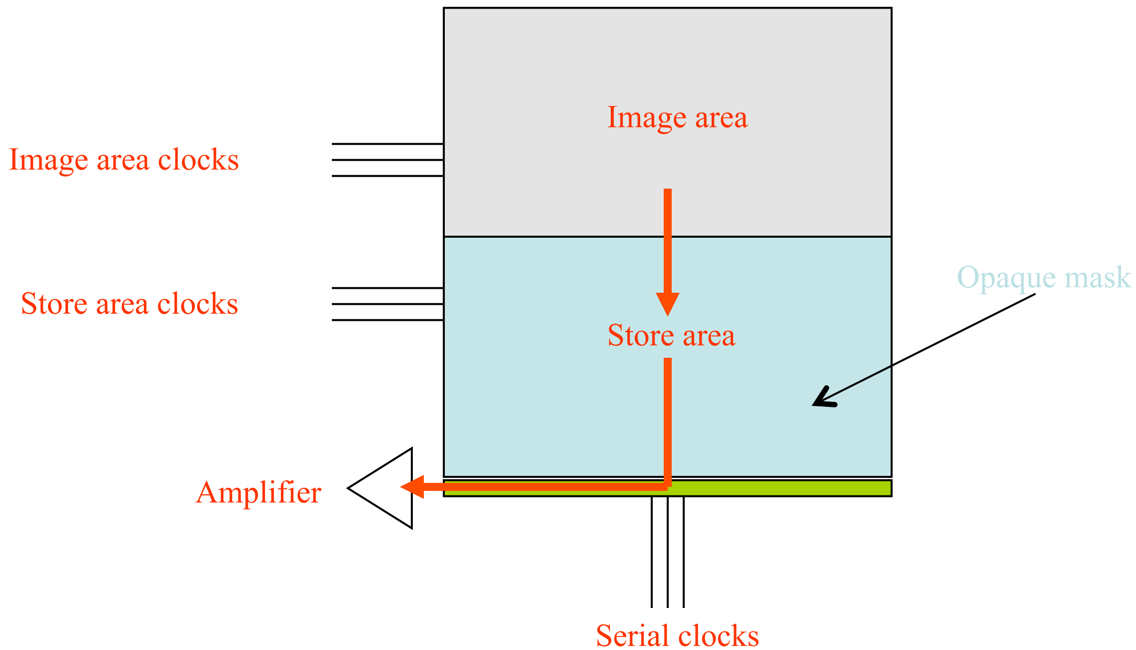
Slow Scan CCDs 2.

A slightly more complex design uses 2 serial registers and 4 output amplifiers. Extra clock lines are required to divide the image area into an upper and lower section. Further clock lines allow independent operation of each half of each serial register. It is thus possible to read out the image in four quadrants simultaneously, reducing the readout speed by a factor of four.



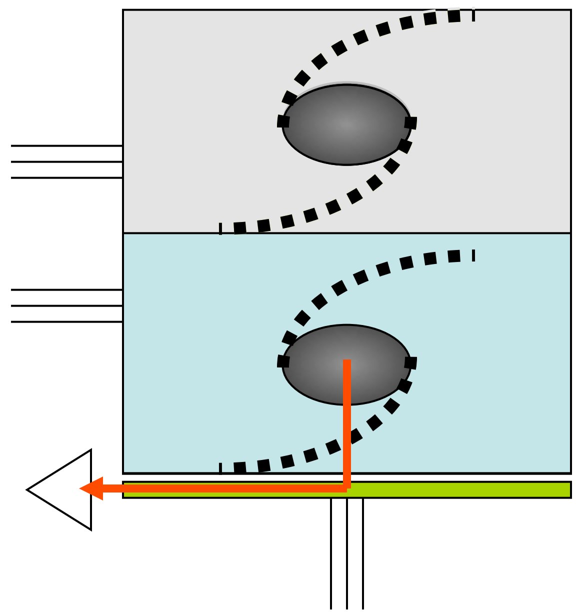
Video CCDs 1.

In the split frame CCD geometry, the charge in each half of the image area could be shifted independently. Now imagine that the lower image area is covered with an opaque mask. This mask could be a layer of aluminium deposited on the CCD surface or it could be an external mask. This geometry is the basis of the ‘Frame transfer’ CCD that is used for high frame rate video applications. The area available for imaging is reduced by a half. The lower part of the image becomes the ‘Store area’.

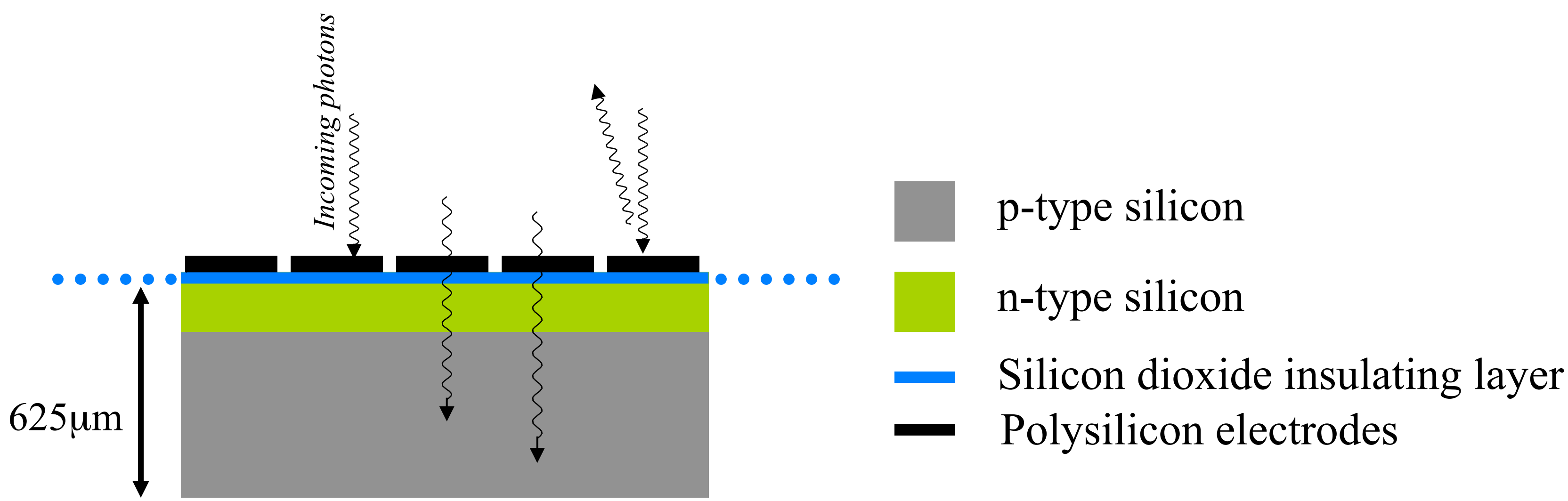


Video CCDs 3.

Once the image is safely stored under the mask, it can then be read out at leisure. Since we can independently control the clock phases in the image and store areas, the next image can be integrated in the image area during the readout. The image area can be kept continuously integrating and the detector has only a tiny 'dead time' during the image shift. No external shutter is required but the effective size of the CCD is cut by a half.



Thick Front-side Illuminated CCD

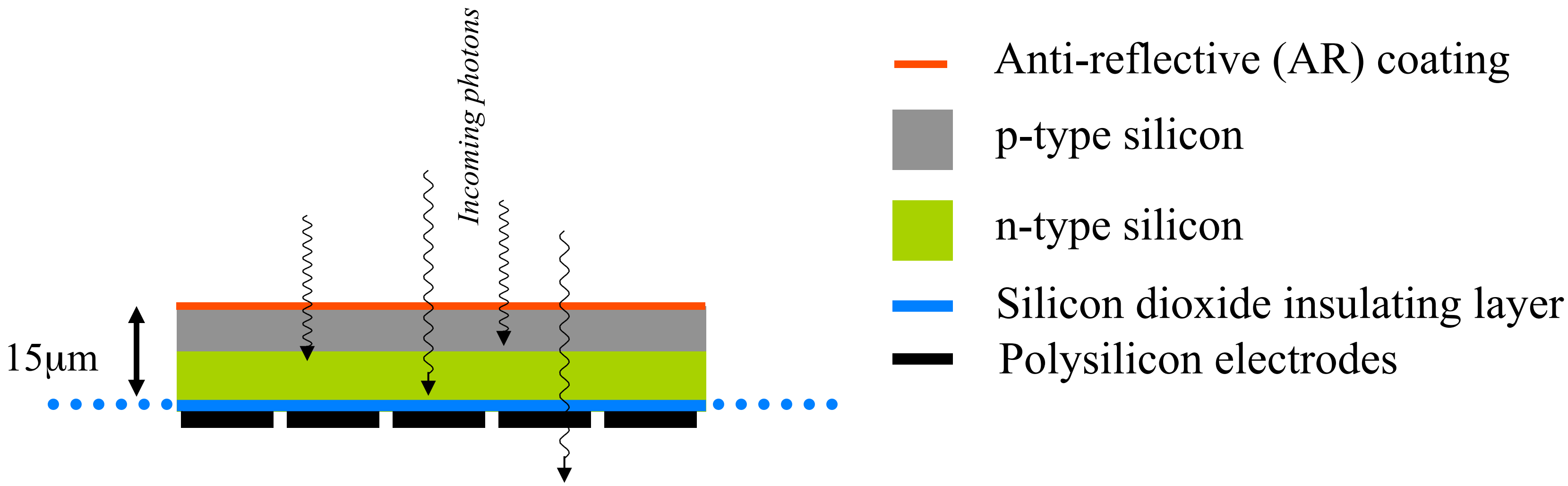


These are cheap to produce using conventional wafer fabrication techniques. They are used in consumer imaging applications. Even though not all the photons are detected, these devices are still more sensitive than photographic film.

They have a low Quantum Efficiency due to the reflection and absorption of light in the surface electrodes. Very poor blue response. The electrode structure prevents the use of an Anti-reflective coating that would otherwise boost performance.

The amateur astronomer on a limited budget might consider using thick CCDs. For professional observatories, the economies of running a large facility demand that the detectors be as sensitive as possible; thick front-side illuminated chips are seldom if ever used.

Thinned Back-side Illuminated CCD



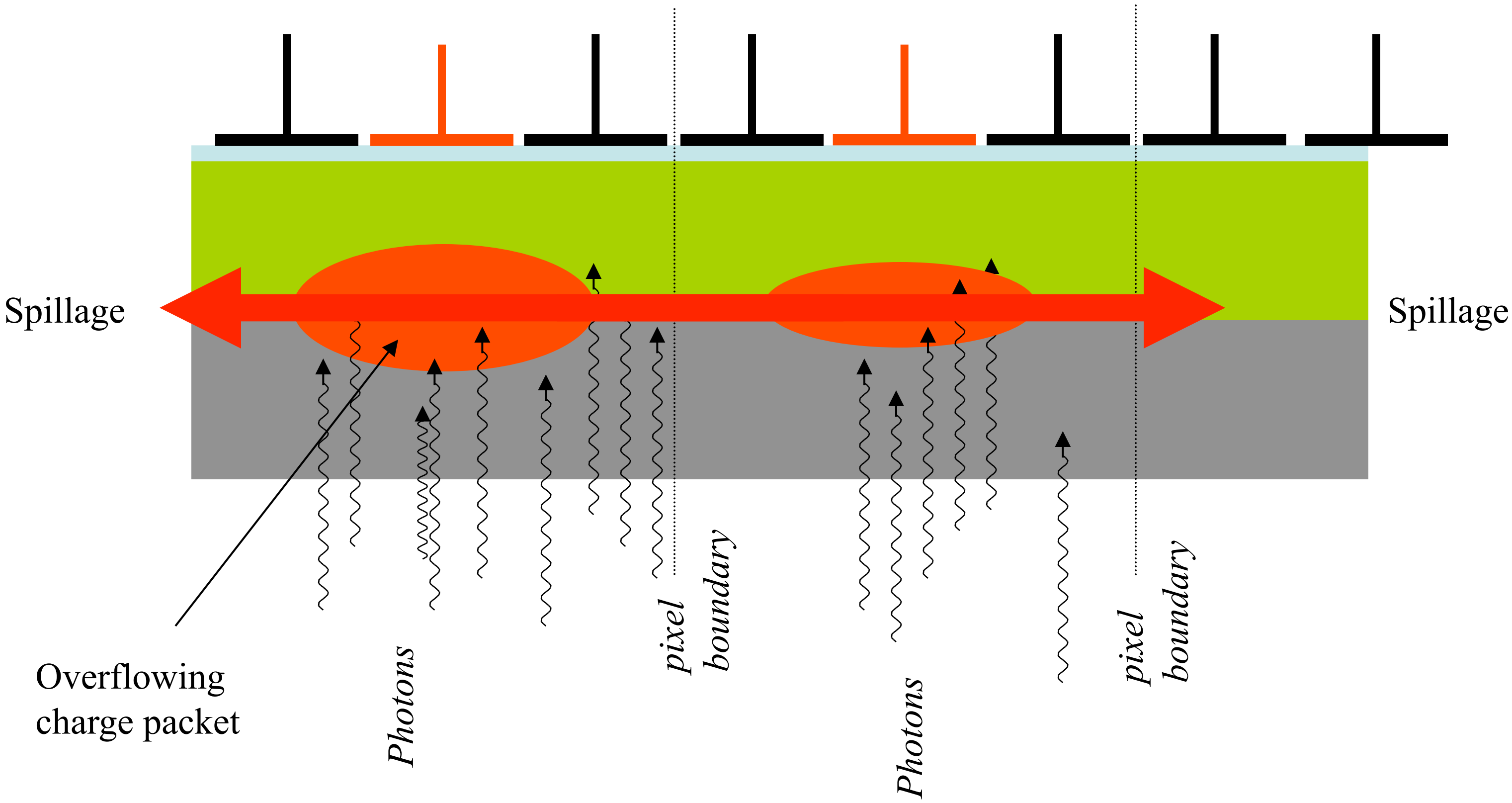
The silicon is chemically etched and polished down to a thickness of about 15microns. Light enters from the rear and so the electrodes do not obstruct the photons. The QE can approach 100% .

These are very expensive to produce since the thinning is a non-standard process that reduces the chip yield. These thinned CCDs become transparent to near infra-red light and the red response is poor. Response can be boosted by the application of an anti-reflective coating on the thinned rear-side. These coatings do not work so well for thick CCDs due to the surface bumps created by the surface electrodes.

Almost all Astronomical CCDs are Thinned and Backside Illuminated.

Blooming in a CCD 1.

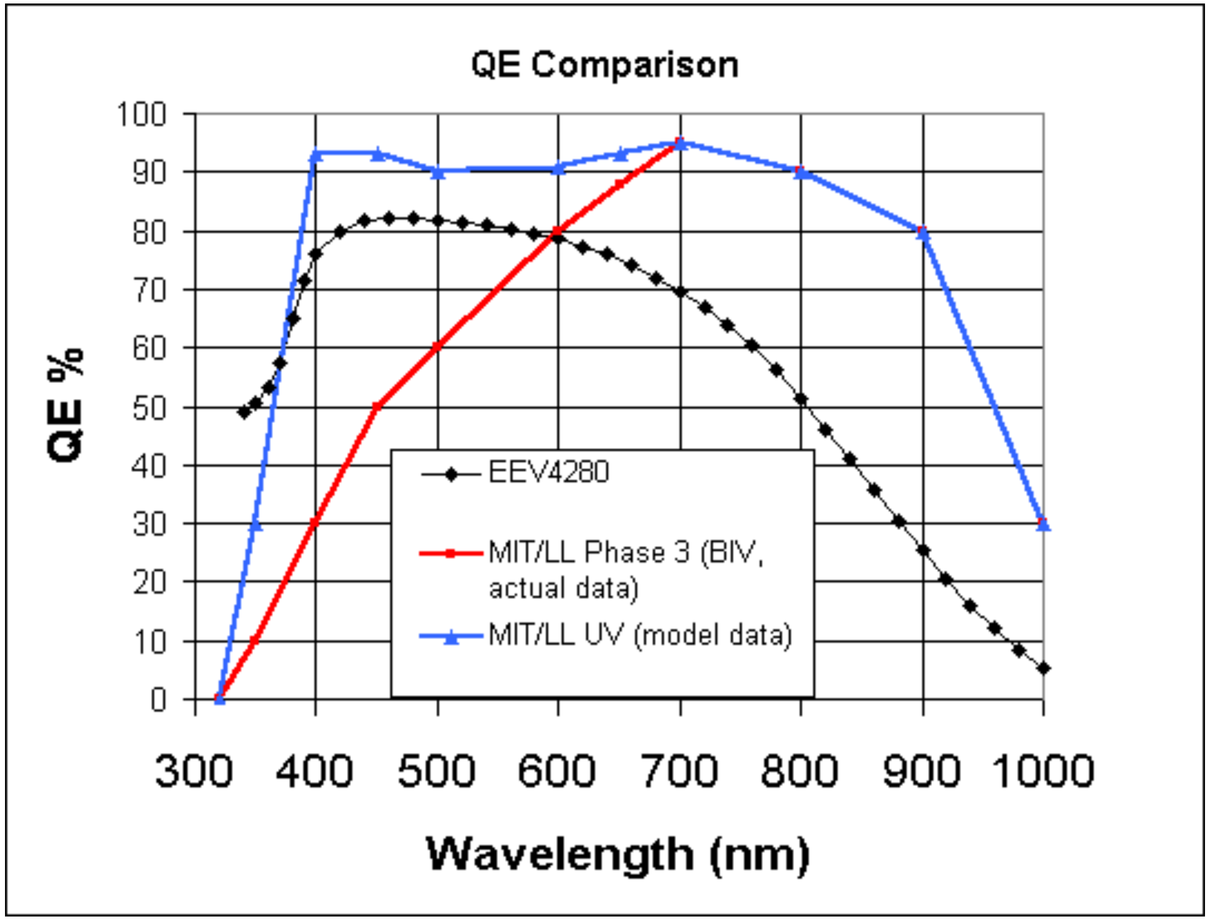
The charge capacity of a CCD pixel is limited, when a pixel is full the charge starts to leak into adjacent pixels. This process is known as ‘Blooming’.



CCDs: The Quantum Efficiency

Nearly a unity through most of the visible

Usually lower in the blue/UV, due to the absorption of photons before they reach the p.e. layer - cured by doping, phosphor dyes, etc.

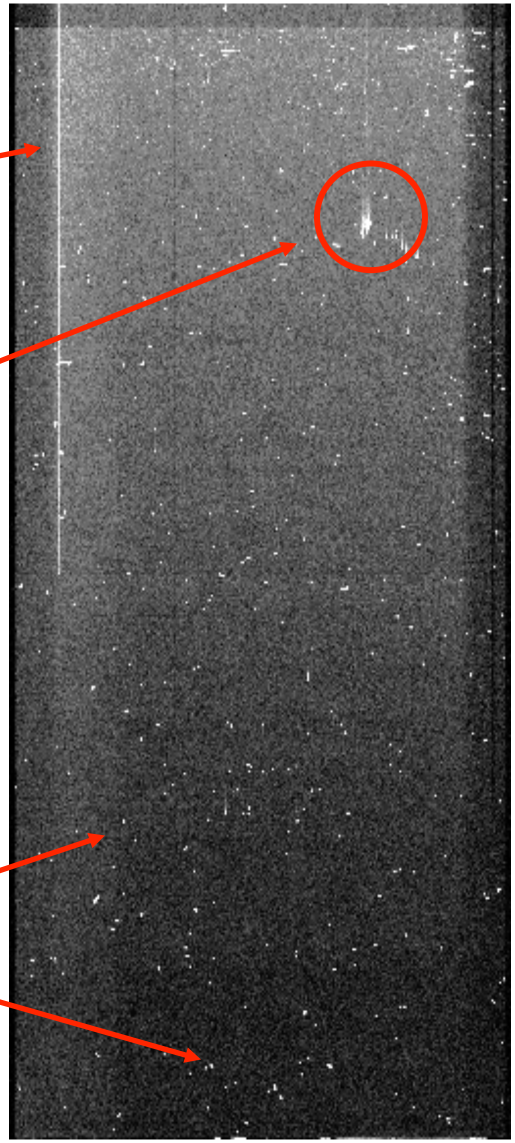


CCDs Are *Not* Perfect …

Bright Column (charge traps)

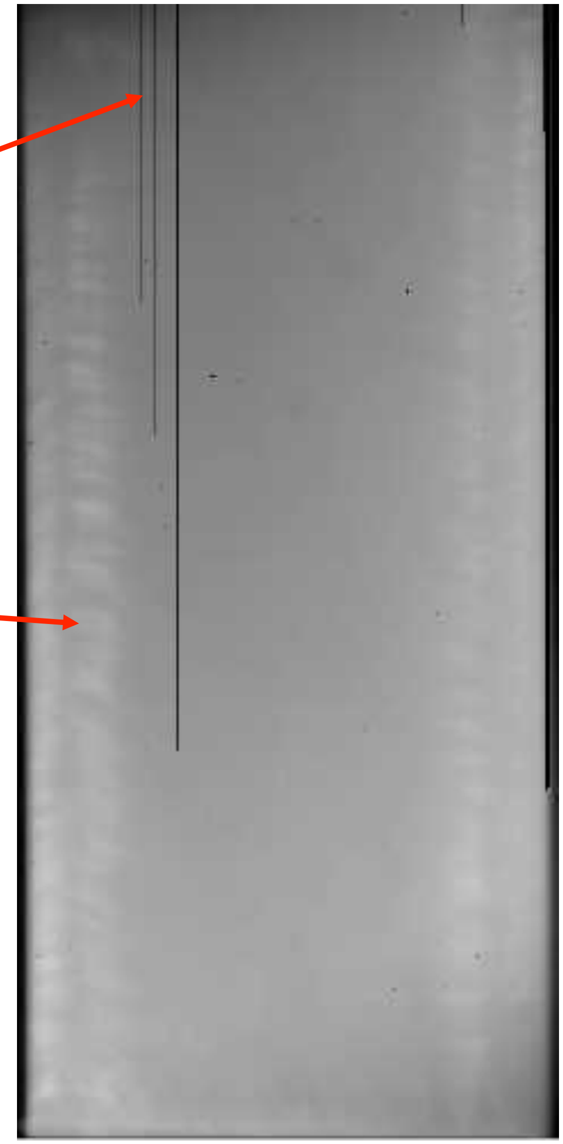
Hot Spots (high dark current, but sometimes LEDs!)

Cosmic rays



Dark Columns (charge traps)

QE variations



Noise Sources in a CCD Image

Readout Noise: Caused by electronic in the CCD output transistor and in the external circuitry; typically $\sigma_{RON} \sim 2\text{-}3\ e^-$

Dark Current: Caused by thermally generated electrons in the CCD. Eliminated by cooling the CCD.

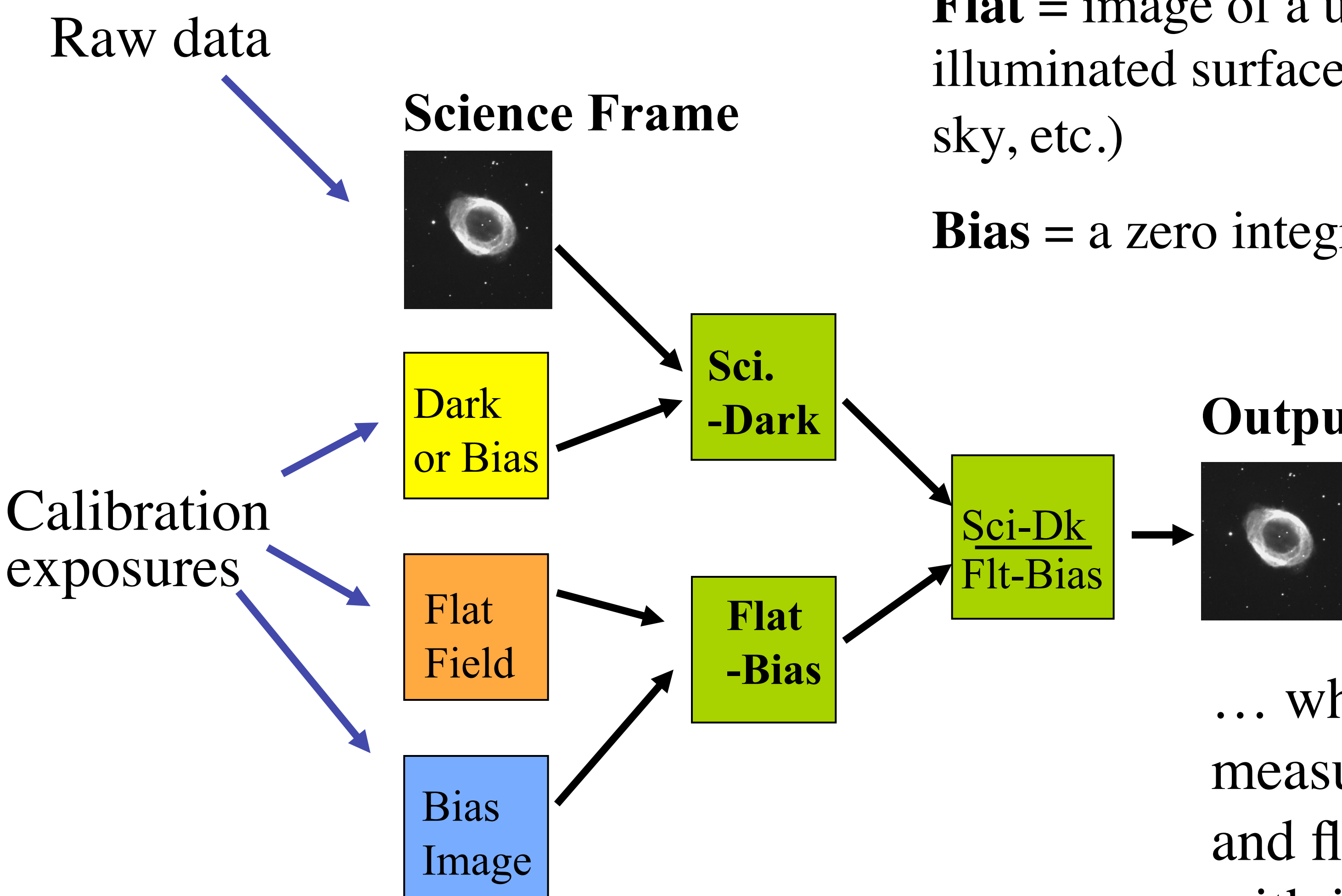
Photon Noise: Also called "Shot Noise". Photons arrive in an unpredictable fashion described by Poissonian statistics.

Pixel Response Nonuniformity: Also called "Pattern Noise". QE variations due to defects in the silicon and manufacturing. Removed by "Flatfielding"

Reducing A CCD Image

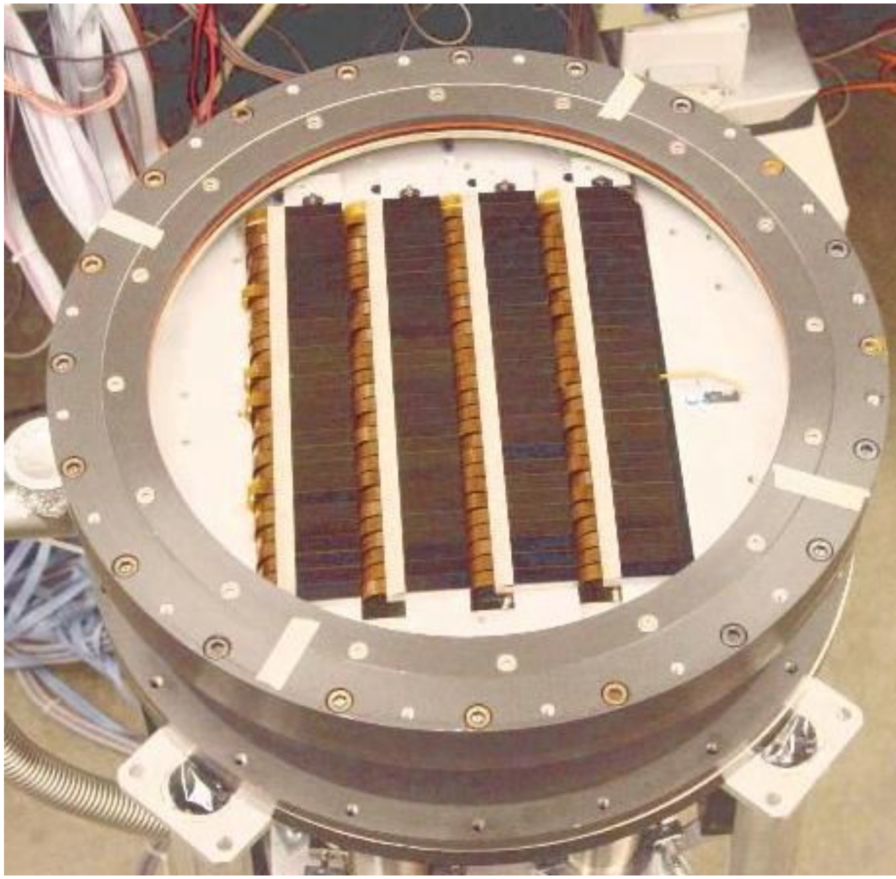
Flat = image of a uniformly illuminated surface (a dome, sky, etc.)

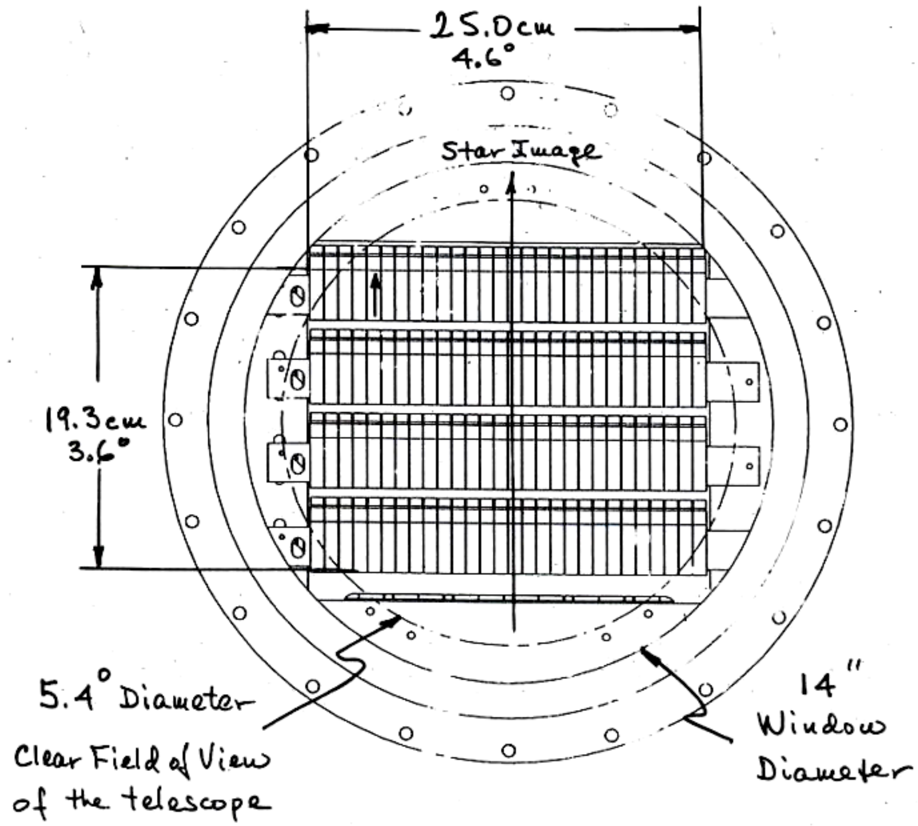
Bias = a zero integration image



… which you measure, analyse, and flux-calibrate with images of standard stars

The Palomar-QUEST 112-CCD Camera





~ 162 million pixels!

And even bigger mosaics are in the works (e.g., Pan-STARRs, LSST)

CFHT MegaCam

CMOS Imagers

- CMOS = Complementary Metal Oxide Semiconductor; it's a process, not a particular device
- Each pixel has its own readout transistor. Could build special electronics on the same chip. Can be read out in a random access fashion.
- Noisier, less sensitive, and with a lower dynamical range than CCDs, but much cheaper; and have some other advantages
- Not yet widely used in astronomy, but might be (LSST?)