OBSERVATIONAL ASTRONOMY

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Lecture 5

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Detectors

The central theme of this course is the detection and characterization of photons with both ground-based instruments and instruments aboard spacecraft.

Detector parameters (1)

- **Quantum Efficiency (QE):** Ratio of the number of detected photons C and the number of incident photons N, as a function of wavelength, $\eta(\lambda)$:

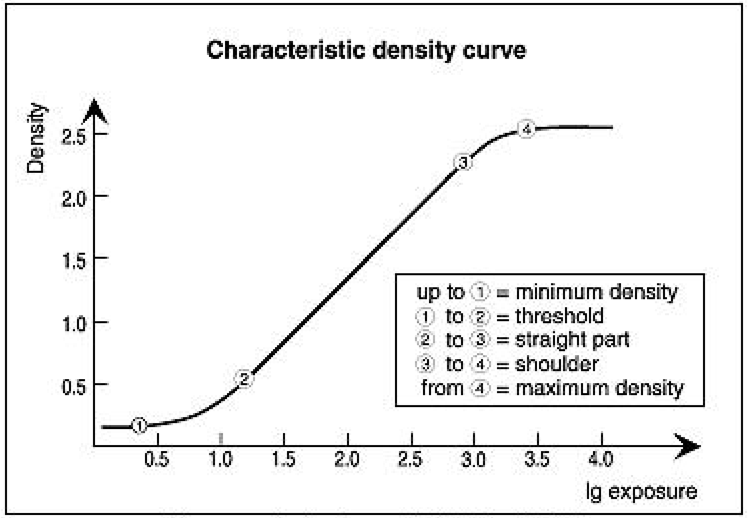
$$\eta = C/N$$

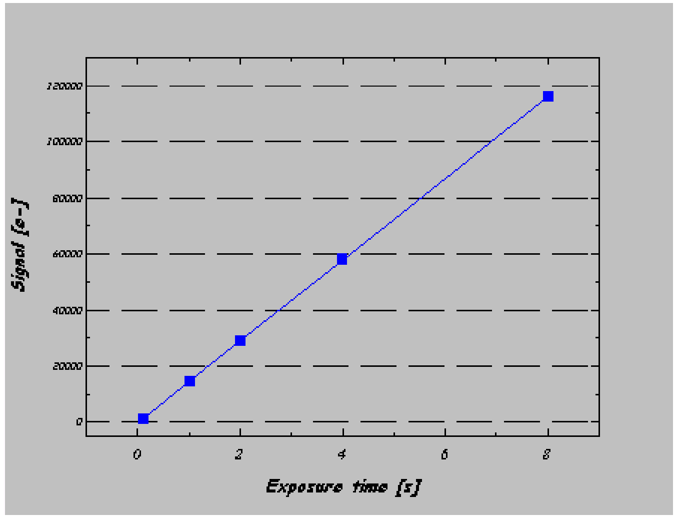
- **Detective Quantum Efficiency:** Square of the ratio of the output signal-to-noise ratio to the input signal-to-noise ratio.

- DQE is always less than or equal to the QE because of the effect of noise.

Detector parameters (2)

- **Detector Linearity:** The range over which the detector response is linearly related to the stimulus: R=Flux×time





- Photographic emulsions are not linear (note pre-flashing, log-log scale).
- CCDs and Photomultiplier Tubes (PMTs) are linear over a large range.

Detector parameters (3)

- **Dynamic Range:** The ratio of the largest measured value to the smallest value should be as large as possible.
- **Spectral Bandwidth:** The range of wavelength over which the detector is useful.
- **Angular Resolution** (spatial resolution) – describes the ability of any image-forming device to distinguish small details of an object. It should be well matched to the telescope and instrument.
- **Ability to integrate:** The ability to collect photons for an extended period of time.

Detector parameters (4)

- **The response time** is the time a device takes to react to a given input.
- **Digital output:** In order for calculations to be carried out, the data received or recorded by an astronomical detector must be made available as numbers.
- **Noise:** Photon statistics limited noise, Readout noise, electronic noise, dark noise, etc.
- **Cooling.**

Types of Detectors

- **Quantum Detectors:**
  respond to incident photons
  (photoemissive, photoconductive, photovoltaic, photochemical)

- **Thermal detectors:**
  respond to temperature rise due to absorption of radiant energy
  (thermocouple/thermopile, bolometer/thermister, pyroelectric device, Golay cell)

The primary interaction processes

- **Photo effect** is one of the most important interaction processes of photons with opaque matter in photon detectors. A photon with energy $h\nu$, impinging on the surface of a material, can release an electron with a maximal energy of

$$W_{max} = h\nu - W_A ,$$

where W_A is an electron work function characteristic of a given material. Typical values are between $W_A \approx 2$ eV and 6 eV.

The primary interaction processes

- **Solid-state detectors:** In solid-state detectors, with donor and acceptor regions forming n-p junctions, the internal photo effect creates electrons and electron holes that can be collected and counted.

The primary interaction processes

- **Pair Production:** At energies above 1.02 MeV, i.e., twice the equivalent rest mass of an electron, m_e, a photon can produce an electron-positron pair in the electric field of a nucleus. The pair production efficiency increases with the photon energy and the interaction cross-section is proportional to Z^2, with the Z charge number of the nucleus. The electron-positron pairs then have to be recorded by appropriate means.

The primary interaction processes

- **Scintillation counters:** In the X-ray and γ-ray regimes, scintillation detectors are in frequent use. The high-energy photons, through the internal photo effect, ionize atoms in certain crystallic materials. The recombination events of the atoms and electrons then produce a large number of optical photons that can be collected by standard photomultipliers.

The primary interaction processes

- **Photon detectors based on superconductivity.** Many modern photon detectors employ superconductive material. *For example:*
  - **Cooper pairs.** Cooper (1956) suggested that electrons (as fermions) in superconducting metallic materials form pairs—later to be called Cooper pairs—due to an electron-phonon interaction at low temperatures, which could overcome the Coulomb repulsion of the electrons. The resulting bosons would be responsible for the superconductive properties, but might easily split into two electrons by an external excitation. Even photons with an energy of a few millielectronvolts can break up a Cooper pair into the electrons, which then have to be collected by suitable circuitry. This could, for instance, be a superconducting tunnel junction (STJ).

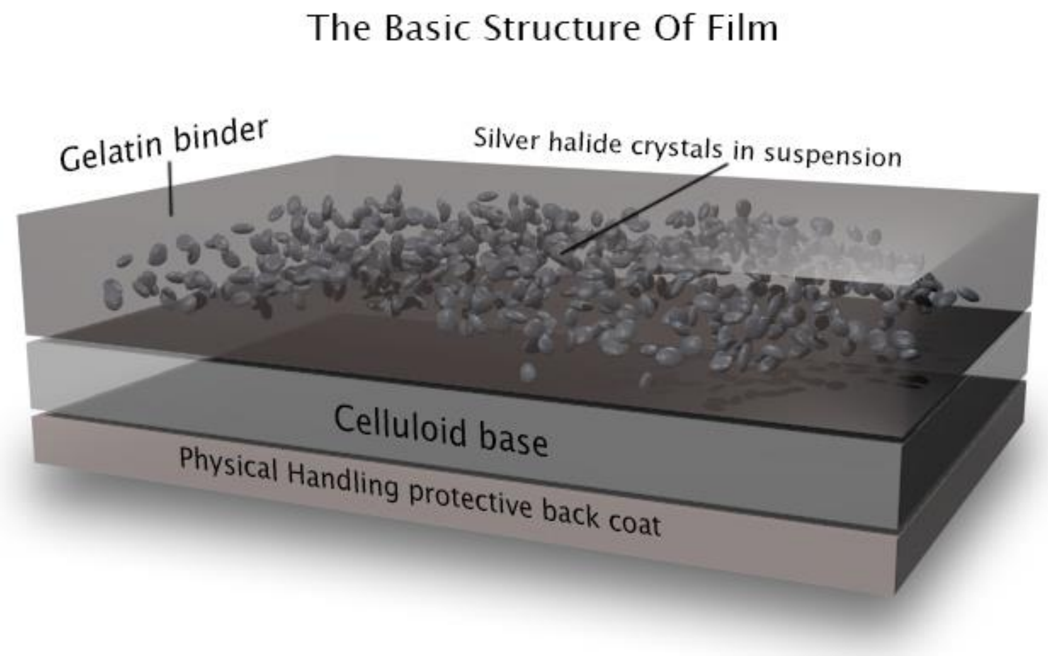
“Ancient” and modern detectors

- Photographic emulsion
- Photomultiplier
- Micro-Channel Plate
- Charge Coupled Device detector (CCD)

Photographic emulsions (1)

The first technological advance in astronomical detectors (1840-60).

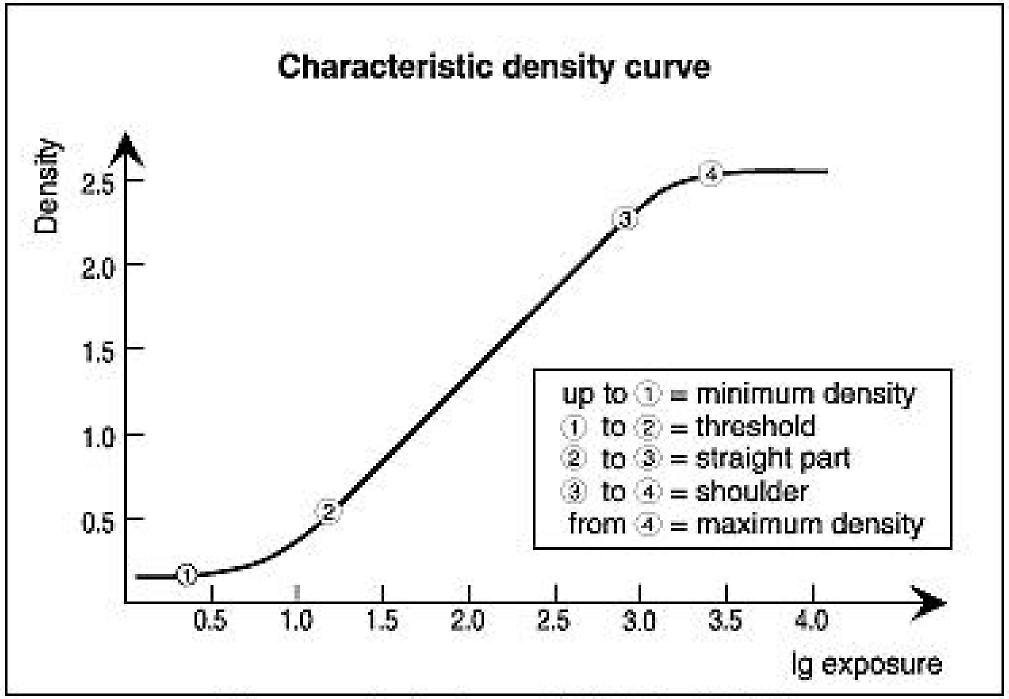
- Typical photographic film / plate contains tiny silver halide crystals suspended in a gelatin.
- When radiation of appropriate wavelength strikes one of the silver halide crystals, a series of reactions begins that produces a small amount of free silver in the grain.
- The free silver produced in the exposed silver halide grains constitutes what is referred to as the "latent image," which is later amplified by the development process.



Thus, photoemulsions can make a permanent record of astronomical objects imaged by telescopes.

Photographic emulsions (2)

- **Disadvantages:**
  - QE is just a few %.
  - Because of the analog (rather than digital) nature of the image record on an emulsion, it is difficult to make quantitative measurements of star brightnesses.
  - Photoemulsions are also nonlinear with input light.
  - Photoemulsions are also nonlinear with increasing exposure time – an exposure of 2 minutes does not give twice the output of a one-minute exposure.

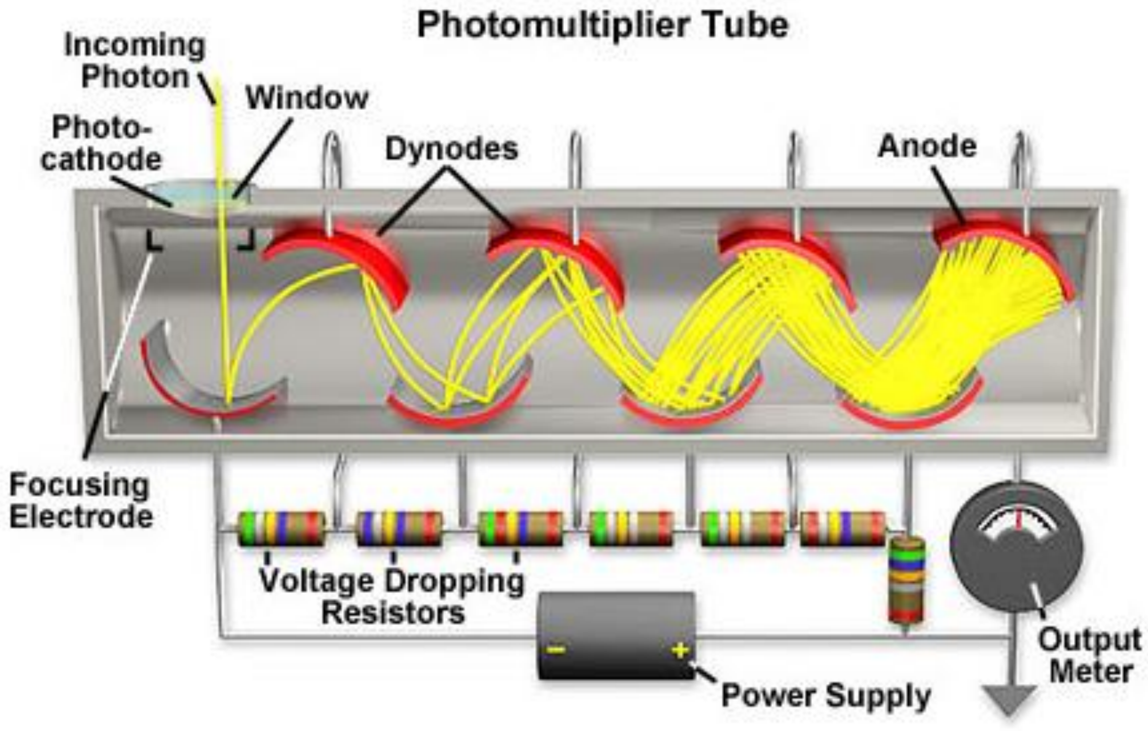


- One **advantage** of the photographic plate is that it can be made very large (40×40cm).
- Photoemulsions are not used for decades.

Then why do we discuss them? → **Archival Data** (e.g., DSS)!

Photomultipliers (1)

- Photomultipliers detect photons through the photoelectric effect: the absorption of a photon results in the emission of an electron.
- The detectors work by amplifying the electrons generated by a photocathode exposed to a photon flux.
- Once a photoelectron has escaped from the photoemitter, it is accelerated by an electric potential until it strikes a second electron emitter.
- Dynodes are successively more positive than the cathode by ~100 V for each stage.
- The final signal pulse may contain 10^6 electrons for each incoming photon.

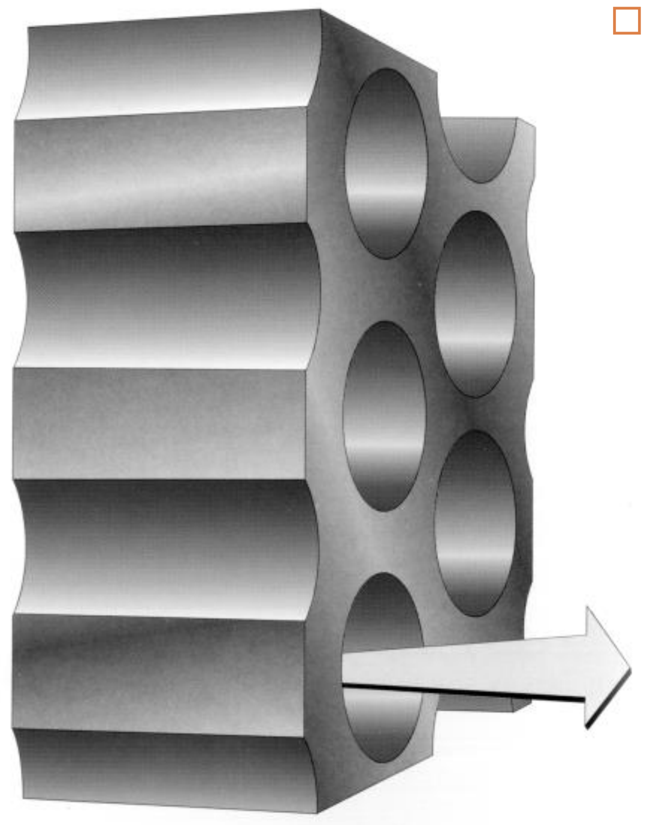


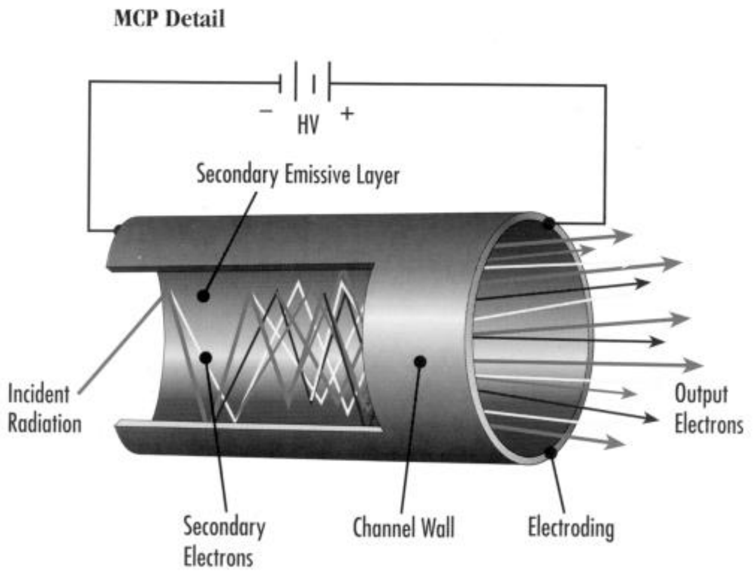
Photomultipliers (2)

- **Advantages:**
  - Have much higher QE of around 20%.
  - Have a digital output.
  - Are linear with input light and exposure time.
  - Can be used in UV.
- **Disadvantage:**
  - It is essentially a single channel device, there is no positional information in the signal. The output signal does not depend on where on the cathode the photon hit, so we get only a measure of all the light that fell on the photocathode.
- Still in use as a photon detector for the Čerenkov telescopes (e.g., in MAGIC).

Micro-Channel Plate (MCP)

- MCPs are basically microscopic photo-multiplier tubes!
- An MCP is simply a matrix of resistive glass tubes constructed using fiber technology. A photon knocks an electron out of the resistive material (lead oxide) coated on the inside of the tube, and is accelerated down the tube by the applied voltage.



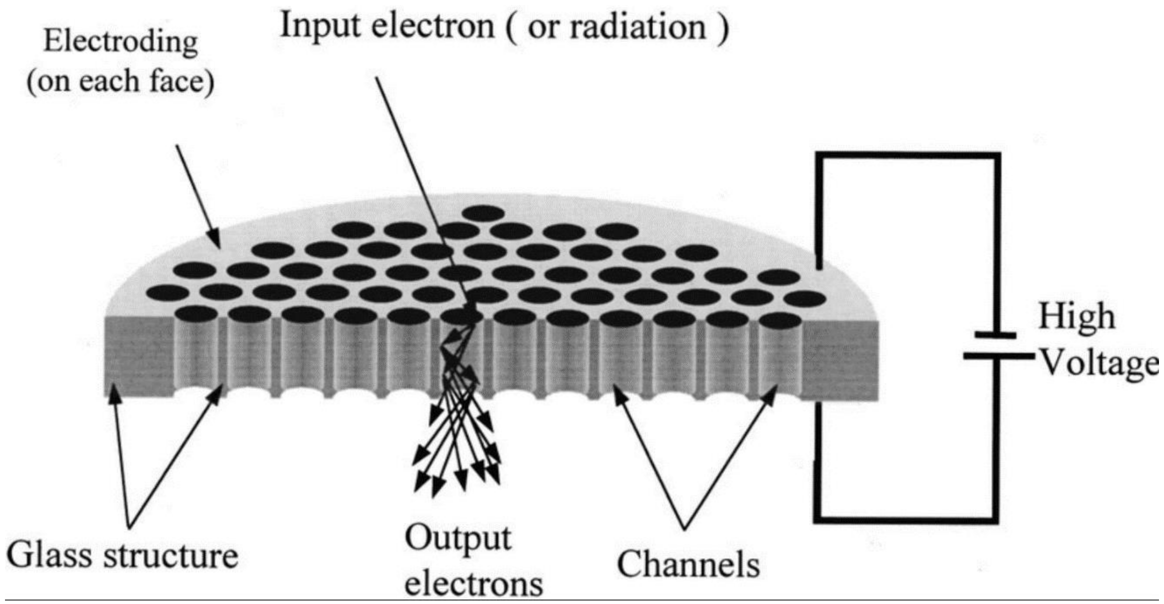


This creates a cascade of events which can then illuminate a detection screen.

Micro-Channel Plate

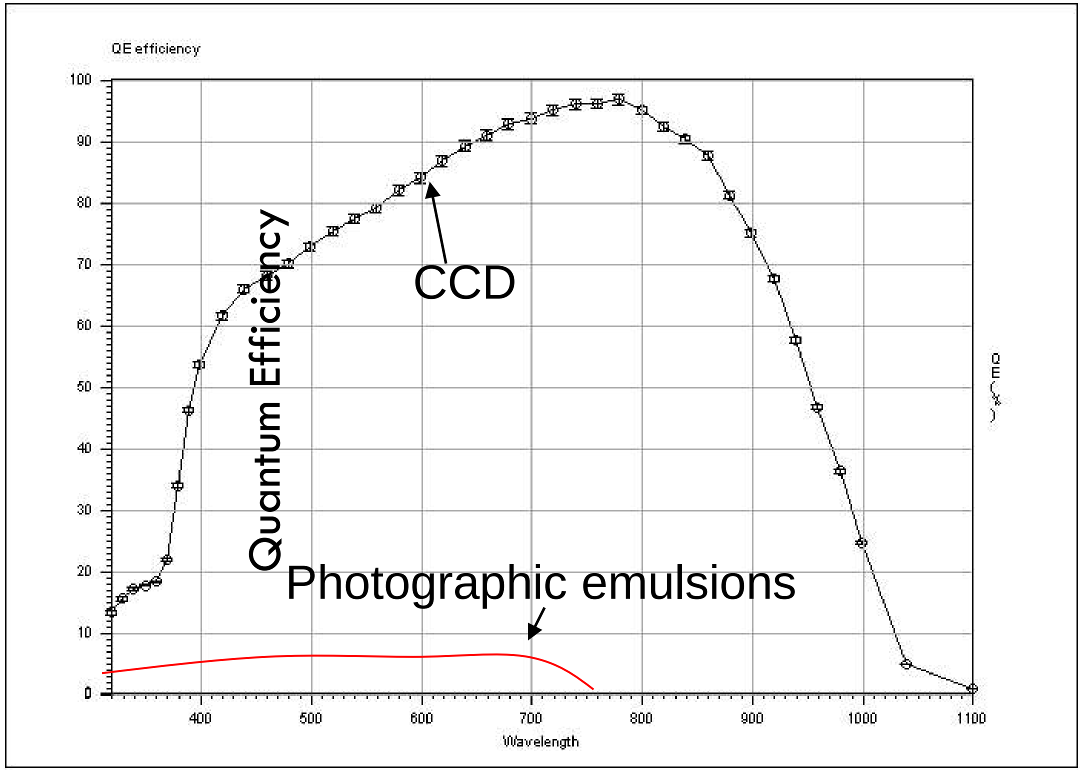
- **Advantages:**
  - QE is up to 50%.
  - Can have excellent spatial resolution and microsecond time resolution possible.
  - Can be used in X-ray, UV and optical wave.

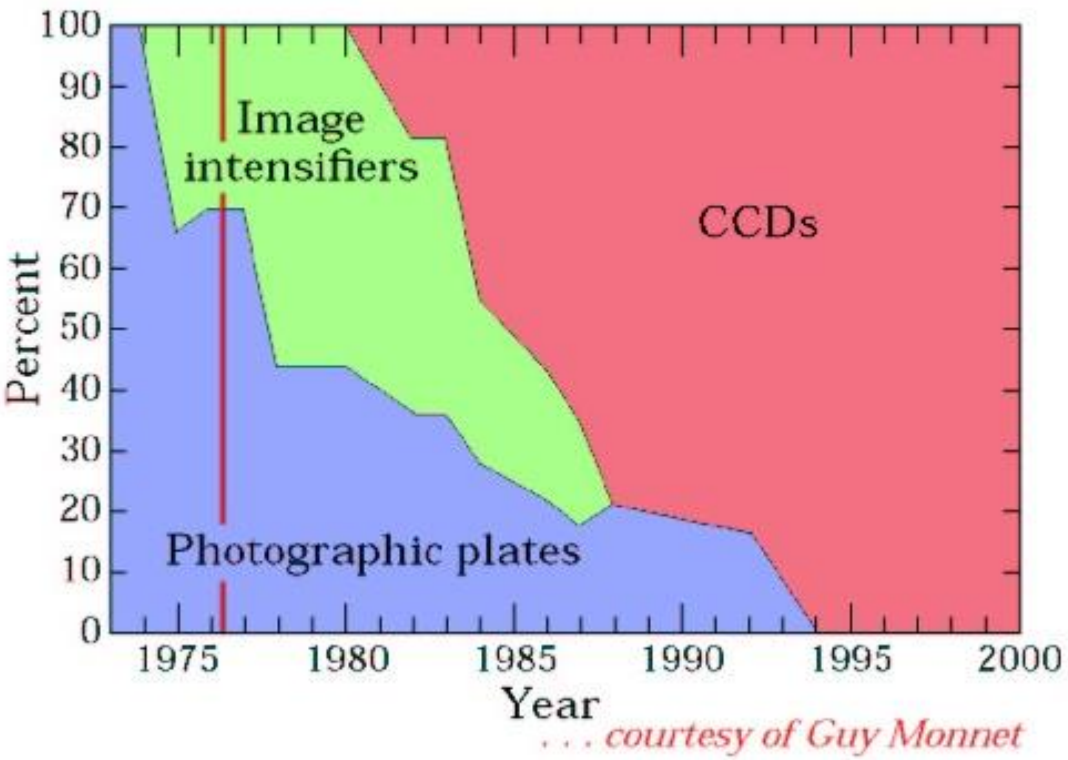
- **Disadvantage:**
  - Lack energy resolution (not a real problem)



Charge Coupled Device detectors (CCDs)

CCDs – a replacement for photoplates: QE is more than an order of magnitude better than photographic plates – an astronomer's dream for decades!





Advantages of CCDs

- Good spatial resolution
- Very high QE of up to 95% (and even higher)
- Large spectral window:
  By far the most common detector for wavelengths
  4000 Å $< \lambda <$ 10000 Å
- Very low noise
- High photometric precision
- High dynamic range
- Very good linearity
- A reliable rigidity (no physical distortion, etc) – robust enough to fly on space missions.

How does a CCD work?

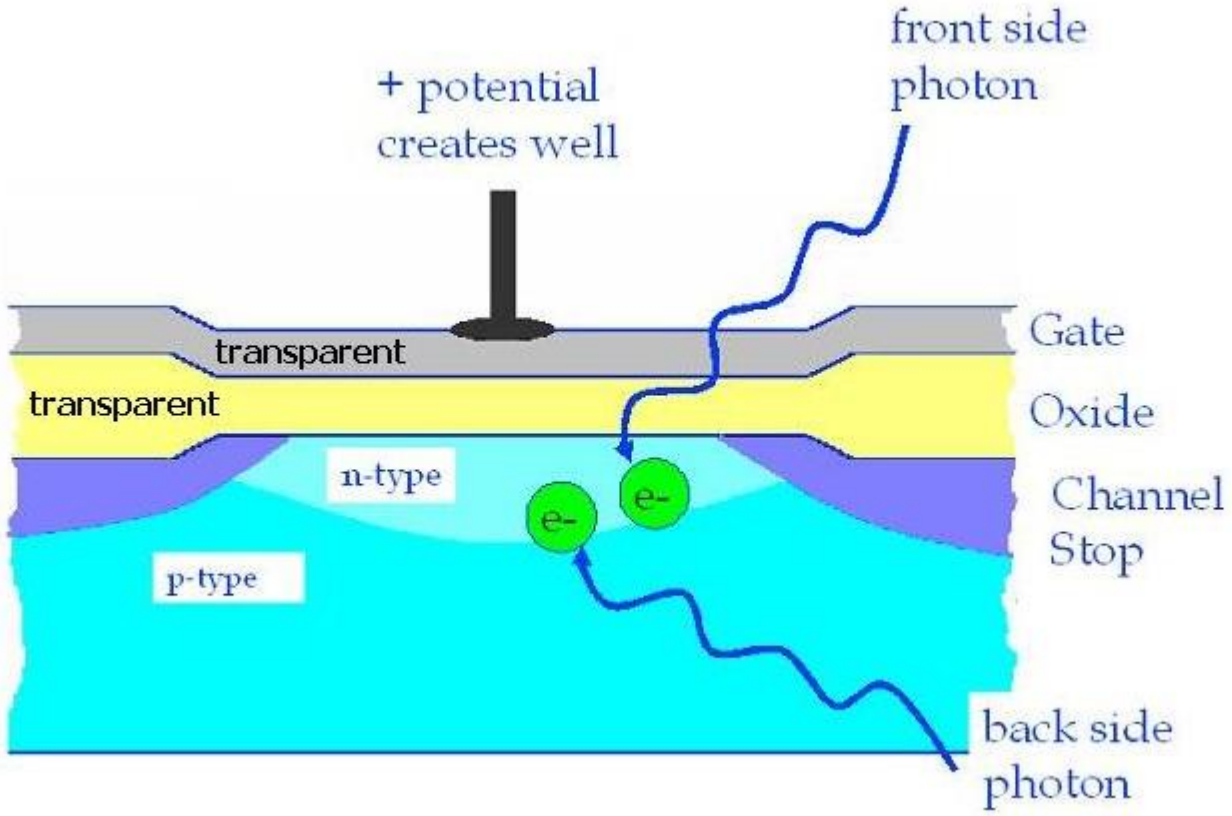
- In order to produce an image, a CCD accomplishes four functions:
  1) generates photoelectrons
  2) collects electrons
  3) transfers the collected charges
  4) reads the charges

How does a CCD work? (2)

- The first function is based on the photoelectric effect.
- A CCD is a silicon wafer which is exposed to radiation.
- The light absorption in the silicate network of the CCD generates these photoelectrons,
  in proportion to the number of incident photons.
- The latter are immediately collected in "picture elements" so-called pixels, closest to where the photons fell on the chip.
  The picture elements (pixels) of the CCD are defined and fixed by the electrode structure which is applied to this wafer.
- The electrodes form potential wells to prevent the collected charges from escaping.

How does a CCD work? (3)

Photoelectrons are collected deep in the well beneath the positive potential set up by the gate electrode, isolated from the surface by the n-type silicon buried channel.

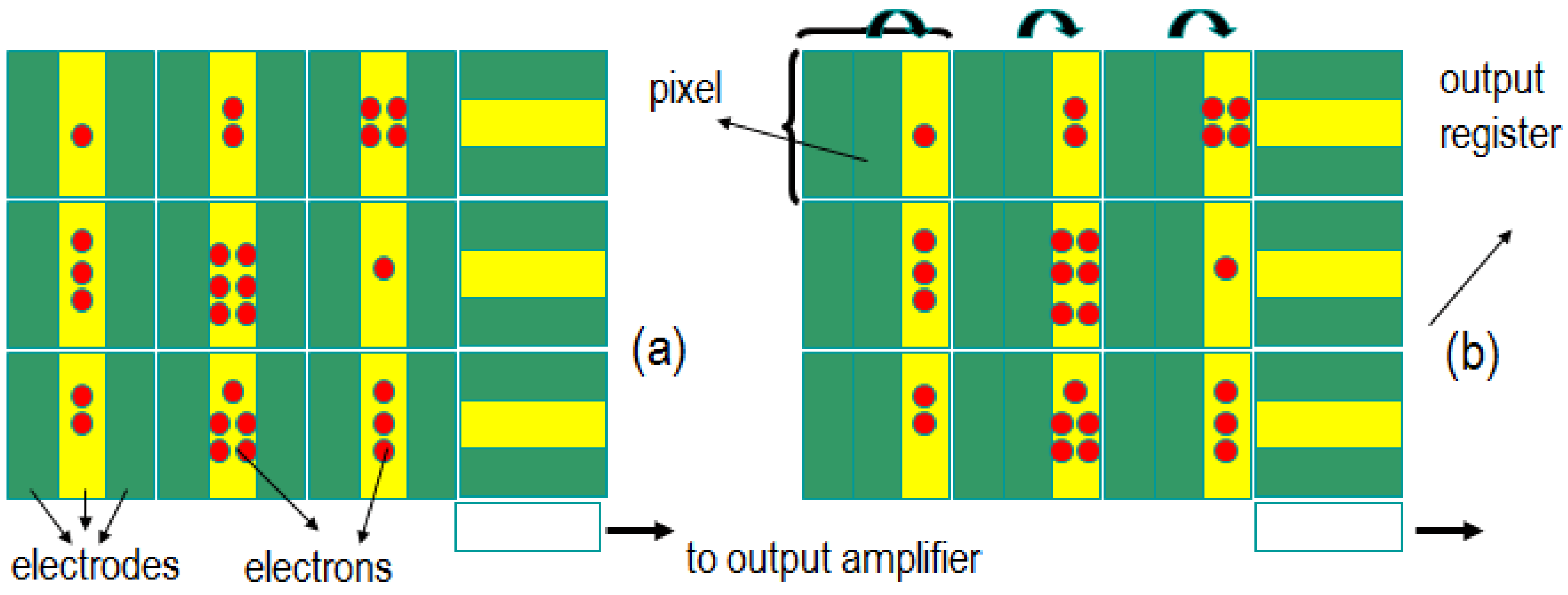


How does a CCD work? (4)

- As you expose the CCD to radiation, electron-hole pairs are generated, and the electrons build up in the electron storage areas immediately below the positive potential electrodes.
- After a while (exposure time – seconds to minutes) the CCD contains an electrostatic representation of the pattern of incident radiation on it.
- This somehow must be read out and stored in digital form.

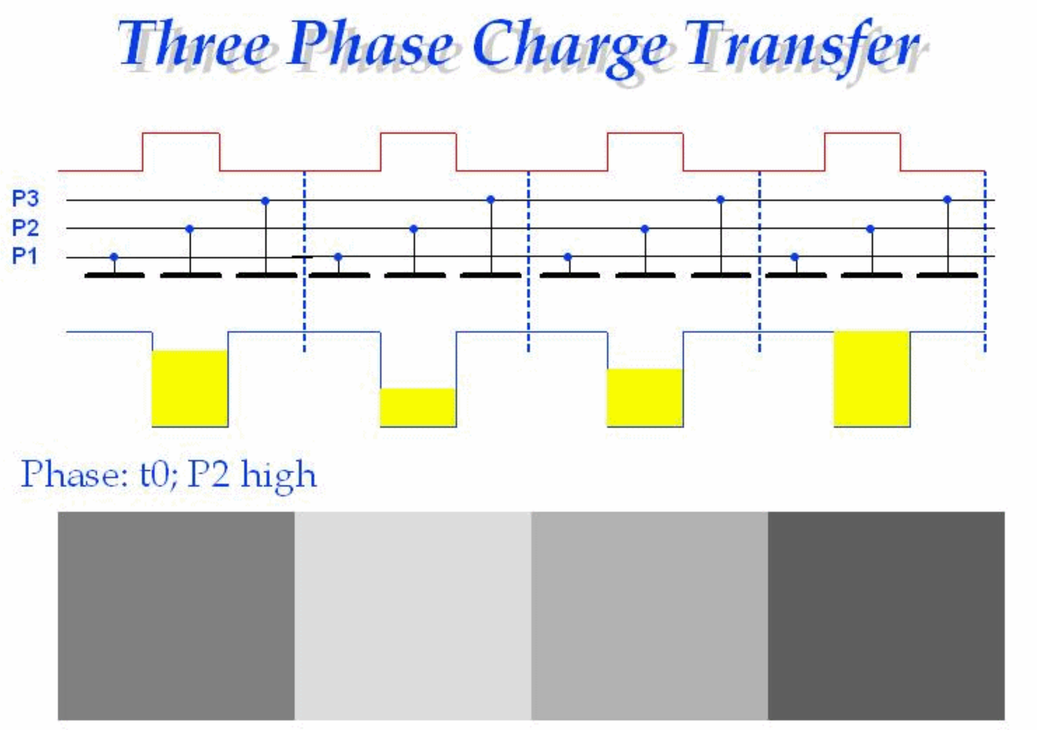
How does a CCD work? (5)

- Each pixel is divided into 3 regions (electrodes who create a potential well). For the charge collection process during an exposure the central electrode of each pixel is maintained at a higher potential (yellow) than the others (green).



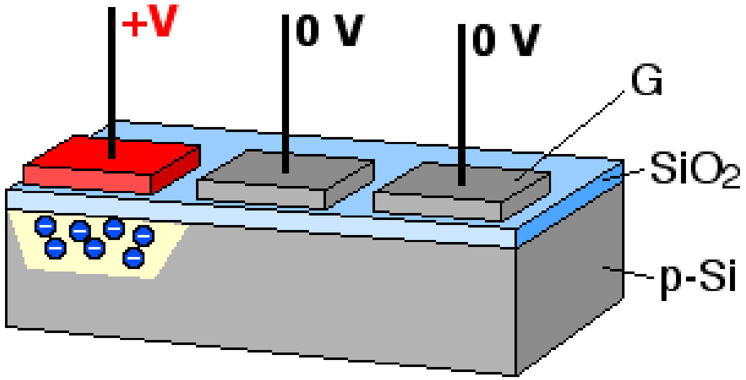
How does a CCD work? (6)

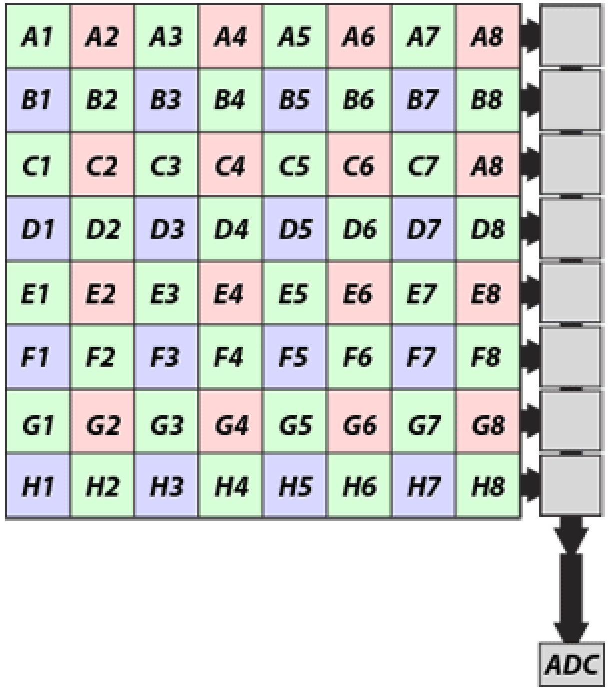
- By changing the potential of the electrodes in a synchronized way, electrons are transferred from pixel to pixel. Charges on the right are guided to the output register



How does a CCD work? (7)

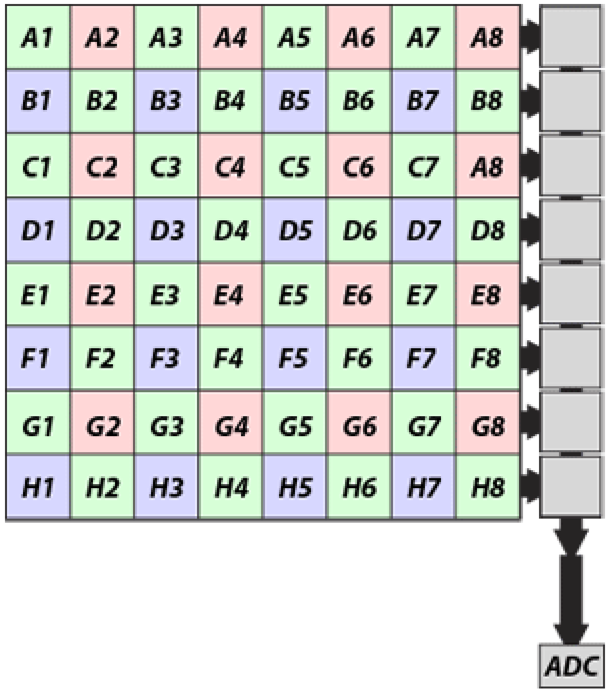
- The readout register is shifted to the right by one pixel, and the pixel at the bottom right is shifted into a readout capacitor.





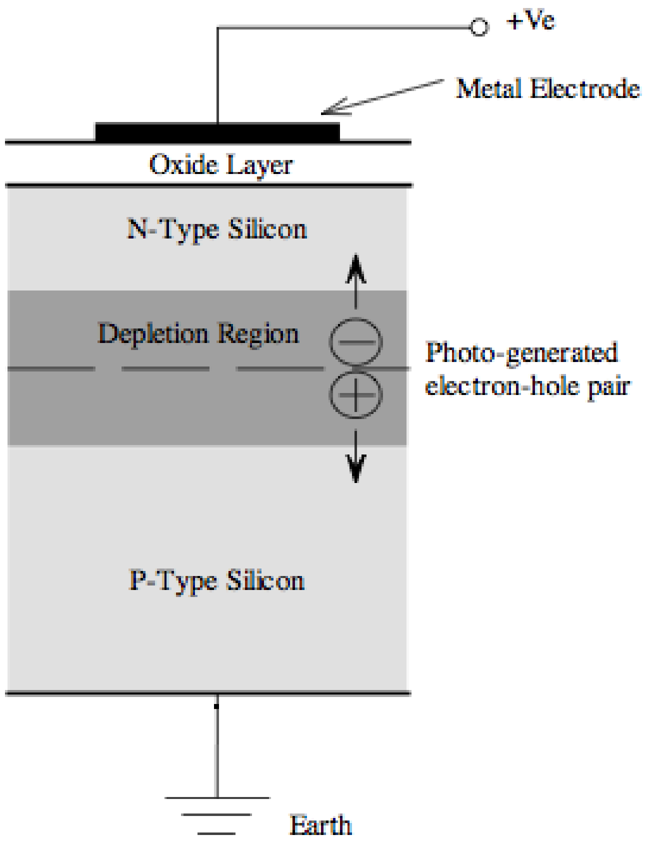
CCD readout

- This process is then repeated until each pixel in the readout register has been digitized.
- The image is then shifted right horizontally by one more pixel, the next collumn is shifted into the readout register, and this is digitized in the same way.
- The whole process is repeated until the entire image is read out.
- For a 2048 x 2048 pixel CCD it takes approximately 10-60 seconds to read out the whole chip.
- A CCD read out this way is a line transfer CCD.
- The channel stops between rows are permanent as charge does not move vertically except in the readout register.
- These channel stops are biased to negative potential by doping, hence charge cannot leak horizontally.



Buried channel CCD

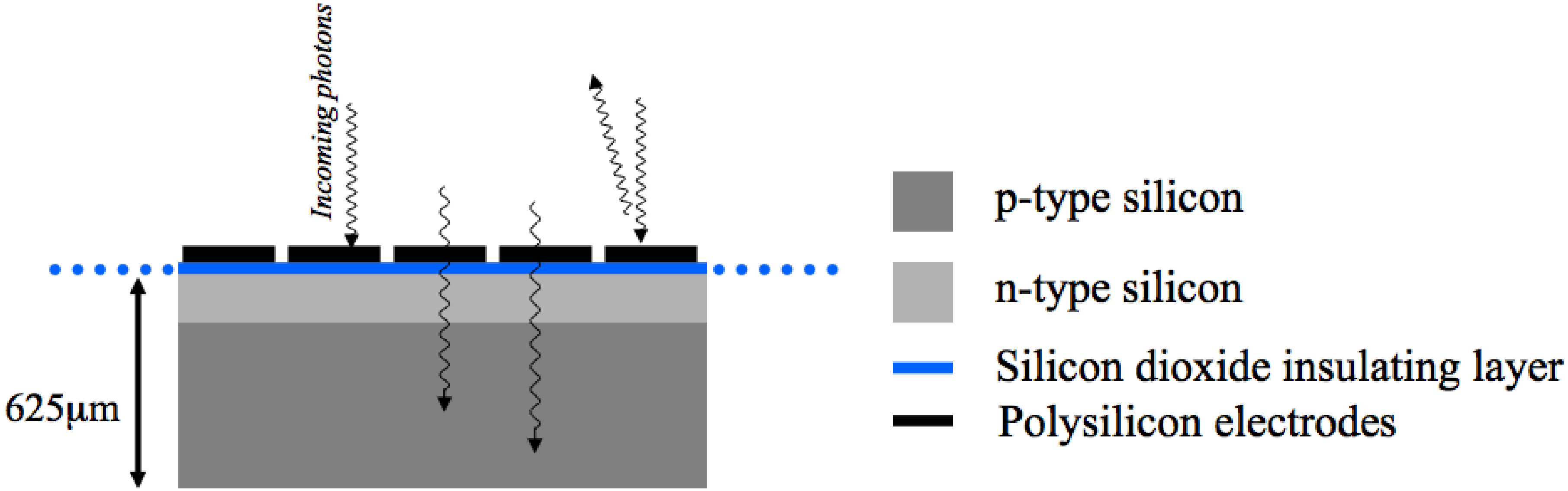
- CCDs described before are surface channel CCDs, but in these the charge is being shifted along in a thin layer just below the oxide insulator.
- Surface layer has crystal irregularities which can trap charge, causing loss of charge and image smear.
- By grounding the p-type silicon substrate and applying a positive voltage to the n-type layer, the p-n junction is reverse biased, widening the depletion region and creating a potential well in the n-type silicon that confines the electrons in the vertical direction
- This is called a buried-channel CCD, and suffers much less from charge trapping.
- Almost **all** scientific CCDs are buried-channel devices



Courtesy of Vik Dhillon

Front-illuminated CCD

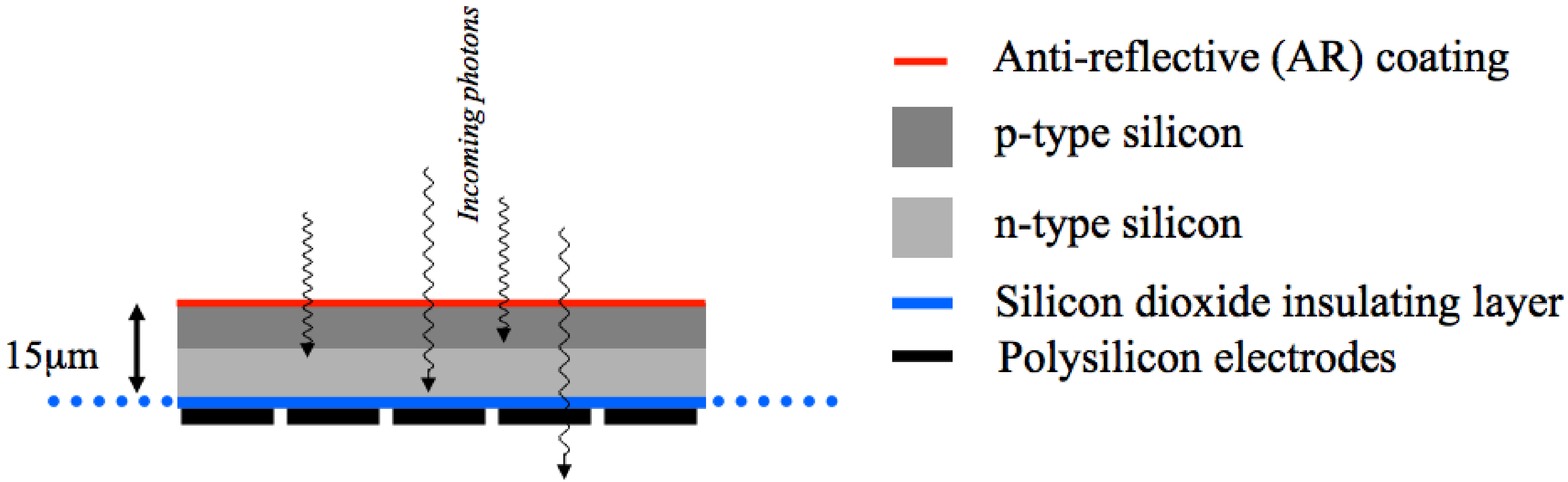
- As described to now, the CCDs are illuminated through the electrodes. Electrodes are semi-transparent, made of a transparent material known as polysilicon, but some losses occur: the electrode structure absorbs and reflects many of the incident photons, particularly at blue wavelengths, preventing them from producing electron-hole pairs in the depletion region.
- They are non-uniform losses, so the sensitivity will vary within one pixel.



Courtesy of Vik Dhillon

Thinned back-illuminated CCD (1)

- Solution is to thin the CCD, either by mechanical machining or chemical etching, to about 10μm, and mount it the other way up, so the light reaches it from the back.
- Thinning is a way of improving sensitivity, especially at blue wavelengths.

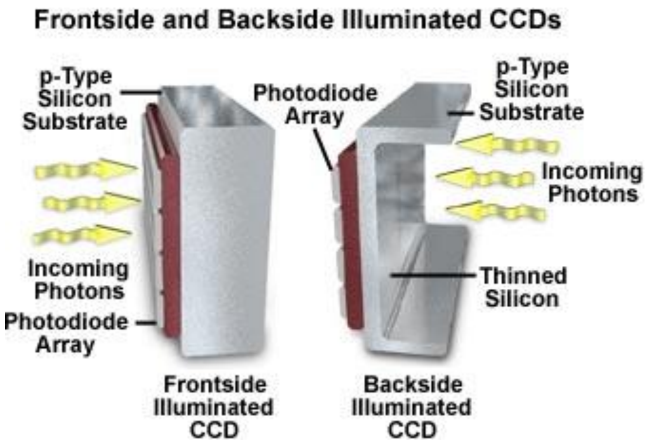


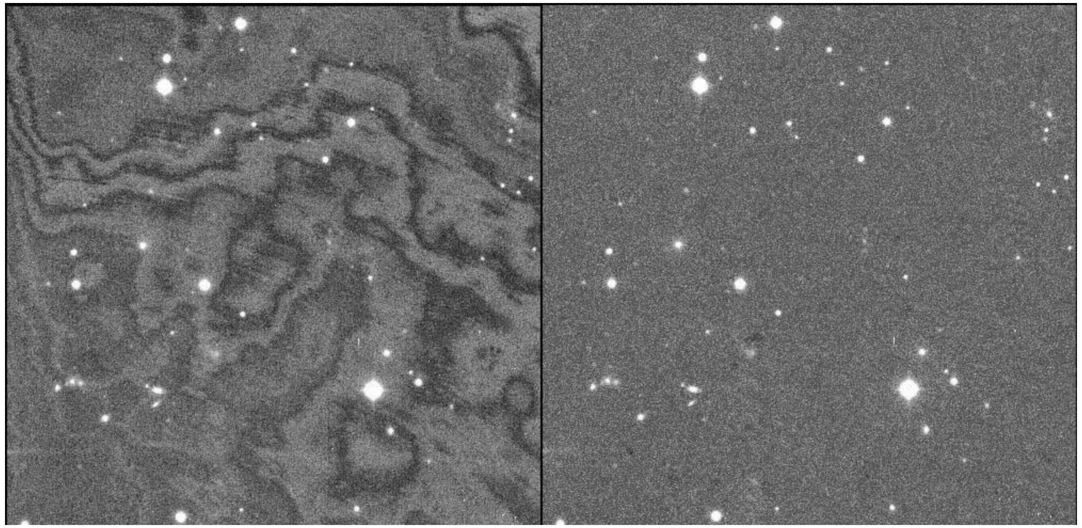
Courtesy of Vik Dhillon

Thinned back-illuminated CCD (2)

Thinned back-illuminated CCDs do **have** a number of disadvantages:

- Thinning can reduce the red response because red photons need more absorption length and if this is not there they will pass right through the silicon.
- Thinned CCDs are also mechanically fragile, prone to warping and expensive to manufacture compared to thick CCDs.
- Another problem is that the thin silicon layer produces interference fringing in the red part of the spectrum, which can limit the accuracy of measurements.





Frame transfer CCDs

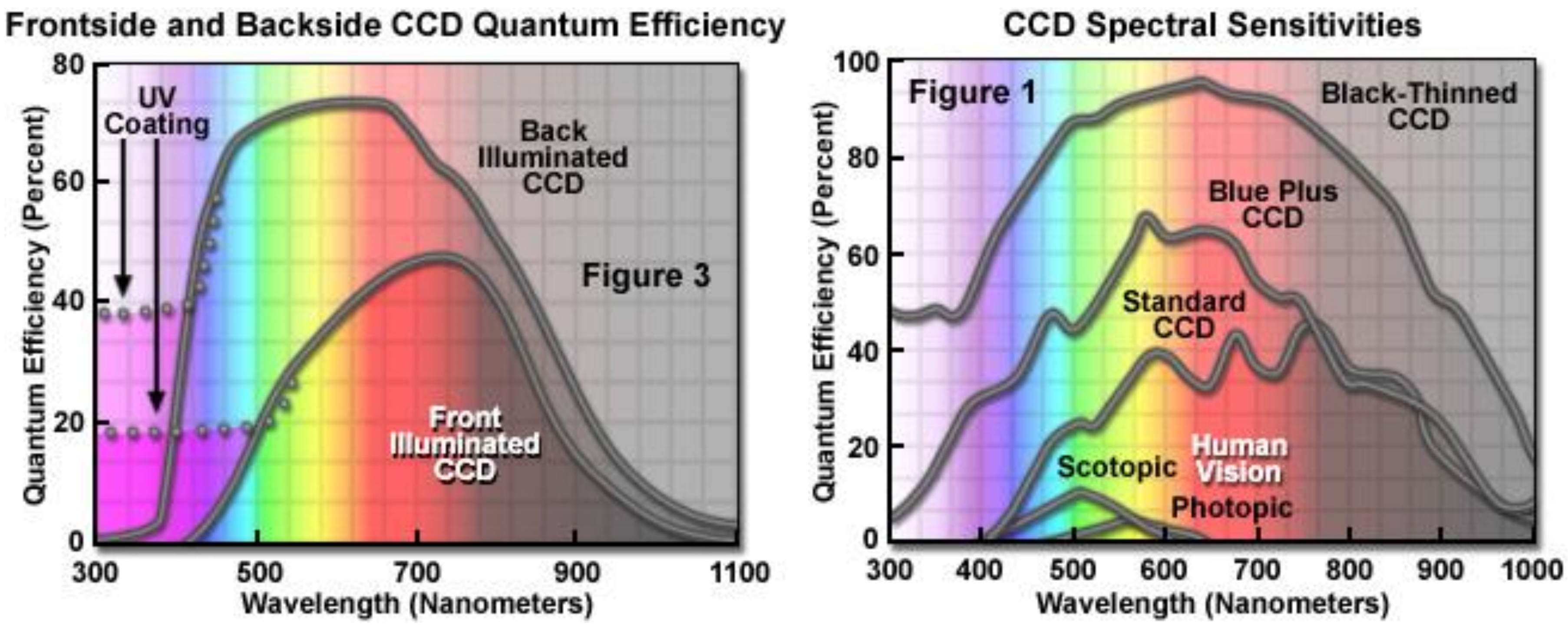
- Instead of reading the CCD out line by line as described before, a Frame transfer CCD has half of its area masked off to stop light reaching it. On readout, the whole CCD is clocked vertically so that the image area is transferred to the storage area.
- The image can then be read out from this storage area whilst the image area is being exposed again.

Advantages of CCDs (2)

- **Good spatial resolution:**
  - Today, most common CCDs have 2048 × 2048 pixels. But there exist even larger CCDs with 4096 × 4096 pixels or 4096 × 8192 pixels (10 k x 10 k will be build soon).
  - For realizing even larger chips (and since larger CCD chips are very expensive), several small chips can be placed together resembling a CCD mosaic.

Advantages of CCDs (3)

- Quantum Efficiency:



Advantages of CCDs (4)

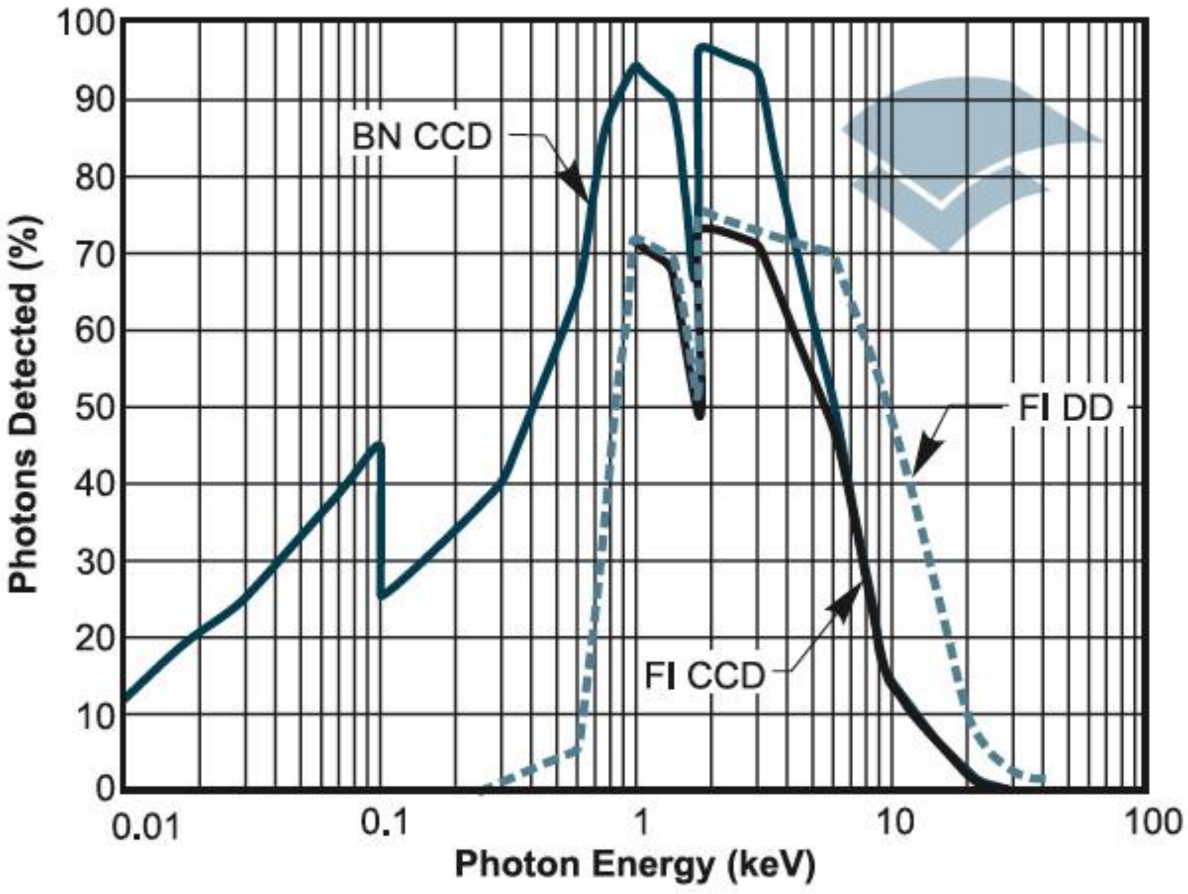
Spectral Range

Goes to X-rays

FI: front illuminated

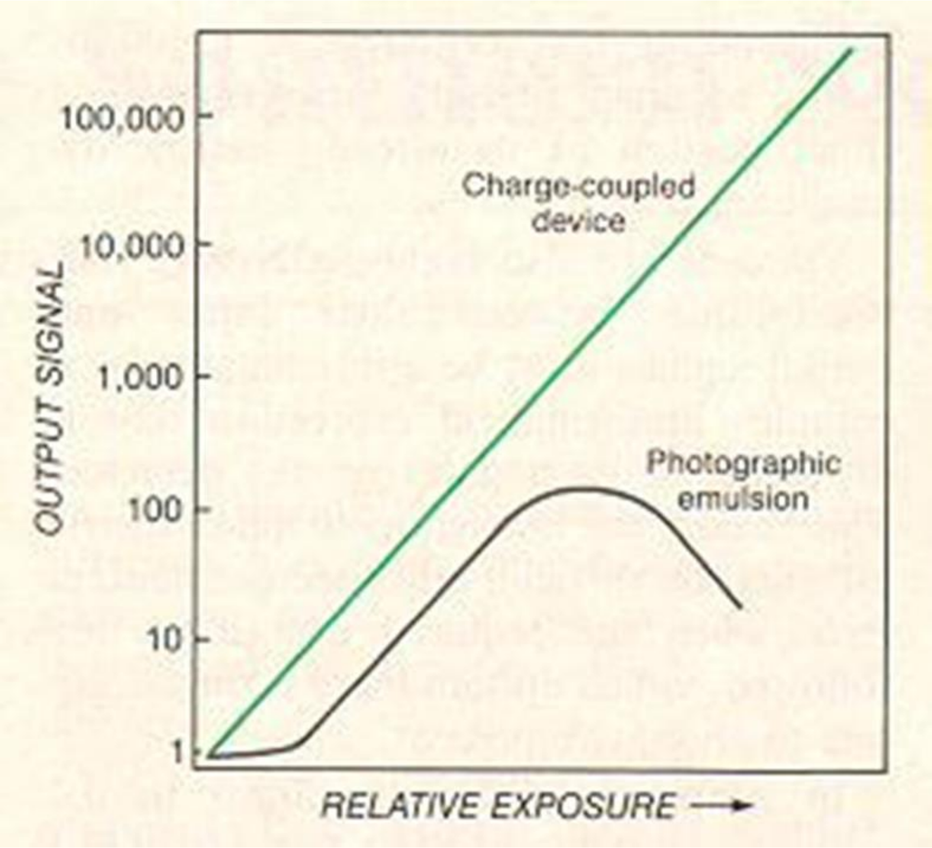
BN: back illuminated, no coating

DD: deep depletion



Advantages of CCDs (5)

- **Linearity and Dynamic Range:** CCDs are extremely linear detectors. Therefore CCDs enable the simultaneous detection of both very faint and very bright objects. The dynamic range of CCDs is about 100 times larger compared to photoemulsions.



Disadvantages of CCDs (1)

- **Size:** The size of a single pixel is in the order of 8 × 8, 15 × 15 or 25 × 25 microns. Therefore the size of CCD chips remain quite small, especially by comparing CCDs to classical photographic plate images. E.g., a CCD with 2048 × 2048 pixels of 15 microns measures only 3 × 3 cm^2. In contrast a photographic plate for a Schmidt telescope can be as big as 30 × 30 cm^2, equivalently to a CCD chip with 400 million pixels!

Disadvantages of CCDs (2)

- **The dark current** (not a real problem) is background signal generated by thermal effects. Because of the dark current CCDs are run cooled, to reduce the possibility of thermal excitation of electrons across the band gap.
- CCDs are operated at temperatures of around 140K, to reduce thermal effects.
- Dark current at 140K is typically 10^{-4} electrons/s/pixel, i.e. negligible.

Disadvantages of CCDs (3)

- **Cosmic rays, X-rays, and particle radiation:**
- There are a number of types of radiation which can interact with the silicon to produce several tens of electron-hole pairs in a cluster, which appears as a bright spot (if the radiation is normal to the detector) or a streak if it is steeply inclined. These radiation events are:
  - Secondary muons in cosmic ray air showers.
  - X rays emitted by UV transmitting glass in the optics of the instrument.
  - Radioactivity from heavy metal impurities in the cryostats.
- These events are identified, classified and rejected by splitting the CCD exposure into two or more equal parts, the hits don’t occur in the same place.

Disadvantages of CCDs (4)

- **Saturation** (not a real problem): Typically the full well capacity of a CCD pixel 25 µm square is 500,000 electrons. If the charge in the well exceeds about 80% of this value the response will be non-linear. If it exceeds this value charge will spread through the barrier phase to surrounding pixels.
- This charge bleeding occurs mainly horizontally, as there is little vertical bleeding because of the permanent doped channel stops.
- Readout register pixels are larger, so there is less saturation effect in the readout register.

Disadvantages of CCDs (5)

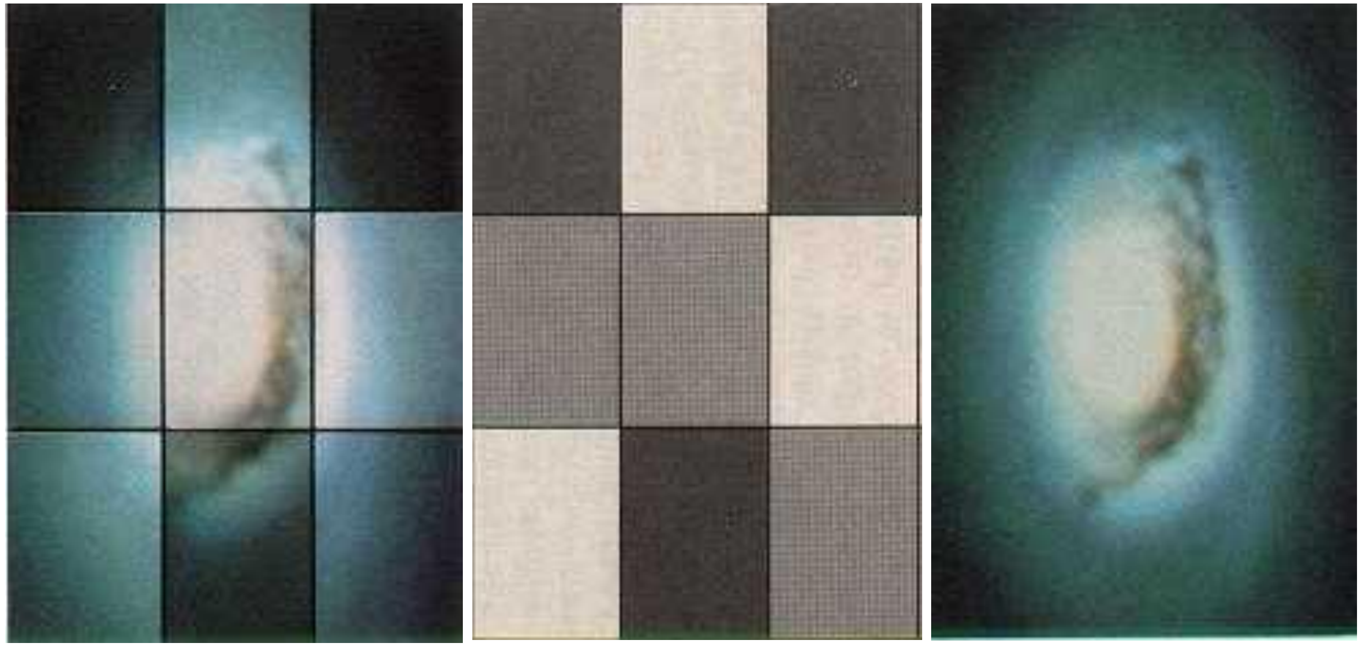
- **Charge Transfer Efficiency:** When the wells are nearly empty, charge can be trapped by impurities in the silicon. So faint images can have tails in the horizontal direction.
- Modern CCDs can have a charge transfer efficiency per transfer of 0.9999995, so after 2000 transfers only 0.1% of the charge is lost.

CCDs: readout noise

- CCDs suffer from **readout noise** which has a variety of sources:
  - The output Field Effect Transistor. This is the ultimate limit to the readout noise, at a level of 2-3 electrons.
  - Transfer loss fluctuations. During transfer an amount of charge is left behind, but this amount varies. Transfer noise is given by: $\sigma_{tr} = \sqrt{(2\zeta n N_0)}$ where ζ = 1-CTE is the fraction of charge not transferred, n is the number of transfers and N_0 is the original charge. For faint sources (≈100 electrons) this noise is less than 1 electron.
- The readout noise is the dominant source of random noise.

CCDs: Other noise sources

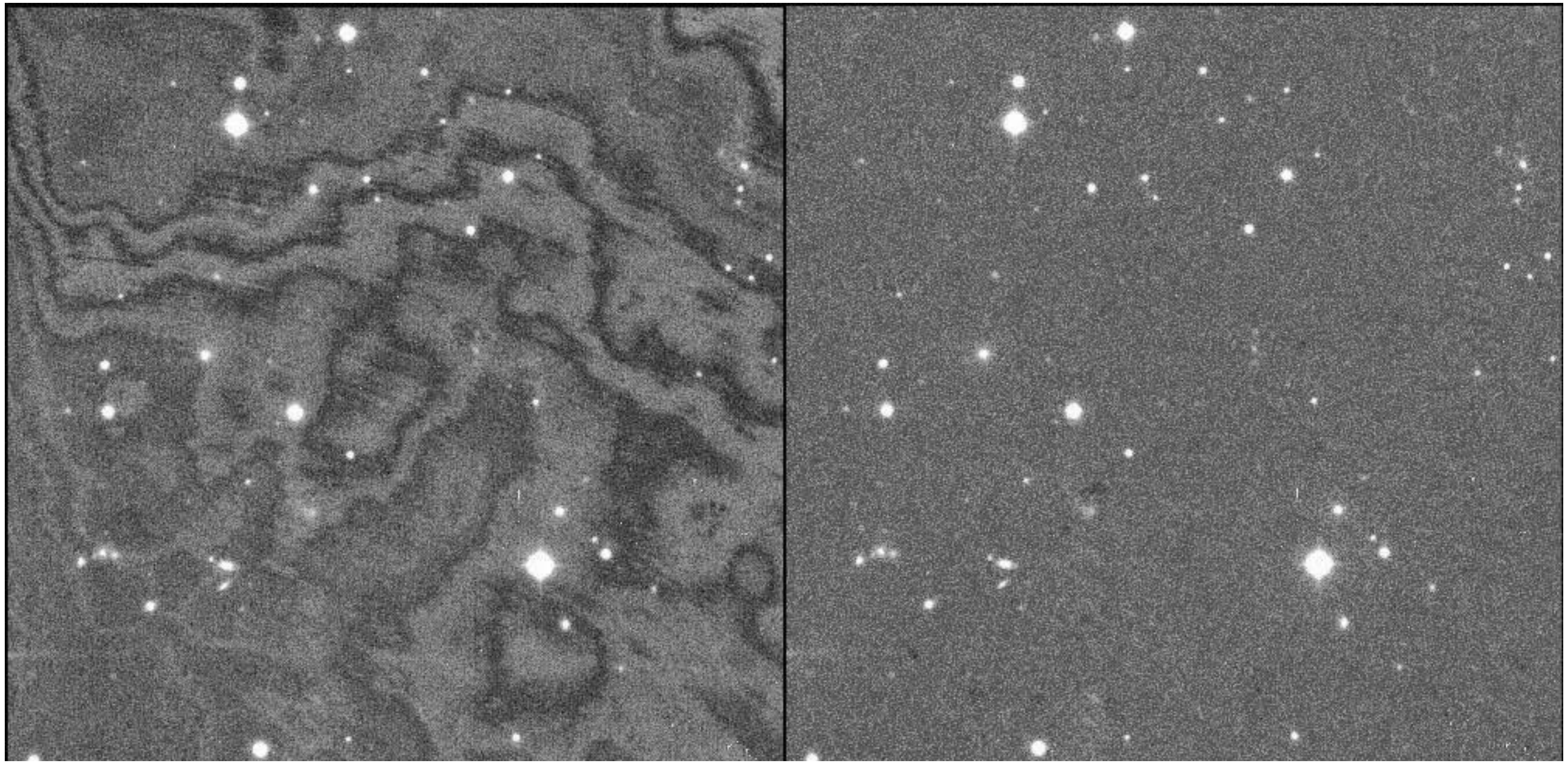
- **Fixed pattern noise.**
  The sensitivity of pixels is not the same, for reasons such as differences in thickness, area of electrodes, doping.
  However these differences do not change, and can be calibrated out by dividing by a flat field, which is an exposure of a uniform light source (**Flat field technique**).



- **Bias noise.**
  The bias voltage applied to the substrate causes an offset in the signal, which can vary from pixel to pixel. This can be removed by subtracting the average of a number of bias frames, which are readouts of zero exposure frames. Modern CCDs rarely display any fixed pattern bias noise.

CCDs: Interference Fringes (1)

- In thinned CCDs there are interference effects caused by multiple reflections within the silicon layer, or within the resin which holds the CCD to a glass plate to flatten it.



CCDs: Interference Fringes (2)

- These effects are classical thin film interference (Newton's rings).
- Only visible if there is strong line radiation in the passband, either in the object or in the sky background.
- Visible in the sky at wavelengths > 7000Å.
- Corrected by subtracting off a scaled exposure of blank sky.
- Fringing can dominate the noise in the redder photometric bands, or in narrow bands, and can sometimes force us back to using thick CCDs despite the loss in QE.