OBSERVATIONAL ASTROPHYSICS AND DATA ANALYSIS

Lecture 6

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Charge Coupled Device detectors

- CCDs – a replacement for photoplates. This was an astronomer's dream for decades.
- Ubiquitous in optical and very near infra-red astronomy.
- The detector of choice at wavelengths from 4000 Å to 10000 Å.
- Robust enough to fly on space missions.

How does a CCD work?

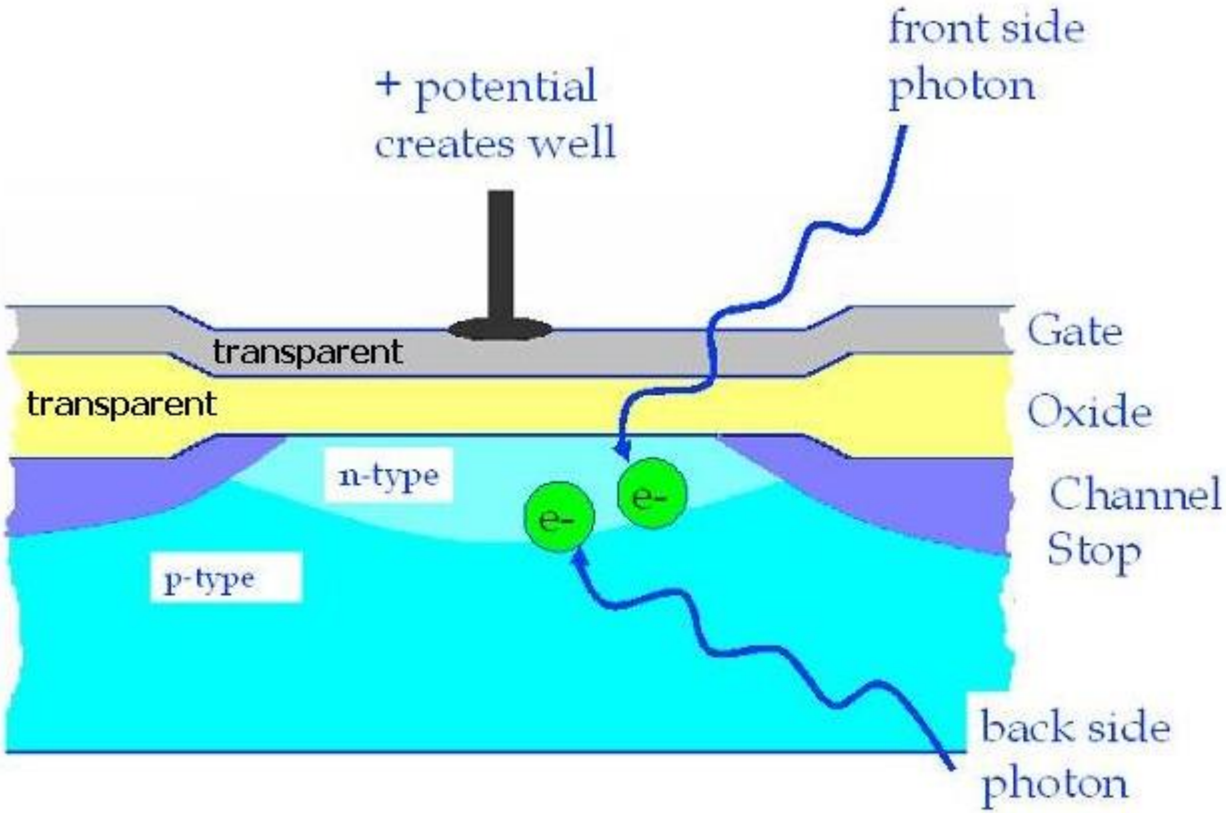
- In order to produce an image, a CCD must accomplish four functions:
  1) generate photoelectrons
  2) collect electrons
  3) transfer the collected charges
  4) read the charges

How does a CCD work?

- 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 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?

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.

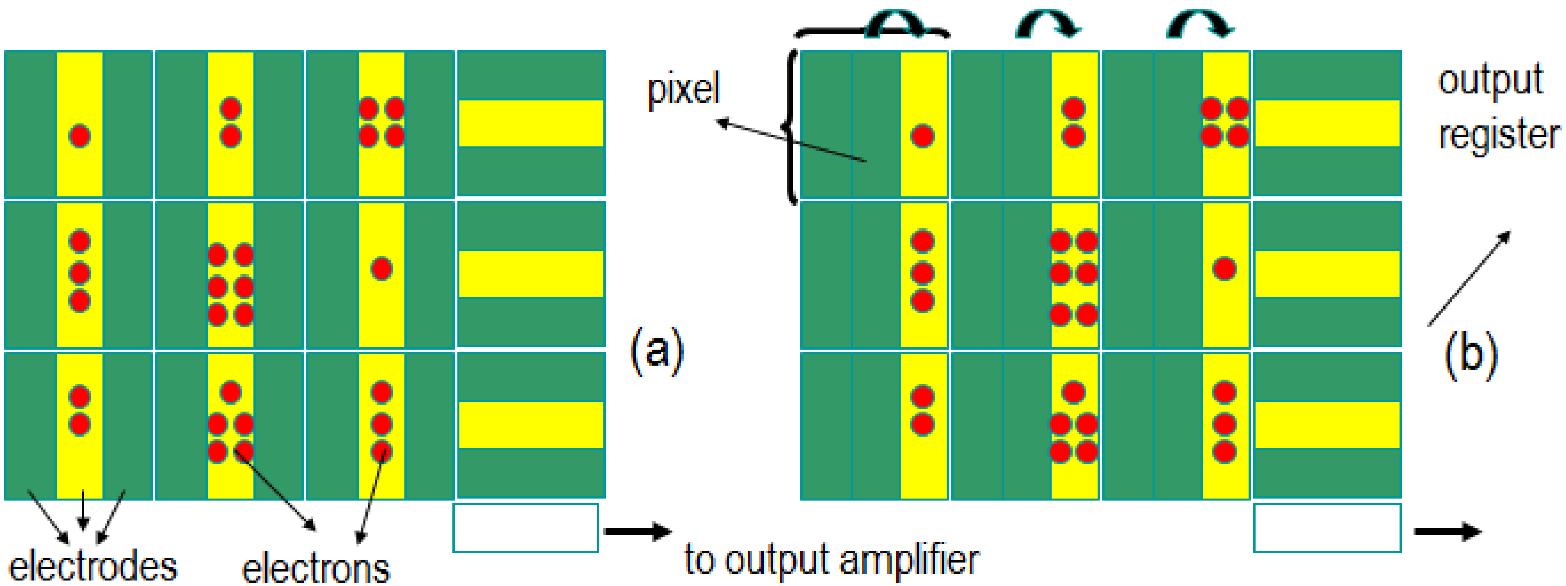


How does a CCD work?

- 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 (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.

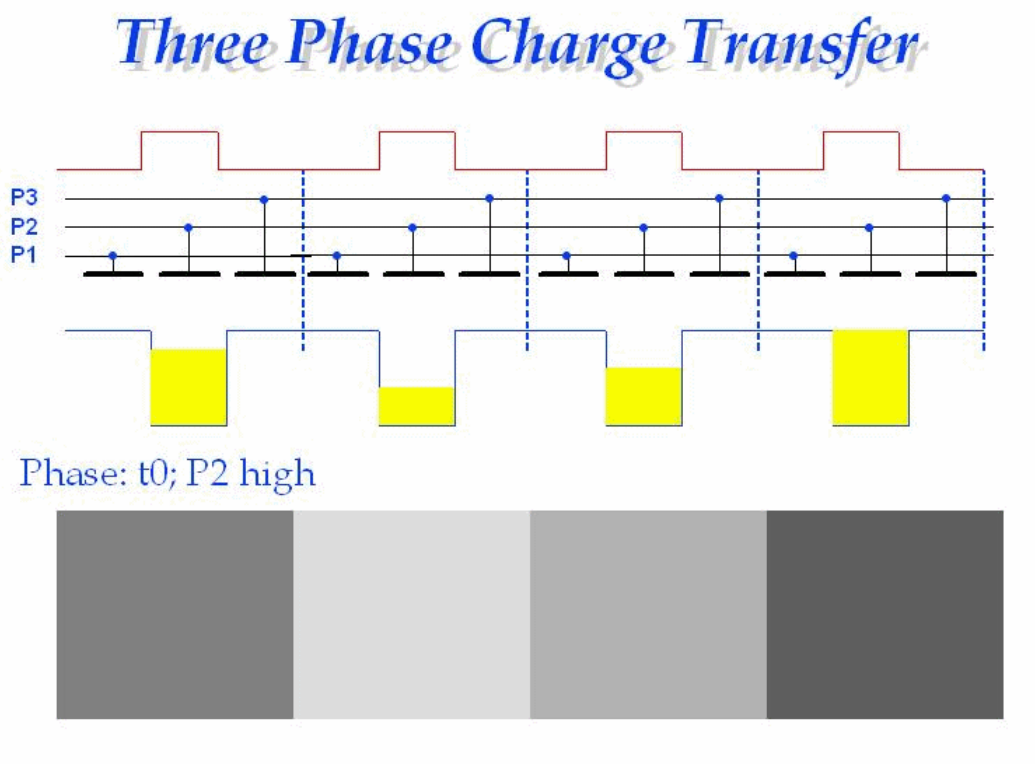
How does a CCD work?

- 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).



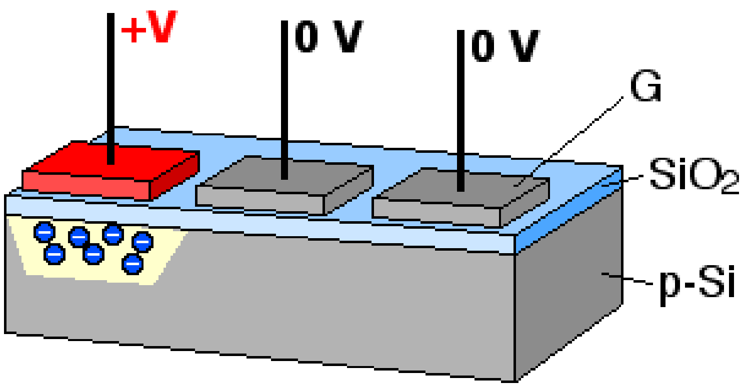
How does a CCD work?

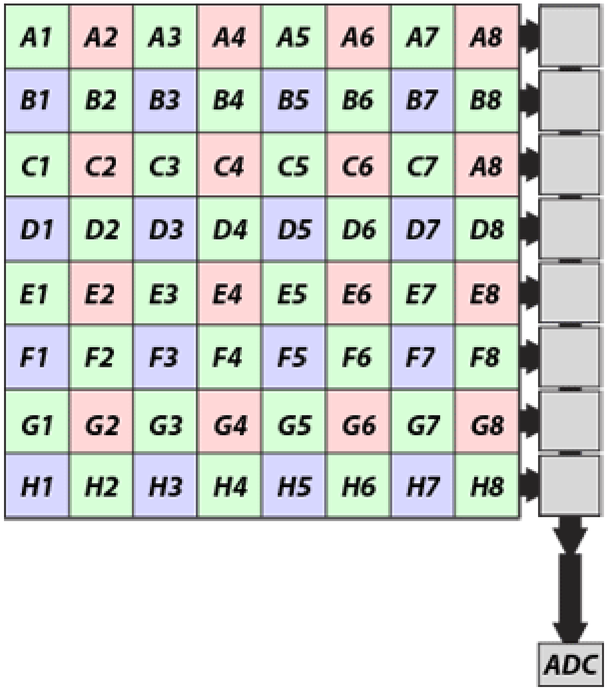
- By changing the potential of the electrodes in a synchronized way, electrons are transferred from pixel to pixel. Charges on the right are guided to the output register



How does a CCD work?

- 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.

CCD readout

- 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.

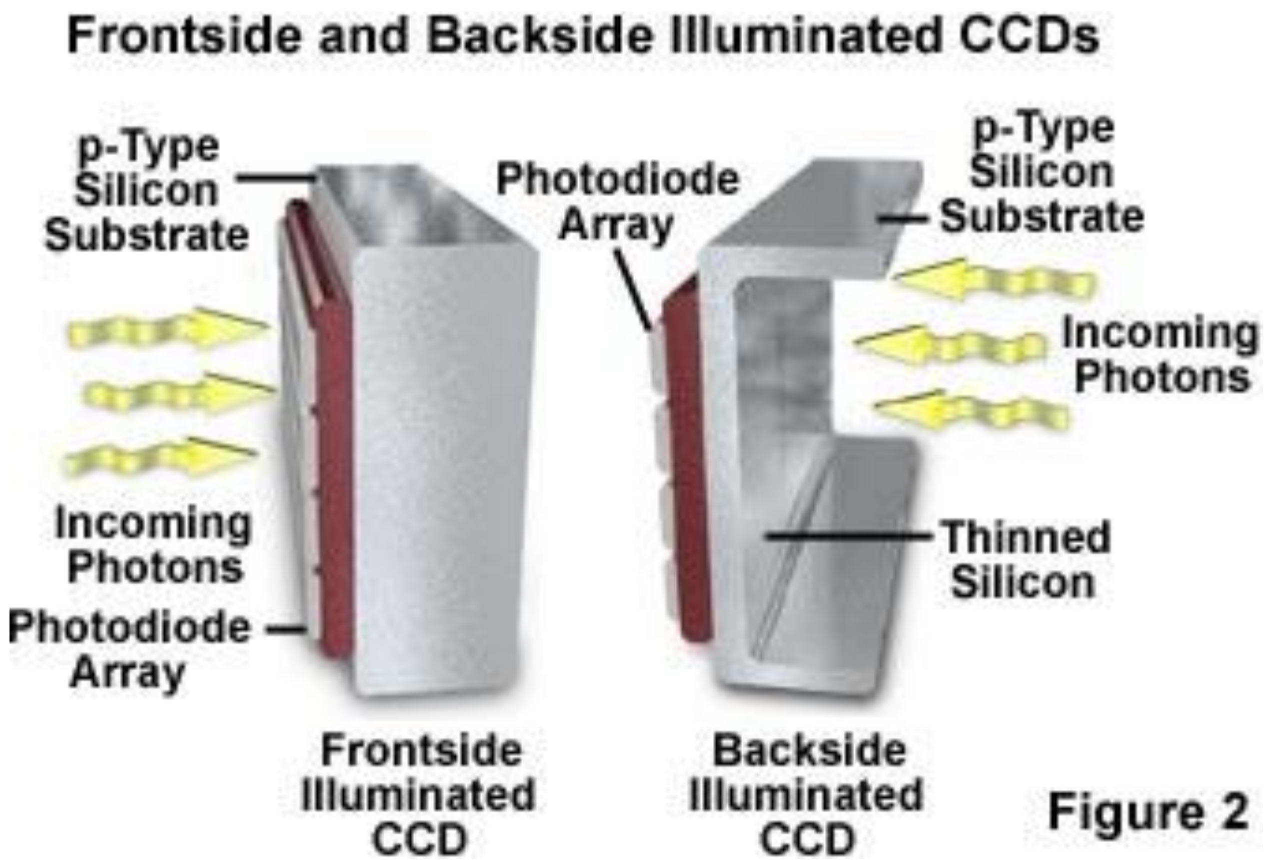
Buried channel CCD

- 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.
- If there is a layer of n-doped silicon above the p-doped layer, and a voltage bias is applied between the layers, the storage region will be deep within the depletion region.
- This is called a buried-channel CCD, and suffers much less from charge trapping.

Thinned back-illuminated CCD

- As described to now, the CCDs are illuminated through the electrodes. Electrodes are semi-transparent, but some losses occur, and they are non-uniform losses, so the sensitivity will vary within one pixel.
- 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.

Thinned back-illuminated CCD



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

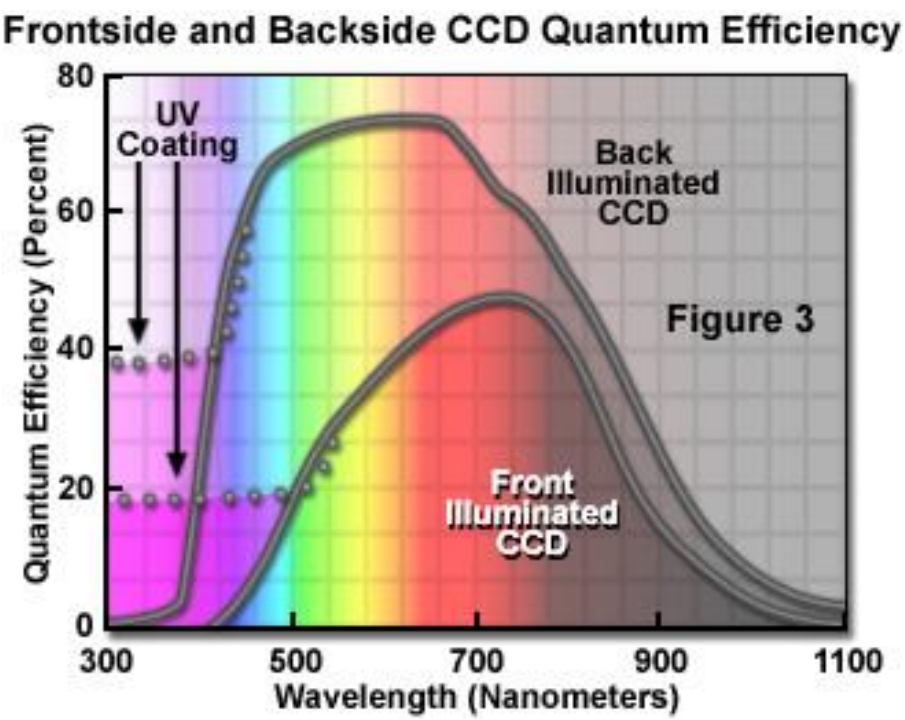
- Good spatial resolution
- Very high QE of up to 80%
- Large spectral window
- Very low noise
- High photometric precision
- High dynamic range
- Very good linearity
- A reliable rigidity (no physical distortion, etc)

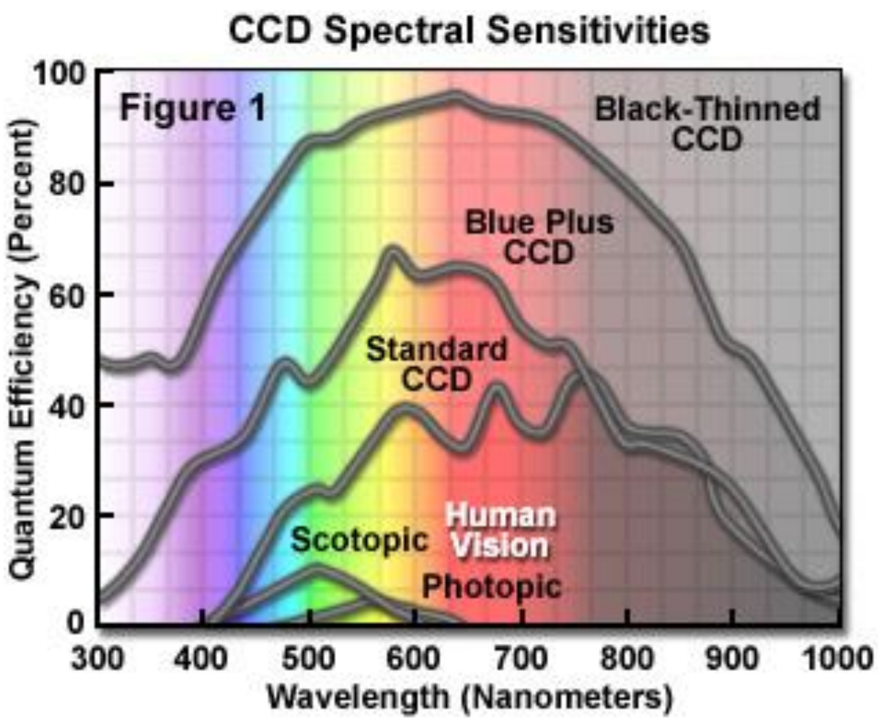
Advantages of CCDs

- **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

- **Quantum Efficiency:**





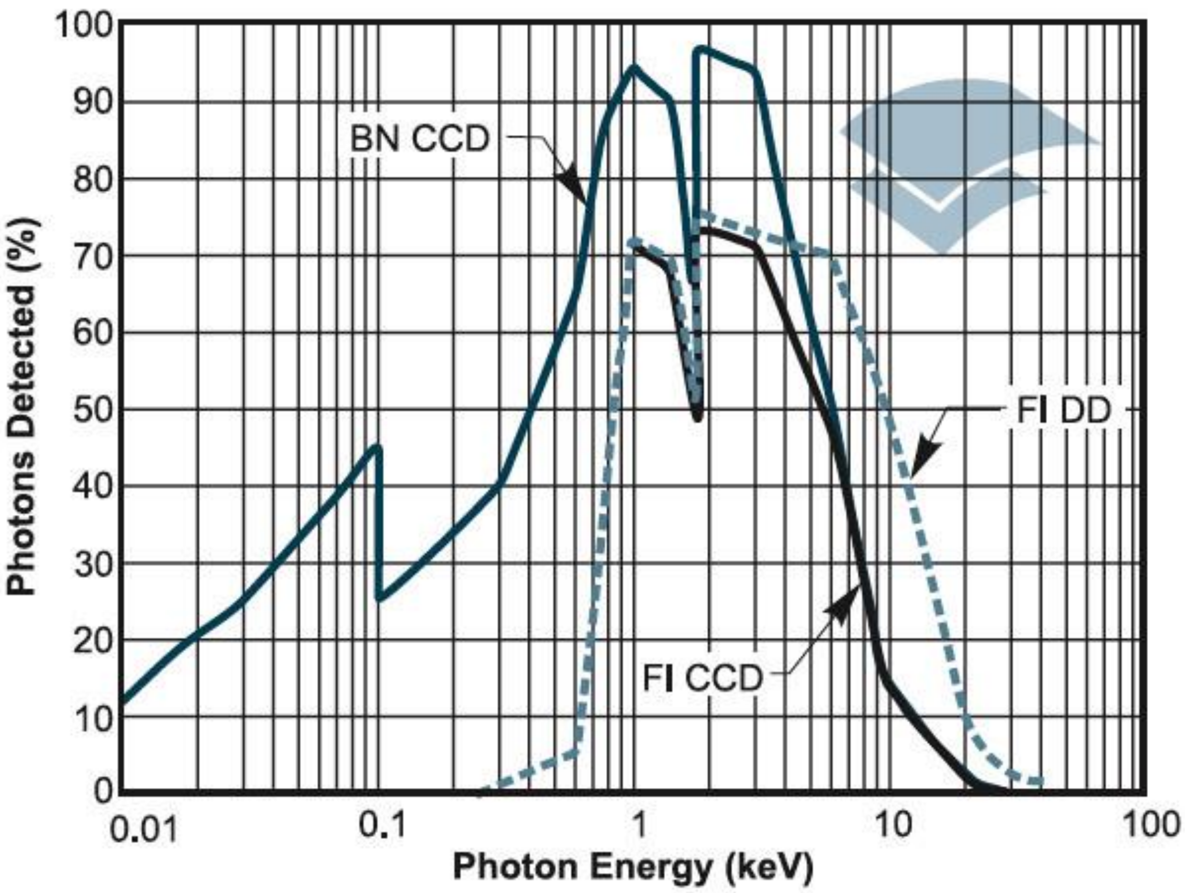
Advantages of CCDs

Spectral Range

FI: front illuminated

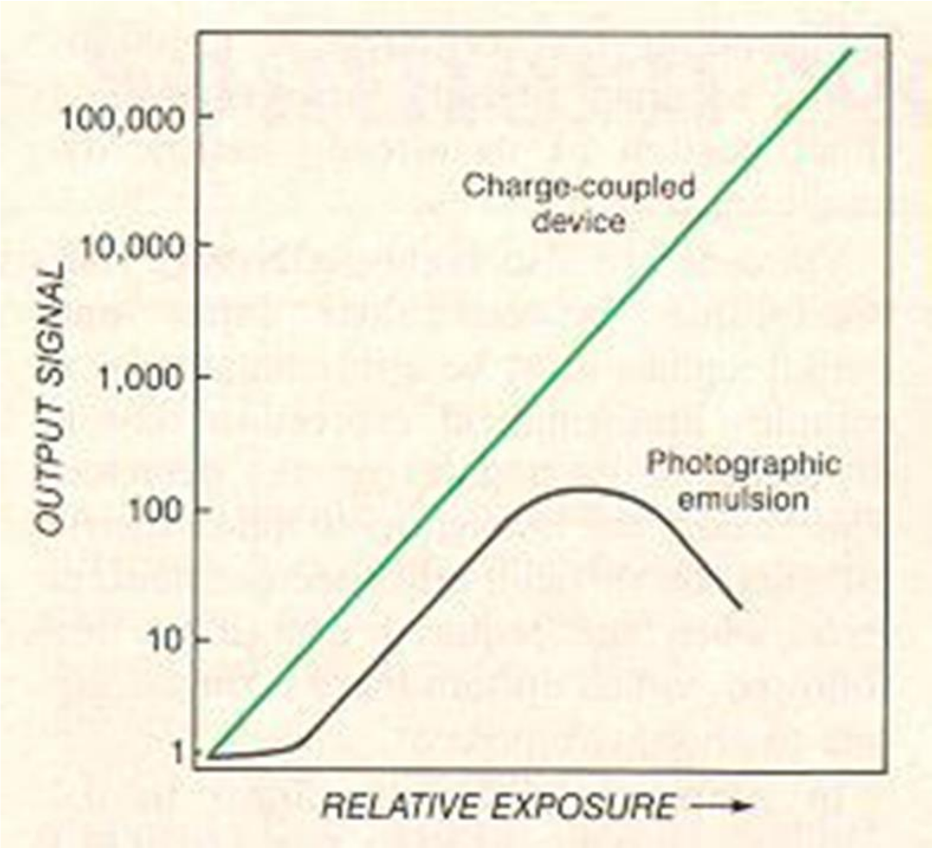
BN: back illuminated, no coating

DD: deep depletion



Advantages of CCDs

- **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.



Advantages of CCDs

- **Flat field technique.**



Disadvantages of CCDs

- **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

- **The dark current** 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

- **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

- **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

- **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: readout noise

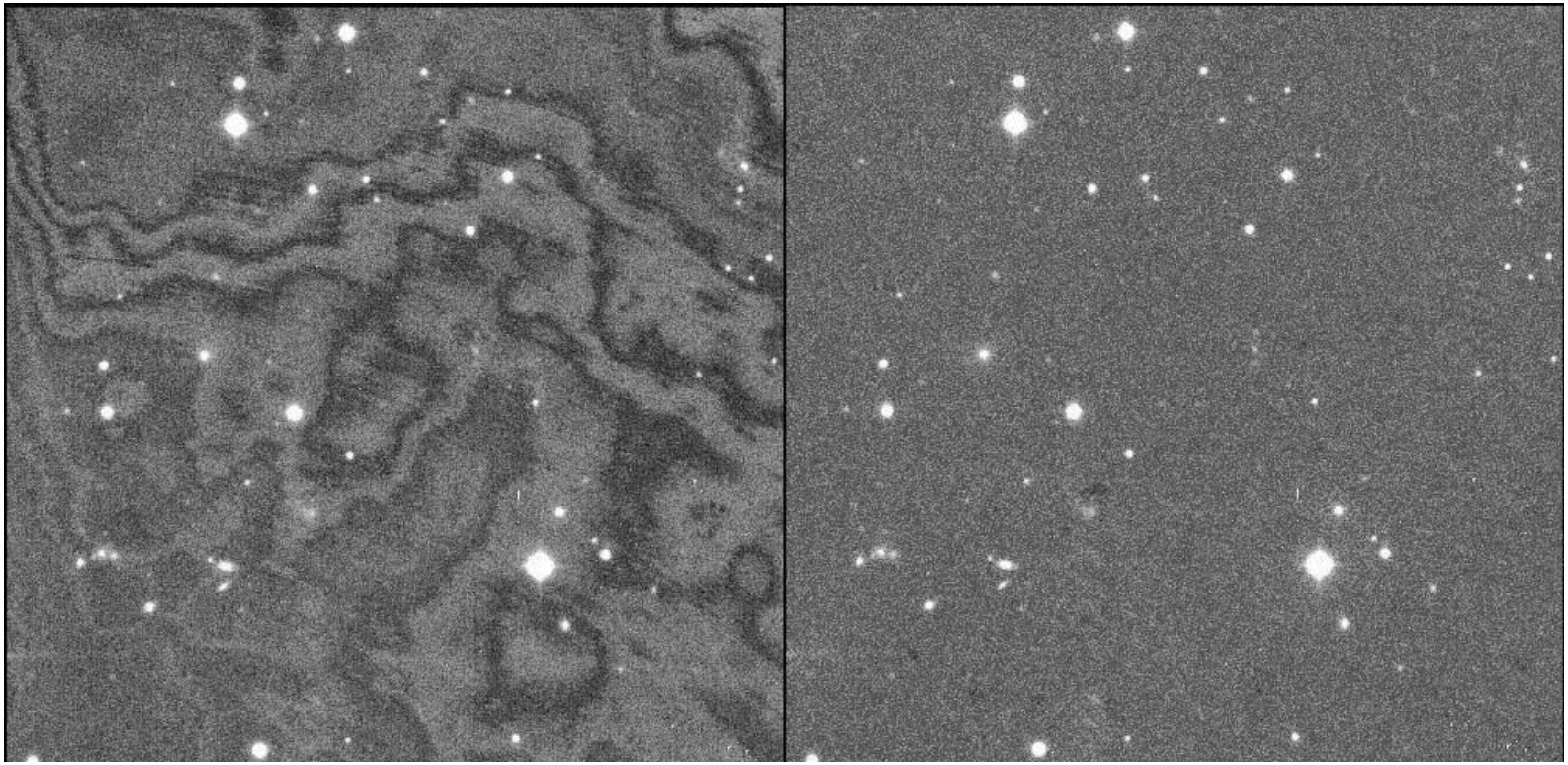
- **Reset noise**: there is a noise associated with recharging the output storage capacitor, given by $\sigma_{res} = \sqrt{(kTC)} / e$ where C is the output capacitance in Farads. This noise could dominate, but it is removed by Correlated Double Sampling, where the reset voltage is measured after reset and again after readout. The first value is subtracted from the second, as this voltage will not change.
- **Surface State noise**, due to fast interface states which absorb and release charges on short timescales. This is given by $\sigma_{ss} = \sqrt{(2kTn\rho_{ss}A)}$, where n is the number of transfers, ρ_{ss} is the density of fast interface states, and A is the pixel area. In buried channel CCDs, ρ_{ss} is very low and this source of noise is less than 1 electron.

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.
- **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

- 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

- 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.
- 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 > 700nm.
- 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.