Introduction to CCDs

9/21/2009

What is a CCD?

- Charge Coupled Devices (CCDs) are two dimensional detector arrays based on the *photoelectric effect* in Si
- Charge transfer architecture (bucket brigade) was invented as a type of computer memory in the late 1960's
- Application to astronomy produced a major revolution

What is a CCD?

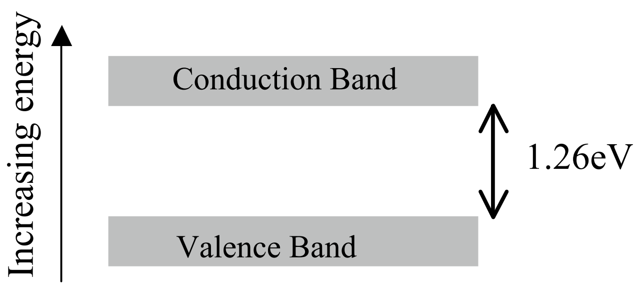
- CCDs improve on the light gathering power of photographic plates by ~ two orders of magnitude
- A 15-cm telescope with a CCD camera can collect as much light as 1-m equipped with a photographic plate
- CCDs work by converting variations in light intensity (an image) into a pattern of electronic charge in a Si chip
  - This pattern of electric charge is converted into an analog signal, digitized, and stored as DN

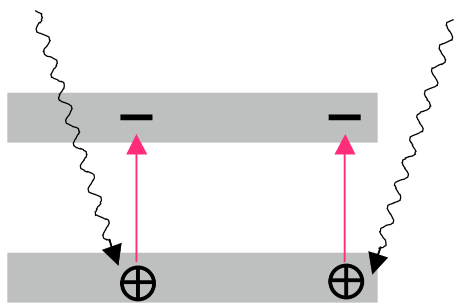
Photoelectric Effect

- In a Si crystal electrons are restricted to discrete energy levels or bands
  - The lower energy band is called the ***Valence Band*** (full)
  - The upper band is the ***Conduction Band*** (empty)
- Most electrons occupy the valence band
  - Excited into the conduction band by absorption of photons or phonons
  - Minimum energy required in Si is 1.26 eV
  - Electrons excited to the conduction band are free to move about in silicon crystal lattice
  - Leaves behind a ‘hole’ in the valence band which acts like a positively charged carrier. In the absence of an external ***E-***field the electron & hole recombine. In a diode an ***E-***field is introduced to sweep these charge carriers apart and prevent recombination.

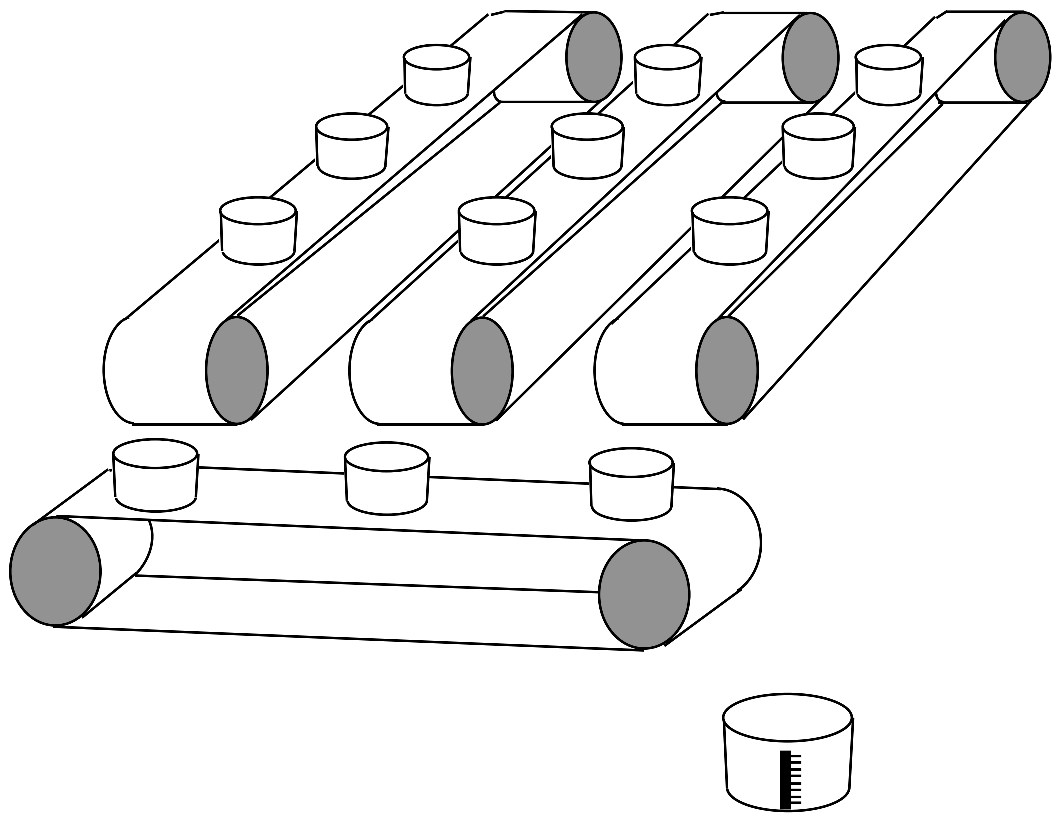
Photoelectric Effect

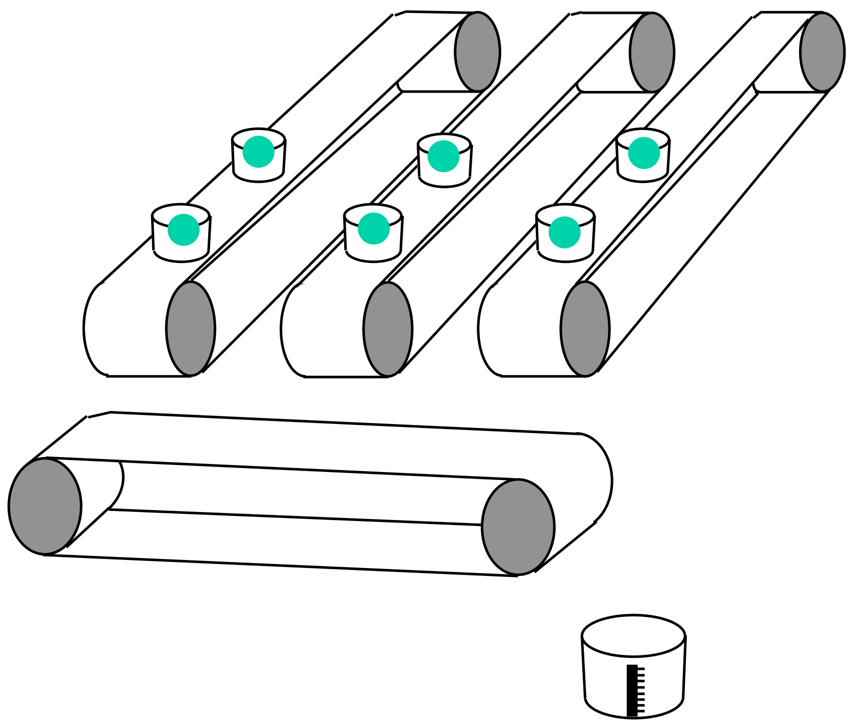
- 1.26eV corresponds to the energy of light with a wavelength of 1.1μm (1100 nm)
  - Beyond 1.1 μm Si is transparent and CCDs are insensitive to light
- Thermally generated electron/hole pairs are indistinguishable from photo-generated electrons
  - Noise source known as ***Dark Current*** and it is important that CCDs are kept cold to minimize this

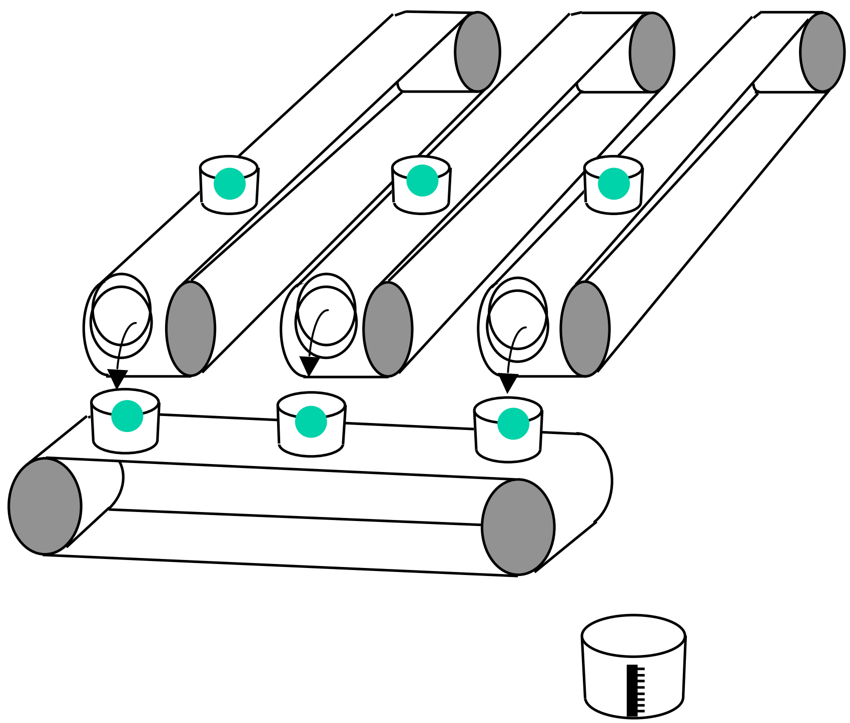


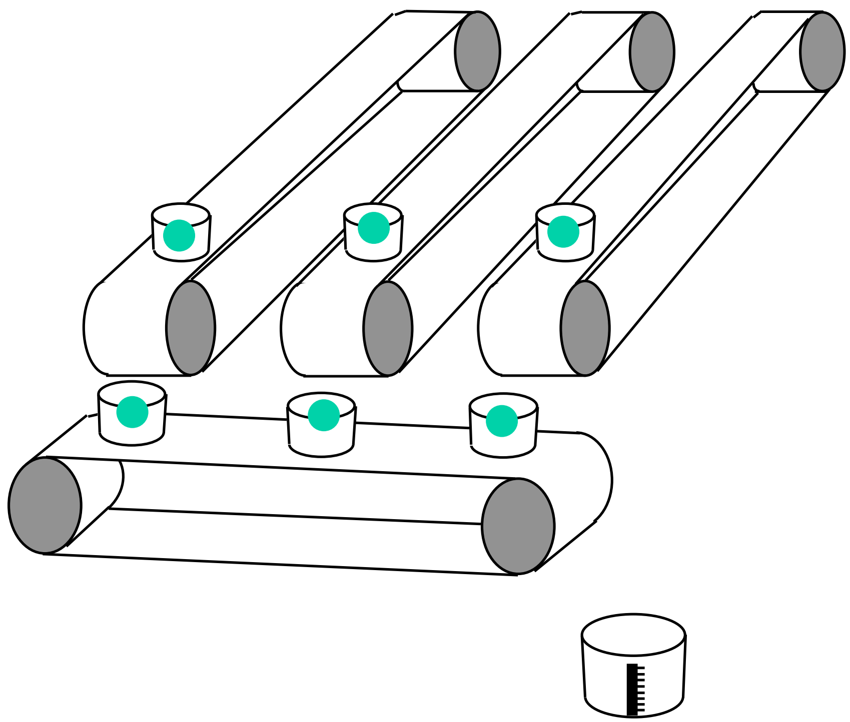


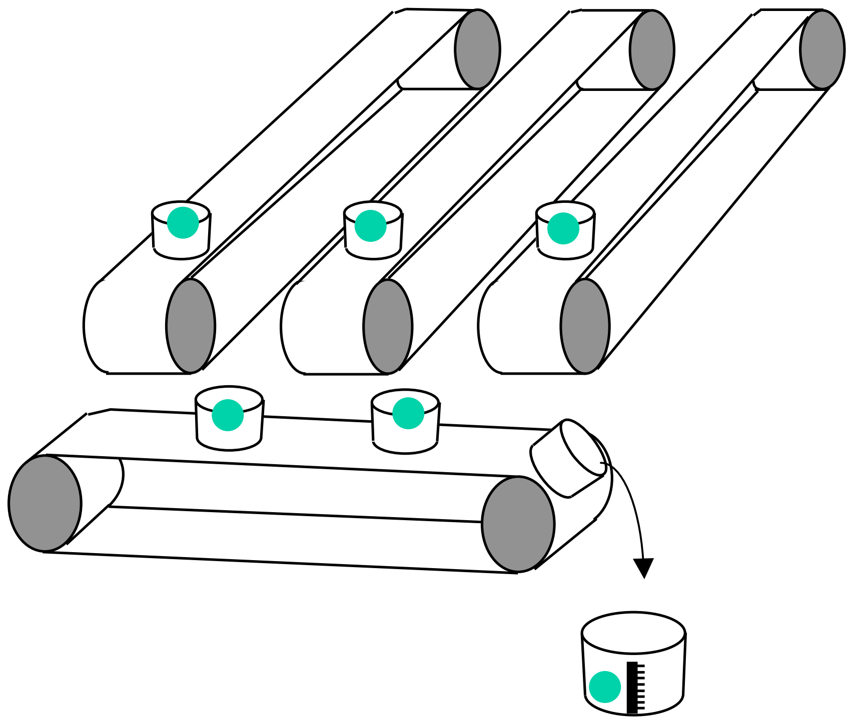
What is a CCD?

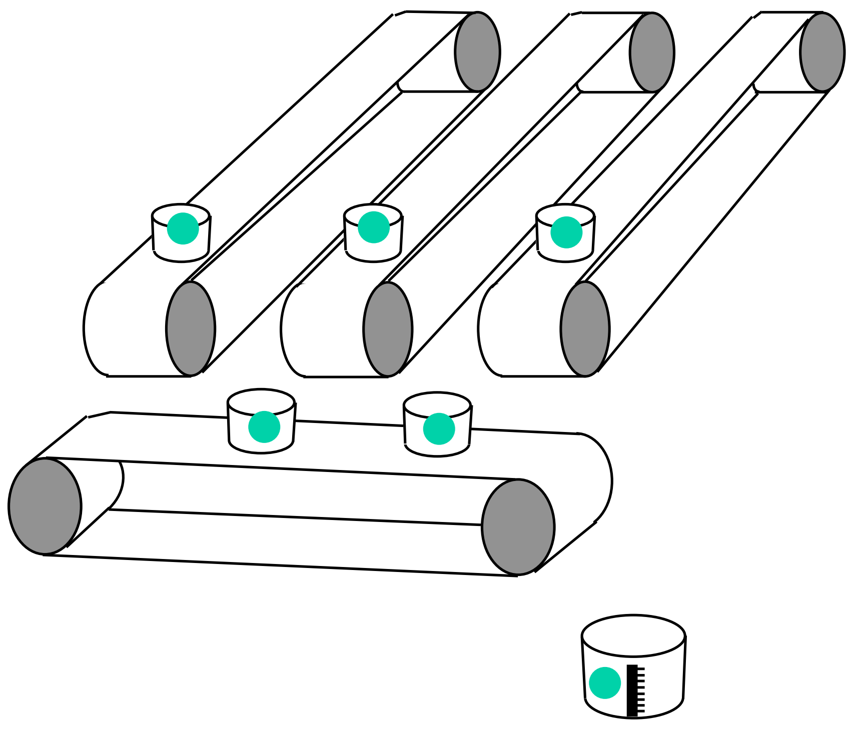


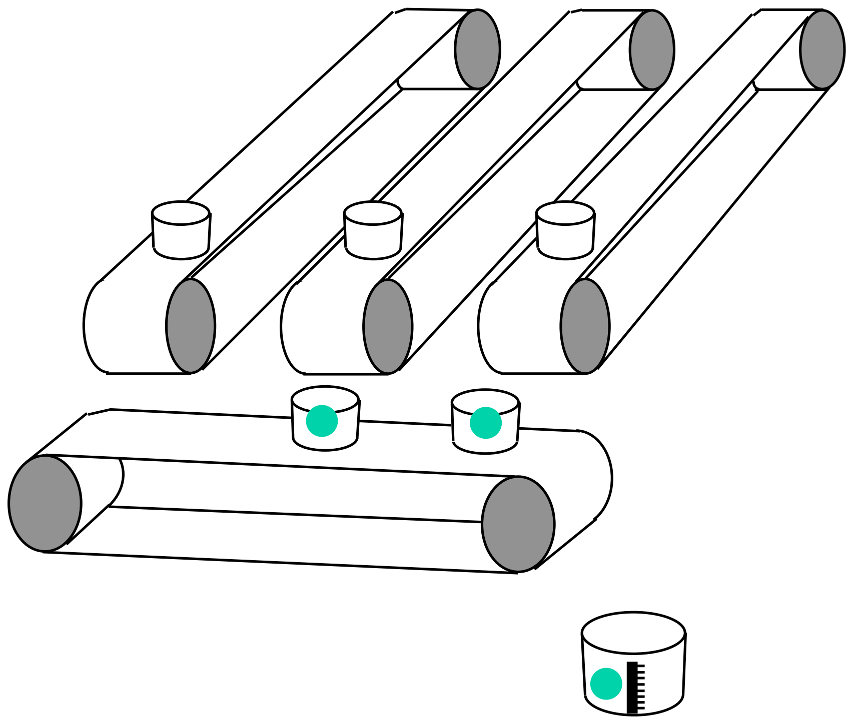


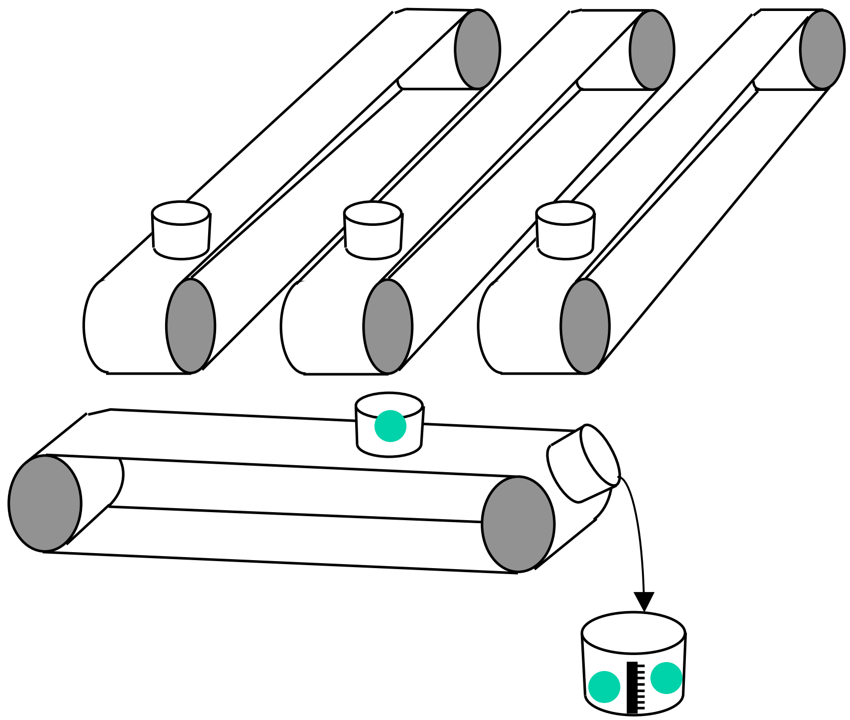


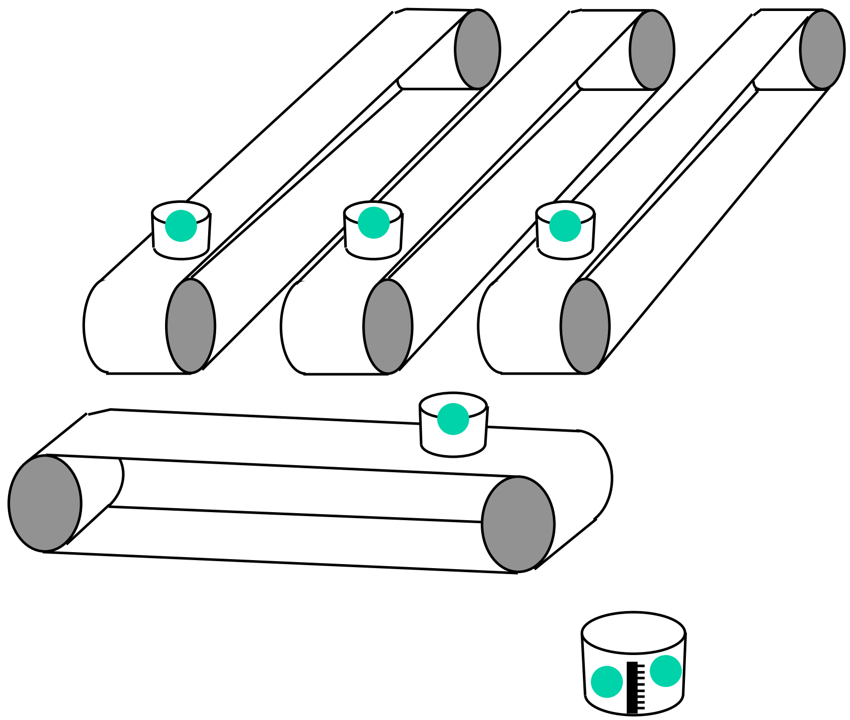


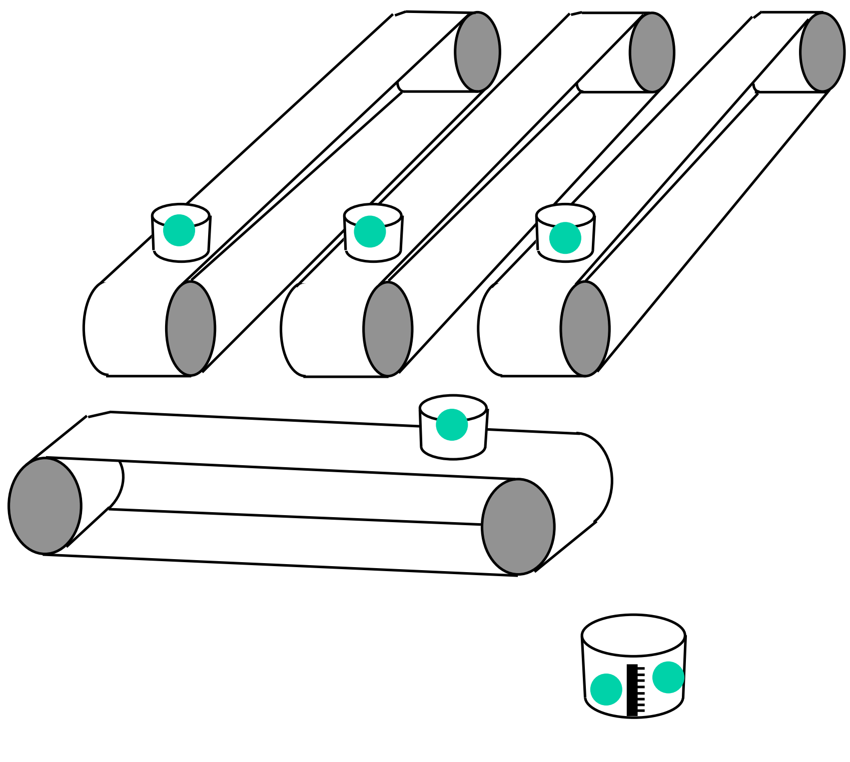


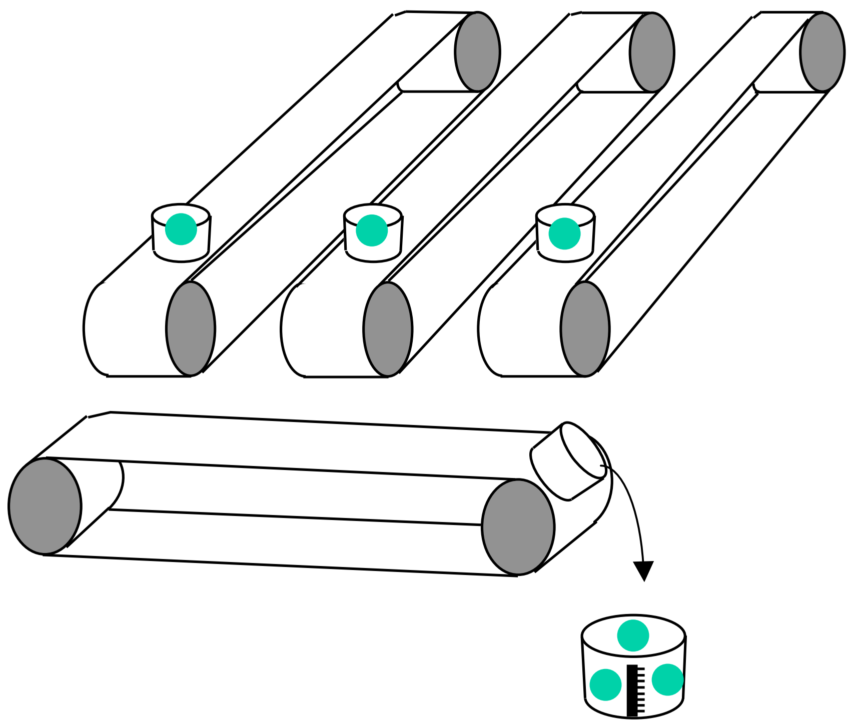


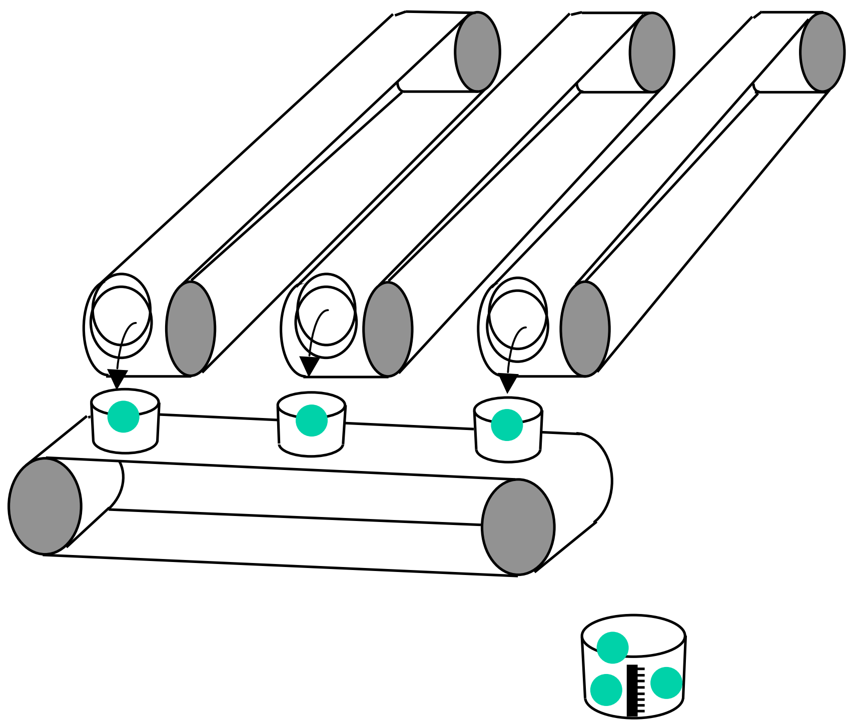


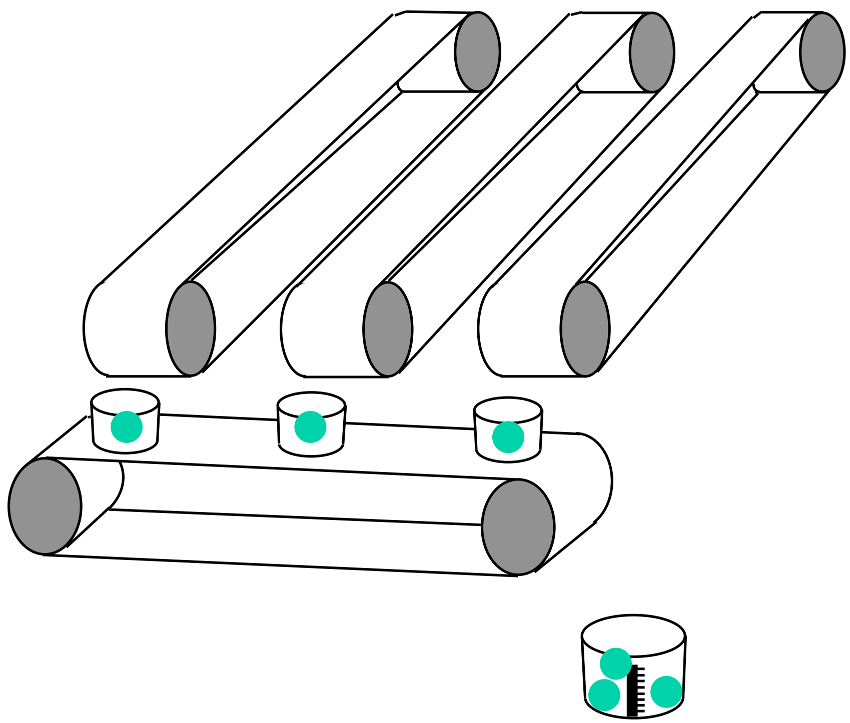


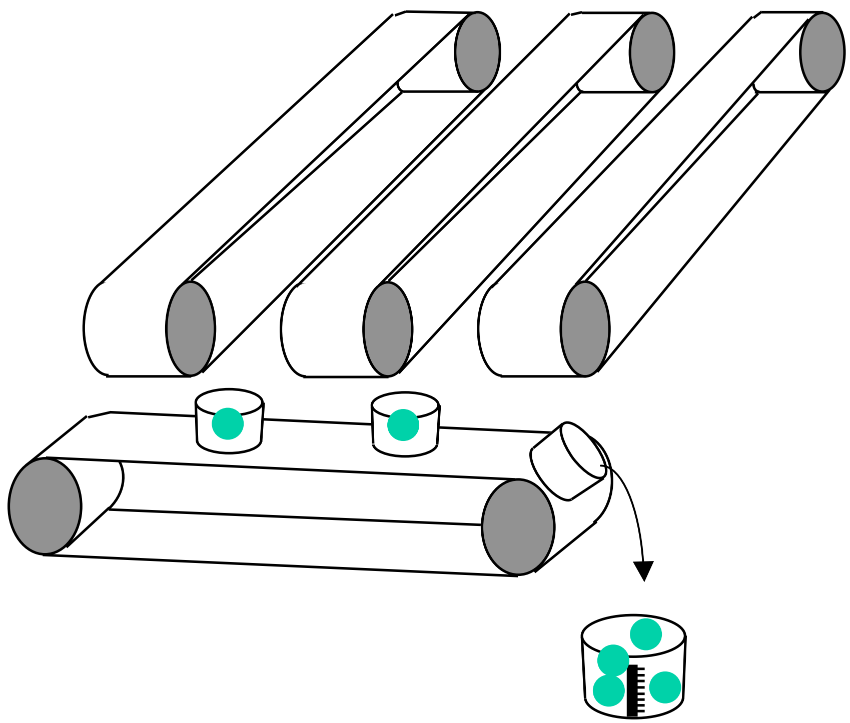


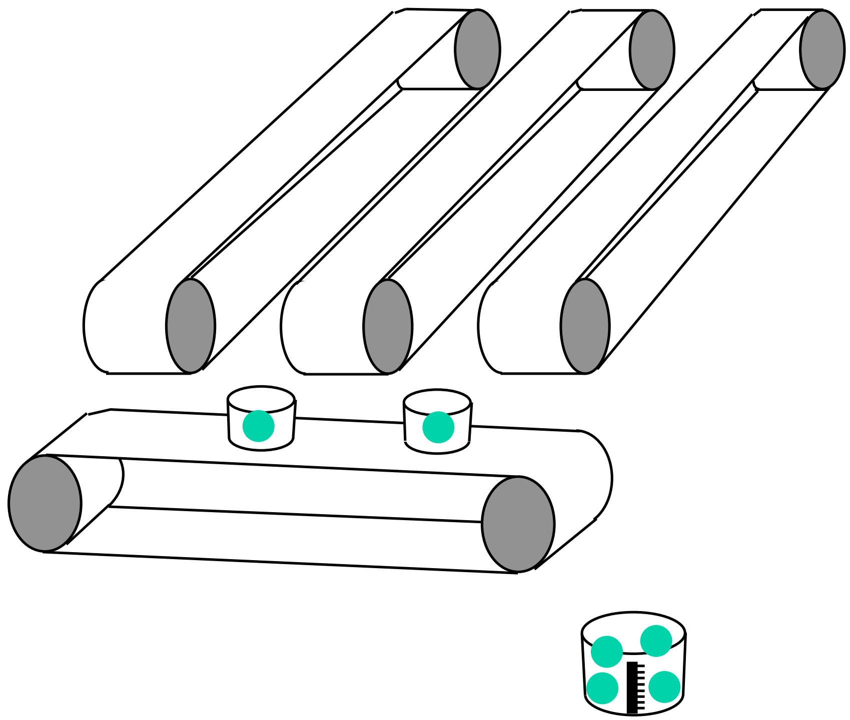


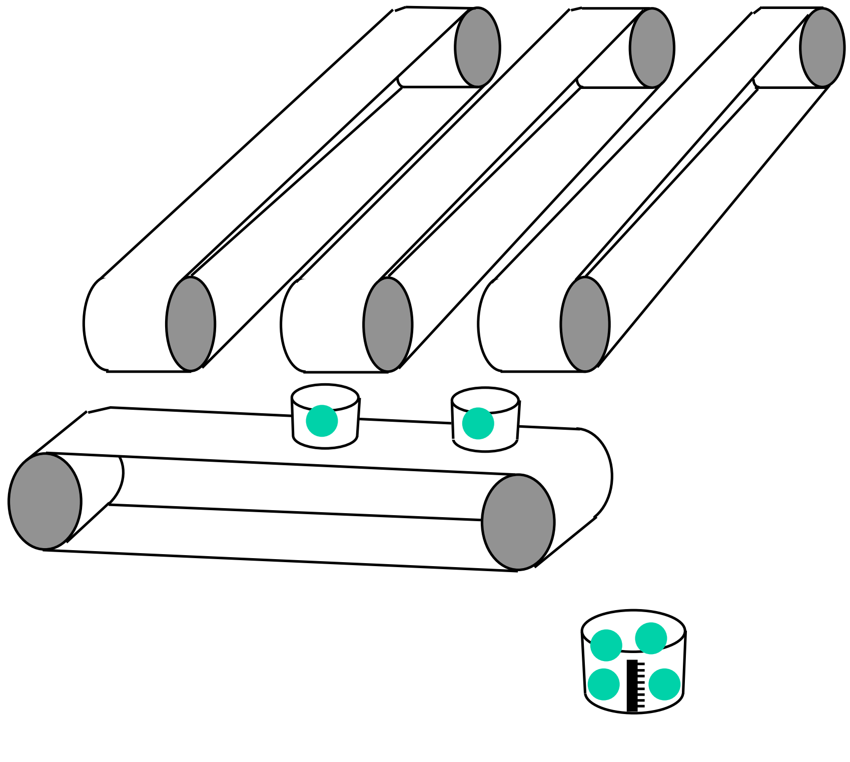


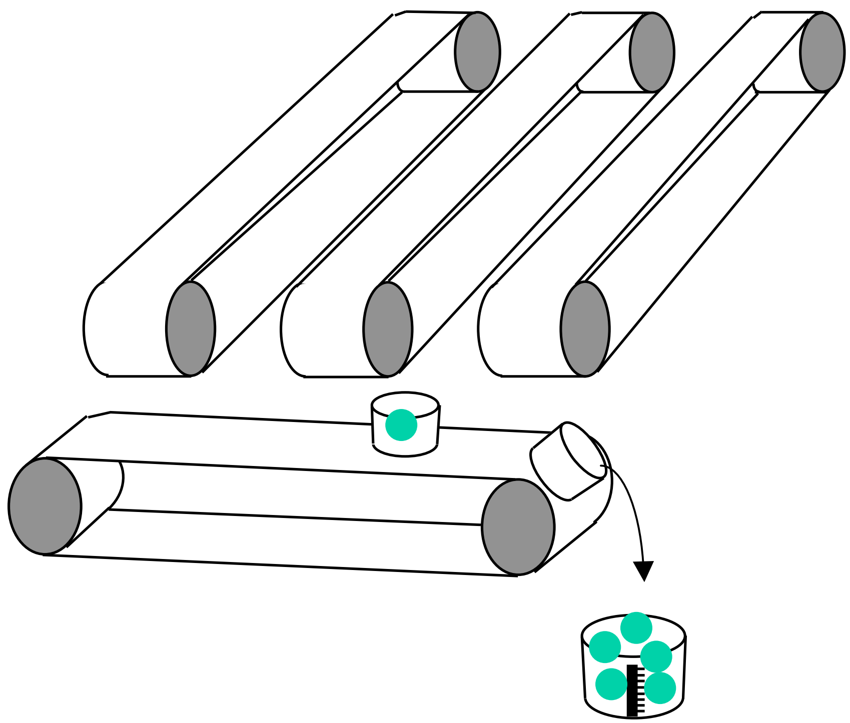


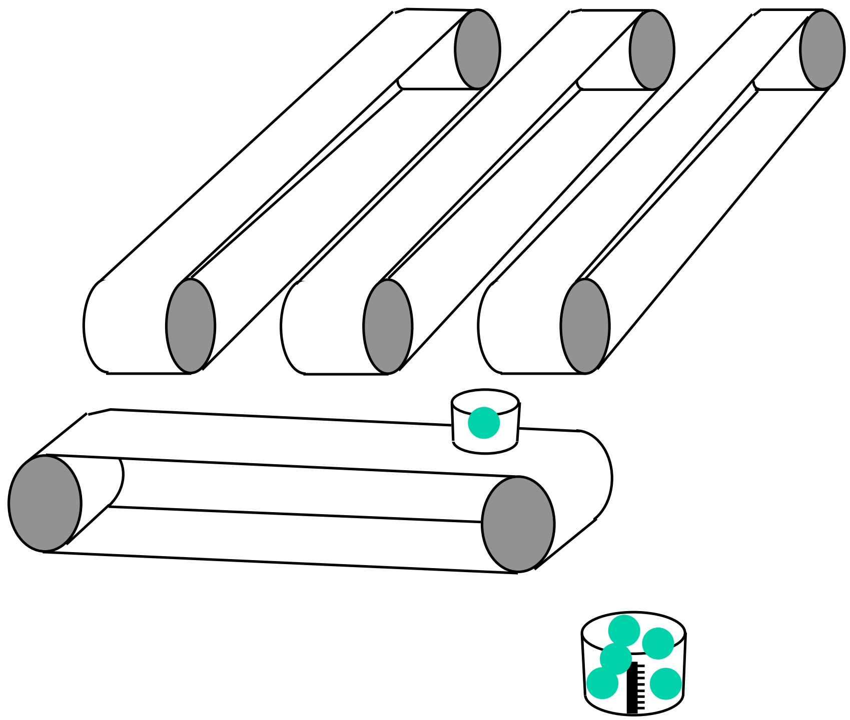


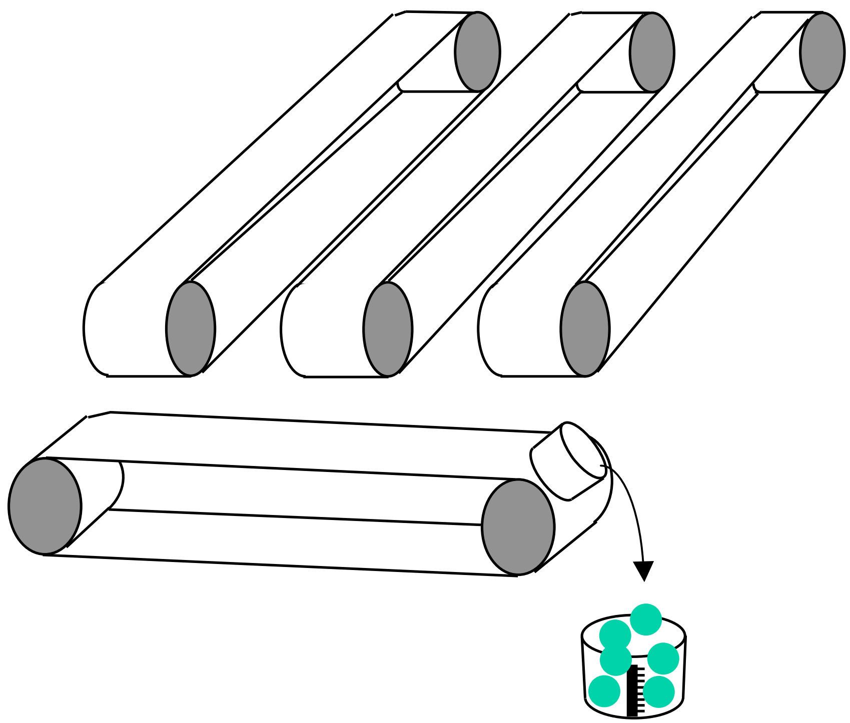


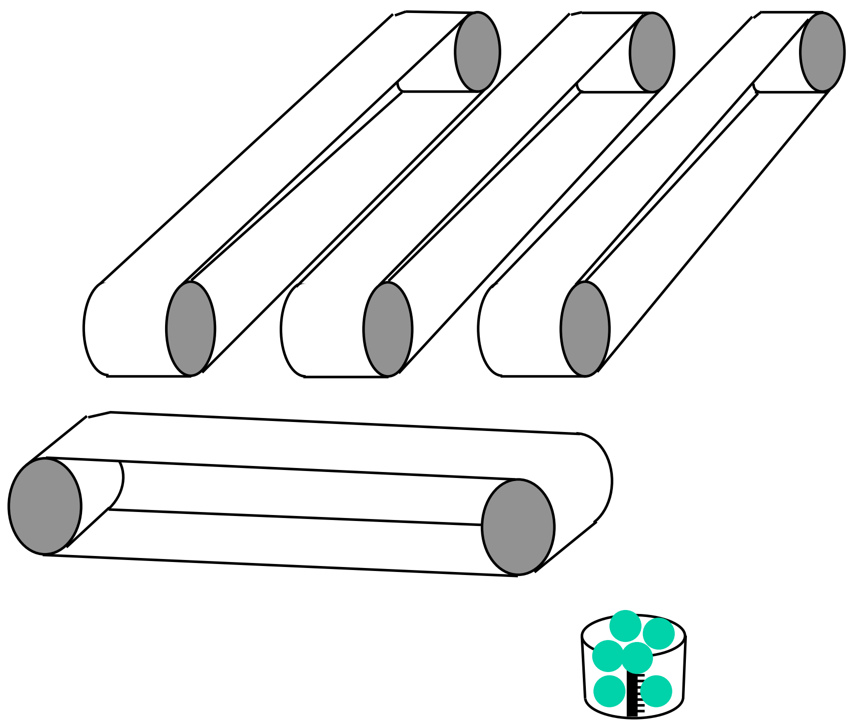






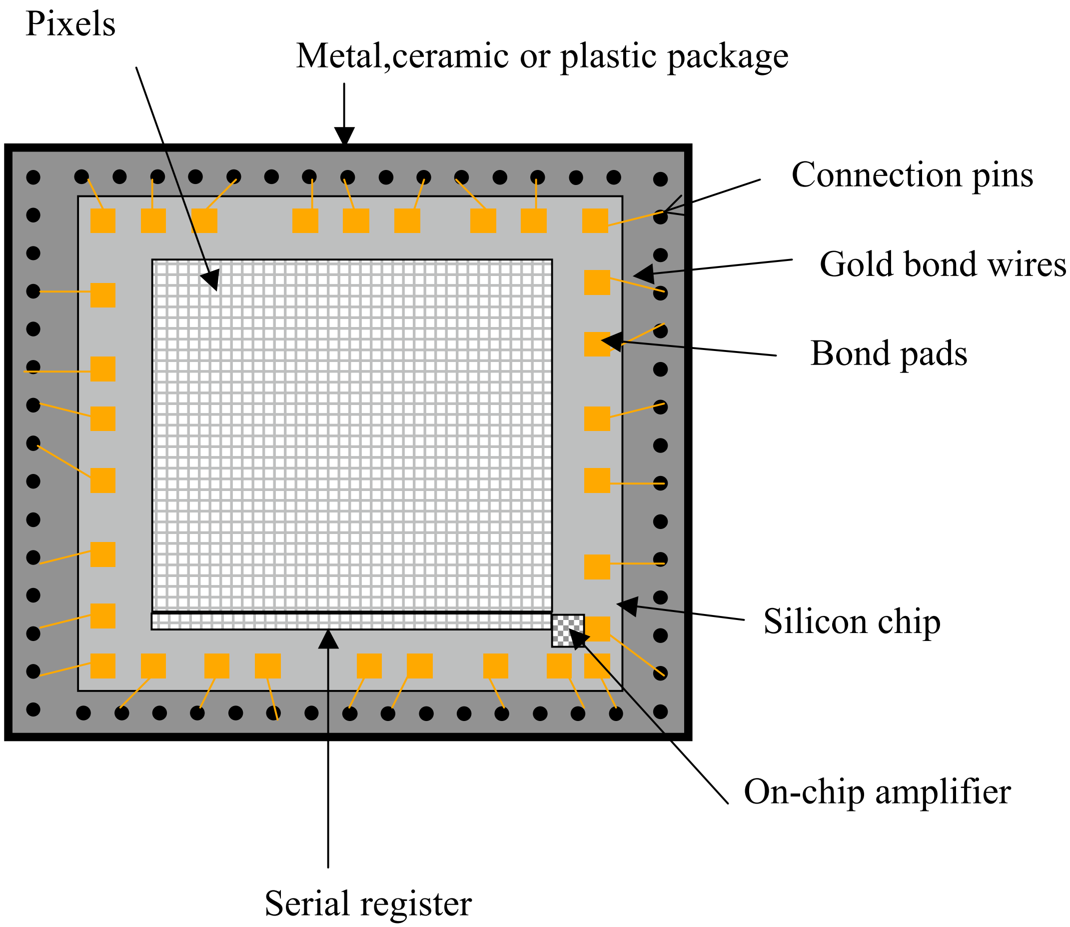






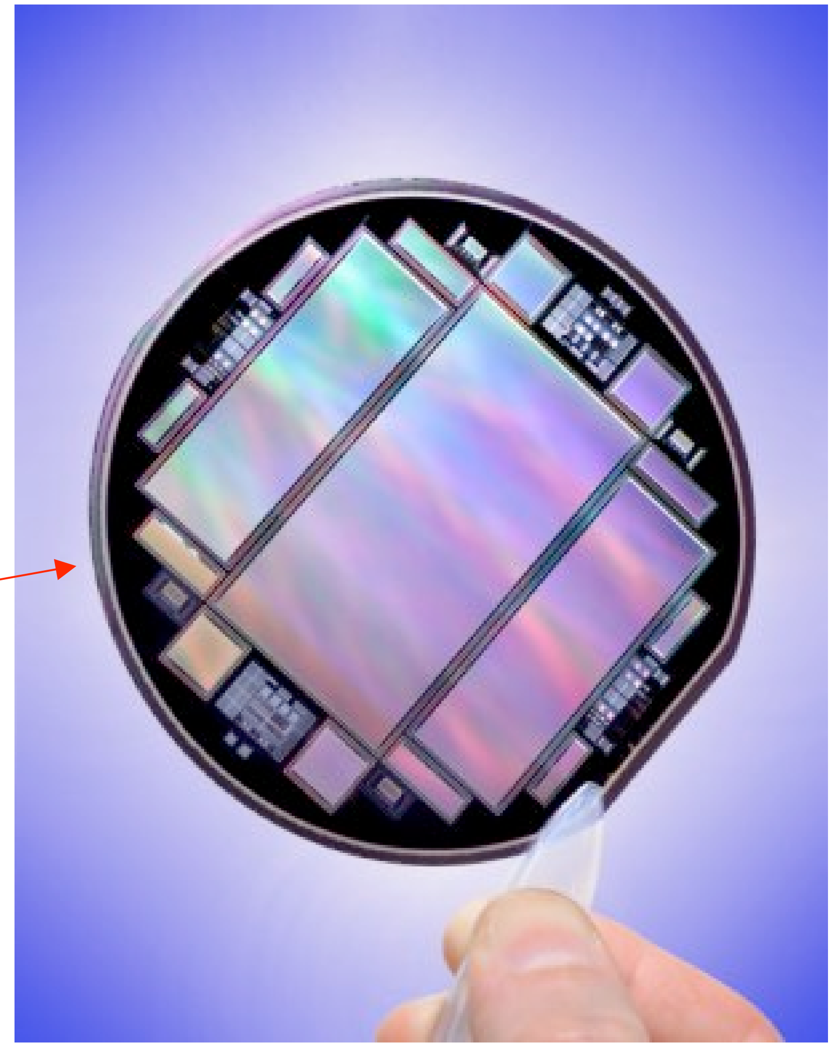
CCD Structure

- A CCD is located at the telescope focal plane
  - An image builds up as a pattern of electric charge
  - At the end of the exposure this pattern is transferred, one pixel at a time, by way of the serial register to an on-chip amplifier
  - Electrical connections are made to the outside world via a series of bond pads and wires around the edge of the chip



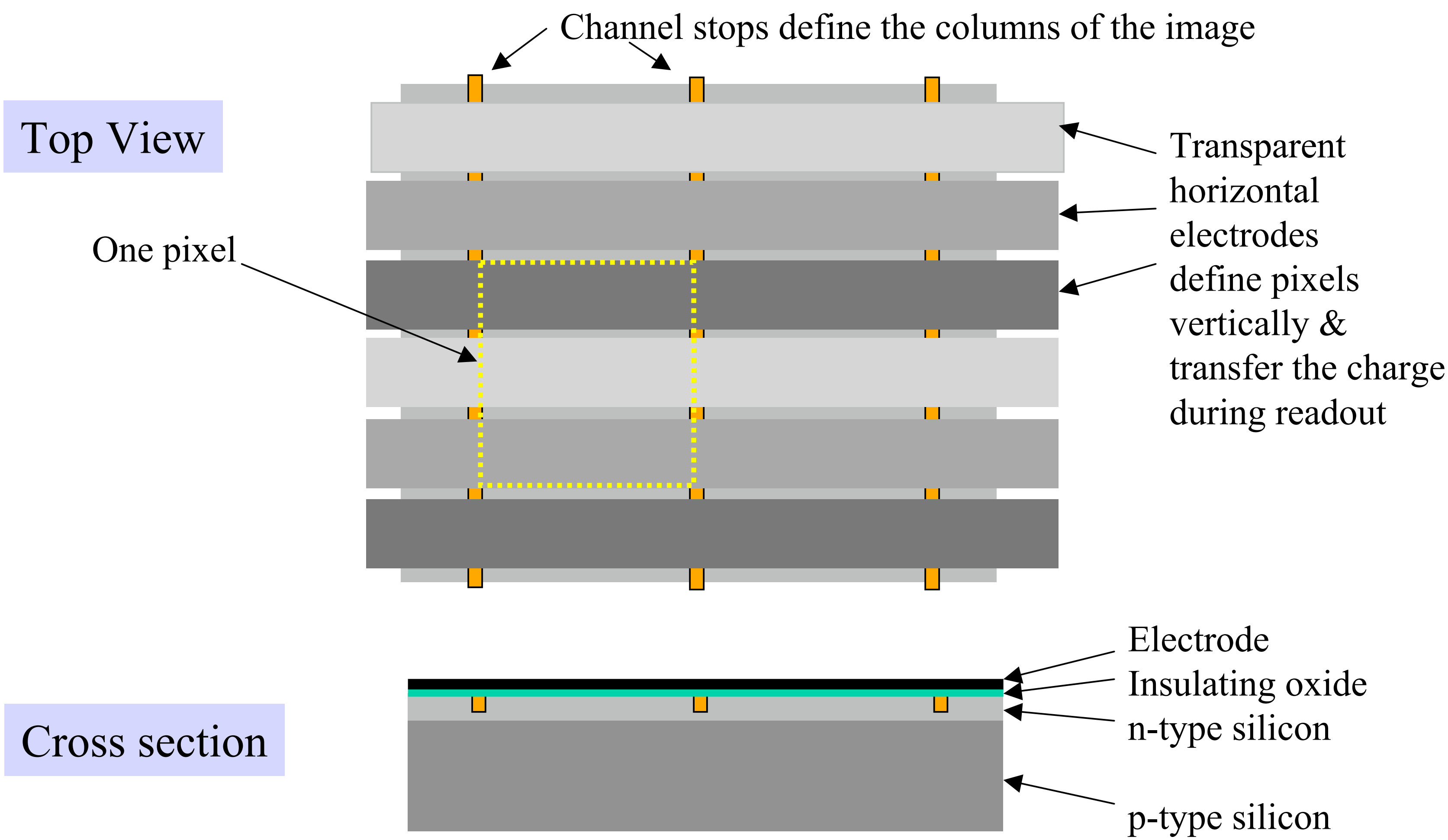
CCD Structure

- CCDs are are manufactured on Si wafers using photo-lithography
- Scientific CCDs are big, only a few per wafer
  - One reason that they are expensive
- LBL Si wafer with three large CCDs and several smaller devices
- A CCD made by Philips fills an entire 6 inch wafer making it the world's largest IC



CCD Structure

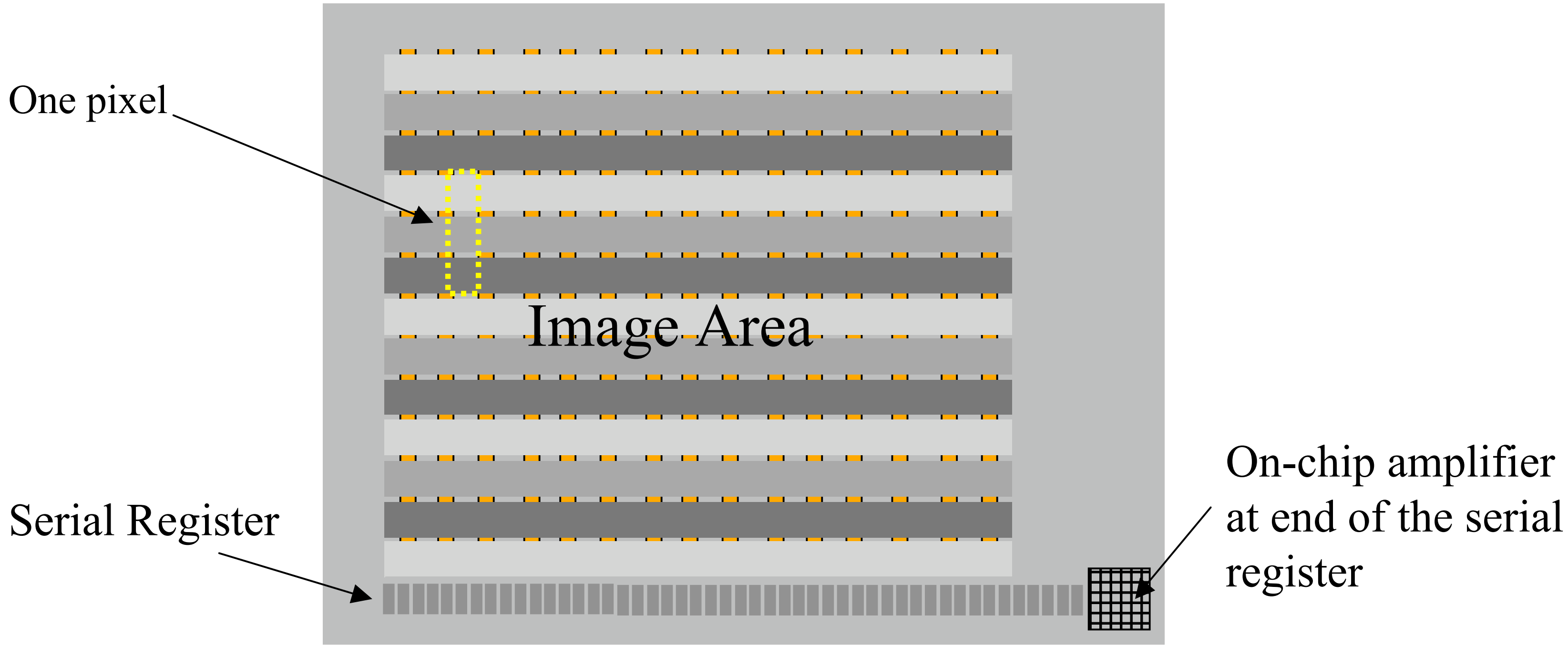
Small section (a few pixels) of the image area of a CCD. This pattern is repeated.



Every third electrode is connected together. Buses at the edge of the chip make the connection. The channel stops are B doped Si

CCD Structure

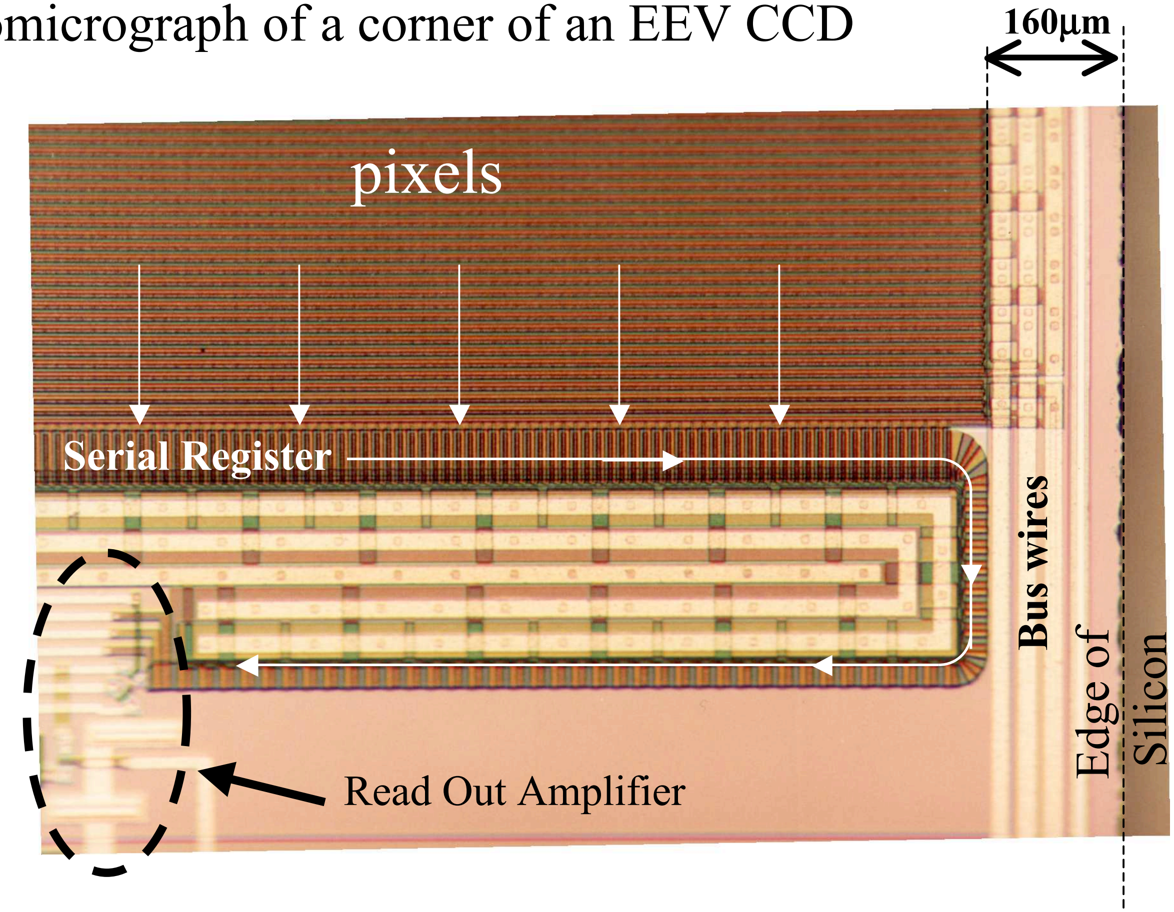
The serial register is below the image area. This also consists of a group of small surface electrodes. There are three electrodes for every column of the image area



Every third electrode is in the serial register connected together.

CCD Structure

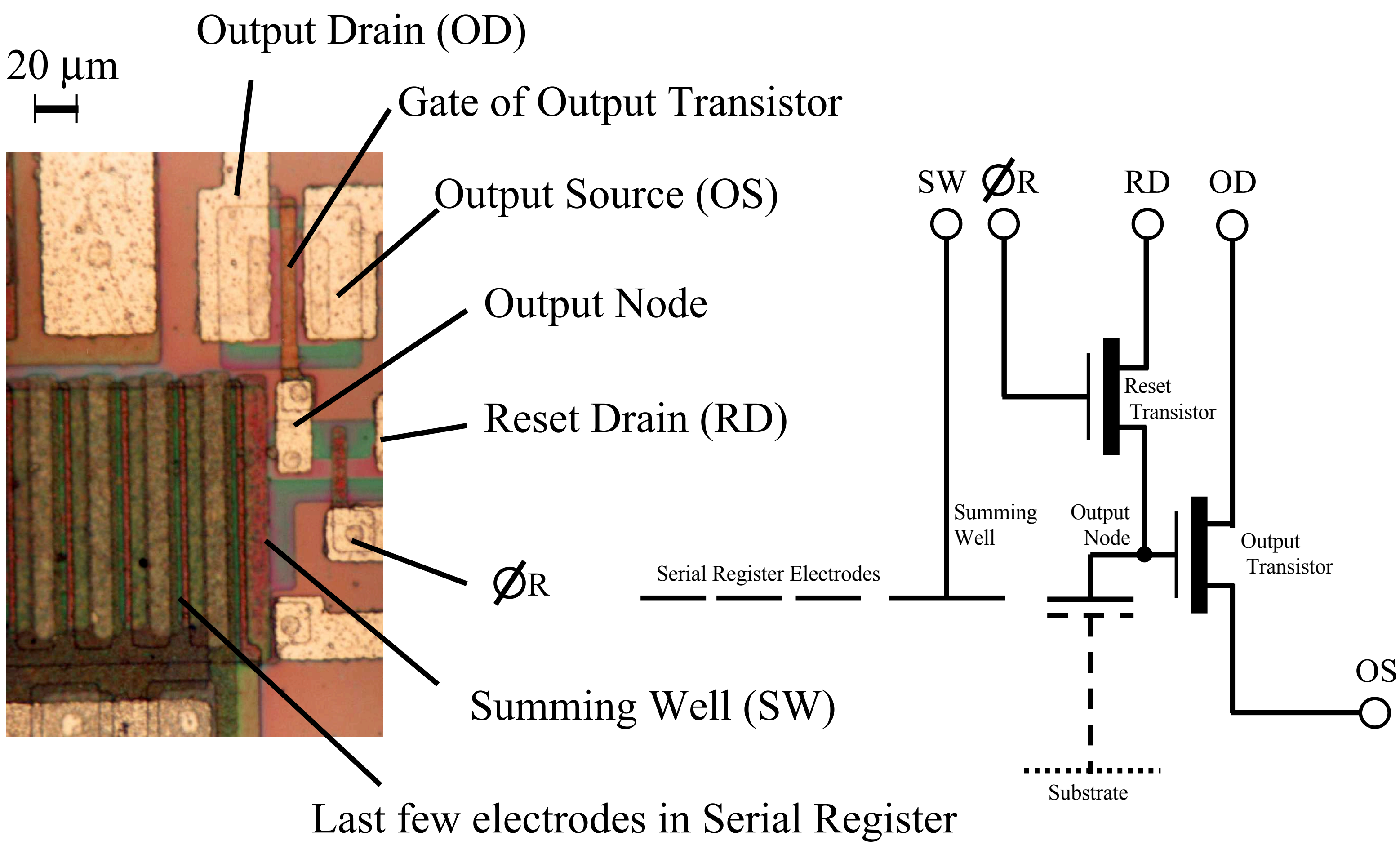
Photomicrograph of a corner of an EEV CCD



Arrows show the direction of charge transferred.The serial register is U-shaped to move the output amplifier away from the edge of the chip. This is convenient if the CCD is used in a mosaic.

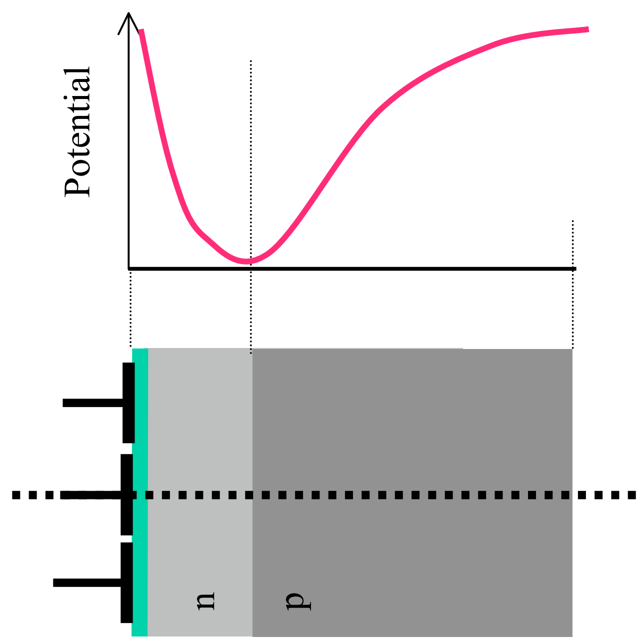
CCD Structure

Photomicrograph of the on-chip amplifier of a Tektronix CCD and its circuit diagram.



Electric Field Distribution

- *n*-region contains excess e^- that diffuse into the p-layer. *p*-region contains an excess e^+ that diffuse into the n-layer
  - Forms a pn-diode junction
- Diffusion creates a charge imbalance and induces an internal ***E***-field
  - The potential reaches a maximum just inside the n-layer, and it is here that any photo-generated electrons will collect.
- All CCDs have this "buried channel" junction structure
  - Keeps the photo-electrons away from the surface of the CCD where they could be trapped
  - Reduces the amount of thermally generated noise (dark current).

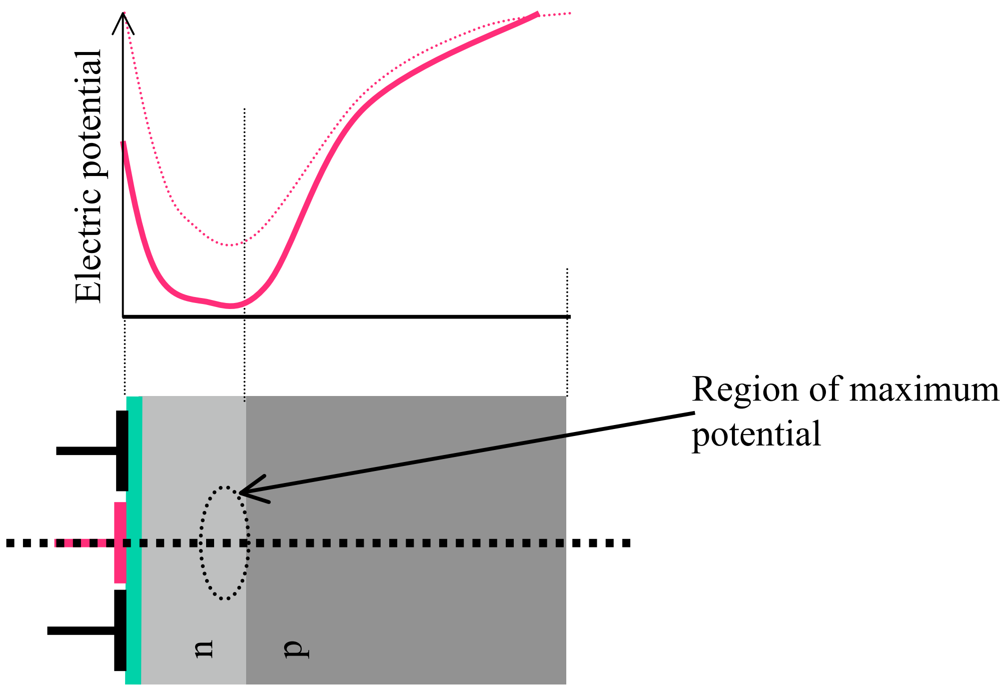


Cross section through the thickness of the CCD

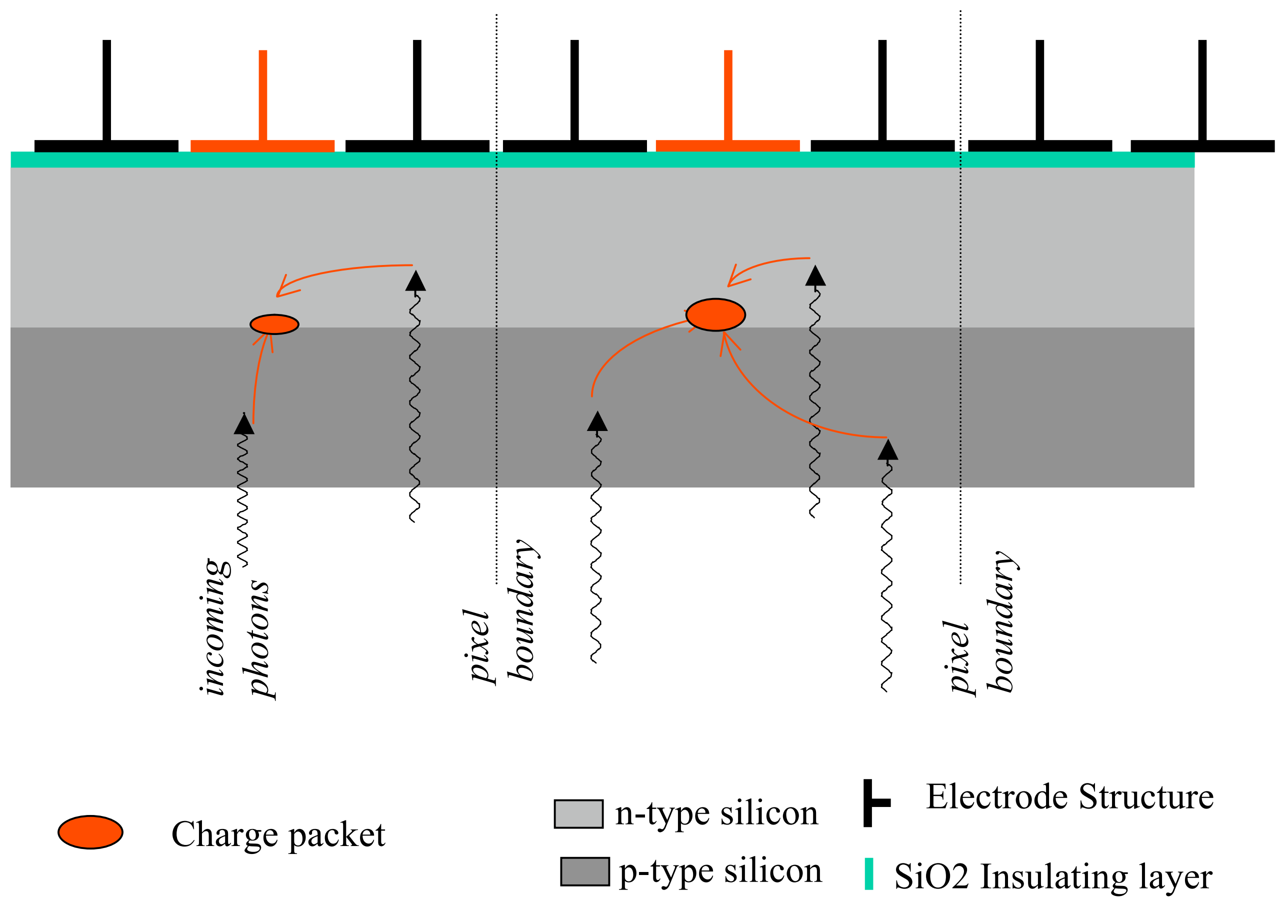
Potential along this line shown in graph above.

Electric Field Distribution

- During integration, one of the three electrodes in each pixel is held at a positive potential (reverse bias)
  - Further increases the potential in the silicon below that electrode and photoelectrons are accumulated here
  - Neighboring electrodes, with lower potentials, act as barriers that define the vertical pixel boundaries
  - Horizontal boundaries are defined by the channel stops

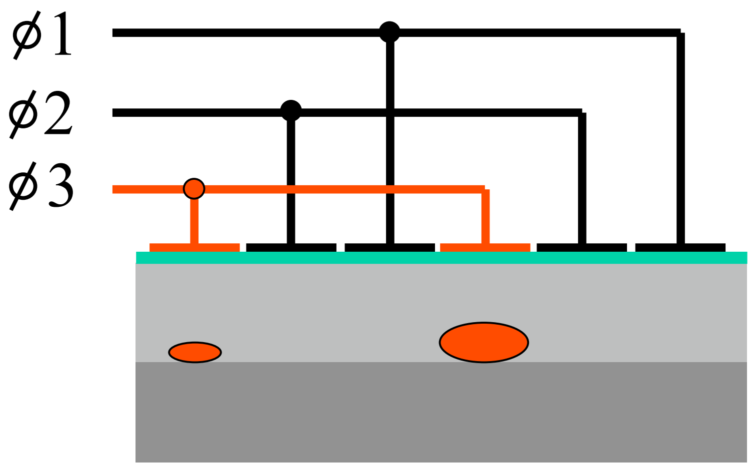


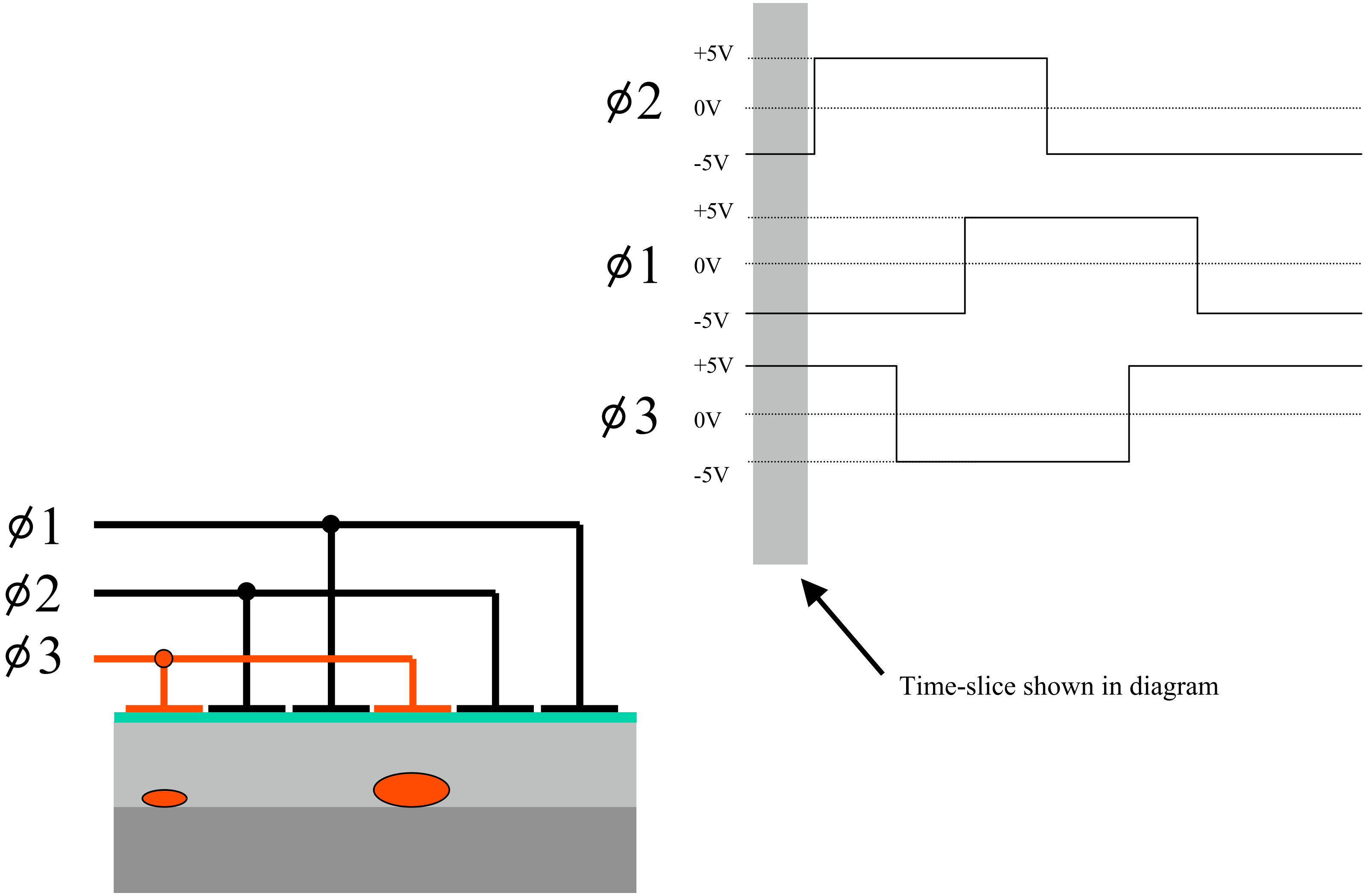
Photons entering the CCD create electron-hole pairs. The electrons are then attracted towards the most positive potential in the device where they create ‘charge packets’. Each packet corresponds to one pixel



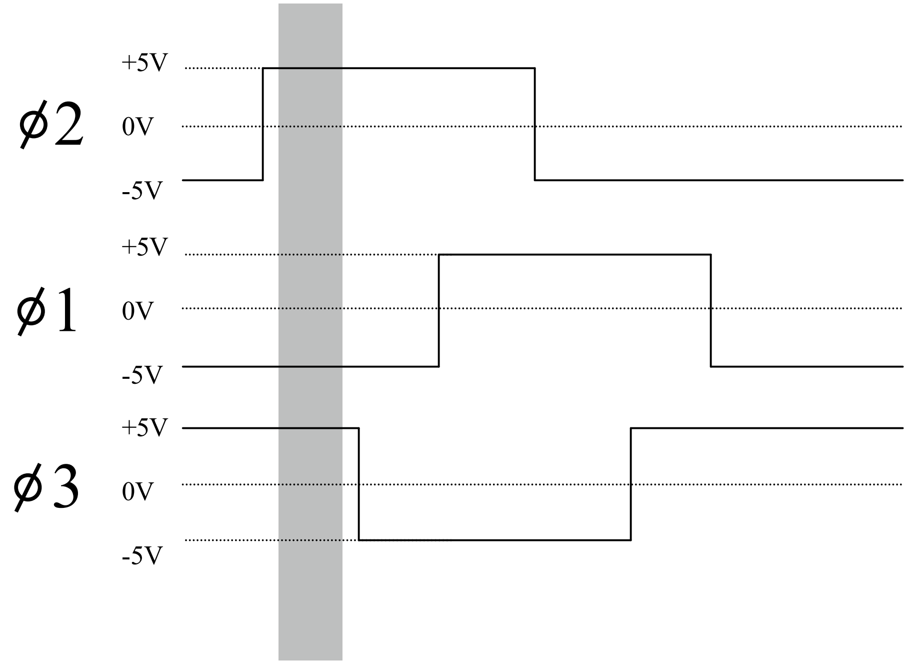
Charge Transfer

Charge is moved by modulating the voltages on the electrodes on the surface of the CCD
Electrodes color coded red are held at a positive potential, those colored black are held at a negative potential.

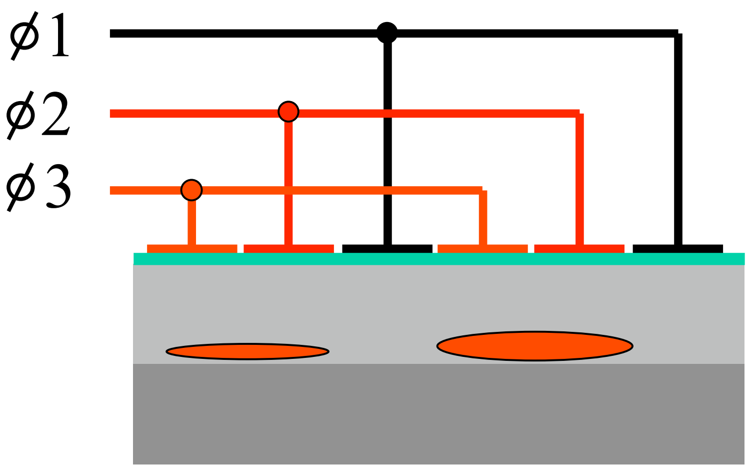




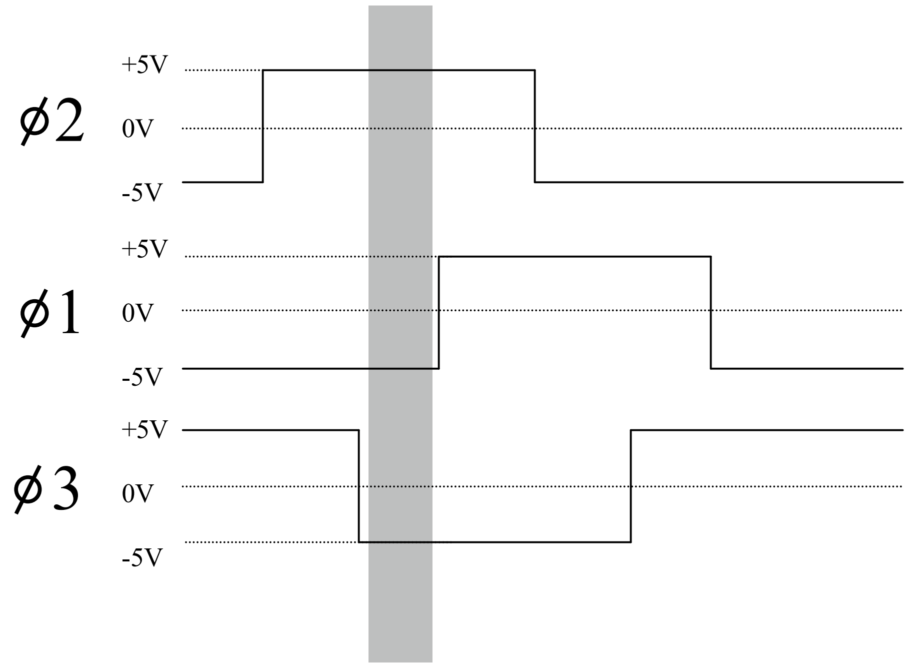
ϕ2
+5V
0V
-5V
ϕ1
+5V
0V
-5V
ϕ3
+5V
0V
-5V
Time-slice shown in diagram
ϕ1
ϕ2
ϕ3



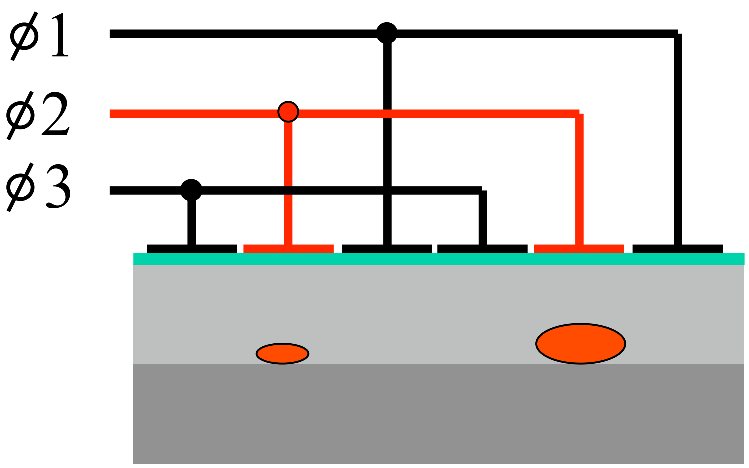
ϕ2
+5V
0V
-5V
ϕ1
+5V
0V
-5V
ϕ3
+5V
0V
-5V



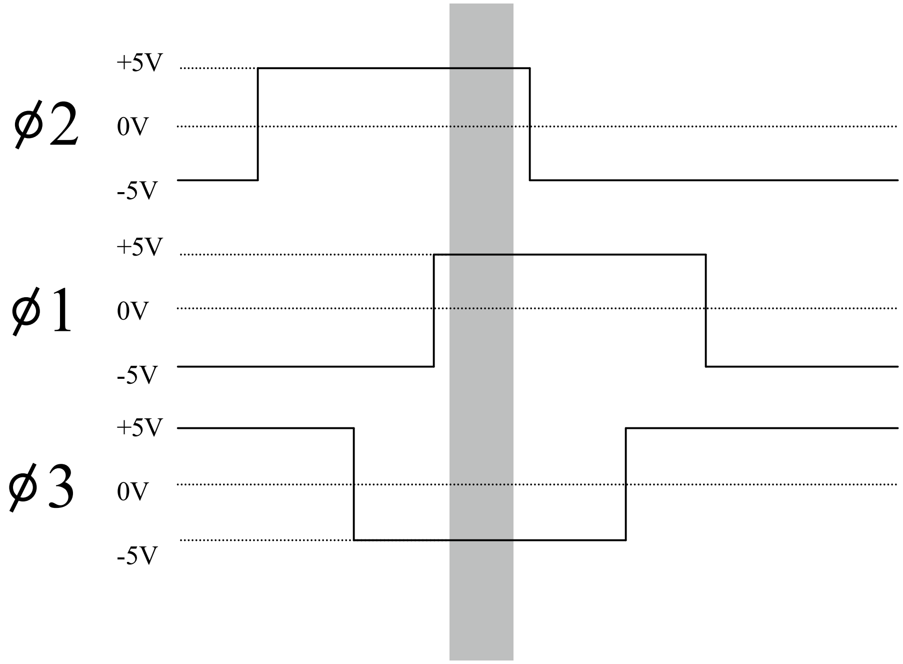
ϕ1
ϕ2
ϕ3



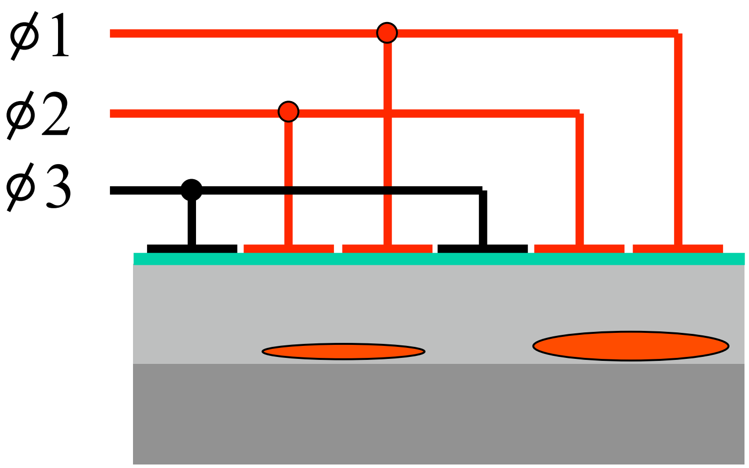
+5V
ϕ2
0V
-5V
+5V
ϕ1
0V
-5V
+5V
ϕ3
0V
-5V



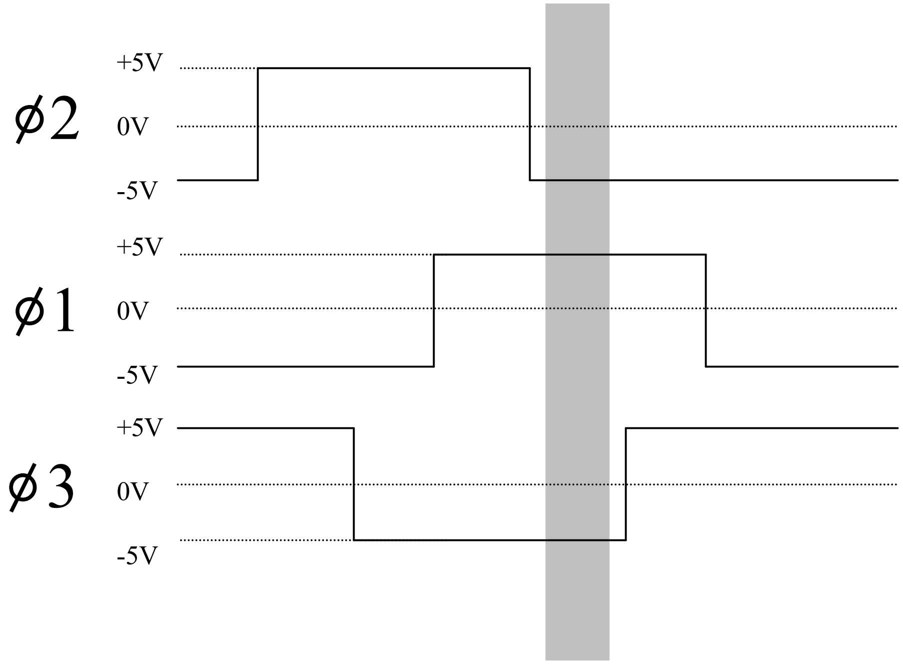
ϕ1
ϕ2
ϕ3



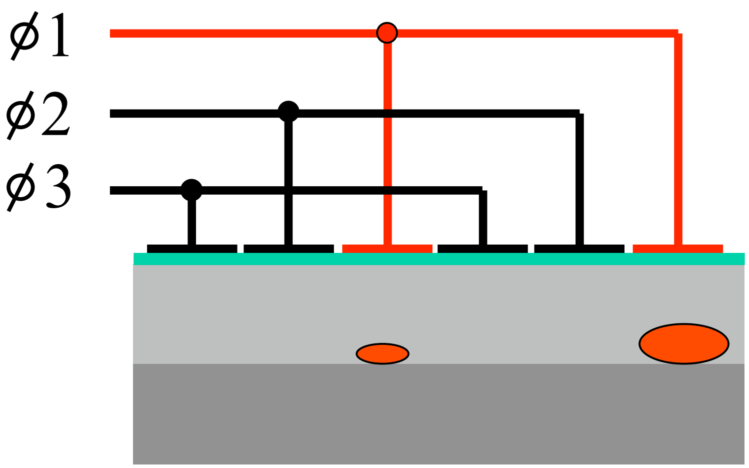
ϕ2
+5V
0V
-5V
ϕ1
+5V
0V
-5V
ϕ3
+5V
0V
-5V



ϕ1
ϕ2
ϕ3

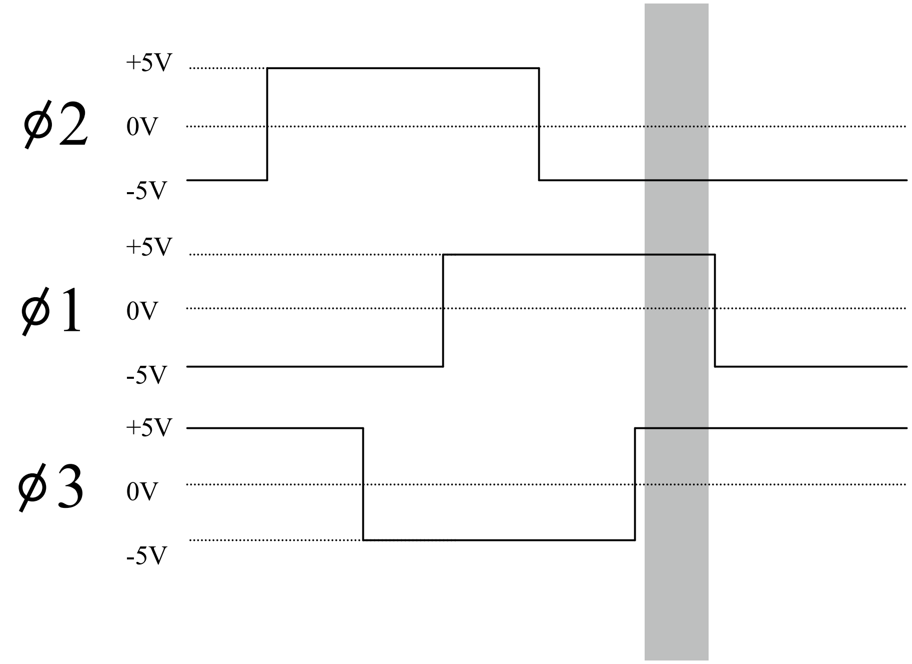


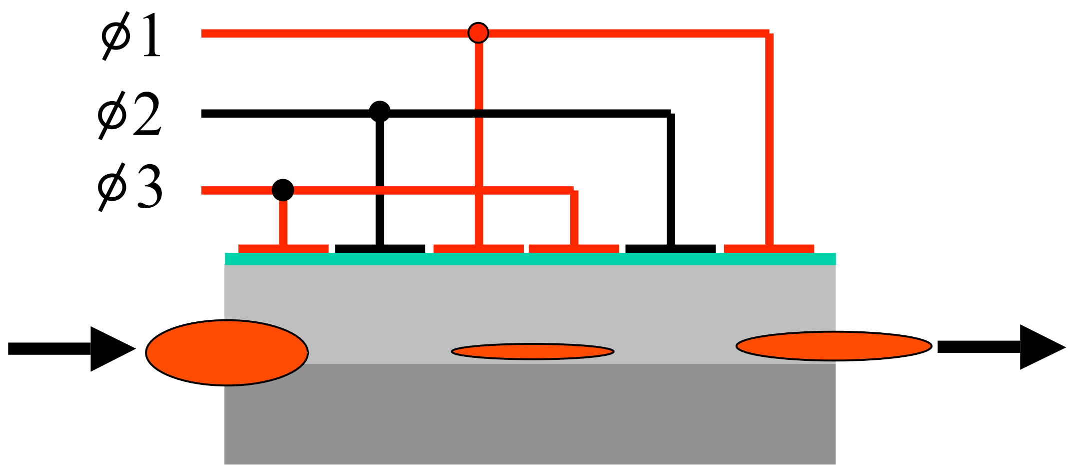
+5V
φ2
0V
-5V
+5V
φ1
0V
-5V
+5V
φ3
0V
-5V

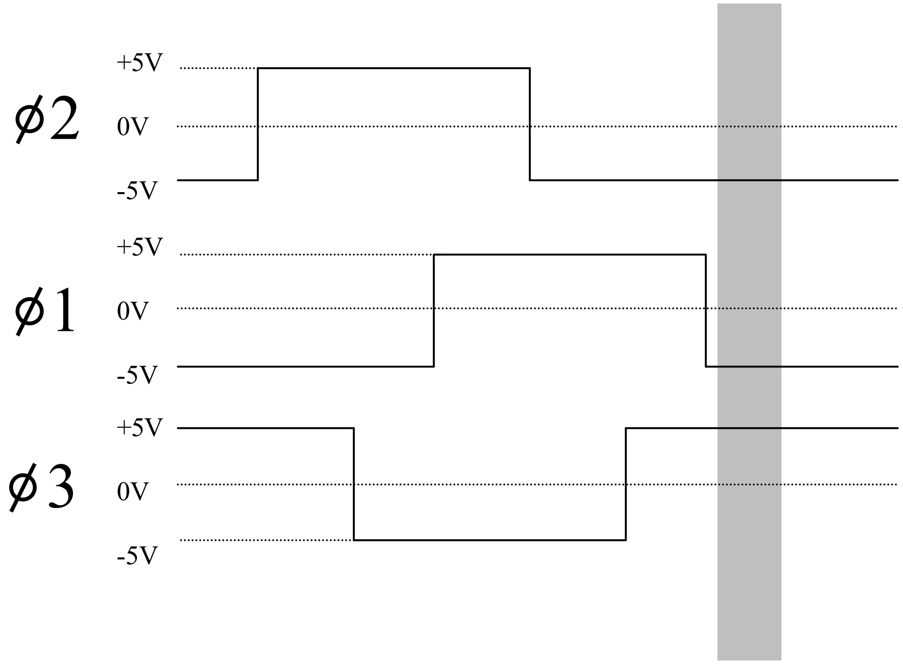


φ1
φ2
φ3

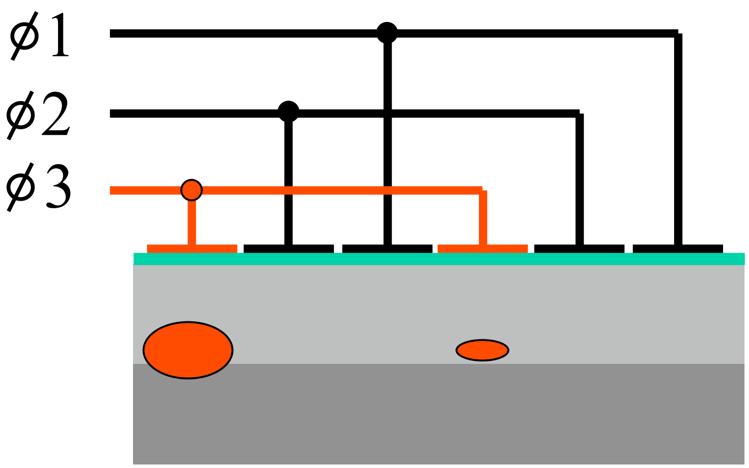
Charge packet from subsequent pixel enters from left as first pixel exits to the right.





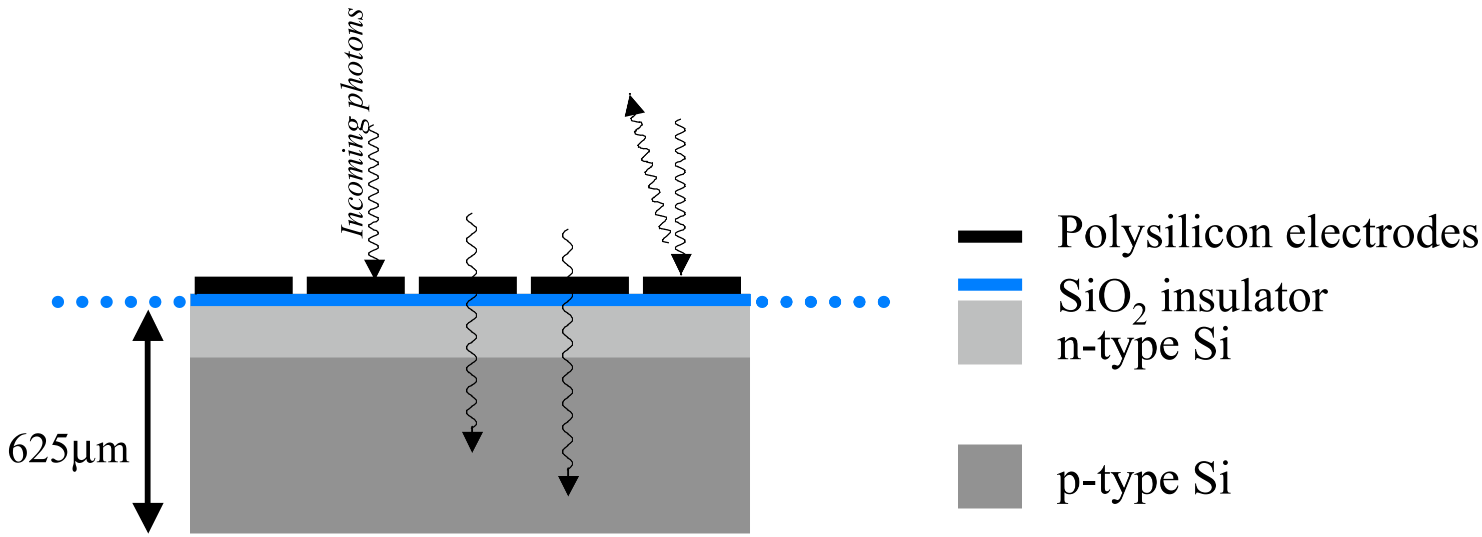


ϕ2
+5V
0V
-5V
ϕ1
+5V
0V
-5V
ϕ3
+5V
0V
-5V



ϕ1
ϕ2
ϕ3

Thick Front-side Illuminated CCD

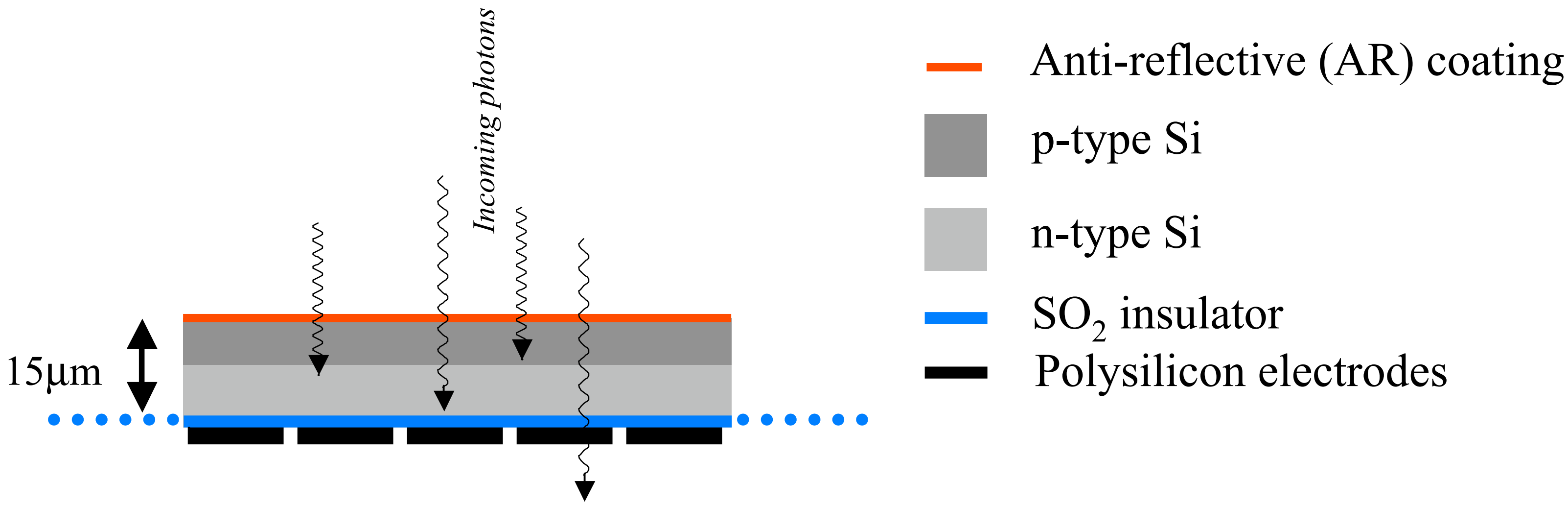


Easy to produce using conventional techniques. Used in consumer imaging applications. Even though not all the photons are detected, still more sensitive than photographic film.

Low QE due to the reflection and absorption of light in the surface electrodes. Poor blue response. The electrode structure prevents the use of an anti-reflection coating that would otherwise boost performance.

Thick front-side illuminated chips are seldom used in professional astronomy applications

Thinned Back-side Illuminated CCD



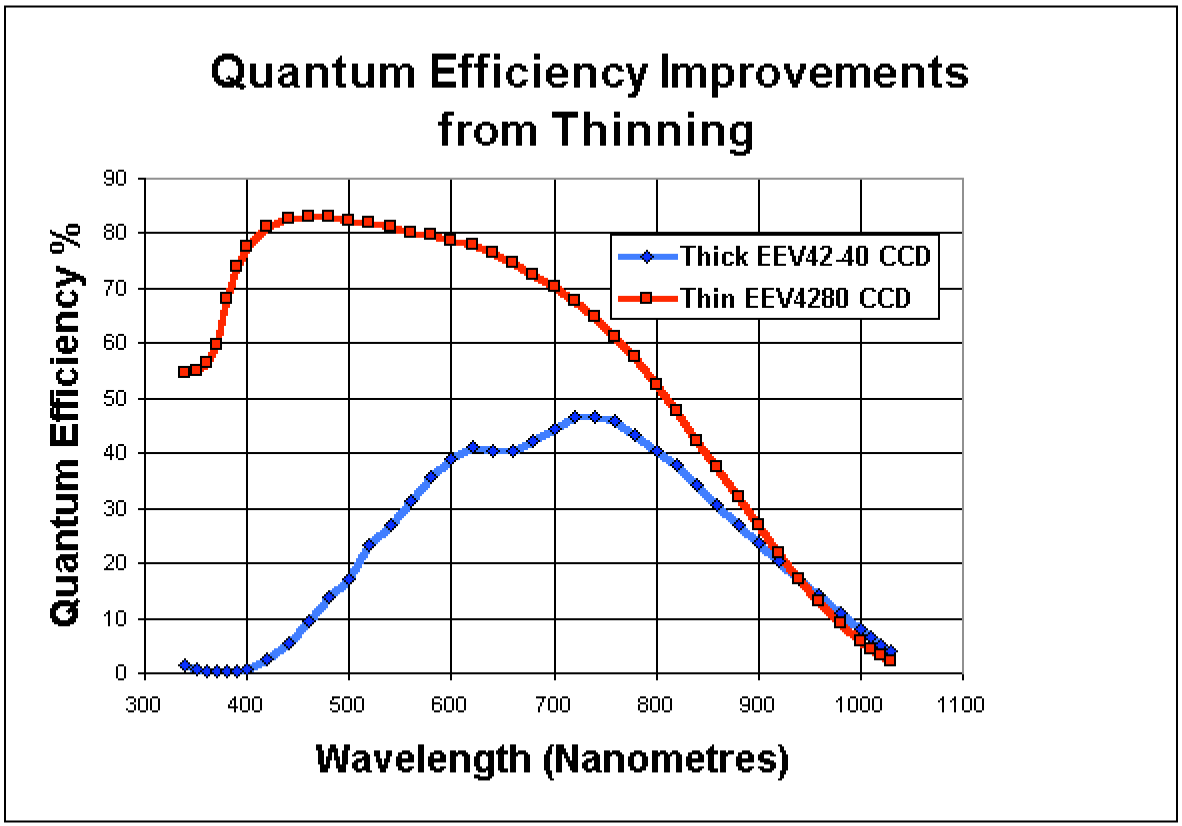
Si is chemically etched and lapped to a thickness of about 15 µm. Light enters from the rear so the electrodes do not obstruct the photons. The QE can approach 100% .

Expensive since the thinning is a custom process that reduces the chip yield. 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.

Most astronomical CCDs are thinned and backside illuminated.

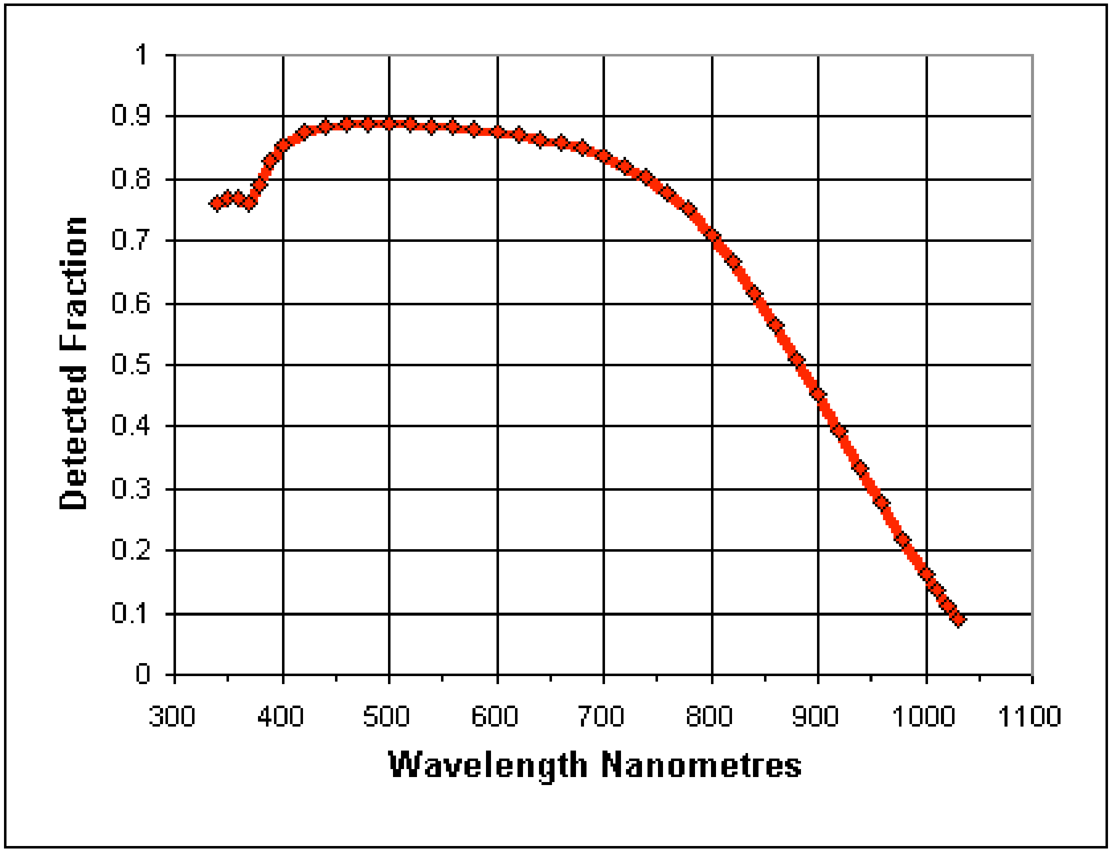
Quantum Efficiency Comparison

Comparison of the QE of a thick, frontside illuminated CCD and a thin backside illuminated CCD



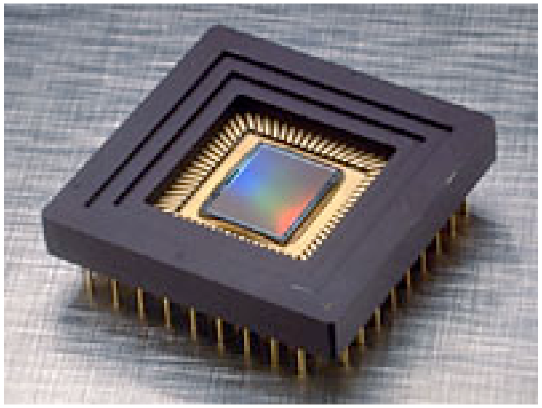
Internal QE

Taking into account surface reflectivity losses we can plot produce the ‘internal QE’: the fraction of the photons that enter the CCD that produce a detected photo-electron. For the EEV 42-80 CCD, shown here, it is > 85% across the visible spectrum. CCDs are close to being ideal visible light detectors.

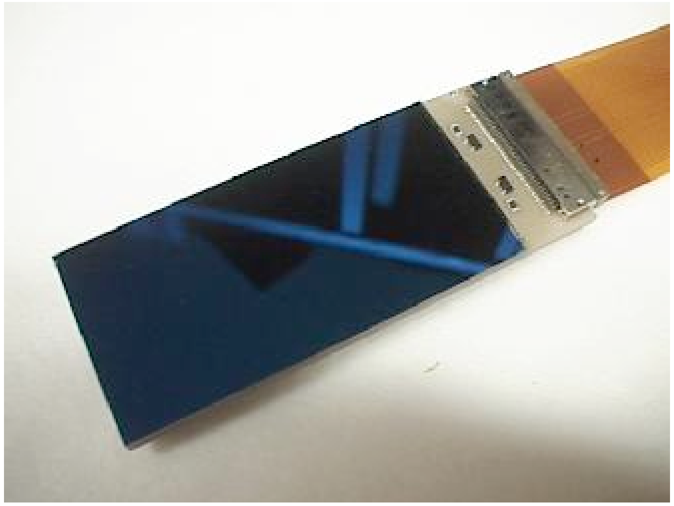


Real CCDs

The fine surface electrode structure of a thick CCD is clearly visible as a multi-colored interference pattern. Thinned, backside illuminated CCDs have a much planer surface appearance. The other notable distinction is the price!



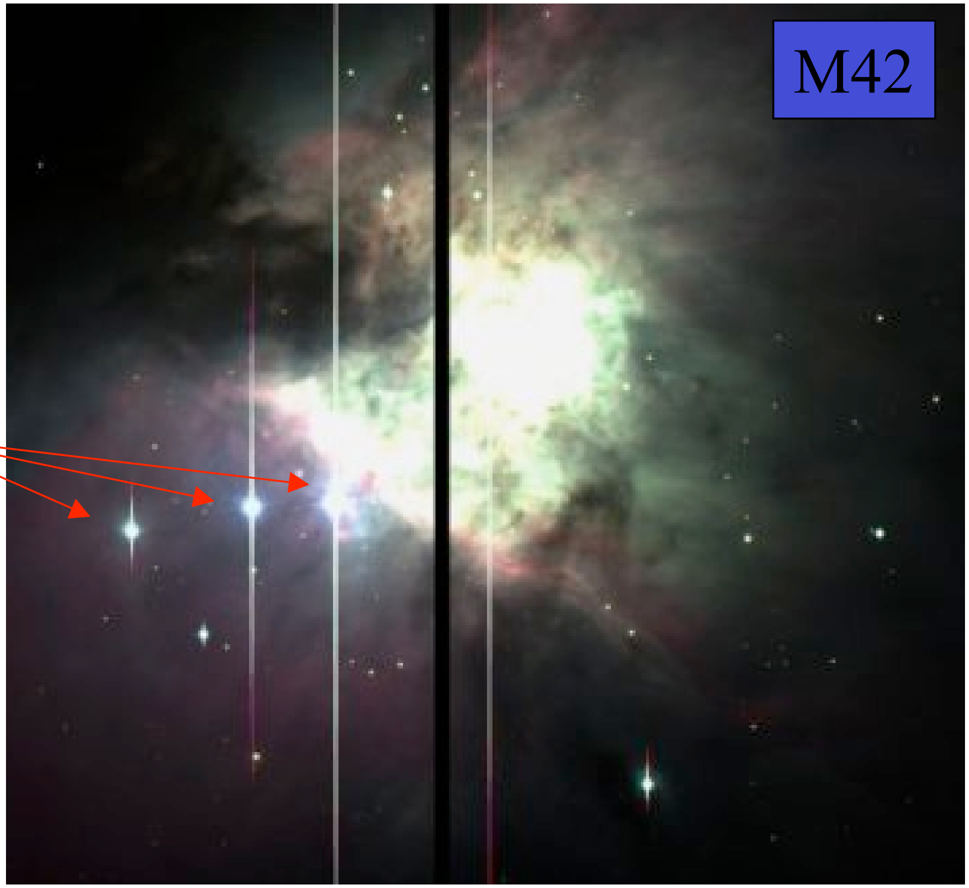
Kodak Kaf1401 Thick CCD



MIT/LL CC1D20 Thinned CCD

Bleeding & Blooming

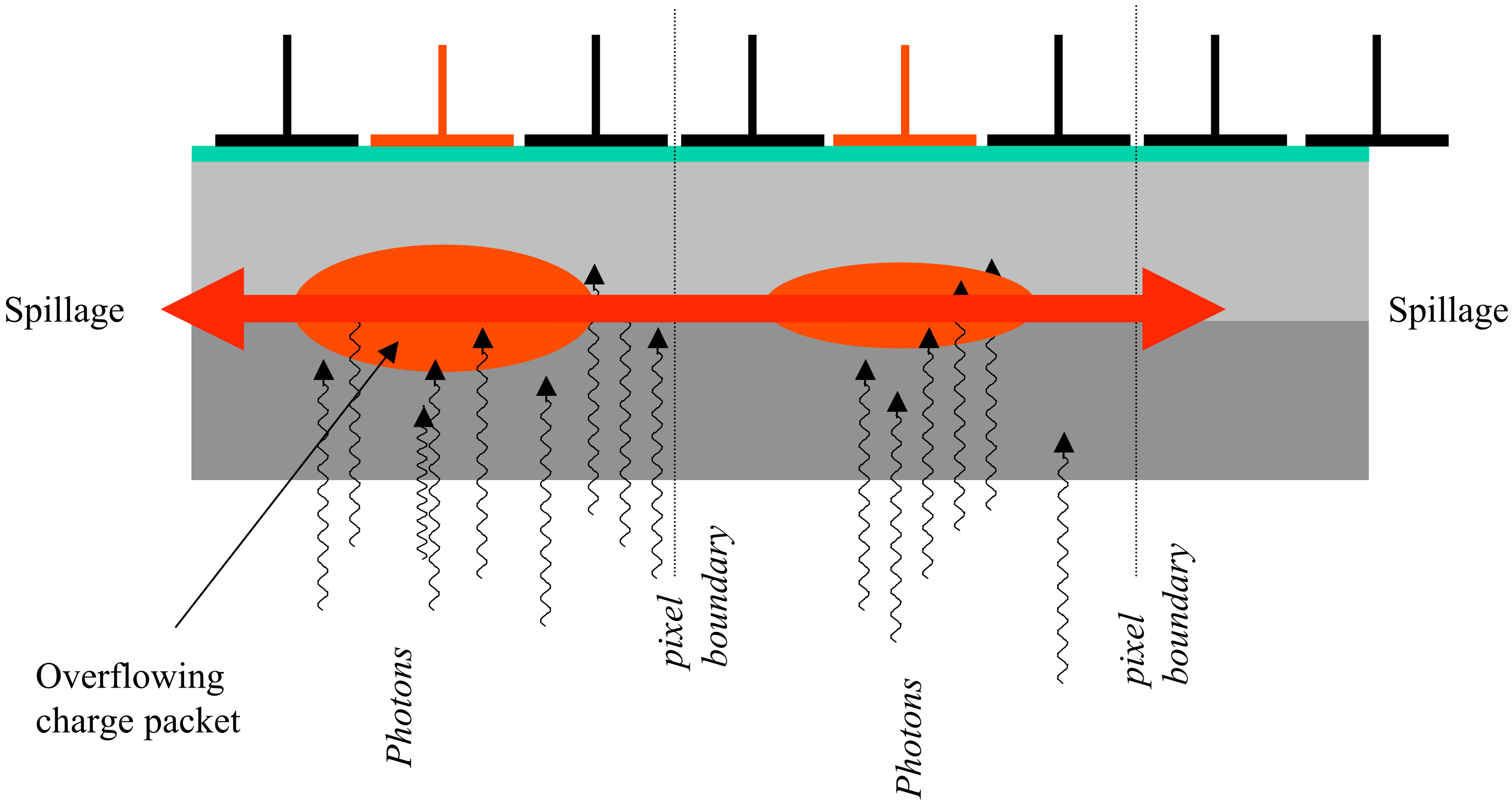
Bloomed star images



The black strip is due to a gap in the CCD mosaic

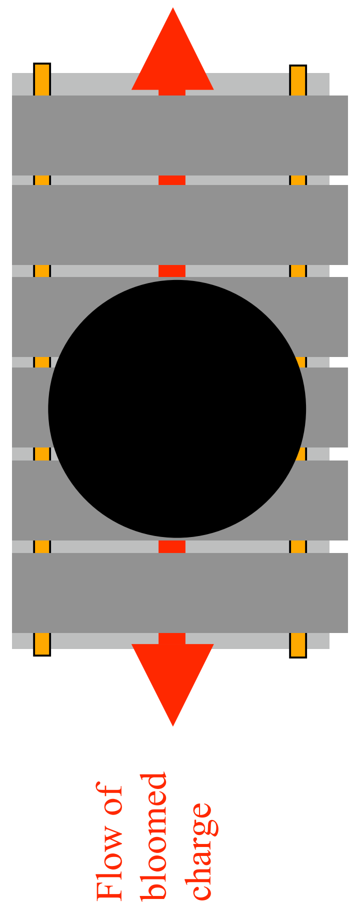
Bleeding & Blooming

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 ***bleeding or blooming***.



Bleeding & Blooming

One column of a CCD with an over-exposed stellar image focused on one pixel.



Channel stops (orange) prevent the charge spreading sideways. Charge confinement provided by the electrodes is less so the charge spreads vertically up and down a column.

The capacity of a CCD pixel is known as the ‘Full Well’. It is dependent on the physical area of the pixel. For Tektronix CCDs, with 24µm x 24µm pixels it can be as much as 300,000 e^-.

Blooming limits the dynamic range of images acquired with CCDs

Image Defects

It is impossible to obtain a CCD free of image defects. One kind of defect is a 'dark column'. Their locations are identified from ***flat field*** exposures.

Flat field exposure of an EEV42-80 CCD

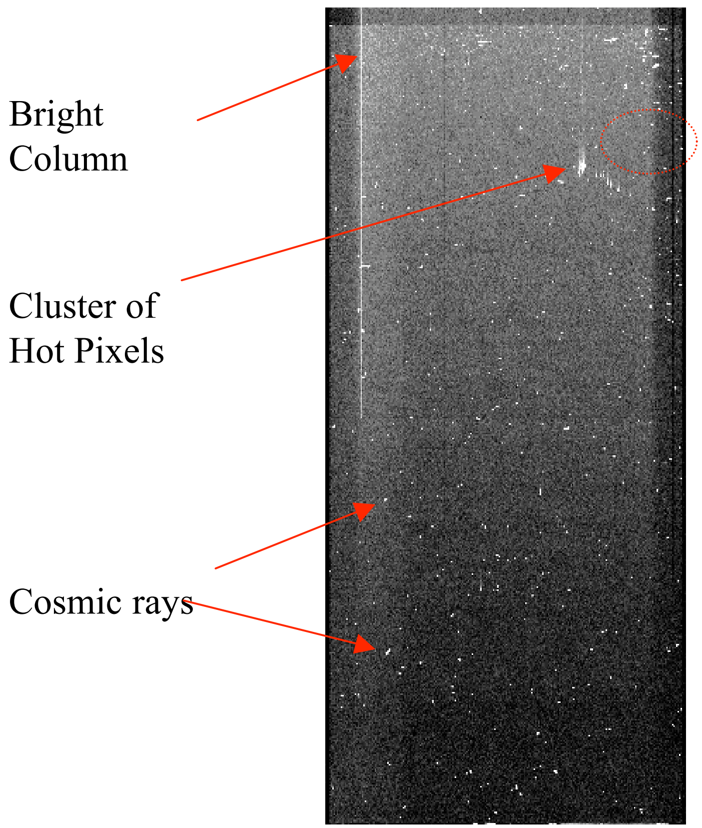
Dark columns are caused by 'traps' that block the vertical transfer of charge during image readout. The CCD shown at left has at least 7 dark columns, some grouped together in clusters.

Traps can be caused by crystal boundaries in the silicon of the CCD or by manufacturing defects.

This chip has 2048 image columns so 7 bad columns represents a tiny loss of data.

Image Defects

There are three other common image defect types: ***Cosmic rays***, ***bright columns*** and ***hot pixels***.Their locations are shown in the image below which is a lengthy exposure taken in the dark (a ***dark frame***)



900s dark exposure of an EEV42-80 CCD

Bright columns are caused by charge traps. Electrons contained in such traps can leak out during readout causing a vertical streak.

Hot Pixels are pixels with higher than normal dark current. Their brightness increases linearly with exposure times.

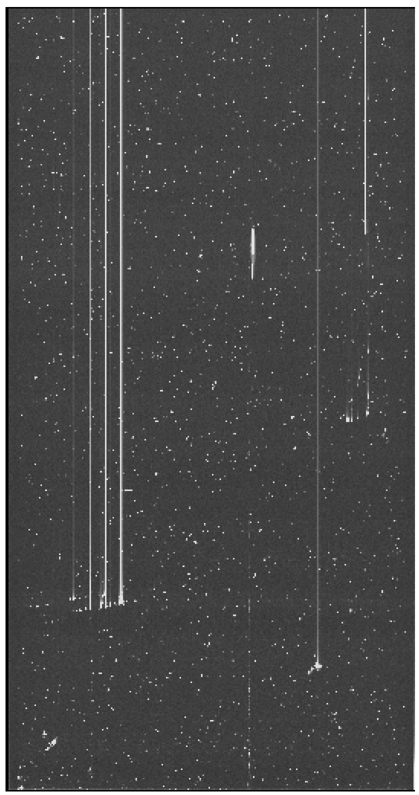
Cosmic rays are caused by ionizing radiation from space or from radioactive traces in the material of the camera. The electrons produced are indistinguishable from photo-electrons. About 0.03 s^{-1} cm^{-2} cosmic ray events will be seen. A typical event will be spread over a few adjacent pixels and contain several thousand electrons.

Somewhat rarer are light-emitting defects which are hot spots that act as LEDS and cause a halo of light on the chip.

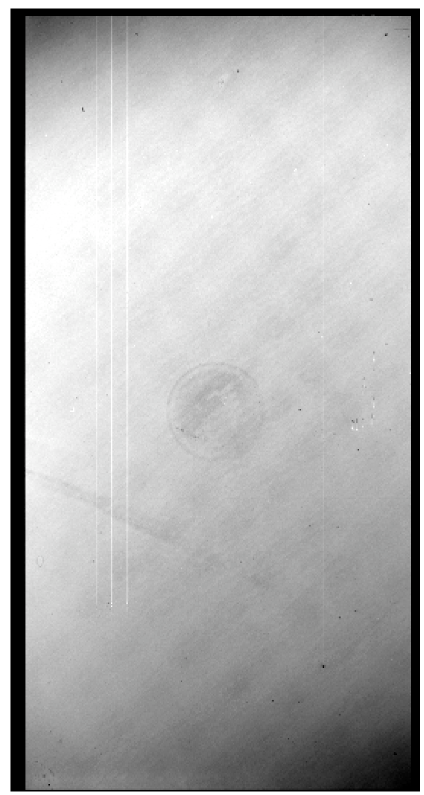
CCD Calibration

A dark frame and a flat field from an EEV42-80 CCD are shown below. The dark frame shows a number of bright defects on the chip. The flat field shows a pattern on the chip created during manufacture and a slight loss of sensitivity in two corners of the image. Some dust spots are also visible.

Dark Frame



Flat Field



Calibrating CCD Data

If there is significant dark current present, the various calibration and science frames are combined by the following series of subtractions and divisions :