

CCD description and characteristics

Description

CCD: *charge-coupled devices*

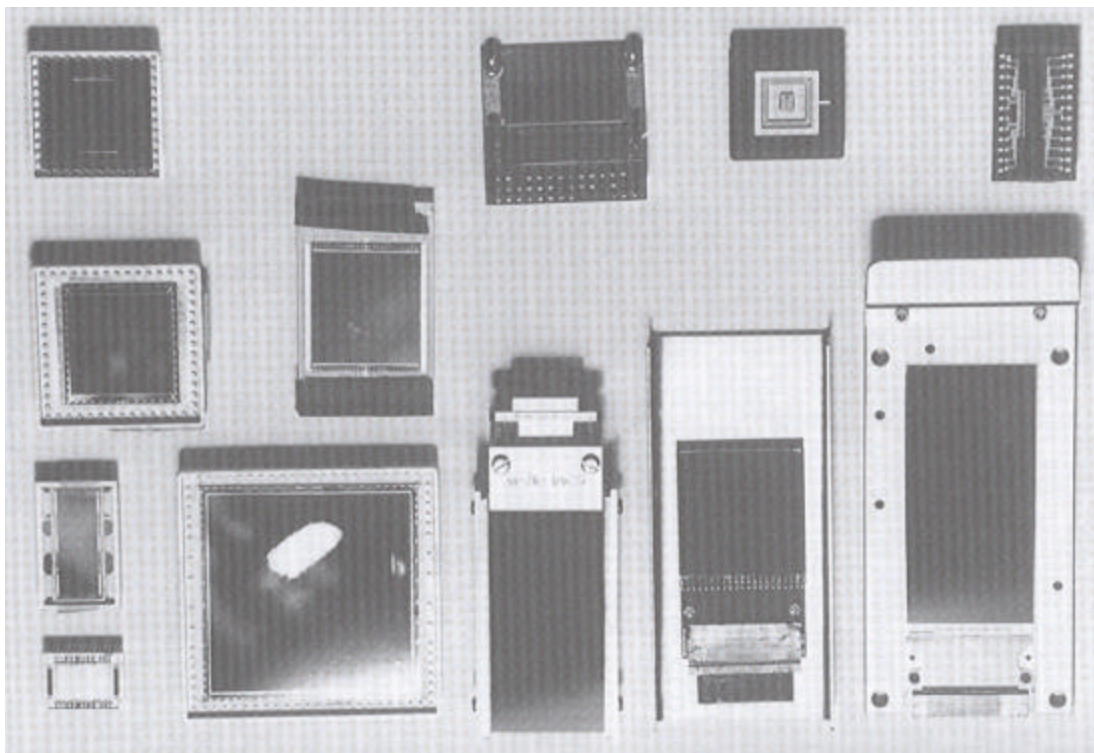
Made of semiconductor material (silicon) \Rightarrow Sensible to optical light: from 3000-10000 Å

IR arrays semiconductor devices: different from CCD, but with similar properties (observation and reduction techniques are almost the same)

CCD naming convention: Company name + size in pixel

Example 1:

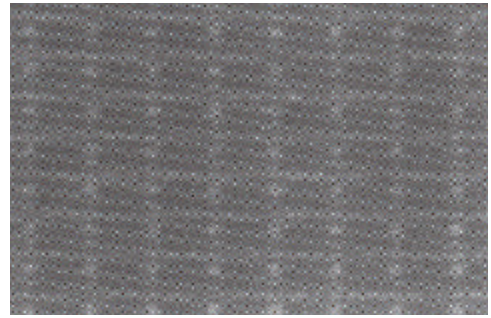
- RCA 512: made by RCA with 512 x 512 pixels
- EEV 4kx2k
- SITe 2048



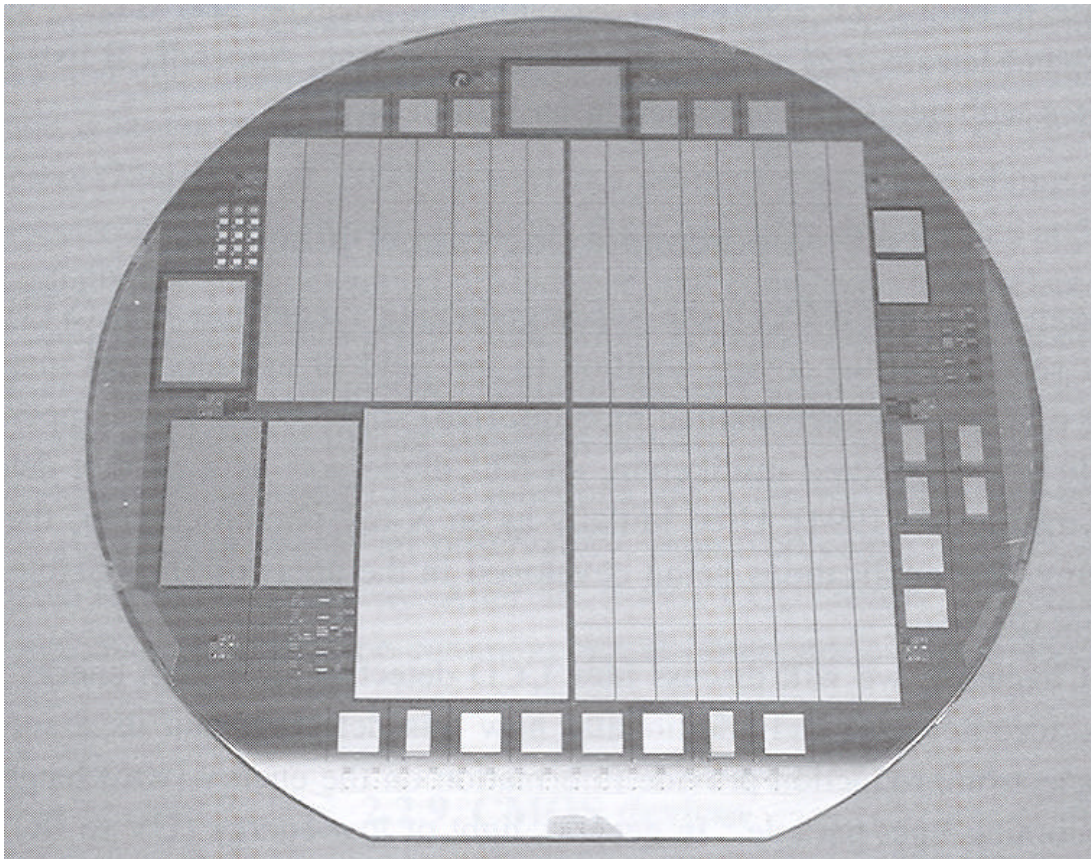
Pixel: active part of CCD (a few microns in size);
mounted as an array

Each pixel is capable of:

- collecting photons
- production of photoelectron
- storage readout



SONY ICX027 BL: 8.3×12 mm



150 ohm-cm Si Wafer

Advantages of CCD

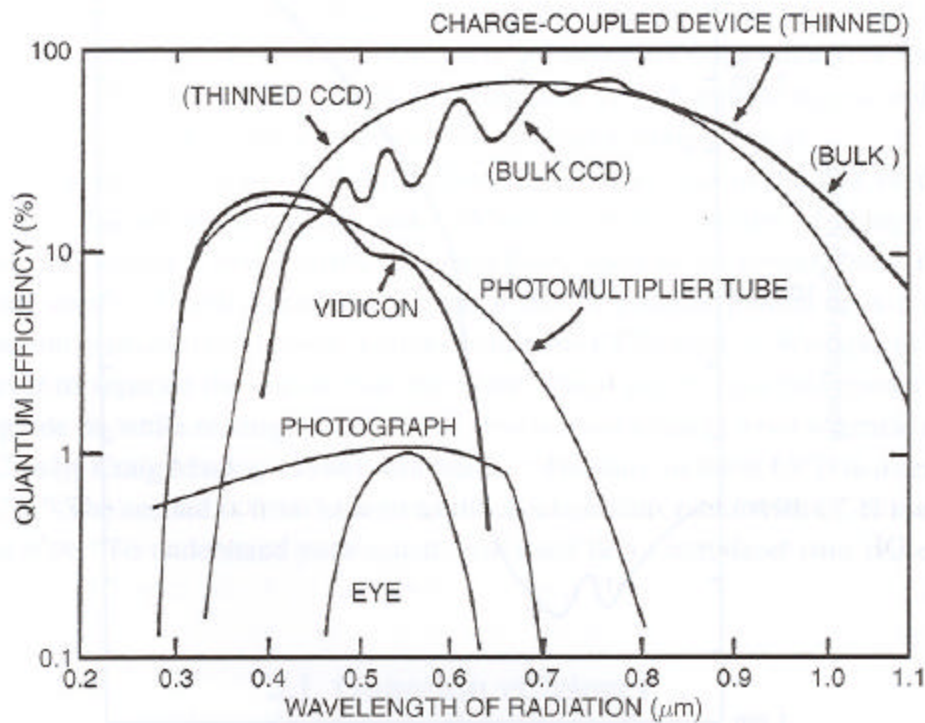
Noise properties: almost noise free -- 15 to just a few $e^- / pixel$, compared to 800-200 e^- for photo-sensible electronic devices

A high noise level limits the signal to noise ratio (S/N) for given measurement and limit the total dynamical range

Quantum efficiency (QE) and bandpass

QE: the ability of a detector to turn incoming photons into useful output

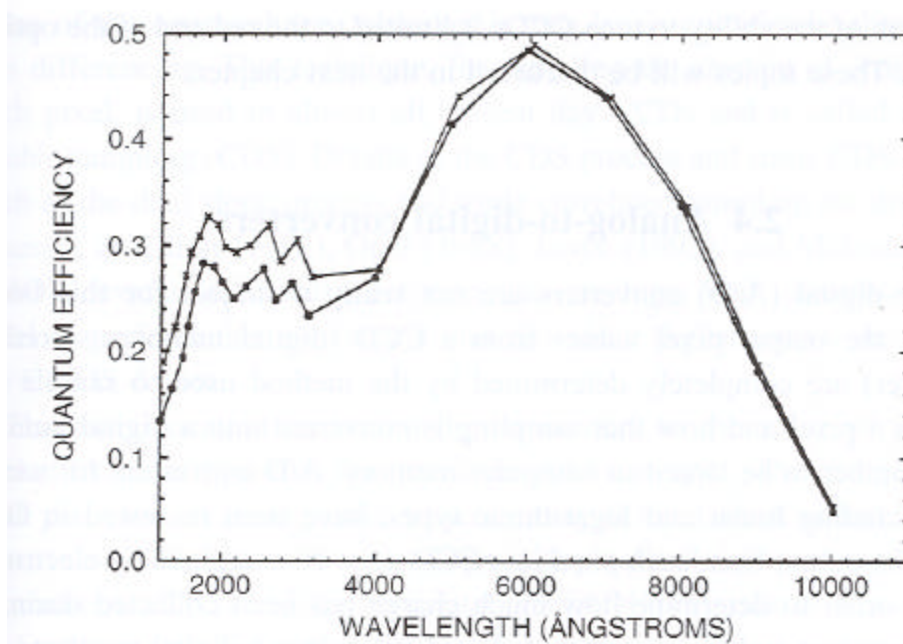
$$QE = \frac{\text{detected (stored) photons}}{\text{incoming photons}}$$



Bandpass: total spectral range for which a detector is sensitive to incoming photons

Detector type	QE	Special property
Photographic plates	2% (3% Kodak IIIaJ)	Sensitive to UV + blue light \Rightarrow need special coating to be sensible in visible.
Hypersensitized plates	10%	(chemically processed and cooled)
Electronic devices	20-40% bandpass similar to CCD	not precise in flux and position need high voltage to work
CCD	90%	reach $\sim 60\%$ over 2/3 of bandpass

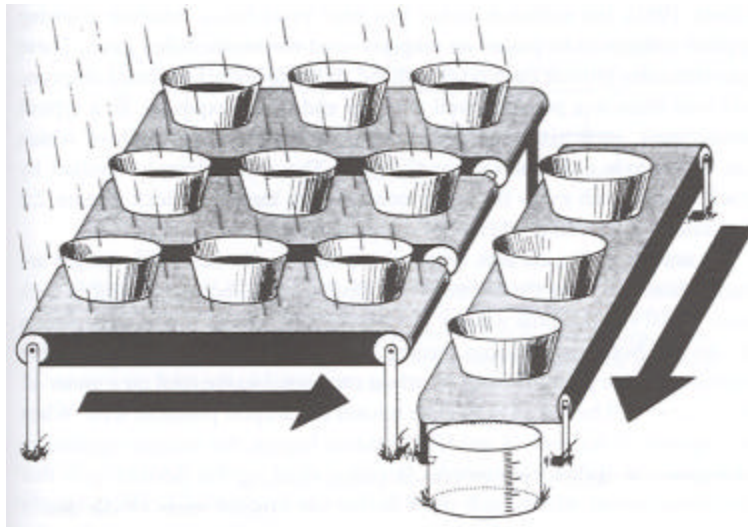
Coatings and phosphor deposit can increase efficiency in special spectral range (blue and UV)



Other advantages

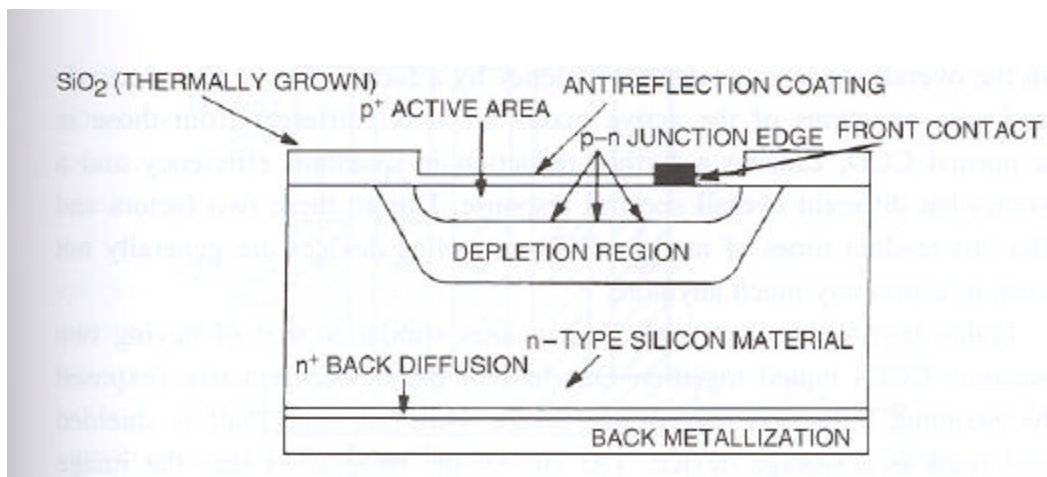
- Linearity (important for astronomy)
- Small weight
- Low power consumption

Principles of functioning of CCD



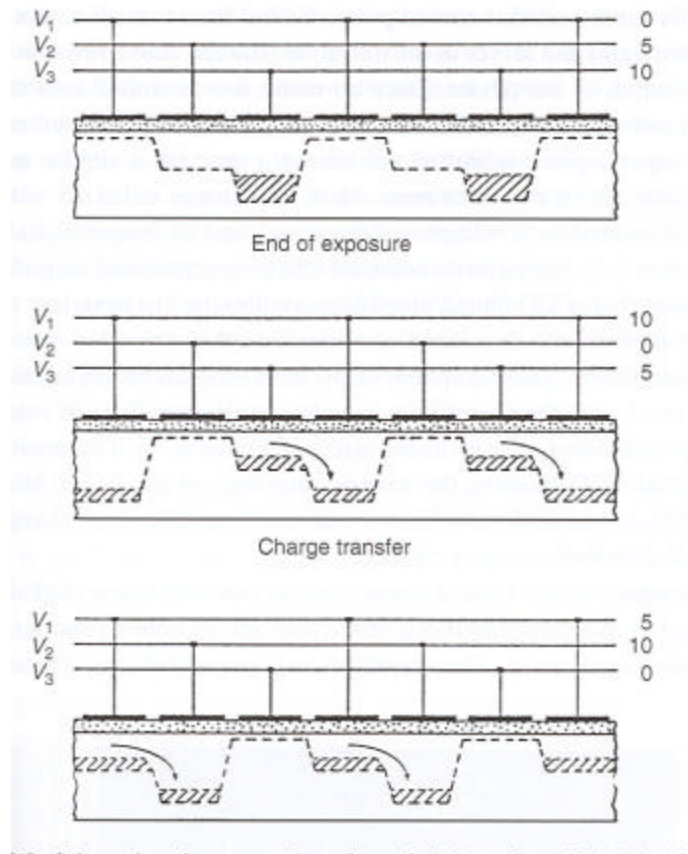
The method of storage and information retrieval depend on the containment and manipulation of pairs of e^- and holes (e-h) produced within the device exposed to light

The produced electrons are stored in the depletion region of the **metal insulator semiconductor (MIS)** capacitor



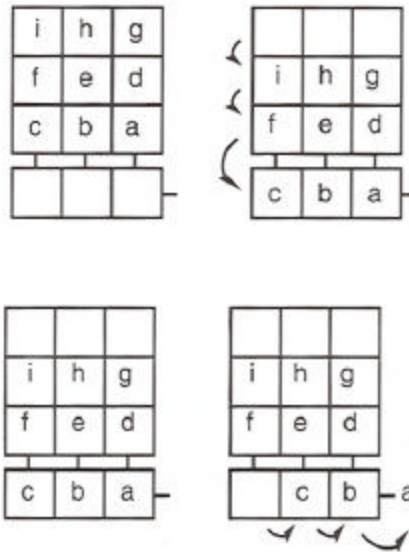
CCD arrays consist of many of these capacitors placed in close proximity and connected together

The voltages are changed during readout in order to retrieve the charge from the capacitor



Ex. 3 phase CCD

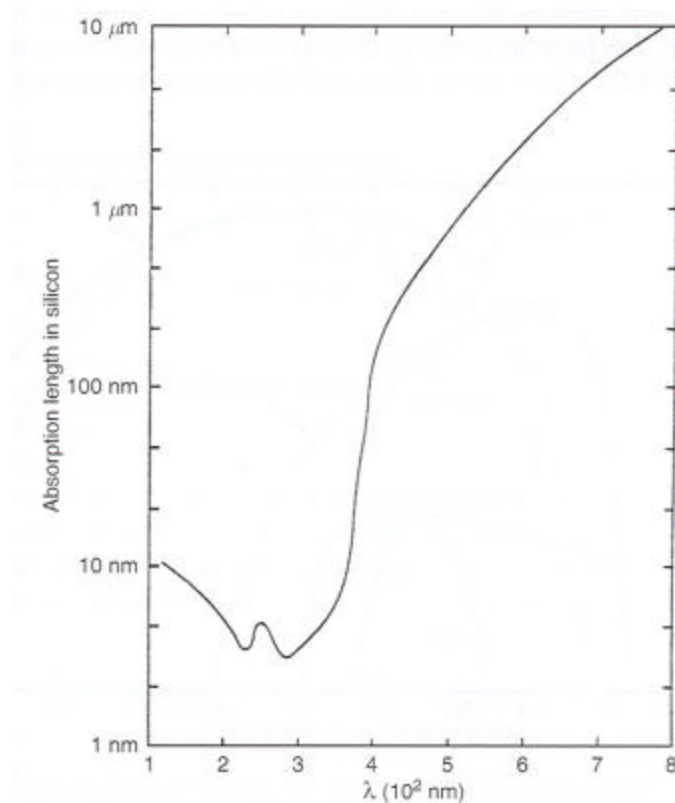
Every charge packet on each pixel passes through the readout electronics that detect and measure the charge in a serial fashion



Input analog signal is transformed into a digital number

The process in details

1. **Photoelectric effect:** incoming photons striking the silicon within the pixel are absorbed if they possess the correct wavelength (energy) – absorption length = 63% of incoming photons are absorbed – QE mirror photon absorption curve of CCD



The band gap of silicon is 1.14 eV, which allows the absorption of photons with energy from 1.1 eV (11000 Å) to 4 eV (3000 Å). Relation between energy in eV and wavelength is:

$$E(\text{eV}) = \frac{12407}{\lambda(\text{\AA})}$$

2. The absorption of the photon causes the silicon to give up a valence electron, which moves into the conductive band

Photons with 1.1 to 4 eV produce a single electron + hole (e-h) pair (photons with higher energy produce multiple pairs → non-linearity)

Silicon shows useful photoelectric effect from 1.1 (Near Infrared) to 10 keV (Soft X-Rays)

Above and below these limits the CCD appears transparent to incoming photons

3. **The gates:** To collect and held the free electron, each pixel has a conductive structures (the gates) allowing voltages to be placed on sub-pixel

Typically CCDs have a 3 gates structure, where the voltage is controlled by clocks circuits connected at each 3 gates

0. By changing the potential sequentially, charges are transferred along columns

The **charge transfer efficiency** (*CTE*) is near 0.99999 (99.999%)

- Each column is connected in parallel so that one clock cycle moves each row of pixels up one column
 - Top row shift off the array into an **output register**, which is another row of pixels unexposed to light
 - This last row of pixel is shifted into the output electronics (the same way as above) where charges are measured as voltage and converted into an output digital number
0. Each pixel charge is sensed and amplified by an output amplifier. These have low noise and are build directly into the circuit (they work with small voltages $0.5\text{-}0.4 \mu\text{V}/e^-$)

The output voltage is converted in a **digital number** (*DN*), counts or *ADU* (**analog-to-digital unit**)

The **Gain** (*G*): is the amount of voltage (number of received photons) to produce 1 ADU

A typical value for *G* is $10e^- / ADU$; it means that every $10e^-$ yield 1 count

Example 2:

$1000e^-$ produce 100 *ADU*, while $17234e^-$ will produce 1723 *ADU* (4 electrons are lost due to A/D conversion in integer)

DN can only be integer numbers → Discrimination between different pixel values can only be as good as resolution of gain and digital conversion

Conversion device: **analog-to-digital converter** (*A/D* or *ADC*)

Readout process may take a few minutes. For a 2048 x 2048 CCD, the charge collected in the last pixel has to be transferred over 4 million times

Array size and pixel sizes are controlled by current limitations. Array as large as possible and pixel as small as possible are ideal

Different types of CCD

0. Buried channel CCD

Charge transfer occurs on the surface of the CCD at a cycle rate of a few kHz. At the boundaries of the gates, imperfections within the silicon form traps for the free electrons, decreasing the CTE. For faint light level applications these trapping states are undesirable

One technique to solve this problem is the **pre-flash**: prior to exposure, the charge level surface of the CCD is raised above the levels of the traps

Another solution is to move the charge via a channel that is far away from the surface (**buried channel**). An additional semiconductor surface is placed under the CCD surface

Advantage: buried channel allows greater transfer rates (100 MHz)

Ideal for low level of light, since the dynamical range and the sensitivity are improved

Disadvantage: storage capacity is reduced by factor 3 or 4

0. Back side illuminated CCD

The gate structure is deposited on the front side. Exposing the front of the CCD, some incoming photons are blocked, decreasing the QE

Front illuminated CCDs are relatively thick $\sim 300\text{ }\mu\text{m}$, which render them sensitive to **cosmic rays**

One solution is to thin the CCD to $15\text{ }\mu\text{m}$ after production, mount it upside down on a substrate and illuminate it from behind. Incoming photons are now able to be absorbed directly into the bulk of the silicon

Advantage: QE is increased and the detector is more sensitive to short wavelength

Disadvantage: The well depth of each pixel is lower; non-uniform thinning produces **flatfield** structures; the CCD is more expensive because more complicated to produce

3. Interline and frame transfer CCD

In an interline CCD, each pixel is parallel with a non-exposed one. After integration the charge is dropped in the unexposed pixel and readout takes place while integrating again

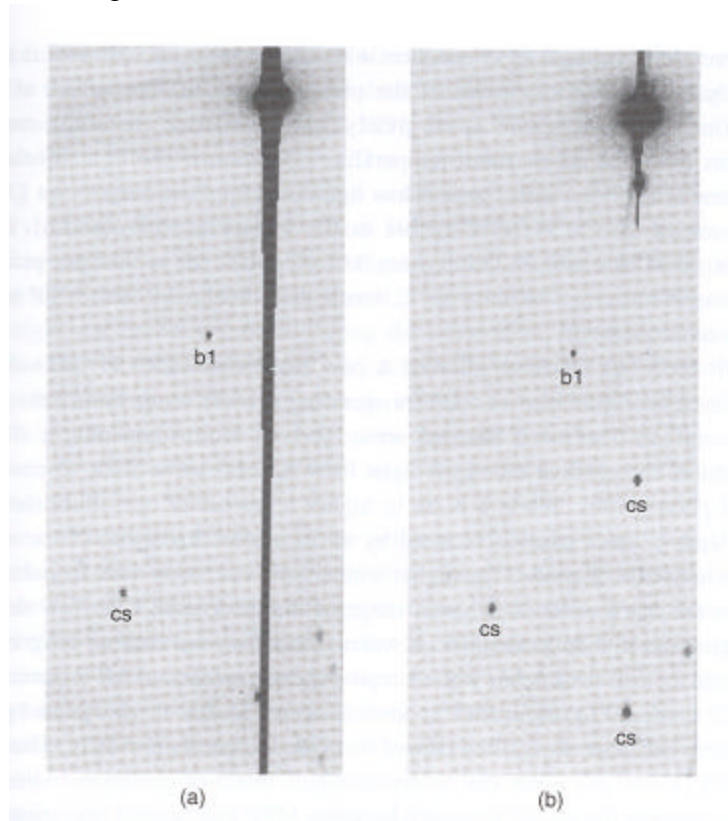
In a frame transfer device, there is two array connected together. This is the system used by commercial video and television

Advantage: fast readout (30 frames/s), since the sampling and conversion happens only at the end of the readout process

Disadvantage: reduce QE → does not work well for faint light source

0. Anti-blooming CCD

When one observes bright objects, electrons may spill over adjacent pixels (the **full well capacity**, *FWC* of the pixel is exceeded). This phenomenon is called bleeding: one or more bright pixels leave a trace leading away from the origin



One simple solution is to integrate for a shorter amount of time. From the point of view of noise, multiple shorter exposures combined together are not always equivalent to one long exposure

Another solution is to form an **anti-blooming gate**. This gate allows saturated pixels to be drained off

Disadvantage: One needs about 30% of the pixel area to form the gate ⇒ reduces the QE and spatial resolution. Integration time must also increase by a factor ~ 2

0. Multipinned phase CCD

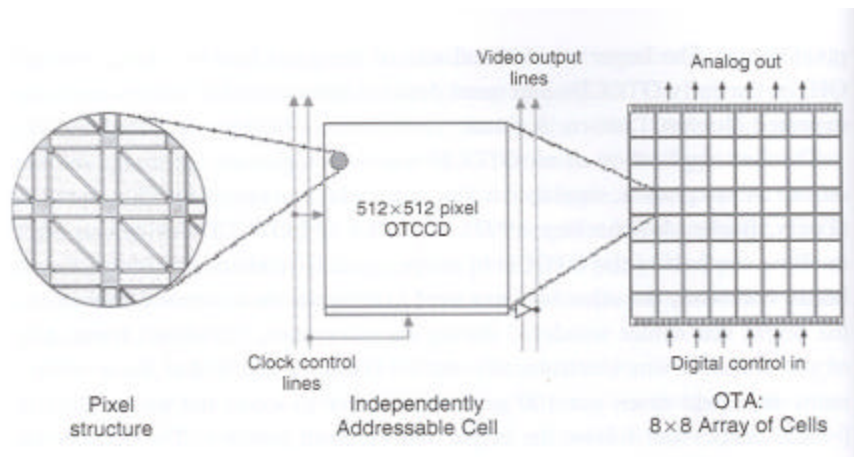
These CCDs achieve very low dark current. They can be used at room temperature (compared to a temperature of $\sim -100^{\circ}\text{C}$ for normal CCD)

Disadvantage: The potential well depths are reduced by 2-3 times

Advantage: ideal for large FOV (small aperture telescope) but not for faint objects

0. Orthogonal transfer CCD (OTCCD)

In 3 phases CCD, readout operation involves moving each charge on vertical direction, from row to row, until it reaches the output register. In new OTCCD, the charge can move vertically and horizontally \Rightarrow four phase mode of operation



First application is to compensate for image motion during integration (low-order tip-tilt correction): 1/2 of OTCCD used to image, quickly readout, and centre a bright star, while other half integrate on target object. As the bright star center wanders during integration, object frame electronically shifted ($\sim 0.5''$) many thousands of times per seconds to follow its position. Final result = image with much improved seeing

Characterization of CCD

QE – is determined by capacity of silicon to absorb photon of given wavelength

Length of absorption: distance for which 63% (1/e) of the incoming photons will be absorbed

Lower than 3500 Å or higher than 8000 Å the photons are either:

- Passing through
- Absorbed at the surface
- Reflected

Shortward of 2500 Å, the QE increases again, but photons create multiple e-h pairs (non-linearity) and the CCD could be damaged

Front side illuminated CCD (thick + gate structures in front) are more sensible to the red, because of the higher chance for the photons to be absorbed at this wavelength. They have low QE in blue, because the gate structures thickness is comparable to the length of absorption

Silicon like other metals is a good reflector of visible light. **Antireflection coating** (AR) increases QE and extends sensitivity in the blue

Curves of QE include:

- Photon loss due to gate structure
- Electron recombination
- Surface reflection
- Lack of absorption

Measuring the QE is a complicated process that can be made only in a LAB

Rough determination at the telescope is possible. One needs:

- A set of narrow band filters (from which we know the throughput)
- A set of spectroscopic standard stars
- We also need to know the throughput of the telescope

RN (Readout noise) given in e^- / pixel

RN = average level (one sigma) of uncertainty

This noise includes:

- Noise due to conversion A/D
- Noise due to electronics – electrons produced spuriously by electronic structure

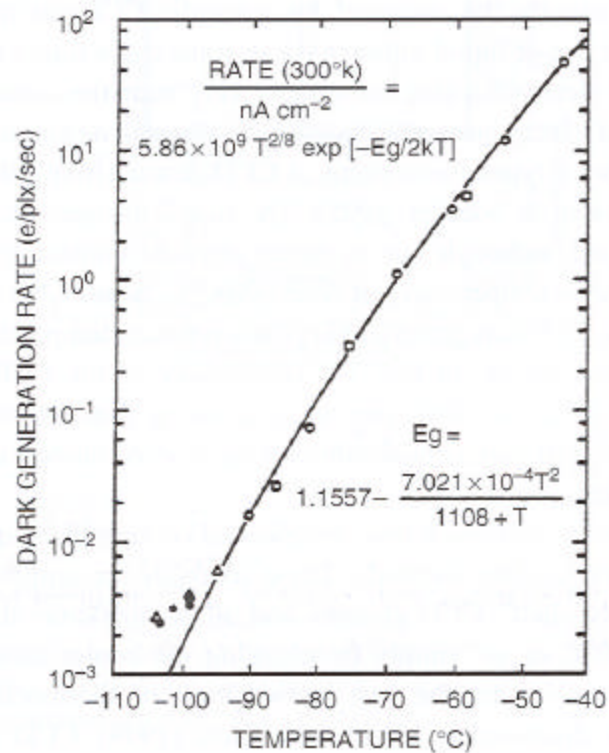
Source of RN:

- Size of the amplifier
- Integrated circuit construction
- Temperature of amplifier
- Readout speed (slower readout means lower noise)
- Temperature of CCD

RN is added to each pixel during the readout. CCDs with high RN are not useful if one has to co-add many images instead of taking one long exposure image

DC (dark current)

The DC is a thermal noise – composed of electrons liberated by thermal energy. It depends on temperature of CCD (T).



At room temperature the DC could be as high as $2.5 \times 10^4 e^- / \text{pixel} / s$. Cooled to -100°C , the DC fall to $2e^- / \text{pixel} / s$.

Example 3:

For a typical exposure time of 15 minutes, a $DC = 1800 e^-$ is added to each pixel.

Noise of DC is Poissonian: $Noise_{DC} = \sqrt{DC}$.

\Rightarrow CCD must be cooled down (using liquid nitrogen $\sim T = -100^\circ \text{C}$).

CCD pixel size

The larger pixels are and the more charge they can collect.

Example 4:

- Kodak CCD $9\mu\text{m}/\text{pixel} \rightarrow$ Full Well Capacity (FWC) $85\,000 e^-$
- SITe CCD $24\mu\text{m}/\text{pixel} \rightarrow$ FWC $350\,000 e^-$

Binning pixels – brought all the charges of multiple pixels together (super pixel).

By binning 2×2 the pixels, for example, the signal is increased by a factor 4, while the RN is decreased by the same factor.

Creating higher pixel, however, reduces the spatial resolution.

Binning can be useful in the following cases:

- Quick readout is needed (but it is better to use windowing: exposed only a predefined portion of the CCD)
- Poor seeing condition (lower than 1 arcsec)
- Study of low surface brightness objects

BIAS – this is the zero noise level, including RN + A/D conversion

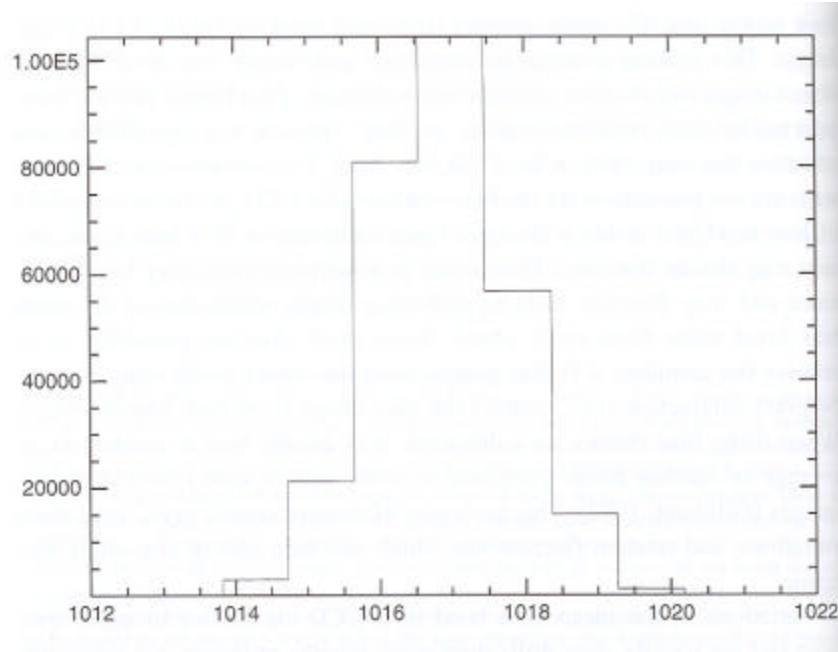
The BIAS is a pedestal noise, which is added to the CCD in order to avoid negative values (negative values need an extra bit to be represented)

Two techniques are used to determine the bias:

- **Overscan** – is obtained by adding a few numbers (~ 32) of columns or rows (or both), which are not exposed to light, to each images. It suffices then to estimate the mean value of the overscan and subtract it (once) from all the images
- **Bias frames** – is obtained by integrating during 0.000s with the shutter closed. It allows to subtract a 2-D bias structures (not uncommon in CCDs). An average or median of many bias frames (10 at least) are subtracted for each images

In a bias frames, the histogram of the intensity (in ADU) should be Gaussian. The mean of the Gaussian is the bias. Its width is related to the gain (G) and read-out noise (RN) through the expression:

$$s_{ADU} = \frac{RN}{G}$$



GAIN (G): is given in e^- / ADU

The largest output number possible is fixed by the number of bits used by the A/D converter is: $2^{\text{\#of bits}}$

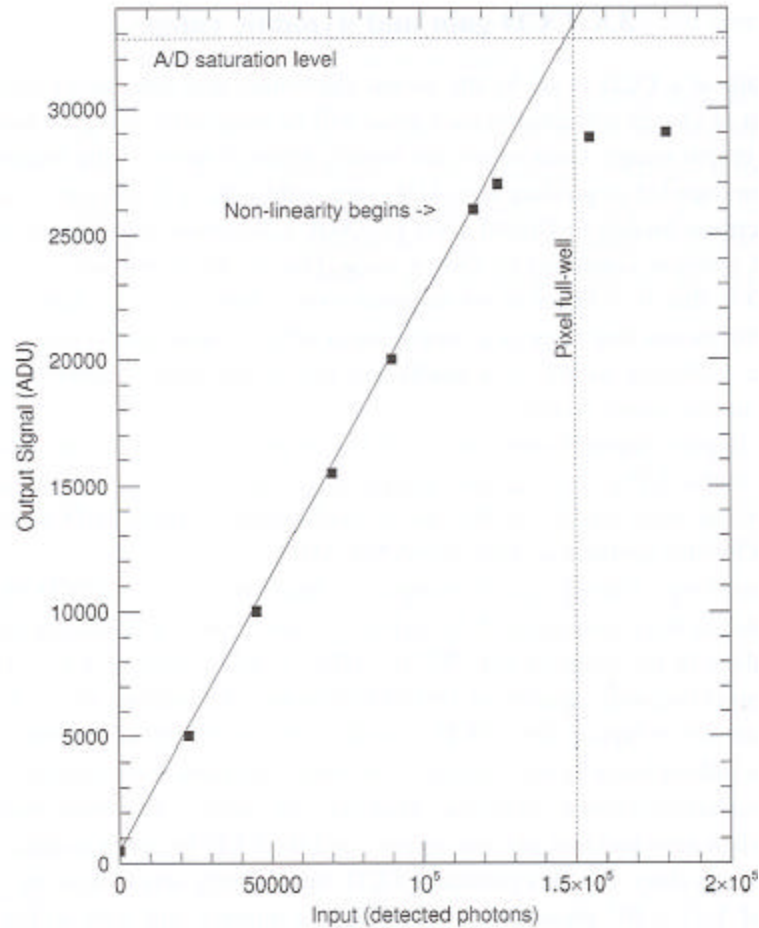
Example 5:

Using 14 bits → values from 0 to 16 383 (2^{14}) ADU are possible;

Using 16 bits → values from 0 to 65 535 (2^{16}) ADU are possible.

Two types of saturation:

- 0. Exceeding A/D conversion or the FWC of a pixel
- 0. Exceeding the non linearity point



Example 6:

For a CCD with the following characteristics:

- 15 bits \rightarrow 32767 ADU;
- $G = 4.5 \text{ } e^- / \text{ADU}$;
- $\text{FWC} = 150000 \text{ } e^-$

Saturation of first type would happen after $32767 \times 4.5 = 145451 e^-$ are detected, or when $150000 / 4.5 = 33333 \text{ ADU}$ are registered. In this case, bleeding will be observed. However, the non-linear part may be reached before that, for example at 26000 ADU

VERY IMPORTANT: if the non-linearity regime is reached before saturation of type1, then one could continue to integrate thinking its exposure time is correct, while in fact it is not

To obtain the linearity curve at the telescope one needs:

- To observe a field of stars with various magnitudes;
- Take multiple expositions doubling time 1, 2, 4, 8, 16, ... up to the time when one or more stars are saturated (first type);
- Trace for each star # of ADU vs t integration

Relation between G and FWC

The gain is determined in order to allow the dynamic range of the detector to be represented by the entire range of output possible

Example 7:

For a Loral CCD 512x1024 with $15\mu\text{m}$ pixel, 90000 e^- FWC and 16 bits A/D, a possible value for G is obtained using the ratio of FWC to the maximum ADU value allowed by 16 bits: $FWC / 2^{16} \sim 1.37$. A gain of $1.4 e^- / ADU$ is henceforth determined

ATTENTION: a case where the above rule does not work is the following: using an 8bit A/D and a CCD with FWC of 100000 e^- . If one chooses $G \sim 100000 / 2^8 = 350 e^- / ADU$, then, since each gain step is discrete and the uncertainty of one output is ± 1 ADU, each value would have an uncertainty of $\pm 350 e^-$, which is extremely high

Another problem with high G is due to the fact that A/Ds yield only integers. For example, consider two different values of G for the same CCD: $5 e^- / ADU$ and $200 e^- / ADU$. Assume that one pixel detects 26703 e^- . This yields 5340 ADU and 133 ADU respectively. In the first case, 3 e^- were lost in the conversion, while in the second case 103 e^- were lost.

Dynamical range: total range over which a pixel operate or is sensitive.

Dynamical range is determined in analogy with audio speaker in decibels.

$$D(\text{dB}) = 20 \log_{10}(FWC / RN)$$

Example 8:

For 100000 e^- FWC, and a 10 e^- RN, the dynamical range is 80 dB.

A more modern definition of dynamical range is:

$$D = FWC / RN$$

Table 3.1. *Some CCDs available at the European Southern Observatory (ESO)*

Instrument	Telescope	Type	CCD	Size (pixels)	Pixel Size (microns)	Pixel Scale (arcsec)	Readout Time (seconds)	Gain (e^- /ADU)	Read Noise electrons	Notes
EMMI	3.6-m NTT	Spectrograph Red channel	MIT/LL	2048×4096	15	0.17	18–48	1.4	4	Thinned, back-side
EMMI	3.6-m NTT	Spectrograph Blue channel	MIT/LL	1024×1024	24	0.37	40	1.4, 2.8	7	Thinned, back-side
FORS2	8-m VLT	Imager/Spectrograph	MIT/LL	2048×4096	15	0.12	40	1.1	6	Deep Depletion, Red optimized
OmegaCam	2.6-m VST	Wide-Field imager	E2V	2048×4096	15	0.21	45	3	5	

Table 3.2. *Typical Properties of Two Old and Six Modern Example CCDs*

	RCA	TI	Kodak	E2V	SITe	Sarnoff	STA (WIYN)	MIT/LL
Pixel Format	320×512	800×800	2048×2048	2048×4608	2048×2048	600×2400	3840×3952	OT 2048×4096
Pixel Size (microns)	30	15	9	13	12	13	12	15
Detector Size (mm)	10×15	12×12	18×18	27×62	25×25	6×25	50	31×62
Pixel Full Well (e^-)	350 000	50 000	100 000	150 000	110 000	> 20 000	> 70 000	> 200 000
Illumination	Front	Back	Front	Back	Back	Back	Back	Back
Peak QE (%) / Wavelength (Å)	70/4500	70/6500	45/6500	90/5000	85/6500	99/6600	96/5500	95/7700
Read Noise (e^-)	80	15	15	3	6	6	< 5	2.5
CTE	0.99995	0.999985	0.99998	0.999995	0.99999	0.99999	0.999998	0.999995
Operating Temp (C)	−100	−120	−30	−85	−85	−60	−60	−110
Typical Gain used (e^- /ADU)	13.5	5	5	1.5	3	5	1.5	1.37

CCD imaging

Plate scale (P)

By analogy with photographic plates, P is given in arcsec/mm.

For CCD, P is better given in arcsec/pixel.

Since the focal ratio ($f/$) of a telescope is given by the following expression:

$$f / = \frac{\text{focal length } (f) \text{ of PM}}{\text{diameter } (D) \text{ of PM}}$$

Taking focal length (f) in mm and the pixel size (μ) in micron yield a plate scale of:

$$P = \frac{206265 \times m}{1000 \times f}$$

Where the value 206265 is the number of arcseconds in 1 radian and 1000 is the factor conversion from mm to micron meter.

Example 9:

For $D = 1m$, $f/=7.5$ and $m = 15$ micron, $P = 0.4$ arcsec/pixel.

One can determine the plate scale by observing a binary star for which the separation is known.

The FOV is then easy to calculate:

$$\text{FOV} = P \times \# \text{pixel}$$

Example 10:

For a 4096×2048 CCD with $P = 0.4$ arcsec/pixel $\Rightarrow \text{FOV} \approx 1638'' \times 819'' \approx 27.3 \times 13.7'$

Calculation of RN and G

The histogram of a flatfield frame must also yield a Gaussian, with a width of:

$$s_{ADU} = \frac{\sqrt{\bar{F} \cdot G}}{G}$$

One recipe to calculate G and RN is the following:

- Take 2 bias frames and 2 flatfields (B_1 , B_2 and F_1 , F_2)
- Determine the mean values \bar{B}_1 , \bar{B}_2 and \bar{F}_1 , \bar{F}_2
- Form two other frames with the differences ($B_1 - B_2$ and $F_1 - F_2$)
- Calculate the standard deviations: $s_{B_1-B_2}$ and $s_{F_1-F_2}$
- G is then equal to:

$$G = \frac{(\bar{F}_1 + \bar{F}_2) - (\bar{B}_1 + \bar{B}_2)}{s_{F_1-F_2}^2 - s_{B_1-B_2}^2}$$

- RN is equal to:

$$RN = \frac{G \cdot s_{B_1-B_2}}{\sqrt{2}}$$

Signal to noise ratio (S/N)

A first definition of the S/N is the following:

$$S / N = \frac{N_*}{\sqrt{N_* + n_{pix} (N_S + N_D + N_R^2)}}$$

Where

N_* is the total number of photons (electrons) collected for the object of interest (this could be in 1 pixel, in several pixel or a rectangle area).

n_{pix} is the number of pixel used to evaluate the terms between parenthesis in the denominator.

N_S is the number of photons/pixel measured in the sky background.

N_D is the dark current photons.

N_R^2 is the RN electron/pixel. Note that this noise is not Poissonian, this is why it enters as itself and not the square root.

According to formula for the noise, an observation **dominated by the source** (bright object) has a noise which is Poissonian:

$$S / N \approx \frac{N_*}{\sqrt{N_*}} = \sqrt{N_*}$$

A second definition of S/N takes into account fainter noise sources:

$$S / N = \frac{N_*}{\sqrt{N_* + n_{pix} \left(1 + \frac{n_{pix}}{n_B} \right) (N_S + N_D + N_R^2 + G^2 \mathbf{S}_f^2)}}$$

The factor $\left(1 + \frac{n_{pix}}{n_B} \right)$ takes account of the error in evaluating the background. n_B is the number of pixel used in evaluating this error (the smaller the higher the noise)

$G^2 \mathbf{S}_f^2 \sim 0.289$ is one sigma error introduced by the A/D conversion

Example 11:

Let consider the following case:

- 300 s exposure time
- $D = 1\text{m}$
- $\mu = 19\text{ micron}$
- $P = 2.6\text{ arcsec/pixel}$
- $RN = 5\text{ }e^-/\text{pixel/readout}$
- $DC = 20\text{ }e^-/\text{pixel/hour}$
- $G = 5\text{ }e^-/\text{ADU}$

Using 200 pixels around the source, we determine a sky background of $N_B = 620\text{ ADU/pixel}$

With such a plate scale, assuming a seeing less than 1 arcsec, a point source will fall on only one pixel.

We measured $N_* = 24013\text{ ADU}$.

According to the first formula, the S/N would then be:

$$S / N = \frac{24013}{\sqrt{24013 \cdot G + 1 \cdot [(620 \cdot G) + 1.8 + 5^2]}} \sim 342$$

This value is very near the bright source approximation $\sqrt{N_*} \sim 346$

The standard error being equal to $s = \frac{1}{S / N}$ one found in magnitude:

$$s_{mag} = \frac{1.0857 \sqrt{N_* + p}}{N_*}$$

Where $p = n_{pix} \left(1 + \frac{n_{pix}}{n_B} \right) (N_S + N_B + N_R^2 + G^2 s_f^2)$ and 1.0857 is the conversion factor from electron to magnitude.

Prediction of S/N from integration time t is:

$$S / N = \frac{Nt}{\sqrt{Nt + n_{pix}(N_S t + N_D t + N_R^2)}}$$

This formula justifies the rule of thumb approximation $S / N \propto \sqrt{t}$.

Solving for t :

$$t = \frac{-B + (B^2 - 4AC)^{1/2}}{2A}$$

Where

- $A = N^2$
- $B = -(S / N)^2 (N + n_{pix}[N_S + N_D])$
- $C = -(S / N)^2 n_{pix} N_R^2$