PH 301

ENGINEERING OPTICS

Lecture_Optical Detectors_28

1970: first articles on CCD

Charge Coupled Semiconductor Devices

By W. S. BOYLE and G. E. SMITH

(Manuscript received January 29, 1970)

W.S. Boyle, G.E. Smith,
Bell Systems Technical Journal 49 (1970) 587

In this paper we describe a new semiconductor device concept. Basically, it consists of storing charge in potential wells created at the surface of a semiconductor and moving the charge (representing information) over the surface by moving the potential minima. We discuss schemes for creating, transferring, and detecting the presence or absence of the charge.

In particular, we consider minority carrier charge storage at the Si-SiO_2 interface of a MOS capacitor. This charge may be transferred to a closely adjacent capacitor on the same substrate by appropriate manipulation of electrode potentials. Examples of possible applications are as a shift register, as an imaging device, as a display device, and in performing logic.

Experimental Verification of the Charge Coupled Device Concept

By G. F. AMELIO, M. F. TOMPSETT and G. E. SMITH

(Manuscript received February 5, 1970)

Structures have been fabricated consisting of closely spaced MOS capacitors on an n-type silicon substrate. By forming a depletion region under one of the electrodes, minority carriers (holes) may be stored in the resulting potential well. This charge may then be transferred to an adjacent electrode by proper manipulation of electrode potentials. The assumption that this transfer will take place in reasonable times with a small fractional loss of charge is the basis of the charge coupled devices described in the preceding paper.[1] To test this assumption, devices were fabricated and measurements made. Charge transfer efficiencies greater than 98 percent for transfer times less than 100 nsec were observed.

G.F. Amelio, M.F. Tompsett, G.E. Smith,
Bell Systems Technical Journal 49 (1970) 593

1970: first articles on CCD

Boyle & Smith

Photo: U. Montan

Charles Kuen Kao

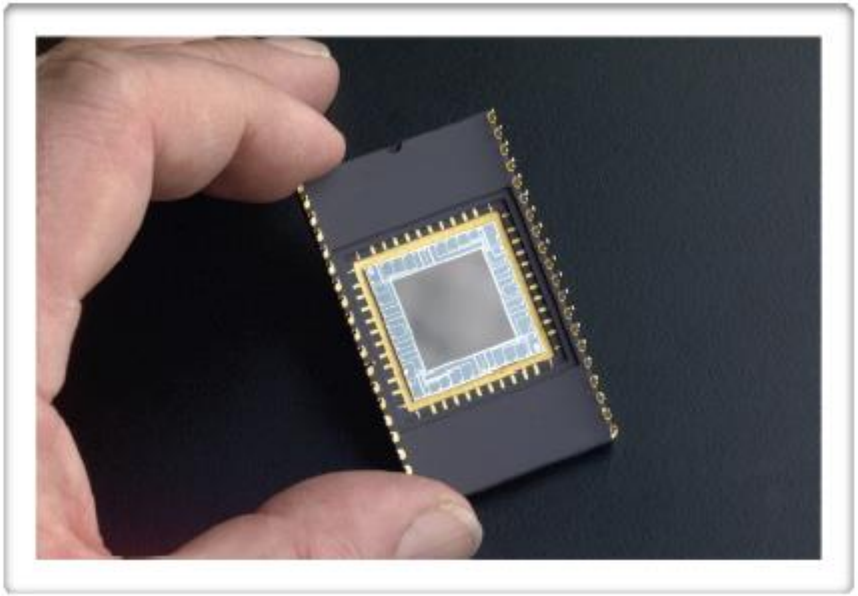
Photo: U. Montan

Willard S. Boyle

Photo: U. Montan

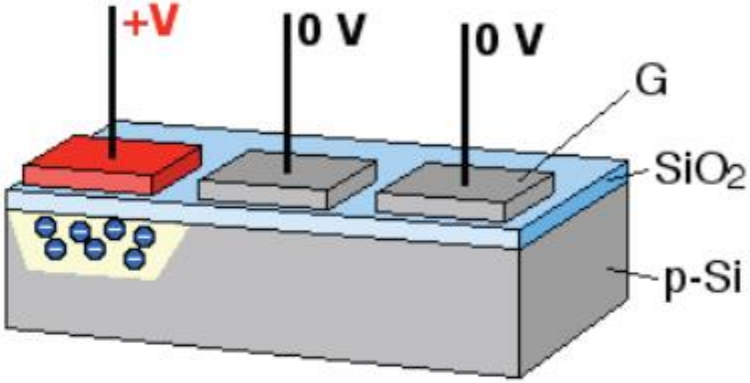
George E. Smith

The Nobel Prize in Physics 2009 was divided, one half awarded to Charles Kuen Kao *"for groundbreaking achievements concerning the transmission of light in fibers for optical communication"*, the other half jointly to Willard S. Boyle and George E. Smith *"for the invention of an imaging semiconductor circuit – the CCD sensor"*.



Charge Coupled Device (CCD)

photo sensor coupled to shift register

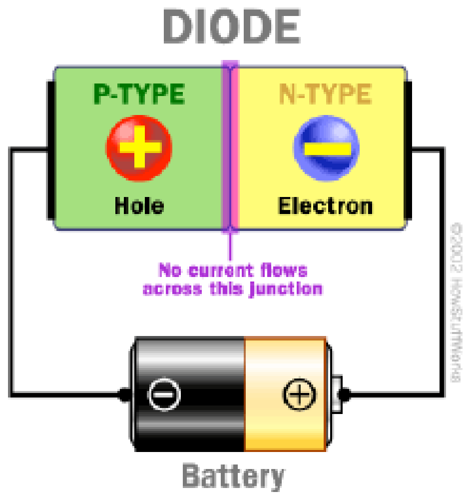


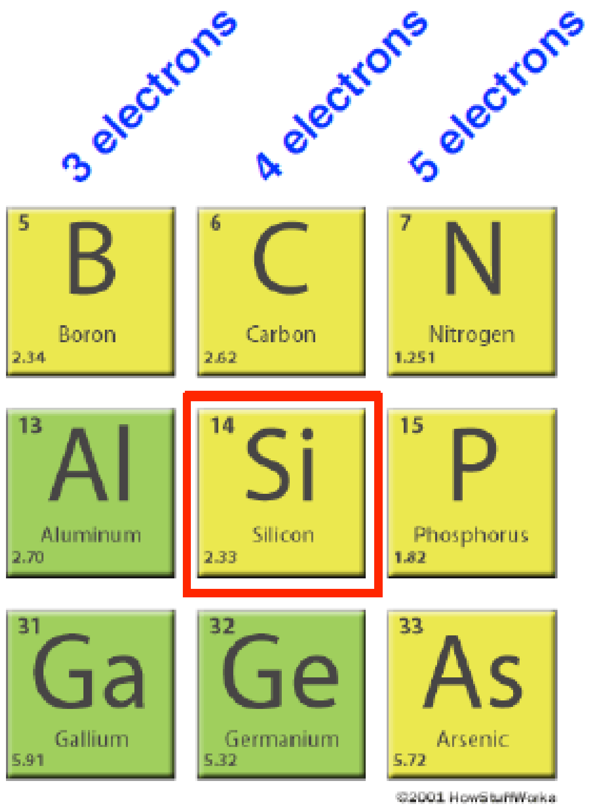
Semiconductor: doping Si

doping: mix small amount of impurity to silicon crystal

N-type: dope with phosphorus or arsenic
5th electron is free
n conductor

P-type: dope with boron or gallium
one electron less -> „hole“
p conductor



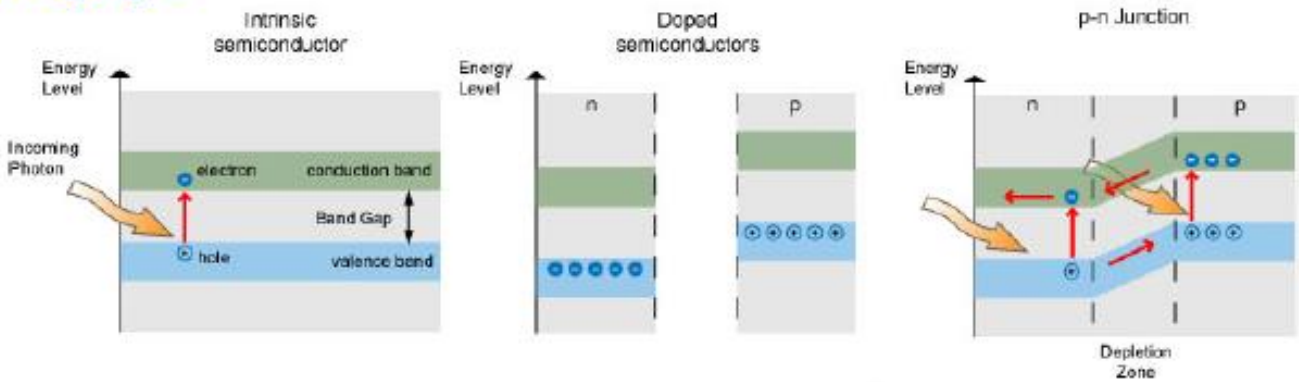


Photo(electric) effect

liberation of electrons through incoming light

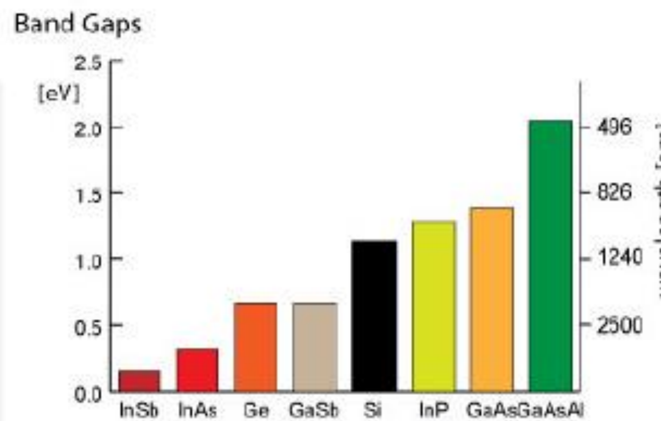
energy per photon: $E = h\nu$

band gaps



To convert electron-Volts into wavelenghts of incoming light, we use the forumla:

$$\lambda = \frac{ch}{e}\frac{1}{b}; \quad \begin{cases} c = 299792458 & \text{Speed of light [m/s]} \\ h = 6.63e-34 & \text{PlanckCons tant [Js]} \\ e = 1.602e-19 & \text{Elementary Charge [C]} \\ b & \text{Bandgap in [eV]} \\ \lambda & \text{Wavelength in [m]} \end{cases}$$

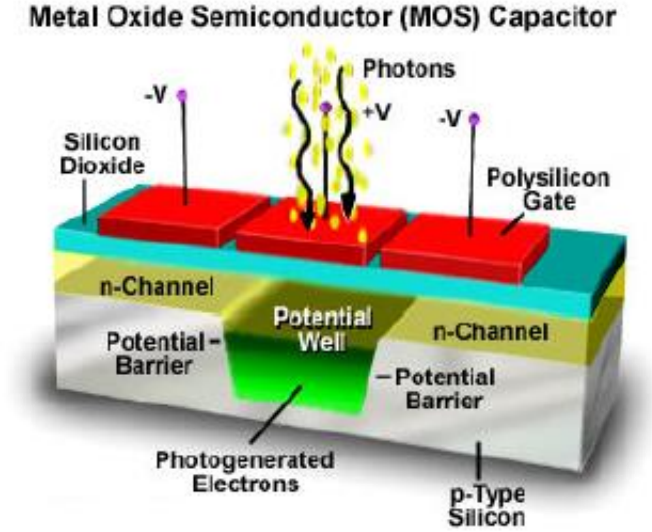


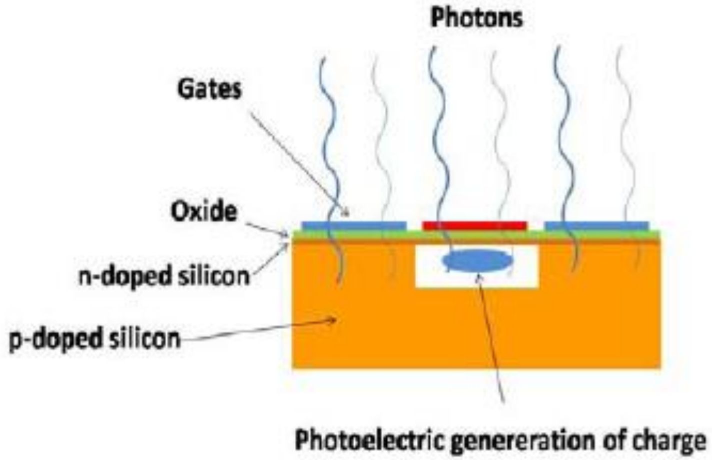
- **Small band gap:** Long waves (e.g. infrared) can still cause the photo effect.
- **Wider band gap:** Long waves can not be converted into an electric current and will just pass through the material unabsorbed.

CCD working principle

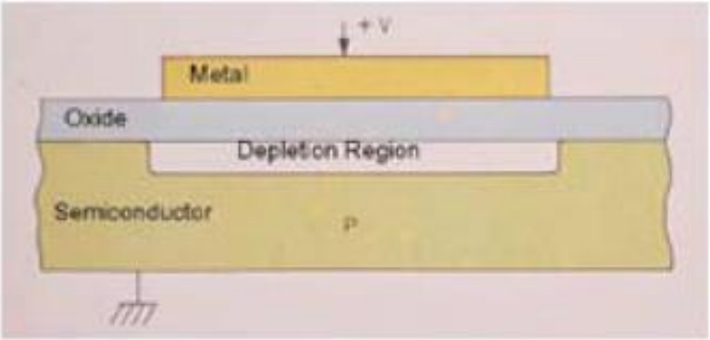
1. photo effect: liberate electrons

2. collect charge - pixels (gates)





A MOS capacitor used as a light sensitive device.

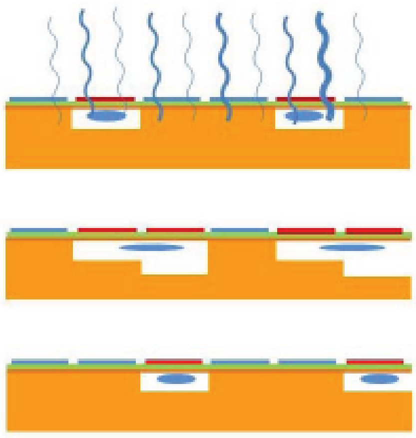


The basic MOS structure

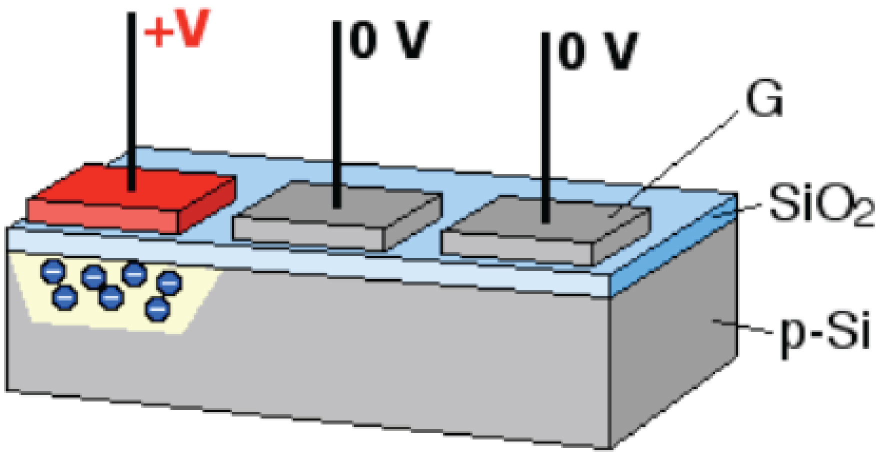
MOS: metal oxide semiconductor

CCD working principle

3. read out:
transfer charge
apply differential voltage across gates



The sequence of collecting and moving the charge along a column of a CCD detector. The charge generated by photons is forced to move one step at a time through the application of voltage pulses on the electrodes.



CCD working principle

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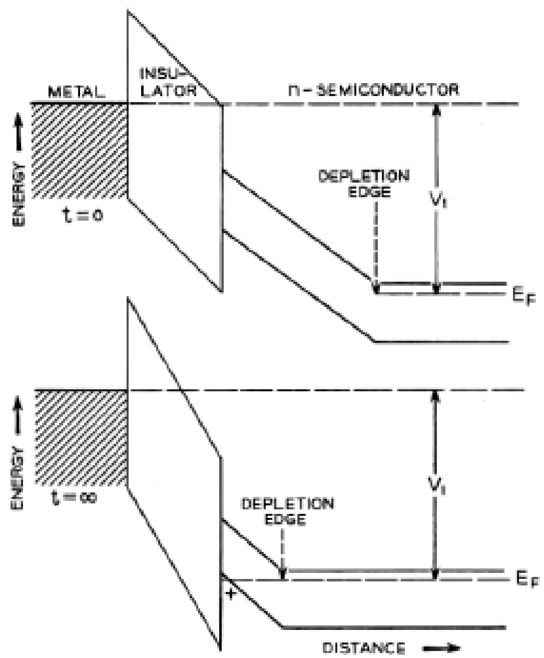


Fig. 1—A plot of electron energy vs distance through an MIS structure both with (at time $t = \infty$) and without (at time $t = 0$) charge stored at the surface.

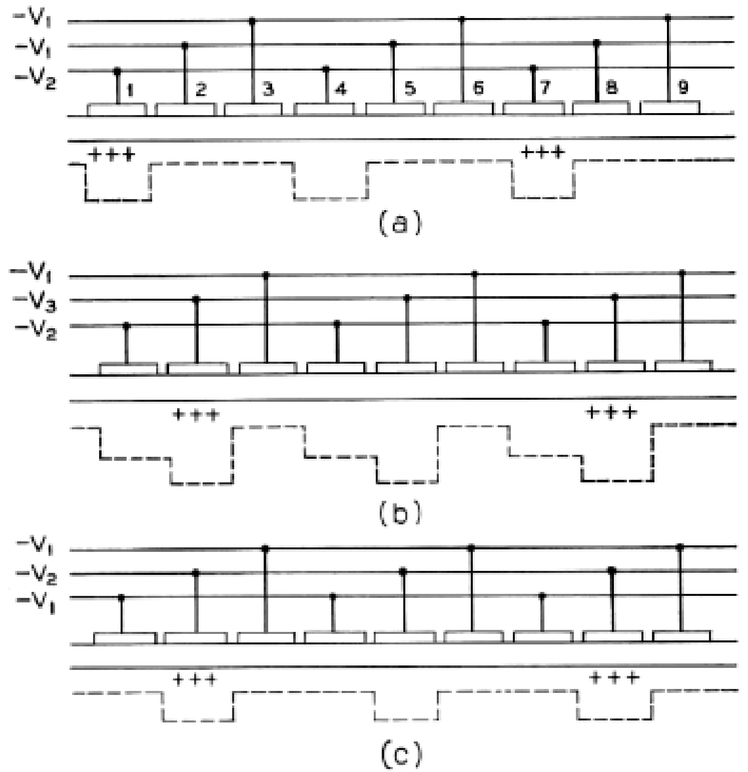


Fig. 2—Schematic of a three phase MIS charge coupled device.

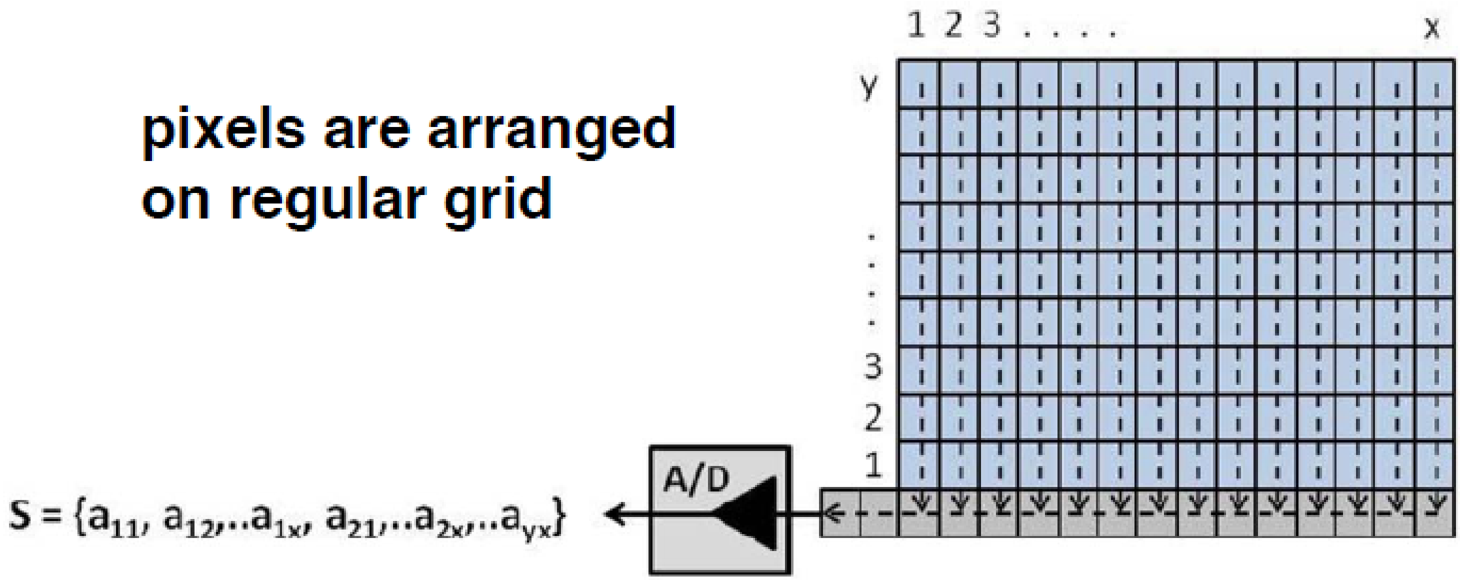
W.S. Boyle, G.E. Smith, Bell Systems Technical Journal 49 (1970) 587

CCD working principle

5. sequential read out column after column

6. detect charge - individual charge packets are converted to an output voltage in digitized form

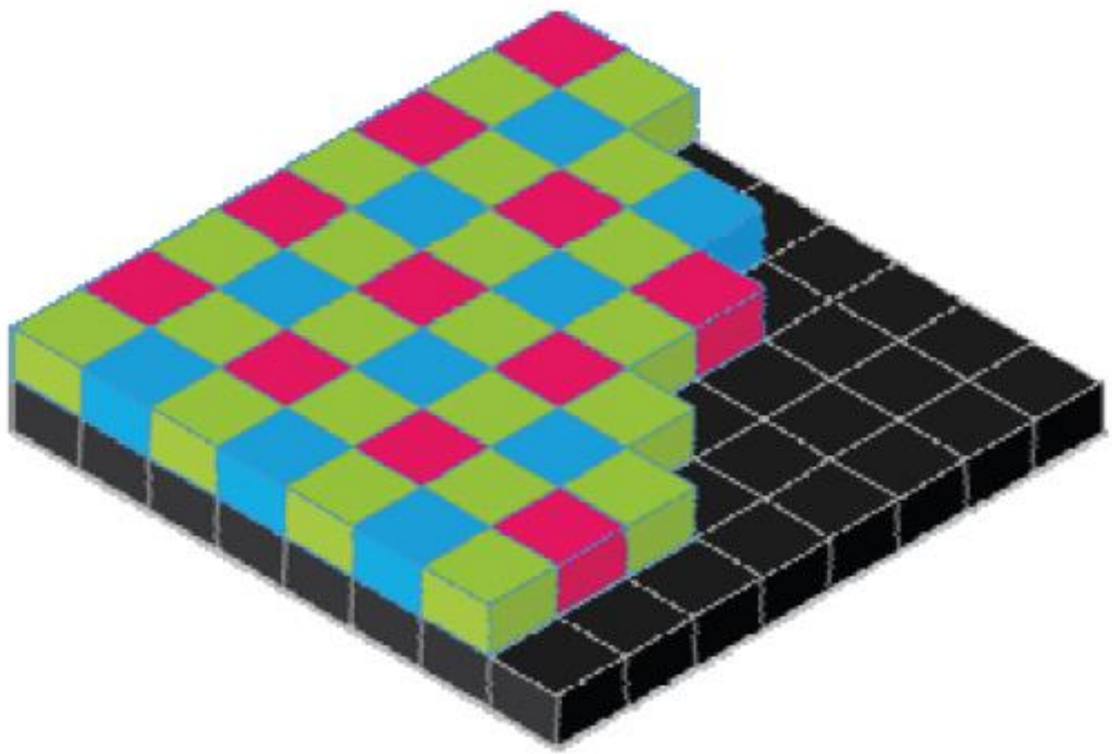
pixels are arranged on regular grid



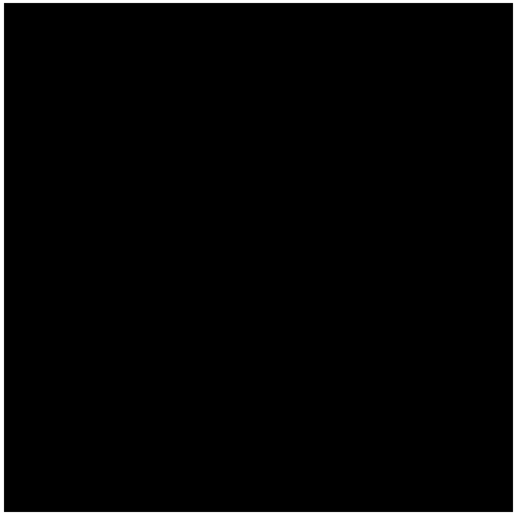
The principle behind read-out of a CCD chip. One row at a time is shifted through an A/D converter which makes the output signal digital.

CCD working principle

color images through RGB (red green blue) filter



Major sources of noise in CCD images



Dark Current

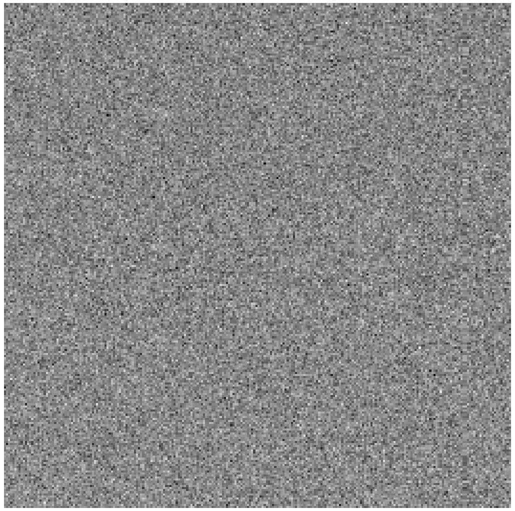
caused by thermally generated electrons

-> temperature dependence

Pixel Non-Uniformity

each pixel has a slightly different sensitivity to light, typically within 1% to 2% of the average signal.

-> flat-field image



Shot Noise

random arrival of photons. This is a fundamental trait of light.

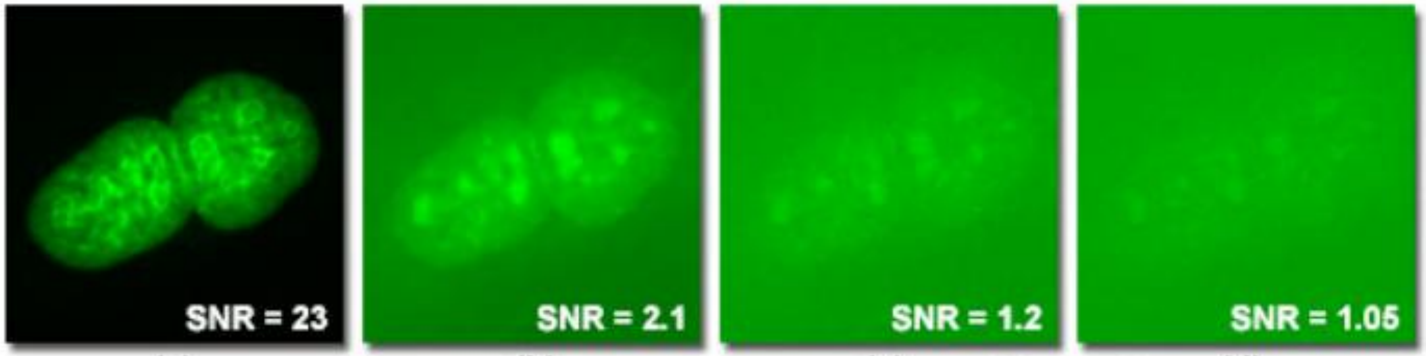
-> longer exposure or combining multiple frames

CCD Read Noise (On-chip)

There are several on-chip sources of noise that can affect a CCD. CCD manufacturers typically combine all of the on-chip noise sources and express this noise as a number of electrons RMS (e.g. $15e^-$ RMS).

CCD Noise Sources and Signal-to-Noise Ratio

Signal-to-Noise Ratios in Fluorescence Microscopy



(a) (b) (c) (d)

Figure 1

The following equation is commonly used to calculate CCD camera system signal-to-noise ratio:

$$\mathbf{SNR = PQ_et \,/\, \sqrt{PQ_et + Dt + N_r^2}}$$

where **P** is the incident photon flux (photons/pixel/second), **Q(e)** represents the CCD quantum efficiency, **t** is the integration time (seconds), **D** is the dark current value (electrons/pixel/second), and **N(r)** represents read noise (electrons rms/pixel).

$$\mathbf{SNR = PQ_et \,/\, \sqrt{(P + B)Q_et + Dt + N_r^2}}$$

B background photon flux

http://learn.hamamatsu.com/articles/ccdsnr.html

CCD Noise - Dark current

An empirical formula, or dark current equation, has been developed to describe the relationship between temperature and dark current produced by a CCD sensor. It precisely corresponds to dark current measurements taken in practice, and is valuable for determining the required operating temperature for elimination of camera dark current. The equation was developed from a general dark current formula, which is combined with an expression describing the variation of the bandgap energy of silicon with temperature, and a measured value of dark current at a standard temperature (300 K). The bandgap of silicon, **E(g)** (electron volts), varies with temperature according to the following, in which **T** represents temperature (kelvins):

$$E_g = 1.1557 - [(7.021 \times 10^{-4} \times T^2) / (1108 + T)]$$

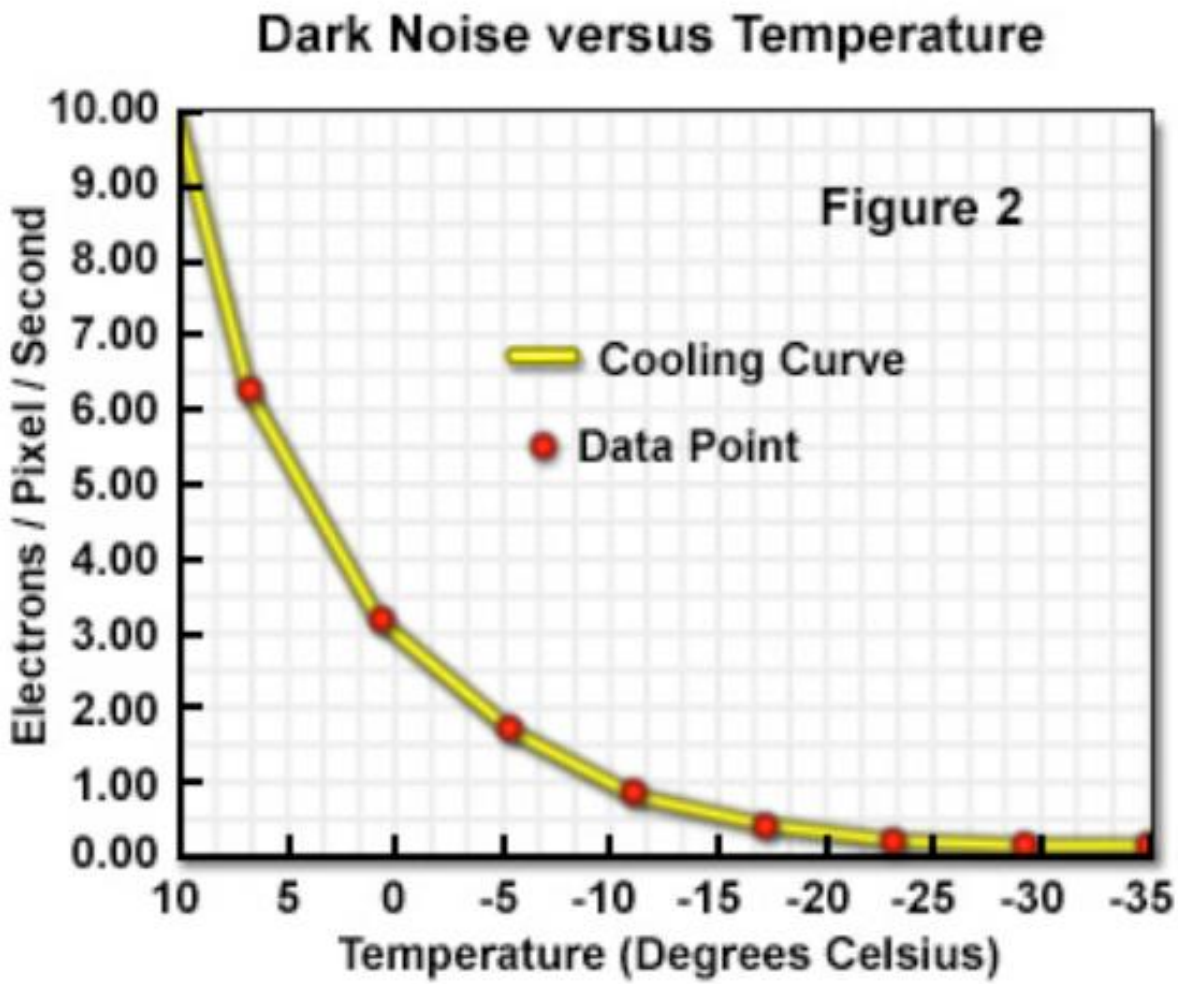
The resulting dark current formula is as follows:

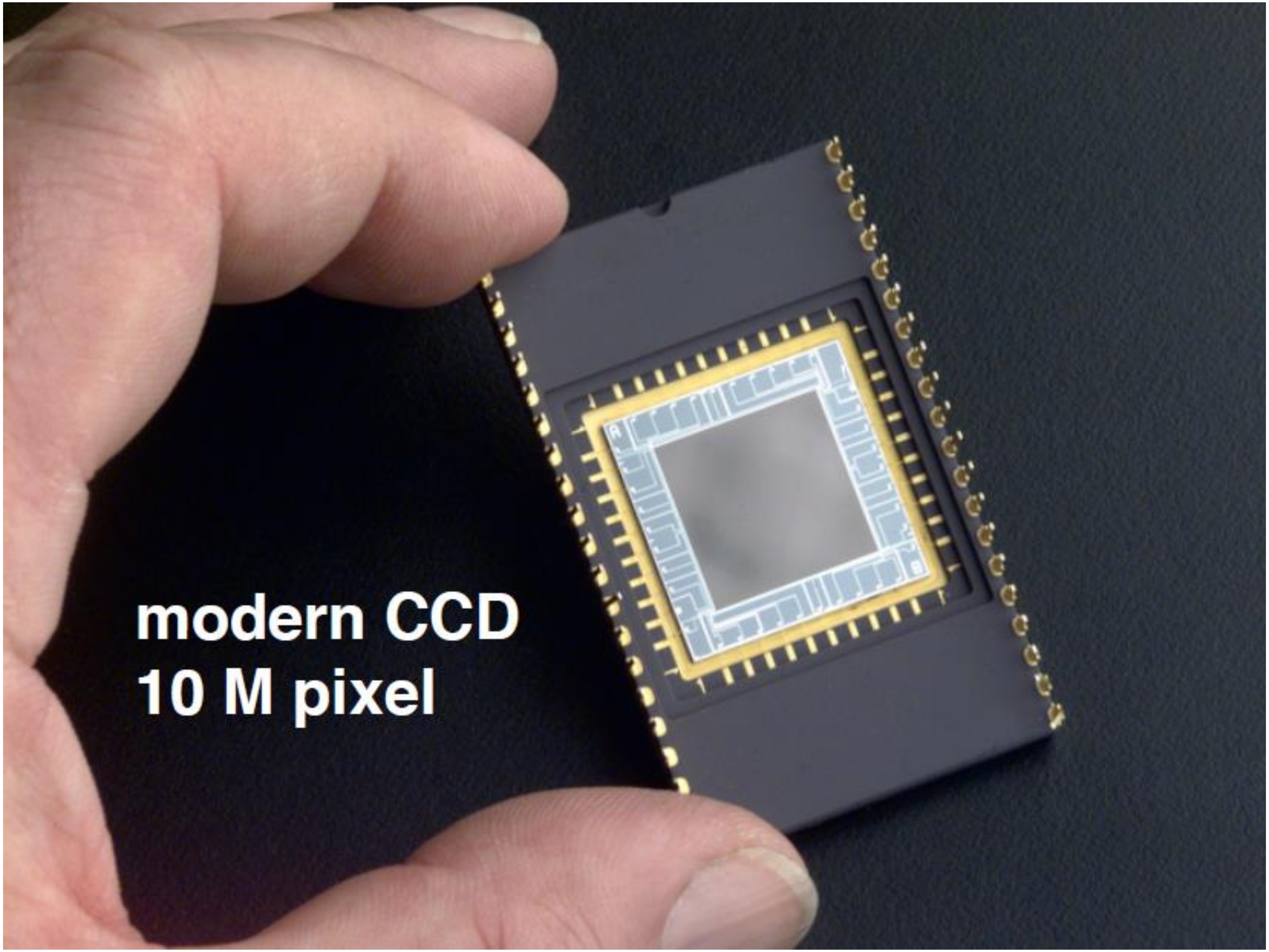
$$D = 2.5 \times 10^{15} \times A \times I_d \times T^{1.5} \times e^{-E_g / (2kT)}$$

in which **D** is the dark current (electrons/pixel/second), **A** is the pixel area (measured in square centimeters), **I(d)** is the dark current measured at 300 K (nanoamperes/square centimeter), **T** is the temperature (K), and **E(g)** is the bandgap at temperature T (electron-volts).

http://learn.hamamatsu.com/articles/ccdsnr.html

CCD Noise - Dependence on temperature




modern CCD
10 M pixel

Advantages of CCD

- Quantum efficiency (QE) ~ 80%
- Low noise
- High dynamic range (~ 50K)
- High photometric precision
- Very linear behaviour
- Immediate digital conversion of data
- Low voltages required (5V-15V)
- Geometrically stable (good for astronomy)
- Rapid clocking

Example: CCD camera on Hubble Space Telescope

Fig. 8. The galaxy cluster Abell 2218. *Image: WFPC2, Hubble Space Telescope, NASA.*