Advanced Measurement Methods
STEN Ph.D. Course
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POLITECNICO DI MILANO

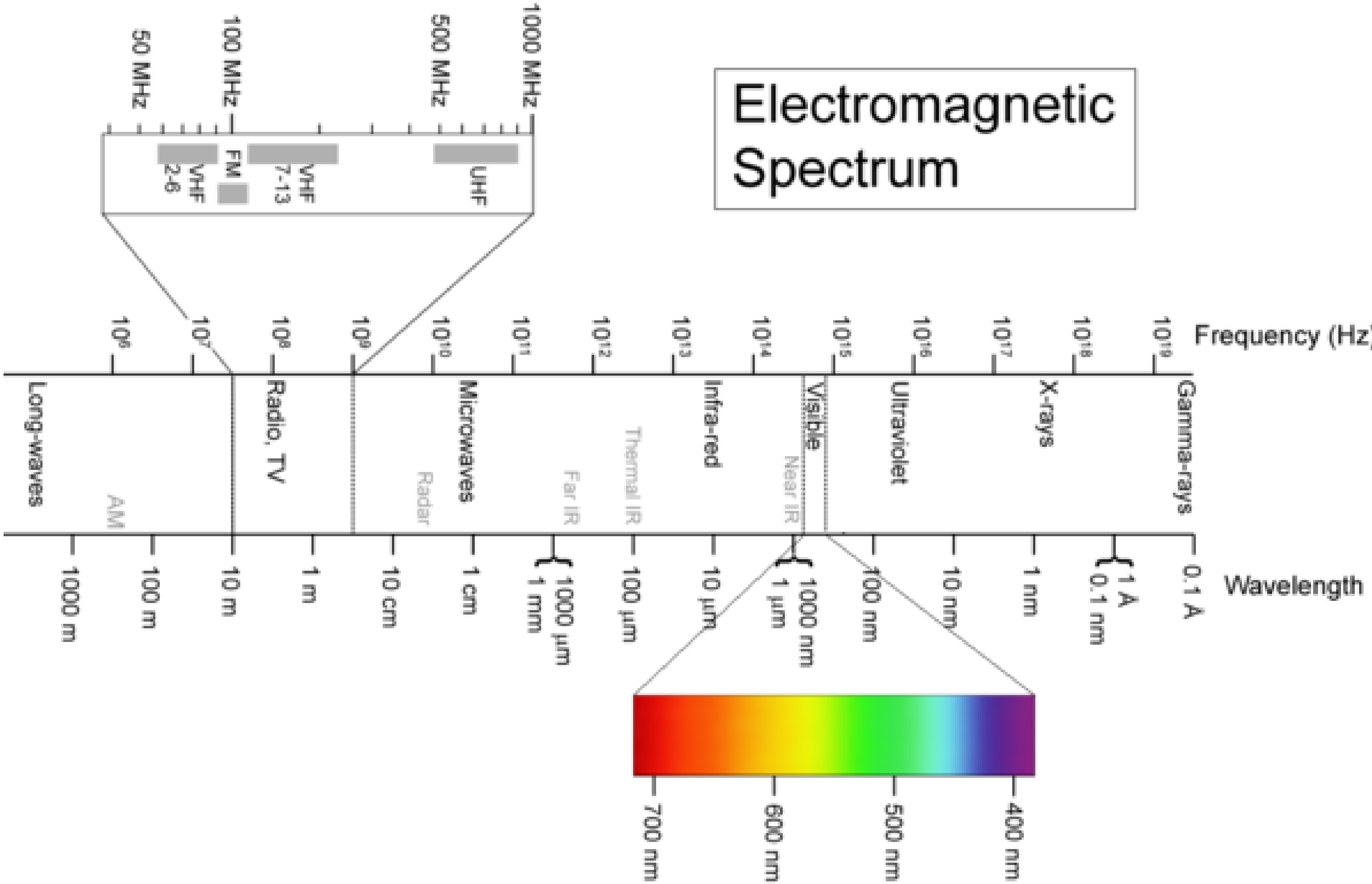
    

An introduction to light detectors and sources

Fabio Cozzi

Combustion and Propulsion Laboratory, Department of Energy

Introduction (1/5)
Electromagnetic Spectrum



Light = electromagnetic waves (EW) laying in the visible part of the spectrum

Frequency of light is >10^{14} Hz

Introduction (2/5)
Energy of EW

Light can be described either as ***wave*** or as ***particle*** (photon)

Photons correspond to the smallest amount of energy carried by the light

Waves are characterized by a frequency, ν, and a wave vector, $\boldsymbol{k}$.

Photons are characterized by an individual energy, $\boldsymbol{W}$, and a momentum $\boldsymbol{p}$.

Planck relationship (along with De Broglie relationship) related the particle and wave aspects of light:

$\boldsymbol{W = h\,\nu}$ *Planck relationship*

$\boldsymbol{h} = 6.626\ 10^{-34}\ J\ s$ *Planck's constant*

ν = *frequency of the E.W.*

The energy of a photon increases (decreases) by increasing frequency (wavelength)

Introduction (3/5)
Light Intensity

EW carries energy, the energy density ***w*** of an EW is given by

$$w = \varepsilon E^2 \quad [\mathrm{J/m^3}]$$ the electric field E is a function of both space and time

We define ***irradiance of a monochromatic*** EW as the energy transported per unit time across a unit surface area (perpendicularly to the propagation direction)

$$I(\lambda) = \frac{c\varepsilon}{2} E^2 \quad [\mathrm{W/m^2}]$$

c = speed of light

ε = absolute permittivity

For a non-monochromatic wave, irradiance is computed as the integral of the spectral irradiance, $I(\lambda)$:

$$I = \int_0^\infty I(\lambda)\, d\lambda$$ for a detector of area A $$I = \iint_A \left(\int_0^\infty I(\lambda)\, d\lambda \right) dA$$

Due to the high frequency of light any detector will sense just the ***mean irradiance of the EW over a time t_c***.
By defining $\dot{N}_p$ as the number of photon per second impinging on a unit surface and λ as the wavelength of the EW, irradiance can be written as:

$$I(\lambda) = \dot{N}_p \frac{hc}{\lambda} \quad \Rightarrow \quad \dot{N}_p = I(\lambda)\frac{\lambda}{hc}$$

At constant irradiance, $I(\lambda)$: the shorter the wavelength the smaller the number of photons

i.e. more photons emitted by a IR (infrared) source than by a VIS (visible) source

Introduction (4/5)
Radiometry and Photometry

RADIOMETRY

Radiometry is the science of measuring light in any portion of the electromagnetic spectrum. It is based on physics (energy and power, units are W and J)

PHOTOMETRY

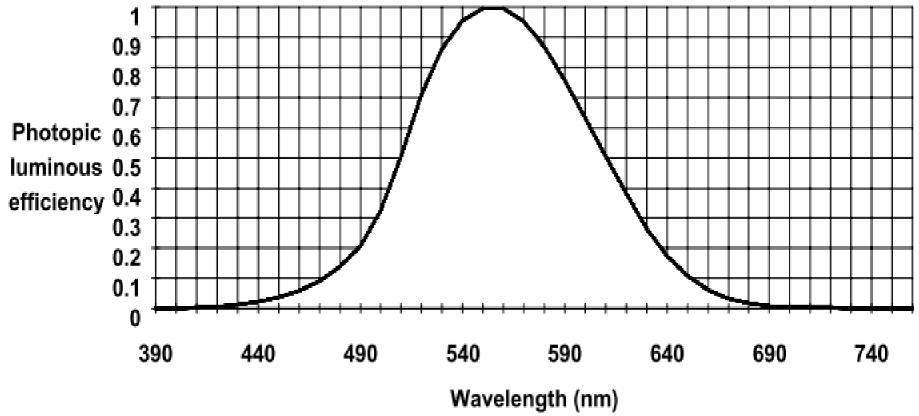
Photometry is the science of measuring visible light in units that are weighted according to the sensitivity of the human eye. It is a quantitative science based on a statistical model of the human visual response to light - that is, our perception of light - under carefully controlled conditions.

1 lumen corresponds to a monochromatic radiation at ~555 nm, corresponding with the wavelength of maximum photopic luminous efficiency, having a radiant power of 1/683 W

Luminous flux: is photometrically weighted radiant flux (power), [lumen].

Luminous flux density (Illuminance): is the photometrically weighted irradiance, [lumen/m^2] i.e. [lux].

photopic luminous efficiency, provided the weighting function used to convert radiometry into photometry units



Introduction (5/5)
Detection of EW

Electromagnetic waves carry informations!

Frequency Phase, Amplitude, Polarization

To detect an EW means to destroy such informations…a part of them

the EW is converted in a form more useful for utilization (voltage, digital number…) !

Quantitative and qualitative information about an object, a physical phenomena or a living organism can be obtained through EW detection

1. Fluidynamics, Gasdynamics, Combustion

   velocity, density, pressure, concentration, temperature

2. Astronomy

   planets, stars, galaxy characterization and analysis.

3. Medical

   tissue analysis, observe/reconstruct body parts or components

4. other…

Flow Visualization

Interested in the use/detection of light for flow visualization purposes.

> *"Flow visualization is the art and science to obtain a clear image of a physical flow field and the ability to capture it on a sketch, photograph, or other video storage devices for display or further processing"*
>
> P. Freymuth *Flow visualization in fluid mechanics* Rev. Sci. Instrum., 64(I), 1993

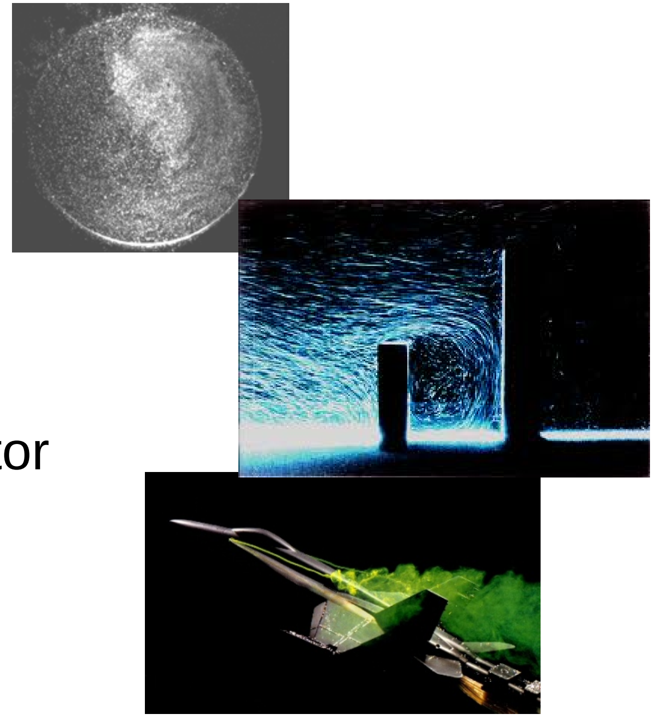
Obtain a clear image of a physical flow field → *Ability to capture and record it* → *Display and analyze*

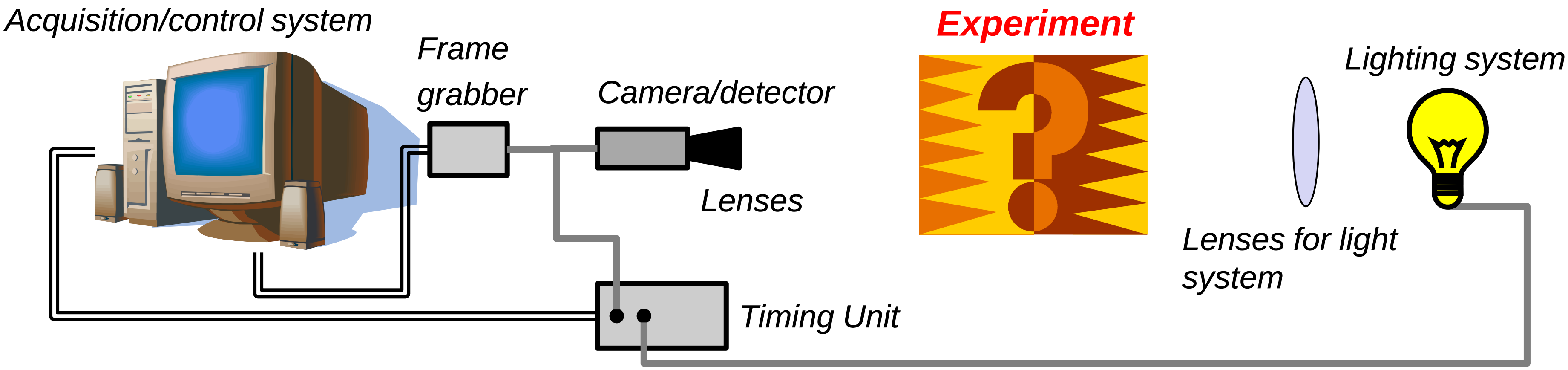
Light sources and light detection systems are required!

Flow Visualization

Basic component for an imaging system

1. Detector, frame grabber, lenses, filters
2. Lighting system (can have his own optics)
3. Timing system
   a) synchronize the lighting system and detector
   b) trigger acquisition
4. Acquisition/control system (PC)





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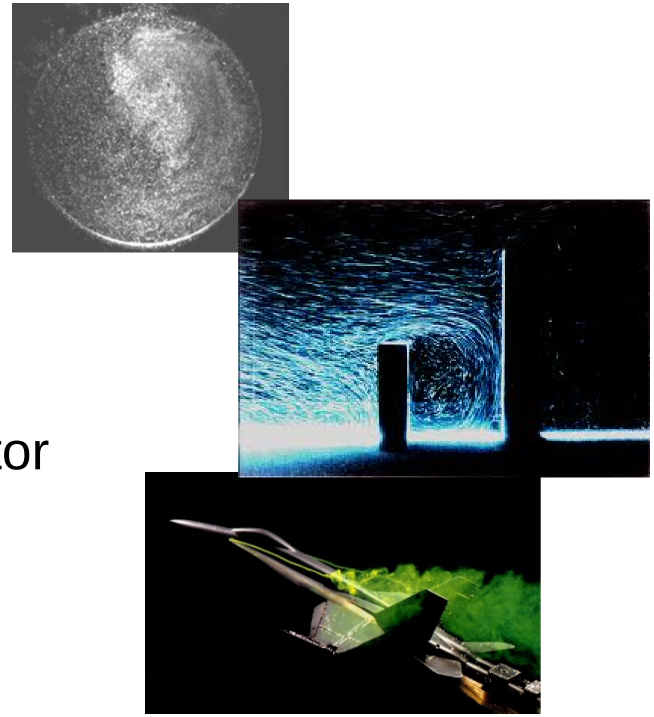
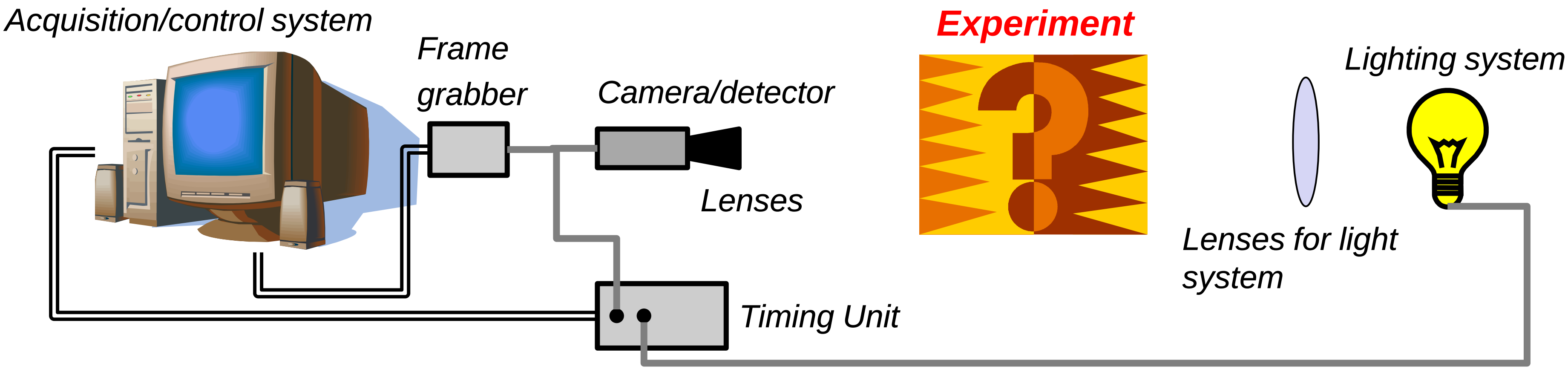


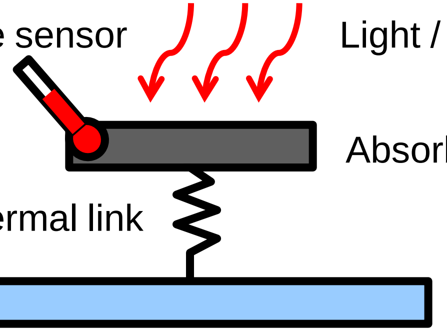


LIGHT DETECTORS

Light/EW detectors are mainly of two different types:

Thermal and Quantum Detectors

Thermal detector



The EW is absorbed by the detector and converted into internal energy.

The detector *actually sense a temperature increase* and output signal is proportional to the temperature.

Temperature sensors based on: *Thermoelectric, Pyroelectric effect*.

PRO: *They can be made sensitive to a wide spectral range of EW*

CON: *Radiation detection is based on a* ***secondary effect*** *thus they are slower and less sensitive than quantum detectors.*

Basic of Light Detection (2/2)

Light/EW detectors are mainly of two different types:

Thermal and Quantum Detectors

Quantum detector

Based on photoelectric effect, i.e. direct interaction between photon and matter (count of single photon possible)

Photoemission (external photoelectric)

Emission of free electron (called photoelectron) due to photon impinging on matter.
Photoelectron is ejected outside the material.

Photovoltaic effect (internal photoelectric)

Electron hit by a photon jump from the valence to the conduction band. A current is generated. Differently from photoemission the photoelectron stay inside the material.

Photoconductive effect (internal photoelectric)

Increase in the electrical conductivity of a semiconductor caused by an EW.
Additional free charge carriers generated by the incident photons.

Photovoltaic Effect (1/4)

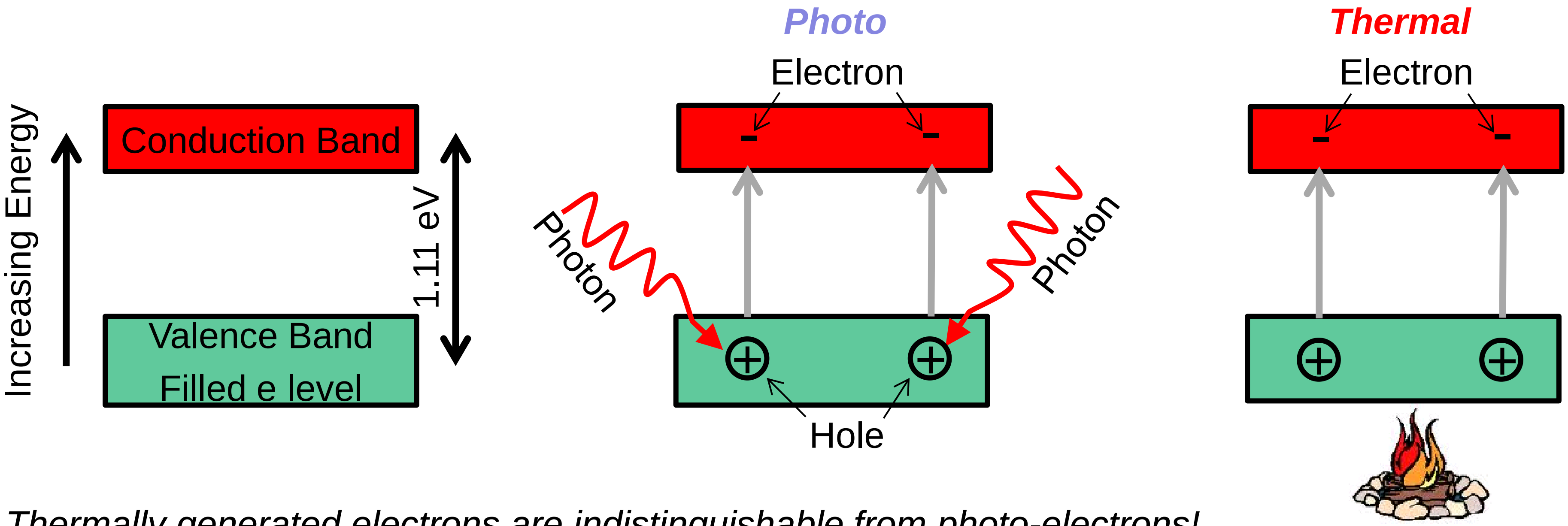
Photovoltaic effect is at the base of CCD and CMOS devices

Atoms in a silicon crystal have electrons arranged in discrete energy bands. The lower energy band is called the *valence band*, the upper band is the *conduction band*.

Most of the electrons occupy the *valence band* but can be excited into the *conduction band* either by the **absorption of a photon** or by **thermal energy**.

The energy required for this transition is 1.11 eV (Si).

In the conduction band the electron is free to move about in the lattice of the silicon crystal. In the absence of an external electric field the hole and electron will quickly re-combine and be lost.



Thermally generated electrons are indistinguishable from photo-electrons!

They are noise (dark current)! Dark current, increase exponentially with sensor temperature!.

Photovoltaic Effect (2/4)

The minimum energy amount required to generate the photoelectric effect is equal to the band gap energy !

The energy, W, of a photon with wavelength λ, is equal to

$$W = h\frac{c}{\lambda} = \frac{6.62\cdot 10^{-34}\times 3\cdot 10^{8}}{\lambda} = \frac{1.986\cdot 10^{-25}}{\lambda}[J] = \frac{1.24}{\lambda}\ [\mathrm{eV}],\ \text{with } \lambda \text{ in } \mu\mathrm{m}$$

h = 6.62 x 10^{-34} Js
c = 3 x 10^{8} m/s
1 eV = 1.6x10^{-19} J

For **Si** the band gap energy, $E_{\text{band gap}}$, is equal to 1.11 eV, thus:

$$\lambda_{\max} = \frac{1.24}{E_{\text{band gap}}}\frac{\mu m\cdot \mathrm{eV}}{\mathrm{eV}} = \frac{1.24}{1.11}\mu m = 1.1\,\mu m$$

Only EW having a wavelength below 1.1 μm can be detected by Si detector!

Quantum Efficiency, η

The ratio between the number of induced elementary charge *e*, N_e, and the number of incident photons, N_p

$$\eta = \frac{N_e}{N_p}$$

Actually N_e is the number of electron-hole pair!

- η can be defined as $QE_I * Y_{QE}$
  - interacting quantum efficiency, QE_I: probability that a photon interact with the material
  - quantum yeld, Y_{QE} : how many photo-electron are generated for each interaction

  for low-energy radiation, i.e. < about 3.1 eV (VIS-NIR), $\eta \leq 1$ (Y_{QE}=1)
- $\eta < 1 \Rightarrow$ Why not all photon generate a electron-hole pair ?
  - Some photon reflected at the sensor surface
  - Some photon absorbed in region where charge are not collected
  - electron-hole pair recombination
- η is a function of wavelength
  - Optical properties of materials are wavelength dependent
  - Band gap energy, i.e. η drop to zero at wavelength above λ_{max}
- Film have η of just 10% while photovoltaic sensor can have η close to 100%

The spectral sensitivity of array sensors (CCD-CMOS) differs from that of a simple silicon photodiode detector!

Quantum Efficiency, η

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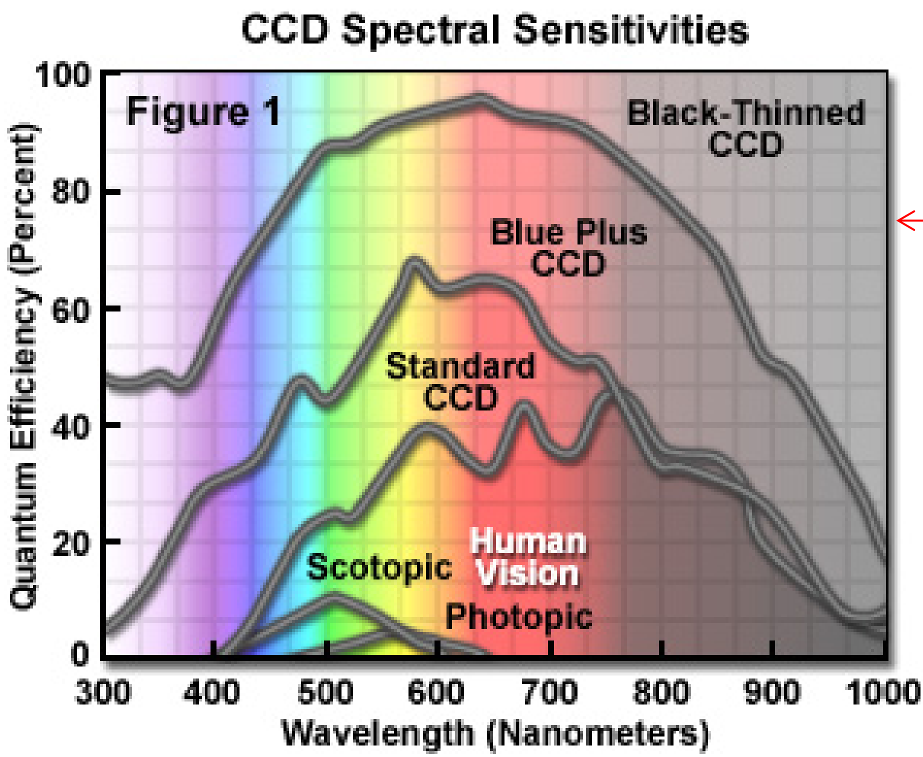


Example of QE for some CCD array sensors

Responsivity, R

Photoelectric conversion efficiency is also sometimes expressed as *Responsivity*, R.

$$R(\lambda)=\frac{signal}{incident\ light\ \ flux}$$

$\longrightarrow$ irradiance [W/m^2]*sensor surface area [m^2]

usually unit of R are either $\left[\frac{A}{W}\right]$ or $\left[\frac{V}{W}\right]$ depending on which signal is measured (current or voltage)

Responsivity and *quantum efficiency* are related:

$$\left.\begin{aligned} generated\ current &= i = e\dot{N}_e = e\eta(\lambda)\dot{N}_p \\ incident\ light\ \ flux &= \Phi = \dot{N}_p\, h\frac{c}{\lambda} \end{aligned}\right\} \quad R(\lambda)=\frac{i}{\Phi}=\frac{\lambda}{hc}e\eta(\lambda)\approx 0.8066\,\underset{\uparrow}{\lambda}\,\eta(\lambda)\left[\frac{A}{W}\right]$$

in µm

Responsivity increases with wavelength, as radiation is quantized in smaller units for large wavelengths (a sensor for the 3-5 µm range is intrinsically 10 times more sensitive than a detector for visible light).

Photomultiplier Tube (PMT)

Photomultiplier tubes are light detectors that are useful in low light intensity applications. Due to their high gain are they able to detect very very weak light radiation.

The main elements are : ***a)*** a windows, ***b)*** a photocatode, ***c)*** a focusing electrode, ***d)*** electron multiplier (dynodes) and ***e)*** a anode usually sealed in a evacuated glass tube.

The signal from the photomultiplier is generated through the following steps

1. Light enters through a glass or quartz window
2. Light impinge over a photosensitive surface, called a photocathode. Due to photoelectric effects electrons are emitted from the surface into the vacuum.
3. Photo-electrons are focused and accelerated by the focusing electrode over the first dynode where they are multiplied by means of secondary electron emissions.
4. The multiplied secondary electrons emitted by the last dynode are finally collected by anode.
5. he current flowing from the anode to ground is directly proportional to the photoelectron flux generated by the photocathode.

PMT can detect single photons

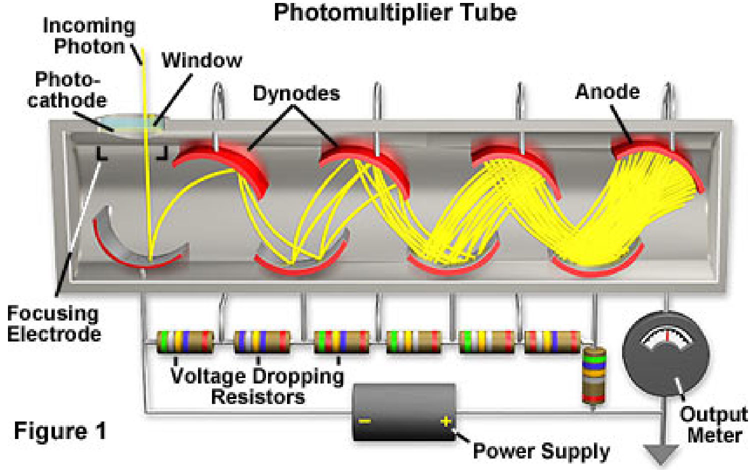


Figure 1

The spectral response, quantum efficiency, sensitivity, and dark current of a photomultiplier tube are determined by the composition of the photocathode.

The best photocathodes capable of responding to visible light are less than 30 percent quantum efficient, meaning that 70 percent of the photons impacting on the photocathode do not produce a photoelectron and are therefore not detected.

Too high photocurrent over a long period of time will damage the PMT

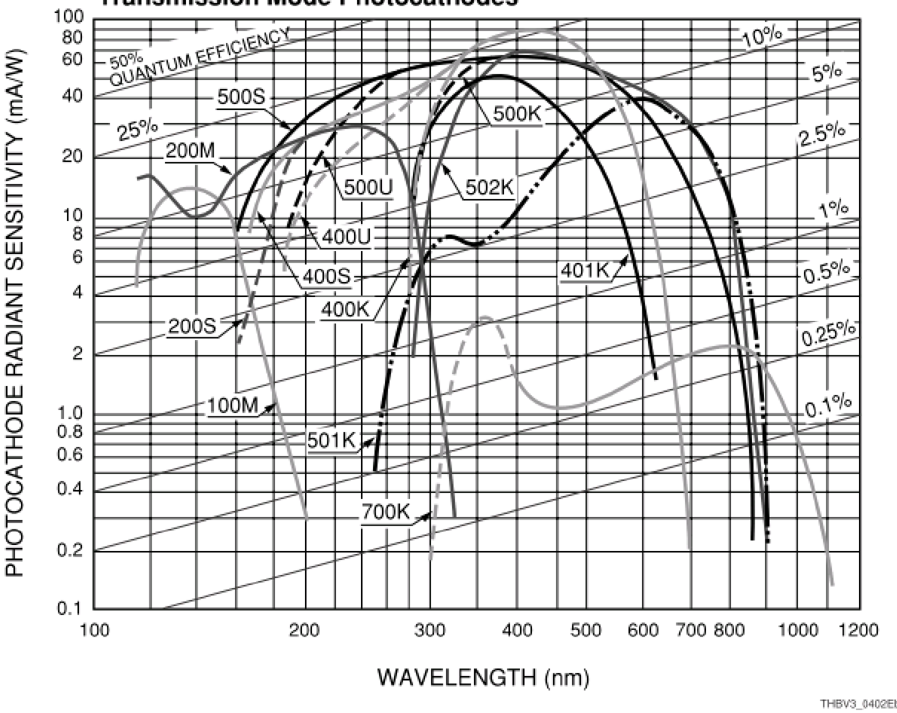
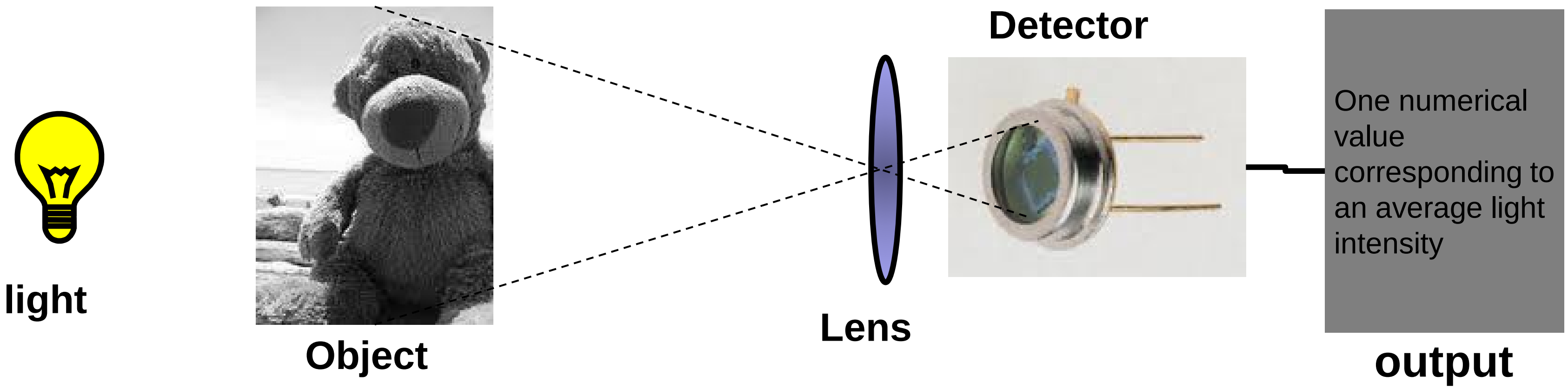


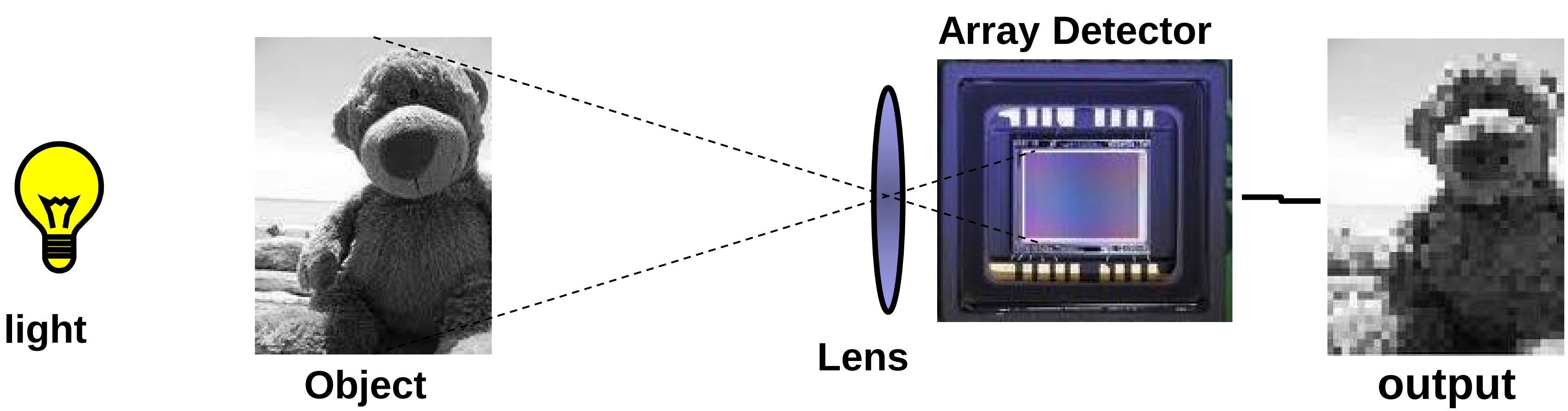
Figure 4-2 (b): Typical spectral response characteristics of transmission mode photocathodes

Array Detectors (1/7)

A quantum detector is able to convert light into an analog/digital signal but it lacks spatial discrimination!



By arranging single detectors in a dense array the light intensity of an image projected on the array is converted into a matrix of number (digital values)



To convert the ***image*** projected on the array detector in a digital format *two operations* are performed by the sensors:

a) SAMPLING

The ***image*** is divided into small interrogation areas (pixels) where the light intensity is spatially averaged and measured.

b) QUANTIZATION

The measured value of light intensity in each interrogation area is converted into a digital value of n bit, from black (0) through all of the intermediate gray levels, to white (2^n-1)

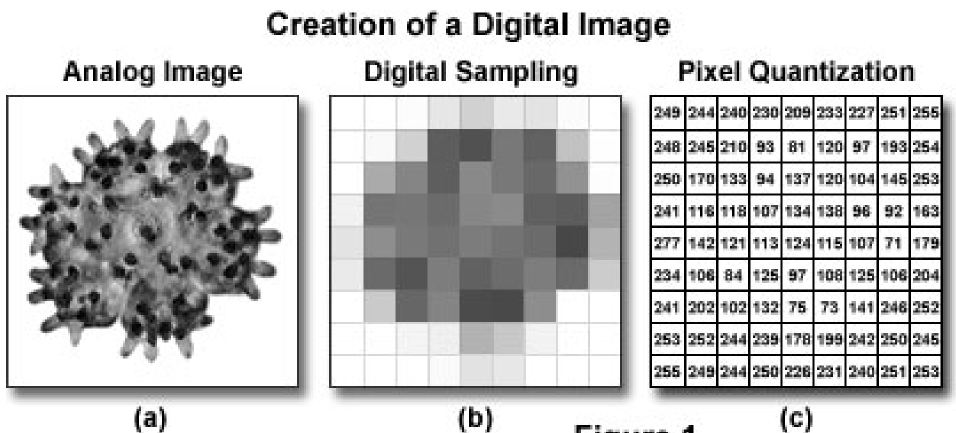


Figure 1

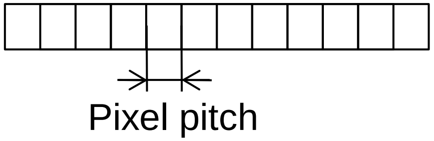
Usually each pixel that results from image digitization is represented by a coordinate-pair with specific x and y values arranged in a typical Cartesian coordinate system. The x coordinate specifies the horizontal position or column location of the pixel, while the y coordinate indicates the row number or vertical position. *By convention, the pixel positioned at coordinates (0,0) is located in the upper left-hand corner of the array*.

Array Detectors (3/7)
Pixel pitch

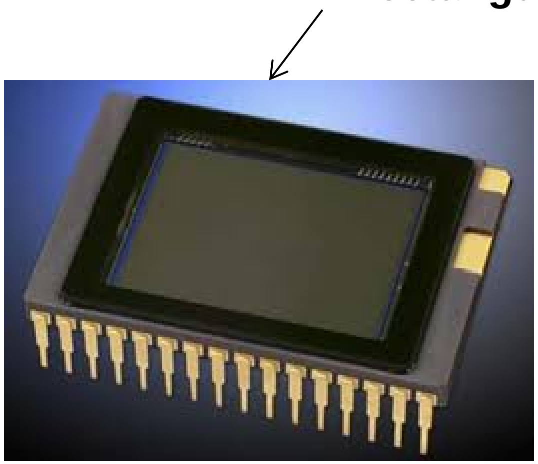
- Array and Linear detectors are composed of elements called pixels.
- Each pixel contain the light sensitive element + "light inert" region
- Pixels are usually aligned in row and column, have square/rectangular shapes
- The **pixel pitch/size** define the distance between two neighborhood pixels. For square pixel it has the same value along the x and y direction. Usually it does not correspond to the size of the light sensitive area!
- **Pixel pitch/size** set the maximum image resolution and light collection capability
- Typical pixel pitch: ***4 - 20 μm***

Linear array

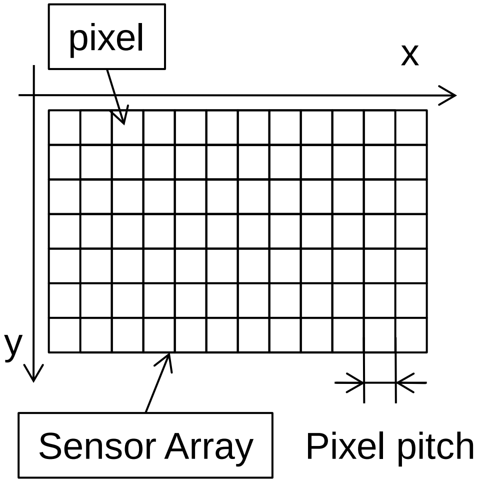
2048 (H) x 1 (V) pixels
14 μm (H) x 500 μm (V)



Rectangular array



3326 (H) x 2504 (V) pixels
5.4µm (H) x 5.4µm (V)



Array Detectors (4/7)
Fill factor

Usually not the whole area of a pixel is light-sensitive. Some of the pixel area can be intentionally (partially) shielded by metallic layer, or used for transistor, electrodes or registers needed by the structure of the pixel.

Only the light sensitive area might contribute to the light signal

Fill factor (FF) is defined as the ratio of light sensitive area versus the total area of the pixel.

- Larger fill factor increase pixel capability to collect photons, Higher the FF ⇨ higher the SNR
- Some sensor can have a fill factor of 100%
- Fill factor can be increased by using microlenses

Microlenses Advantage:

Light collecting area enlarged by a factor of 2-3

Microlenses Disadvantages:

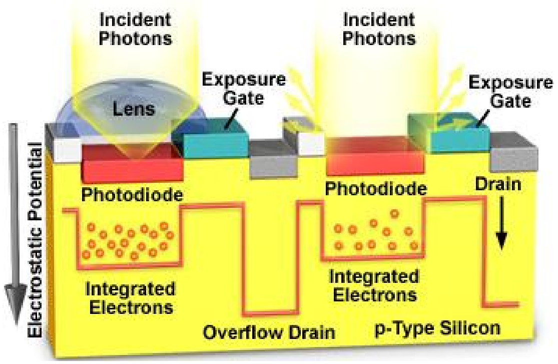
smaller acceptance angle for incoming light

lower than expected sensitivity at f-number<2, stronger fall off towards the edge of the array for wide angle lenses

limit UV sensitivity

size limitation for microlenses

In many cases Disadv are overcome by the increased sensitivity!



Microlenses array architecture

Array Detectors (5/7) Shuttering

- Shuttering refers to the ability to start and stop exposure of the sensor to light arbitrarily.
  - can be obtained either by a mechanical device or electronically
  - useful to avoid motion blur, to reduce unwanted ambient light, to avoid sensor overexposure

Mechanical Shutter

- Allows the sensor to be physically shield from the incoming light, does not allow very short exposure time (say below 1 ms). If located just in front of the sensitive element it is called focal plane shutter.
- An electronic LCD shutter can be used in place of the mechanical one (faster, not totally opaque to incoming light when closed, reduce light transmitted to the sensor)

Electronic Shutter

- Some sensor architecture allows to directly control for how long pixels have to collect the charge generated by the incoming light.

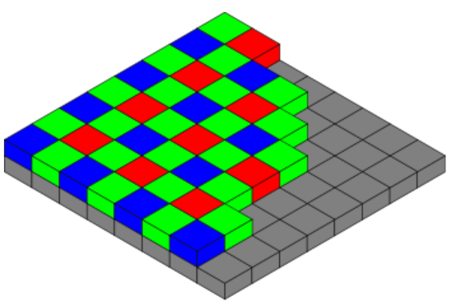
mechanical leaf shutter

Some sort of shuttering can be obtained by using flashlight.

Array Detectors (6/7)
Color Camera

An Electron-hole pair is formed by each photon having an energy above the band gap energy, independently from the photon wavelength. **Image sensors are ‘color blind’!**

Red, green, and blue are the primary colors that, mixed in different combinations, can produce most of the colors visible to the human eye. Thus by recording these three colors separately it is possible to reconstruct color tones at each pixel. This can be implemented in several way:



RGB filter (Bayer Filter)

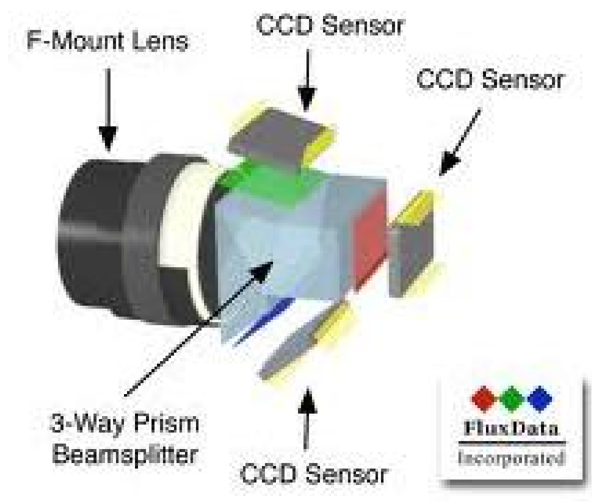
1 pixel for red,

1 pixel for blue,

2 pixel for green

(eye more sensitive to green)

Color reconstructed at each pixel by interpolating neighborhood color data (demosaicing)



3 Array Camera

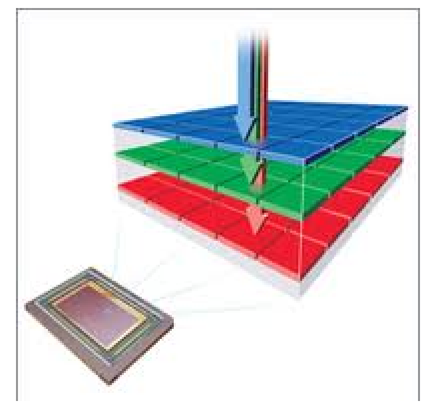
1 sensor for red,

1 sensor for blue,

1 sensor or green

No need for demosaicing!

More expensive

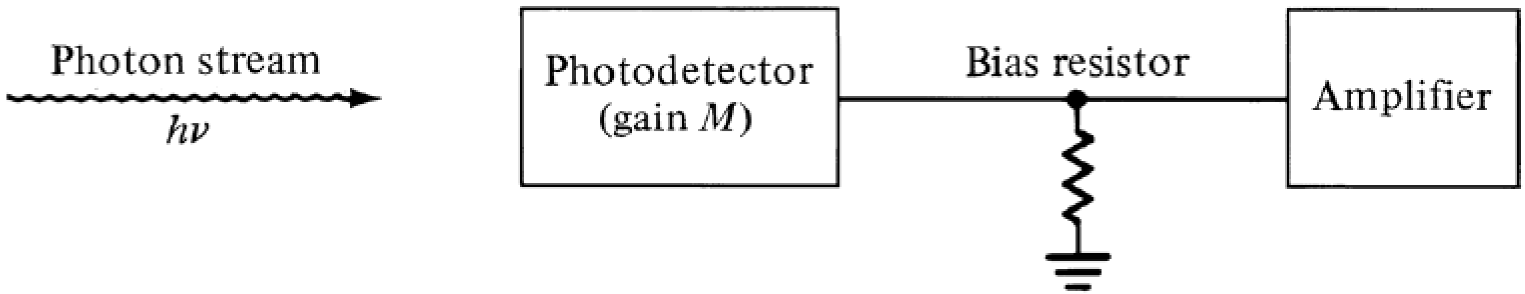


Vertical color filter

based on the wavelength-dependent absorption of light in silicon.

3 sensors stacked one in top of the other

Noise Source in Array Detectors



- Photon detection quantum noise (Poisson fluctuation)

- Bulk dark current
- Surface leakage current
- Statistical gain fluctuation (for avalanche photodiodes)

- Thermal noise

- Amplifier noise

Photon noise

Dark noise

Read noise

Noise Source in Array Detectors (1/3)
Three principal source of noise

1) Dark Noise – *signal not generated by light, but by thermally induced electrons!*

Due to thermally induced electrons even in absence of light the sensor will output a signal called **dark current**. *Dark current depends exponentially upon sensor temperature and a temperature reduction of 7-10 K will halve the value of the dark current.*

Charge generated by dark current is a random signal obeying to Poisson statistics. Its mean value can be removed from the signal, anyway its statistical fluctuation gives rise to ***dark noise***.

Being a Poisson process the **variance of dark noise, σ^2_{dn}**, and the mean value of the charge generated by the dark current are equal.

$$\sigma_{dn}^2 = \text{dark current} \cdot t_{\text{exposure}}$$

$$\text{Poisson distribution P(z)=}\frac{z_{mean} e^{-z_{mean}}}{z!}, \quad z_{mean} = E(\text{z}), \ \text{var(z)} = z_{mean}$$

Higher the dark current, higher the noise, lower the SNR!

Dark current and **dark noise** are respectively given in e^-/s and e^- *(RMS)*

2) Read Noise

It is a combination of system noise components inherent to the process of converting charge carriers into a voltage signal, and the subsequent processing and analog-to-digital (A/D) conversion. *Usually read noise, σ^2_r, dominate over dark noise*

3) Photon-noise

Even an ideal noise-free detector will give a noisy measurement!

This because generation of photon itself is a random process, thus the instantaneous number of photon impinging on the detector will vary with time even if their average values is constant (**photon-noise**).

Photon-noise obey to Poisson statistics, thus its variance, $\sigma^2_{photon-noise}$, is equal to the average number of photon impinging, N_p, on the sensor during the exposure time:

$$\sigma^2_{(photon-noise)} = N_p$$

The corresponding electronic noise is given by ($\eta =$ quantum efficiency):

$$\sigma^2_{e(photon-noise)} = \eta\sigma^2_{(photon-noise)} = \eta N_p$$

The *full well capacity* fixes the maximum signal level (the accumulated charge N_e) thus it set also the maximum SNR!

Whenever the detector related noise is below the photon noise a detector is said to have

photon-noise limited performances.

Noise Source in Array Detectors (3/3)

Dynamic Range

Is the ratio of the maximum output signal to the standard deviation of noise ($\sigma^2_{dn} + \sigma^2_r$), it is usually expressed in dB (a more accurate definition of DR is given in EMVA Standard 1288)

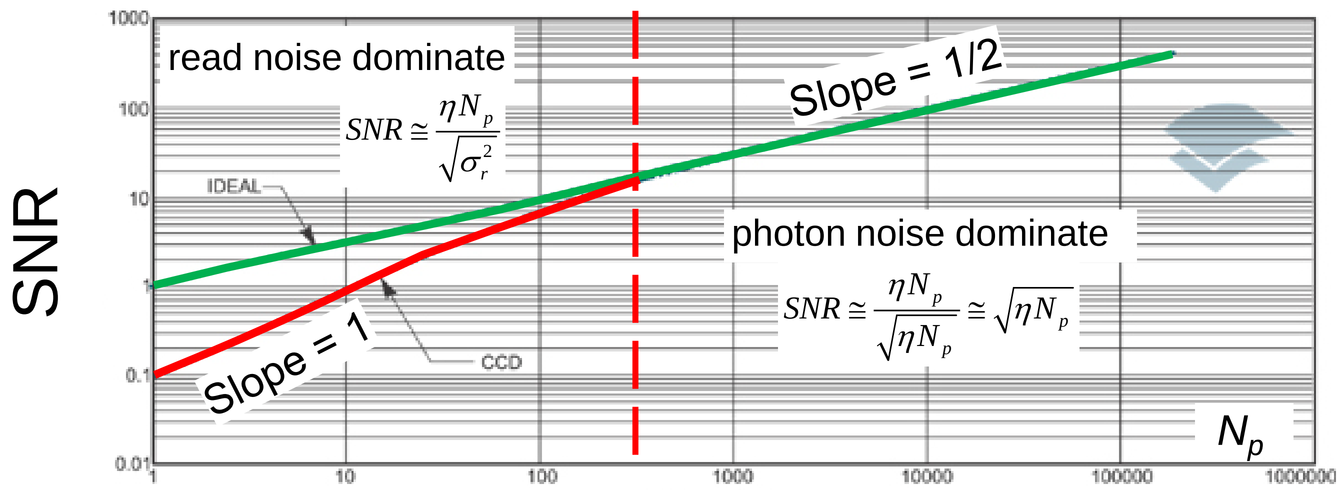
$$DR = 20 \log \frac{S_{max}}{\sqrt{\sigma_{dn}^2 + \sigma_r^2}} \qquad S_{max} = \text{full well capacity}$$

Signal to noise ratio (SNR)

The precision of measured irradiance depends on the ratio of the received signal and its standard deviation

$$SNR = \frac{\eta N_p}{\sqrt{\sigma_{dn}^2 + \sigma_r^2 + \eta N_p}} = \text{if negligible small dark noise} = \frac{\eta N_p}{\sqrt{\sigma_r^2 + \eta N_p}}$$

At low irradiance the SNR is limited by read noise, while at high irradiance limited by photon noise



The most commonly used image array (focal plane array) for quantitative (scientific) imaging are :

Charge-Coupled Device (CCD)

and

Complementary Metal-Oxide Semiconductor (CMOS) sensors

What is a CCD ?

Fundamentally, a charge-coupled device (CCD) is an integrated circuit etched onto a silicon surface forming light sensitive elements called pixels.

Photons incident on this surface generate charge that can be read by electronics and turned into a digital copy of the light patterns falling on the device.

What is a CMOS ?

Fundamentally, a Complementary metal-oxide semiconductor (CMOS) sensors is an integrated circuit etched onto a silicon surface forming light sensitive elements called pixels.

Each pixel acts as a photodiode and has his own electronics (at least to address the pixel).

Differently from CCD some (3-6) transistors are contained in each pixel.

Technology to build CMOS is the same used for PC memory and microprocessor, but different from that of CCD (different performances).

CCD sensor

CCD was invented in 1969 at Bell's laboratory by W.S. Boyle and G.E. Smith

Originally developed as a memory device, alternative to magnetic bubble memories.

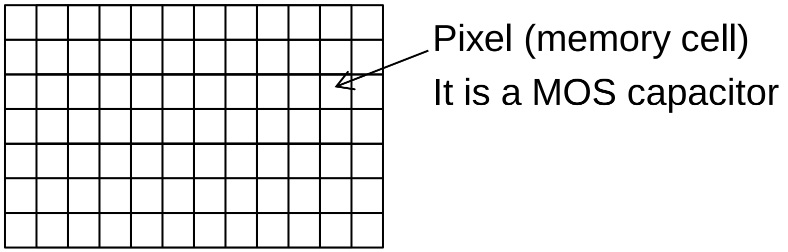
The physical quantity representing a bit of information is an electrical charge stored in a metal-oxide semiconductor (MOS) capacitor.

Charge can be moved about the CCD by arranging MOS capacitors very close to each other and by manipulating the voltage on the gate of capacitor in such a way that the charge spill from one capacitor to the next (this is why: charge-coupled device).

Charges are moved to a point where a charge detection amplifier detects the presence of the charge packet.

In CCD sensor the charge packets are generate by photovoltaic effect (optically)

CCD is a serial device! Charge packets are read one at time!



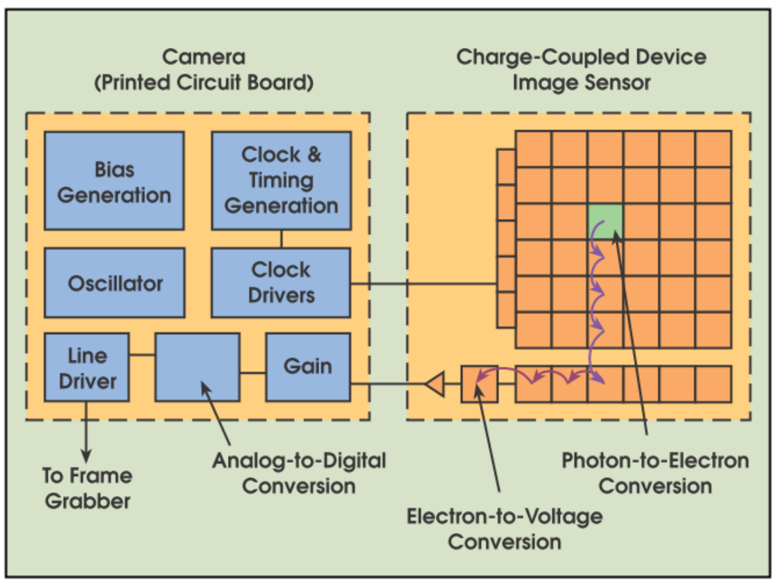
CCD array

CCD sensor
Tasks

For a CCD sensor four principal tasks can be higlighted

Charge generation → Charge collection → Charge transfer → Charge Measurements

$\underbrace{\text{Charge transfer} \rightarrow \text{Charge Measurements}}_{\textbf{readout}}$



Architecture of a CCD camera

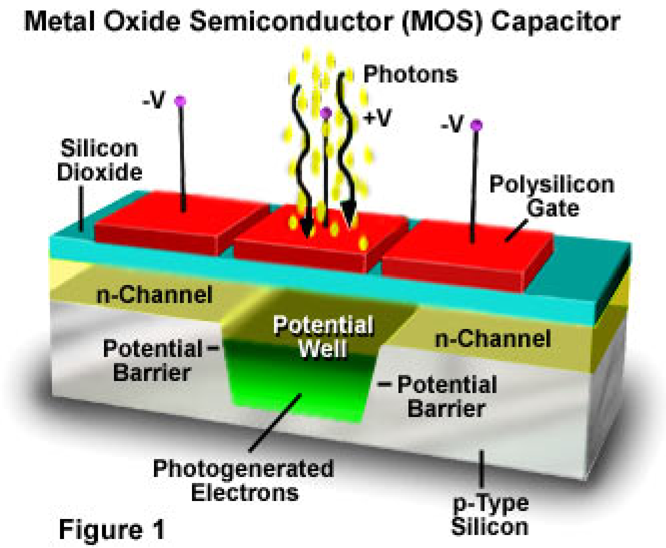
*The spatial arrangement of the accumulated charge has to be converted into an electrical signal. This process is referred as **read-out** and can be divided in two phases:*

charge transfer** and **charge measurements

CCD sensor
Charge generation and collection

For a CCD sensor four principal tasks can be higlighted

Charge generation → Charge collection → Charge transfer → Charge Measurements

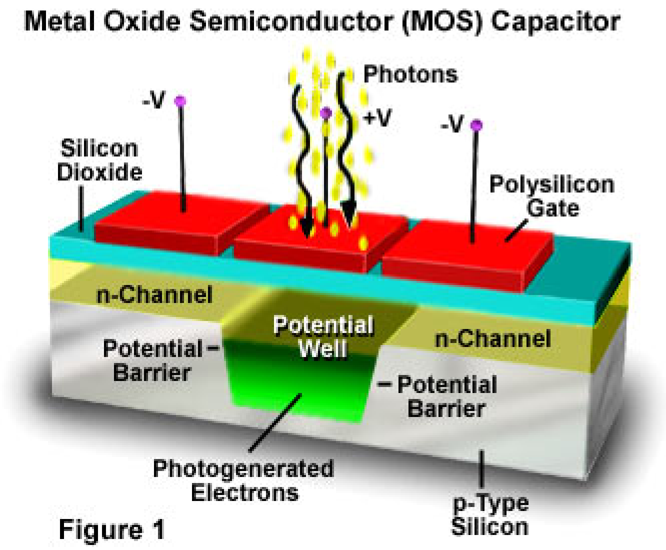


- Charge generated by photovoltaic effect in the light-sensitive region of each pixel
- Fill Factor can be higher than 90% (depends upon sensor architecture)
- Sensitive to near IR (below 1.1 μm)
- Reduced sensitivity in the blue and UV regions (short absorption length and Si reflectivity)

CCD sensor
Charge generation and collection

For a CCD sensor four principal tasks can be higlighted

Charge generation → **Charge collection** → Charge transfer → Charge Measurements



- The photo-electron are captured by potential well in cells (a capacitor)
- Photoelectrons accumulate in the potential well for a certain time (integration time)
- A limited number of photoelectrons can be stored: **Full well capacity**

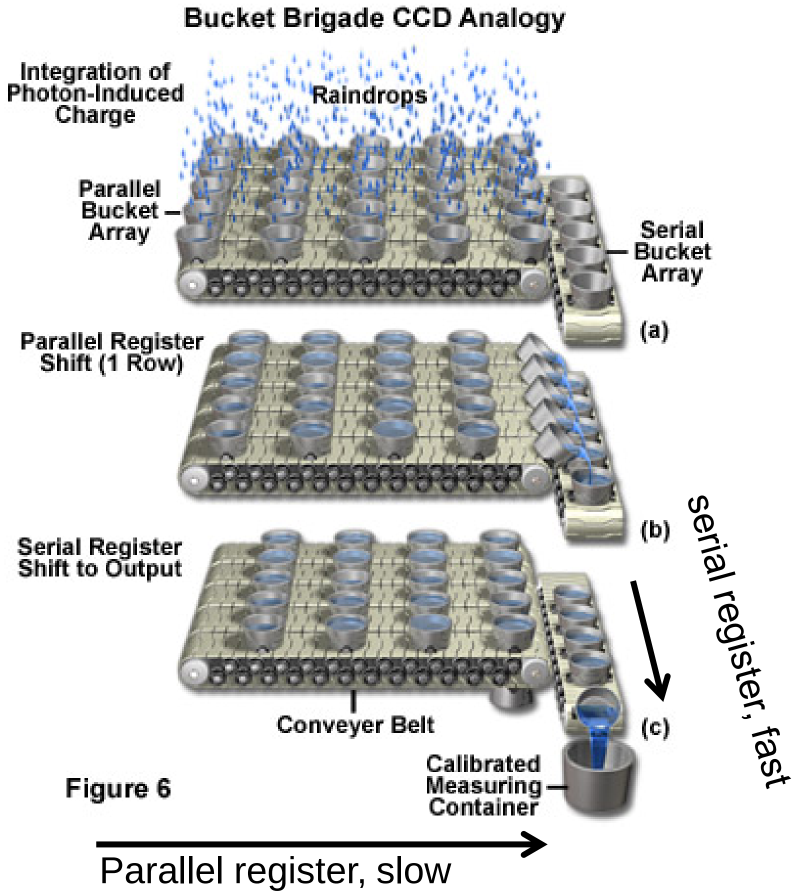
  Full well capacity limits SNR !
- **Blooming**: too much photoelectron $\Rightarrow$ they migrate to neighborhood pixels

  needs for antiblooming devices

CCD sensor
Charge transfer (1/6)

For a CCD sensor four principal tasks can be higlighted

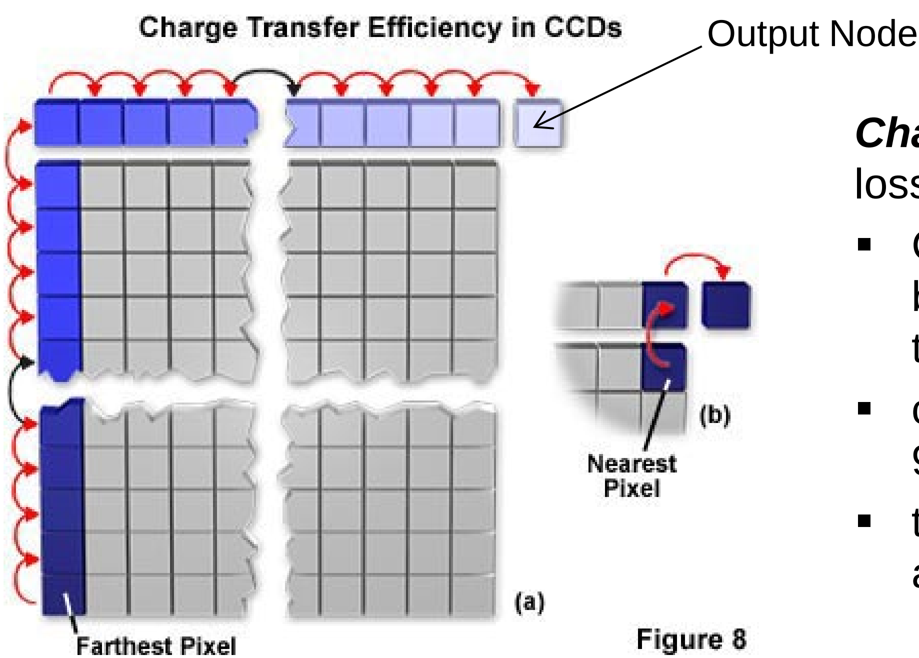
Charge generation → Charge collection → **Charge transfer** → Charge Measurements



CCD sensor
Charge transfer (2/6)

For a CCD sensor four principal tasks can be higlighted

Charge generation → Charge collection → **Charge transfer** → Charge Measurements



Charge transfer has to be accomplished without loss of the collected charge

- Charge Transfer Efficiency (**CTE**) is the ratio between the amount of transferred charge versus the original charge stored in the pixel
- currently high-end CCD sensors have a CTE of 99.999 %
- the highest CTE obtained at low transfer speed and low temperature

CCD sensor
Charge transfer (3/6)

For a CCD sensor four principal tasks can be higlighted

Charge generation → Charge collection → **Charge transfer** → Charge Measurements

For large sensor, or to improve frame rate, parallel readout can be implemented

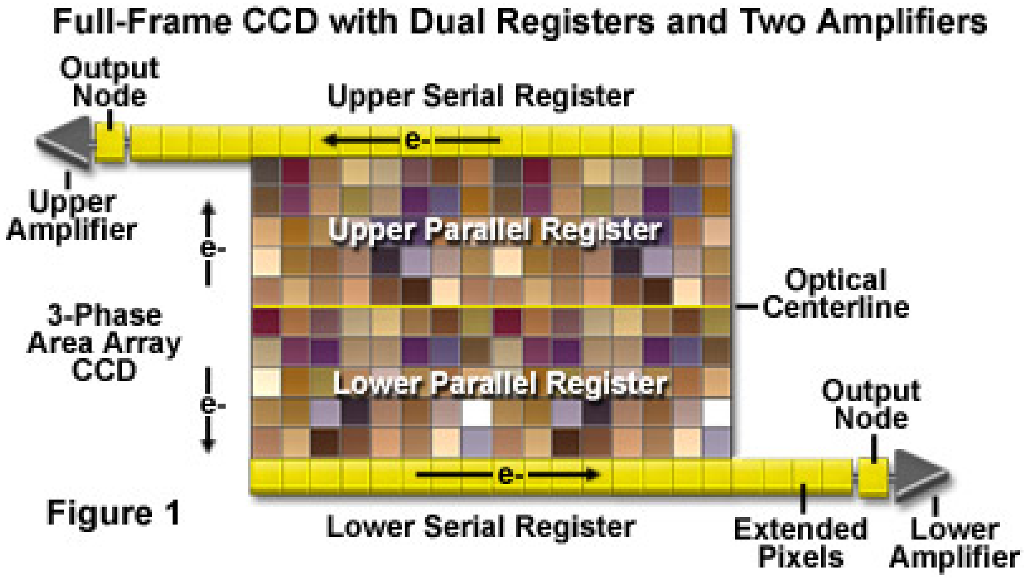


Figure 1

Mismatch between different channels !!

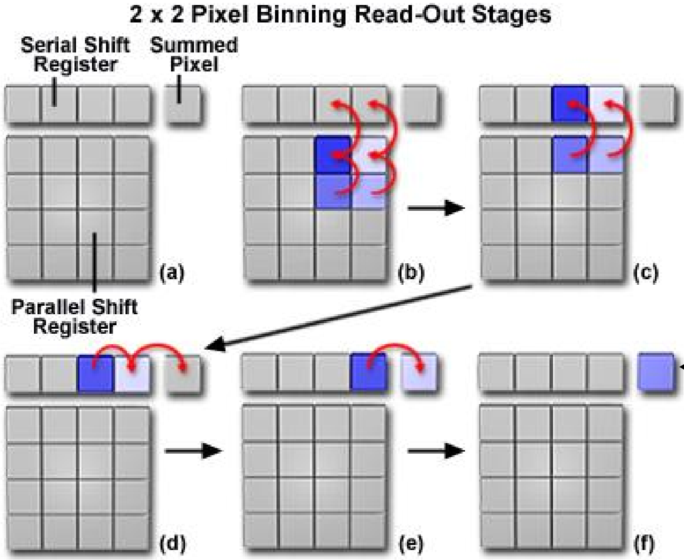
CCD sensor
Charge transfer (3/6)

For a CCD sensor four principal tasks can be higlighted

Charge generation → Charge collection → **Charge transfer** → Charge Measurements

To improve SNR and frame rate pixel can be binned (2X2, 3X3…*nxn*)
i.e. the charge generated by neighborhood pixel is summed!!!

- less rows to read-out
- signal increases with n^2, while noise just as n



Output Node: summing well, large enough to accommodate the binned charges

CCD sensor
ARCHITECTURE FOR CHARGE TRANSFER (1/3)

For a CCD sensor four principal tasks can be higlighted

Charge generation → Charge collection → **Charge transfer** → Charge Measurements

1) FULL FRAME TRANSFER CCD (FFT CCD)

The pixels are read-out sequentially (progressive scan) on a row-by row basis

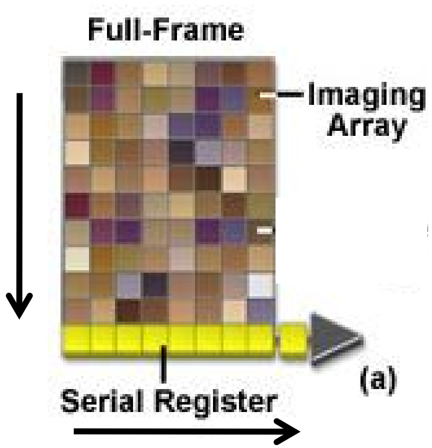
Most of scientific and professional digital cameras use FFT sensors

ADVANTAGES

- pixel have very high Fill Factor (close to 100% for back-illuminated back-thinned sensors)
- very low noise-level and high dynamic range is possible
- very large array available (more than 10^7 pixels)

DISADVANTAGES

- the sensor stay active during charge transfer, (mechanical shutter or flashlight required)



CCD sensor
ARCHITECTURE FOR CHARGE TRANSFER (2/3)

For a CCD sensor four principal tasks can be higlighted

Charge generation → Charge collection → **Charge transfer** → Charge Measurements

2) FRAME TRANSFER CCD (FT CCD)

Lower half of rows of CCD sensors are masked, and used as charge storage area before conversion

Once exposed the charge in imaging array are quickly shifted in the storage array (transfer time about 0.5-1 ms)

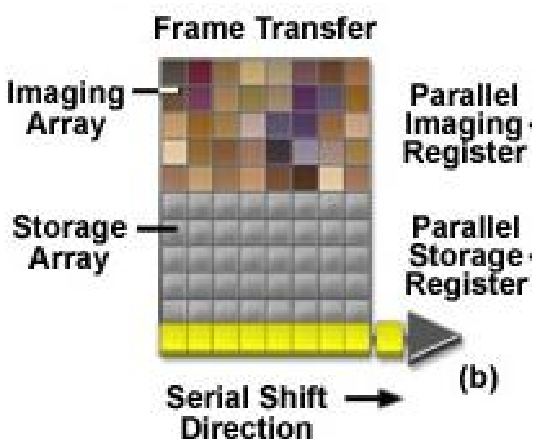
Charges in storage array read as in FFT CCD

ADVANTAGES

- pixel have very high Fill Factor
- shutter capability

DISADVANTAGES

- The sensor stay active during vertical transfer time, vertical smear is possible (mechanical shutter or flashlight required)
- due to the need of a storage area, vary large array can not be afforded



CCD sensor
ARCHITECTURE FOR CHARGE TRANSFER (3/3)

For a CCD sensor four principal tasks can be higlighted

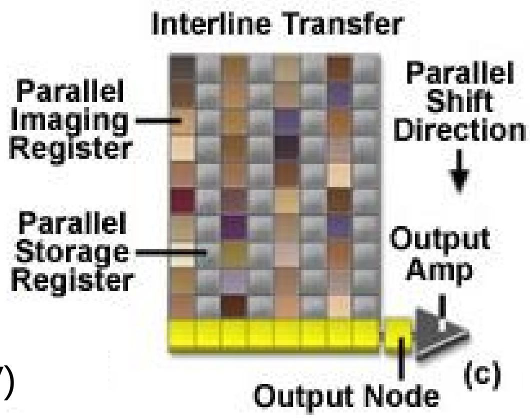
Charge generation → Charge collection → Charge transfer → Charge Measurements

3) INTERLINE FRAME TRANSFER CCD (IT CCD)

Each pixel has a charge storage area at its side.

At the end of the exposure period the charge is transferred to the storage site (transfer time <1 μs)

Charges from storage sites are shifted one row at time in the serial register and then read-out sequentially.



ADVANTAGES

very fast electronic shutter

a couple of images can be collected within a very short time interval (PIV)

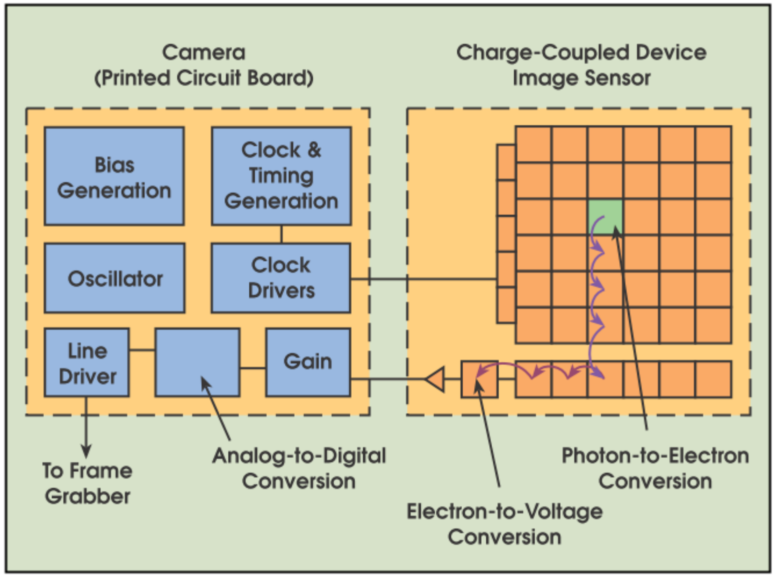
DISADVANTAGES

Due to storage register, fill factor is quite small ~20-30%(microlenses)

CCD sensor
Charge measurement

For a CCD sensor four principal tasks can be higlighted

Charge generation → Charge collection → Charge transfer → Charge Measurements



The latest node is connected to a charge amplifier to convert the charge into a voltage.

An ADC external to the sensor convert the analog signal into a digital one (of n bit)

ADC works at pixel frame rate frequency

$$ADC_f = 2*pixel_y*pixel_x*frame\ rate$$

From kHz to few 10MHz bandwidth

i.e. max. frame rate ~ 1-10 Hz

Signal conditioning, ADC and noise reduction systems implemented outside the sensors.

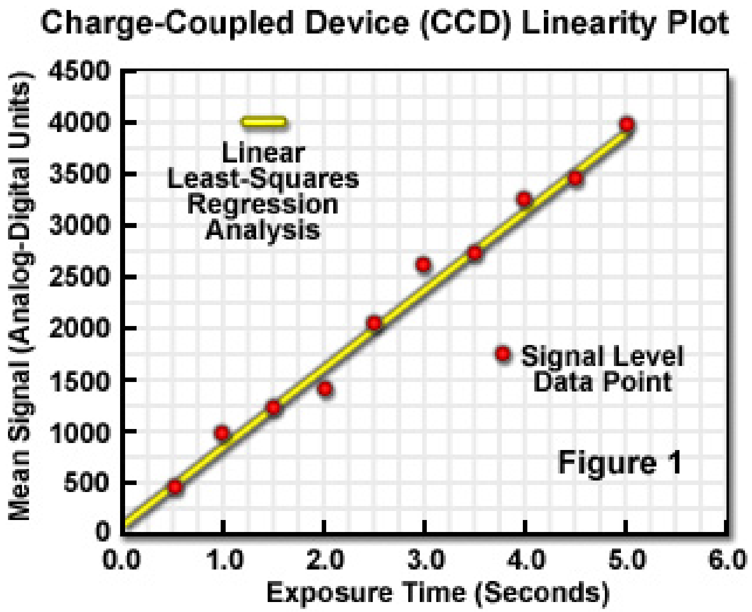
CCD sensor Linearity

An important characteristic of a scientific imaging system is the linearity in response to radiant energy, particularly when applied for quantitative photometric analysis.

In digital camera systems employing charge-coupled device (CCD) sensors, the fundamental function of the CCD is to convert photons carrying image information into an electric signal.

After digitization, the signal output should ideally be linearly proportional to the amount of light incident on the sensor (number of photons).

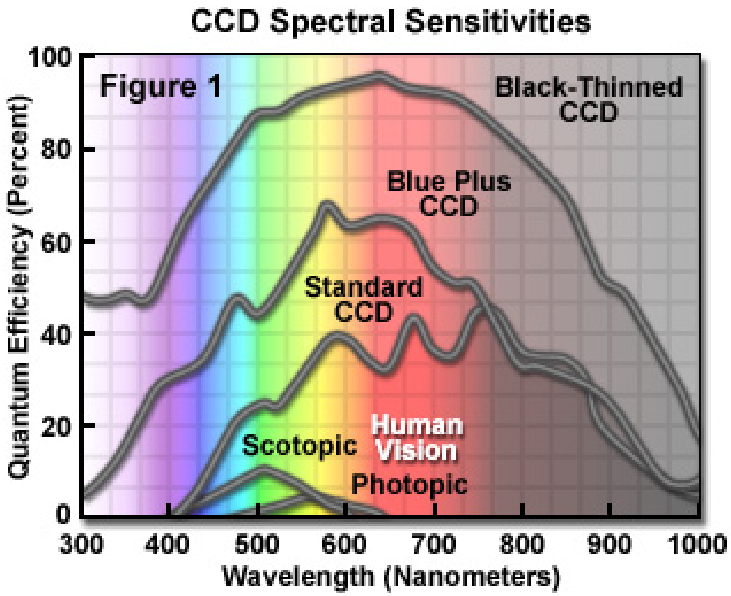
The norm issued by the European Machine Vision Association Standard: “Characterization of Image Sensors and Cameras” EMVA Standard 1288, fix a standard procedure for evaluating sensor and camera performances.

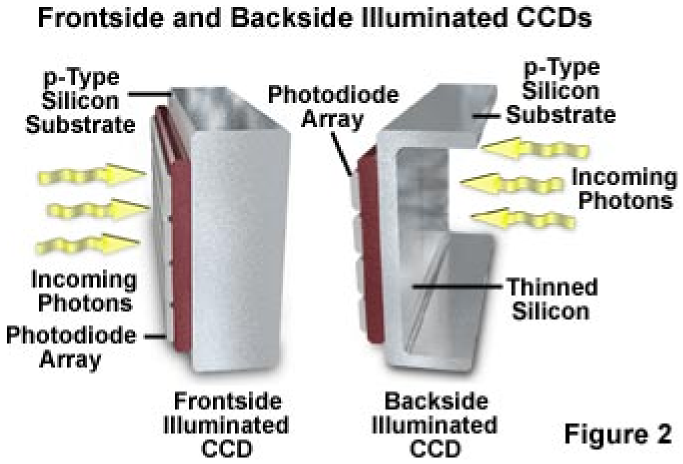


Non-linearity can be defined as a deviation of the measured data from the ideal straight line

CCD sensors have a very good linear response! Non-linearity below 1-2%

CCD sensor Quantum Efficiency





- Higher Quantum Efficiency means higher signal level!
- Quantum efficiency is usually is much less than 100%. It can be improved
  - AR coating
  - Phosphor coating to enhance UV response
  - Back-illuminated and Back-thinned sensors can reach 100% QE
    difficult to manufacture, expensive

CMOS sensor

From the point of view of charge generation, CMOS sensors are similar to CCD

CMOS sensors conceived at the end of 60s, nevertheless CMOS technology at that time do not allows to manufacture sensors of good quality (noisy images and not uniform array response)

The CMOS technology allows transistors to be easily integrated in the sensor array, thus both charge storage and conversion can be obtained at pixel level.

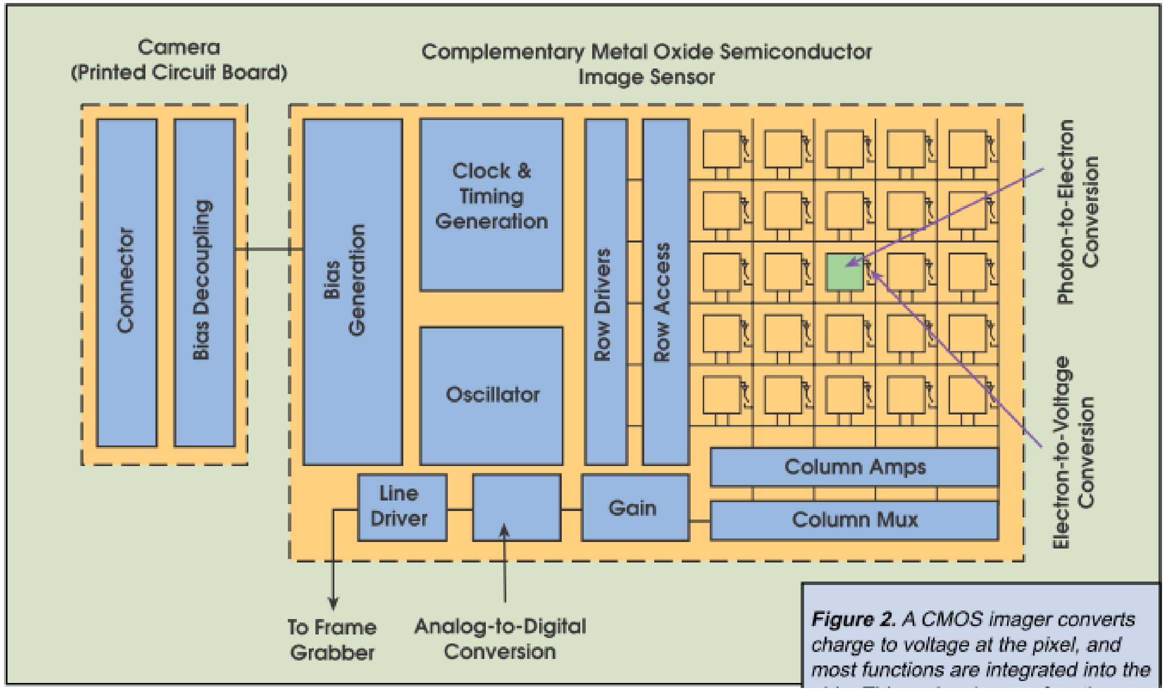


Figure 2. *A CMOS imager converts charge to voltage at the pixel, and most functions are integrated into the*

CMOS sensor

Two different pixel architectures:

- ***Passive Pixel Sensor Array (PPS CMOS)***

  each pixel contains only transistors used for row and column addressing

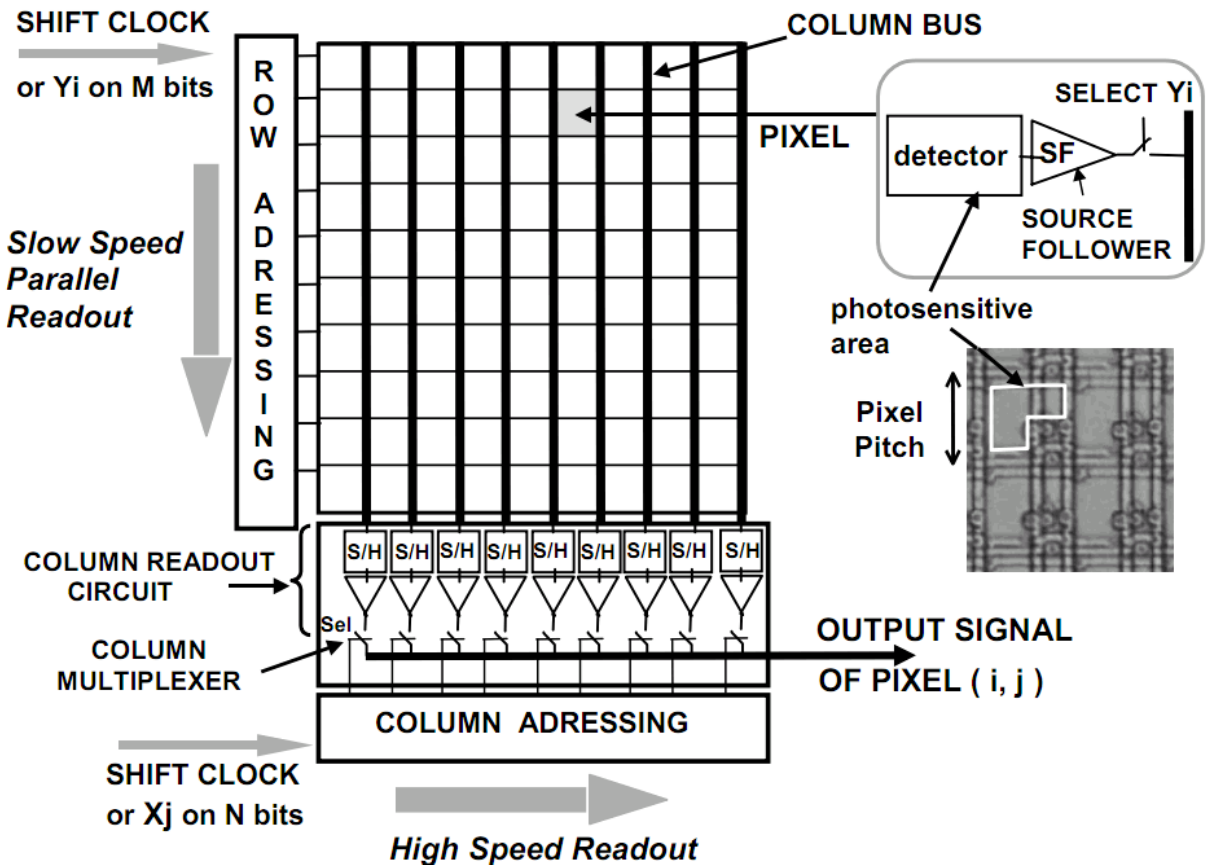
- ***Active Pixel Sensor Array (APS CMOS)***

  each pixel contains transistors for charge to voltage conversion, amplification and addressing

Massively parallel readout circuits can be easily added to the sensor, thus high speed imaging is possible (up to several 100kHz) by reading out just a portion of the sensor array (**windowing**).

Phantom V710	1’400’000 fps @ 128*8 pixels, 7’530 fps @ 1280x800 pixels
Photron SA5	1’000’000 fps @ 64*16 pixels, 7’500 fps @ 1024x1000 pixels
NAC HX1	1’300’000 fps @ 384*8 pixels, 7’000 fps @ 1280x1024 pixels

CMOS sensor
APS - CMOS



Each pixel has a photosensitive area + some transistors (3-6), fill factor in APS CMOS is 20-65 %

Benefits to FF from improving in manufacturing technologies (shrink transistor size)

Microlenses array to improve FF (increases manufacturing costs)

Higher SNR than PPS

CMOS sensors
Shuttering

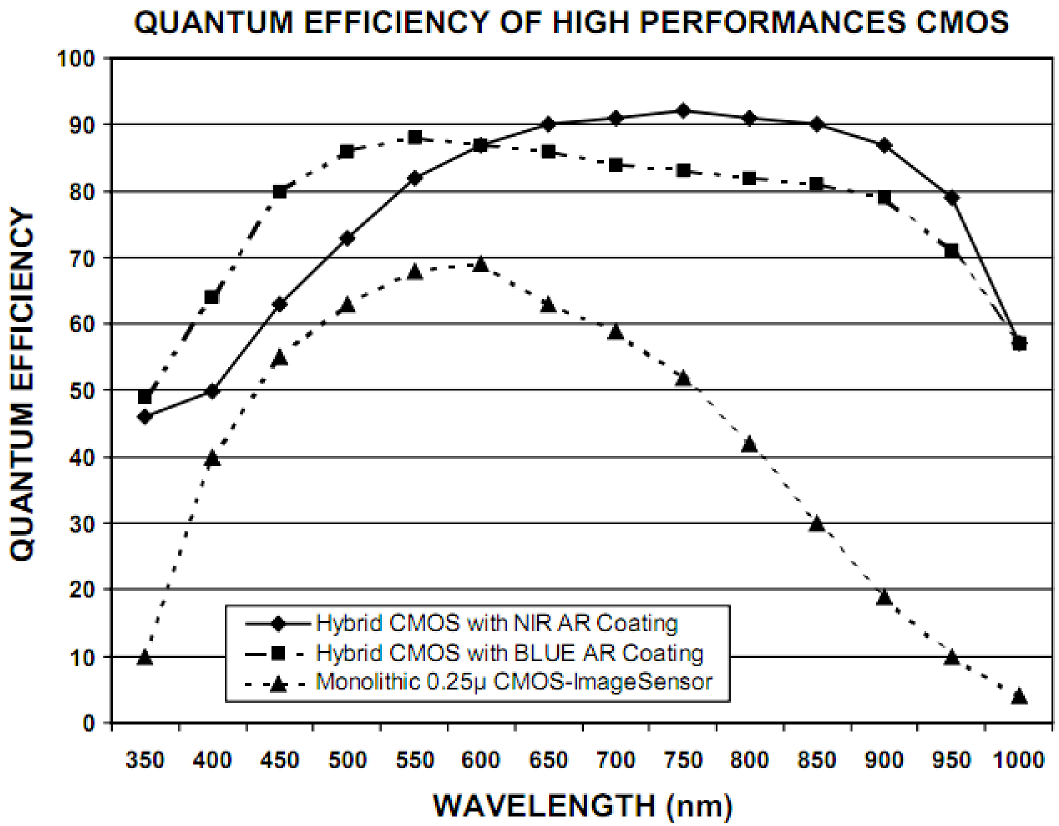
Both mechanical and electronic shutter can be implemented in CMOS sensors

A uniform synchronous shutter, **global (non-rolling) shutter**, exposes all pixels of the array at the same time. A charge storage area (similar to IT-CCD) is required!

In CMOS array sensors, global electronic shuttering comes at the expense of fill factor (more transistor needed)

A non uniform shutter, **rolling shutter**, exposes different lines of an array at different times. Simpler to implement (less in-pixel transistors), improves fill factor but distorts image of a moving object.

CMOS sensor
Quantum Efficiency



- Quantum efficiency for CMOS is about 20-30%. It can be improved
  - AR coating
  - Back-illuminated and Back-thinned sensors (very recent, difficult to implement)

CMOS vs CCD

CCD sensor

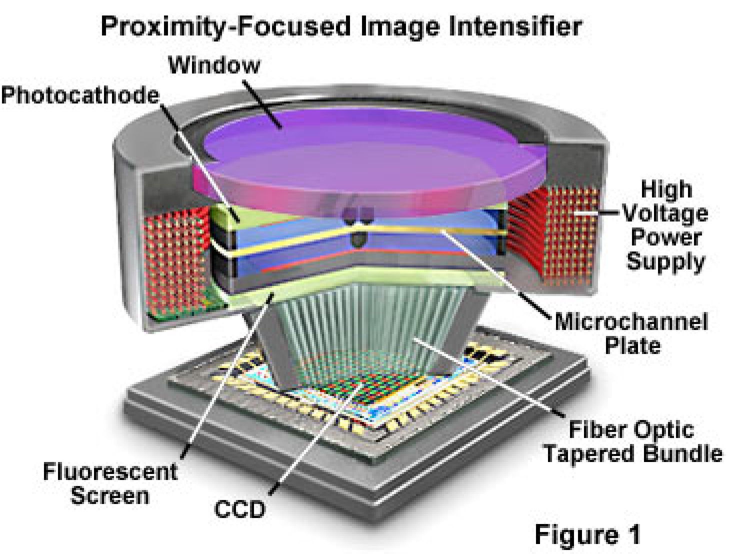
- Lowest noise
- Lowest dark current
- Linear sensor response
- Small pixel non-uniformity
- output is a analog signal
- Slow frame rates
- High power dissipation

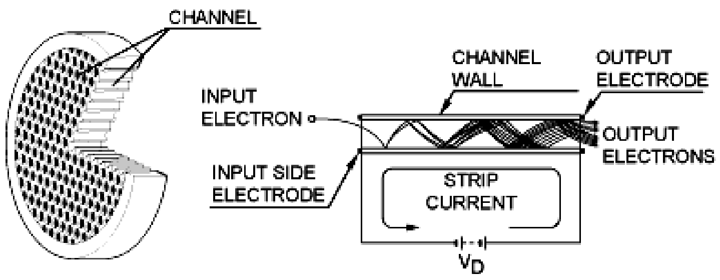
CMOS sensor

- can output directly digital data
- High frame rates
- Small power dissipation
- Random pixel access
- Almost no smear and no blooming
- Noisier than CCD (Higher dark current)
- Slightly non-linear sensor response
- Pixel non-uniformity

CCD sensors usually preferred when low noise and high images quality are required
CMOS only choice when long recording time at high frame rates are required

Scientific CMOS having very low noise have been recently released (2011)





MCP (microchannel plate)

An image intensifier is a device that intensifies low light-level images to light levels that can be detected by a video camera.

An image intensifier is a vacuum tube.

Input window on which inside surface a light sensitive layer called the photocathode has been deposited.

Photons absorbed in the photocathode give rise to emission of photo-electrons into the vacuum.

Photo-electrons are accelerated by an electric field.

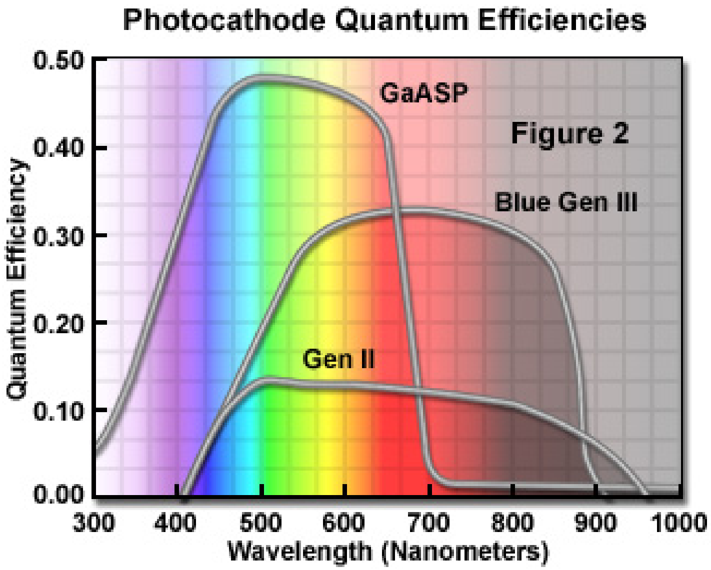
Photo-electrons multiplication by a MCP (micro-channel plate)

Electrons accelerated towards the anode (+) screen. (anode screen contains a fluorescent layer).

Energy of electrons striking the anode converted into photons (a much brighter image is generated).

Photons are delivered to the array sensor by a fiber optics bundle or either a relay lens system (the latter has a poor light transfer efficiency)

Low light imaging
INTENSIFIER



Photocatode material has its own QE

Thus its choice depends upon the wavelength of light to be detected.

- Intensifier can be switched on and off very very quickly (~ns), it can act as a shutter
- Intensifier for high frame rate sensor available (short time decay of fluorescent layer to avoid image persistence)
- Electron gains of more than 10^3 are possible (from 1 photo-electron $\rightarrow$ 1000 electron)

- Image resolution of CCD+Intesifier is about 75% of CCD alone, set by geometry of microchannel plate
- Dynamic range is reduced as compared to slow-scan CCD. (wells fill much faster upon intensification due to the electron multiplication, MCP saturation)
- High photocurrent over a longer period of time will damage the intensifier

Low light imaging
EMCCD sensor

Imaging capability of very low signal level limited by the read noise floor of the sensor

An innovative method of amplifying low-light-level signals above the CCD read noise is employed in electron multiplying CCD technology. The electron multiplying CCD incorporates a structural enhancement to amplify the captured signal *before* the charge is transferred to the on-chip amplifier, which has the effect of reducing the read noise, relative to signal, by the value of the multiplication gain factor.

High SNR at frame rate higher than standard CCD

EMCCD offers some advantages over intensifier

- Cheaper, preserve resolution, spectrally broad quantum efficiency, immunity to damage from high light levels
- Not appropriate for very fast gating

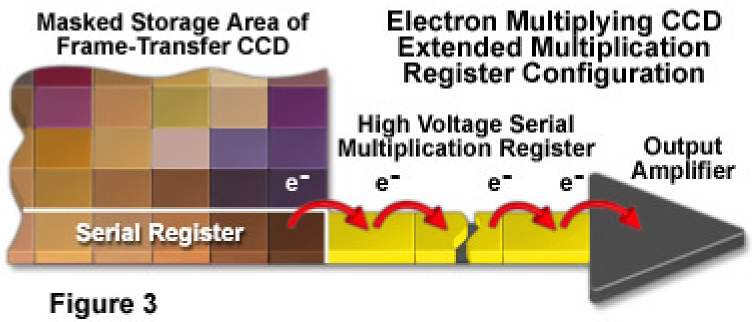


Figure 3

Electron Multiplying and Intensified CCD Quantum Efficiencies

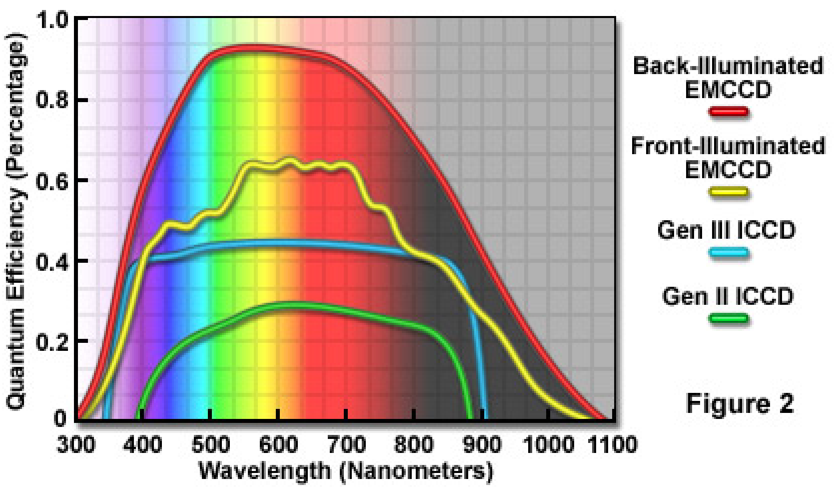


Figure 2

LIGHTING SYSTEMS

Usually lighting systems are a fundamental requirement for any experimental activity based on imaging or light detection

In some cases (flame chemiluminescence, heated surfaces, astronomy) light can be generated by the investigated physical phenomena, so lighting system is not required

Several types of light sources are available, besides the different ways by which light can be generated, their most interesting properties for imaging purposes are:

- Emitted light spectrum
- Emitted light flux (and its temporal stability)
- Strobe capability (repetition rate, pulse length, peak power)
- Collimated light
- ……

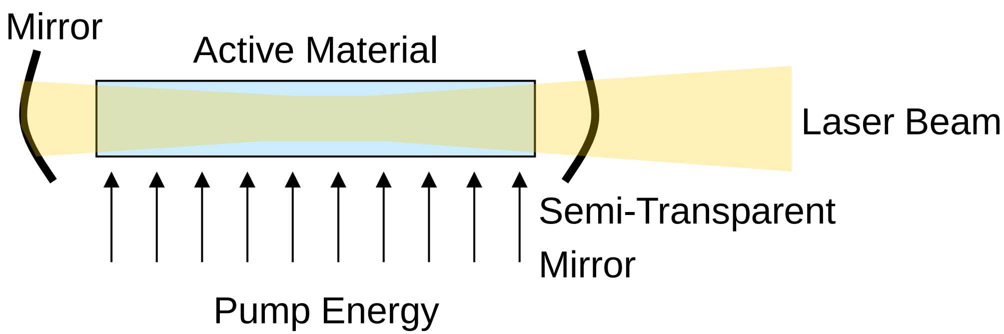
- **LASER** (stimulated light emission in an optically active media)
  - Solid state
  - Dye Laser
  - Gas
  - Semiconductor
- **GAS-DISCHARGE** (spontaneous light emission from excited gas molecule)
  - Xenon arc lamp (white light, pulsed, continuous, high power, used to simulate sunlight)
  - Deuterium arc lamp (strong UV source)
- **INCANDESCENCE** (thermal radiation)
  - Tungsten halogen lamp (visible+IR emission, high operating temperature)
- **ELECTROLUMINESCENCE** (light emission due to recombination of electron-hole pair)
  - LED (monochromatic emission, high pulse frequency and short pulse duration, low power, no IR)
- ……

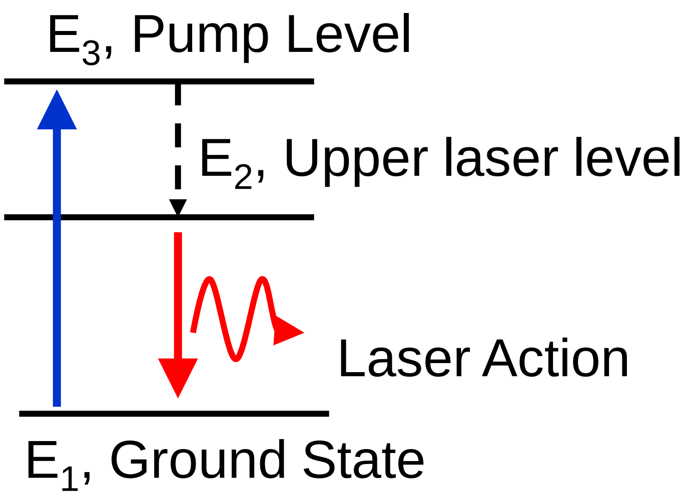
LASER PRINCIPLE

Laser is based on **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation

Population inversion ($N_2 > N_1$) is forced to take place in a active material by means of a pump mechanism (flash lamp, electrical discharge)

Once population inversion is achieved stimulated emission rapidly increases and an highly collimated, monochromatic light beam is emitted





Laser systems can be classified in several ways (active materials, wavelenght of emitted radiation,..)

Continuous

Relatively low power light (P_{max} = 0.01 – 50 W) of good beam quality, easy to set up and maintain

- ***Helium–Neon**,* $\lambda = 633$ nm
- ***Argon Ion*****,** several wavelengths, 488 nm, 514 nm ..

Single Pulse

- ***Ruby***

  $\lambda = 694.3$ nm, high pulse energy 1J, two pulses 1 to 500 μs apart with one laser, 1 pulse each ~30 s)

Repetitive Pulse

- ***Nd:YAG*** (yttrium aluminum garnet,$Y_3Al_5O_{12}$, *heavily used in PIV, pretty cheap ~40 k€*)

  2nd harmonic $\lambda = 532$ nm, max pulse energy ~0.5 J, double pulse require 2 lasers, flash lamps 10-50 Hz, high repetition rate are also available 1-10 kHz @ 10 mJ
- ***Nd:YFL*** (yttrium lithium fluoride,$YLiF_4$, $\lambda = 527$ nm)

  high repetition rate 1-10 kHz @ 10 mJ
- ***Copper Vapour***

  very expensive!, high repetition rates: 10-100 kHz, low pulse energy ~ 10mJ

Semiconductors, Diode-pumped Solid State Laser (DPSS)

WHY USE LASER IN FLOW IMAGING?

Laser radiation has some peculiar/useful properties:

- *Monochromatic*
  Easier to reject unwanted light (filtering)
  No chromatic aberration, no light dispersion

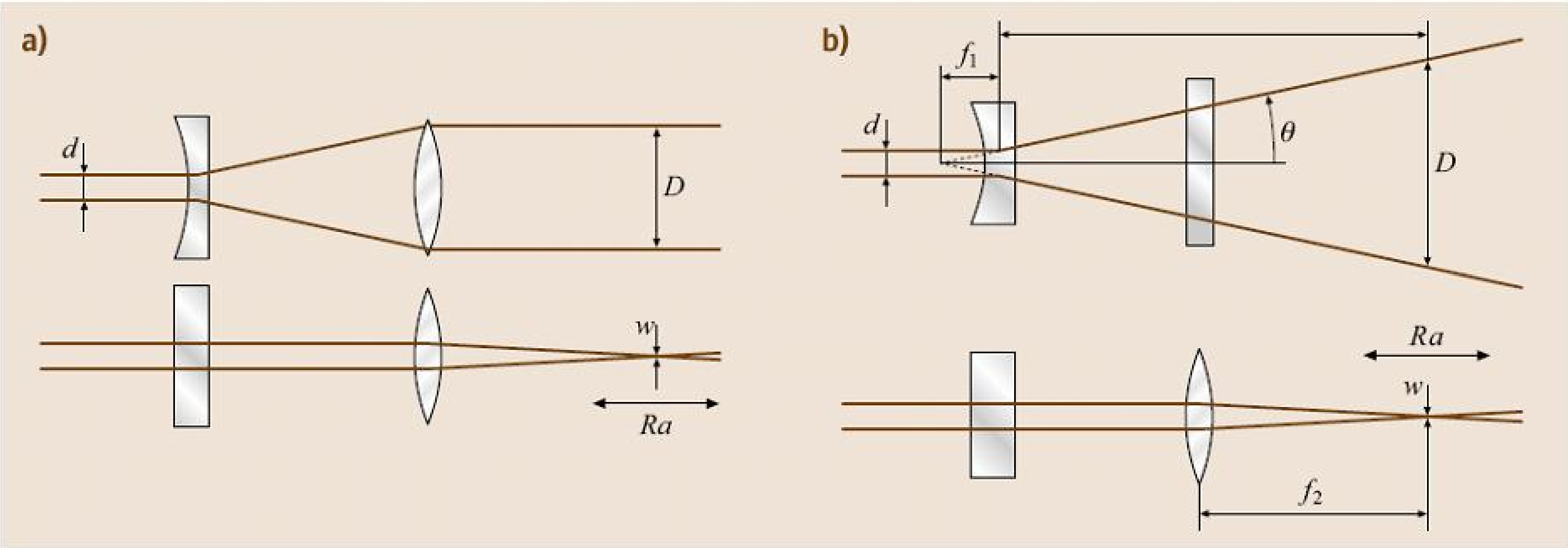
- *Collimated light beam*
  easy to generate sharp light sheet and to small beam waist

- *Spatial and temporal coherence*
  easy to generate interference, holography

- *Pulsed laser, very high pulse power (tens of MW, J in tens of ns)*
  useful when imaging very small particle (PIV, Rayleigh and Raman scatter)

- *Very short pulse duration (ns - fs)*
  allows to avoid blur when imaging very fast object

LIGHT SHEET OPTICS



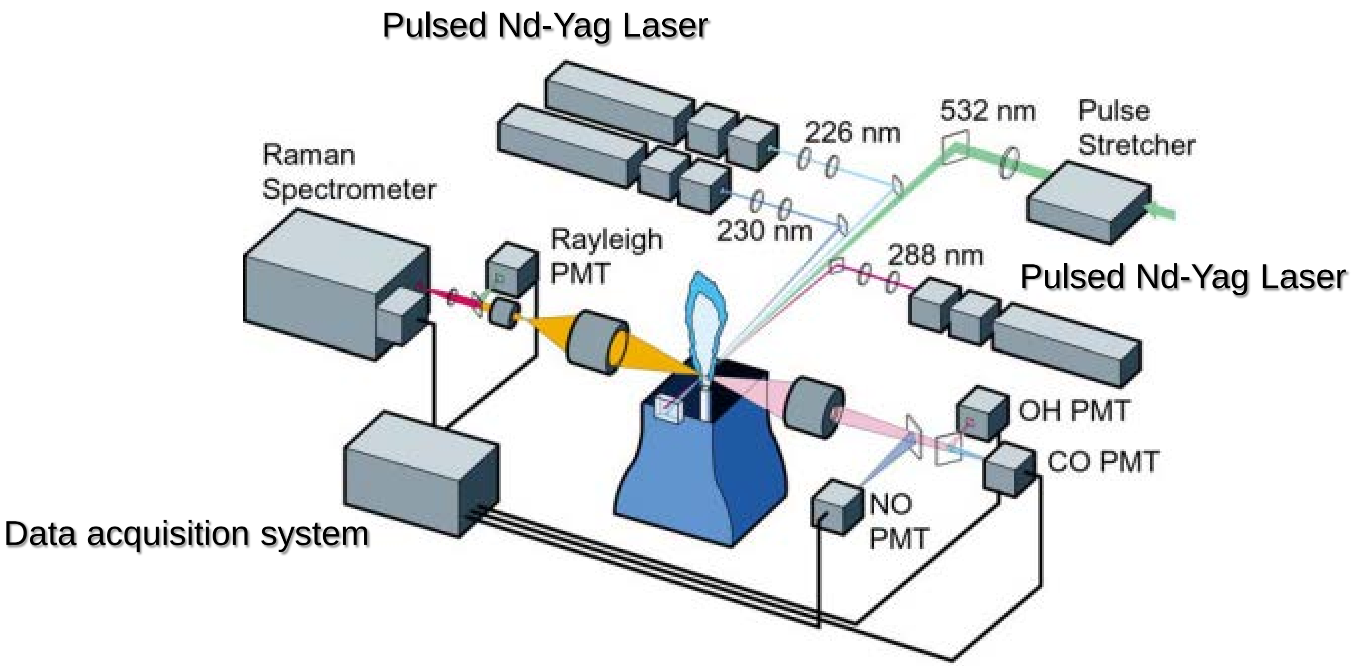
a) constant sheet width

b) linearly expanding sheet width

- Due to beam divergence and diameter (~1 cm) one single lens is not sufficient to provide a thin laser sheet when using Nd-Yag laser
- Lens configuration can be chosen by using geometric optics rules

w = laser sheet thickness at beam waist, *Ra*=Rayleigh length

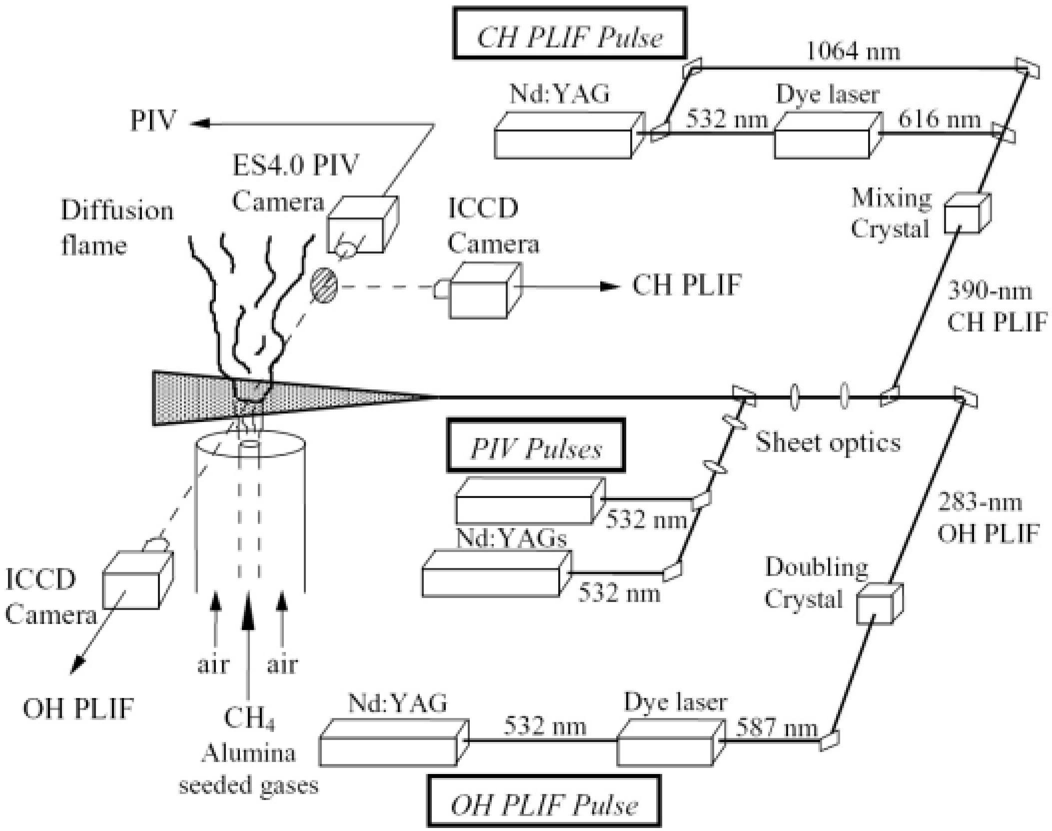
Examples of Flow Imaging Systems



Simultaneous Raman/Rayleigh/LIF point measurements

R. Barlow, 31 Int. Symposium on Combustion, 2006

Examples of Flow Imaging Systems



Simultaneous PIV/PLIF measurements

R. Barlow, 31 Int. Symposium on Combustion, 2006

References

- Janesick J. R., *Scientific Charge-Coupled Devices*, SPIE Press, 2001
- Clemens N.T., Flow imaging. in *Encyclopedia of imaging science and technology*, Hornak JP (ed), John Wiley and Sons, 2002
- Hain R., Kähler C., Tropea C., Comparison of CCD, CMOS and intensified camera, *Exp. Fluids*, **42**, 2007
- Magnan P., Detection of visible photons in CCD and CMOS: A comparative view, *Nuc. Instr. Meth.* **504** (2003)
- Bernd Jähne, Data Acquisition by Imaging Detectors, in *Handbook of Experimental Fluid Mechanics*, Springer Verlag, 2007
- Photomultiplier Tubes – Basics and Applications- Hamamatsu Photonics, 2007

A few electronic resources

- **http://learn.hamamatsu.com/** many info on CCD, EMCCD, intensifier
- **http://www.stanfordcomputeroptics.com**
- **http://www.pco.de/knowledge-base/**