OPTICAL SENSORS

subjects:

Electromagnetic spectrum
UV-light-IR band
Light sources and unit of measures
Radiation-matter interaction
Optical sensors
- Photoconductivity
- Photodiodes
- Photomultipliers

Color sensors
Infrared detectors
- Bolometers

Fiber optics sensors

Electromagnetic radiation

- Electric charges generate the electric field. Additionally, when in motion the electric charges generate the magnetic field. If the charges are accelerated, the electric and magnetic fields are mutually orthogonal and they propagate in the space as a wave. The wave carries energy and power.
- Many experiments at the beginning of the XX century shown that the radiation in some conditions behaves as a flow of particles called **photons**.
- Both the waves and the particles show peculiar characteristics
  - The electromagnetic waves propagates in vacuum
  - The rest mass of the photon is zero.
    - since photons always travel at the speed of light, the concept of rest mass is meaningless
  - The speed of light is independent from the reference frame and its value in vacuum is the upper limit of any achievable speed.

Electromagnetic spectrum

- Photons are elementary particles carrying an amount of energy proportional to the frequency of the radiation (or inversely proportional to the wavelength)

$$E = h \cdot \nu = \frac{h \cdot c}{\lambda} \qquad c\text{: light speed in the media of propagation } c = \frac{1}{\sqrt{\mu \cdot \varepsilon}};\; c_{vacuum} = 3 \cdot 10^{8}\,\frac{m}{s}$$

$$h\text{: Planck constant; } h = 6.26 \cdot 10^{-34}\, J \cdot s$$

- In practice the radiation consists in a mixture of photons of different wavelengths.
  - purely monochromatic radiation cannot occur due to Fourier transform between t and f.
- The power per unit of irradiated area is represented as a spectrum as a function of either frequency or wavelength

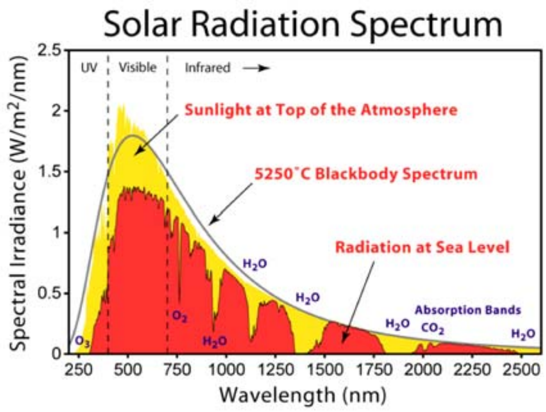
Quantitative descriptors of the radiation:

$$\text{flux of photons per area: } = \frac{photons}{sA} = N_\lambda \quad [\frac{1}{sm^2}]$$

$$\text{spectral power per area: } P_\lambda = N_\lambda \frac{hc}{\lambda} \quad [\frac{W}{m^2 nm}]$$

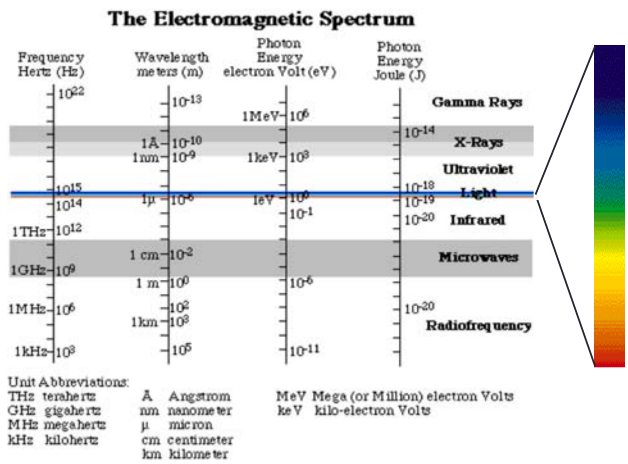
Total power in a wavelength range received in an area A

$$P = A \cdot \int_{\lambda_{min}}^{\lambda_{max}} P_\lambda d\lambda$$



Electromagnetic spectrum

- Since frequency and energy are associated, the spectrum takes into account the different processes leading to radiation emission.
- The radiation behaves in different ways according to the frequency. In particular, the scale of the matter interacting with the radiation depends on λ.
- The detection of radiation requires different principles for each frequency interval.
- A small spectral interval (400 – 700 nm) corresponds to the radiation perceived by the human eyes. The radiation in this interval is called *light*. The two adjacent regions are called ultraviolet and infrared.
- Noteworthy, many semiconductors (e.g. silicon) are sensitive to the radiation around this range.



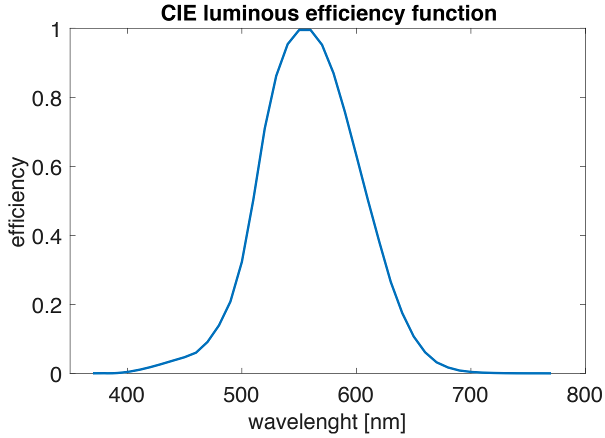
Human perception based units (photometric units)

flux (lumen) and illumination (lux)

- In order to evaluate the efficiency of illumination the spectrum of the radiation is weighted by the spectral response of human eyes (CIE standard).
- The largest sensitivity is found at 550 nm.
- Luminous flux: **Lumen** (lm):

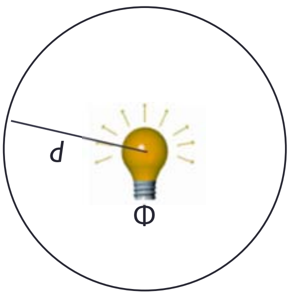
$$\Phi = 683 \cdot \int_{360}^{830} P(\lambda) \cdot L(\lambda) \cdot d\lambda$$

$$P = 1\ W\ at\ \lambda = 550\ nm = \Phi = 683\ lm$$
$$P = 1\ W\ at\ \lambda = 490\ nm = \Phi = 136\ lm$$



- Luminance: **Lux** (lm/m^2) luminous flux impinging on a surface at distance d.

$$L = \frac{\Phi_{source}}{4\pi d^2} \quad lux = \frac{lm}{m^2}$$

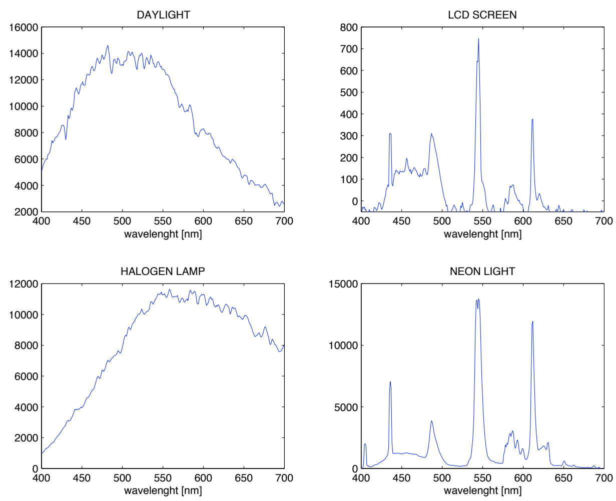


TIPO DI AMBIENTE	ILLUMINAMENTO Lux		
	MIN	MED	MAX
Classe, illum. generale	300	500	750
Classe, lavagna	300	500	750
Lab. artistici e scientifici	500	750	1000
Aule universitarie, ill. gen.	300	500	750
Aule universitarie, lavagna	500	750	1000
Aule universitarie, banchi per dimostrazioni	500	750	1000

Radiation sources

- In classic electromagnetism, the radiation is emitted by accelerated charges. In quantum mechanics, the emission is also associated to the transition of charged particles from discrete energy states.
- These phenomena give rise to different spectral signatures
  - Discrete spectra (spectral lines)
    - Transitions of electrons between atomic or molecular states
  - Continuum spectra
    - Thermal spectrum (thermal equilibrium between radiation and matter)
      - Black-body radiation
    - Bremmstrahlung (radiation from decelerated electrons)
      - X-ray sources
    - Cerenkov radiation (emitted by particles whose speed in a media exceeds the phase speed of light)

examples of light sources spectra



Electromagnetic radiation and temperature: The black-body radiation

- Matter in thermal equilibrium with the environment spontaenously emits radiation whose ideal behaviour is described by the Planck's law.
  - thermal equilibrium: all energy is absorbed and thermal radiation is emitted: black body
- At room temperature, thermal radiation is emitted in the infrared.
- The black-body radiation spectrum is described by the **Planck's law**

$$W_\lambda = \frac{2\cdot\pi\cdot c^2\cdot h}{\lambda^5\cdot\left(exp\left(\frac{h\cdot c}{k\cdot\lambda\cdot T}\right)-1\right)}$$

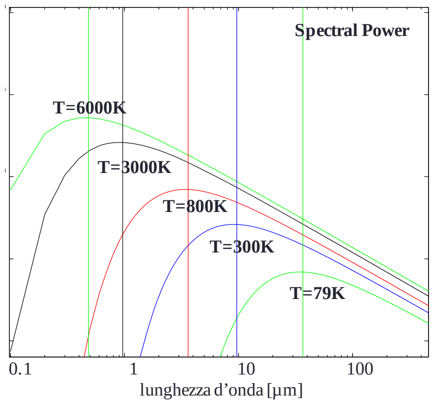
- Integral laws:
  - Total power: **Stefan-Boltzmann law**

$$\int_0^\infty W_\lambda d\lambda = \sigma\cdot T^4$$

$$\sigma = 5.67\cdot 10^{-12}\frac{W}{cm^2K}$$

  - Peak displacement: **Wien law**

$$\lambda_{\max} = \frac{b}{T};\quad b = 2897\ \mu m\cdot K$$



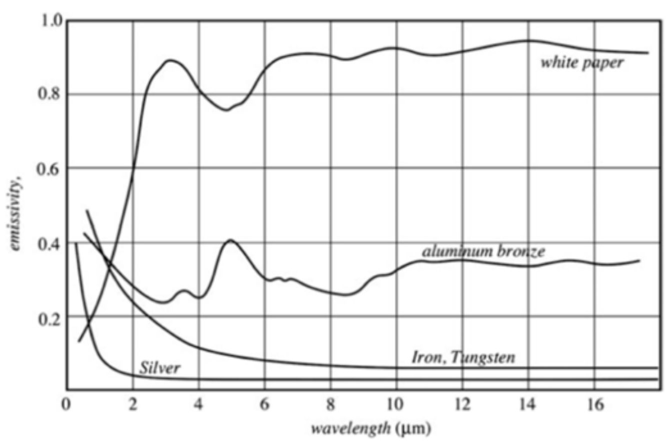
Temperature	*example*	λ_{max}
79 K	*Liquid nitrogen*	*36.6 μm*
300 K	*Environment*	*9.6 μm*
800 K	*Incandescent body*	*3.62 μm*
3000 K	*Tungsten wire*	*0.96 μm*
5700 K	*Sun surface*	*0.58 μm*

Emissivity

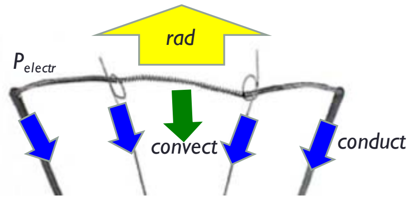
- The emissivity (ε) measures the attitude of a body to behave as a ideal black-body.
- It depends on the composition of the materials and on the conditions of the surface (e.g. polished or rough).
- If the emissivity is close to one, the black-body laws can be applied with the emissivity as a correction parameter.

$$W_\lambda = e(\lambda)\cdot\frac{2\cdot\pi\cdot c^2\cdot h}{\lambda^5\cdot\left(\exp\left(-\frac{h\cdot c}{k\cdot\lambda\cdot T}\right)-1\right)}$$

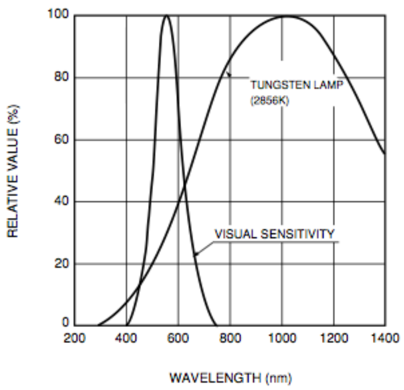
- In these cases the measure of the power of the emitted radiation provides a measure of the temperature of a body.



Example of applicaton of the Stefan-Boltzmann law: the temperature of a bulb lamp



$$equilibrium: T(t) = const$$
$$P_{el} = P_{rad} + P_{convect} + P_{conduct}$$
$$P_{rad} \gg P_{convect} + P_{conduct}$$



Let us consider a 100 W bulb lamp

$$P_{electric} = P_{radiation} \rightarrow P_{el} = A\sigma T^4$$

typical size of filaments: $L = 15\ cm;\ d = 100\ \mu m$

$$A = \pi d L = \pi 100 \cdot 10^{-}415 = 0.47\ cm^2$$

$$T = \sqrt[4]{\frac{P_{el}}{A\sigma}} = \sqrt[4]{\frac{100}{0.47\ 5.67 \cdot 10^{-12}}} = 2475\ K$$

$$\lambda_{max} = \frac{2897}{T} = \frac{2897}{2475} = 1.17\ \mu m$$

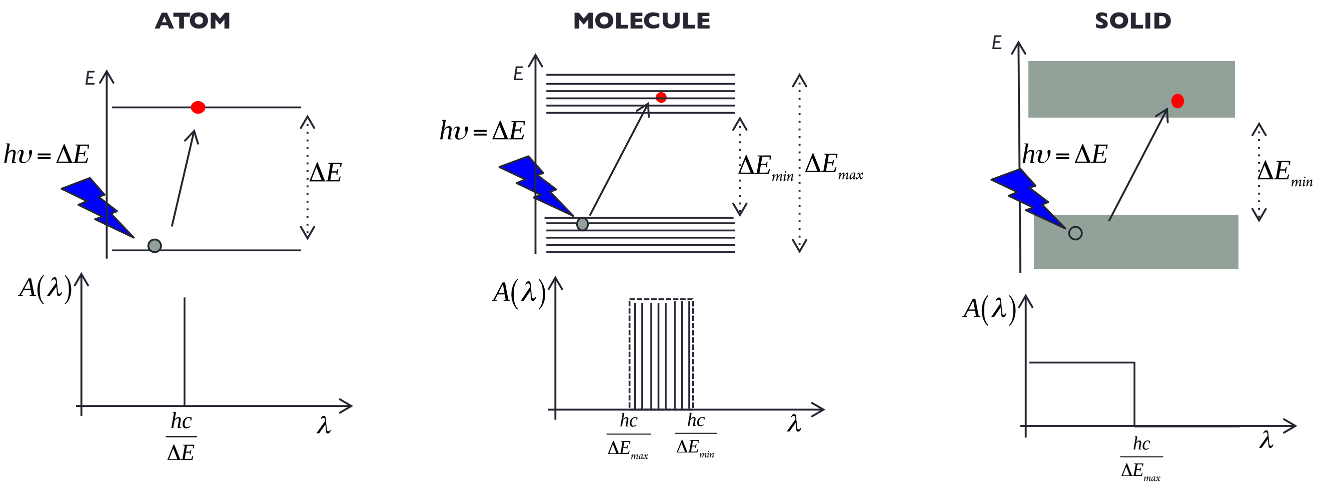
Radiation-matter interaction

- At different wavelengths the dimensions of the matter interacting with the radiation changes.
- The electromagnetic radiation is a powerful probe to investigate the structure of the matter.

denomination	wavelength	probed matter scale
Radio waves and microwaves	> 10^{-3} m	Materials, electric components
Infrared	10^{3} – 0.75 μm	Molecules, molecular bonds, atomic bonds
Visible light	0.7 – 0.45 μm	External molecular and atomic orbitals
Ultraviolet	450 – 100 nm	Deep molecular and atomic orbitals
X rays	100 nm – 0.1 Å	Deep atomic orbitals, atomic nucleii
γ rays	< 0.1Å	Internal nuclear structures, elementary particles, sub-elementary particles

Adsorbance of light

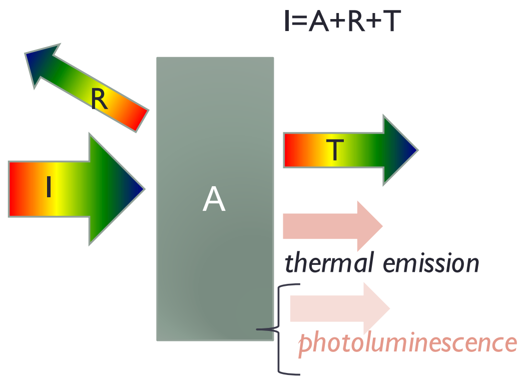
- The main mechanism of absorbance is the transfer of energy from the photon to one electron in the material.
- Electrons can acquire the energy necessary to a transition between orbitals, then the absorbance depends on the energy of the photon.
- The energies at which absorption occurs depends on the density of states and the electrons population. In molecules and solids, atomic energy levels degenerate in number, in solids they become so numerous to form a continuum (band).

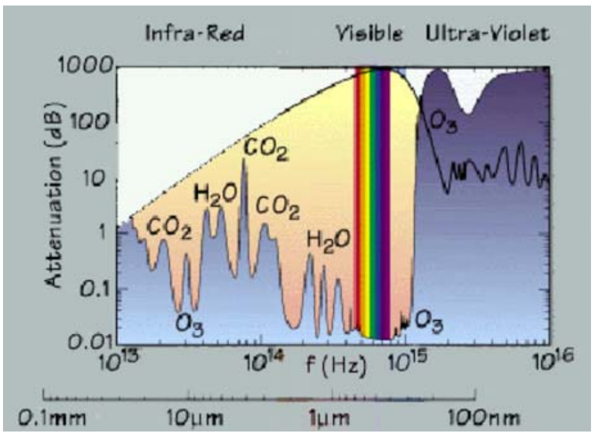


actually, pure spectral lines cannot exist because of Fourier transform between period and frequency.

Transmission, absorbance, and reflection

- Absorption is a function of wavelength.
- Only a portion of the incoming light is absorbed, the rest of radiation is either transmitted or reflected.
- *The matter always emit a thermal radiation, function of the temperature, and proportional to the emissivity*



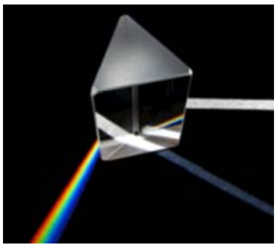


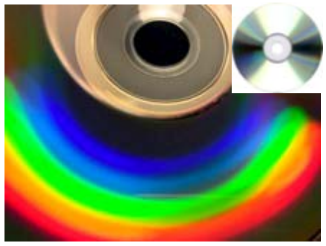
Absorption in terrestrial atmosphere

- The sun is the most important extraterrestrial source of radiation. The spectrum is thermal with extra emissions beyond UV due to nuclear phenomena at the solar surface
- The radiation is attenuated (absorbed and reflected) by the atmosphere
  - molecular absorbance: water, carbon dioxide, ozone, methane……
- *The visible light corresponds to the largest solar emission and the smallest atmospheric absorbance*

Spectrophotometers

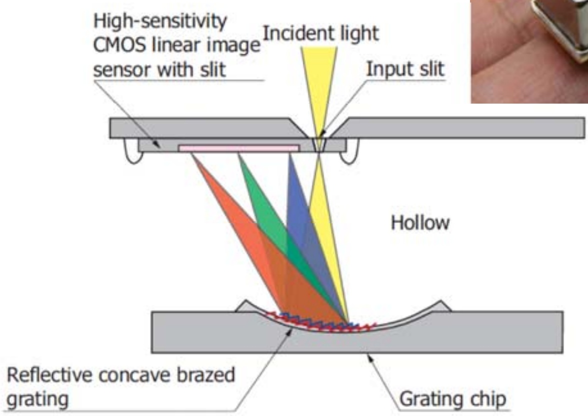
- Spectrophotometer is the instrument to measure the spectra.
- It separates the light in individual wavelengths.
- This is obtained exploiting the phenomena of refraction (prism, rainbows…) or diffraction (gratings, CD surface…)





Ocean Optics HR4000

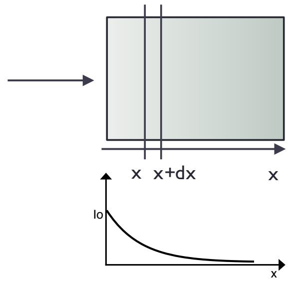
Hamamatsu C12666MA



Optical sensors

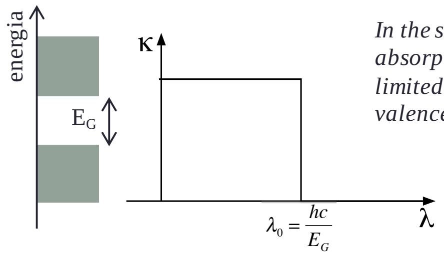
- Optical sensors, or photo-detectors, are based on the absorption of radiation and on the conversion of the adsorbed energy into a measurable signal.
- The term optical sensor is limited to the detectors of radiation from UV to infrared.
- Photo-detectors are classified in two categories according to their working principle.
  - **Photonic photo-detectors**
    - In these devices, the individual photons of the radiation interacts with the individual electrons of the material changing some measurable electrical property.
    - examples: photoconductors, photodiodes, photoemitters
  - **Thermal photo-detectors**
    - These devices measure the temperature change elicited by absorbed radiation power. In practice these are temperature sensors coupled with a material with a large extinction coefficient.
    - examples: bolometers, pyroelectric devices

Light absorption in materials

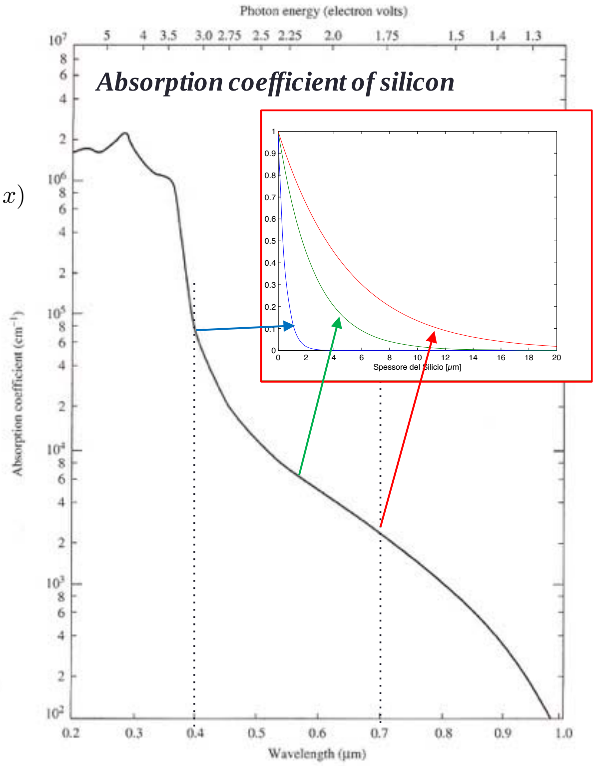


α absorption coefficient [cm^{-1}]

$$I(x+dx) - I(x) = dI = -\alpha \cdot I(x) \cdot dx$$
$$\frac{dI}{I} = -\alpha \cdot dx$$
$$\int_{I_0}^{I(x)} \frac{dI}{I} = -\int_0^x -\alpha \cdot dx$$
$$ln\frac{I(x)}{I_0} = -\alpha \cdot x \rightarrow I(x) = I_0 \cdot exp(-\alpha \cdot x)$$



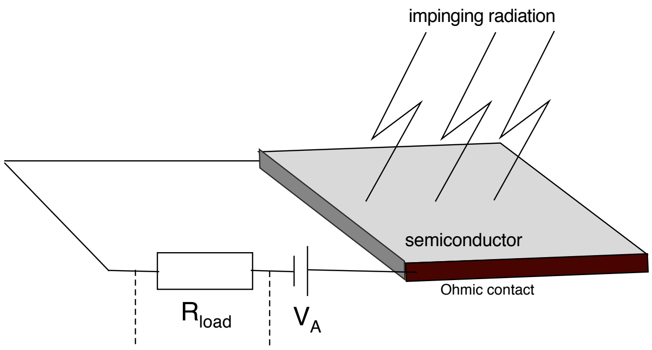
In the simplest model, the absorption in semiconductors is limited to the transitions from valence to conduction bands



In silicon, the absorbance coefficient in the visible range is in the range 3000 – 10^5 cm^{-1}.
It corresponds to depths of penetration between 3.3 µm and 100 nm.

Photoconductors

- Most of the absorbed photons interact with electrons in the valence band. The energy is transferred from photons to electrons and if the energy is greater than the energy gap the electron can be promoted to the conduction band leaving a hole in the valence band.
- As a consequence, the concentration of charge carriers increases and the resistivity of the material decreases.
- The concentration of charge carriers is larger than the thermally generated carriers, then the photocarriers are recombined by generation-recombination processes.
- The signal is detected as a variation of the voltage drop across a load resistor, or as the variation of the current in the sensor.



Photoconductors

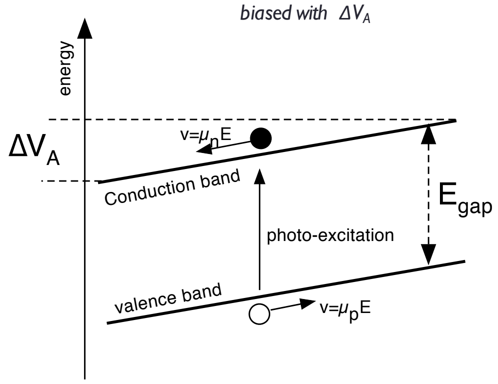
- The photo-conductivity is based on the creation of electron-hole couples. The energy released by the photon has to exceed the energy gap.

$$h\nu \geq E_G \qquad \frac{hc}{\lambda} \geq E_G$$

- Therefore a cut-off wavelength exists over which the photo-conductivity cannot be activated.

$$\lambda_0 = \frac{hc}{E_G} = \frac{1.24}{E_G(eV)} \mu m$$

photo-excitation in a semiconductor biased with ΔV_A

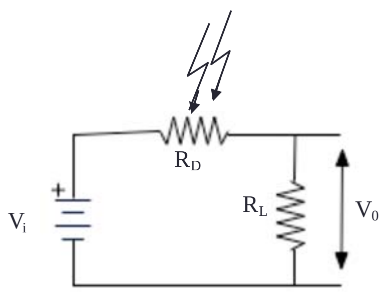


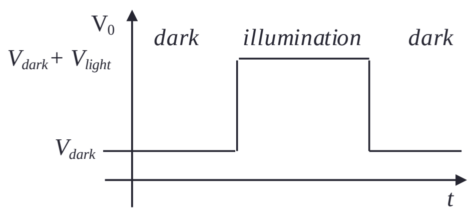
Material	Band gap (eV)	Longest wavelength (μm)
ZnS	3.6	0.345
CdS	2.41	052
CdSe	1.8	0.69
CdTe	1.5	0.83
Si	1.12	1.10
Ge	0.67	1.85
PbS	0.37	3.35
InAs	0.35	3.54
PbTe	0.3	3.75
PbSe	0.27	4.58
InSb	0.18	6.90

Photocurrent

- The exposure to light gives rise to an excess of current (photo-current) respect to the current observed when the detector is not illuminated (dark current)
- The photo-current is produced by the photo-generated electrons and holes kept in movement by the applied voltage.
- The photocurrent is observed as a variation of the output voltage of a voltage divider.

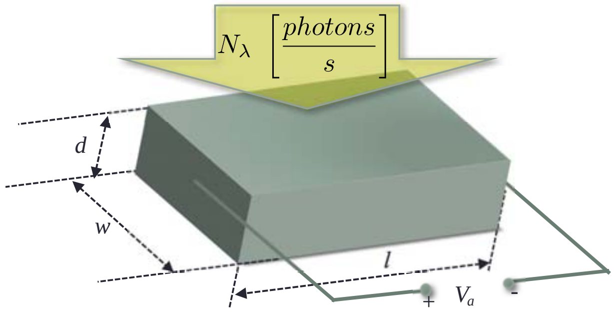
$$V_0 = R_L \cdot (I_{dark} + I_{light}) = R_L \cdot \frac{V_i}{R_L + R_D} + R_L \cdot I_{light}$$





Photocurrent

Let us consider a flux N_λ of photons impinging on a N-type semiconductor.
Being *wl* the area of collection of photons and *d* the depth of the detector.
The semiconductor is contacted by two electrodes at distance *l*.
wd is the area of the electrodes.



Let us suppose that all the incident photons are absorbed. The rate of generation of electrons and holes is a fraction (η) of the rate of arrival of photons divided by the volume of the detector. *η is the quantum efficiency.*
hypothesis: photons are uniformely absorbed in the volume.

$$\left(\frac{dn}{dt}\right)_G = \eta\frac{N_\lambda}{wld}\left[\frac{electrons}{s\cdot cm^3}\right] = \left(\frac{dp}{dt}\right)_G = \eta\frac{N_\lambda}{wld}\left[\frac{holes}{s\cdot cm^3}\right]$$

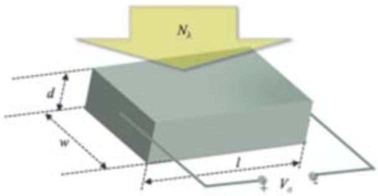
The concentration of photo-generated charges is an excess of charges respect to the equilibrium concentration. If the material is N-type, *the recombination of holes is the dominant phenomena.*

$$\left(\frac{dp}{dt}\right)_R = \frac{p}{\tau_p}\left[\frac{holes}{s\cdot cm^3}\right]$$

Photocurrent

The charge with the smallest mobility determines the current, then let us limit our attention to the holes.
At the equilibrium the rate of generation and recombination are the same and the steady concentration of holes (p_{eq}) is :

$$\eta\frac{N_\lambda}{wld} = \frac{p_{eq}}{\tau_p} \rightarrow p_{eq} = \eta\tau_p\frac{N_\lambda}{wld}$$



These charges determine a photocurrent equal to:

$$I_{ph} = JA = qpv_pwd = q\eta N_\lambda\tau_p\frac{v_p}{l}$$

The quantity l/v is the transit time of the holes in the semiconductor.
The ratio between the recombination time and the transit time is the *detector gain*.
For a high gain, the lifetime should be long and electrode spacing short. Gain is in the range 10^3-10^6.

Introducing the bias voltage: $I_{ph} = q\eta N_\lambda\tau_p\frac{\mu_p\mathcal{E}}{l} = q\eta N_\lambda\tau_p\frac{\mu_pV_A}{l^2}$

and the gain G is: $G = \tau_p\frac{\mu_pV_A}{l^2}$

Parameters for optical sensors

- Responsivity
  - Ratio between the signal and the incident power. In case of linearity it coincides with the sensitivity

$$\Re = \frac{v_{ph}}{P_{in}} \left[\frac{V}{W}\right] \; or \; \Re = \frac{i_{ph}}{P_{in}} \left[\frac{V}{W}\right]$$

- Noise Equivalent Power (NEP)
  - Minimum detectable power, it is the similar to resolution where responsivity replaces the sensitivity

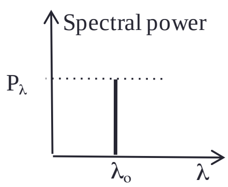
$$NEP = \frac{v_{noise}}{R} \left[\frac{W}{\sqrt{Hz}}\right]$$

- Detectivity (D)
  - NEP is a negative figure of merit, namely better sensors have a small NEP. In order to use a positive figure of merit the detectivity is introduced

$$D = \frac{1}{NEP}$$

Dependence from wavelength and geometry

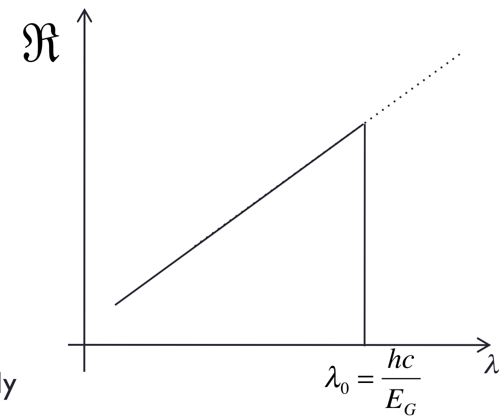
To evaluate the spectral responsivity, let us consider the response to a monochromatic source of power P_λ



$$P_\lambda = N_\lambda \cdot E_{photon} = N_\lambda \cdot \frac{hc}{\lambda}$$

$$I_{ph} = q\eta N_\lambda G = \frac{q\eta}{hc} G P_\lambda \lambda$$

$$\Re = \frac{I_{ph}}{P_\lambda} = \frac{q\eta}{hc} G\lambda$$



The responsivity is a growing function of wavelength, this behavior is typical for photonic detectors. The curve is abruptly interrupted at the cut-off frequency.

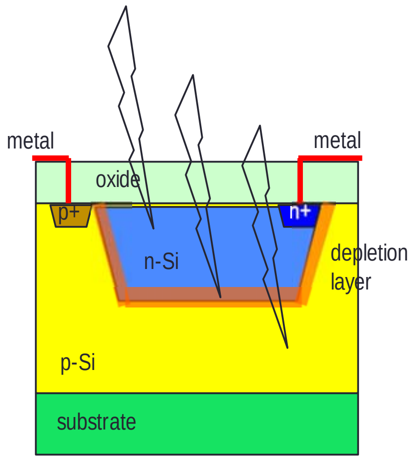
Photoresistor

20mm CdS photoresistor with plastic cover

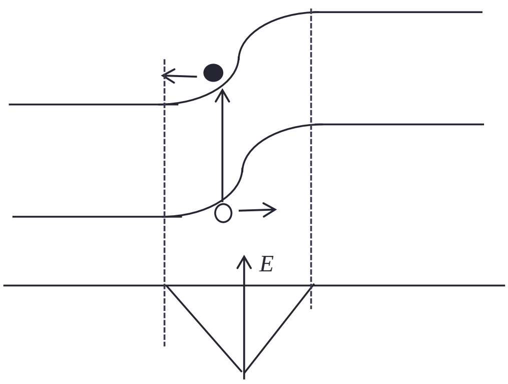
Power Consumption: 100 mw
Photo resistance (10Lux): 5 to 200k Ohms
Dark resistance: 0.5 to 20M Ohms R100 10: 0.5 to 0.9
Response time: 30ms, rise time, 30ms decay time

Interdigitated electrodes contribute to increase the gain reducing the distance between the electrodes.

Photovoltaic effect

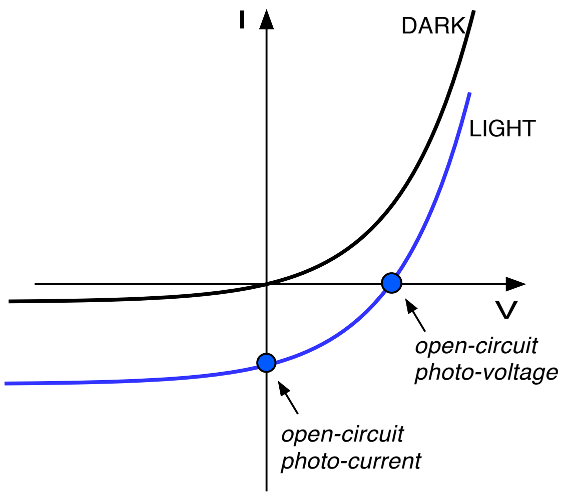


- Photovoltaic effect takes place in junction devices where a built-in electric field exists.
- Radiation can generate electron-hole pairs everywhere in the semiconductur.Those created in the neutral regions are soon recombined, while those generated in the depletion layer are separated by the built-in electric field.
- Photovoltaic sensors are active sensors:the photo-charges increase the drift current in the depletion layer then a current is observed without bias.
- Typical photovoltaic sensors are P-N junctions (photodiodes) where the depletion layer is the sensitive volume of the device.



Photodiodes

- The photocurrent is a drift current, then it is additive to the reverse current.
  - respect to photoconductors, the signal is due to majority charges which are not subjected to recombination. Then photodiodes are expected to be more fast than photoconductors
- The photovoltaic effect is manifested as a open-circuit voltage or a short-circuit current.
- Photodiodes are typically operated in a reverse bias regime, and the photovoltaic effect is observed as a voltage drop across a load resistor (photoconductive mode).
  - Avalanche detectors: The device is fabricated and biased in order to work at the edge of the avalanche effect. In this way the amplification effect leads to high sensitive devices as it happens in SPADs (single photon avalanche detectors).



Photocurrent calculation

- Respect to a photoconductor, charges are not recombined, indeed the depletion layer is reverse biased then the generation dominates. All photocharges contribute to the current

$$i_{ph} = \eta \cdot q \cdot N_\lambda$$

- Considering the relationship between the rate of arrival of photons and the radiant power in case of a monochromatic radiation we have:

$$i_{ph} = \frac{\eta \cdot q \cdot \lambda \cdot P_\lambda}{h \cdot c}$$

- The open-circuit voltage is the given by the product of the photovoltage and the dynamic resistance at V=0;

$$\frac{1}{R} = \left.\frac{dI}{dV}\right|_{v=0} = \frac{d}{dV} I_S \cdot \left.\left[\exp\left(\frac{q \cdot V}{\beta \cdot k \cdot T}\right) - 1\right]\right|_{v=0} = \frac{q \cdot I_s}{\beta \cdot k \cdot T}$$

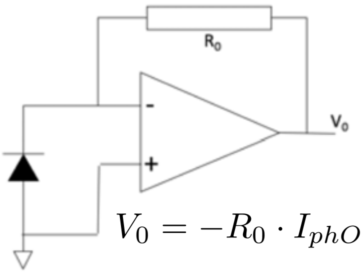
- It leads to

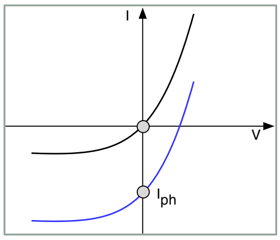
$$v_{ph} = i_{ph} \cdot R = \frac{\eta \cdot q \cdot \lambda \cdot P_\lambda}{h \cdot c} \cdot \frac{\beta \cdot k \cdot T}{q \cdot I_s} = \frac{\eta \cdot \beta \cdot k \cdot T}{h \cdot c \cdot I_s} \cdot \lambda \cdot P_\lambda$$

Bias circuits

Photovoltaic mode

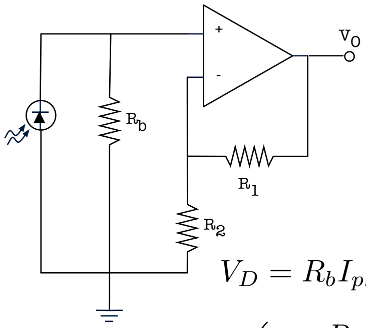
no dark current

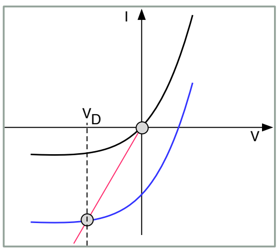




$$V_0 = -R_0 \cdot I_{phOC}$$

quasi Photovoltaic mode





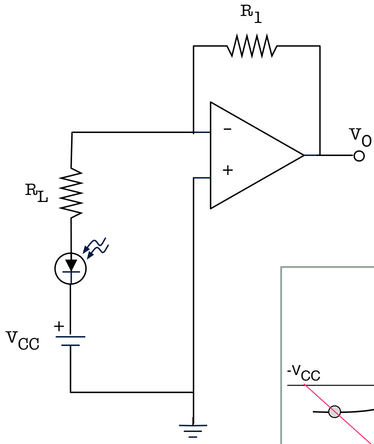
$$V_D = R_b I_{ph}$$

$$V_0 = \left(1 + \frac{R_1}{R_2}\right) R_b I_{ph}$$

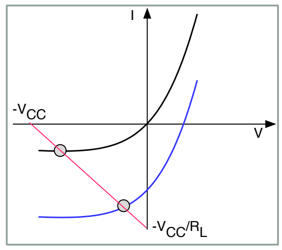
Photoconductive mode

dark current different from zero

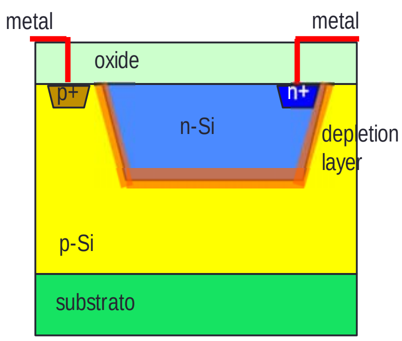
smaller capacitance

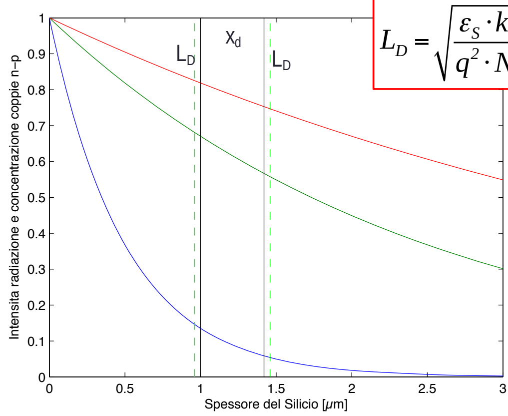


$$V_0 = -R_1 I_{ph}$$



Geometrical properties



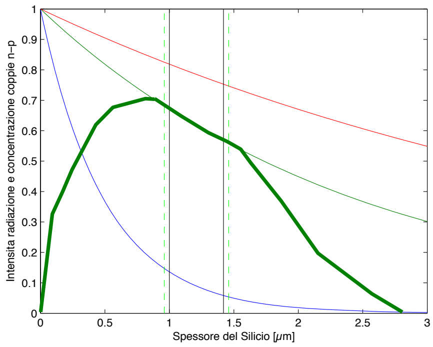


$$x_d = \sqrt{\frac{2\varepsilon_S \cdot \phi_i}{q} \cdot \left(\frac{1}{N_A} + \frac{1}{N_D}\right)};$$

$$L_D = \sqrt{\frac{\varepsilon_S \cdot kT}{q^2 \cdot N_D}}$$

- The penetration depth depends on the wavelength. The concentration of photo-generated electron-hole pairs is proportional to the adsorbed light.
- The signal is contributed by the charges created where the electric field is not null.
- This is found in the depletion layer and in the neutral zone for a length of about 4 Debye lengths.
- Charges generated in the neutral zone diffuse before to be recombined. This extend the sensitive region of a distance of the order of the recombination length.

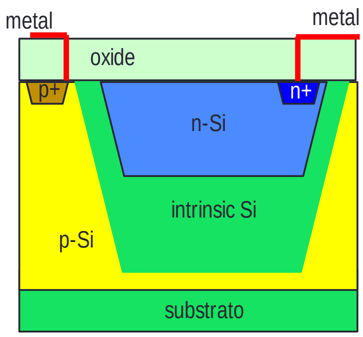
Photo-signal versus depth

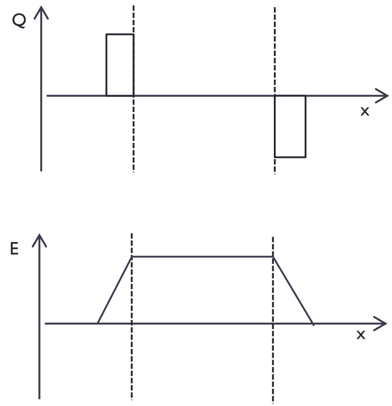


- Qualitative behavior of the fraction of photo-generated charges contributing to the photocurrent.
- At the surface, the generated charges are completely recombined by the large density of traps and defects.

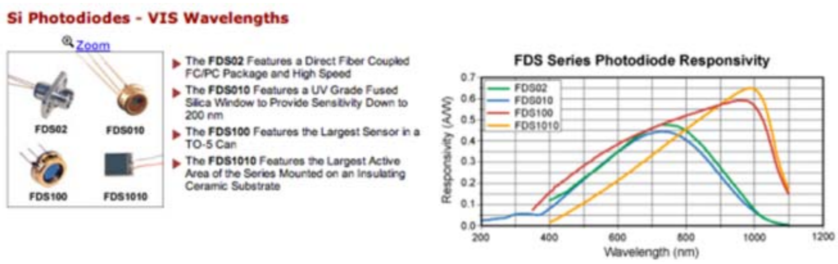
The depletion layer should stay close to the surface, but not too much to avoid defects, and should be large enough to collect many photons

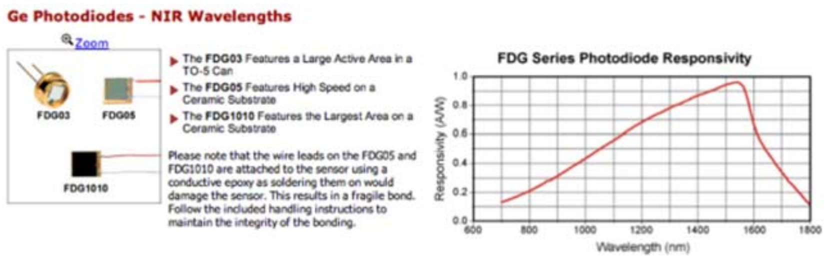
- The effective sensitive area is increased with a **p-i-n** configuration.





Examples of photodiodes





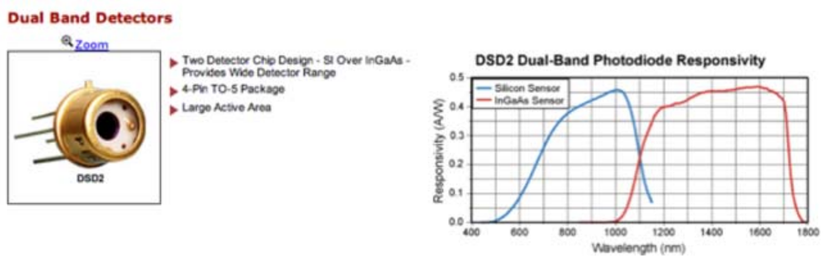
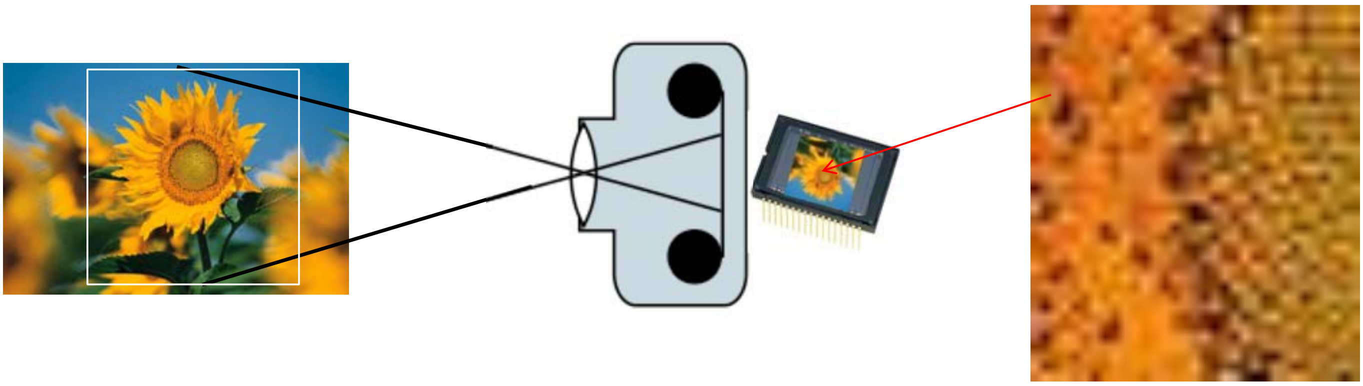
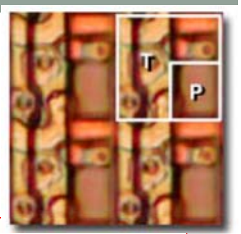


Image detectors

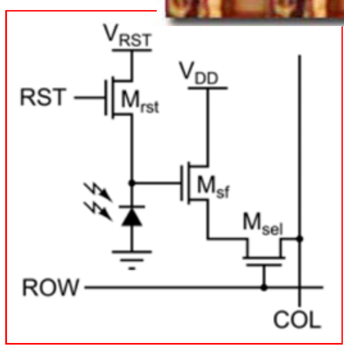
- Each individual sensor is sensitive to the radiation collected through its own field-of-view
- To detect an image, it is necessary a planar array of detectors, a suitable electronic interface able to read in order and sequentially the signals of the detectors, and a system of lenses reconstructing the scene onto the planar array.
- Each individual sensor is called pixel, and the whole scene is transformed into a matrix of signals. Each pixel measure the light intensity from a portion of the scene.



CMOS array



- Photodiodes are arranged in array. Each photodiode is connected to a minimal circuit allowing for the individual reading of signals. Each photodiode is the pixel of the image.
- Reset (RST) pulse reversely biases the photodiode to the voltage V_{RST}. Then the voltage can fluctuate. Due to the reverse bias, charges are generated in the depletion layer. Generated charges are accumulated in the depletion layer capacitor in order to cancel the reverse bias. This is the dark charge of the detector. The integration time determines the actual value of the charge.



$N_D \gg N_A$

Built-in potential $\phi_{bi} = \frac{kT}{q} ln\left(\frac{N_A \cdot N_D}{n_i^2}\right)$

Depletion layer at V_{RST} $x_{d,RST} = \sqrt{\frac{2\varepsilon_S}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(\phi_{bi} - V_{RST})}$

Charge in the depletion layer $Q_{d,RST} = q \cdot N_A \cdot x_d$

Rate of dark charges generation $\frac{dQ_{dark}}{dt} = q \cdot \frac{n_i}{2\tau} \cdot x_d$

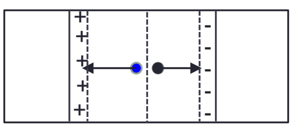
In dark after integration time T_{int}:

generated charge $Q_{dark} = -q \cdot \frac{n_i}{2\tau} \cdot x_d \cdot T_{int}$

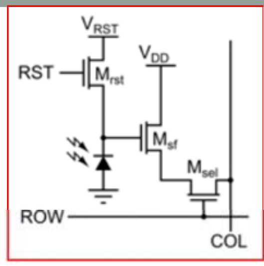
Charge in the depletion layer $Q_d = Q_{d,RST} - Q_{dark}$

Depletion layer size $x_d = \frac{Q_{d,RST} - Q_{dark}}{q \cdot N_A}$

signal $V = \frac{q x_d^2}{2\varepsilon_S \left(\frac{1}{N_A} + \frac{1}{N_D}\right)} - \phi_{bi}$



CMOS pixel current



- In presence of an impinging radiation (N_λ) an additional charge (Q_{sig}) is generated by the absorbed photons. Q_{sig} contributes to decrease the pixel voltage.

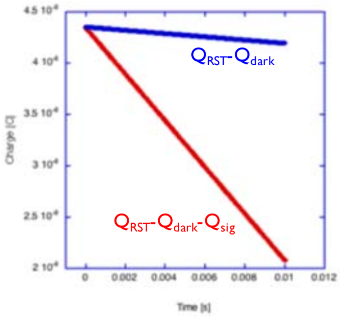
$$Q_{sig} = -q \cdot N_\lambda \cdot \eta \cdot T_{int}$$

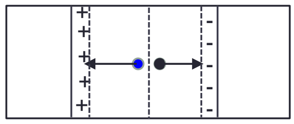
$$Q_{dark} = -q \cdot \frac{n_i}{2\tau} \cdot x_d \cdot T_{int}$$

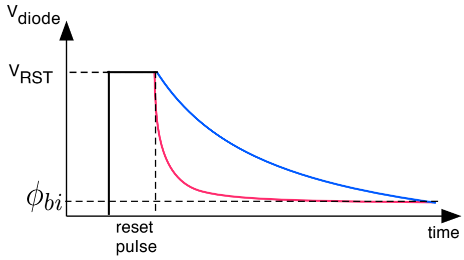
$$Q_d = Q_{d,RST} - Q_{sig} - Q_{dark}$$

$$x_d = \frac{Q_{d,RST} - Q_{sig} - Q_{dark}}{q \cdot N_A}$$

$$V = \frac{q x_d^2}{2\varepsilon_S \left(\frac{1}{N_A} + \frac{1}{N_D} \right)} - \phi_{bi}$$



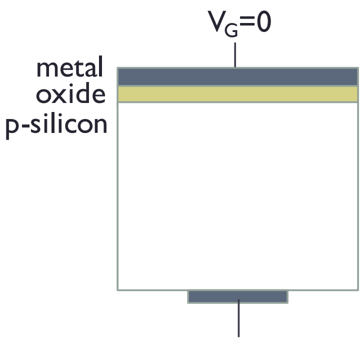


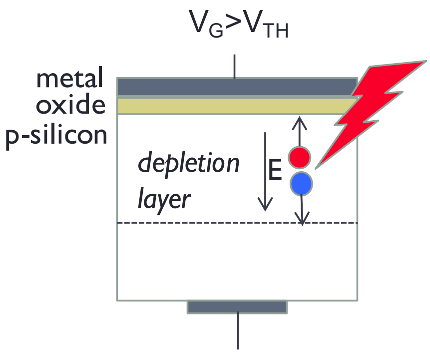


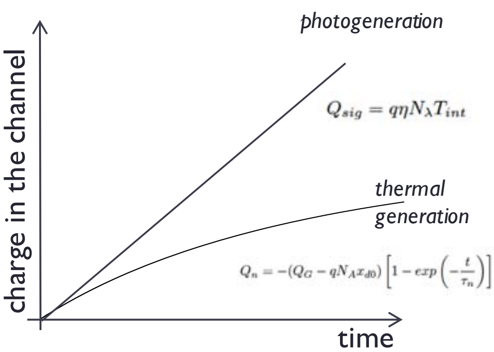
ROW signal transfers the pixel signal to the COL terminal.

MOS photo-detector

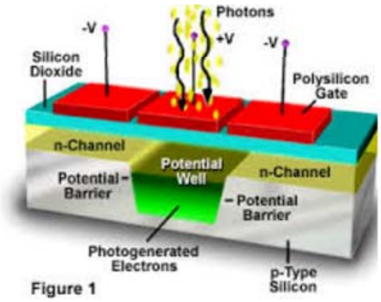
- The MOS structure can also be used as a light detector considering that the time for inversion charge creation is long.
- The MOS is polarized in inversion ($V_G > V_{TH}$) and exposed to light.
- Photoelectrons are dragged at the interface populating the inversion layer, thermal electrons generated by the semiconductors in response to the polarization are the dark signal.
- The dark charge can be reduced cooling the detector.

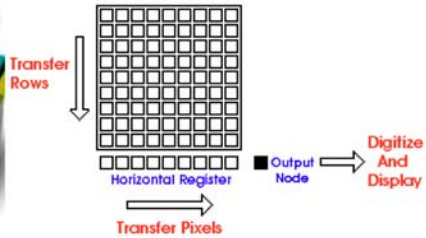




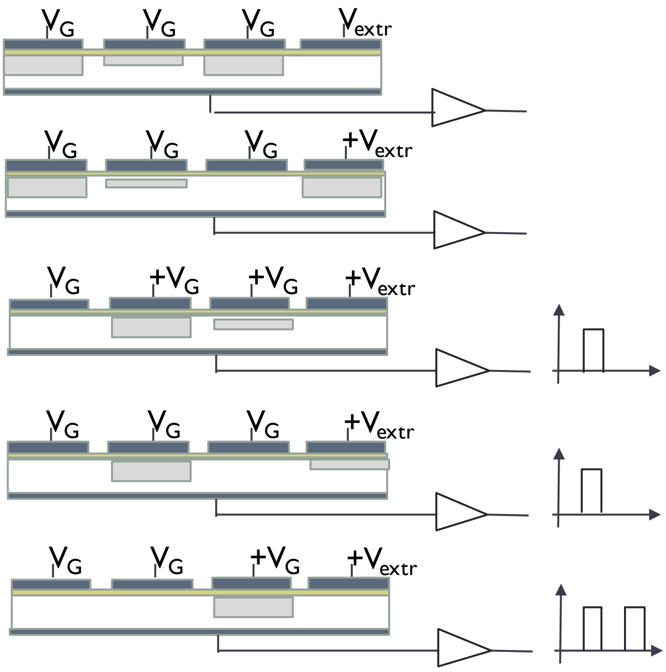


charge read-out
Charge Coupled Detectors





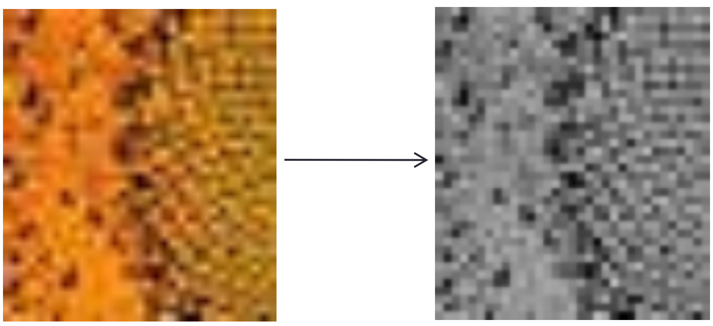
- At end of the exposure each pixel carries a quantity of charge proportional to the intensity of light.
- The charge is moved from one pixel to the adjacent by a proper potential profile.
- Channels are connected by n-silicon layers.

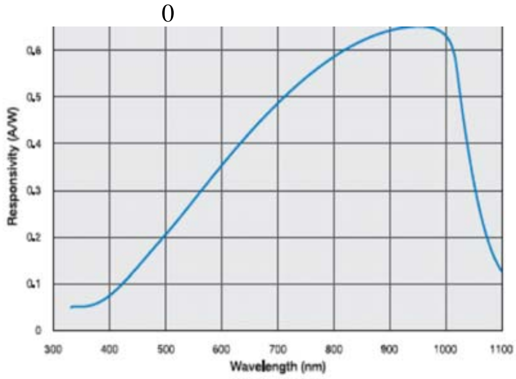


Monochromatic detection

- The detectors measure the integral of the spectrum of the adsorbed light weighted by the sensor responsivity.
- Then, the notion of color (wavelength) is lost and the sensors are intrinsecally monochromatic.
- To measure the color is necessary to use a system of filters that makes possible the measure the light in a limited wavelength range.

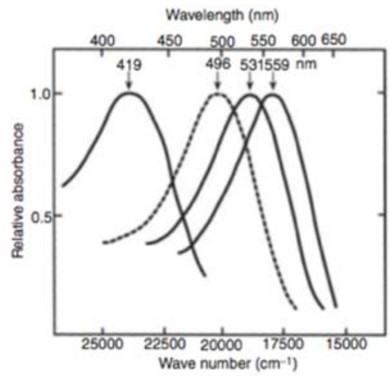
$$i \approx \int_0^{\infty} S(\lambda)\cdot R(\lambda)\cdot d\lambda$$

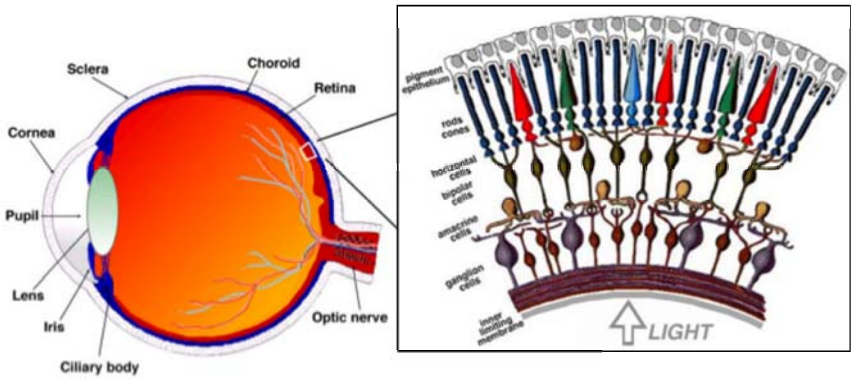


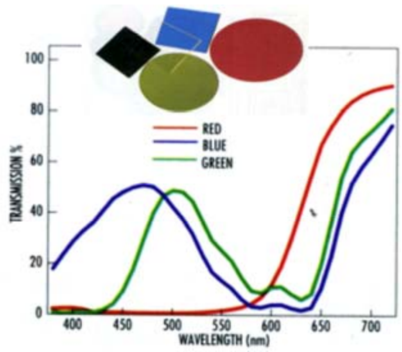


Colour

- Colour is the human perception of the spectrum of light. It is obtained evaluating the signals of three receptors whose responsivity is peaked at different wavelengths.
- The RGB colour code is an attempt to recreate colour sensing and actuation.

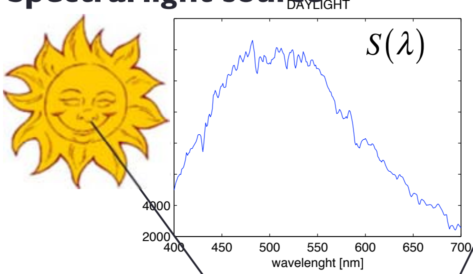


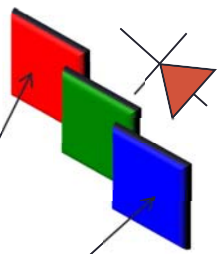




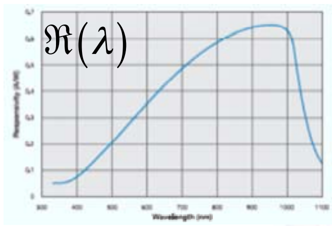
Colour measurement

Spectral light source



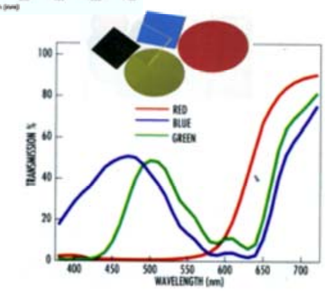


Spectral responsivity of the detector



$F_{red}(\lambda);\ F_{gre}(\lambda); F_{blu}(\lambda)$

Spectral transmission of the filters



$R(\lambda)$

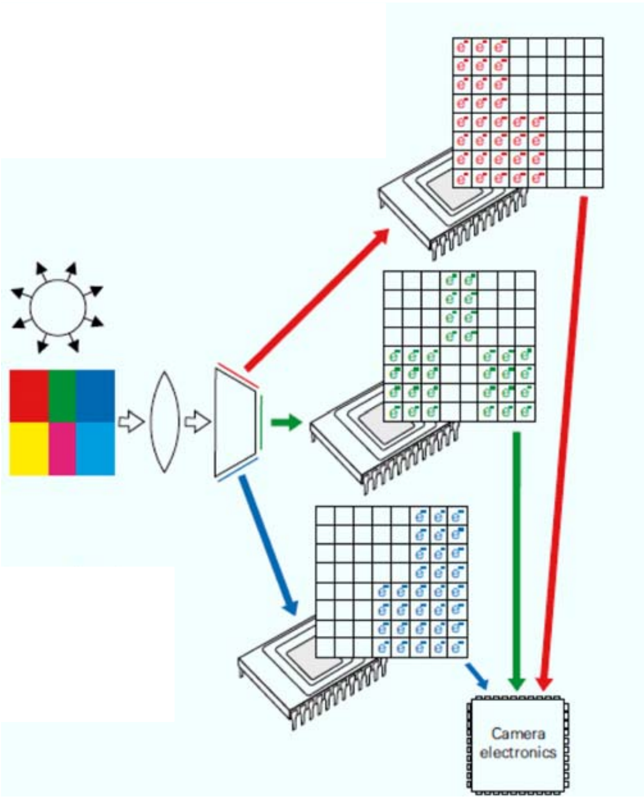
Spectral reflection of the object

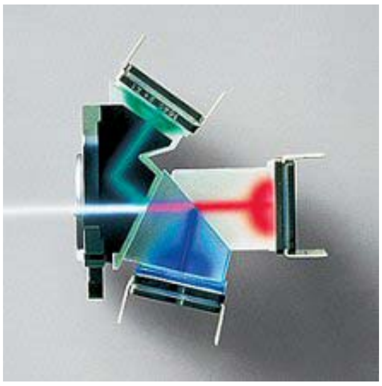
$$i_{red} \approx \int_0^\infty S(\lambda)\cdot\Re(\lambda)\cdot F_{red}(\lambda)\cdot R(\lambda)\cdot d\lambda$$

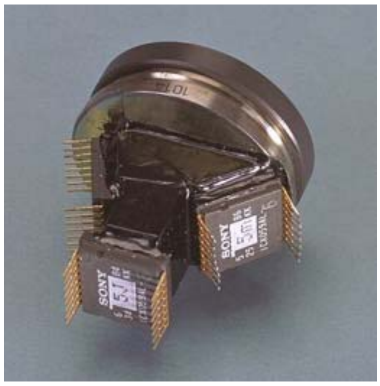
$$i_{gre} \approx \int_0^\infty S(\lambda)\cdot\Re(\lambda)\cdot F_{gre}(\lambda)\cdot R(\lambda)\cdot d\lambda$$

$$i_{blu} \approx \int_0^\infty S(\lambda)\cdot\Re(\lambda)\cdot F_{blu}(\lambda)\cdot R(\lambda)\cdot d\lambda$$

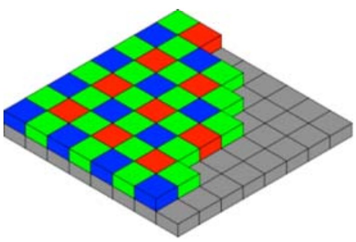
3-detectors colours camera

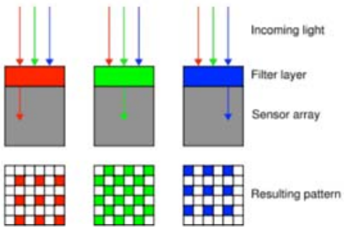


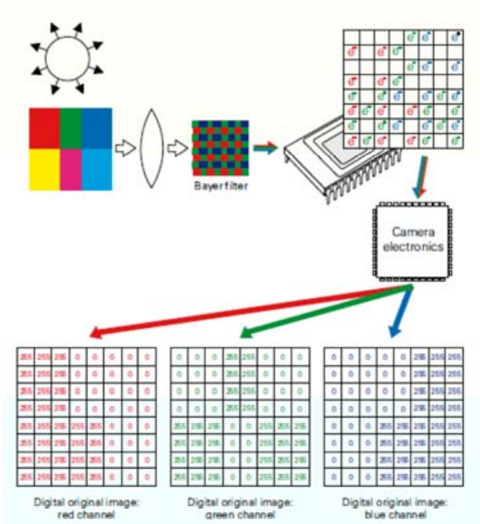




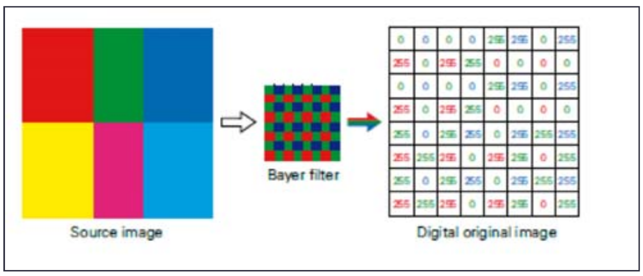
One detector colour camera: Bayer filter

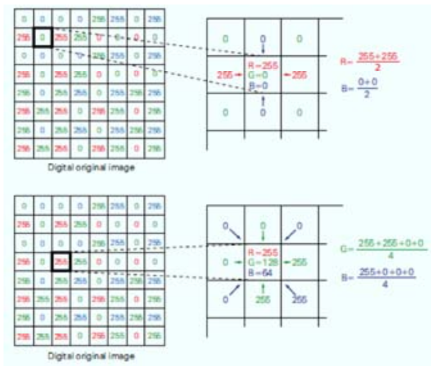




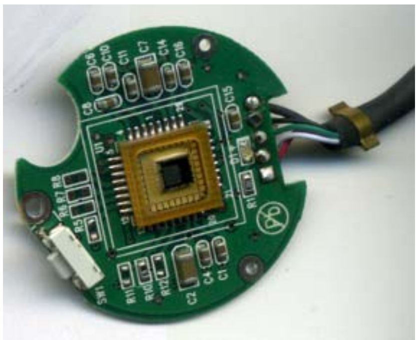


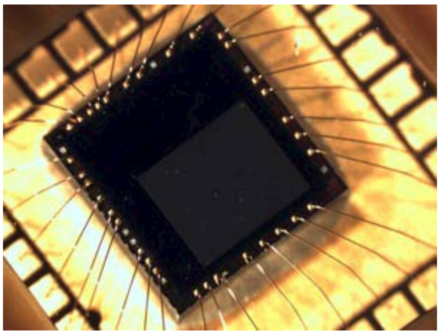
Demosaicising algorithm

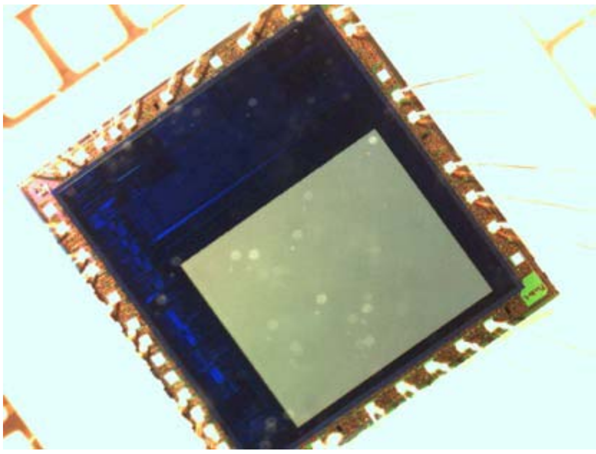


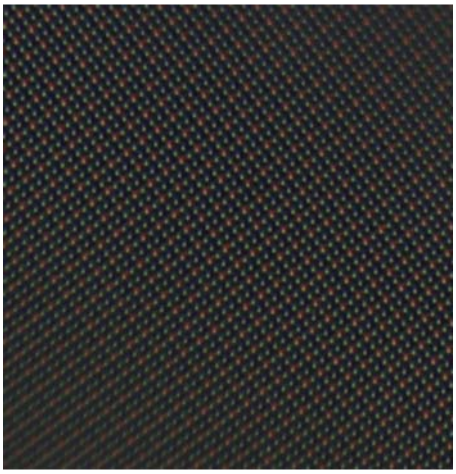


Low-cost webcam



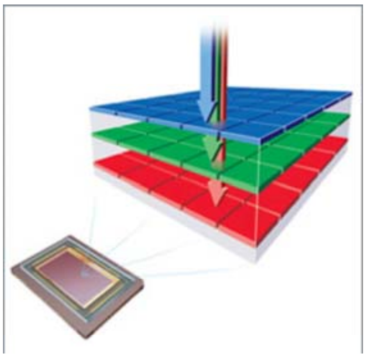


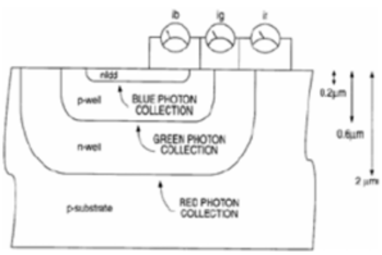


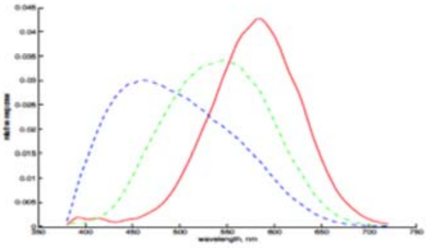


FOVEON sensor

- Foveon technology exploits the relationship between the depth of penetration and the wavelength to design color single pixel detector.
- It is formed by a stack of three photodiodes buried at different depths so that each diode collects a prevalent colour.
- In this way, each pixel of the image is actually sensitive to the three colour bands.

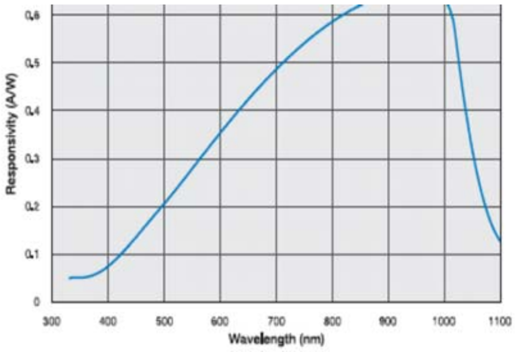






Photodiodes spectral response with a NIR cut filter

Near Infrared (NIR) filter



The maximum responsivity of silicon detectors is in the NIR region

NIR cut filter
Applied to the objective of a webcam

Burnt slide film can be used to block the visible light allowing for a NIR camera

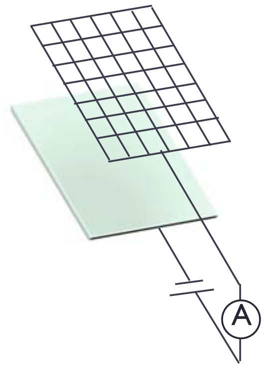
NIR image of a 5 € banknote, images printed with NIR ink appears.

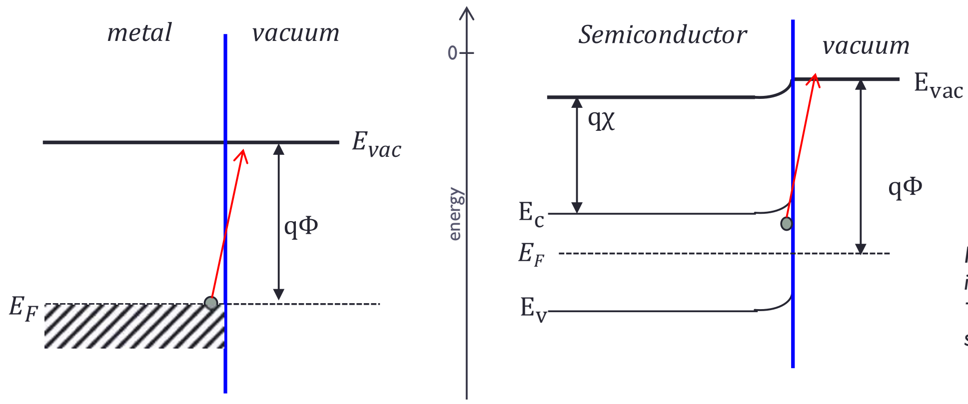
Photo-emission

- In photoemission electrons receive enough energy to leave the material.
- The energy necessary for the emission is called *work function*, it is defined as the difference between the vacuum energy and the Fermi level of the electrons in the material.
- The work function is then the minimum photon energy necessary for photoemission.

$$\frac{hc}{\lambda} \geq q\Phi \qquad \lambda_0 = \frac{hc}{q\Phi}$$

- The emitted electron can be collected by an external electrode (photoanode) suitably biased with respect to the emitting material (photocathode).

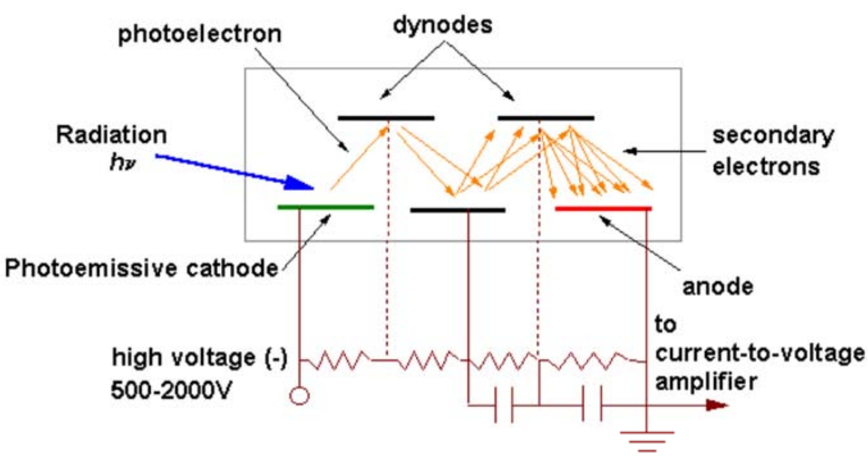




In semiconductors, the work function is affected by the surface states. Then, it can be modulated by a suitable modifications of the surface.

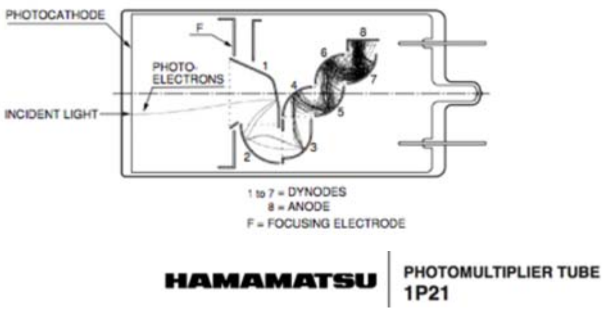
Photomultiplier

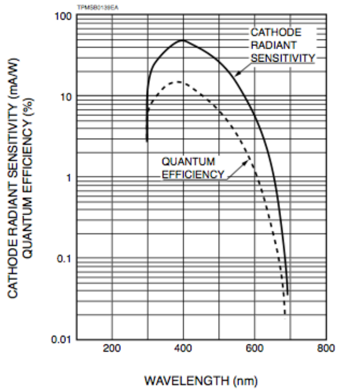
- The photomultiplier is an avalanche device based on the emission process.
- Emitted electrons are accelerated up to an energy enough to produce secondary emission in a metallic target.
- A voltage drop ladder is maintained among the electrodes (dynodes) in order to give rise an avalanche phenomenon.
- This gives rise to the most sensitive photodetector.
- To avoid energy loss by scattering with gas molecules, the device is kept under vacuum.



Transmission mode photocathode

- In this device electrons are emitted from the opposite surface with respect to the incident light. Then, a large area detector and a compact arrangement are made possible.





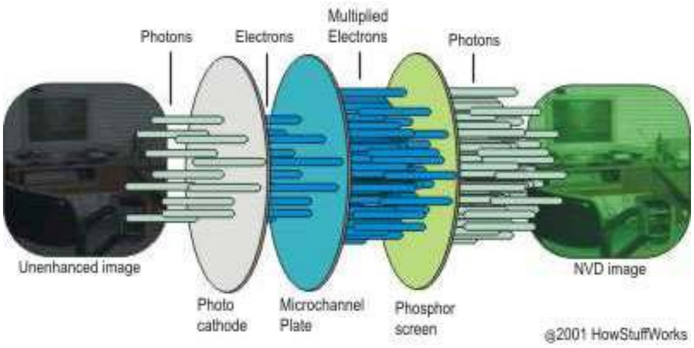
Parameter		Min.	Typ.	Max.	Unit
Anode Sensitivity	Luminous (2856K)	50	250	—	A/lm
	Radiant at 400nm	—	3.0 × 10⁵	—	A/W
Cathode Sensitivity	Luminous (2856K)	25	40	—	µA/lm
	Radiant at 400nm	—	48	—	mA/W
	Quantum Efficiency	—	13 at 350nm	—	%
Gain		—	6.25 × 10⁶	—	—
Anode Dark Current (after 30 minute)		—	1	5	nA
Time Response	Anode Pulse Rise Time	—	2.2	—	ns
	Electron Transit Time	—	22	—	ns

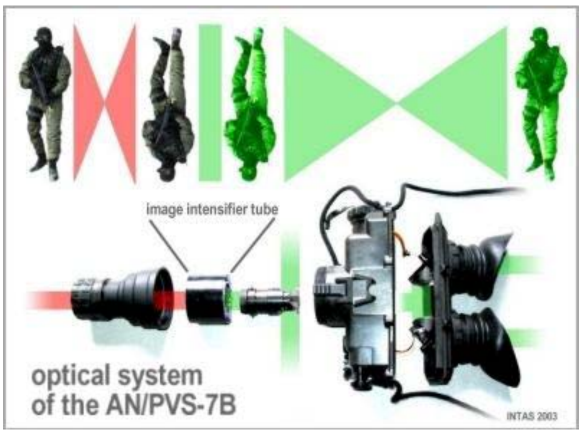
$$NEP = P_{ris} = \frac{1\ nA}{3\cdot 10^{5}\ \frac{A}{W}} = 3.3\cdot 10^{-15}\ W$$

to estimate the NEP in terms of photons rate, let us consider the peak wavelength λ*=400 nm*

$$N_{\lambda,\ res} = \frac{NEP}{h\cdot c}\lambda = \frac{3.3\cdot 10^{-15}}{6.6\cdot 10^{-34}\cdot 3\cdot 10^{8}} 400\cdot 10^{-9} \approx 6000\frac{photons}{s}$$

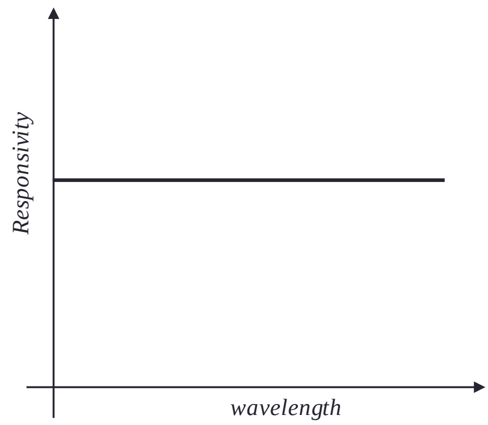
Image enhancement





Thermal detectors

- Photonic sensors are defined by a limit wavelength corresponding to the energy gap of the detector material.
- In spectral regions were photonic detectors cannot be used, the radiation intensity can be measured through the measure of the temperature change due to the absorbance of radiant power.
- These devices are temperature sensors coupled with a large absorbance material (ideally a black body) so that the total incident power is absorbed and then transformed in a temperature variation.
- The amount of temperature change depends on the heat dissipation towards the environment.
- The response of these sensors depends uniquely on the radiant power and not on the wavelength (in the interval of opacity of the material), then the responsivity is constant with respect to the wavelength.

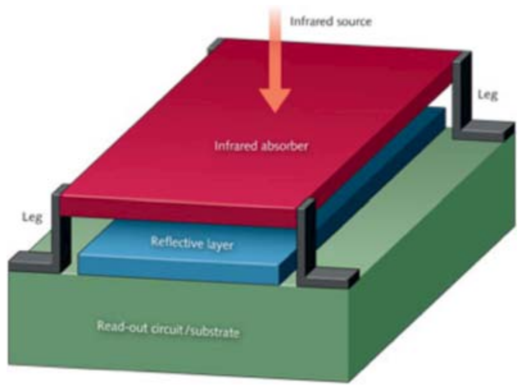


Thermistor bolometer

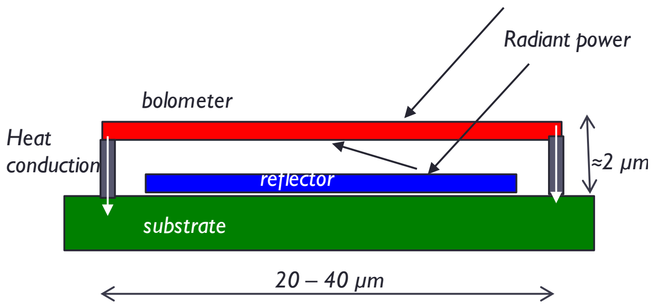
- The bolometer is a device measuring the total absorbed power.
- The thermistor bolometer is a thermistor used to measure the change of temperature due to the absorbance of infrared radiation.
- The changes of temperature are typically tiny so the detector is always described by a linear characteristics and then the temperature coefficient is the important quantity:

$$\alpha = \frac{1}{R}\frac{dR}{dT}$$

- The performance depends on the heat dissipation with the surrounding environment. The heat received from a radiant source is dissipated through conduction (convection is usually negligible). The conduction can take place through the substrate and through the electric contacts.

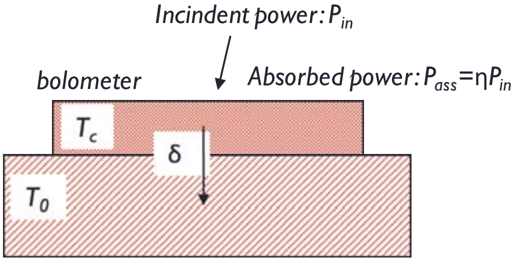


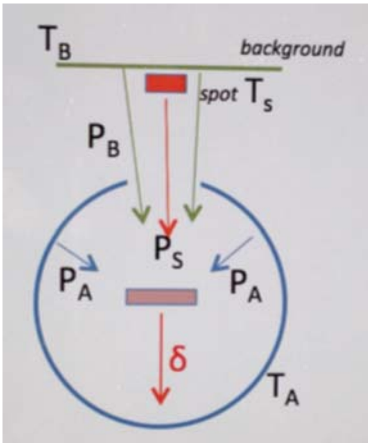
structure of a microbolometer for IR image arrays.



An IR mirror reflects back the transmitted radiation

Bolometer heat balance



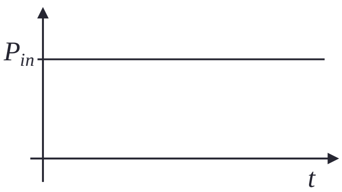


- A portion η of the incident radiation is absorbed by the bolometer.
  - The ideal bolometer is a black body
- The absorbed radiation contributes to increase the bolometer temperature.
- In a wide range of wavelength η is almost constant.
- The change of temperature is ruled by the heat exchange equation between the bolometer and the environment.

$$\eta \cdot P_{in} - \delta \cdot (T - T_A) = m \cdot c \cdot \frac{dT}{dt}$$

Bolometer: the case of constant illumination

- Let us suppose a bolometer subjected to a step input of illumination: $P_{in}(t<0)=0$;: $P_{in}(t\geq 0)=P_{in}$
- The bolometer is connected to a voltage divider where $R_L \gg R_S$ (current source).



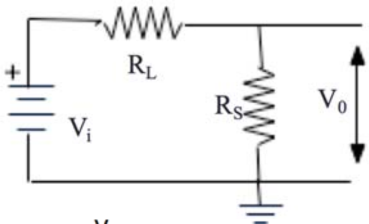
Thermal equilibrium:

$$m \cdot c \cdot \frac{dT}{dt} + \delta \cdot (T - T_A) = \eta \cdot P_{in}$$

$$at\ t=0; T=T_A \Rightarrow\ T - T_A = \frac{\eta \cdot P_{in}}{\delta}\left[1-\exp\left(-\tfrac{\delta}{mc}t\right)\right];$$

$$\frac{m \cdot c}{\delta}: \textit{thermal time constant}$$

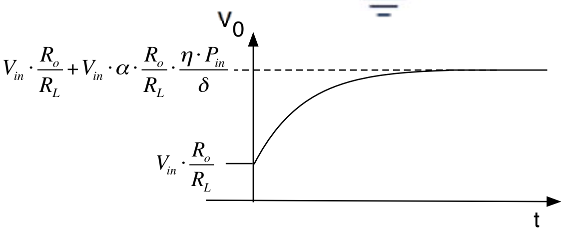
$$\textit{steady-state temperature}\quad T - T_A = \frac{\eta \cdot P_{in}}{\delta}$$



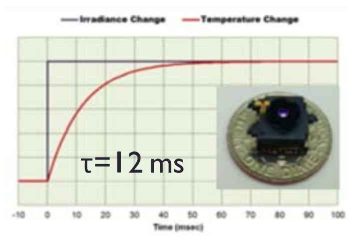
Voltage signal:

$$V_{out} = V_{in} \cdot \frac{R_o \cdot (1 + \alpha \cdot (T - T_A))}{R_L} = V_{in} \cdot \frac{R_o}{R_L} + V_{in} \cdot \alpha \cdot \frac{R_o}{R_L} \cdot \frac{\eta \cdot P_{in}}{\delta}\left[1-\exp\left(-\tfrac{\delta}{mc}t\right)\right];$$

$$\textit{Steady-state responsivity}: \Re = \frac{V_{out}}{P_{in}} = V_{in} \cdot \alpha \cdot \frac{R_o}{R_L} \cdot \frac{\eta}{\delta}$$

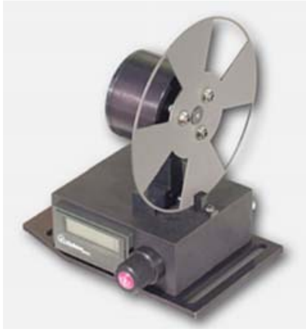


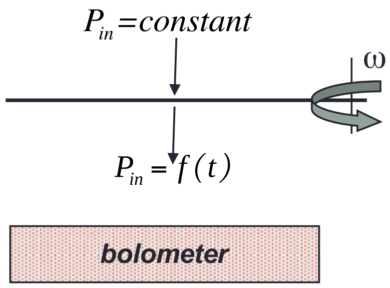
Observation: smaller is the heat dissipation, more responsive but slower is the sensor.

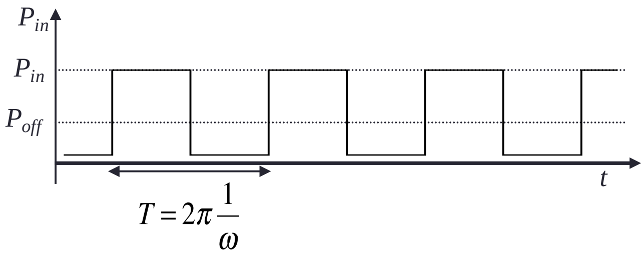


Bolometer: modulated incident radiation

- The incident radiation is modulated in time
  - Example: a masked disk (chopper) rotating at the steady pulsation ω.
  - Then, P_{in}, P_{ass}, and T are modulated at the pulsation ω







Limiting the Fourier development to the first harmonic, the incident power is:

$$P_{tot} = P_{off} + P_{in}\cdot e^{j\omega t}$$

Bolometer: modulated incident radiation

$$P_{tot} = P_{off} + P_{in}\cdot e^{j\omega t} \Rightarrow T = T_{off} + T_c\cdot e^{j\omega t}$$

$$\eta\cdot P_{off} + \eta\cdot P_{in}\cdot e^{j\omega t} - \delta\cdot\left(T_{off} + T_c\cdot e^{j\omega t} - T_o\right) = c\cdot\frac{d}{dt}\left(T_{off} + T_c\cdot e^{j\omega t}\right)$$

$$\eta\cdot P_{off} + \eta\cdot P_{in}\cdot e^{j\omega t} - \delta\cdot\left(T_{off} - T_o\right) - \delta\cdot T_c\cdot e^{j\omega t} = c\cdot j\omega\cdot T_c\cdot e^{j\omega t}$$

$$\textit{offset component}:\ \eta\cdot P_{off} - \delta\cdot\left(T_{off} - T_o\right) = 0 \Rightarrow T_{off} = T_o + \frac{\eta\cdot P_{off}}{\delta}$$

$$\textit{modulated component}:\ \eta\cdot P_{in}\cdot e^{j\omega t} - \delta\cdot T_c\cdot e^{j\omega t} = c\cdot j\omega\cdot T_c\cdot e^{j\omega t} \Rightarrow T_c = \frac{\eta\cdot P_{in}}{\delta + j\omega\cdot c}$$

$$\left|T_c\right| = \frac{\eta\cdot P_{in}}{\sqrt{\delta^2 + \omega^2\cdot c^2}}$$

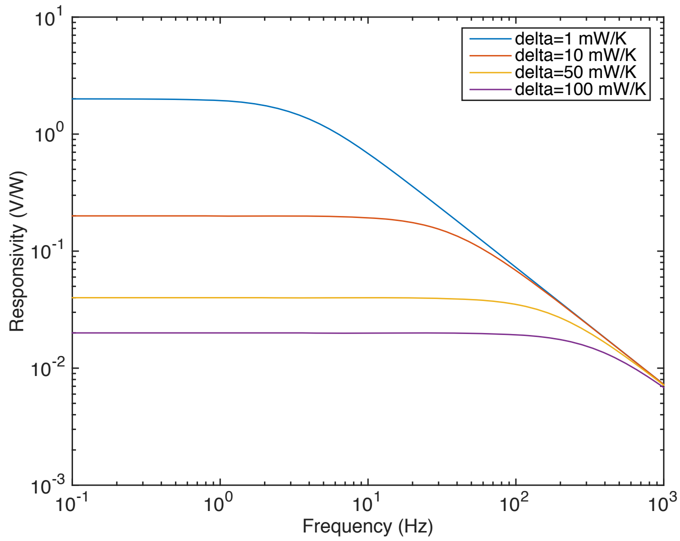
$$\left|V_{out}\right| = V_{in}\cdot\alpha\cdot\frac{R_o}{R_L}\cdot\left(T_o + \frac{\eta\cdot P_{off}}{\delta} + \frac{\eta\cdot P_{in}}{\sqrt{\delta^2 + \omega^2\cdot c^2}}\right)$$

$$\Re = \frac{V_{out}}{P_{in}} = V_{in}\cdot\alpha\cdot\frac{R_o}{R_L}\cdot\frac{\eta}{\sqrt{\delta^2 + \omega^2\cdot c^2}}$$

$$\Re = V_{in}\cdot\alpha\cdot\frac{R_o}{R_L}\cdot\frac{\eta}{\delta}\cdot\frac{1}{\sqrt{1 + \omega^2\cdot\frac{c^2}{\delta^2}}}$$

The responsivity to the modulated power is a low-pass function of the modulation frequency.

Bolometer: modulated incident radiation



example carbon black resistor:

$$c = 0.69 \cdot 10^{-3} \frac{J}{kg \cdot K} \quad \alpha = 0.01\ K^{-1} \quad \eta = 1$$

$$R_0 = 1\ k\Omega; \quad R_L = 50\ k\Omega; \quad V_{in} = 10\ V$$

- The cut-off frequency depends on the capability of the sensor to dissipate the absorbed heat.
- The increase of the frequency range results in a decrease of the pass-band responsivity.

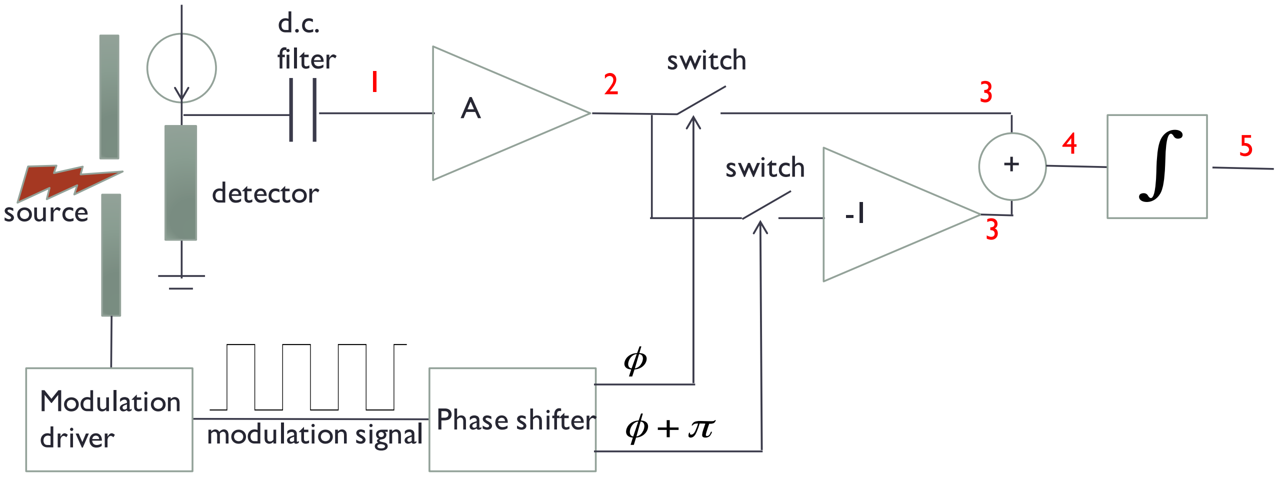
With respect to a continuous exposure, the modulation of the source results in an apparent decrease of performance but:

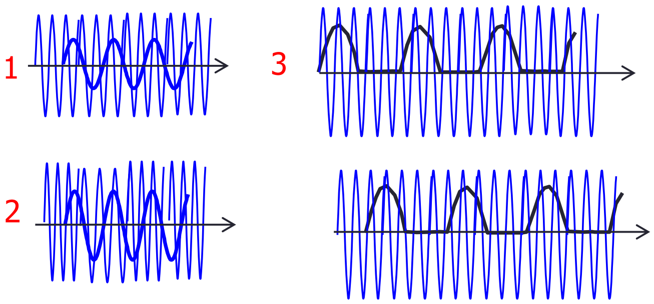
- Real world applications requires a differential measurement
- It makes possible the use of the lock-in amplifier. A measurement technique and an electronic amplifier that makes possible to extract signals embedded in noise.

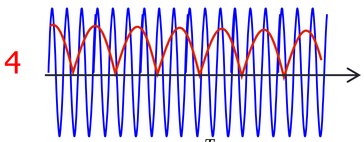
Lock-in amplifier

- The lock-in amplifier is an amplifier with an adaptive filter centered at the frequency at which the signal is modulated.
- The signal to noise ratio depends on the integration time, and for a long measurement time, signals embedded in noise can be measured.
- The measurement requires a steady modulation of the radiant power driven by a known and accessible signal.

Principle of a Lock-in amplifier





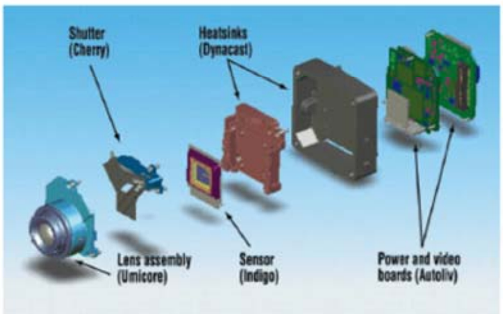


5

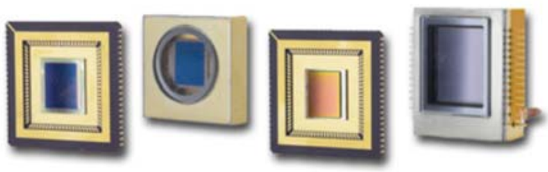
$$V_{out} = \frac{1}{T}\int_0^T \left(|v_s \cdot \sin x| + v_{noise}\right)dt \xrightarrow[T\to\infty]{} = v_s \frac{2}{\pi}$$

$$\lim_{T\to\infty} \frac{1}{T}\int_0^T v_{noise}\, dt = 0$$

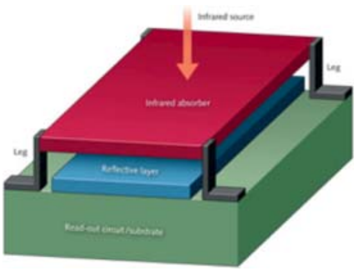
Thermal camera

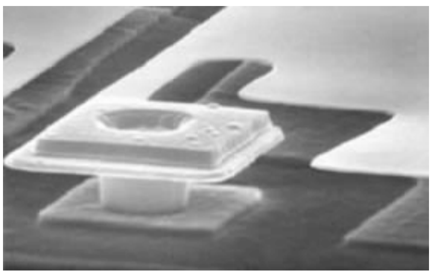


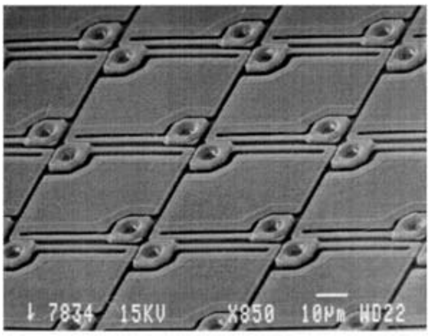
2. Development of the BMW Night Vision Camera required close cooperation among many firms. Other companies developed many of the camera's parts.



arrays of bolometers made of VO2.







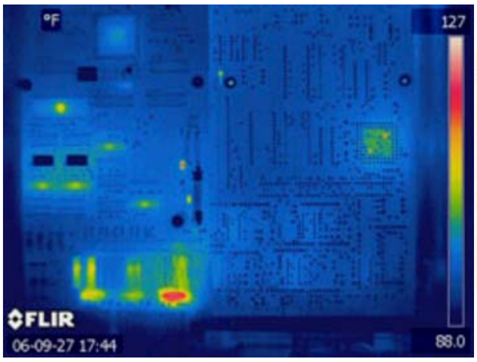
Electron Microscope Image of microbolometer FPA

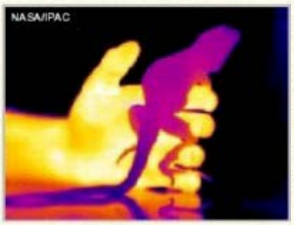
Infrared imaging

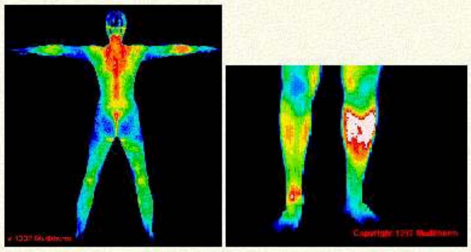
Courtesy of Mitsubishi Electronics and Raytheon Commercial Infrared

(Top or left) Visible/infrared images (left/right) taken from the cockpit of an airplane preparing to land in a dense fog. (Bottom or right) An infrared night-vision camera installed in an automobile warns the driver of a deer in the road at night.

1. The far-IR Night Vision system developed by Autoliv for BMW is mounted on the car's front bumper's left side (bottom). The display is shown as in the instrument panel (top).





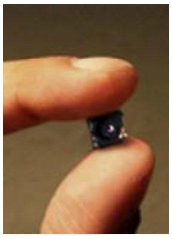


copyright Meditherm Australia

Infrared view of human body and infrared study of blood flow in legs (showing injured right ankle and weight transfer to the left leg)

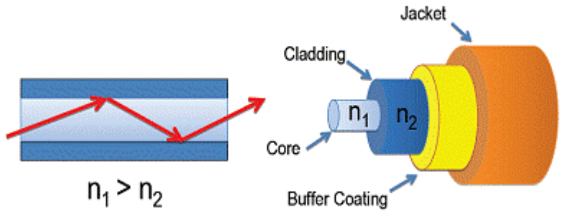
Thermal Camera

FLIR



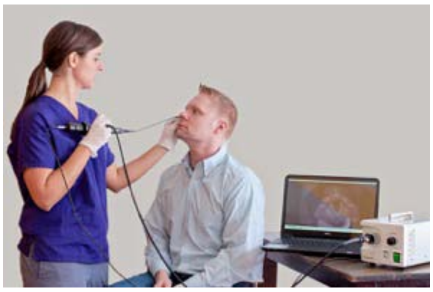
Rilevatore di immagine	Microbolometro Focal Plane Array (FPA) FLIR Lepton®
Otturatore	Otturatore automatico integrato
Risoluzione immagine (A x L)	4.800 pixel (80 x 60)
Risposta spettrale	da 8 a 14μm

Fiber optics sensors



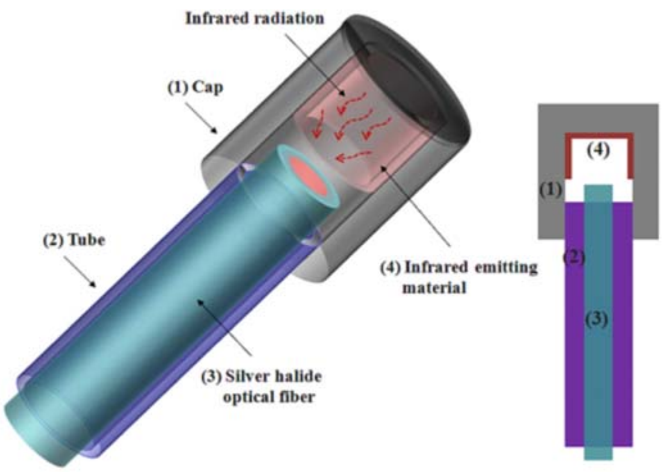
- The condition of entrapment of light inside a waveguide depends on the ratio between the refraction indexes of the core and the cladding.
- There are two main applications of fiber optics for sensors
  - Light transport:
    - The fiber can deliver and collect light from non directly accessible locations (e.g. endoscopy)
  - Sensitive properties of fiber optics performance
    - Changes in the refractive index of the cladding result in variation of the transmitted power. Then if the refractive index of the cladding is sensitive to some environmental quantity (e.g. temperature) the fiber optics can be turned into a sensor.
    - Such a sensor can be distributed. Namely the signal is the average along the length of the fiber.

$$\sin i > \frac{n_{cladding}}{n_{core}}$$



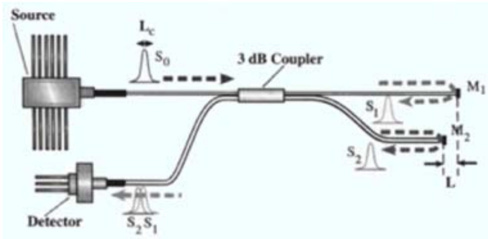
Fiber optics sensors pyrometer

- Measurement of thermal radiation emitted by thin film black body on the tip of the fiber optics.
- Black body radiation can be measured in a suitable spectral range using a proper filter.
- Dynamic range: 200 – 500 °C.

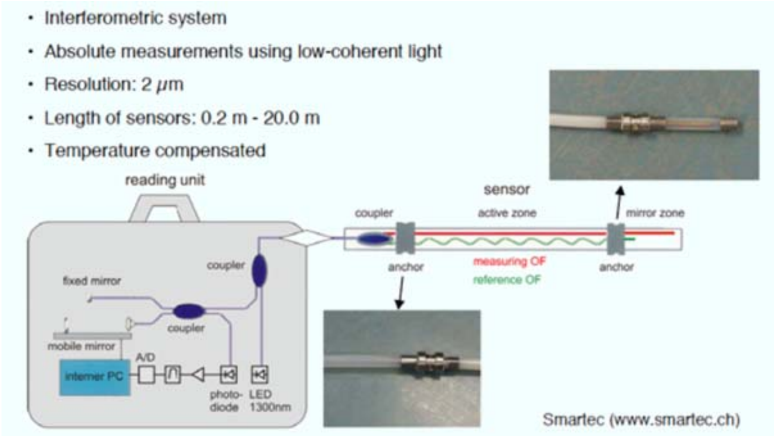


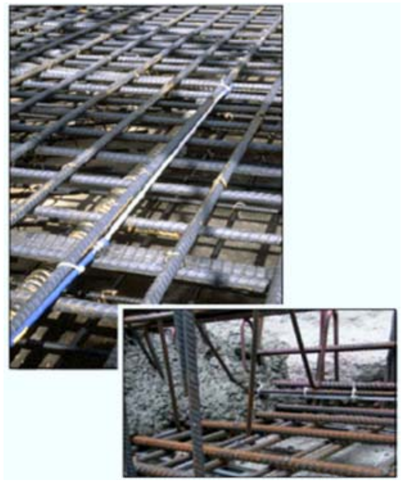
Sensori a fibra ottica:variazione di fase:interferometro

- Sensori a variazione di Fase
  - In questi sensori si misura lo sfasamento tra la luce che viaggia in una fibra di riferimento e quella che percorre la fibra di misura.
  - La misura dell'interferenza tra i due raggi luminosi consente di effettuare misure di alta sensibilità



Esempio sensore di deformazione:

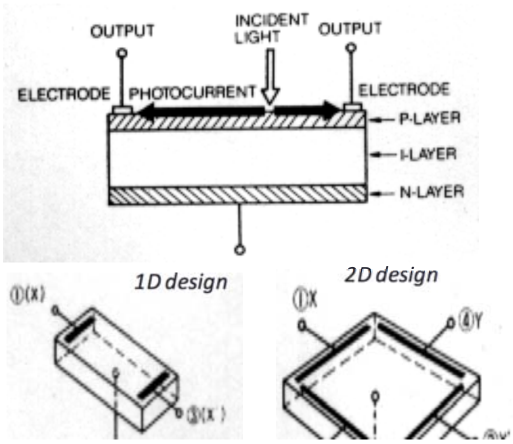




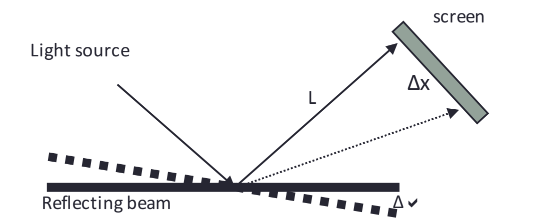
Optical sensors for mechanical measurements

1: position sensitive detectors

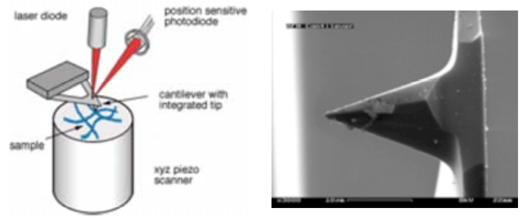
- PSD is a special photodiode designed to be sensitive to the position of the point of impact of the light
- It can be designed for 1D and 2D detection
- The linear detector is a p-i-n diode with 3 electrodes. The sensitive area is larger than the light beam size, so from the point of impact two photocurrents are generated. Since the resistivity of the materials is uniform, the current collected at the electrodes is inversely proportional to the distance between the point of impact and the electrodes.



deflected beam $\Delta x = L \cdot \tan\alpha$



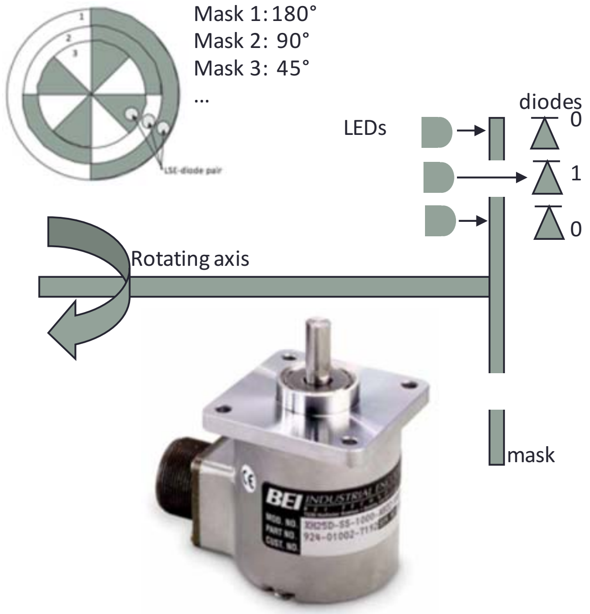
atomic force microscopy



Optical sensors for mechanical measurements

2: optical encoder of angular rotation

- The rotation axis is connected to a series of concentric masks containing a pattern of opaque and transparent parts that modulates the optical path of LED-photodiode couples.
- The number of transparent parts in each circle encode the angular position in a digital code (0: opaque, 1: transparent).
- The number of concentric masks determines the number of bits and then the angular resolution.



- Given a 8 bits encoder, which is the angular position corresponding to the following output signal: 10010110?

Mask order	Mask angle	Observed pattern	Contribution to the total angle
1	180	1	180
2	90	0	0
3	45	0	0
4	22.5	1	22.5
5	11.25	0	0
6	5.625	1	5.625
7	2.8125	1	2.8125
8	1.40625	0	0
		Total angle:	210.94

The last bit determines the resolution → 1.40625°
Then, the result of the measurement is (210.9 ±0.7)°