UNIVERSITÉ DE ROUEN

UFR Sciences et Techniques

Optical Detectors

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Schedule & place (Madrillet)
Monday 23/09 08h30-12h15, Room 11
Monday 30/09 08h30-12h15, Room 11
Monday 07/10 08h30-12h15, Room 11
Monday 14/10 08h30-12h15, Room 11

2019.09

Outline of Course

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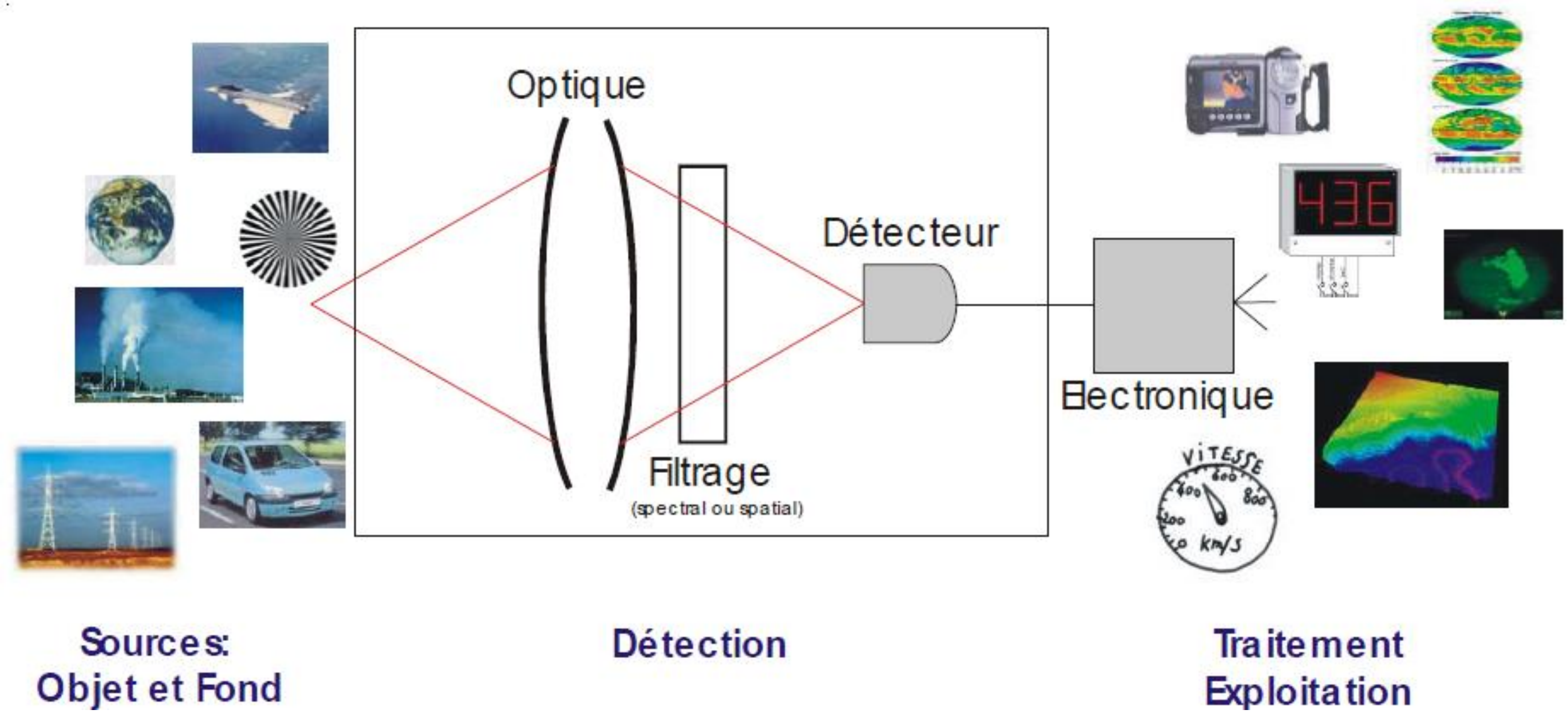
- **Introduction**
  - Objectives of the course
  - Optronic systems
  - Characteristic of optical detectors
- **Models of light**
  - geometric model
  - wave model
  - corpuscular model
- **Photometry**
  - Radiation quantities
  - Luminous quantities
- **Light Sources**
  - Classification of sources
  - Black body
- **Fundamental laws**
  - Law of inverse square
  - Law of cosine
  - Law of Beer
  - Criterion of Rayleigh
- **Optical Detectors**
  - Classification of detectors
  - Principles of optical detectors
    - Eyes
    - Detectors based on photoelectric effect
    - Diode and photodiode
    - Optical detectors CCD and CMOS
    - Bolometric detectors
    - Thermocouples
    - Pyroelectric detectors
  - Characteristics of optical detectors

Introduction

- **Why Optical Detectors:**
  - **Optical Metrology**
    - **Limit of the eyes**
    - **Limit of other measurement techniques (mechanical ...) - accuracy, accessibility, speed ...)**
    - **Measurable quantities - Electrical / Electronic**
  - **Automatization - precision**
- **Objectives**
  - **Be acquainted with the physical quantities**
  - **Be acquainted with the basic laws**
  - **Understand the principles of different detectors**
  - **Applications in various areas**
- **Control and Exam**
  - **A mi-term control**
  - **A final exam**

An optical imaging system



The detection unit that includes optics, spectral and spatial filtering, sensor and electronics (current-voltage converter, amplification, ...) is at the core of the system and requires the greatest attention. Detection must be adapted to the observed scene and the nature of information to be extracted.

Introduction

Optical Detectors

The **Optical Detectors** are Detectors which convert the signal of light (from ultraviolet to infrared) into an electrical signal.

They are omnipresent in today's society. Their usages are diverse and may be presented in four main categories:

- The Optical Imaging Detectors: CCD, CMOS, ... for photography and videography, photodiodes, etc. are very commonly used in daily life today.
- The Optical Detectors for research: they can be very different and must be specifically designed for certain applications.
- The Industrial Optical Detectors : photocell, photomultiplier ... in technical fields that match the needs of particular automation process.
- The military Optical Detectors: used in the detection, recognition and observance, both in the area of space, land or marine.

****

?? Give some applications of Optical Detectors ??
?? that you know. ??

****

Introduction

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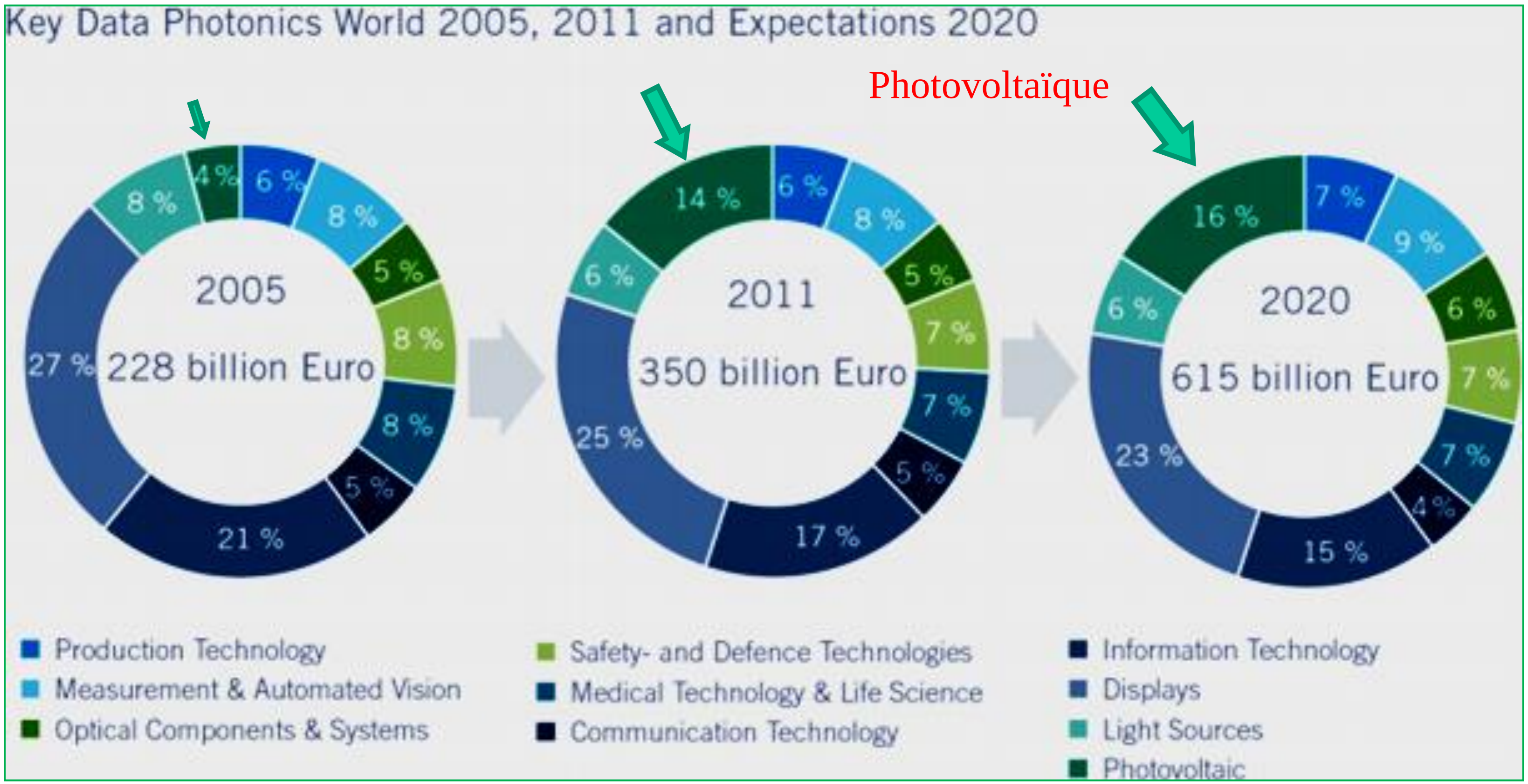
2015 INTERNATIONAL YEAR OF LIGHT AND LIGHT-BASED TECHNOLOGIES

United Nations Educational, Scientific and Cultural Organization · International Year of Light 2015

http://www.light2015.org/Home/WhyLightMatters/Economic-Impact.html



Introduction

Characteristics of Optical Detectors

- **Limit and extension of measurement (**in particular ***λ, I*),**

  The sensor must be used in its normal field of usage. Beyond this limit, the measurement is not reliable or the sensor may be destroyed.

- **Sensibility**

  The sensitivity S determines the output quantity of the sensor as a function of the input variable:

- **Resolution**

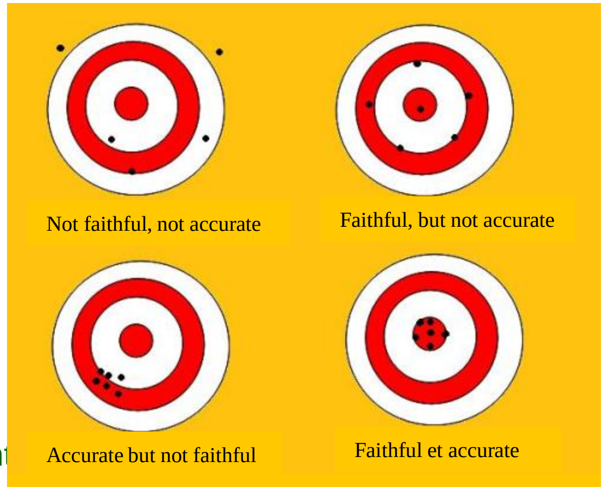
  The smallest change that the sensor is able to detect in the measurement.

- **Faithfulness - Accuracy – Precision**

  Do not confuse these three terms.

  See Figure for the faithfulness and the accuracy,

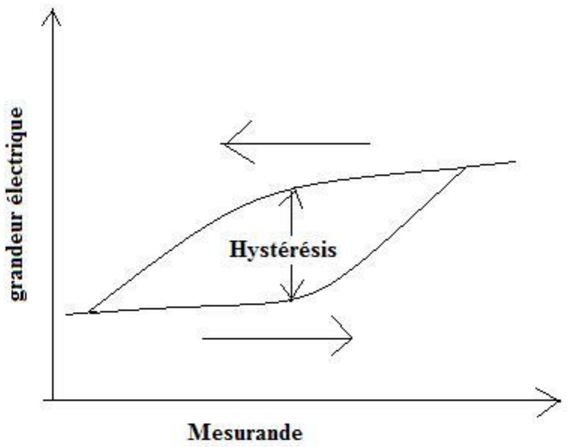
  The **precision** of each measured value depends on the instrument



Introduction

- **Hysteresis**

  Hysteresis is the maximum difference between the two output variables obtained for the same measurand. If hysteresis is null, the measurement is reversible.



- **Reproducibility or repeatability**

	échantillon	méthode	laboratoire	personne	équipement
Repeatability same conditions	same	same	same	same	same
Reproducibility certaine conditions variied	same	same	different	different	different

- **Response time**

  This is the time interval which elapses after a sudden change of the measurand until the variation of the sensor output is less than a fixed deviation limit ε.

Models of light

- **Geometric Model:**

  The light is associated with trajectories described by the energy carried by the light : light rays

- **Wave model:**

  The light is described as an electromagnetic wave.

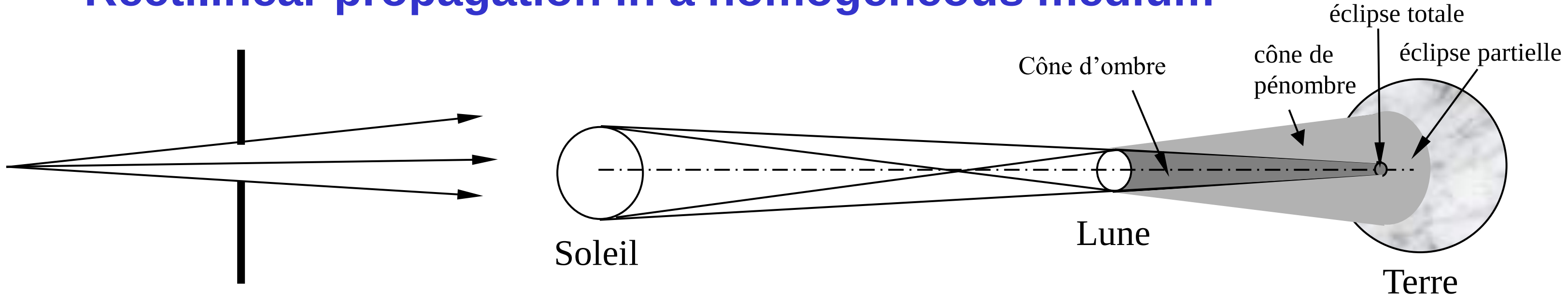
- **Corpuscular / quantum model :**

  The light is interpreted as "grains" of energy called photons, whose properties (energy and momentum) are connected to the frequency ν or wavelength λ.

Models of light

1. Geometric model

- Rectilinear propagation in a homogeneous medium

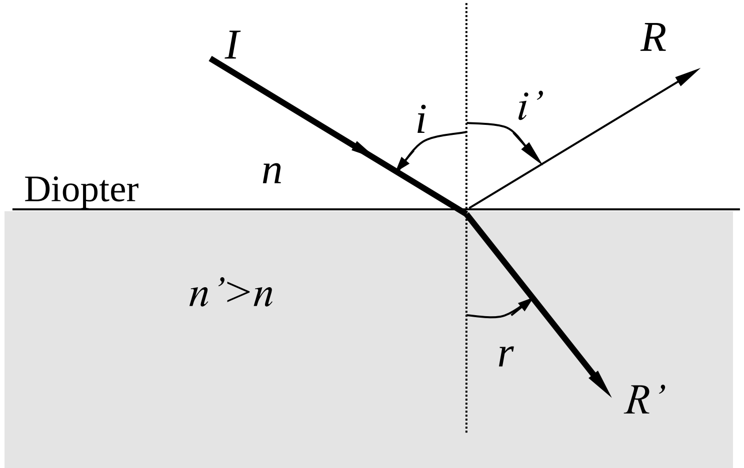


- Reflection and refraction on a surface

Laws of reflection and refraction

$$n \sin i = n' \sin r$$

See geometrical optics courses for more details



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2. Wave model

- Light is an electromagnetic wave,
- The wavelength for light in the visible range is between

  400 nm ~ 800 nm

- Color is related to the wavelength,
- Some fundamental relationship:
  - The wavelength λ, the frequency ν and the period T:

$$\nu = \frac{c}{\lambda}$$

$$T = \frac{\lambda}{c}$$

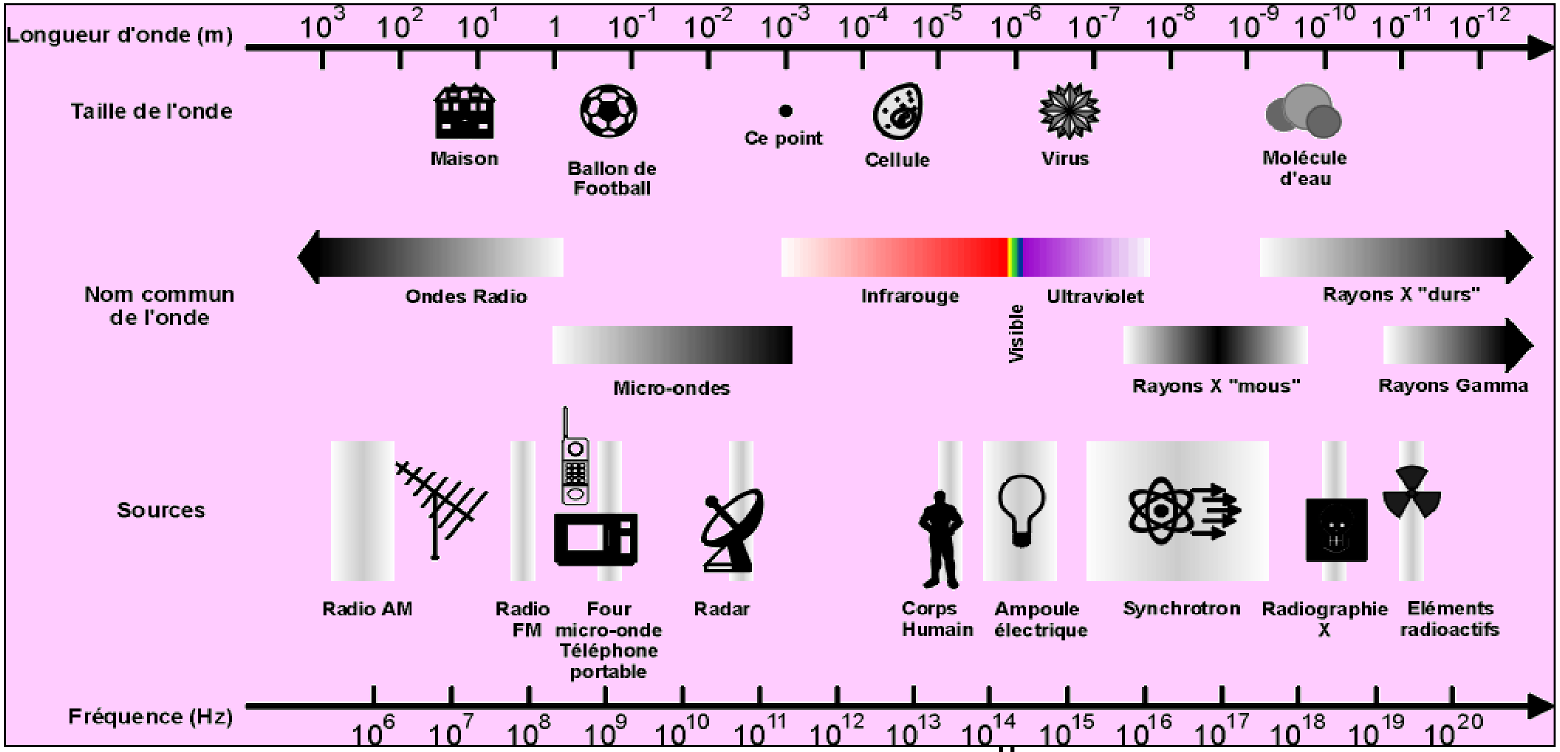
  - The velocity of light:

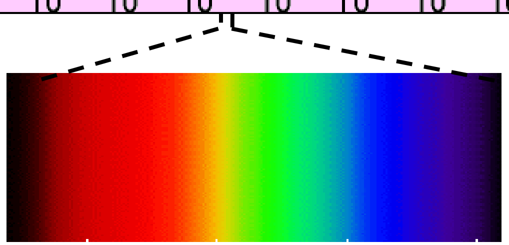
    $c = 3.10^8$ m/s in a vacuum,

    c/n in a medium of index de n

Models of light

Electromagnetic radiation and light





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3. Corpuscular model

- **The light is interpreted as "grains" of energy called photons.**
- **Each photon carries an amount of energy :**

$$E_p = h\nu = \frac{hc}{\lambda}$$

où h=6.62 10^{-34} J.sec is the Planck's constant.

- **Photons move at the speed of light :**

  c =3.10^8 m/s in a vacuum, c/n in a medium of index de n.

- **A light beam can be considered as a wind of "photons ",**
  - the "wind" is as strong as the photons are numerous,
  - The intensity is proportional to the flux of photons.

$$n = \frac{P}{h\nu}$$

n : number of photons/second.
P : energy flux / power.

Models of light

Some examples

- **Calculate the frequency of light for the two wavelengths :**

  0,45 µm (blue) and 0,6328 µm (red)

  – $c=\nu\lambda$, $\nu=c/\lambda$
  – $\nu_{0,45}=6,67\ 10^{14}$Hz, $\nu_{0,6328}=4,74\ 10^{14}$Hz,

- **Calculate the wavelengths of the EM waves** ($\lambda = c/\nu$)

  – radio GO : ν=100 ~ 375 kHz → λ_{GO} =3~0,8 km
  – radio AM : ν=520 ~ 1062 kHz → λ_{AM} =577~185 m
  – radio FM : ν=87,5 ~107,9 MHz → λ_{FM} =3,4~2,8 m
  – television : ν=30 ~300 MHz → λ_{TV} = 10 ~ 1 m

- **Calculate the energy of a photon in the above cases**

  – $E=h\nu$, $h=6,62\ 10^{-34}$ J.sec, $1eV=1,6022\ 10^{-19}$ J
  – $E_{0,45}=4,4\ 10^{-19}$ J=2,75 eV, $E_{0,6326}=3,14\ 10^{-19}$ J=1,96 eV,
  – $E_{GO}=3,4\sim12,8\ 10^{-29}$ J=2,1~8 10^{-10} eV
  – $E_{TV}=1,02\sim10,2\ 10^{-26}$ J=6,4~64 10^{-8} eV (~1000 fois de E_{GO})

- **Calculate the number of photons as a function of energy flux**

  – $n=P/h\nu$: $n_{0,45}=10^{-3}/4,4\ 10^{-19}$ =2,27 10^{15} p/s, $n_{0,6326}=10^{-3}/3,14\ 10^{-19}$ =3,18 10^{15} p/s

Photometry

Generality

- **The sensitivity of the eye depends on the wavelength of light.**
  - The eye has a maximum sensitivity at about 555 nm
  - Around this wavelength, the sensitivity decreases and vanishes at 380nm and 800nm
  - 1 watt (W) of light emitted at 555 nm is 683 lumens (lm).

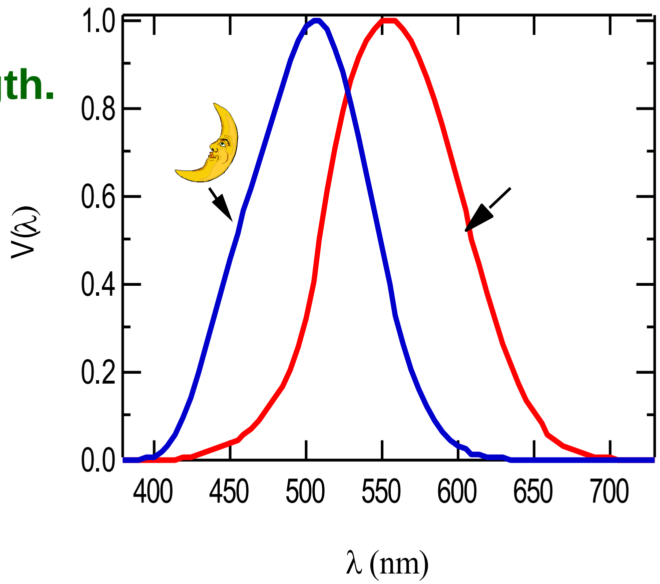
- **The sensors also.**

  Its sensitivity depends on the wavelength.

  So :

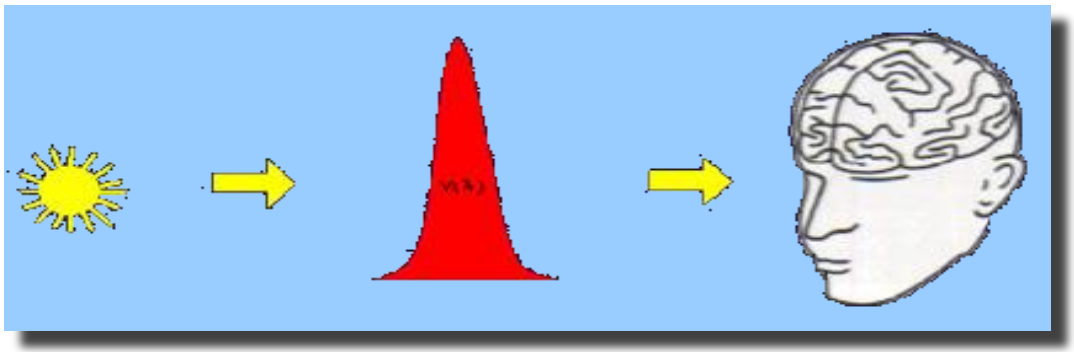
➢ **Radiant photometry (radiometry)**

➢ **Luminous photometry**



Generality

- The sensitivity of the eye as function of the wavelength of light.



Emitted energy (W)

efficiency V(λ)

luminous flux (lm)

Radiometry

Luminous photometry

$$F_v = \kappa \int_{380\text{nm}}^{760\text{nm}} F_e(\lambda) V(\lambda) d\lambda$$

$$\kappa = 683 \text{ lm/W}$$

Photometry

Luminous efficiency of some light sources

Light Source	K ($lm.W^{-1}$)
Lampe filament C	6
Lampe filament W (vide)	10
Lampe filament W + Gaz inerte	11-20
Lampe à vapeur d'Iode	22-25
Tube fluorescent	50-80
Lampe à vapeur de Na	55
Soleil	91

Quantities of photometry

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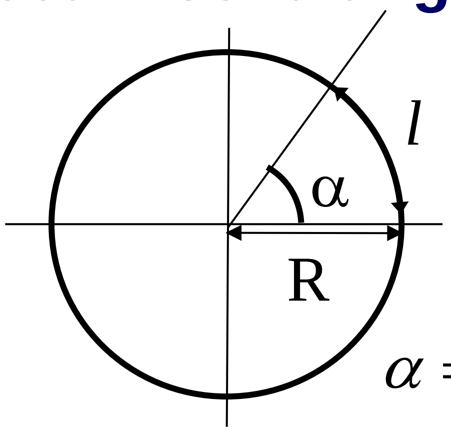
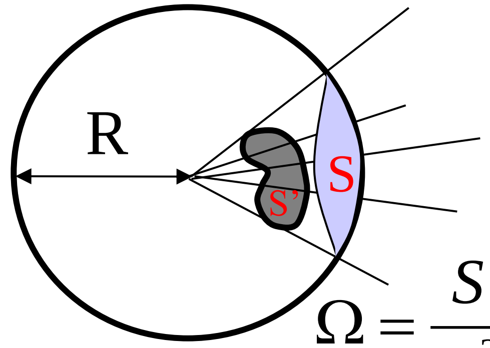
0. Recall: solid angle Ω :



$$\alpha = \frac{l}{R}$$



$$\Omega = \frac{S}{R^2}$$

L'angle (d'arc) est la longueur de l'arc intercepté sur un cercle de rayon unitaire.
Un tour complet correspond à un angle 2π **radians.**

L'angle solide est l'aire de la surface interceptée sur une sphère de rayon unitaire.
L'espace entier correspond à un angle solide 4π **steradians.**

The solid angle of a circular cone: $\Omega = 2\pi(1-\cos\alpha)$,
For small α : $\Omega = \pi\alpha^2$

Ex : The angular diameter of the sun : 0,5°=8,7 10^{-3} radians
The solid angle of the sun: 6 10^{-5} steradians.

$$S = r^2\Omega = \int_0^{2\pi}\int_0^{\alpha} r^2 \sin\theta \, d\theta \, d\phi = 2\pi(1-\cos\alpha) r^2$$

Quantities of photometry

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1e. Energy (radiant) Q_e : *(énergie rayonnée)*

Unit: Joule (J, kJ …), kWh

You pay the energy consumed: kWh to EDF, liters of gasoline…

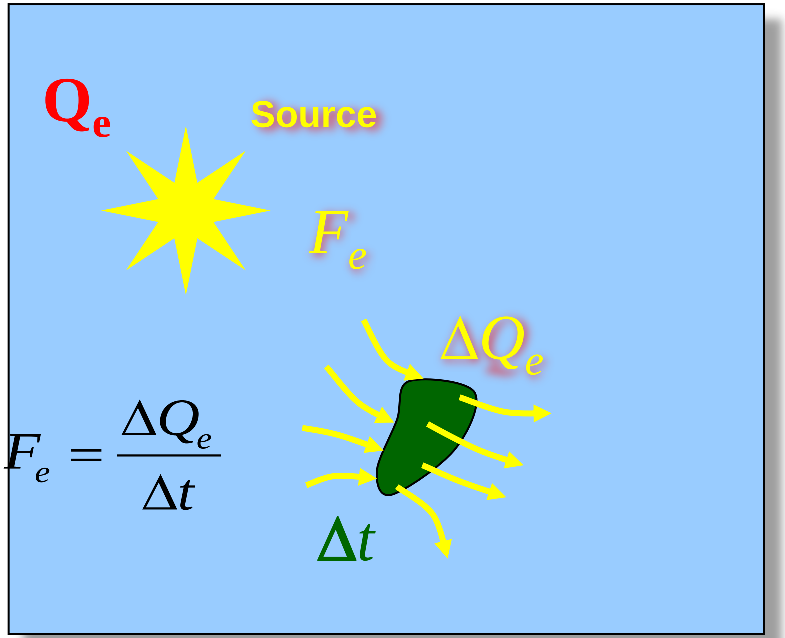
2e. Radiant flux F_e : *(flux énergétique)*

Definition :

$$F_e = \frac{dQ_e}{dt}$$

Unit: Watt =J/s (kW, …)

- A lamp : qqs W
- A continuous laser: mW ~ W
- Thermal / nuclear power plants : ~ 10^8 W



Quantities of photometry

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1v. Luminous quantity Q_v : *(quantité de lumière)*

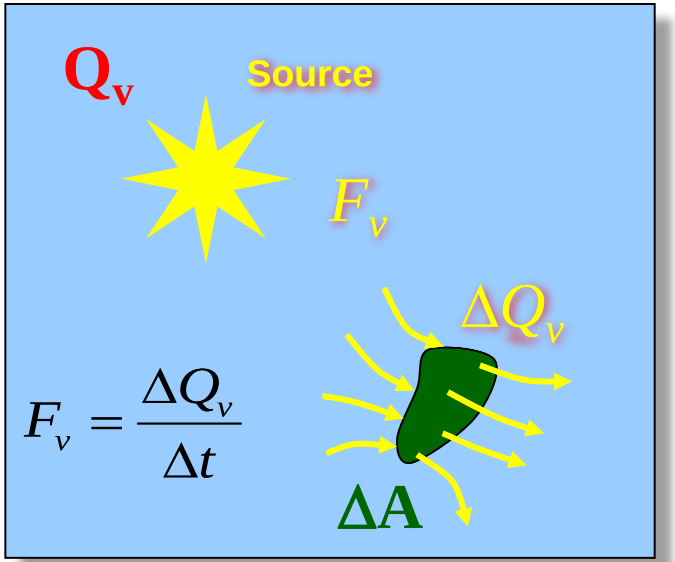
– **Unit: lumen-second (lm.s)**

2v. Luminous flux F_v : *(flux lumineux)*

– **Definition :**

$$F_v = \frac{dQ_v}{dt}$$

– **Unit: lumen (lm)**



The larger the aperture ***D*** of camera / telescope, the greater the light output is important.

– Professional camera ***D*** ~ cm

– Astronomical telescope ***D*** ~ m

Quantities of photometry

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3e. Irradiance E_e : *(éclairement énergétique)*

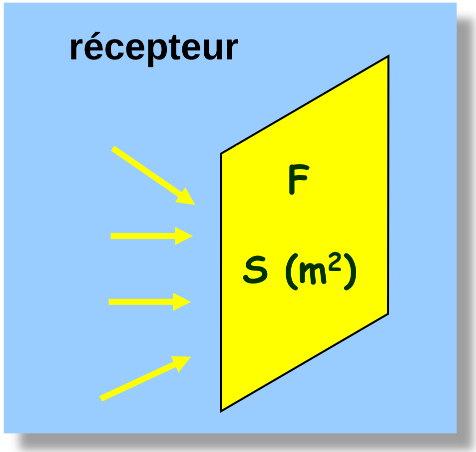
Definition :

The radiant flux received per unit area:

$$E_e = \frac{dF_e}{dA}$$

Unit: W/m², A : area

– $E_e = F/A$



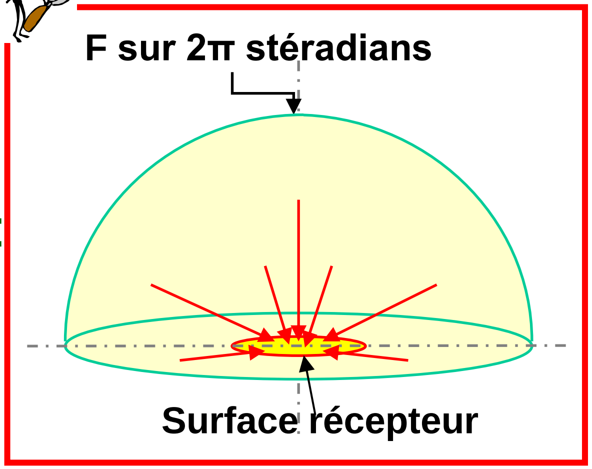
3v. Illuminance E_v : *(éclairement lumineux)*

– **Definition :**

The luminous flux received per unit area:

$$E_v = \frac{dF_v}{dA}$$

– **Unit: lux = lumen.m⁻²**



Quantities of photometry

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Correspondence btw film sensitivity (ISO), illuminance (lx) and aperture (f/)

vitesse d'obturation env. 1/50 sec.)								
ISO	**f/1,4**	**f/2**	**f/2,8**	**f/4**	**f/5,6**	**f/8**	**f/11**	**f/16**
50	500	1000	2000	4000	8000	16000	32000	64000
100	250	500	1000	2000	4000	8000	16000	32000
200	125	250	500	1000	2000	4000	8000	16000
400	63	125	250	500	1000	2000	4000	8000
800	32	63	125	250	5000	1000	2000	4000

Quantities of photometry

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Valeur repère d'éclairement	
Situation	*Eclairement*
Pleine lune	0,5 lx
Lumière d'une bougie	10 lx
Rue de nuit bien éclairée	20 - 70 lx
Appartement lumière artif.	100 lx
Bureau, atelier	200 - 3000 lx
Grand magasin	500 - 700 lx
Stade de nuit, salle de sport	1500 lx
Studio ciné./TV	2000 lx
Extérieur à l'ombre	10000 - 15000 lx
Ciel couvert	25000 - 30000 lx
Soleil "moyen"	48000 lx
Plein soleil	50000 - 100000 lx

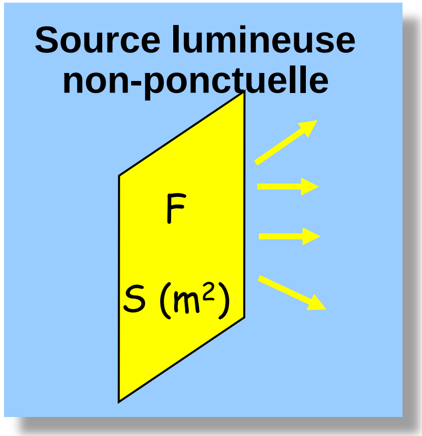
Quantities of photometry

4e. radiant emittance M_e : *(émittance énergétique)*

– **Definition :**

The radiant flux *emitted* per unit area:

$$M_e = \frac{dF_e}{dA}$$



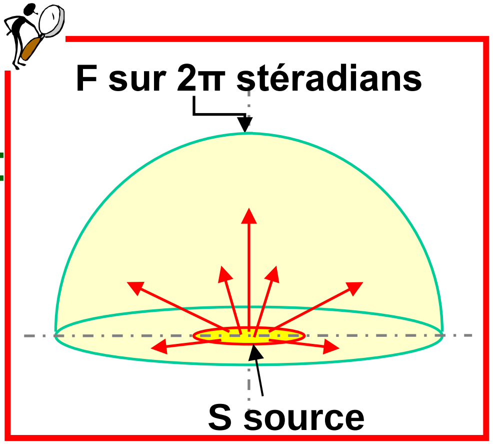
A : area, Unit: W/m^2,

4v. luminous emittance M_v : *(émittance lumineuse)*

– **Definition :**

The luminous flux *emitted* per unit area:

$$M_v = \frac{dF_v}{dA}$$



– **Unit: lux = lumen.m^{-2}**

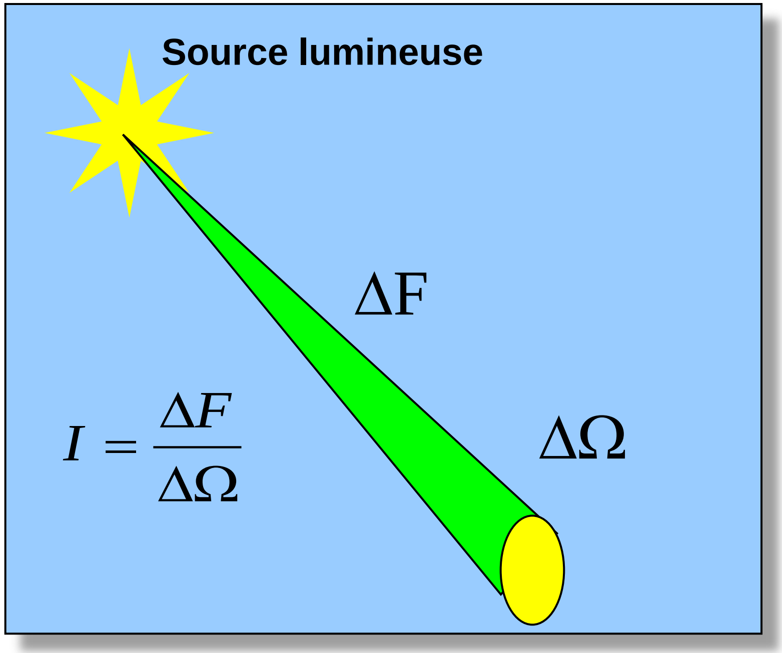
Quantities of photometry

5e. Radiant intensity I_e : *(intensité énergétique)*

– **Definition :**

$$I_e = \frac{dF_e}{d\Omega}$$

– **Unit : W.sr^{-1}**



5v. Luminous intensity I_v :

(intensité lumineuse)

– **Definition :**

$$I_v = \frac{dF_v}{d\Omega}$$

– **Unit:**

candela (cd)
1 cd = 1 lm/sr

Quantities of photometry

6e. Radiance L_e : *(luminance énergétique = radiance)*

– **Definition :**

$$L_e = \frac{dI_e}{dA\cos\theta}$$

– **Unit :**

W.m^{-2}.sr^{-1}

6v. Luminance L_v :

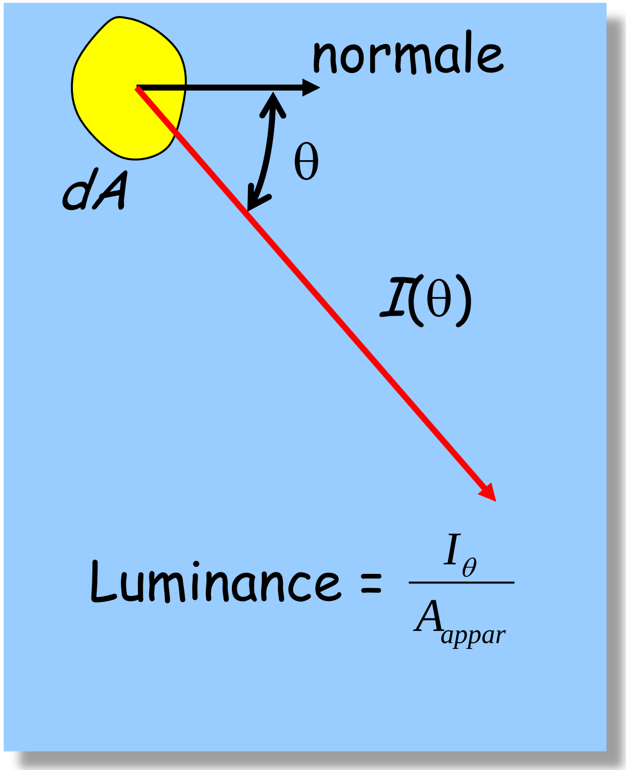
(luminance [lumineuse])

– **Definition :**

$$L_v = \frac{dI_v}{dA\cos\theta}$$

– **Unit :**

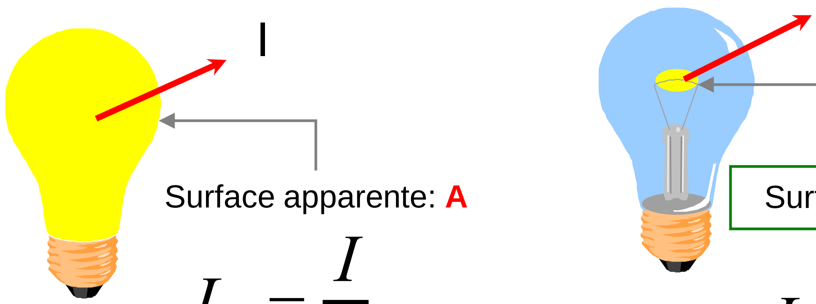
cd.m^{-2}, lm.sr^{-1}.m^{-2}



Quantities of photometry

Illustration

1. Luminance of two identical power bulbs.

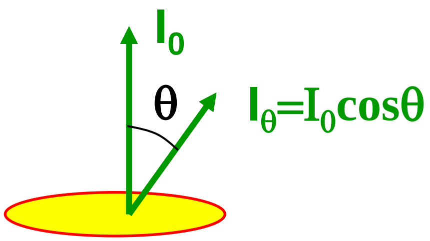


$$L_1 = \frac{I}{A}$$

$$L_2 = \frac{I}{a}$$

$$\Rightarrow \quad L_1 < L_2$$

2. Lambertian source: constant brightness in all directions

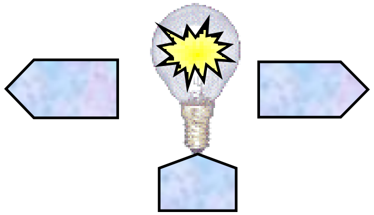


$$L(\theta) = \frac{KdA \cdot I_0 \cos\theta}{dA \cos\theta} = \text{constante}$$

Quantities of photometry

7e. Electrical efficiency (%) :

$$\varepsilon = \frac{F_e}{P_{in}} = \frac{\int_0^{\infty} f_e(\lambda)d\lambda}{P_{in}}$$



7v. Luminous efficiency (lm/W) :

$$K = \frac{F_v}{F_e} = K_m \frac{\int_0^{\infty} f_e(\lambda)V(\lambda)d\lambda}{F_e}$$

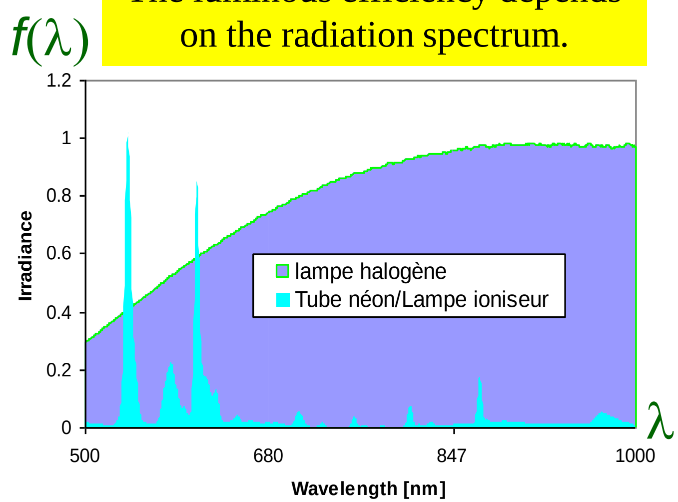
$$K_m = 685 \text{ lm/W}$$

A lamp consumes 100 W of electricity, emits energy flows of 80 W and a luminous flux of 2000 lm.

ε = 80/100 = 80 %

K = 2000/80 = 25 lm/W

The luminous efficiency depends on the radiation spectrum.



Quantities of photometry

8. Intensity indicator :

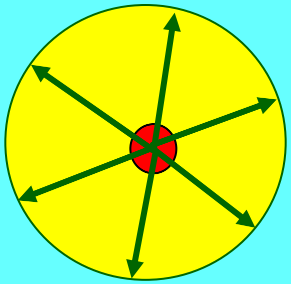
$$I_d(\theta) = \frac{I(\theta)}{I_0}$$

perfectly isotropic source

I_θ = constant

$I_d = 1$

Examples :
- Sun
- Point source
- Isotropic lamp



Lambertian Source

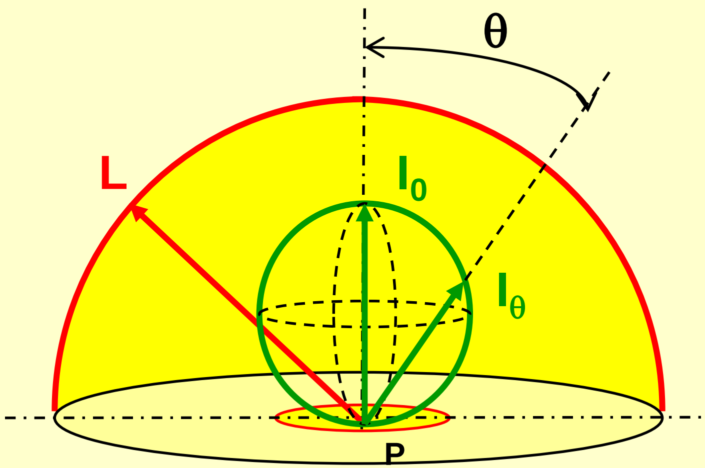
a surface perfectly diffusing

$L(\theta)$ = constant

$I_\theta = I_0 \cos\theta$

$I_d = \cos\theta$

Law of Lambert



Quantities of photometry

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Unité de quantités énergétiques

Units of *radiant* quantities

Quantities	Symbols	Definition	Units	Abbrév.
Énergie rayonnée *Radiant Energy*	Q_e		joule calorie kilowatt-heure	J cal kWh
Flux énergétique *Radiant Flux*	F_e	$F_e = dQ_e / dt$	watt	W
Éclairement énergétique *Irradiance* Émittance énergétique *Radiant emittance*	E_e M_e	$E_e = dF_e / dA$ $M_e = dF_e / dA$	watt / Unit de surface	$W \cdot m^{-2}$ $W \cdot cm^{-2}$
Intensité énergétique *Radiant Intensity*	I_e	$I_e = dF_e / d\Omega$	watt / stéradian	$W \cdot sr^{-1}$
Luminance énergétique *Radiance*	L_e	$L_e = dI_e / (dA \cos \Theta\, d\Omega)$	watt / Unit de surface / stéradian	$W \cdot m^{-2} \cdot sr^{-1}$

Quantities of photometry

UFR Sciences et Techniques

Unité de quantités visuelles

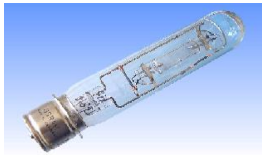
Units of luminous quantities

Paramètre	Symbols	Définition	Units	Abbrév.
Quantité de lumière Luminous quantity	Q_v	$\int K(\lambda)Qe(\lambda)\, d\lambda$ $380 < \lambda < 760$	lumen-seconde lumen-heure	lm s lm h
Flux lumineux Luminous Flux	F_v	$F_v = dQ_v / dt$	lumen	lm
Éclairement lumineux Illuminance Émitance lumineux Luminous emittance	E_v M_v	$E_v = dF_v / dA$ $M_v = dF_v / dA$	lumen · m^{-2} = lux lumen · cm^{-2} = phot lumen · pi $^{-2}$ = footcandle	lx ph fc
Intensité lumineuse Luminous intensity	I_v	$I_v = dF_v / d\Omega$	lumen / stéradian = candela	cd
Luminance lumineuse Luminance (brightness)	L_v	$L_v = dI_v / (dA \cos \Theta)$	candela · m^{-2}	cd · m^{-2}

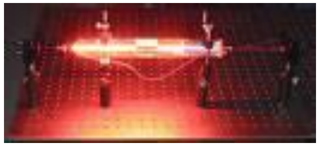
Light sources

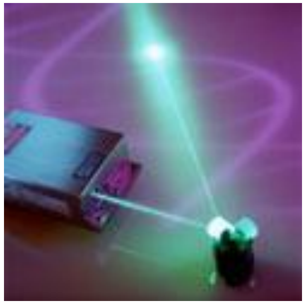
Classified according to the emitted spectrum

- **Thermal emission**
  - continuous spectrum (all wavelengths).
  - oven, tungsten lamps, fire, human body
  - …

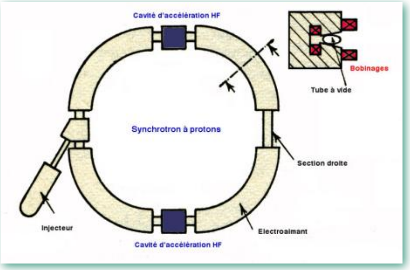


- **Spectral lamps**
  - discontinuous spectrum made up of several lines
  - widths of the lines are relatively wide.
  - coherence length: $l=\lambda^2/\Delta\lambda \sim \mathrm{mm}$.



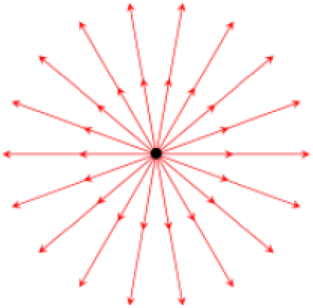


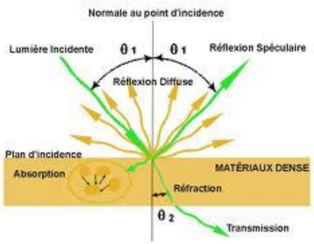
- **Laser :**
  - Mono - dispersed radiation,
    coherence length : $l=\lambda^2/\Delta\lambda \sim \mathrm{m}$.
  - Beam waist radius w_0: µm ~ mm
  - Irradiance: $M = F/A \sim 10^6$ W/m^2
- **Synchrotron** (high-energy accelerator)**:**
  - High energy radiation
  - Very broad spectral range



Particular Sources

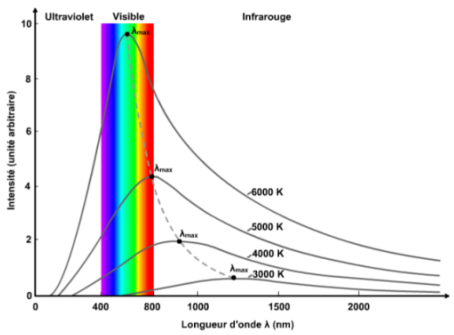
- Point source - isotropic
  - Lamp, sun, …
  - $M = P/4\pi r^2$





- Lambertian source
  - Constant luminance

    L=const et $I=I_0\cos\theta$



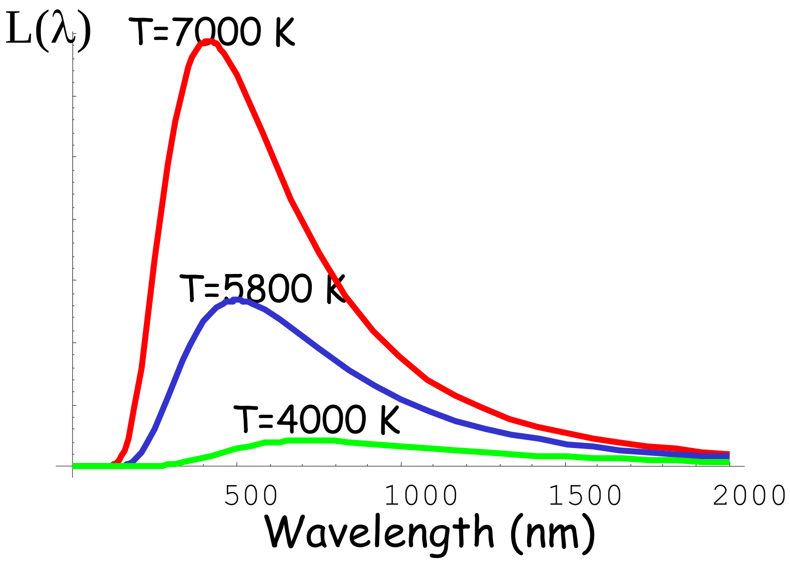
- **Black body source :**
  - Sun, human body, oven ...
  - Standard reference of the detector
  - Emission spectrum depends only on the temperature.

Black body

An ideal black body is an object whose electromagnetic spectrum depends only on its temperature

The object itself absorbs all the external light that would fall on it, and does not reflect any radiation either. In practice, such a material object does not exist, but it represents an idealized case as reference for physicists.

To calibrate the optical detectors, it is necessary to produce luminous flux fully known and reproducible. This can be achieved from the blackbody radiation whose behavior depends only on the temperature.



Black body

1 Planck's law :

The spectral radiance of a solid, at temperature T, is given by: (shown in 1900 by Planck):

$$L_e(\lambda) = \frac{C_1}{\lambda^5\left(e^{C_2/\lambda T} - 1\right)} (\text{W.m}^{-2}.\text{sr}^{-1}.\text{nm}^{-1})$$

C_1 = 1.19088 10^{20} W.m^{-2}.nm^4, C_2 = 1.439 10^7 K.nm

2 Stefan's law :

The emittance (total radiant emittance of all wavelengths in all directions) of the black body is given by :

$$M_e = \pi \int_0^{\infty} L(\lambda) d\lambda = \sigma T^4$$

where σ represents the Stefan's constant (σ = 5,67 10^{-8} W.m^{-2}.k^{-4}.).

3 Wien's displacement law:

The maximum radiation wavelength λ_{max} evolves according to the law:

$$\lambda_{\max} T = 2897 \ \ \mu\text{m K}$$

Examples of black body:

1. Estimate the radiant emmitance and the total flux emitted by a human body if it is considered as a black body without cover. What is the maximum emission wavelength?

- Stefan's law : $M_e=\sigma T^4= 5{,}67\ 10^{-8} X 310^4= 524\ W.m^{-2}$

$F_e=M_e\ A = 524X2 = 1048\ W$

- Wien's law : $\lambda = 2897/310 = 9{,}3\ \mu m$

2. The fire in the furnace can be regarded as a black body. Estimate wavelength λ_m knowing that the maximum emission temperature is 2000 °C and 5000°C.

Wien's law : $\lambda_m = 2897/ (T+273)$

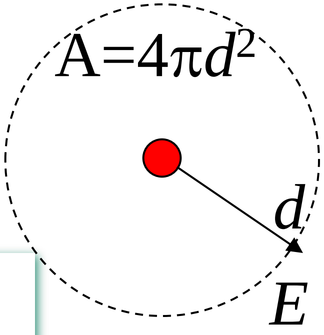
$\lambda_m = 1{,}27\ \mu m,\ 0{,}55\ \mu m$

Fundamental laws

1. Law of the inverse square of the distance::

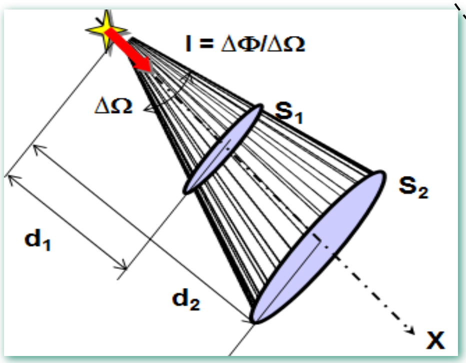
– **For an isotropic power source *P*, the irradiance/illuminance *E* at a distance *d* is constant and inversely proportional to *d* :**

$$E = \frac{F}{4\pi d^2} \propto \frac{1}{d^2}$$



– **For an anisotropic source :**

$$E = \frac{\Delta F}{\Delta S}, \quad I = \frac{\Delta F}{\Delta \Omega} \Rightarrow E = \frac{I}{d^2}$$



– **Consequence :**

$$\frac{E_1}{E_2} = \frac{d_2^2}{d_1^2}$$

The irradiance/illuminance decreases away from the source.

The irradiance/illuminance of a lamp at 10 cm is 100 times greater than that at 1 m.

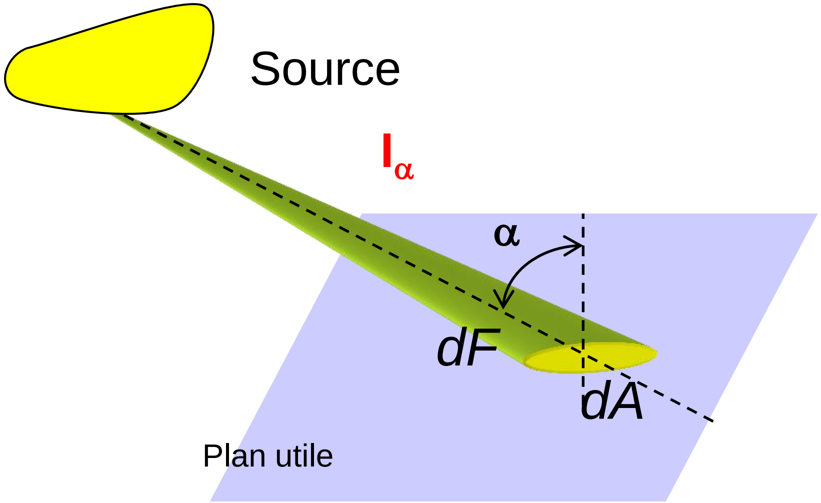
Fundamental laws

2. Law of cosine :

– **The flux received on a small area : d*A* :**

$$dF = E\cos\alpha dA$$

α Is the angle of incidence - angle between the direction of the incident radiation and the normal to the surface..



– **For an extended source:**

$$F = \sum_i \Delta F_i = \sum_i E_i \cos\alpha_i$$

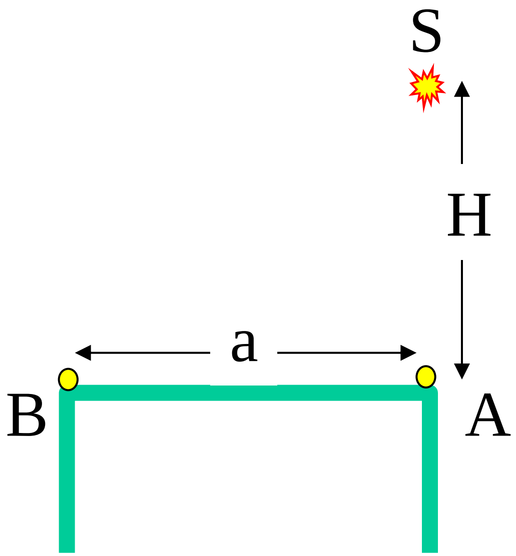
The illuminance of the sun is much higher at midday than in the evening.

Fundamental laws

Examples: maximum illumination from a table

A table width a=1 m is illuminated by a lamp S of 100 W. The source is considered as a point hanging over the table at a distance H (see fig.).

1. Calculate the radiant intensity of the lamp.
2. Knowing that the luminous efficiency of 25 lm/W, calculate the luminous intensity of the lamp.
3. Express the irradiance and illuminance of the lamp at the points A just below the lamp and B at the edge of the table.
4. For what value of H the illuminance on the edge of the table is maximum ?



Correction:

1. I_e : $I_e = \frac{100}{4\pi} = 8 \text{ Wsr}^{-1}$
2. I_v : $I_v = 25 I_e = 200 \text{ lm.sr}^{-1}$
3. E : $E = \frac{dF}{dA} = I\frac{d\Omega}{dA} = \frac{I}{d^2}$, $E_{eA} = \frac{8}{H^2}, E_{eB} = \frac{8H}{(H^2+a^2)^{3/2}}$ $E_{vA} = \frac{200}{H^2}, E_{vB} = \frac{200H}{(H^2+a^2)^{3/2}}$
4. E_{max} : $\frac{dE}{dH} = 0 \rightarrow H = \frac{a}{\sqrt{2}} = 0,71 \text{ m}$

Fundamental laws

3. Beer's law

Consider a radiation passing through an absorbing or scattering medium. The illuminance of this radiation undergoes an exponential decrease depending on the distance :

$$E(l) = E_0\, \mathrm{e}^{-\alpha l}$$

E_0 is the illuminance of the incident radiation

E is the illuminance of the outgoing radiation.

α is the absorption coefficient (en m^{-1}).

Example: The coefficient of the atmosphere is 0.1 1 / km. The application of the solar cream of index 5 permits to divide by 5 the amount of radiation received by the skin. Determine the thickness of atmosphere offering equivalent protection.

$$\frac{E}{E_0} = \frac{1}{5} = \mathrm{e}^{-0{,}1l} \rightarrow l = \frac{\ln 5}{0.1} = 16 \text{ km}$$

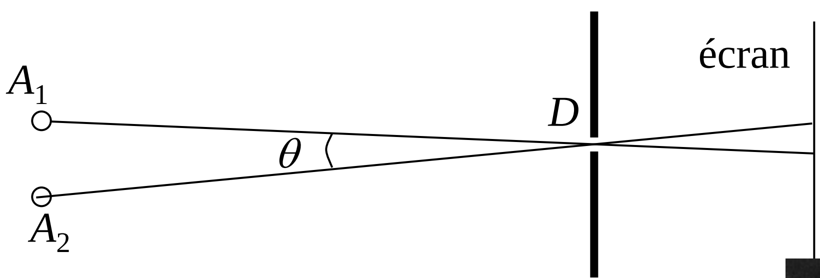
4. Rayleigh criterion:

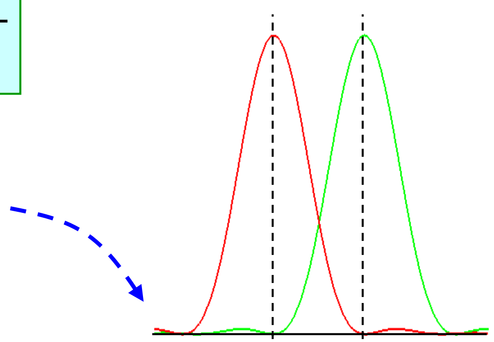
The diffraction intensity by a circular hole is given by:

$$I = I_0 \frac{J_1(x)}{x} \qquad \text{avec } x = \frac{\pi D}{\lambda}\sin\theta$$

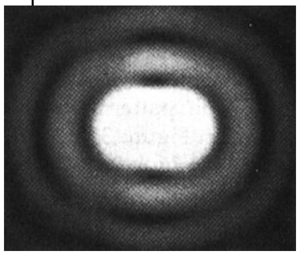
The first minimum (null) of J_1(x) is obtained for x=3.832, that is :

$$\theta_c = \frac{1.22\lambda}{D}$$

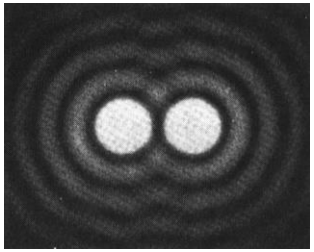




- Il est intéressant d'avoir une ouverture important pour une meilleur résolution (lunette astronomique, appareil photo, …)
- Limite de microscope optique ~ λ



θ too small,
images confusing



$\theta > \theta_c$
images distinct

Application of Rayleigh criterion

1. Calculate the theoretical angular resolution of a Hubble Space Telescope mirror whose main objective is 2.4 m in diameter, observing in the visible at λ = 500 nm, in the UV (115 nm) and near IR (1000 nm).
   - $\theta = 1.22 \ \lambda/D$

     $\theta_{500} = 1.22 \times 500\ 10^{-9}/2.4 = 2.5\ 10^{-7}$ rad

     $\theta_{115} = 1.22 \times 115\ 10^{-9}/2.4 = 0.6\ 10^{-7}$ rad

     $\theta_{1000} = 1.22 \times 1000\ 10^{-9}/2.4 = 5.8\ 10^{-7}$ rad

2. Compare the angular resolution of a reflex photo camera of aperture D_1=10 cm with the compact camera of D_2=0.5 cm.
   - $\theta_{0,5}/\theta_{10} = D_{10}/D_{0,5} = 20$,

     The resolution is 20 times high.

Optical Detectors

1. Classification of Optical Detectors

Two types of detectors are distinguished according to the phenomena involved

Thermal Optical Detectors:

Conversion of absorbed light energy to thermal agitation energy:

- increase of the temperature of the material,
- modification of the electrical properties:
  - ☞ resistance (bolometers);
  - ☞ voltage (thermocouples):
  - ☞ charges (pyroelectric detectors).

oeil

Photonic Optical Detectors:

Radiation-matter interaction

Internal Effects :

photoconduction
- semi-conductors.

Photovoltaic effect
- PN, PIN junction, avalanche,...

Photo- electromagnetic effect

External effects::

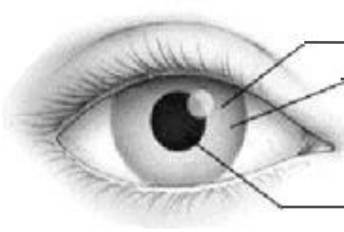
photoemission (empty cell, photomultiplier, ...)

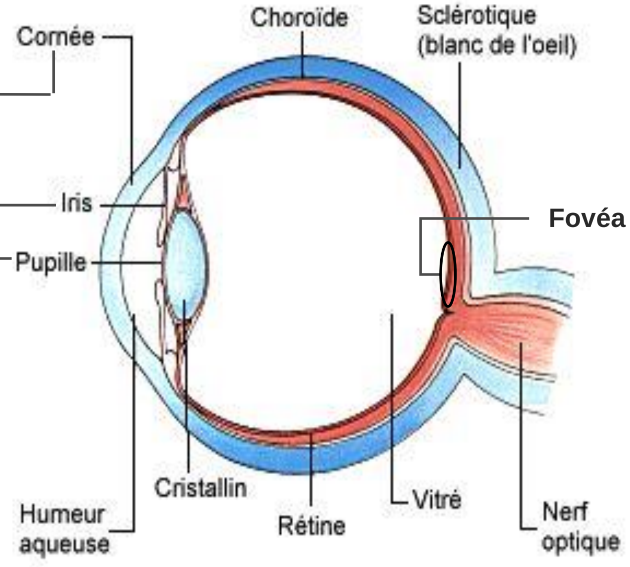
Pyro=高温

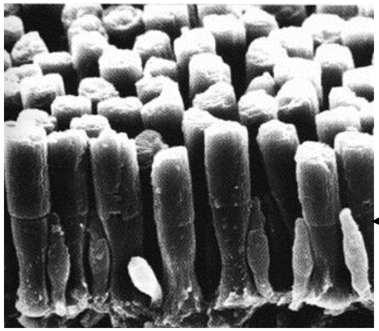
Optical Detectors

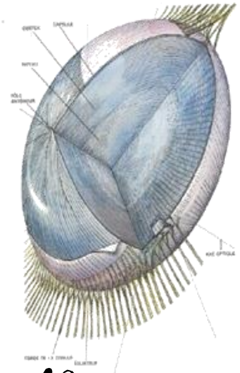
2. Principles of different detectors

2.1 Eye

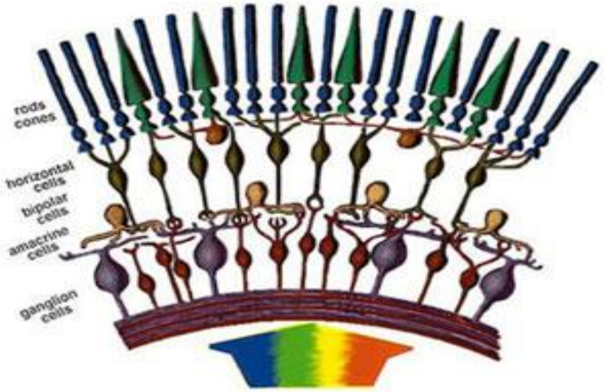








retina



Cones &
rods

The human eye is like a camera it can not detect the response of the brain to a single photon.

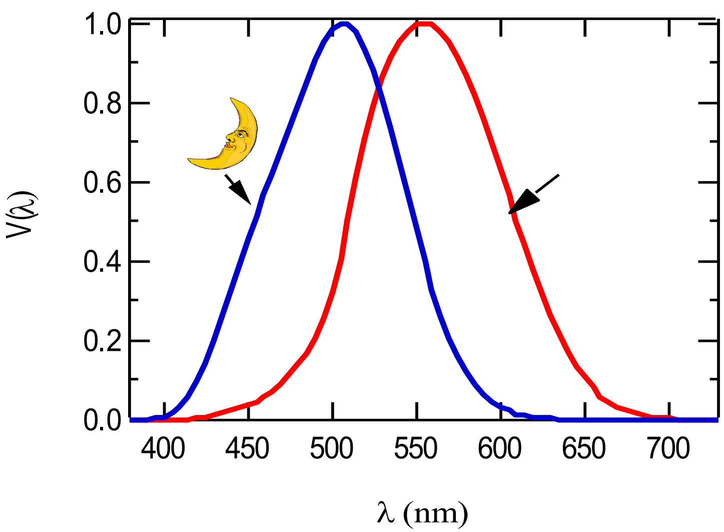
Optical Detectors

2.1 Eye

rods

- Great number (~125 millions),
- Highly sensitive (one rods may respond to a single photon, but the quantum efficiency η is only 50 %)
- Insensitive to the color,
- Slow adaptation.

- The eye has maximum sensitivity at λ=555 nm under the conditions of photopic vision.
- 1 watt (W) emitted at 555 nm is 683 lumens (lm)
- Around this wavelength the sensitivity decreases and becomes null beyond 380 nm and 760 nm.

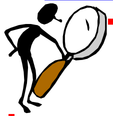


Optical Detectors

2.1 Eye

Cones

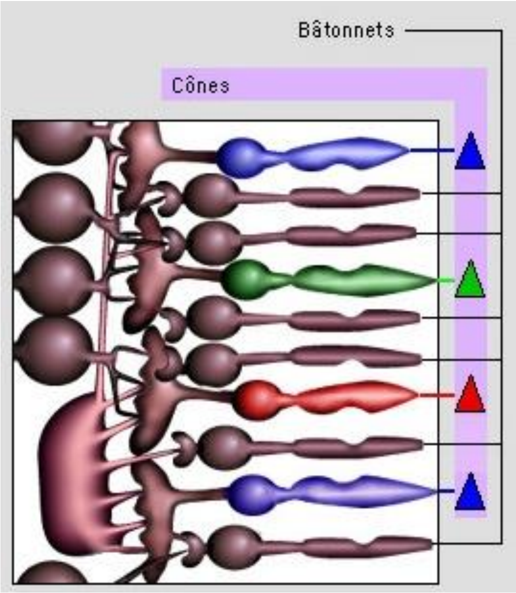
- In small numbers : ~ 5 millions/eye)
- Medium sensibility
- **High response speed**
- **Color-sensitive**



The eye perceives the wavelengths and the brain interprets it to colors.

An object appears to be colored because it absorbs selectively certain wavelengths of the incident light.

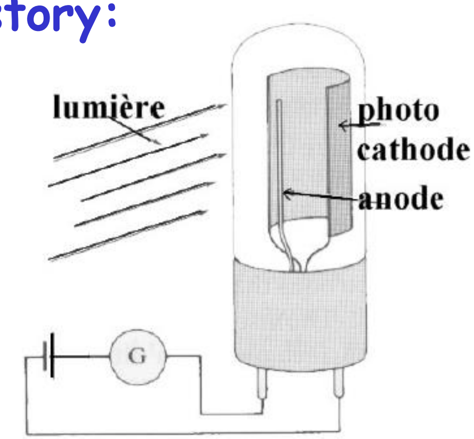
- The sensitivity threshold of the rods is about 100 times lower than that of the cones !
- The response speed of the cone is at least 4 times greater than that of the rods (100 ms)



Optical Detectors

2.2 Optical Detectors based on photoelectric effect

1. History:



1887

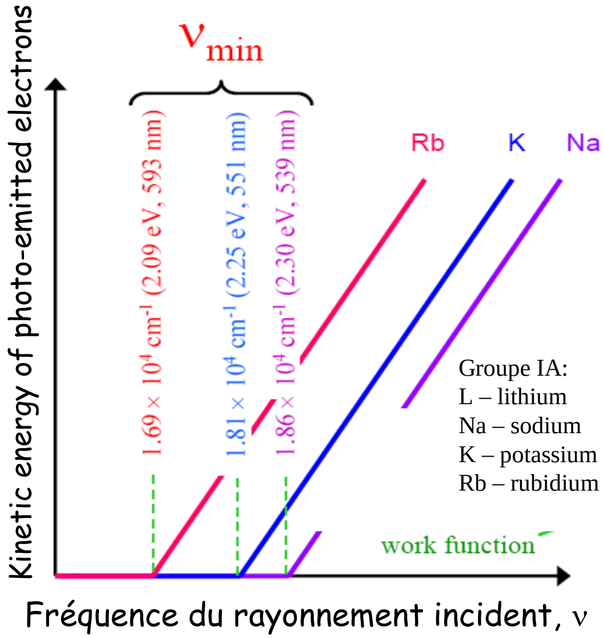
Heinrich Hertz

- The irradiation of the photocathode covered by an alkali metal can induce in some cases the extraction of electrons which jump at the anode and thus produce an electric current detected by the galvanometer G.
- The photoelectric effect occurs only when the incident light is above a certain ***frequence*** ν_s (threshold frequency).
- The red light (low frequency), even of very high intensity, has no effect, while the violet light (high frequency), even of low intensity, produces the photoelectric effect.

Optical Detectors

2.2 Optical Detectors based on photoelectric effect

2. Experimental observations



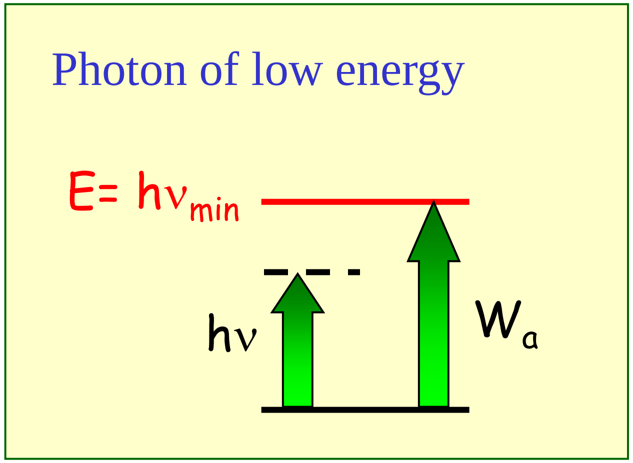
1. No electron is extracted whatever intensity if the frequency is below ν_s.
2. The released kinetic energy of the electrons E_c increases linearly with the frequency ν (independent of the intensity I).
3. At low intensity I, electrons are ejected immediately if $\nu > \nu_s$.
4. Above ν_s the emitted current depends on the intensity of the light and not of ν.

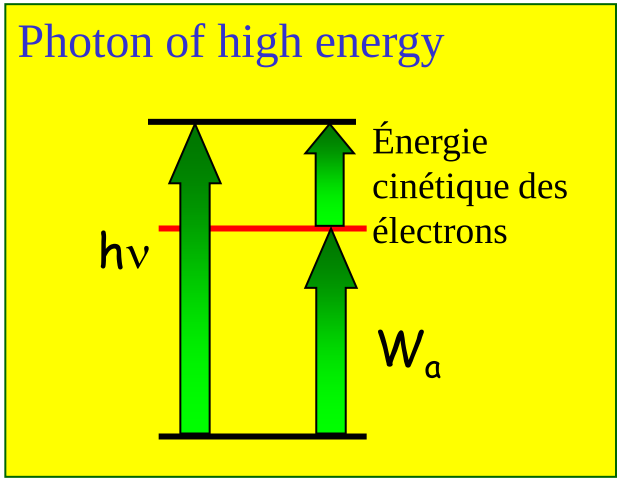
Work function: W_a dependent on materials, $h\nu_s = W_a$
Electron's kinetic energy : $E_c = h\nu - W_a$
Stop potential U_0 : opposite potential for $I = 0$, so we have $U_0 = E_c$

UFR Sciences et Techniques

2.2 Optical Detectors based on photoelectric effect

3. Explication of Einstein (1905)





Energy of a photon → $h\nu = W_a + \frac{1}{2} m_e V^2$ ← Kinetic energy

↑ Work function is a characteristic of the material.

The photon strikes an electron and the energy is transferred to it.

⇒ The light has properties of particle = jet of photons, $E_p = h\nu$,

⇒ Wave-particle duality.

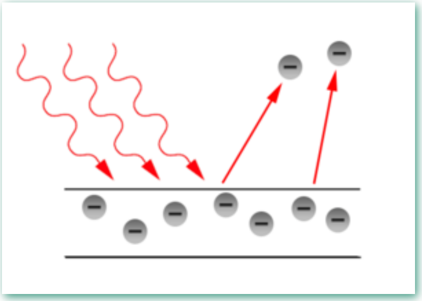
Optical Detectors

2.2 Optical Detectors based on photoelectric effect

4. Some important characteristics:

- Radiant power of light:

$$P_e$$



- Number of photons per second:

$$n_p = P_e / E_p = P_e / h\nu$$

- quantum efficiency: η.

The ratio of the number of photo-emitted electrons n_e to the number of effective photons (received) n_p:

$$\eta = n_e / n_p$$

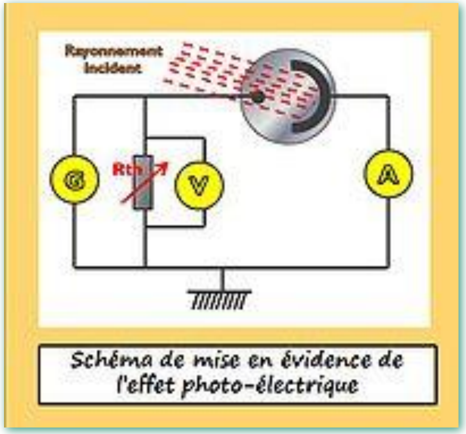


Schéma de mise en évidence de l'effet photo-électrique

- Generated courant:

$$I_e = n_e e$$

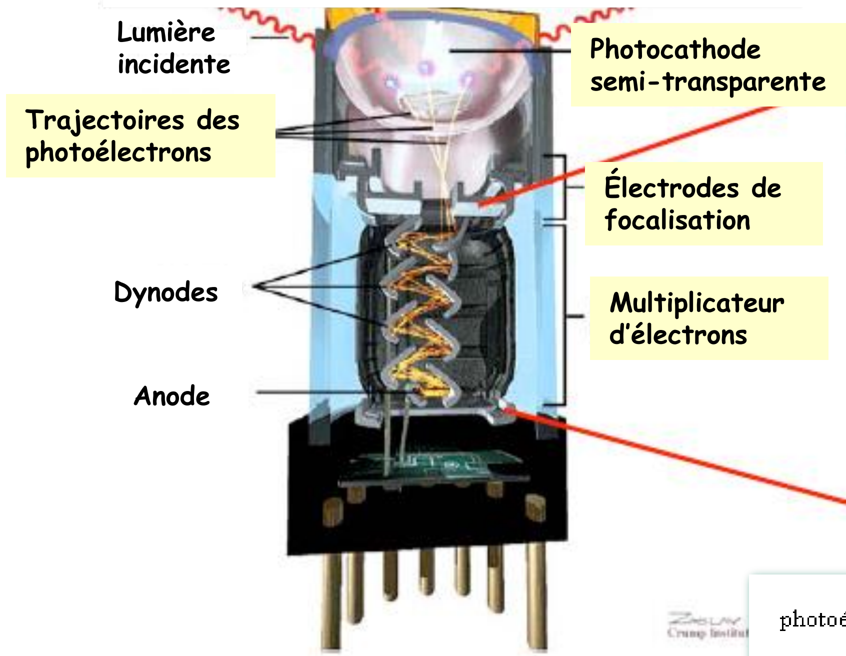
$$e = 1.60218\times10^{-19}\text{C}, \quad h = 6,62607\times10^{-34}\text{J.s}$$

- Spectral response:

$$R(\lambda) = \frac{I_e(\lambda)}{P_i(\lambda)} = \frac{e\eta(\lambda)}{h\upsilon}(A/W)$$

2.2 Optical Detectors based on photoelectric effect

5. Photomultiplier - principle

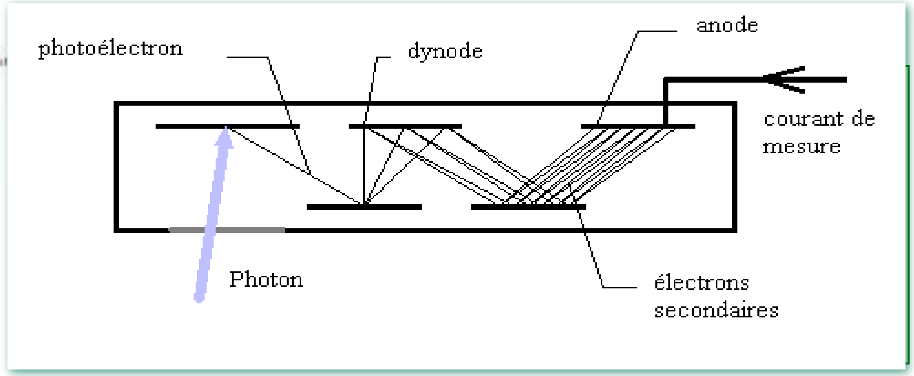


Accélération des e⁻ par le champ électrique

collision avec la Dynode suivante

Chaque e⁻ arrache 2 - 3 e⁻

Multiplication



High voltage: typically ~ **900 V**

gain ~ 10^6

Dynode中间极

Optical Detectors

2.2 Optical Detectors based on photoelectric effect

5. Photomultiplier

Many choices according to form and performance

Manufacturers: Hamamatsu, Honeywell, … …

Photomultiplier matrices

Multi-Anode Photomultiplier Tubes (MAPMT)

Haute tension appliquée:typiquement ≈ 900 V

Type No.	R5900U	R5900U-00-M4	H6568 (R5900-00-M16)	H7546 (R5900-00-M64)	R8520-C12	R5900U-00-L16	H7260 (R7259)
Anode format							
Number of anodes	1	4	16	64	6(X)+6(Y)	16	32
Number of dynode stages	10	10	12	12	11	10	10

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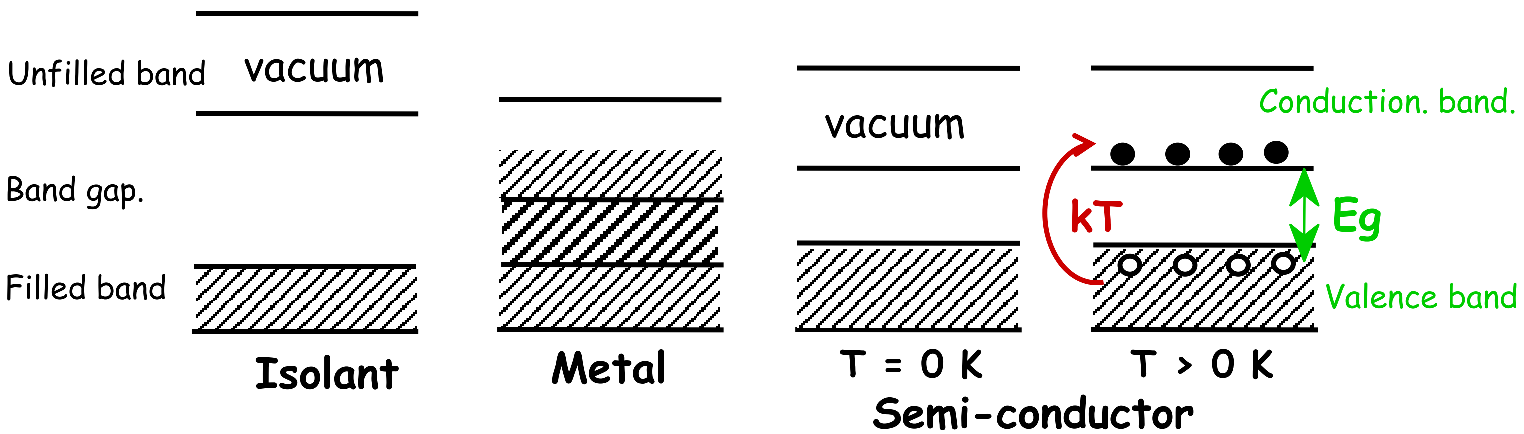
2.3 Diode and photodiode

1. Semi-conductors

Electrical conduction implies that e⁻ can have access to the state infinitely close to the last state occupied by it in equilibrium.



Definitions :

- **Valence band : last almost entirely filled band.**
- **Conduction band : first (almost) completely empty band.**
- **Band gap : gap between valence band and conduction band of width Eg**

Valence=化合价

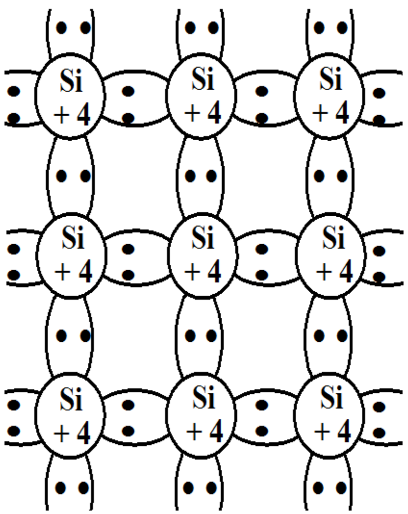
Optical Detectors

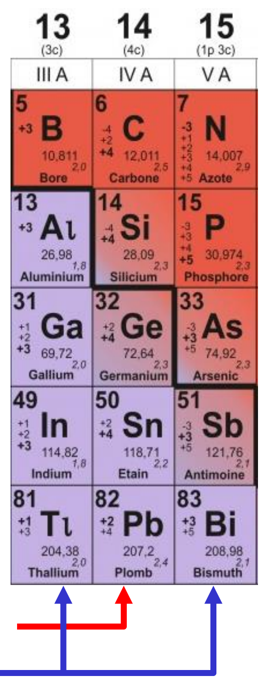
2.3 Diode and photodiode

1. Semi-conductors

Covalent bonds and Doping

pure silicon





elementary semi-conductors

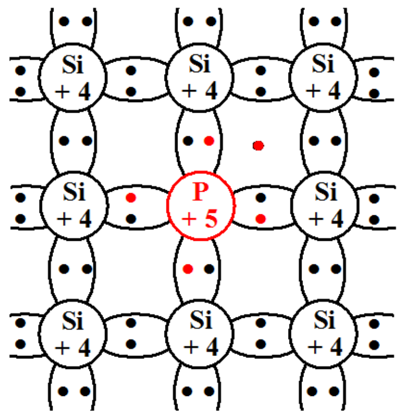
components III-V

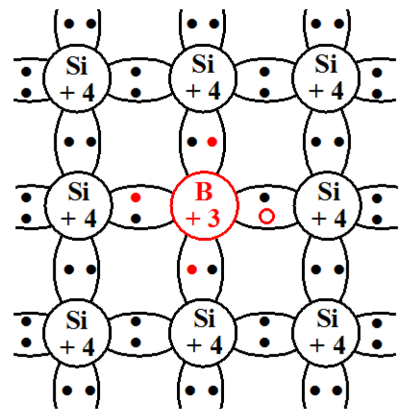
Donor

X^0 --> X^+ + e^-

Acceptor

X^0 --> X^- + h^+





P, As, Sb

type « n »

B, (Al, Ga, In)

type « p »

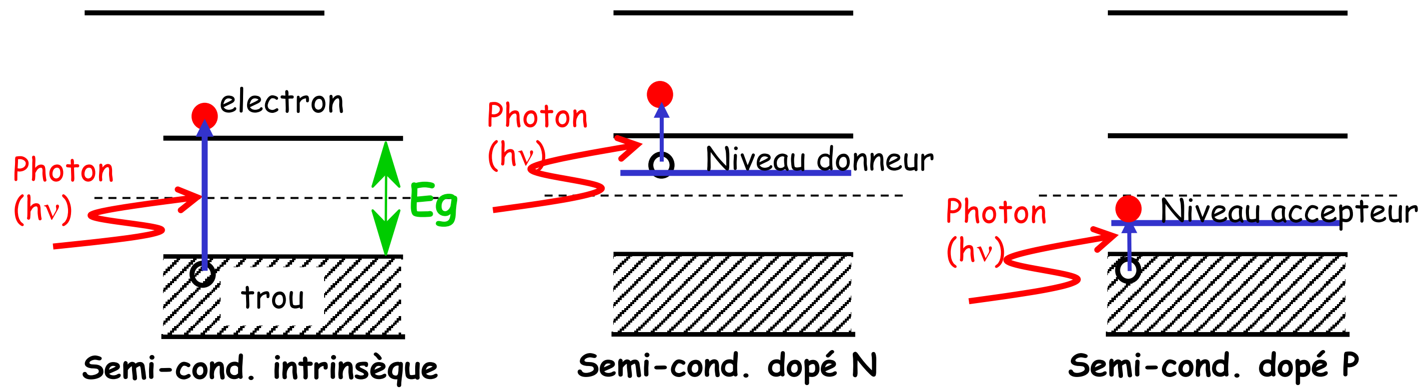
La valence du bore est +5 => donneur,
alors celle du phosphore est 3 => récepteur..

B=bore
P=Phosphore
In=Indium
Sb=Antimoine

2.3 Diode and photodiode

1. Semi-conductors

Extrinsic semi-conductors



- The energy of the incident photon must be above the gap of the material for creation of free carriers in the conduction band.

The threshold wavelength is given by:

$$\lambda_{seuil} = \frac{1,24}{E_g(eV)}(\mu m)$$

Example :

Silicon -> E_g = 1,12 eV $\Rightarrow \lambda_{seuil}$ = 1.1 µm
Germanium -> E_g = 0,67 eV $\Rightarrow \lambda_{seuil}$ = 1.85 µm

- **The doping of the semiconductor introduces intermediate levels, which reduces the gap and therefore increases the threshold wavelength.**

$\frac{hc}{\lambda} \geq E_g,\ \lambda_{seuil} = \frac{hc}{E_g} = \frac{1,24}{E_g(eV)}(\mu m)$, avec $1\,\text{eV}=1.6\times10^{-19}\,\text{J}$, $hc = 6.63\times10^{-34}\times3\times10^{8}\,\text{J}\cdot\text{m}$

2.3 Diode and photodiode

1. Semi-conductors

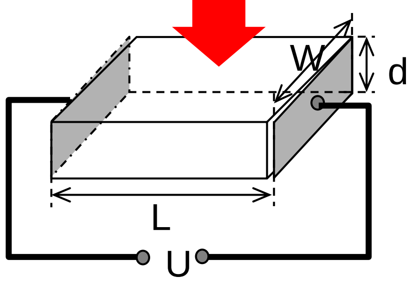
Photoconductive cell

A semi-conductor sample of volume *V* supplied with a voltage *U*. The total current through the cell is given by:

$$I_{tot} = I_0 + I_{ph}$$

where I_0 is the dark current (no illumination) and I_{ph} the current due to the illumination.

$$I_{ph} = \eta q \mu_n \tau \frac{W}{L} \Phi U$$



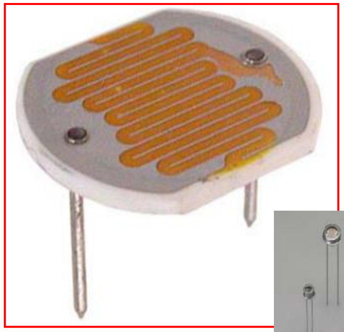
η : quantum efficiency of the cell

q : elementary electron charge (1,6 10^{-19} C)

μ_n : mobility of electrons in the material

τ : life time of the carriers

Φ : incident photon flux on the sample.

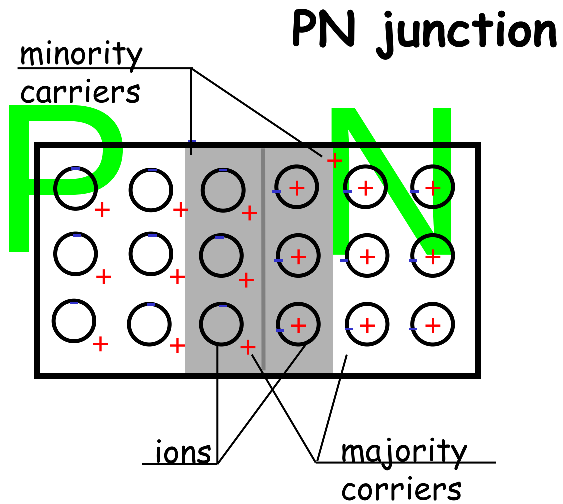


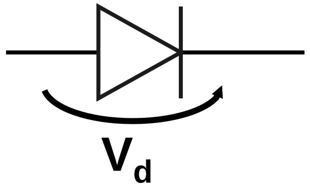
To increase the photocurrent one may use a cell of large W and small L.

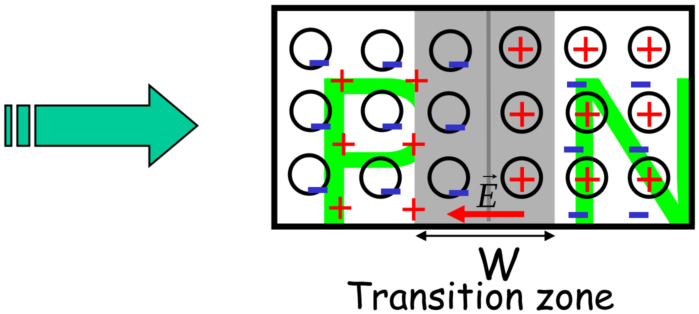
Optical Detectors

2.3 Diode and photodiode

1. Semi-conductors







Width of the zone:

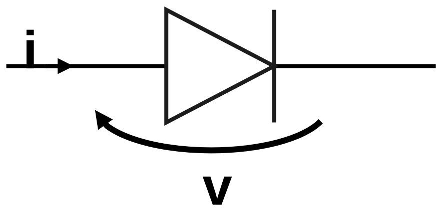
$$W = \sqrt{\frac{2\varepsilon_{sc}\varepsilon_0}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(V_d - V)}$$

N_A: doping density of acceptor in the zone P
N_D: doping density of donors in zone N
ε_0 : vacuum permittivity
ε_{sc} : elative permittivity of the semiconductor
V : external voltage applied across the diode.

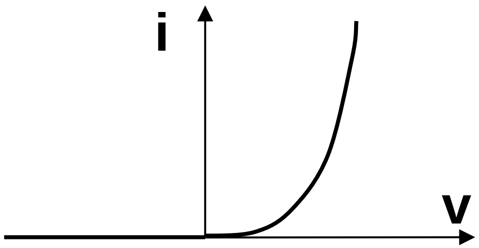
De part et d'autre de la jonction d'un semi-conducteur « P » et un semi-conducteur « N » se forme une zone de déplétion vide de porteurs libres en équilibre car il règne un champ électrique. Ce dernier établit entre les deux éléments semi-conducteurs une barrière de potentiel V_d (qq dixièmes de V).

2.3 Diode and photodiode

2. Principle of the diode



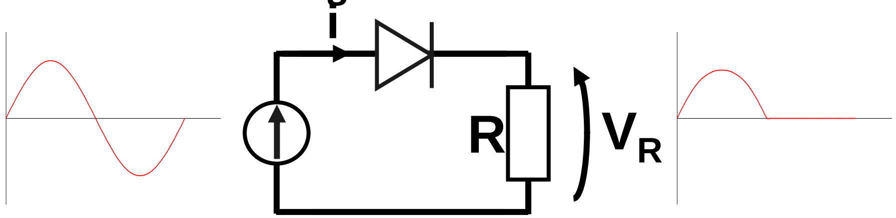
$$i = I_{sat}\left(e^{\frac{qV}{KT}} - 1\right)$$



I_{sat} is the saturation current of the diode, it is of the order nA (10^{-9}A).

The PN diode behaves like a closed switch for lower voltages V_d and open for higher voltage V_d.

Application : rectification of an AC signal



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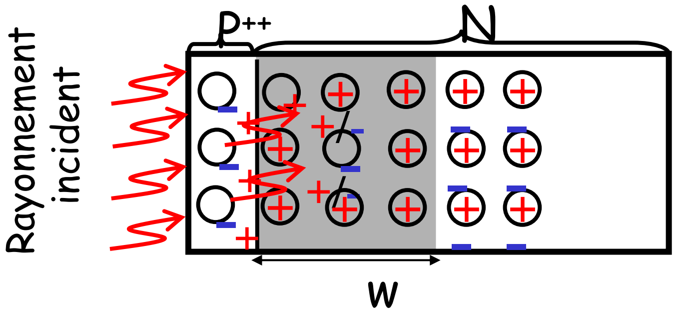
2.3 Diode and photodiode

2. Principle of the diode



1. When illumination is incident on a $P^{++}N$, junction, electron/hole pairs are released into the transition zone.
2. The electrons thus created are immediately swept away by the electric fields to the zone N (and holes to the zone P^{++}).

This results in a reverse photocurrent is given by: $$I_{ph} = qA\eta\Phi$$

where A is the cross section of the photodiode, Φ the luminous flux entering the structure, and η the quantum efficiency of the material.

Moreover if the diode is supplied with a voltage V, the total current is given by:

$$i = I_{sat}(e^{\frac{qV}{kT}} - 1) - I_{ph}$$

Des semi-conducteurs fortement dopés (appelés N++ et P++) ont une conductivité proche de celle des métaux.

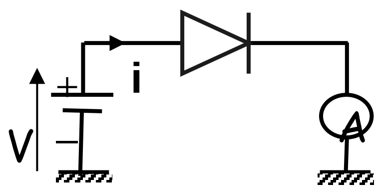
kT/e ~ 26 mV à T=300 K

Optical Detectors

2.3 Diode and photodiode

3. different assemblies

In photocurrent :



A : low impedance circuit (resistance)
Example: Ammeter

$$i = I_{sat}(e^{\frac{qV}{kT}} - 1) - I_{ph}$$

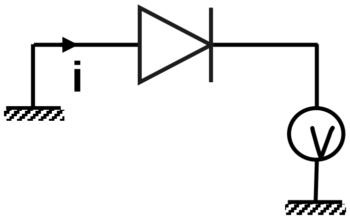
If the photodiode is biased reversely (V <0), the total current can be written as:

$$i = -(I_{sat} + I_{ph})$$

I_{sat} is of the order of nA (10^{-9}A) while I_{ph} of the order µA (10^{-6}A) or more, so that

I_{sat} is negligible to I_{ph}.

in photovoltaic :



V : very high impedance circuit
Example: voltmeter

$$i = I_{sat}(e^{\frac{qV}{kT}} - 1) - I_{ph} = 0$$

In this case, the voltage across the photodiode V_{ph} is :

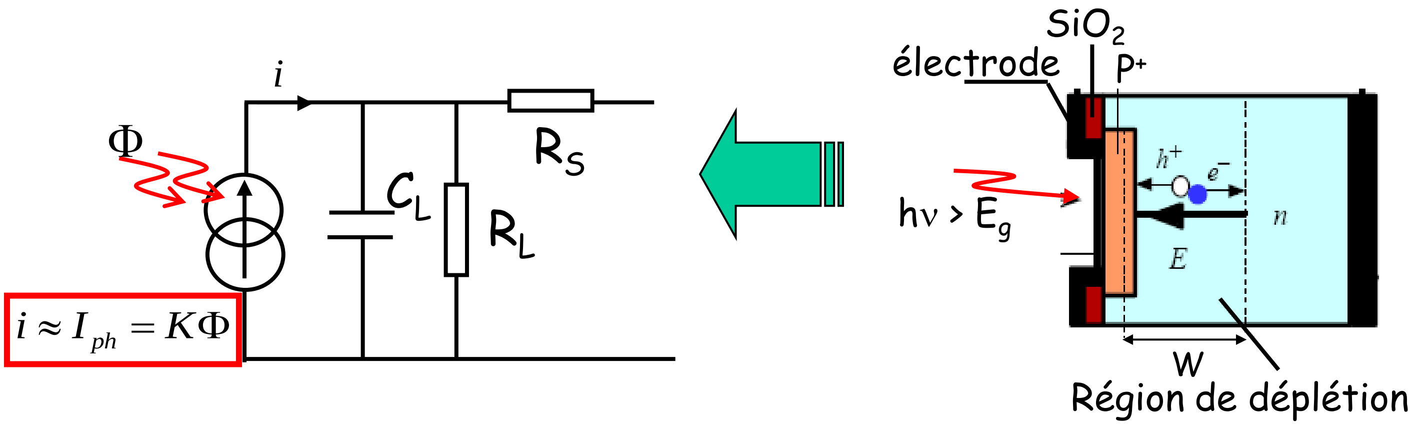
$$V_{ph} = \frac{kT}{q} \log\left(1 + \frac{I_{ph}}{I_{sat}}\right)$$

Optical Detectors

2.3 Diode and photodiode

3. Equivalent circuit diagram

The photodiodes are used in photocurrent with a reverse bias which gives a linear response as a function of light flux. The equivalent circuit in this configuration is given below.



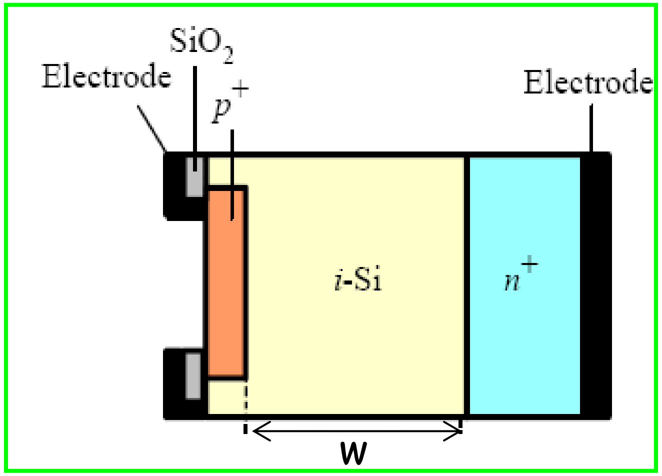
1. The series resistance R_s corresponds series resistance and the layers P and N, it remains low: in order of Ω and negligible in general.
2. The resistance R_L corresponds to the depletion zone, it is therefore very large, of the order of 10^{10} Ω.
3. The capacity C_L of the transition region depends on the type of material, the surface of the detector, but also the applied inverse voltage.

2.3 Diode and photodiode

4. Photodiode PIN

The PIN photodiodes consist of an intrinsic semiconductor layer (non-doped) *i* crammed between two highly doped zones P^+ and N^+.

The transition zone spreads mainly in the intrinsic region and its width is determined by the width of the area.



Avantages :
- High quantum efficiency
- Very short response time
- Bandwidth (>30 GHz)

2.3 Diode and photodiode

5. Avalanche photodiode (APD)

When the reverse bias of the diode is close to the breakdown voltage, photocarriers created in the transition region are multiplied by avalanche effect.

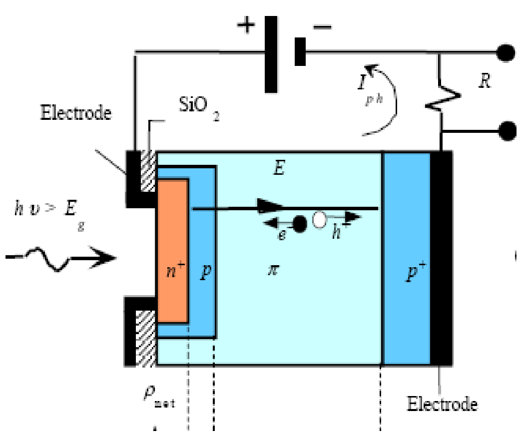
This effect occurs to an electric field of about 105 V/cm.

Under the influence of such a field, the few photo- created carriers can gain sufficient speed to enable them to generate pairs electron / hole impact ionization of atoms of the crystal.

These pairs are in turn accelerated, and may create other pairs.

This results in a chain process called avalanche effect which amplifies the photocurrent.

<u>**The avalanche photodiode is the equivalent of the photomultiplier.**</u>



Advantages :
- high sensitivity,
- current amplification ≈ 100.

Disadvantages :
- sensible to temperature and bias voltage,
- noise due to the multiplication of charges

2.3 Diode and photodiode

6. Characterization of a photodiode

– Response time (time constant)

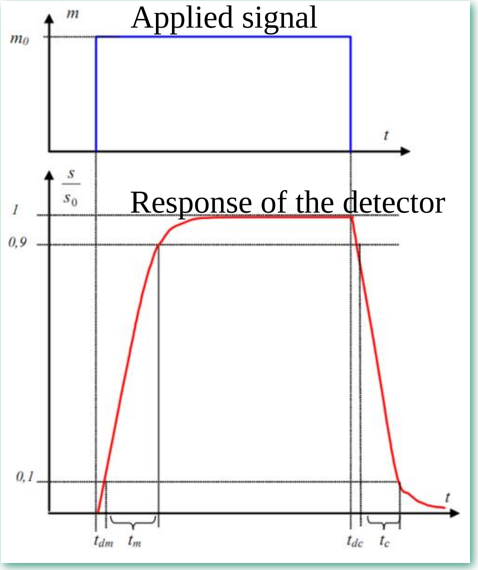
The response time is the time that elapses after a sudden change (called : echelon) of the measurand (quantity to be measured) until the variation in the sensor output does not differ more than ε% of the final value.

The rise of the signal is often in exponential form:

$$S = S_0(1 - e^{-t/\tau})$$

he response time τ is defined by::

$$\frac{S_0 - S(\tau)}{S_0} = \frac{1}{e}$$



t_{dm} : temps de retard à la montée ou délai de montée. Temps nécessaire pour que la grandeur de sortie s augmente, à partir de sa valeur initiale, de 10% de sa variation totale.

t_m : temps de montée. Intervalle de temps correspondant à la croissance de s de 10% à 90% de sa variation totale.

t_{dc} : temps de retard à la chute ou délai de chute. Temps nécessaire pour que la grandeur de sortie s diminue, à partir de sa valeur initiale, de 10% de sa variation totale.

t_c : temps de chute. Intervalle de temps correspondant à la décroissance de s de 10% à 90% de sa variation totale.

Optical Detectors

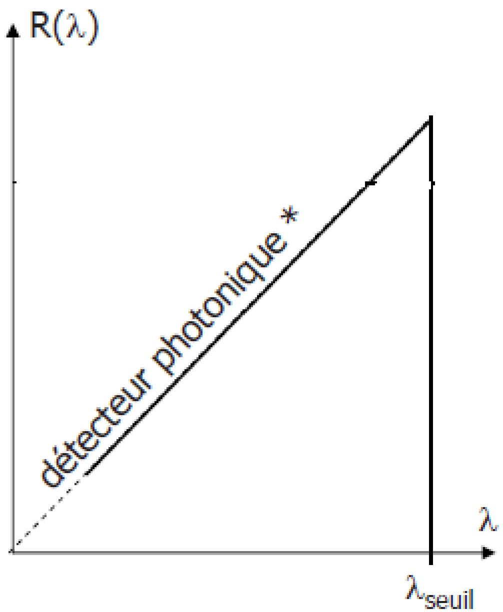
2.3 Diode and photodiode

6. Characterization of a photodiode

– **Threshold of wavelength:**

The energy of a photon E_p is greater than the work function W_a : $E_p > W_a$ → $hc/\lambda > W_a$

$$\lambda_{seuil} = \frac{1,24}{W_a(eV)}(\mu m)$$



– **Theoretical sensitivity** $R(\lambda)$ (A/W)**:**

An incident radiant flux F_e generates a photon flux F_p :

$n_p = F_p/h\nu = \eta F_e/h\nu = \eta F_e\lambda/hc$, so a current :

$$i = en_p = e\eta\frac{\lambda}{hc}F_e = R(\lambda)F_e$$

such that

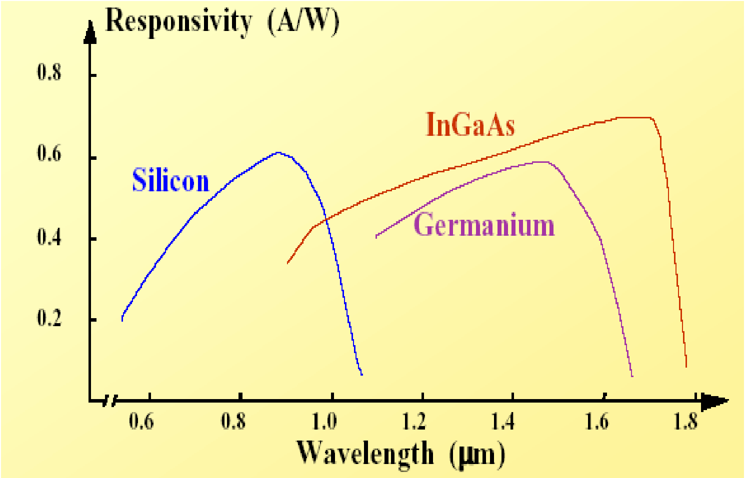
$$R(\lambda) = K\lambda$$

2.3 Diode and photodiode

6. Characterization of a photodiode

- **Actual sensitivity** $R(\lambda)$ **:** *See Figure*
  - *The curve is not a straight line.*
  - *It depends on the materials.*
  - *It does not cuts sharply at the threshold wavelength.*
  - *It also has a limit in small wavelength.*
  - *We must also consider the transition zone in the sensitive area.*
- **Overall sensitivity** R

$$R = \frac{\text{delivered signal}}{F_{e,total}} = \frac{\int_{\lambda_{\min}}^{\lambda_{\max}} R(\lambda)\frac{dF_e}{d\lambda}d\lambda}{\int_{\lambda_{\min}}^{\lambda_{\max}} \frac{dF_e}{d\lambda}d\lambda}$$



2.3 Diode and photodiode

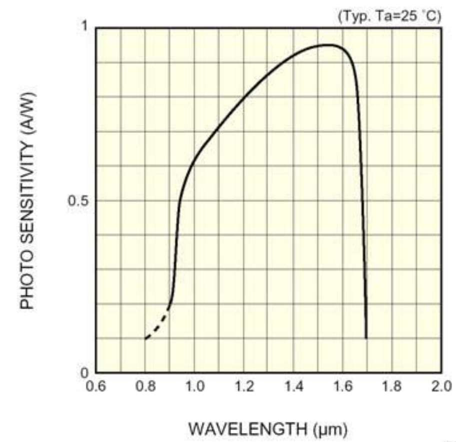
6. Characterization of a photodiode

– **Spectral sensitivity:**

Example: *InGaAs PIN photodiode, Standard type, G8376 series.*

Type No.	Spectral response range (μm)	Peak sensitivity wavelength λp (μm)	Photo sensitivity S 1.3 μm (A/W)	Photo sensitivity S λ=λp (A/W)
G8376-01	0.9 to 1.7	1.55	0.9	0.95
G8376-02				
G8376-03				
G8376-05				

■ Spectral response



– **bandwidth : Dynamic behavior:**

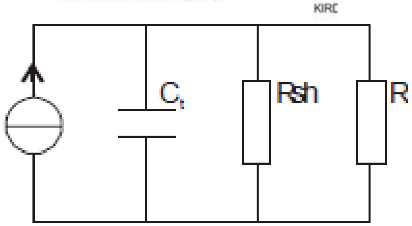
The circuit is equivalent to a low pass filter with the first order cutoff frequency given by:

$$F_c = 2\pi/(RC_t)$$

Two parameters are involved in the value of the parasitic capacitance:

- dimension of the active surface.
- Bias voltage.

Active area (mm)	Cut-off frequency fc VR=2 V RL=50 Ω -3 dB (MHz)	Terminal capacitance Ct VR=5 V f=1 MHz (pF)
ϕ0.04	3000	0.5
ϕ0.08	2000	1
ϕ0.3	400 *	5
ϕ0.5	200 *	12



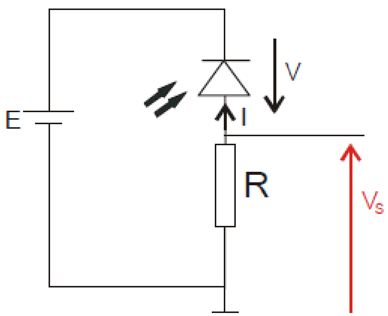
equivalent circuit with load resistance, parallel parasitic capacitance.

Optical Detectors

2.3 Diode and photodiode

6. Characterization of a photodiode

– **Linéarité :**



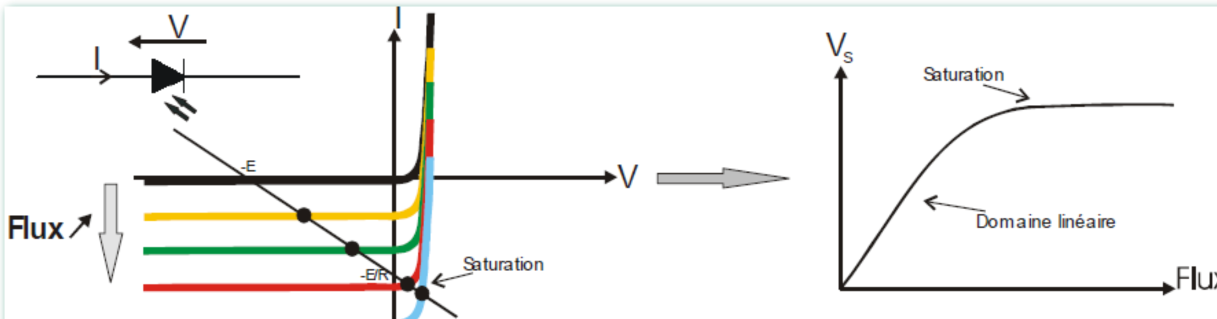


Figure 23- Mode photoconducteur. Un phénomène de saturation se produit aux forts flux

Typical installation with polarization and load resistance.

The current varies linearly with the incident light flux if this does not exceed certain threshold - saturation.

The voltage Vs (= — RI) is directly proportional to the photocurrent generated by the photodiode.

Optical Detectors

2.3 Diode and photodiode

6. Characterization of a photodiode

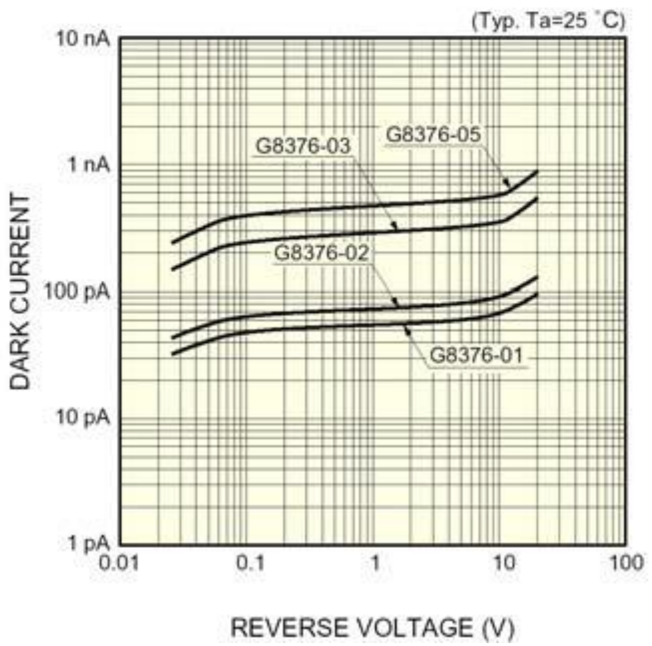
– **Dark Current:**

Example: *InGaAs PIN photodiode, Standard type, G8376 series*

Without light, there is still a reverse current I_o. This current is called "dark current". It increases with the reverse voltage applied to the photodiode and it is zero when the voltage is null.

Dark current I_D V_R=5 V	
Typ. (nA)	Max. (nA)
0.06	0.3
0.08	0.4
0.3	1.5
0.5	2.5

■ Dark current vs. reverse voltage



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2.3 Diode and photodiode

6. Characterization of a photodiode

– Detection noise :

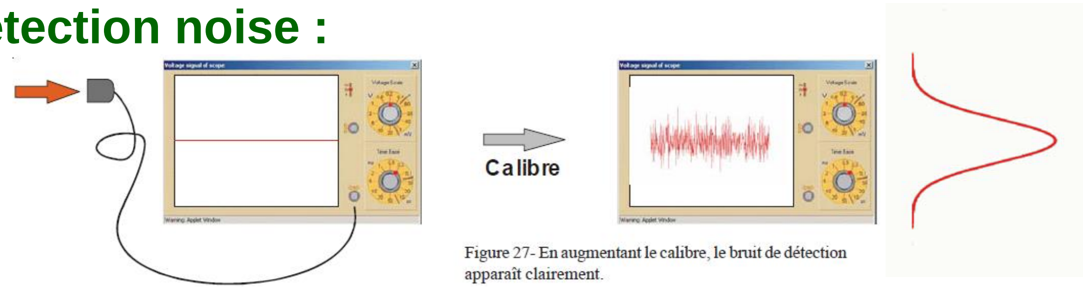


Figure 27- En augmentant le calibre, le bruit de détection apparaît clairement.

For a constant intensity of the light beam, the measured terminal voltage is a horizontal line. However, increasing the size of the oscilloscope shown a slight fluctuations around the mean value. This unpredictable fluctuation is the noise which is superimposed on the useful signal.

Different sources of noise :

- **Scintillation noise :** This noise is related to the slow fluctuations of the charge carriers in a photodiode. This noise due to technology manifests mainly at low frequencies and decreases rapidly negligible a few kHz.
- **Thermal noise** (or Johnson) : The thermal agitation in a resistor R generates a current noise (white noise). $\sigma_i = \sqrt{4kT\Delta f / R}$
- **Shot noise :** This noise originates the discreet nature of the charge carriers in a circuit and present in all the electrical circuit where energy transfer is described by quantum phenomena.

Optical Detectors

– NEP: Noise Equivalent Power:

In the absence of incident flux, the photodiode is therefore the source of a current of noise from its own and spectral density S_b (in A²/Hz). This minimum equivalent flux is called NEP (Noise Equivalent Power). It is defined as the flux giving a signal just equal to the rms noise $s(\lambda)=\sqrt{\langle I_B^2\rangle}$. It depends on the wavelength since the sensitivity of the photodiode $R(\lambda)$ depends on the wavelength.

To obtain a characteristic of the photodiode and independent of the electronic circuit in use, the manufacturers generally provide NEP reduced to the Unit Root of the bandwidth. It is therefore expressed in W/√Hz and written as

$$NEP(\lambda)=\frac{\sqrt{S_b}}{R(\lambda)\sqrt{\Delta f}} \quad (\mathrm{W/Hz^{1/2}})$$

Example: If the photodiode 1 is associated with a circuit of bandwidth of 1MHz, the equivalent flux to the inherent noise of the photodiode is: $2{*}10^{-15} * 10^3 \approx 2\ pW$. This value is very small.

Type No.	Outline No. (P. 34,35)	Package	Active Area (mm)	NEP λ=λp (W/Hz^1/2)
■Standard Types (0.9 to 1.7 μm)				
G3476-01	❶	TO-18	ϕ0.08	2×10^{-15}
G3476-03			ϕ0.3	4×10^{-15}
G3476-05			ϕ0.5	8×10^{-15}
G5832-01			ϕ1.0	2×10^{-14}

Optical Detectors

– specific detectivity D*:

- **Detectivity *D***

The detectivity is defined by $$D(\lambda) = \frac{1}{NEP(\lambda)}$$

and is expressed in $W^{-1}Hz^{1/2}$.

To compare more easily the detectors, we use the NEP or detectivity to a unit surface. The power of internal noise usually varies linearly with the surface *A*

$$\sqrt{\langle I_B^2 \rangle} \propto S_B \propto \sqrt{A}$$

Hence the specific NEP: $\frac{NEP(\lambda)}{\sqrt{A}}$ and specific detectivity.

- **Specific detectivity D*:**

Manufacturers have introduced a more commercial value – specific detectivity to characterize their detectors.

$$D^*(\lambda) = \frac{\sqrt{A}}{NEP(\lambda)}$$

where A is the surface area in cm². D* is the detectivity for a 1cm² surface in a circuit of 1Hz bandwidth.

Indication of measurement conditions for the value of D*:

$$D^*\left(\begin{matrix}\lambda \text{ for monochromatic radiation} \\ T \text{ for radiation of a corps noir}\end{matrix}, \text{frequency, passing bandwidth}\right)$$

Examples:

– D*(500 K, 800, 1) means that the color temperature of the source is 500 K, the modulation frequency is 800 Hz, the bandwidth 1 Hz.

– D*(6,3 µm, 800, 1) means that the measuring wavelength is 6,3 µm.

Optical Detectors

2.4 Image sensors CCD and CMOS

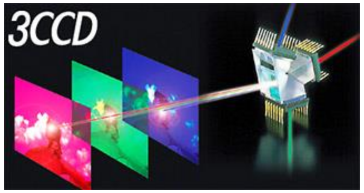
- **Optical Imaging sensors**

Optical sensors CMOS, CCD, MOS, BSI-CMOS, 3MOS, SuperCCD ...

A lot of technologies are used in our digital cameras and it is often difficult to distinguish the differences on paper. Who has never asked about the differences? A little vulgarization may be useful to understand the principles!

The optical sensors operate all in the principle of conversion of light (photons) into electrical signals by the photosensitive cells. The signals pass then by an analogue/digital converter in order to recover the final color with pixels. They are finally processed by the imaging processor. The result is stored in the camera's buffer before being transferred to your memory card.

Historically, the first Optical Sensors appeared between 1970 and 1980 as CCD (Charge Couple Device) and CMOS (Complementary Metal Oxide Semiconductor). Nowadays, these Optical Detectors are always used in our digital cameras, with their improvements and variations specific to each manufacturer (SuperCCD and BSI-CMOS Fujifilm 3MOS Panasonic...).



Optical Detectors

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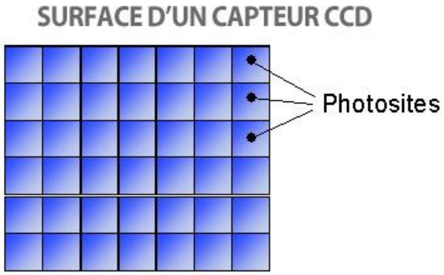
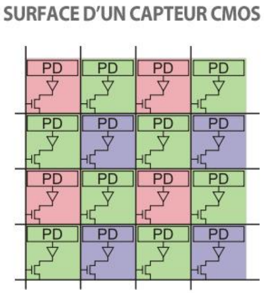
2.4 Image sensors CCD and CMOS

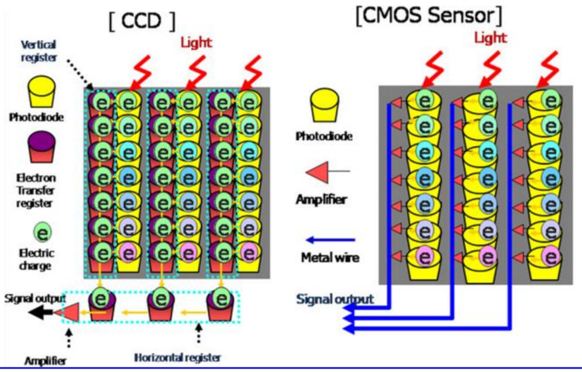
- **CCD or CMOS:**

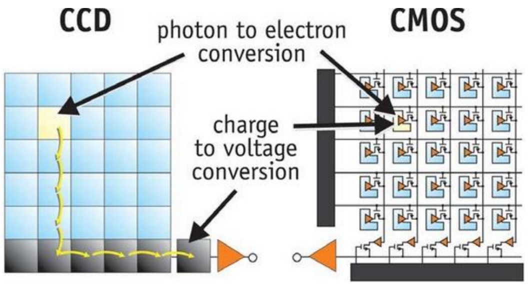
The principle of **Optical Sensors CCD** is based on the photosites field, small cells that accumulate light individually. The color is then determined by an analog filter (Bayer) as a function of the received intensity. Usually four photosites constitute a pixel of a color image.



Conversely, the **Optical Sensors CMOS** operate by a field of photodiode (PD), each sensitive to one of the primary colors (red, green and blue). This is a field of "yes" and "no" that covers the sensor. In the end it is a combination of the values of each photodiode (0 or 1), which provides the "estimated" color of each pixel. The end result will be a set of calculation of pixels, which is often the source of electronic noise.







2.4 Image sensors CCD and CMOS

- **System Operation**

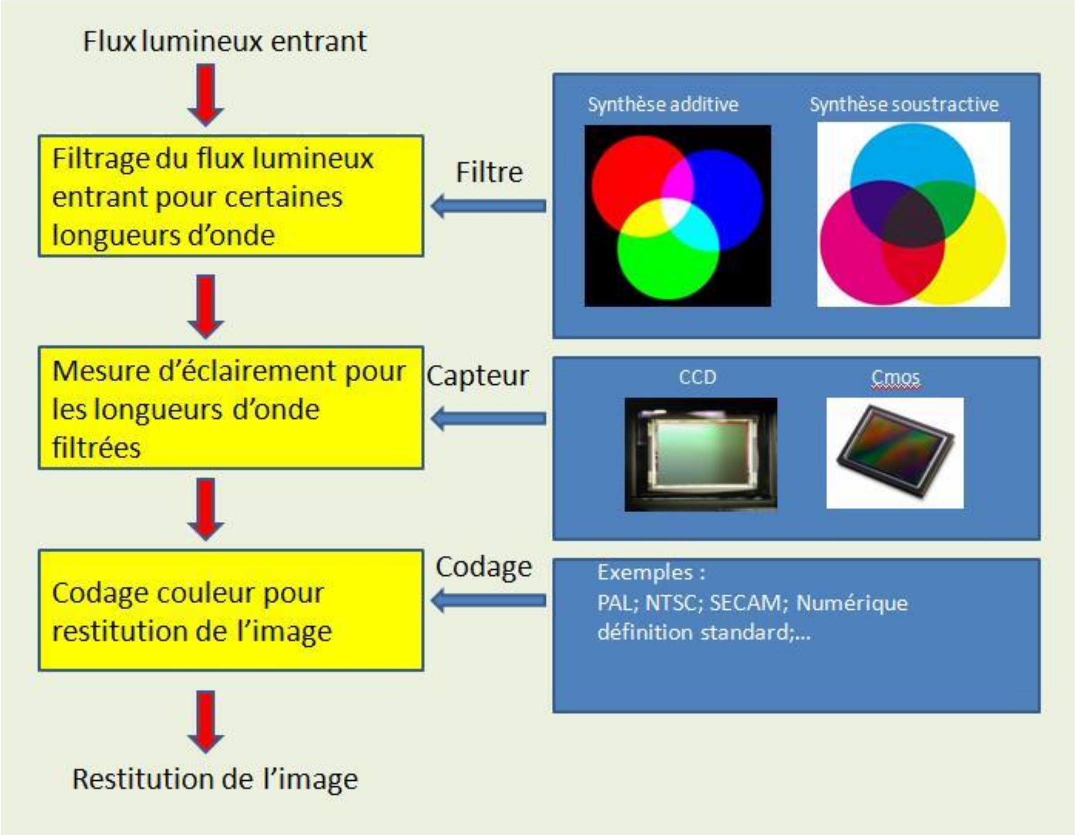
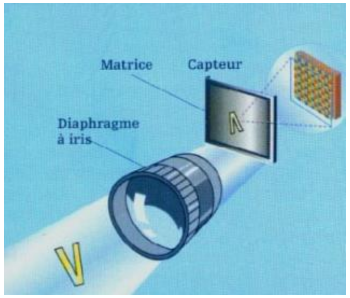
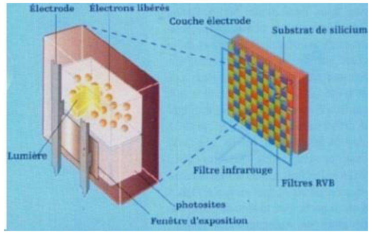
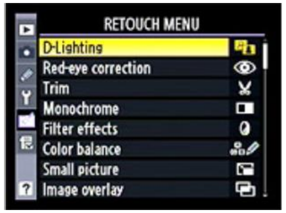
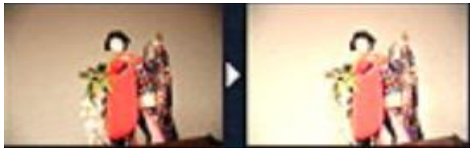


Figure 1 : Schématisation du processus de numérisation.







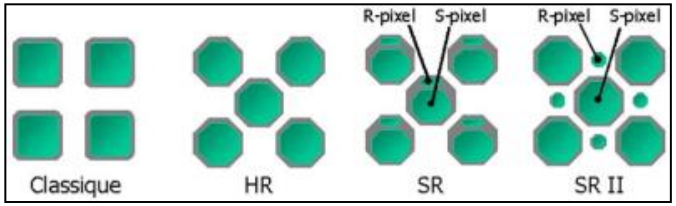


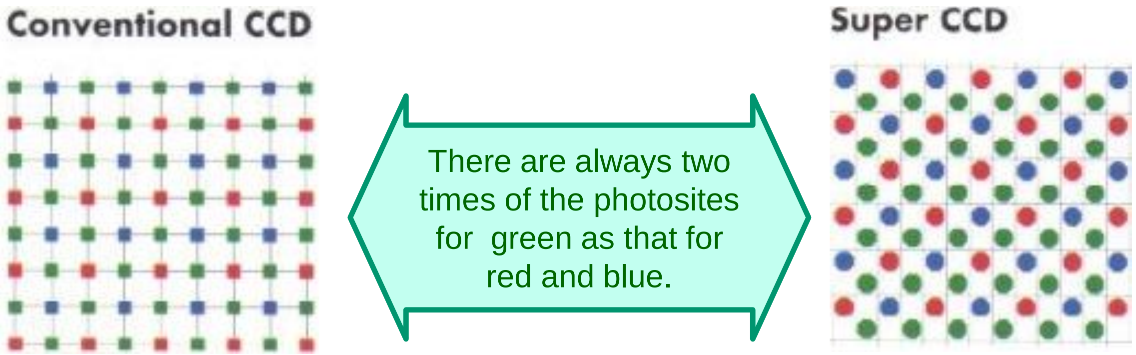
2.4 Image sensors CCD and CMOS

- **Bayer filter**

The set of filters for all three colors form the Bayer filter. Regular improvements are made to the sensor in order to improve the sensitivity by increasing the active surface. These improvements are achieved for example by modifying the shape of pixels or by changing the nature of the electrodes (which happens to be above the pixel) to obtain a better light transparency

- Changing shape of Optical Sensors:



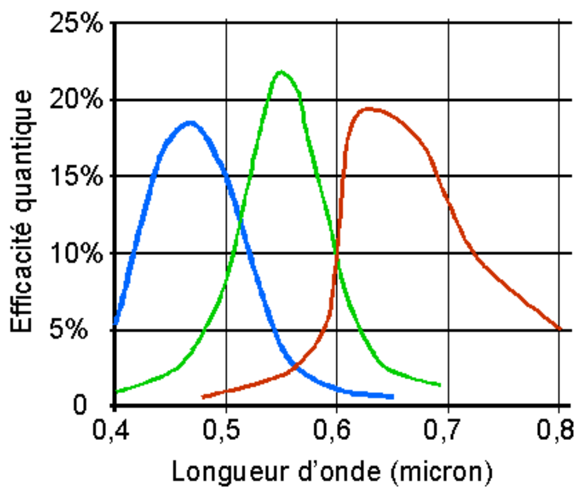


2.4 Image sensors CCD and CMOS

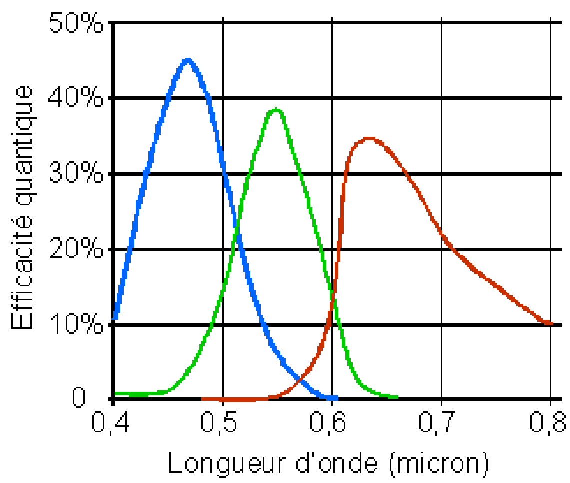
- **Colors**

With a color filter array, eg a Bayer filter, made of stained cells of the primary colors, each photosite sensor sees only one color: red, green or blue. Each group of four photosites is composed of one for blue, one for red and two for green; This distribution corresponds to the sensitivity of our vision.

It is the software of the "camera" that will recreate colors, taking into account the spectral response curves for an end trichromatic result (interpolation, filtering ...).



CCD pleine trame avec LOD



CCD interligne + microlentilles

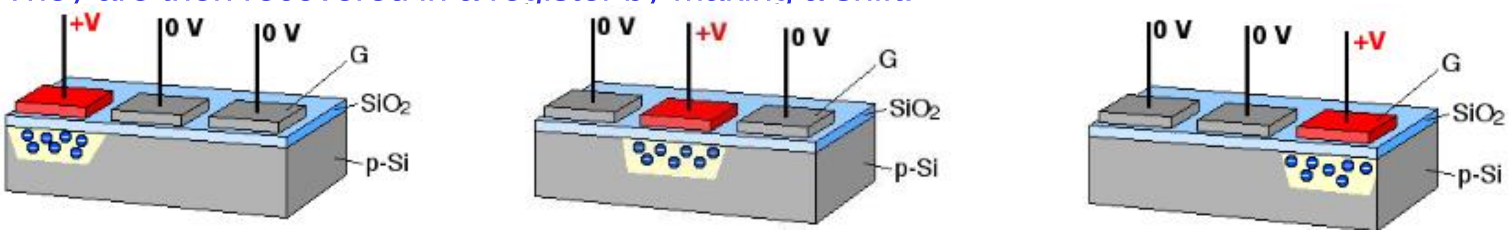
Optical Detectors

2.4 Image sensors CCD and CMOS

- **Charge transfer**

By changing the potential in a grid can move from place to place loads a photosite to another to extract the sensor.

Using the technique described above, the charges are moved down from line to line. They are then recovered in a register by making a shift.



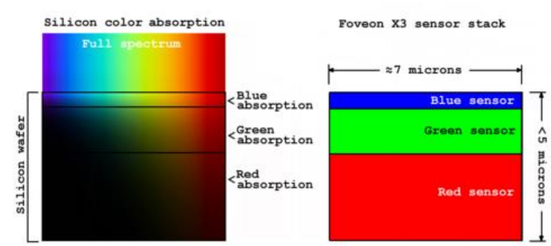
- **Optical Detectors Foveon**

This sensor enables the capture of the three colors (red, green and blue) by a **single** photosite, by means of **three silicon layers** of photosites covered and arranged in sandwich and filtered through a filter of blue, green or red; Each of the photoreceptor layers is precisely spaced with respect to wavelength blue, green and red in the visible light.

Advantages::

- The color is directly obtained from the photosite.
- It expected to obtain "pure" images

Therefore cheaper and cleaner.



2.4 Image sensors CCD and CMOS

- **some characteristics**
  - **Surface area:**

Full frame: 24 mm x 36 mm, high quality.

APS-H(Canon): 19.1 mm x 28.7 mm, **APS-H(Nikon):** 15.5 mm x 23.7 mm

  - **Pixels:**

Hauteur	Longueur	Nbre pixels	Surface [mm^2]	Densité pixels/mm^2
3 000	4 000	12 M	864	13 889
4 000	5 000	20 M	864	23 148
5 000	6 000	30 M	864	34 722
6 000	6 000	36 M	864	41 667

  - **Performance**
    - **Resolution.**
    - **Dynamics (CCD) and noise level (CCD and CMOS)**

$$\text{Dynamics}(dB) = 20\log\left(\frac{\text{Capa}}{\text{Courent+noise}}\right)$$

where the dynamics is obtained in dB (decibels); "Capa" (storage capacity of a photosite) "Current" (dark current) and "Noise" (sound playback) are assessed electrons.

    - **Sensitivity, quantum efficiency,**
    - **… …**

APS-H ou APS-C: Advanced Photo System type-H/C)

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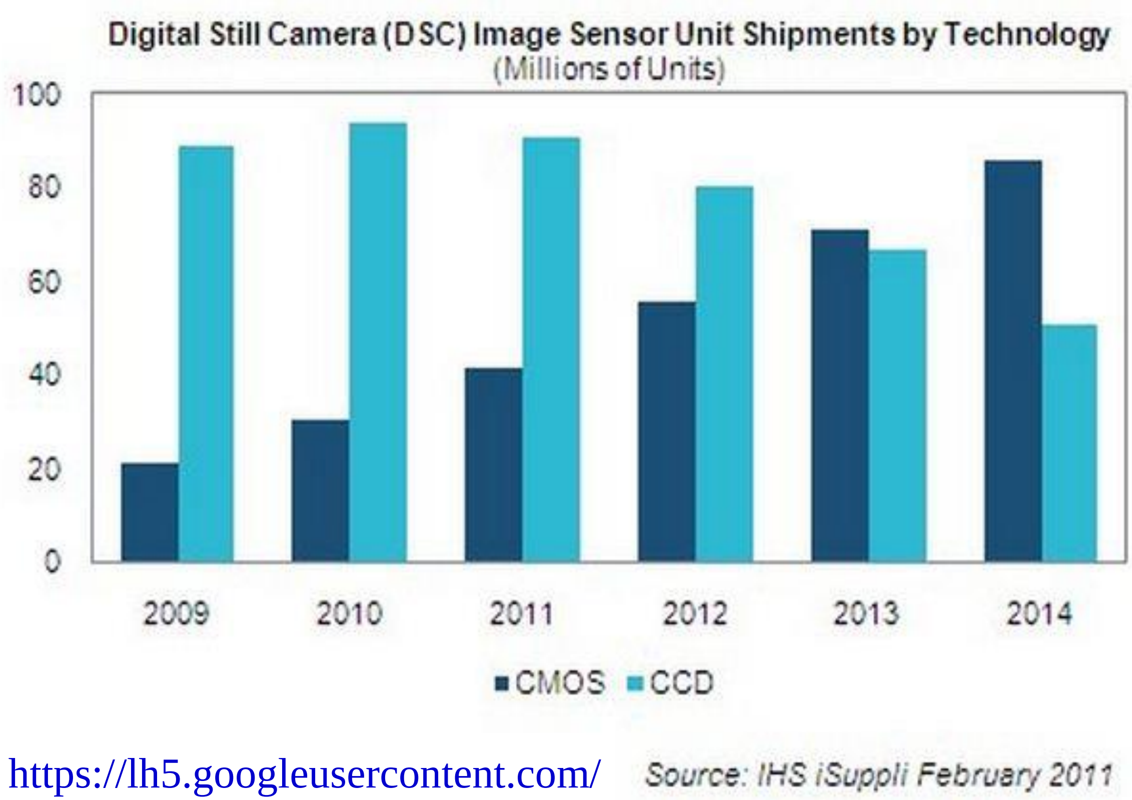
2.4 Image sensors CCD and CMOS

- **What trend for tomorrow?**

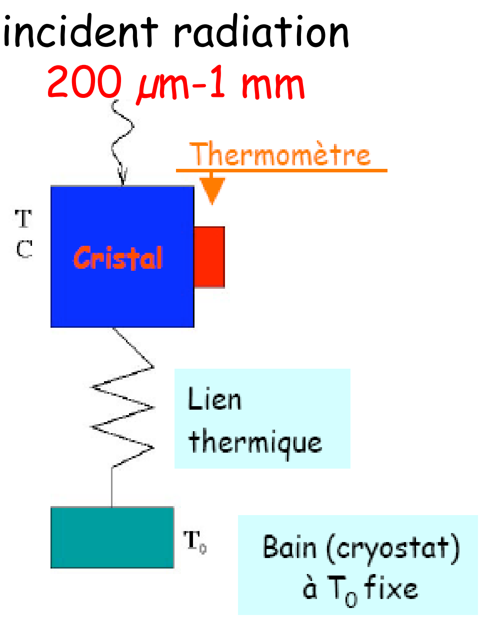
- A CMOS sensor can be replaced by a CCD or conversely.
- Consumer cameras CCD tend to be replaced by CMOS, of comparable quality and at a lower cost.
- CCD continues to be used in very high speed imaging applications or very low light level because it generates less noise than CMOS image.



https://lh5.googleusercontent.com/

Optical Detectors

2.5 Bolometer



- The crystal is heated by the radiation:
- The thermometer measures the rise of the temperature,
- The thermal link will reset the crystal temperature,
- The sensitivity will be better when the heat capacity of the crystal is low *i.e.* in low temperature (Law of Debye : $C \approx T^3$)

Caracteristics :

- Thermal resistance sensor, $\Delta T \rightarrow \Delta R \rightarrow \Delta V$
- Sensitivity in the passband: 100 V/W
- Time constant : 1 to 10 ms

cryo=低温

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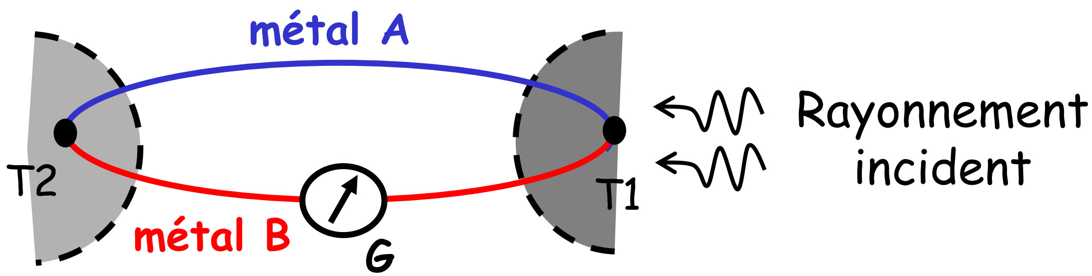
2.6 Thermocouples



Seebeck effect:

When welding the ends of two metals of different natures and maintaining the two welds at different temperatures T and T0, it is observed that in the closed circuit between the two points circulates a flow of electric charges, i.e. electric curent.

Thermocouple

When the weld of a thermocouple is heated by the absorption of radiation, it produces an **electromagnetic force** thus variation of voltage. The latter is measured by an external voltmeter.

Characteristics:

- Sensitivity : 0.1 à 100 V/W
- Time constant: 1 à 100 ms

热电计

Optical Detectors

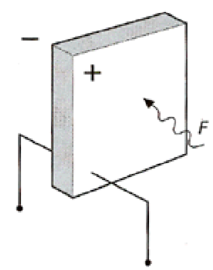
2.7 Optical Detectors pyroélectriques

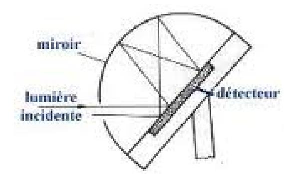
Principle :

Pyroelectricity is the property of a material – the temperature change of the material causes a change in electrical polarization. This polarization change creates a temporary potential difference, it disappeared after the dielectric relaxation time.

This kind of Optical Detectors consists of crystalline plates (example lithium niobate: $LiNbO_3$) that, under radiation, produce electrical surface charges. This results in the generation of an electric current in the circuit in which they are inserted.

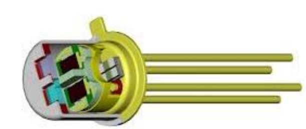
They are particularly used in infrared detectors.





Characteristics :

- Current sensitivity: 0.1 to a few mA/W
- Voltage Sensitivity: up to 105 V/W
- time constant: 0.1 ms to 1 ns
- Bandwidth :1 kHz to 100 MHz



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