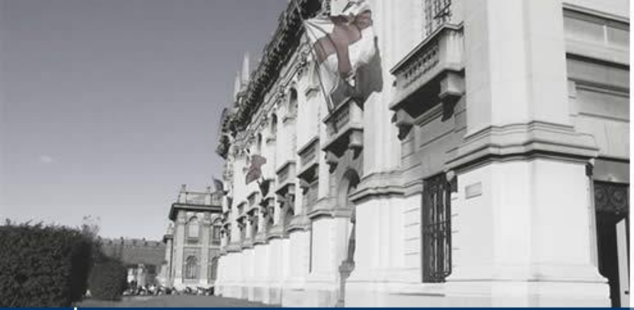


DIPARTIMENTO di ELETTRONICA, INFORMAZIONE e BIOINGEGNERIA

POLITECNICO DI MILANO





Lecture 10
Photodiodes

the principles of photodiodes are common in other signals

Units and measures of light

indeed it's how much watt are in a given surface

	radiometric term (unit)	photometric term (unit)
Q	Radiant energy (J)	Luminous energy (lm·sec)
Φ	Radiant flux or power (W)	Luminous flux or power (lm)
E	Irradiance (W m^{-2})	Illuminance (lm m^{-2} = lx) lux
I	Radiant intensity (W sr^{-1})	Luminous intensity (lm sr^{-1} or cd) aka candle
L	Radiance (W m^{-2} sr^{-1})	Luminance (lm m^{-2} sr^{-1})

power for a given surface

power relative to the unit of solid angle. we can also say, at a given distance d, we consider this angle and we can say in that surface how much is the power

note: each variable can be expressed per wavelength (or frequency) unit

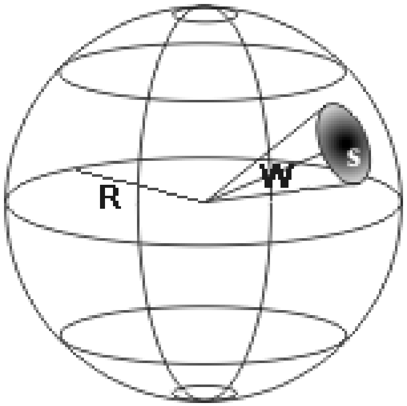
measuring light? transducing from a form of energy to another (usually electric) We would like to say "how much light is here". We can express "how much light there is" in different ways. Radiometric terms, or in the photometric terms. So we can talk about the amount of energy per se (radiant energy, jouls) which has a corrispondence in luminous energy, lumens per seconds.

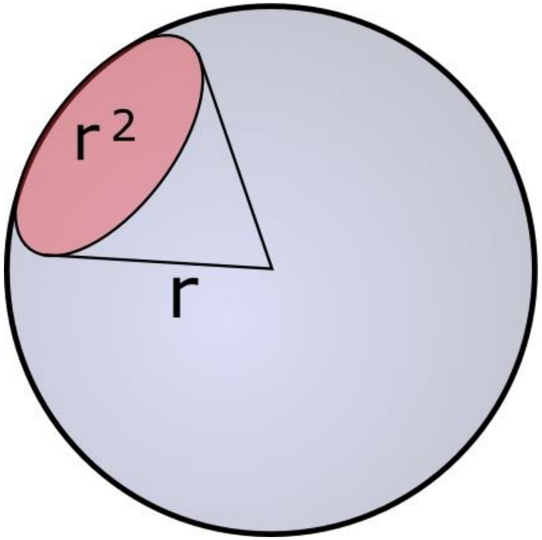
Steradian

Steradian (symbol **sr**; name from Greek *stereos*, solid) is the SI unit of the solid angle (three-dimensional correspondent of radian).

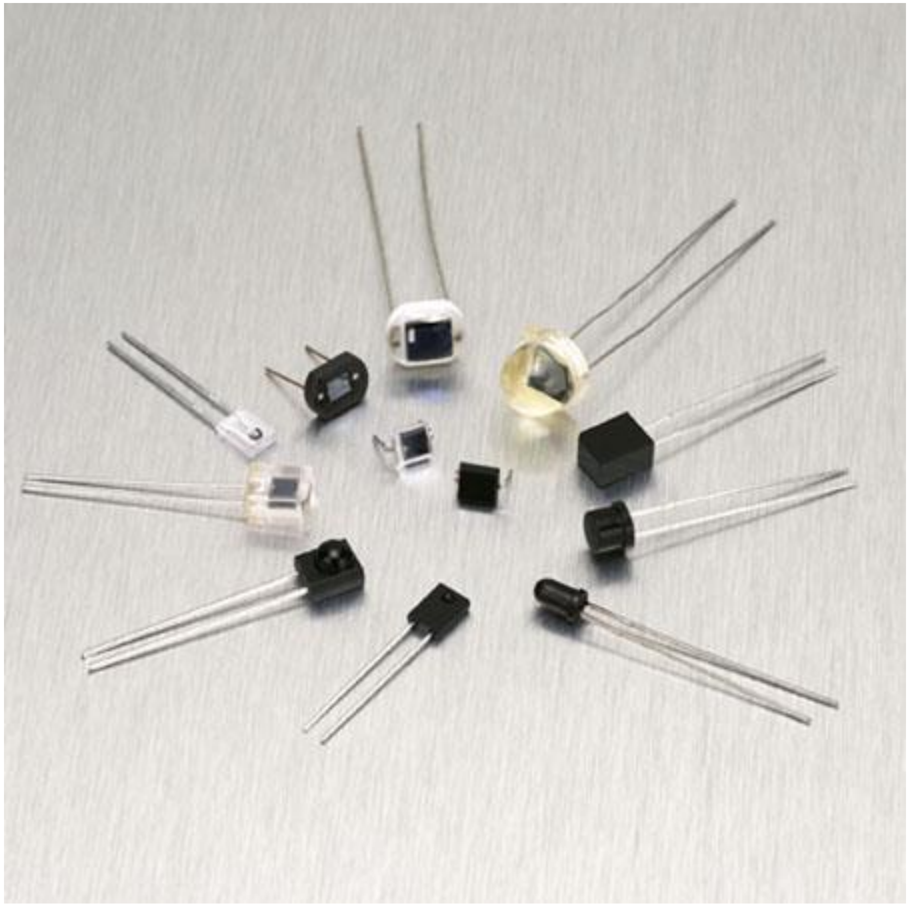
A steradian is defined as the “solid angle subtended at the center of a unit sphere by a unit area on its surface. For a general sphere of radius r, any portion of its surface with area $A = r^2$ subtends one steradian.

Because the surface of the entire sphere is equal to $4\pi r^2$, it follows that the solid angle subtended by the entire sphere is equal to 4π sr.





Photodiodes



Planar diffused silicon photodiodes

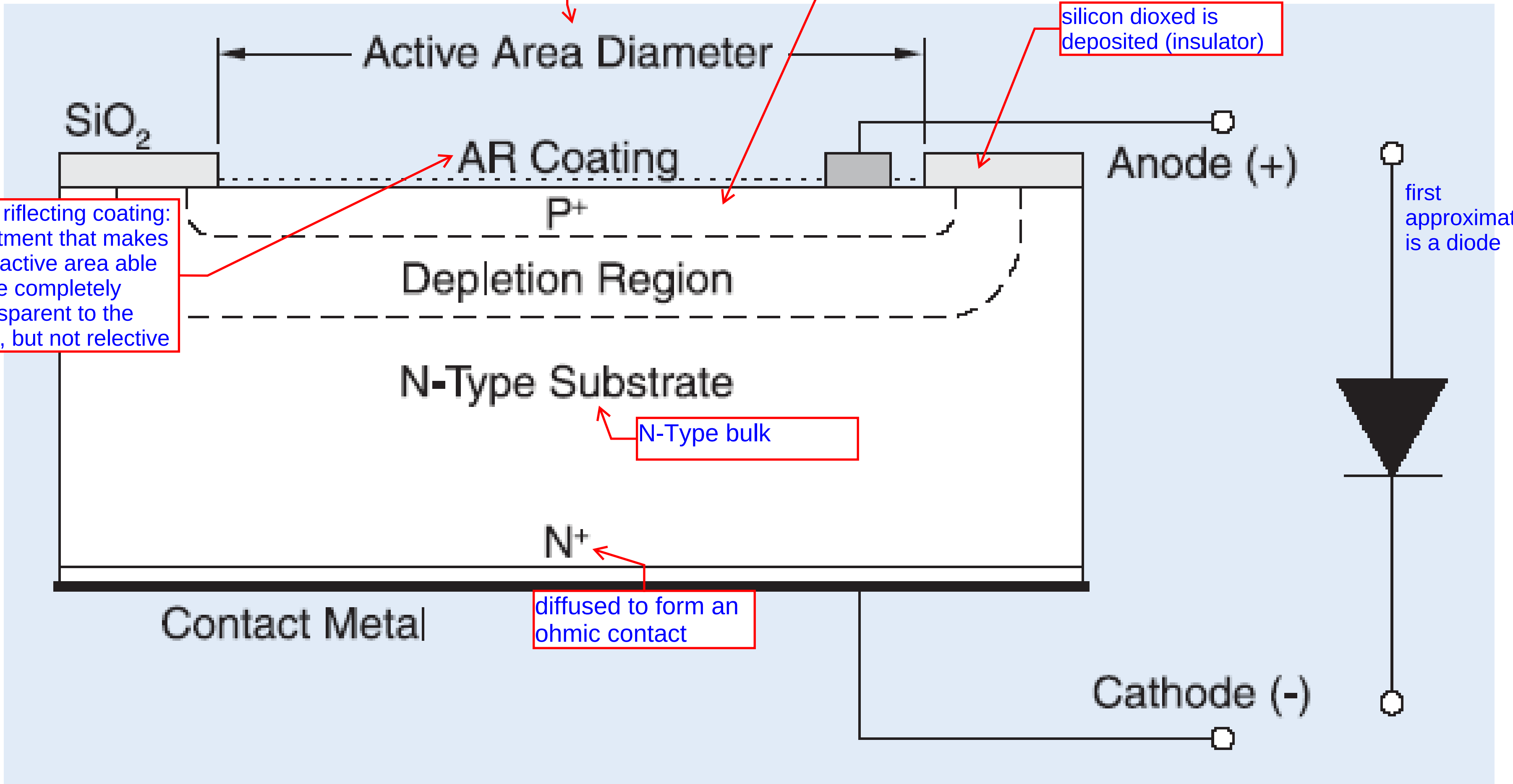
planar technology on the silicon, as we have seen

diffusion of dopant atoms in the silicon. In this case we have diffused a p+ n

"open" window where light can pass through

diffused, active area

silicon dioxed is deposited (insulator)



Anti riflecting coating: treatment that makes this active area able to be completely transparent to the light, but not relective

first approximation is a diode

N-Type bulk

diffused to form an ohmic contact

In this case we have a p-n junction, with a give deplation region, with the electric field obtained as a space integral of the density charges. When the photons enter the device the energy associated can be relased to the material in order to create an electron-hole pair generating a charge, which can happen within the DL. Since it has an electrical field the charge can be collected with two electrodes.

Planar diffused silicon photodiodes

Planar diffused silicon photodiodes are simply **pn junction diodes**. A pn junction can be formed by diffusing either a p-type impurity (anode), such as Boron, into a n-type bulk silicon wafer, or a n-type impurity, such as Phosphorous, into a p-type bulk silicon wafer.
The diffused area defines the photodiode **active area**. To form an ohmic contact another impurity diffusion into the backside of the wafer is necessary. The impurity is an n-type for p-type active area and p-type for an n-type active area.
The contact pads are deposited on the front active area on defined areas, and on the backside, completely covering the device.
The active area is then passivated with an **antireflection coating** to reduce the reflection of the light for a specific predefined wavelength.
The non-active area on the top is covered with a thick layer of silicon oxide. By controlling the thickness of bulk substrate, the speed and responsivity of the photodiode can be controlled. Note that the photodiodes, when biased, must be operated in the reverse bias mode, i.e. a negative voltage applied to anode and positive voltage to cathode.

pn photodiode

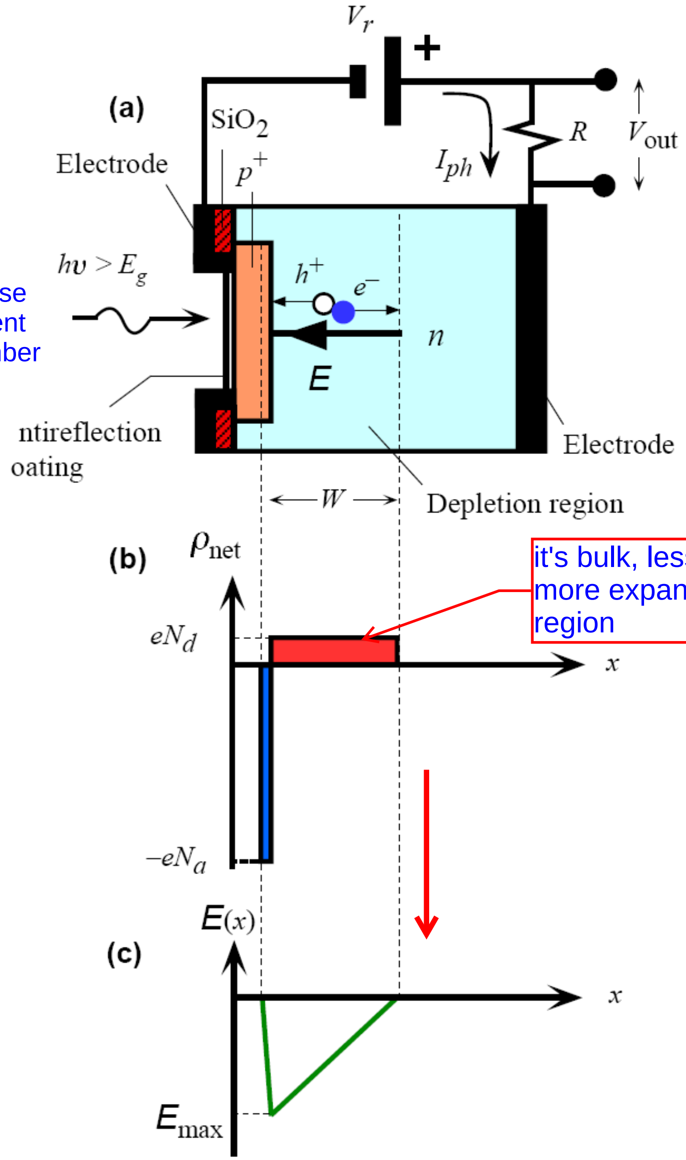
why is it a PHOTO diode? the transduction between a given photon (quantum of energy, light energy) and an electrical signal, that is physically constituded by the generation of an electron called pair in the DL.

a) Schematic diagram of a pn photodiode in reverse bias mode

("-" connected to the p region, typically it works in this condition), because we have a generation of the electron-hole pair, we can generate a current ("reverse current", indicated as Iph) and it's greater with increasing number of photons incident on the device.

b) Space charge in the depletion region (N_d and N_a = concentration of donors and acceptors in p and n regions)

c) Electric field in the depletion region



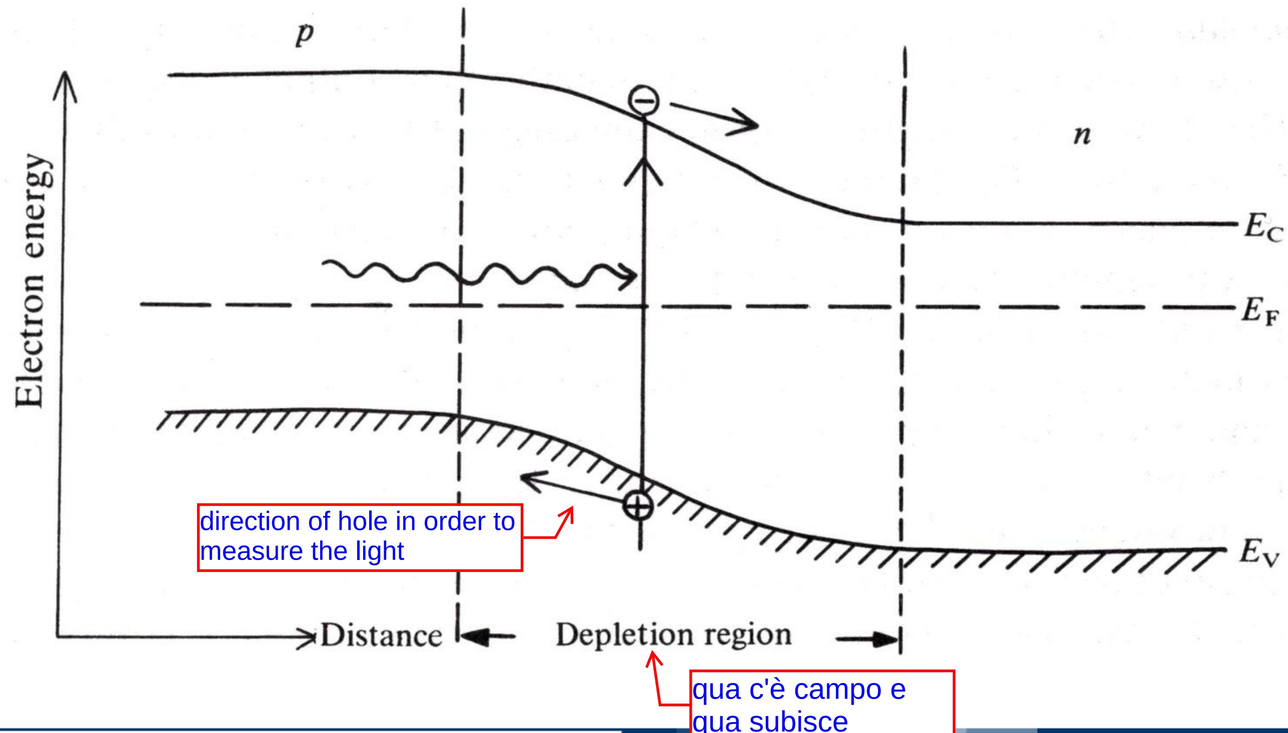
Photodiode: basic principles

We can consider it in the terms of energy levels

Absorption of a photon in the depletion region
$\Rightarrow$ generation of electron-hole pair

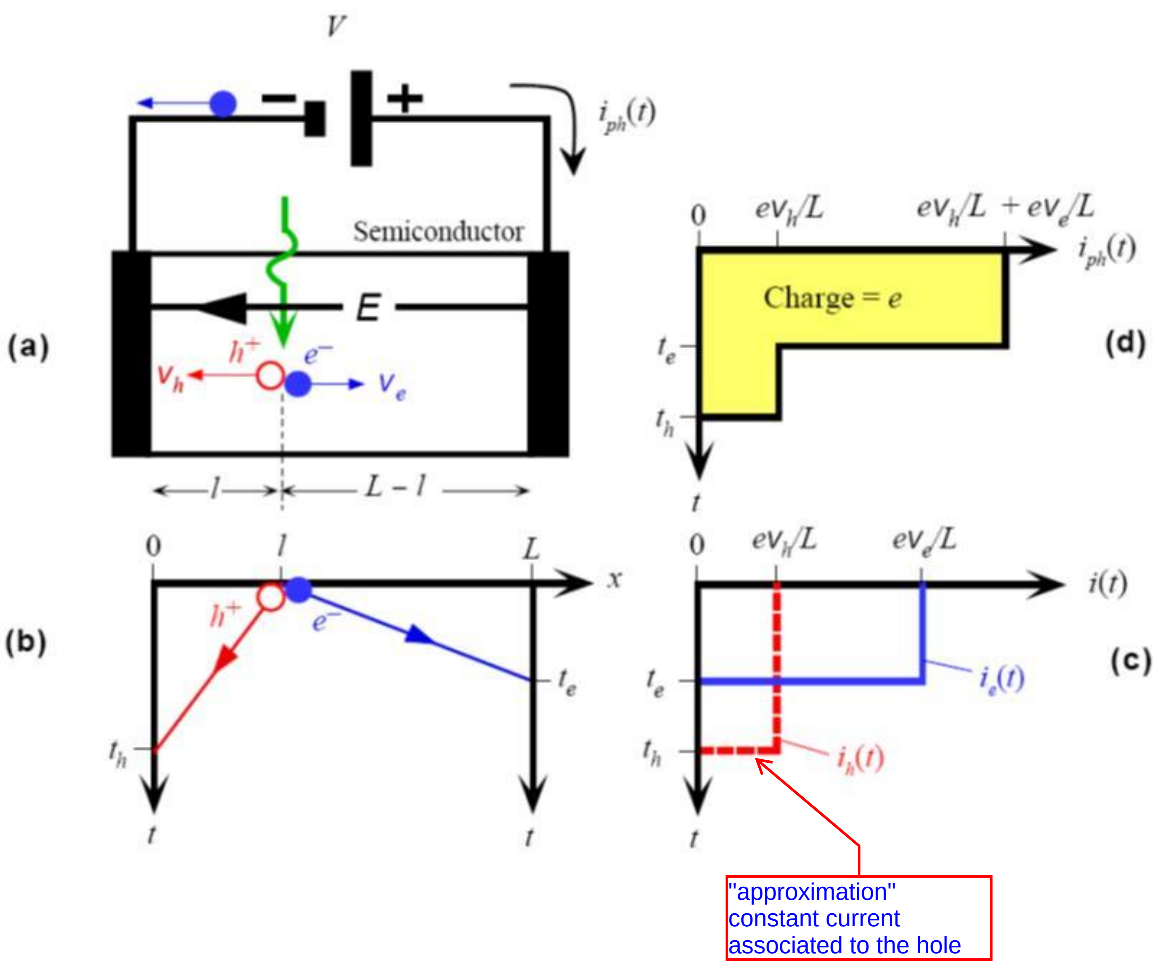
The electric field in the depletion region determines the separation between electron and hole and the diffusion of charge carriers at the limit of the depletion region before recombination can occur

Without a bias the e/h pair it's generated by a photon, but recombination takes place (meaning that the e- decays in the valance band emitting a photon that remains in the material



Photodiode: basic principles

L: lenght of the DL, l is the distance that the h. has to cover, while L-l is the e- one.



a) Generation of electron-hole pair in position $x=l$. Electron and hole then drift in opposite directions with drift velocity v_e and v_h, respectively

b) The electron and the hole reach the electrodes respectively at times $t_e = (L-l)/v_e$ and $t_h = l/v_h$

slighly different times due to the difference in paths

c) During the drift, the electron and the hole generate an "external photo-current" (i_h and i_e)

d) Total photocurrent is the sum of the hole and the electron photocurrent that last t_h and t_e, respectively

$$t_e = \frac{L-l}{v_e} \qquad t_h = \frac{l}{v_h}$$

$$Electric\ field\ \ E = \frac{V}{L}$$

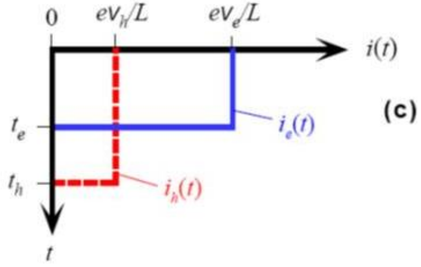
LA CORRENTE E' LA DERIVATA RX AL TEMPO DELLA CARICA

$$i_e(t) = \frac{ev_e}{L}; \quad t < t_e \qquad velocity\ \ v_e = \frac{dx}{dt}$$

$$i_h(t) = \frac{ev_h}{L}; \quad t < t_h$$

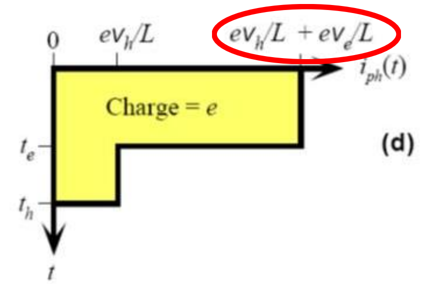
By time integrating the current, we obtain the collected charge Q:

$$Q = \int_0^{t_e} i_e(t)\,dt + \int_0^{t_h} i_h(t)\,dt = e$$



This result can be verified by integrating the area shown in figure d):

$$Q = \int_0^{t_e} \left[i_e(t) + i_h(t) \right] dt + \int_{t_e}^{t_h} i_h(t)\,dt = e$$



The collected charge, is not 2e, but equal to that of one electron (*Ramo's theorem*).

Photodiode: characteristic curves - I-V curve

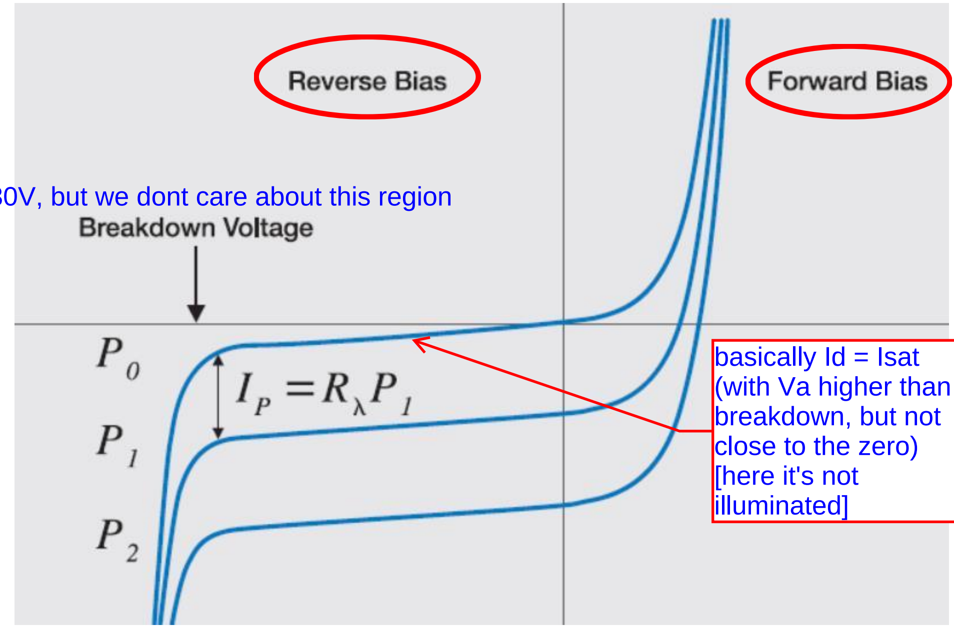
The current-voltage characteristic of a photodiode with no incident light is similar to a rectifying diode. When the photodiode is forward biased, there is an exponential increase in the current. When a reverse bias is applied, a small reverse saturation current appears. It is related to dark current as:

It's the general equation of a diode, Id it's called dark because it's the current in dark conditions.

$$I_D = I_{SAT}\left(e^{\frac{qV_A}{k_BT}} - 1\right)$$

where I_D is the photodiode dark current, I_{SAT} is the reverse saturation current, q is the electron charge, V_A is the applied bias voltage, k_B=1.38 x 10^{-23} J / K, is the Boltzmann Constant and T is the absolute temperature (273 K= 0 ºC).

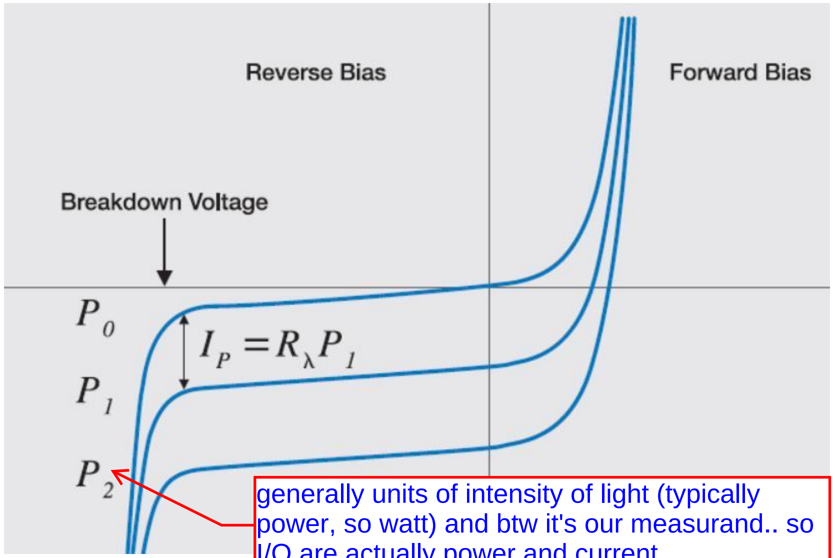
~-30V, but we dont care about this region



basically Id = Isat (with Va higher than breakdown, but not close to the zero) [here it's not illuminated]

In a give illumination the V/I characteristic changes. Keeping the same applied voltage, Va (aka Vr) constant, we can measure the photodiode current, which changes with changing of the illumination. So we go typically in the 3rd diagram (we apply a reverse voltage, and we measure the (change in) photocurrent, as relationship to the light

Photodiode: characteristic curves - I-V curve



generally units of intensity of light (typically power, so watt) and btw it's our measurand.. so I/O are actually power and current

a) **V = 0**, In this state, the dark current I_P=0.
b) **V = +V**, In this state the current increases exponentially. This state is also known as **forward bias mode**.
c) **V = -V**, When a large **reverse bias** is applied to the photodiode, the dark current becomes the reverse saturation current, I_{SAT}.

Illuminating the photodiode with optical radiation, shifts the I-V curve by the amount of photocurrent (I_P):

$$I_D = I_{SAT}\left(e^{\frac{qV_A}{k_B T}} - 1\right) - I_P$$

where

$$I_P = R_\lambda \cdot P$$

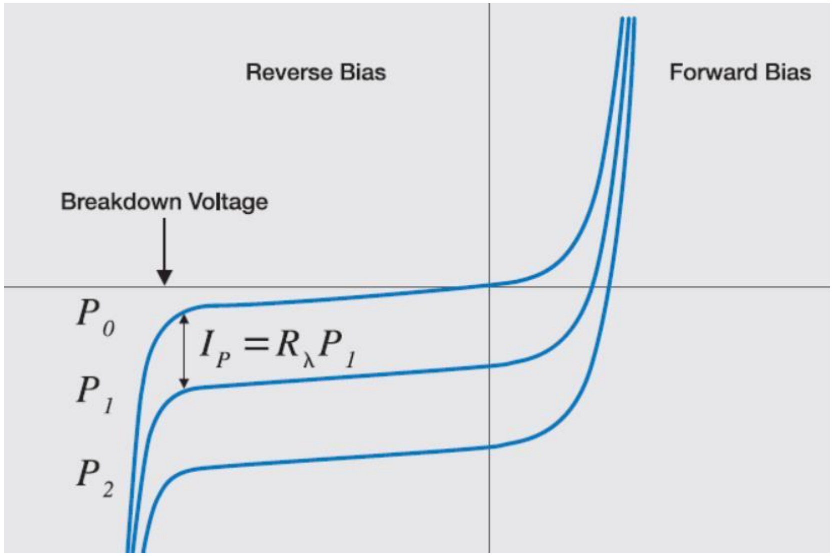
"change as much as possibile with the change in light", it's also specified for a specific wavelength

R_λ is the **responsivity** of the photodiode - a measure of the sensitivity to light, defined as the ratio of the photocurrent I_P to the incident light power P at a given wavelength

Photodiode: characteristic curves - I-V curve

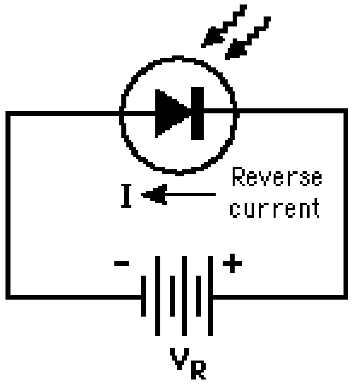
"just be careful not to apply an high reverse voltage. Nothing more needed to know".

As the applied reverse bias increases, there is a sharp increase in the photodiode current. The applied reverse bias at this point is referred to as **breakdown voltage**. This is the maximum applied reverse bias, below which, the photodiode should be operated (also known as maximum reverse voltage).

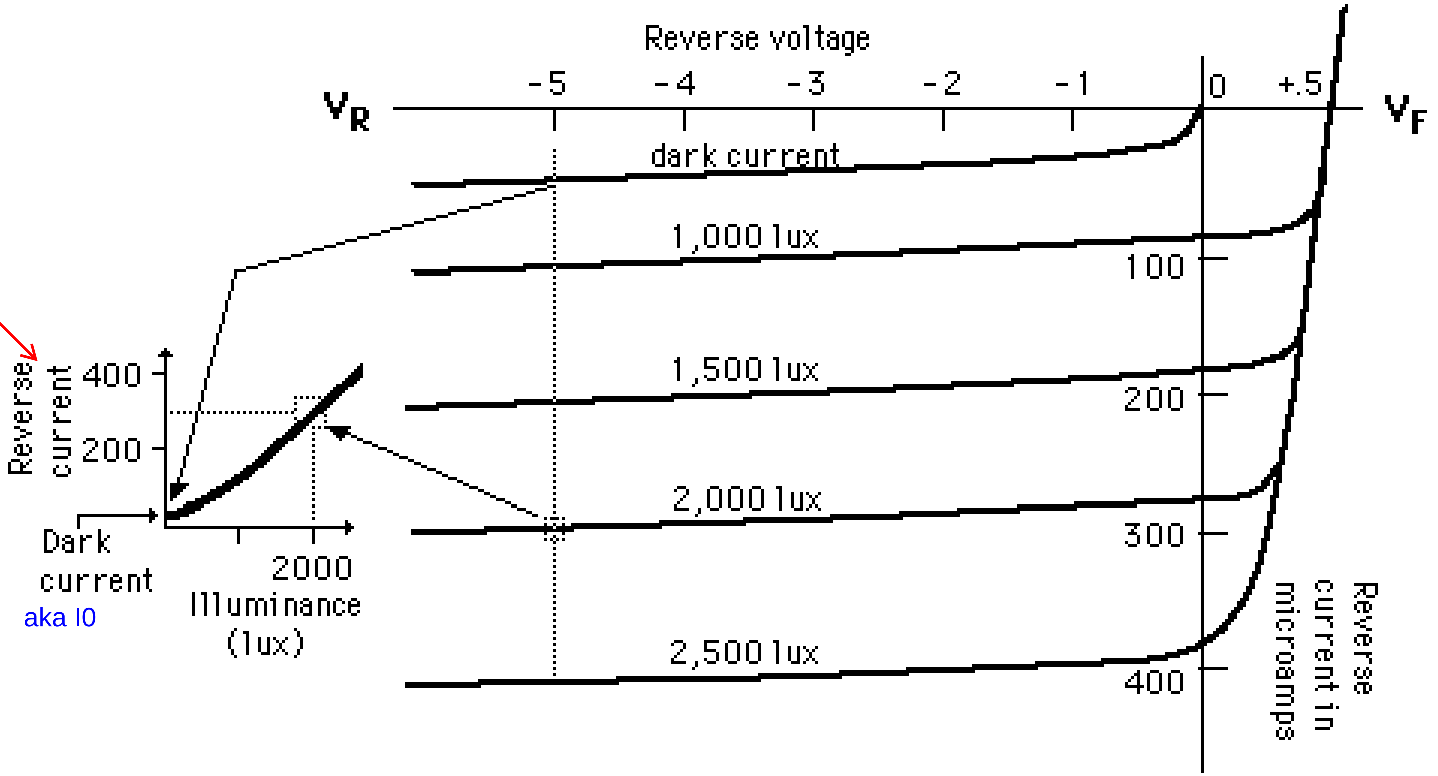


Breakdown voltage, varies from one photodiode to another and is usually measured, for small active areas, at a dark current of 10 μA.

Photodiode: characteristic curves



we can plot the actual I/O curve and it's quite linear! This is the curve for the specific condition of -5 as reverse voltage applied



aka I0

Photodiode: equivalent circuit

"what we see in electrical terms when we look inside the device". There's not only a diode! But also Rs (series resistance between the two terminals), sh (shunt, parallelo), capacitance junction, and the current generator of the photodiode current (philosophycally). In practice we can use a photodiode even without supplying any current or voltage generator (in a so called OpenCircuit configuration)!

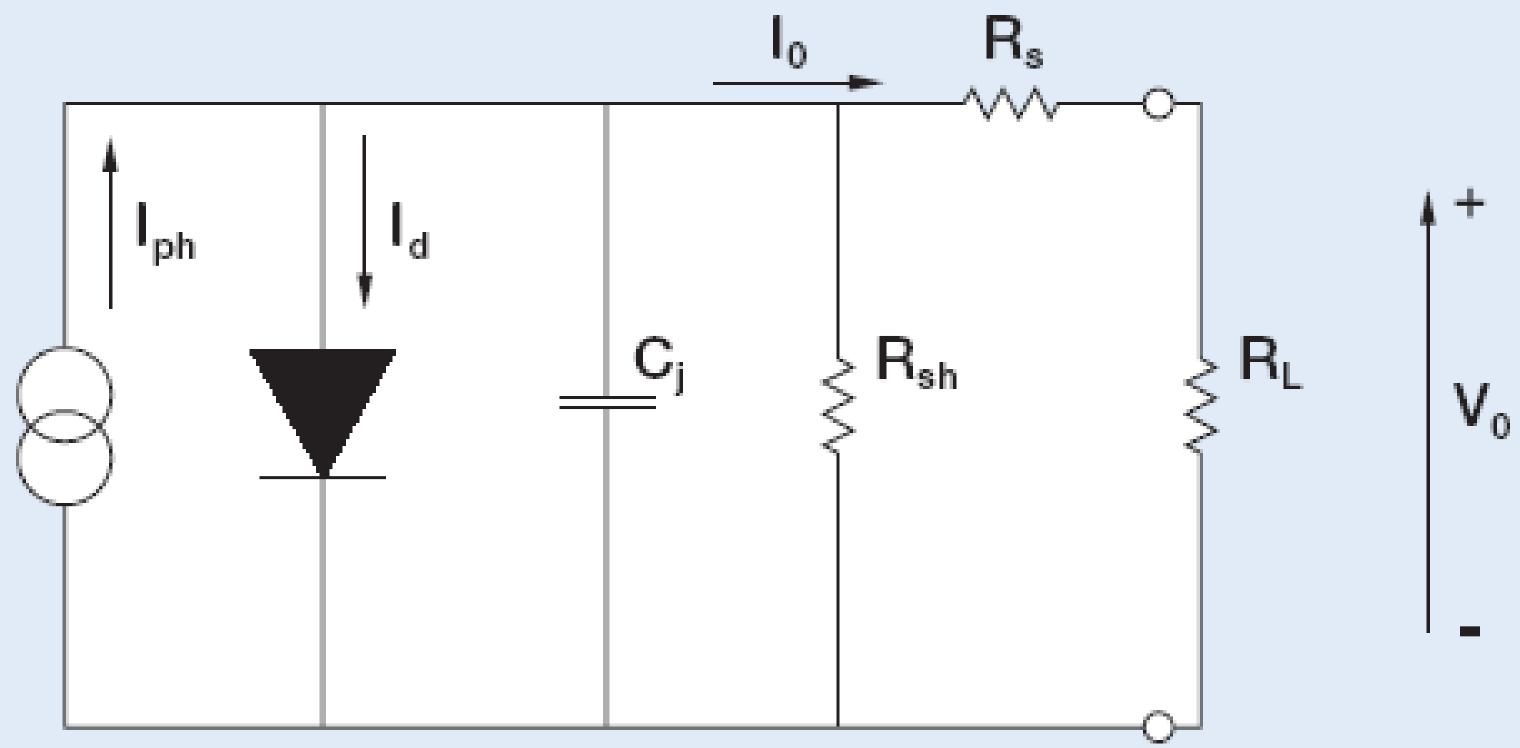


Figure 3. Equivalent Circuit for the silicon photodiode

Shunt resistance R_{sh}: pensaci: shunt significa in corto, cioè V=0

Shunt resistance is the slope of the current-voltage curve of the photodiode at the origin, i.e. V=0. Although an ideal photodiode should have an infinite shunt resistance, actual values range from 10 to 1000 of MΩ.

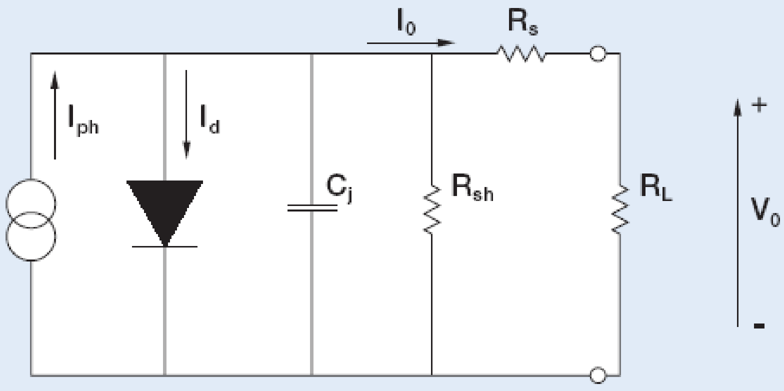


Figure 3. Equivalent Circuit for the silicon photodiode

Series resistance R_S:

arises from the resistance of the contacts and the resistance of the undepleted silicon.

$$R_S = \frac{(W_S - W_d)\rho}{A} + R_C$$

tipica formula per la R

W_S = thickness of the substrate
W_d = thickness of the depletion region
ρ = substrate resistivity
A = diffused area of the junction
R_C = contact resistance
Typical values of R_S = 10 Ω ÷1000 Ω

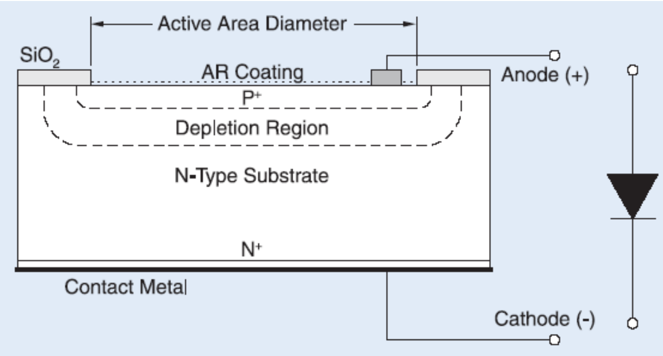


Figure 1. Planar diffused silicon photodiode

Photodiode: equivalent circuit

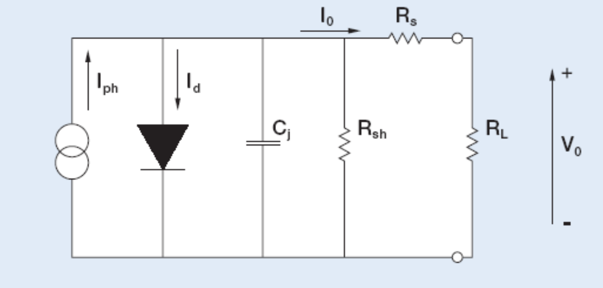


Figure 3. Equivalent Circuit for the silicon photodiode

Junction Capacitance

The boundaries of the depletion region act as the plates of a parallel plate capacitor:

$$C_j = \frac{\varepsilon_{Si}\varepsilon_0 A}{\sqrt{2\,\varepsilon_{Si}\varepsilon_0 \mu\,\rho\left(V_A + V_{bi}\right)}} = A\sqrt{\frac{\varepsilon_{Si}\varepsilon_0}{2\,\mu\,\rho\left(V_A + V_{bi}\right)}} = \frac{\varepsilon_{Si}\varepsilon_0 A}{W_d}$$

$$\left(W_d = \sqrt{2\,\varepsilon_{Si}\varepsilon_0 \mu\,\rho\left(V_A + V_{bi}\right)}\right)$$

ofc the largeness of the DL depends on the voltage applied and the built in

(The junction capacitance is calculated using the expression for the parallel plate capacitance. This might at first seem unexpected since the charge is distributed throughout the depletion layer. However, when applying small voltage variations one finds that charge is only added and removed at the edge of the depletion region so that the capacitance simply depends on the dielectric constant, the area and the depletion layer width)

ε_0 = 8.854 x 10^{-14} F/cm
ε_{Si} = 11.9
μ = 1400 cm^2/Vs (a 300K)
ρ = Si resistivity
V_{bi}= Si built-in voltage
V_A = applied reverse voltage

The junction capacitance is directly proportional to the diffused area and inversely proportional to the width of the depletion region.
In addition, higher resistivity substrates have lower junction capacitance.
Furthermore, the capacitance is dependent on the reverse bias

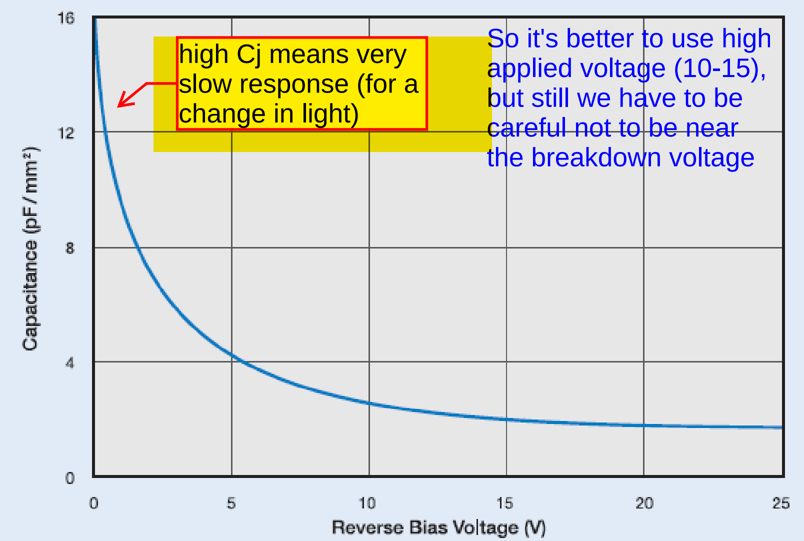
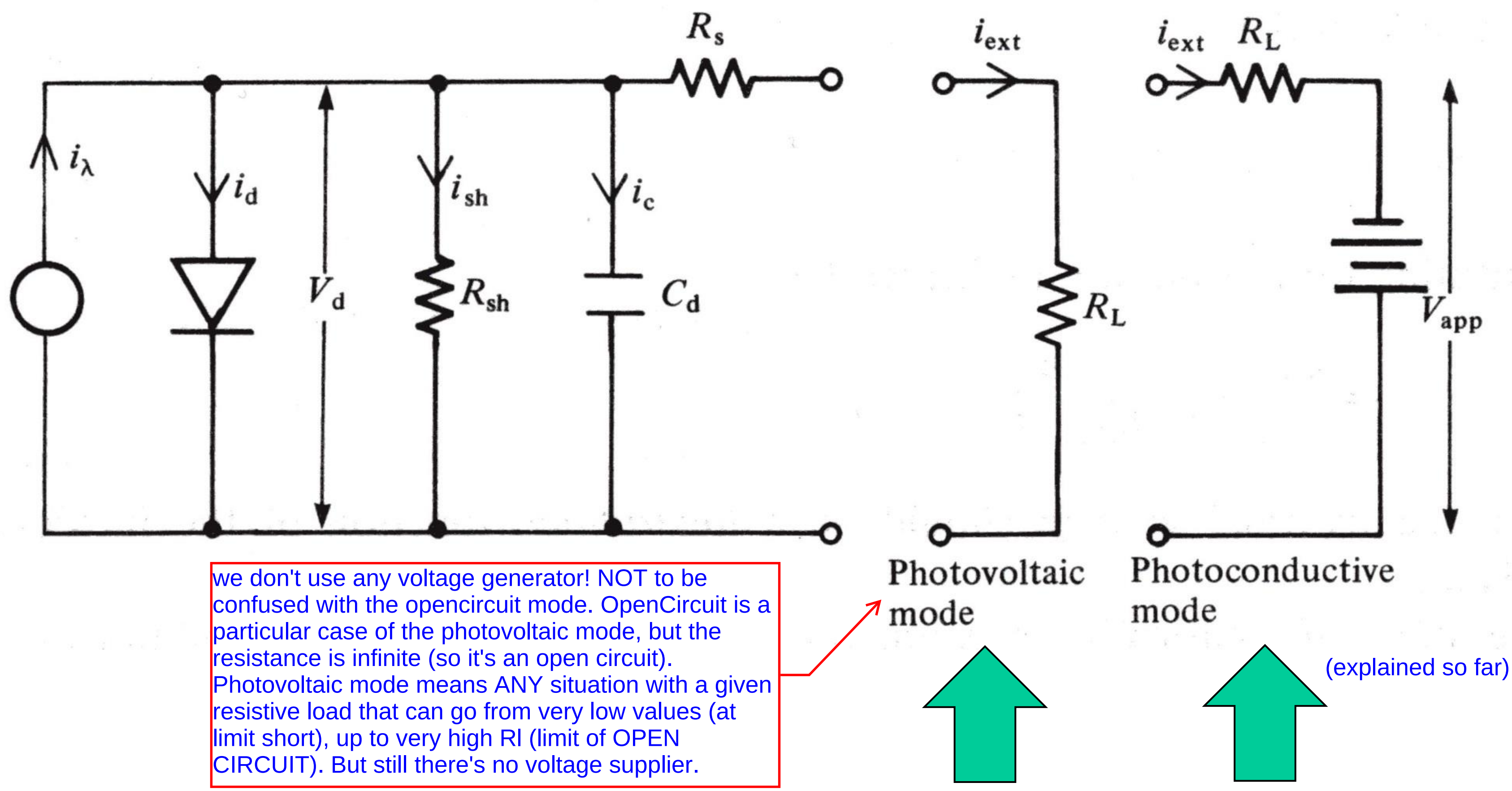


Figure 4. Capacitance of Photoconductive Devices versus Reverse Bias Voltage

Photodiode: modes of operation



we don't use any voltage generator! NOT to be confused with the opencircuit mode. OpenCircuit is a particular case of the photovoltaic mode, but the resistance is infinite (so it's an open circuit). Photovoltaic mode means ANY situation with a given resistive load that can go from very low values (at limit short), up to very high Rl (limit of OPEN CIRCUIT). But still there's no voltage supplier.

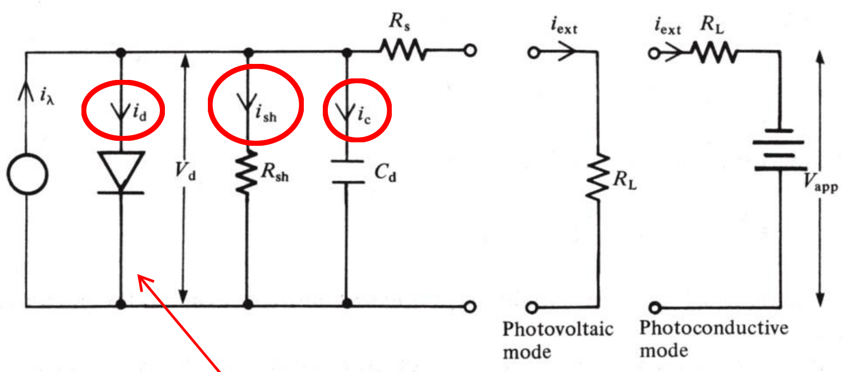
(explained so far)

Photodiode: modes and equations of operation

i_λ = current generated by incident light (of irradiance I_0, wavelength λ), on the sensor of area A and quantic efficiency η

Intensity of the light at a given wavelenght lambda (our measurand)

$$i_\lambda = \frac{\eta I_0 \, A e \lambda}{h c}$$



Il diodo fa la dark current alla quale poi va aggiunta R(lambda)*P. Oppure fa la corrente normale del diodo se è Vd > 0

By omitting, for simplicity, the effects of C_d (i_c = 0):

stationary conditions

whatever is the mode of operation we can write the sum of the current lambda as the 3 contributes:

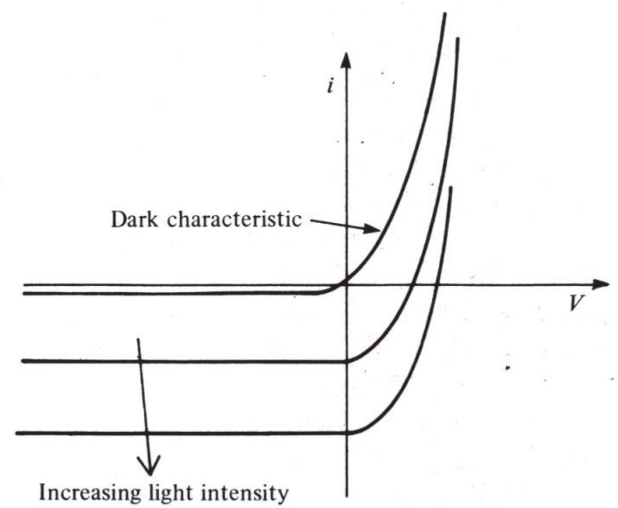
$$i_\lambda = i_d + i_{sh} + i_{ext}$$

$$V_{ext} = V_d - i_{ext} R_S$$

$$V_d = i_{sh} R_{sh}$$

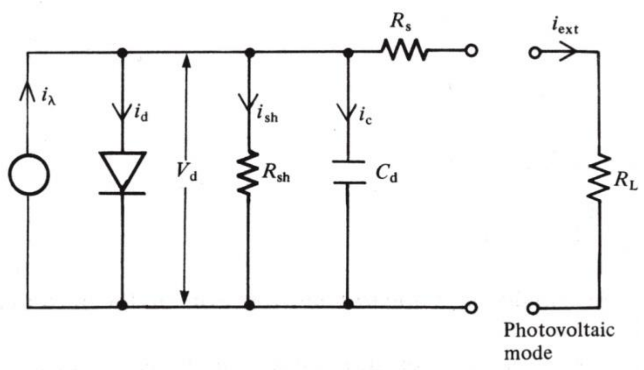
$$i_d = i_0 \left[\exp\left(\frac{eV_d}{kT} \right) - 1 \right]$$

Current that describes the normal characteristic of the diode



Photovoltaic mode (open circuit)

(OC., Rl = infinite + typical condition of Photovoltaic mode, i.e. no applied external voltage)



$$i_{ext} = 0 \quad \Rightarrow \quad i_\lambda = i_d + i_{sh}$$

$$V_{ext} = V_d$$

$$\Rightarrow \quad i_\lambda = i_0\left[\exp\left(\frac{eV_d}{kT}\right) - 1\right] + \frac{V_d}{R_{sh}}$$

$$\exp\left(\frac{eV_d}{kT}\right) = 1 + \frac{i_\lambda}{i_0} - \frac{V_d}{i_0 R_{sh}}$$

Typical operative conditions:

saturation current (dark current) very low

$$i_\lambda >> i_0$$

$\Rightarrow$ (in first approximation)

$$i_0 \approx 10^{-8}\,A$$

$$R_{sh} \approx 10^8\,\Omega$$

$$V_d \approx 0.6V$$

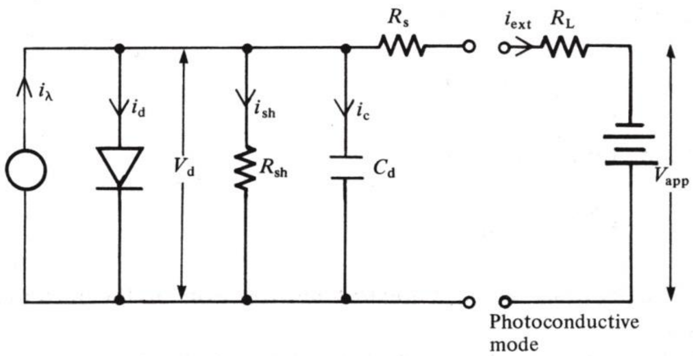
$$\exp\left(\frac{eV_d}{kT}\right) = \frac{i_\lambda}{i_0}$$

In these conditions the relationship between the measurand (I0, illumination) and the output which is the Ve (==Vd) is a logaritmic one. When the illumination is very low we have a good separation between the curves.. but when it becomes very high the relative distance between the curves becomes lower.

$$V_d\,(=V_{ext}) = \frac{kT}{e}\ln\left(\frac{i_\lambda}{i_0}\right) = \frac{kT}{e}\ln\left(\frac{\eta\, I_0\, A e \lambda}{h c i_0}\right)$$

infatti diventa "orizzontale" dove si muove la Vd e basta, la corrente rimane zero. Quindi tutte le curve diventano ultra vicine per intensità alte

Photoconductive mode



Typical operative conditions:

High (≈ 10V) reverse bias voltage

⇒ Diode current saturates at i_0 ≈10 nA

La corrente del diodo dipende da Vd. Anche se qua non è chiaro, la tensione come punto di lavoro è sicuramente nel 3° quadrante, perciò Vd negativa, perciò la corrente del diodo satura a quella """ dark""" che è 10nA quindi chissene. La Vd sarebbe comunque più o meno quella applicata, se non consideriamo la caduta di tensione su Rs in realtà, ed Rl anche, però comunque possiamo pensare a quella.

photocurrent generated by the device

very low

very low

$$i_\lambda = i_0 + i_{sh} + i_{ext}$$

$$i_{sh} = \frac{V_d}{R_{sh}} \approx 10V/100M\Omega \approx 100nA$$

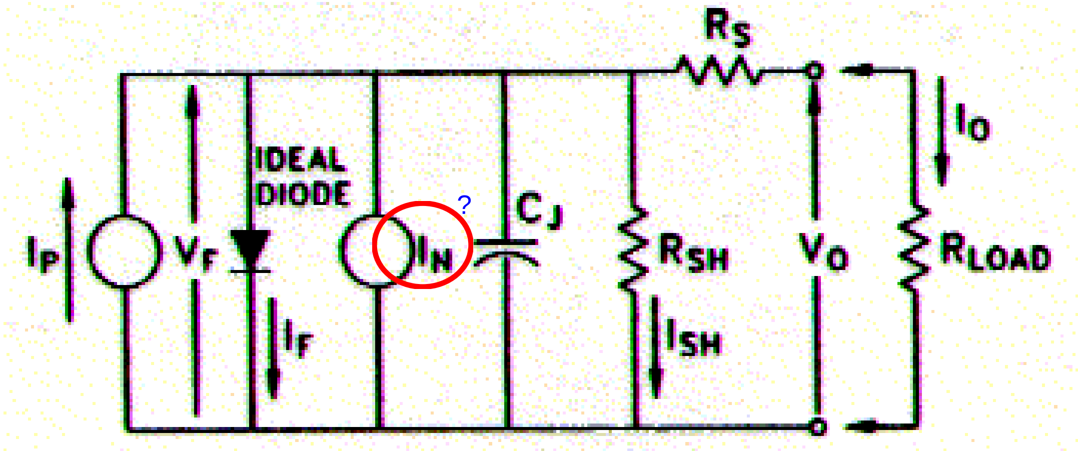
Anche se questo passaggio è un po' buttato lì comunque la corrente se avessimo considerato Vd come quella del diodo sarebbe stata anche più bassa, quindi in generale ish è bassissima e la trascuriamo

$$\Rightarrow \quad i_{ext} = i_\lambda$$

$$i_\lambda = \frac{\eta\, I_0\, A e\, \lambda}{h\, c}$$

Photodiode: noise

Model in presence of noise



this is very low if the device is well made..

$$I_{tn} = (I_{jn}^2 + I_{sn}^2 + I_F^2)^{½}$$

sort of average of the noises

- I_{tn} = total current noise
- I_{jn} = thermal current noise or Johnson (thermal random movement of the electrons, proportional to $T^{1/2}$, independent on λ, “white noise”)
- I_{sn} = ‘shot’ current noise (random fluctuations of current across the pn junction, proportional to $I_{dc}^{1/2}$)
- I_F = “flicker” current noise or rumore “1/f noise” (not fully understood, dependent on the device structure, proportional to $1/f^{1/2}$) frequency of the signal

NEP (Noise Equivalent Power)

the level of the noise define the lower detection limit, meaning the minimum signal that we can measure, because it's a littel bit greater than the noise level

Lower detection limit of the photodiode (intensity of the light necessary to generate a current equal to noise current I_N).

$NEP = I_{tn} / S_R \quad (W/Hz^{½})$

we want to pass from the measurand to the current, "between" there's the gain!

Questa è tipo la potenza equivalente del noise. E' come se ci domandassimo: che segnale "reale" potrebbe generare questo livello di corrente? la risposta è il NEP che è espresso come """ potenza""" anche se è W/Hz^0.5

I_{tn} = total noise current($A/Hz^{½}$);

S_R = sensitivity (A/W) Dovrebbe essere la RESPONSITIVITY vista precedentemente, R(lambda)

NEP values are usually between 10^{-15} $W/Hz^{½}$ and 10^{-12} $W/Hz^{½}$.

D (detectivity)

Detection capacity, defined as the inverse of NEP.
It is a measurement of the minimal detectable radiant power or S/N ratio of the detector.
An high value of D indicates the ability to detect low levels of radiation.

$D = 1/NEP \quad (Hz^{½}/W)$

"NEP-star" and "D-star"

Normalized by the area, indeed the larger is the area the absolute answer is different

As the noise is generally proportional to the square root of the photosensible area (A_D), the lower this area is, the better NEP and detectivity are.

Specific NEP, N* ('NEP-Star') is defined as:

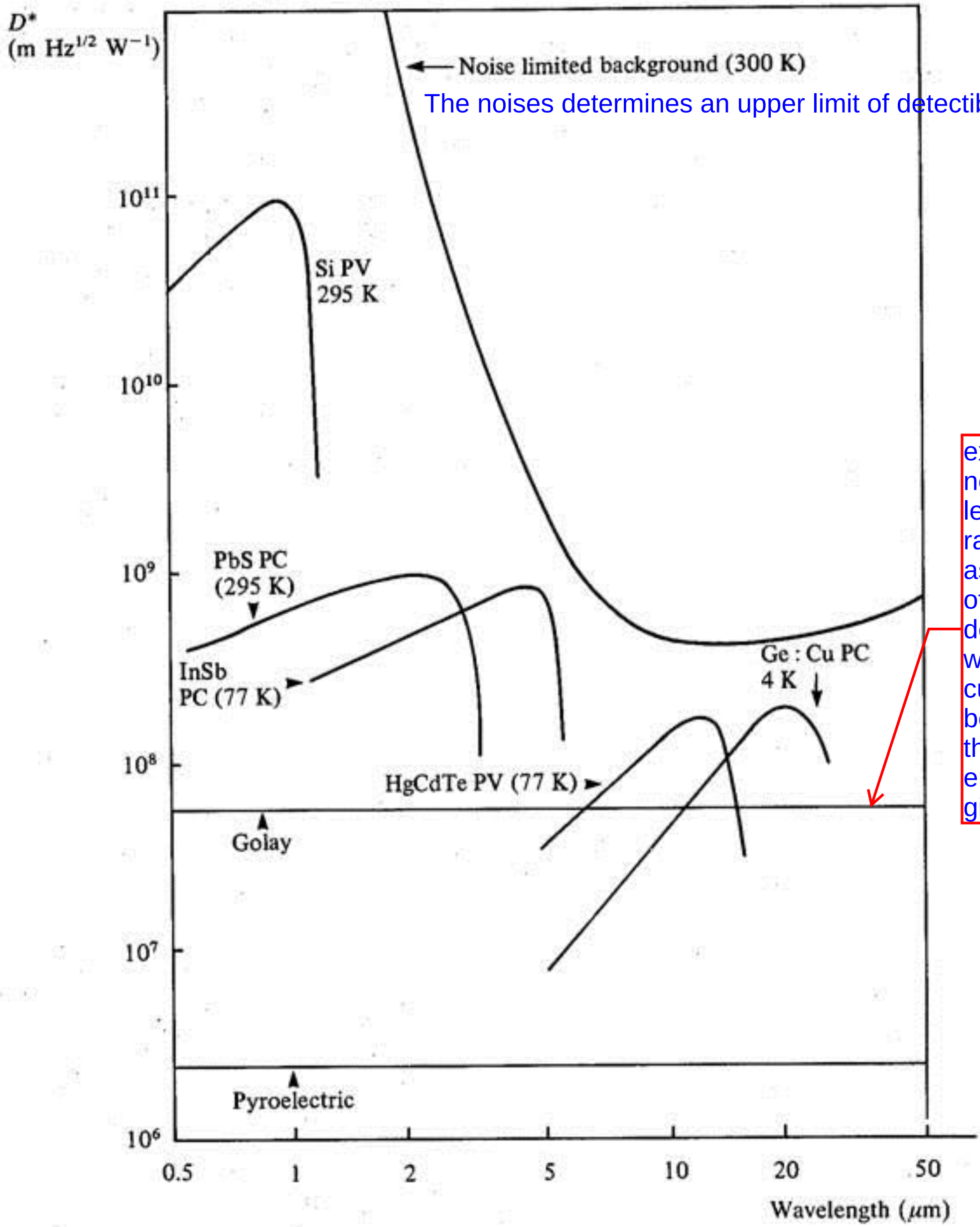
$$\mathbf{NEP^* = NEP / A^{1/2}}$$

Specific detectivity, D* ('D-Star') provides values which are independent on the sensor area :

$$\mathbf{D^* = D \times A_D^{1/2} \quad ([(cm)Hz^{1/2}]/W)}$$

Typical values of D* : from 10^{13} (cm)$Hz^{1/2}$/W to 10^{11} (cm)$Hz^{1/2}$/W.

The higher the better



The noises determines an upper limit of detectibility

example of radiation sensor not dependent on the wave lenght. "Called Termal radiation sensor, it's associated to the overall level of radiation energy. Which is defined by the plank curve, which is like integrating the curve.. It's a radiation of a body at a given temperature, these measure the TOTAL energy emitted by a body at a given temperature

Fig. 7.42 Specific detectivity D^* as a function of wavelength for a number of representative photodetectors (PC = photoconductive, PV = photovoltaic).

$$I_{ph} = i_{\lambda} = \frac{\eta I_0 A e \lambda}{hc} = \frac{\eta P_0 e \lambda}{hc}$$

current generated within the sensor associated to the power P0 (irradiance I0 * area A) of the radiation

$$\eta = \frac{I_{ph}/e}{P_0/h\nu}$$

equal to the numer of generated e-hole pairs for every incident photons, ideally equal to 1 (real it's lower), indeed we can have phenomena like reflection, recomb., crossing, thus a photon can be not able to generate a pair (like, it could be reflected, discontinuity in the reflection index). Recombination means that the el. pair ricombine before it reaches the electrodes. Crossing means that the photon crosses the DL. The absorbance accours outside

quantic effciency

$$\eta = \frac{num.\ of\ generated\ \ electron - holes}{num.\ incident\ \ photons}$$

Phenomena of:

- Reflection
- Recombination
- crossing

The photon crosses the DL!!!!

Sensitivity (responsivity)

$$R = \frac{photocurrent\ \ (A)}{incident\ optical\ power\ \ (W)} = \frac{I_{ph}}{P_0}$$

Grafico di qualche slide fa:
Iph = P0*R

Power: quando semplifichiamo la formula si semplifica Io*A

$$R = \eta \frac{e}{h\nu} = \eta \frac{e\lambda}{hc} = \frac{\eta}{1.24}\lambda$$

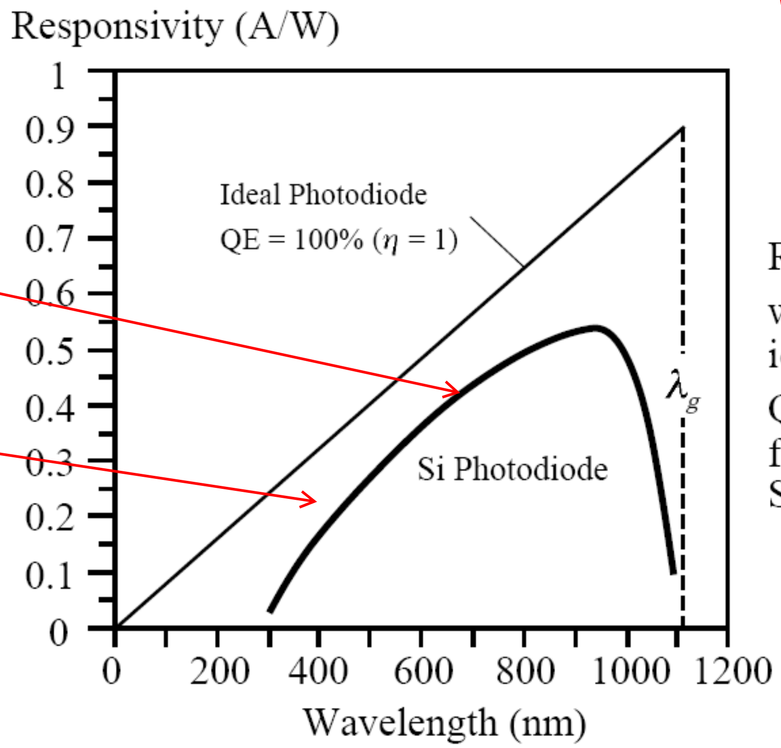
ofc the highest the efficiency the highest the responsibility

e, h, c are constant

Linearly related to lambda!! If we have a plot R-wavelength, we have a linear relationship, the real plot is represented, the ideal is that line. If the wavelength is overe a certain number it's not able to provide enough energy to surpass the energy gap, so the response is 0.

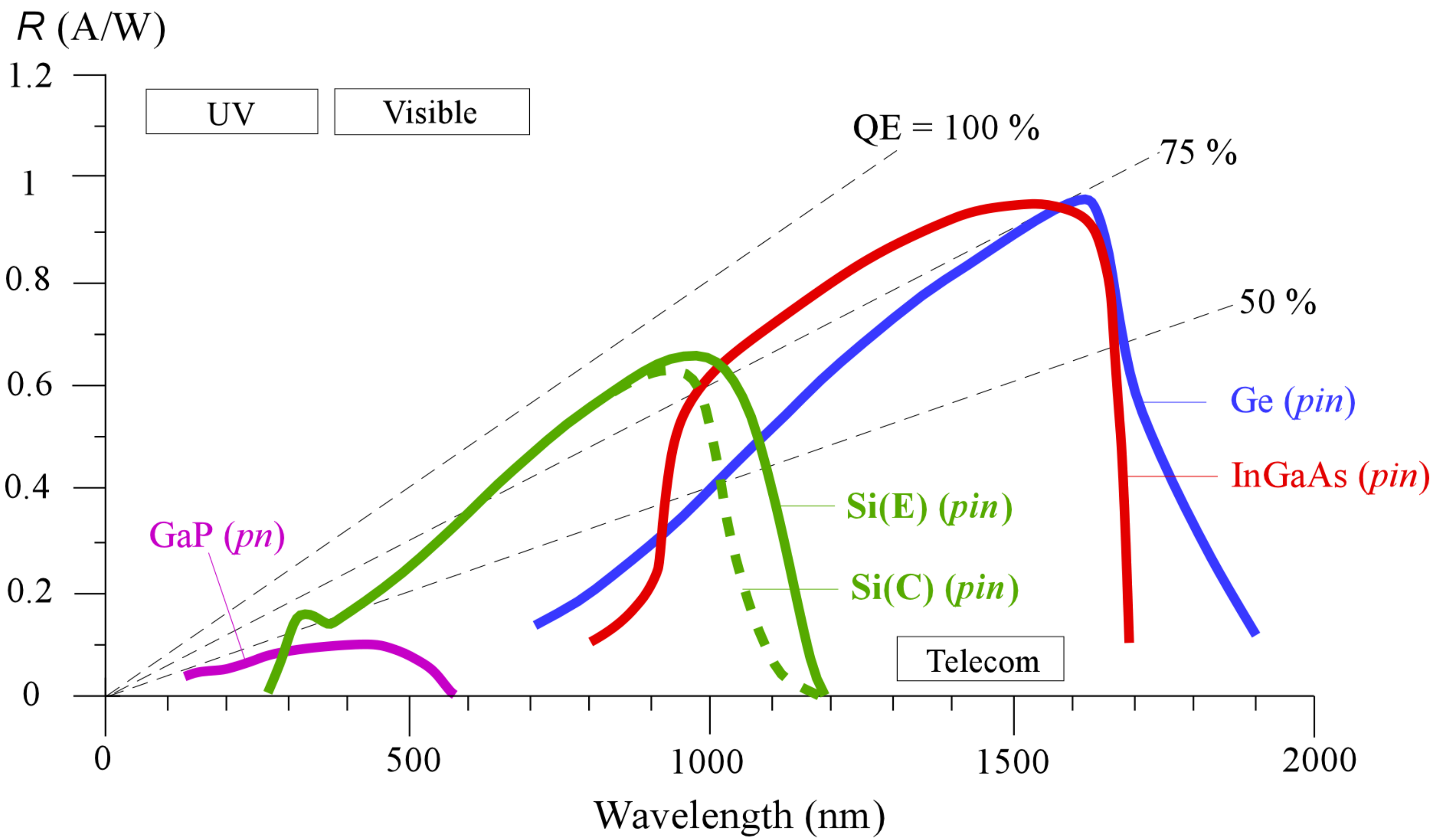
it's here because eta it's not 1 8)

This is lower! why is that? isn't this more energy associated to the wave?!? the response in few slides



Responsivity (R) vs. wavelength (λ) for an ideal photodiode with QE = 100% (η = 1) and for a typical commercial Si photodiode.

Sensitivity (responsivity)



The responsivity of Si, InGaAs and Ge *pin* type photodiodes. The *pn* junction GaP detector is used for UV detection. GaP (Thorlabs, FGAP71), Si(E), IR enhanced Si (Hamamatsu S11499), Si(C), conventional Si with UV enhancement, InGaAs (Hamamatsu, G8376), and Ge (Thorlabs, FDG03). The dashed lines represent the responsivity due to QE = 100 %, 75% and 50 %.

Maximal wavelength :

$$\lambda_g(\mu m) = \frac{1.24}{E_g(eV)}$$

E.g.: for Si, E_g=1.12 eV $\Rightarrow \lambda_g = 1.11\ \mu m$
for Ge, E_g=0.66 eV $\Rightarrow \lambda_g = 1.87\ \mu m$

The incident photons with lower wavelength are absorbed by the material and the light intensity decays exponentially with distance x from the surface of the semiconductor material :

the ones with the most energy are absorbed by the material with this law.

$$I(x) = I_0\, exp(-\alpha x)$$

photon with this intensity

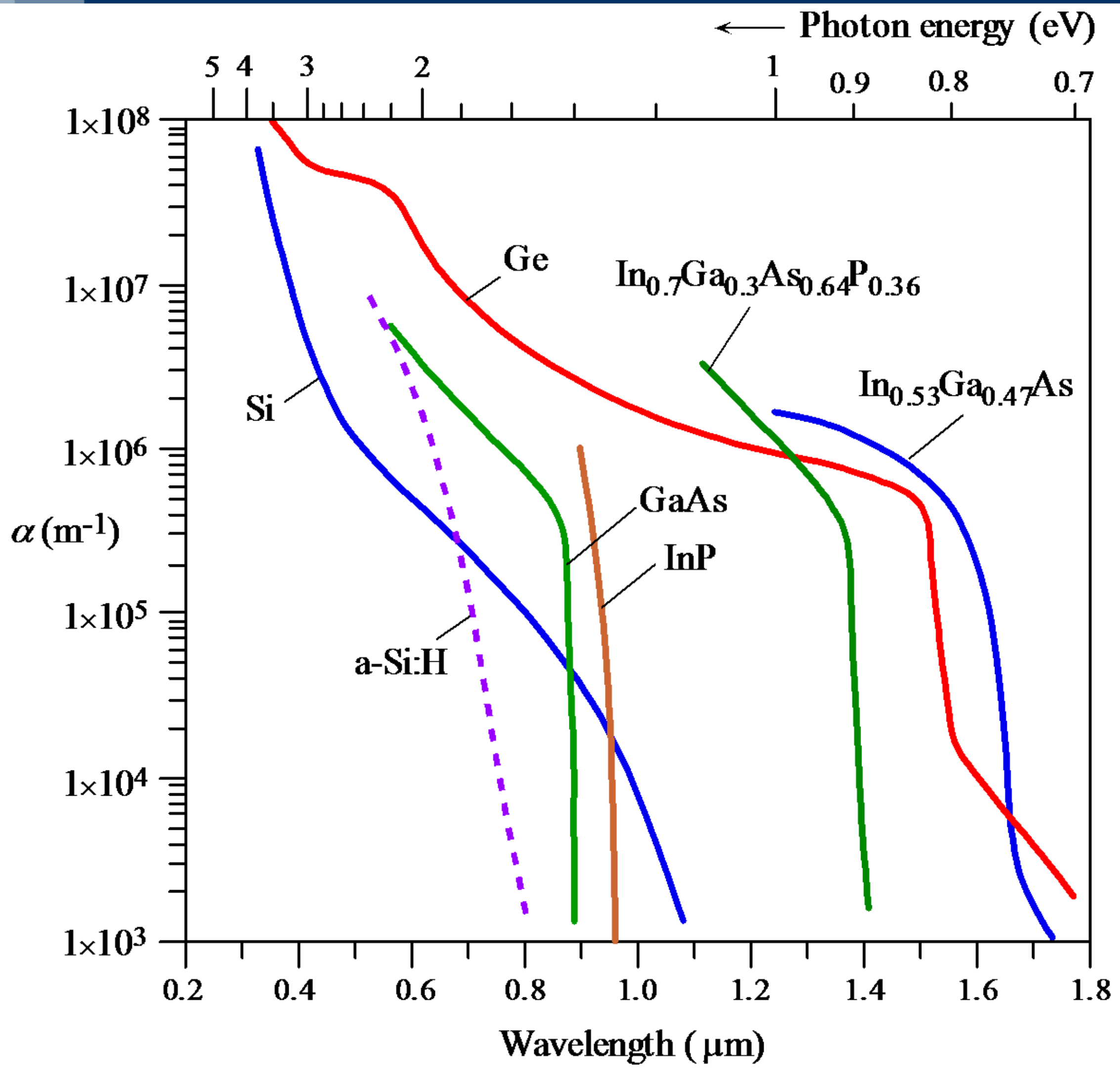
depending on the space: into the material. It attenuates the wave.

I_0 = incident light intensity
α = absorption coefficient
$\delta = 1/\alpha$ = penetration depth

it actually depends on the wavelength!!! slide 33

Con lunghezze d'onda troppo corte i fotoni sono assorbiti dal materiale e l'intensità della luce diminuisce esponenzialmente con la distanza x.

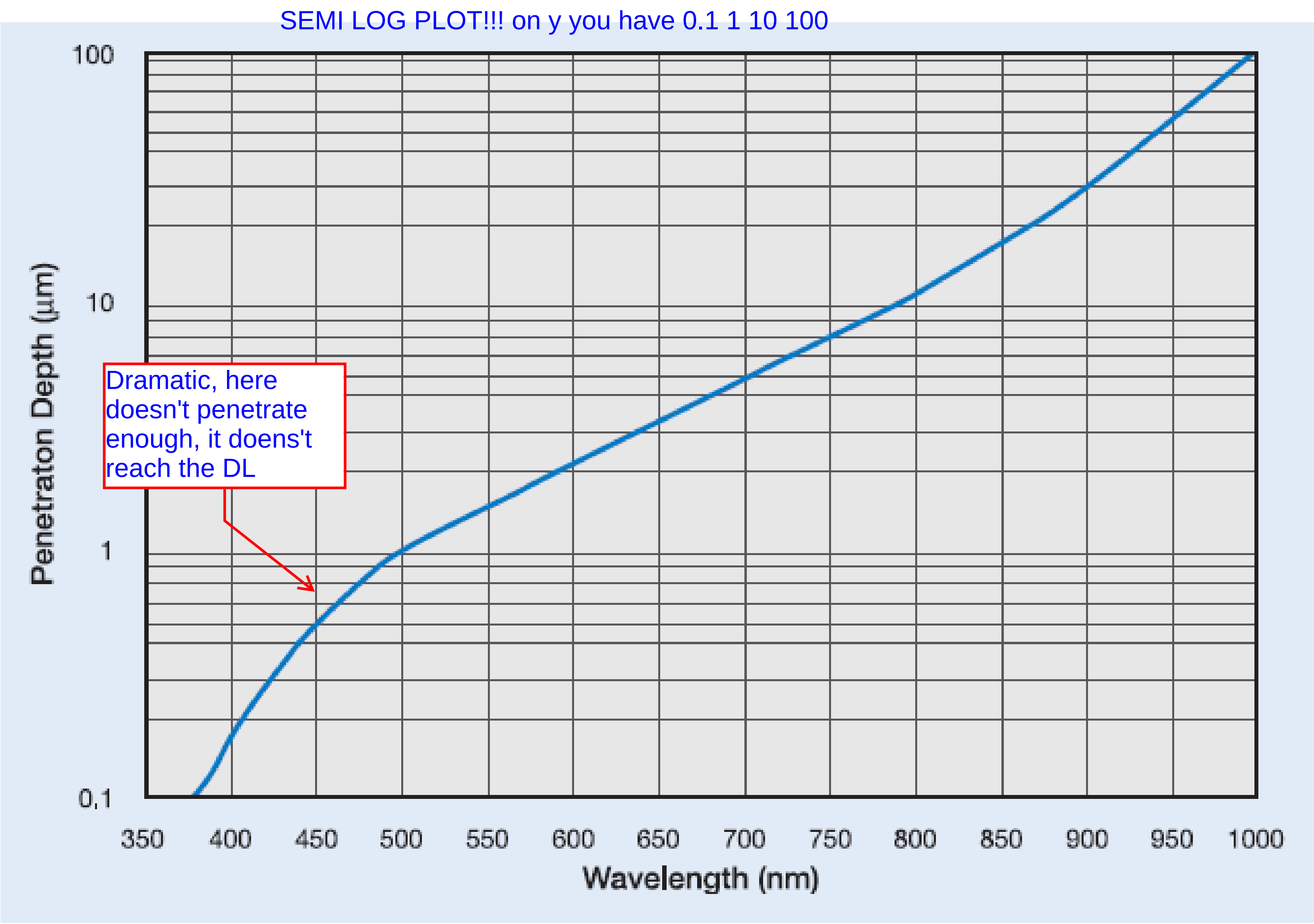
Absorption coefficient



Absorption coefficient (α) vs. wavelength (λ) for various semiconductors
(Data selectively collected and combined from various sources.)

Penetration depth

$\delta = 1/\alpha$



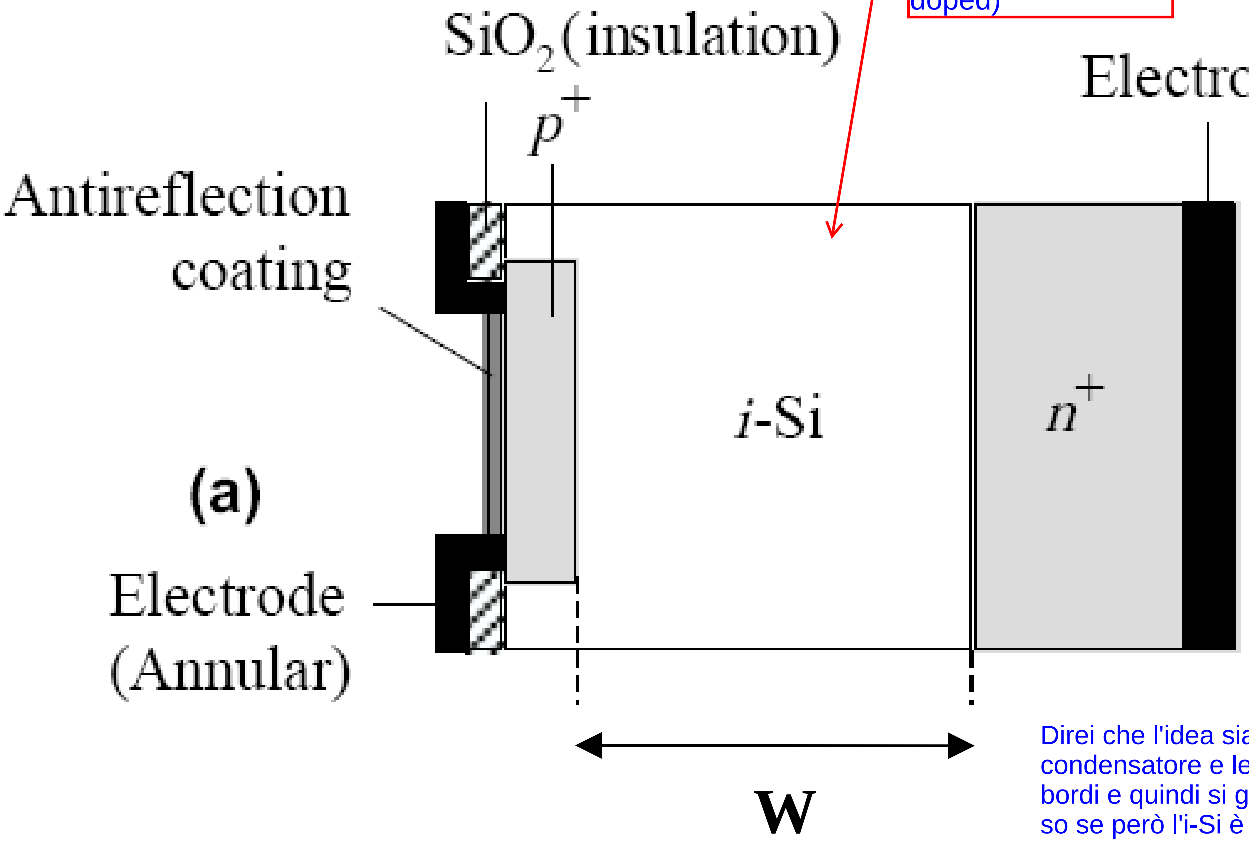
1) Junction capacity is not low enough to allow measurements at high frequency

2) The thickness of the depletion region is few microns, that means that a lot of photons are absorbed outside this region and therefore do not generate electron-hole pairs crossing?

pin (p-intrinsic-n) photodiode

solution for both of these problems

intrinsic semiconductor(not doped)



Direi che l'idea sia tipo che i-Si è il dielettrico di un condensatore e le cariche sono accumulate ai bordi e quindi si genera un campo elettrico. Non so se però l'i-Si è un dielettrico (cioè essendo intrinseco a t ambiente conduce poco, però non ultra poco come dielettrici)

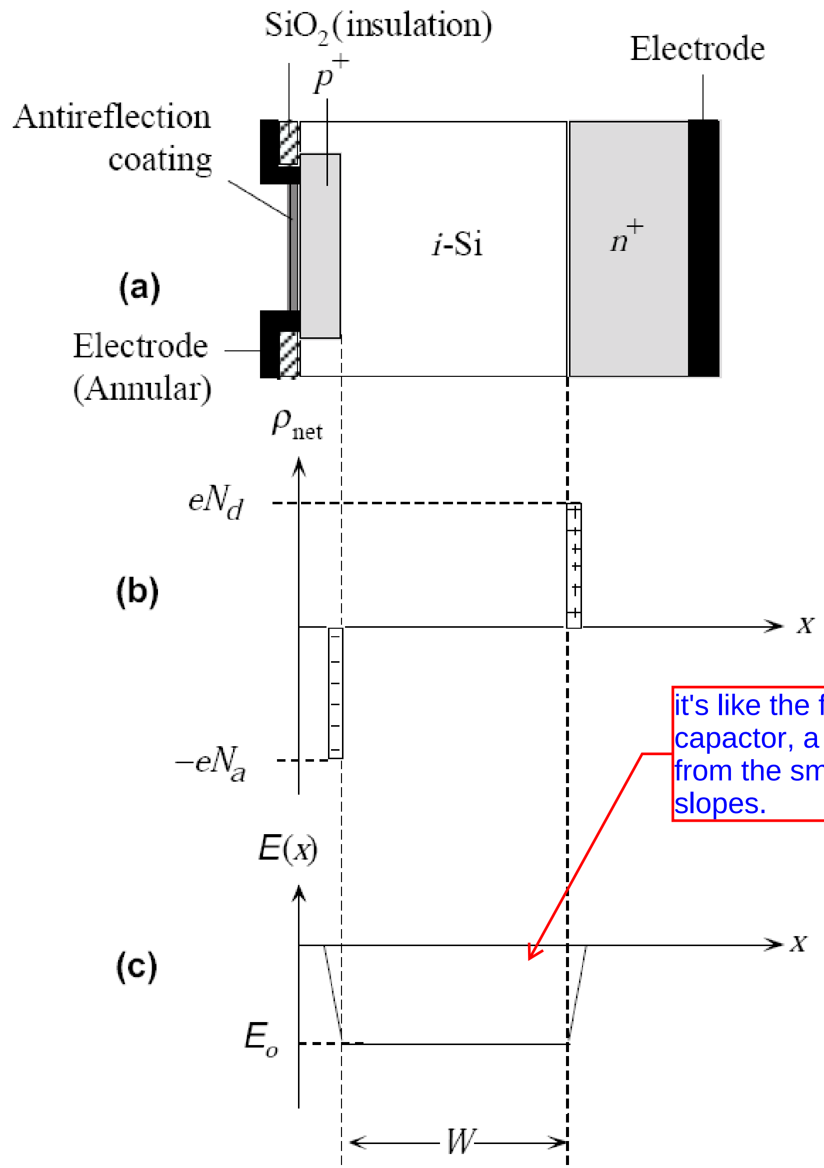
In this photodiode the thickness of the intrinsic material is much greater than that of the p+ and n+ regions (5-50 μm)

This structure creates two thin zones of opposite charge in the p+ and n+ regions, separated by a region with thickness W in which there is an electric field E_0.
(in the depletion region of a pn junction the electric field is instead not uniform)

Without applied bias, the equilibrium is maintained by the electric field E_0 that prevents the diffusion of the majority charge carriers in the layer of the intrinsic Si.

pin (p-intrinsic-n) photodiode

it's equivalent to have a capacitor, becauase charges accumulate in the two different regions



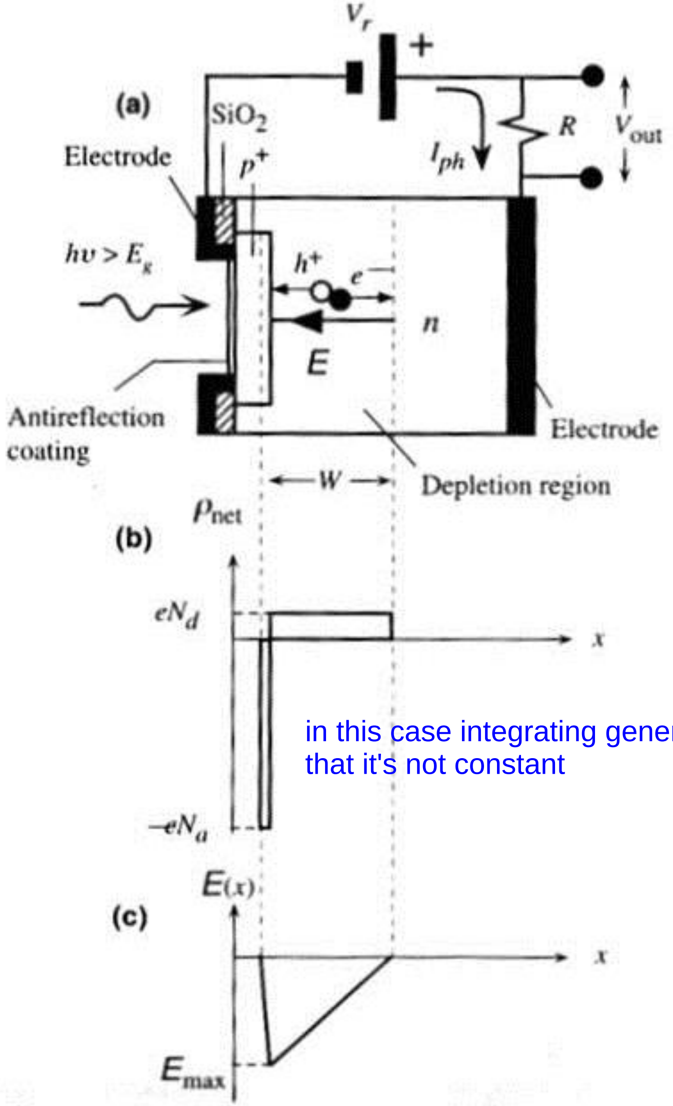
large part and constant elecetric field! So we have fixed our problem.

Net space density charge

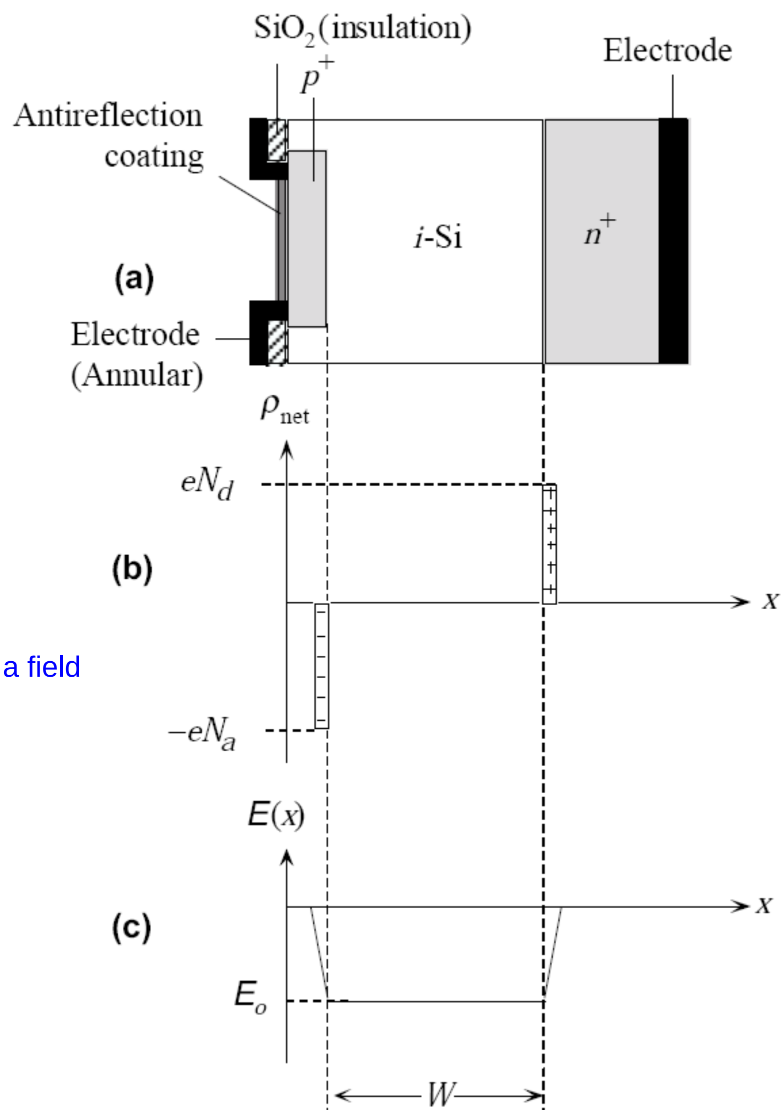
Electric field

it's like the field in a capacitor, a part from the small slopes.

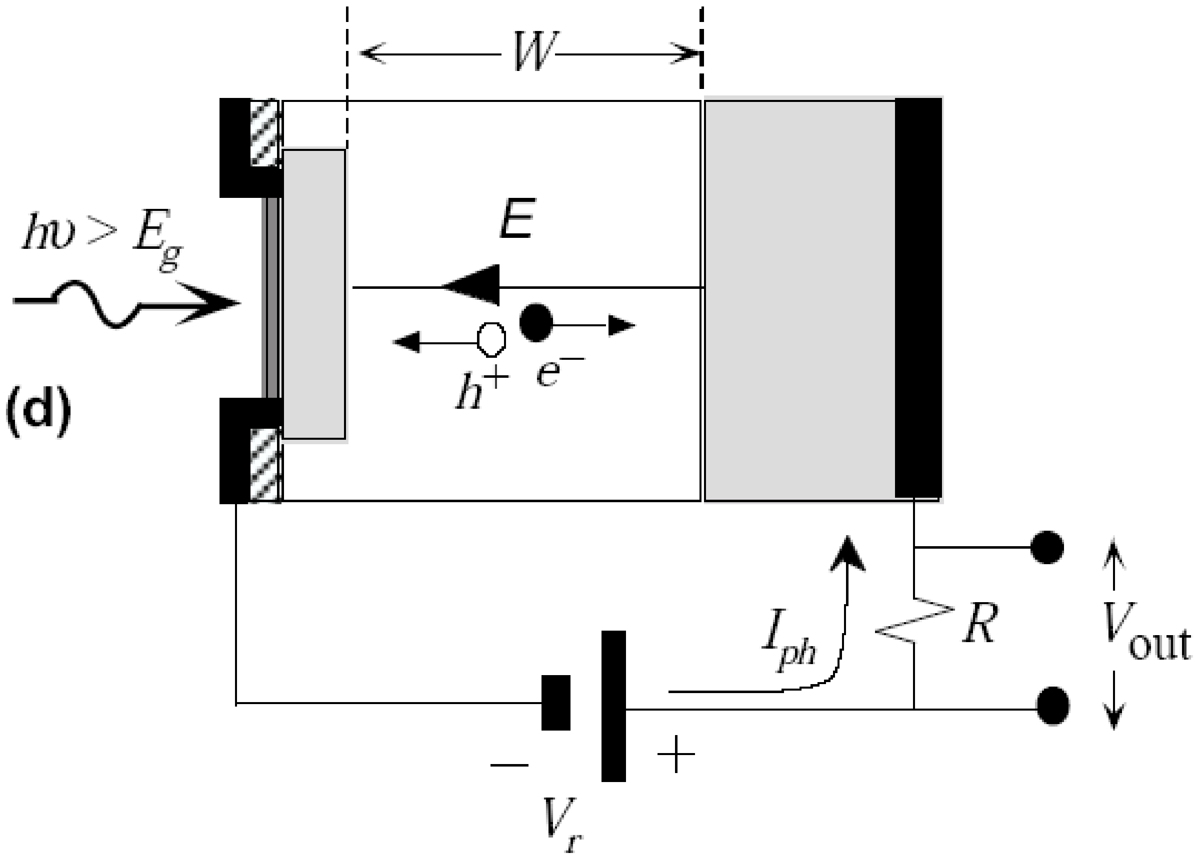
p-n *vs* p-i-n photodiode



in this case integrating generates a field that it's not constant



reversed biased pin photodiode



pin (p-intrinsic-n) photodiode

The junction capacity

$$C_j = \frac{\varepsilon_0 \varepsilon_r A}{W}$$

Does not depend on the applied electric field.

It becomes constant and the area is the area of the window of the photodiode, and W is the thickness (intrinsic region of the substrate)

The structure of the pin photodiode is done in a way to allow the absorption of the photon in the layer of the intrinsic Si.

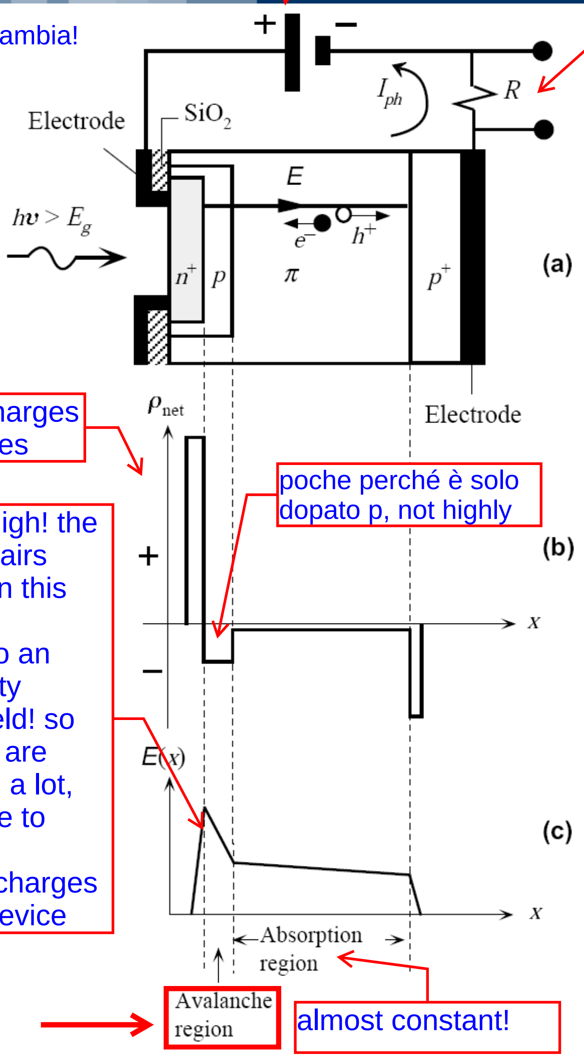
Avalanche photodiode (APD)

the signal is somehow amplified

si girano n e p quindi anche questo :)

Il dopaggio cambia!

this is working in the potoconductive mode



how the charges accumulates

poche perché è solo dopato p, not highly

peak very high! the electronic pairs generated in this region are submitted to an high intensity electrical field! so the carriers are accelerated a lot, and are able to produce a secondary charges within the device

almost constant!

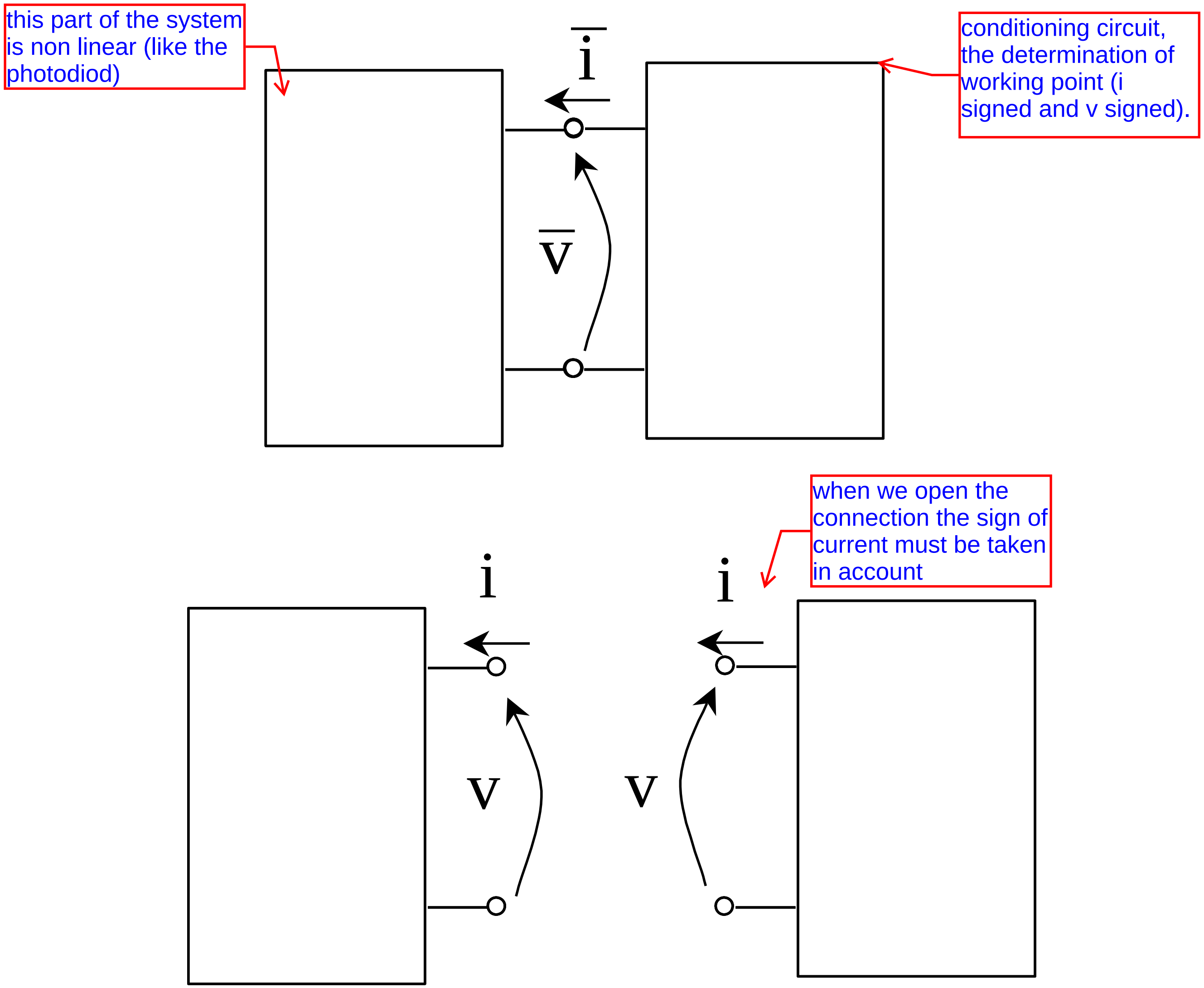
(a) A schematic illustration of the structure of an avalanche photodiode (APD) biased for avalanche gain. (b) The net space charge density across the photodiode. (c) The field across the diode and the identification of absorption and multiplication regions.

The avalanche photodiodes are named so because if a reverse bias is applied to the p-n junction and a **high-intensity field** is formed with the depletion layer, photon carriers will be **accelerated by the field** and collide with the atoms, producing the **secondary carriers**. In turn, the new carriers are accelerated again, resulting in the extremely fast avalanche-type increase in current. Therefore, these diodes work as **amplifiers**, making them useful for detecting extremely **low levels of light**.

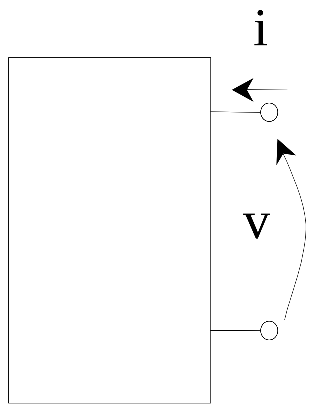
it starts a sort of avalanche phenomenon, where basically you have an amplification in terms of current generated for each single photon entering the device

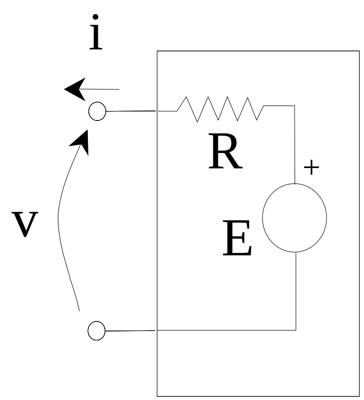
Mode of operation of the photodiode: determination of the working point

how to condition the system



"example"





non linear bipole

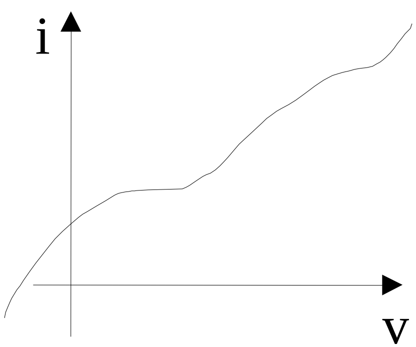
$$i = f(v)$$

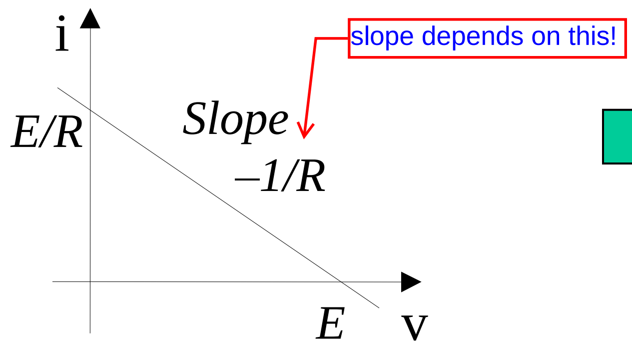
Real voltage generator

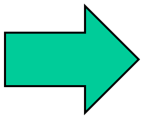
$$v + R \cdot i - E = 0$$

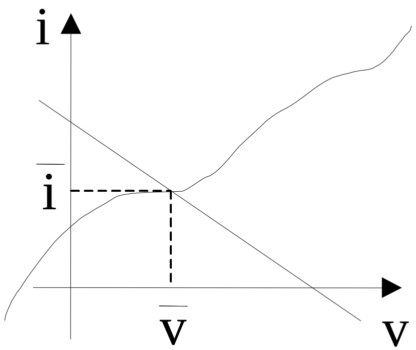
$$i = -1/R \cdot v + E/R$$

overlapping the two characteristics
we obtain the working point

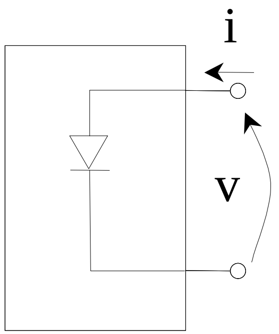


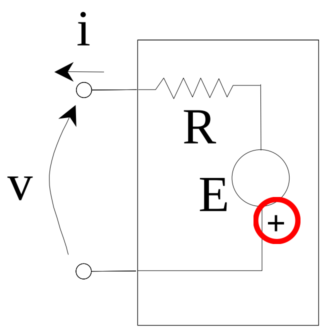






Determination of the working point in a circuit with the photodiode in photoconductive mode



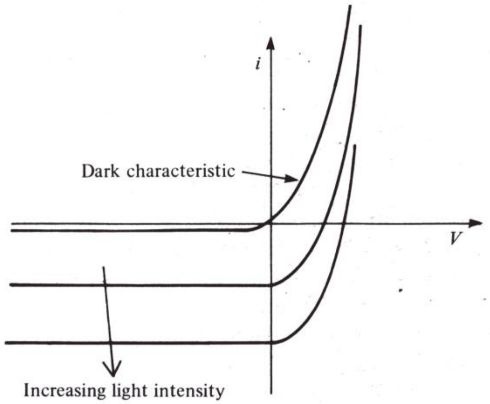


V is a reverse voltage

In this photoconductive mode the working points are the possible intersection, according to the light entering the device

photodiode

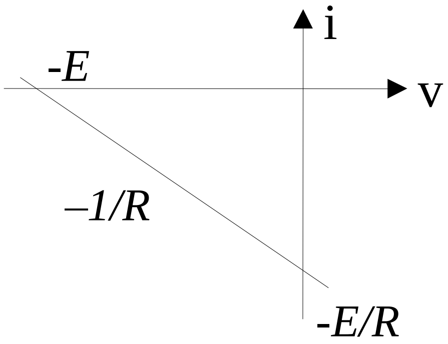
$$i = f(v)$$



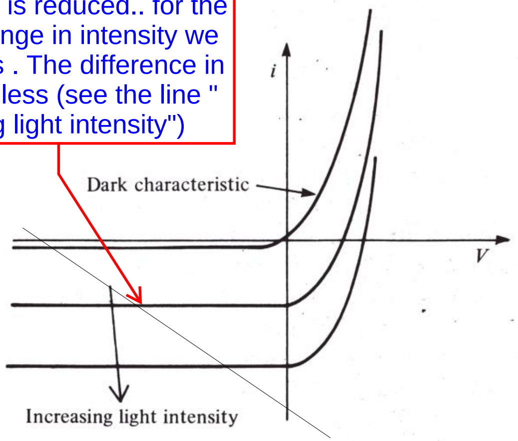
Photoconductive mode

$$v + R \cdot i + E = 0$$

$$i = -1/R \cdot v - E/R$$



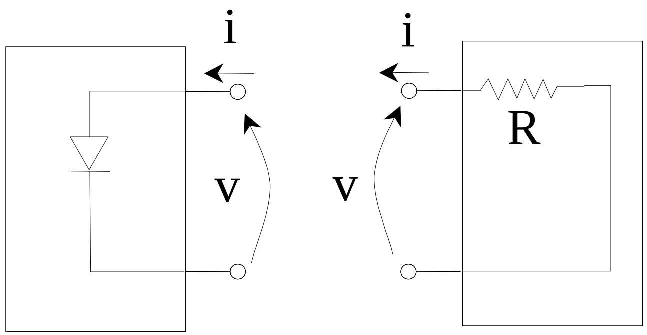
possible working point. Increasing R it's not really a good idea, because the sensitivity is reduced.. for the same change in intensity we move less . The difference in current is less (see the line " increasing light intensity")



Determination of the working point in a circuit with the photodiode in photovoltaic mode

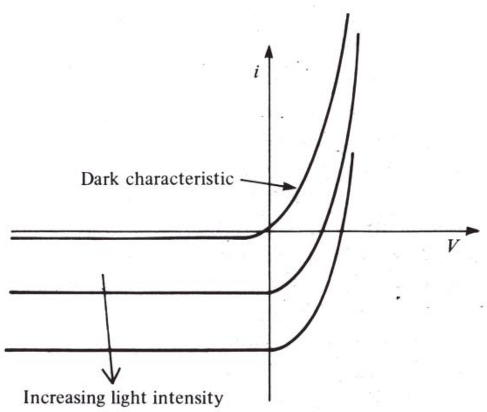
we don't have any voltage supplier!

Iif R increases, the slope becomes lower and lower, for extremely high R (open circuit) we have a horizontal line, it works in "open circuit" mode, as we have seen before. We just read on the device different voltages that depends on different light intensities. If R decreases, it becomes steeper and steeper, thus if we consider the limits (R->0, short circuit). So, vertical line.. it means no more to measure voltages, but it means measuring current that changes because of changing of intensity light.



photodiode

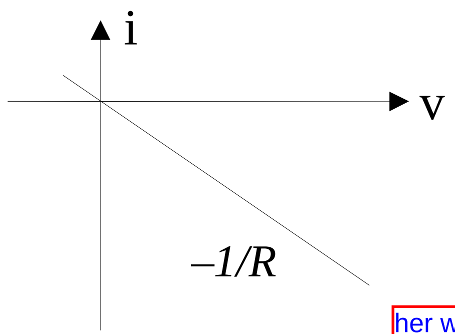
$$i = f(v)$$

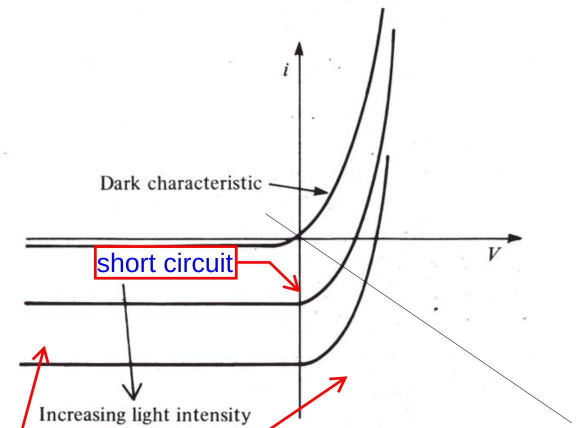


Photovoltaic mode

$$v + R \cdot i = 0$$

$$i = - v / R$$



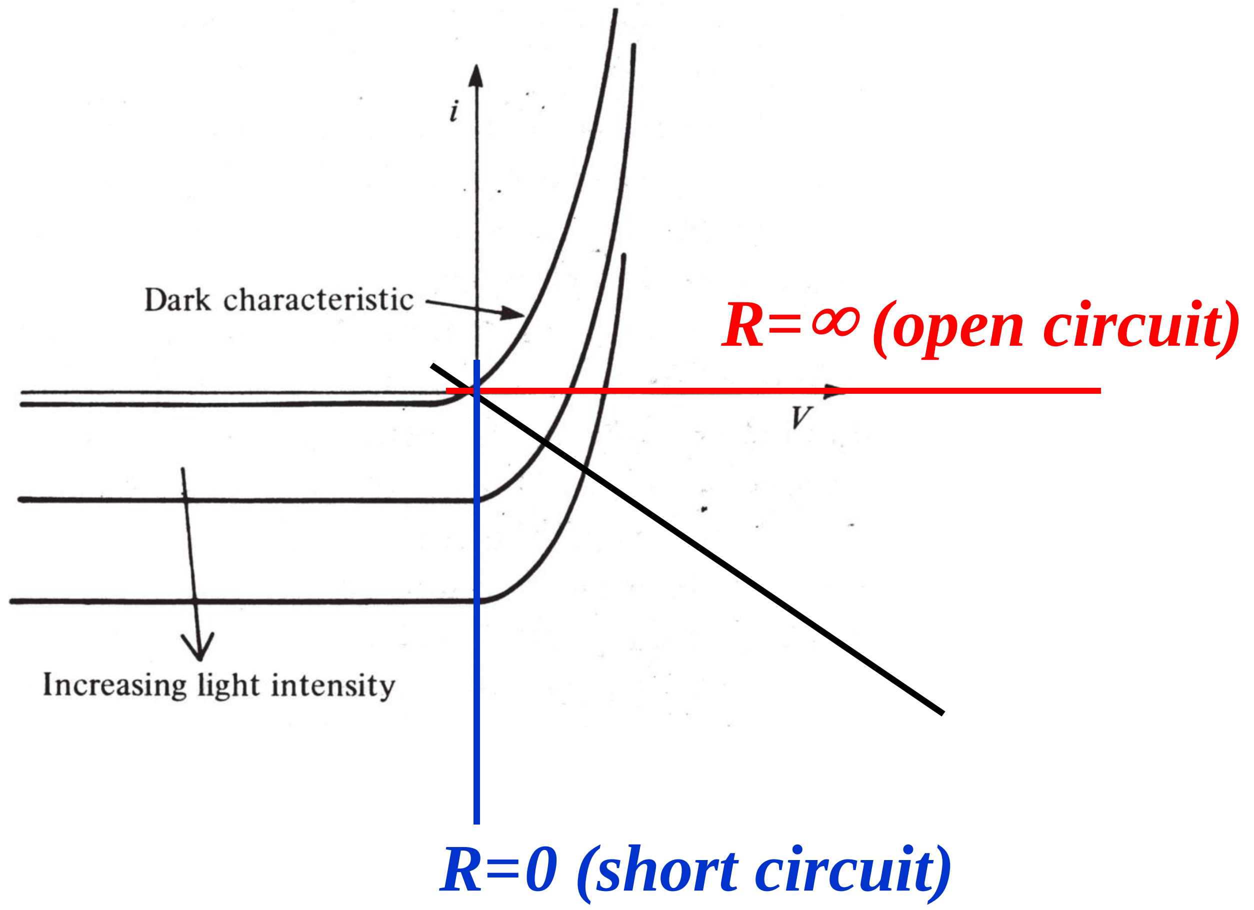


short circuit

her we usually work in photoconductive mode

photovoltaic mode: we work in this region (the 4°)

Photovoltaic mode at open circuit and short circuit



Photovoltaic mode

- high R

  High sensitivity

  low linear dynamic range

  (voltage)

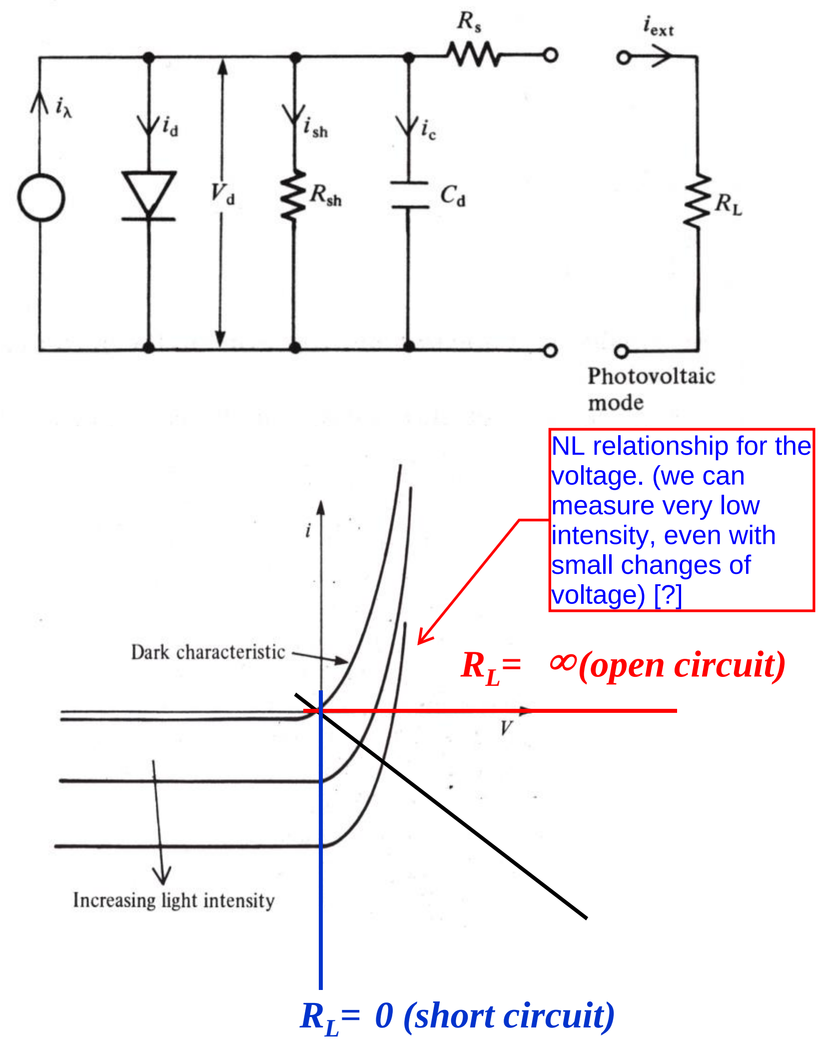
  (high logaritmic dynamic range)

- low R

  Low sensitivity

  high linear dynamic range

  (voltage)



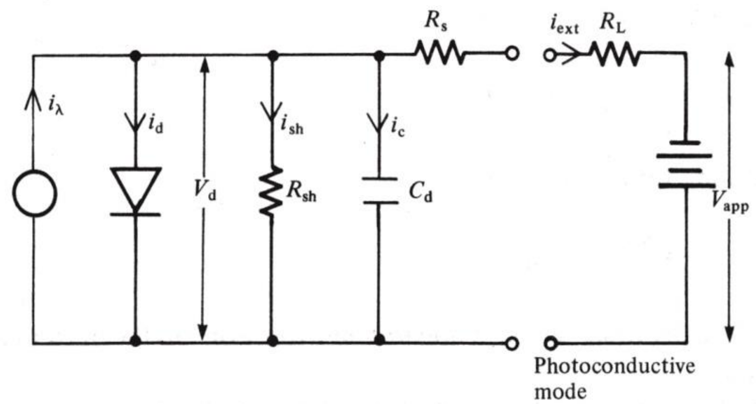
Photoconductive mode

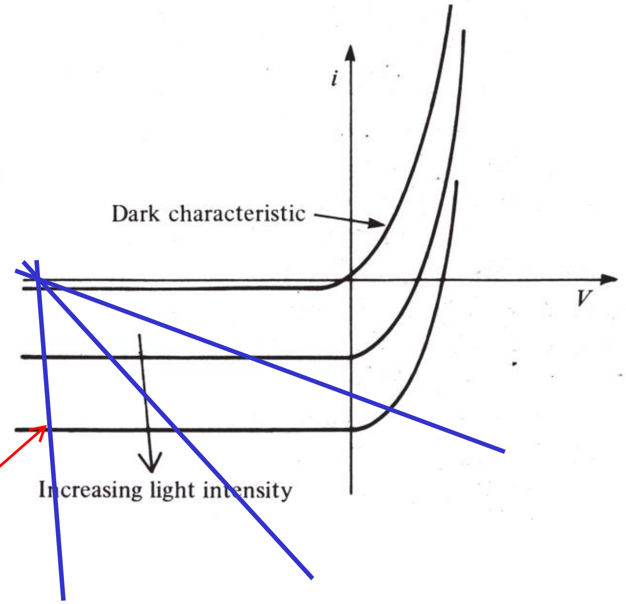
- high R

  High sensitivity
  low linear dynamic range
  (voltage)

- low R

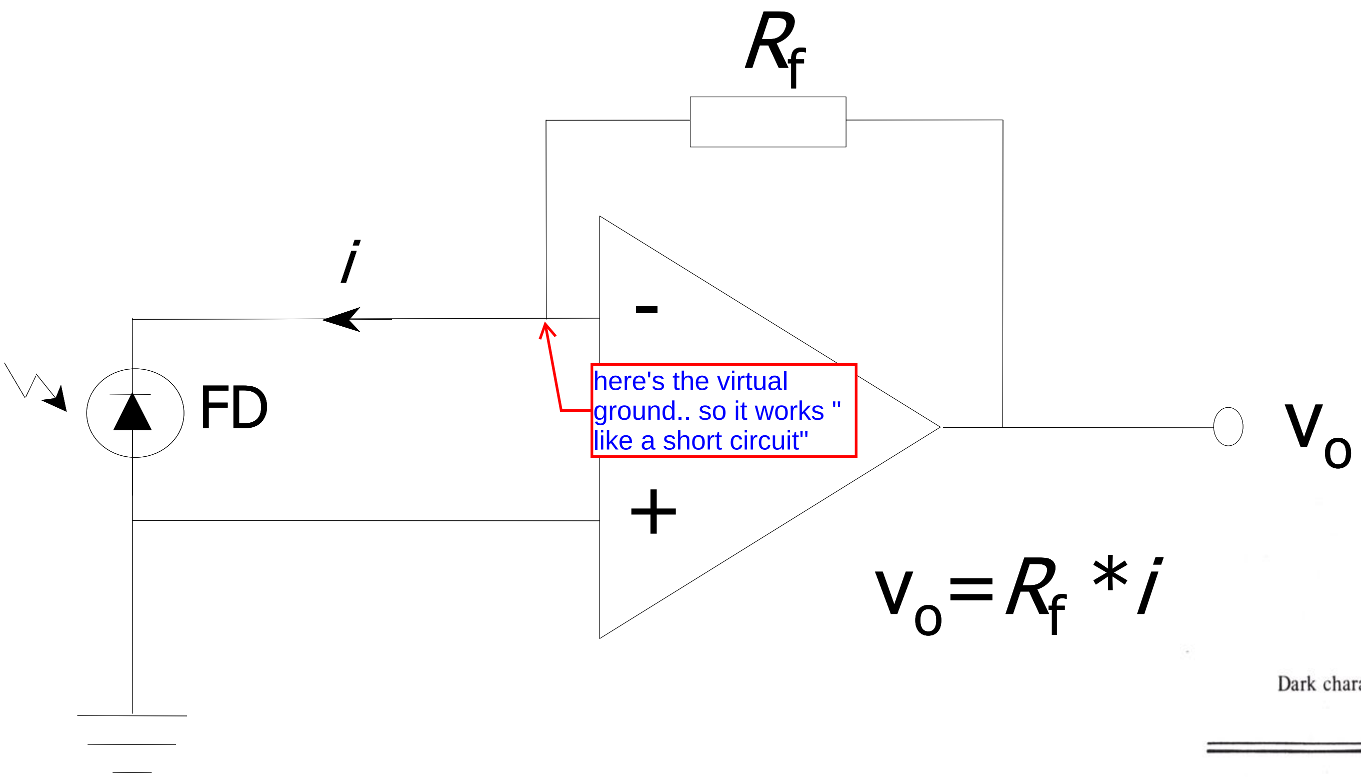
  Low sensitivity
  high linear dynamic range
  (voltage)



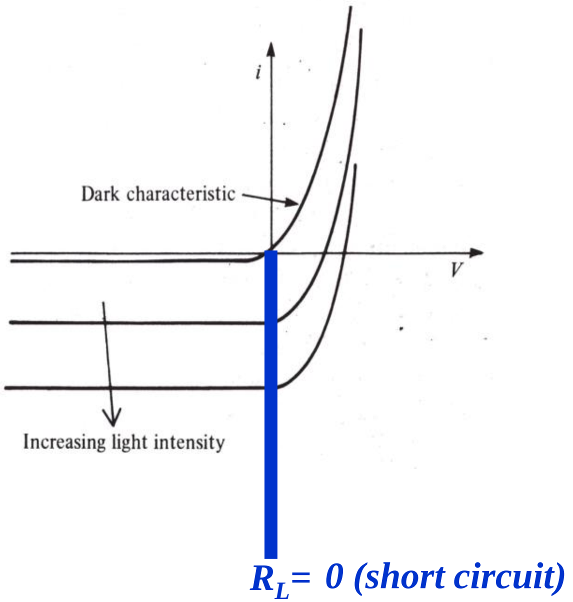


lower sensitivty in voltage, but higher sensitivty in current

Photovoltaic mode (short circuit)

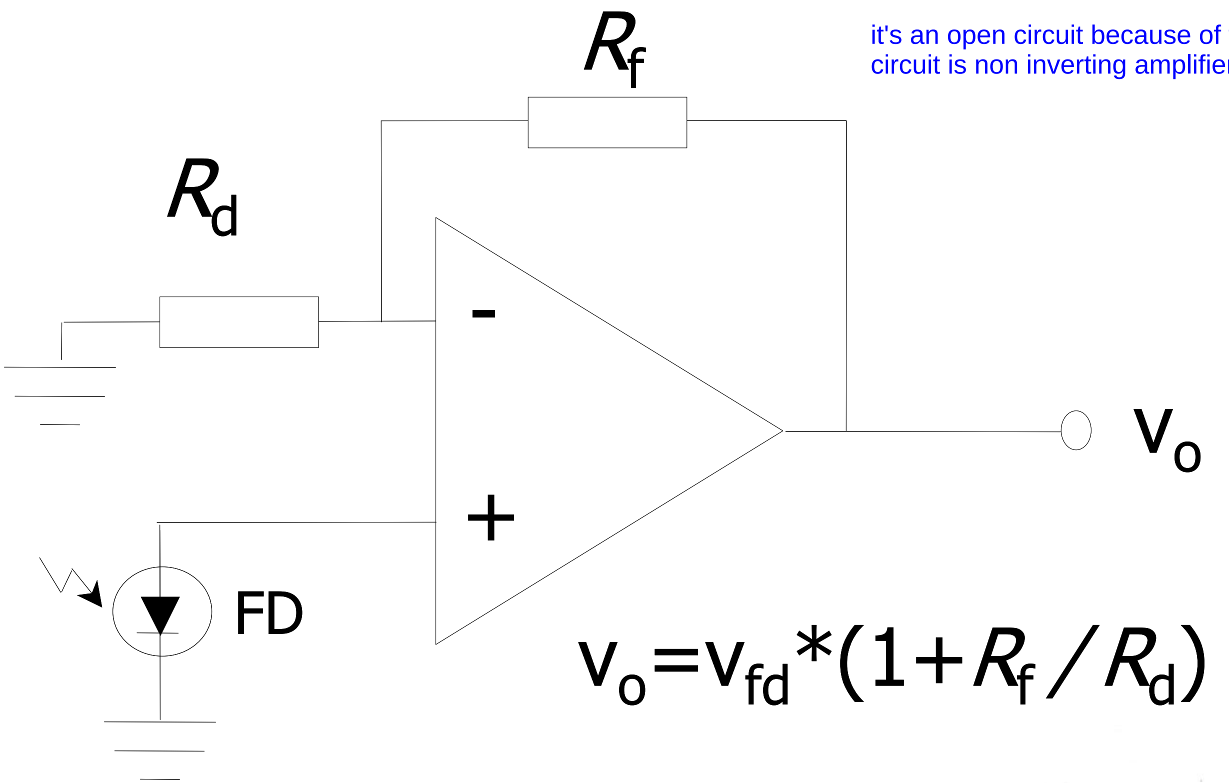


$$V_o = R_f * i$$

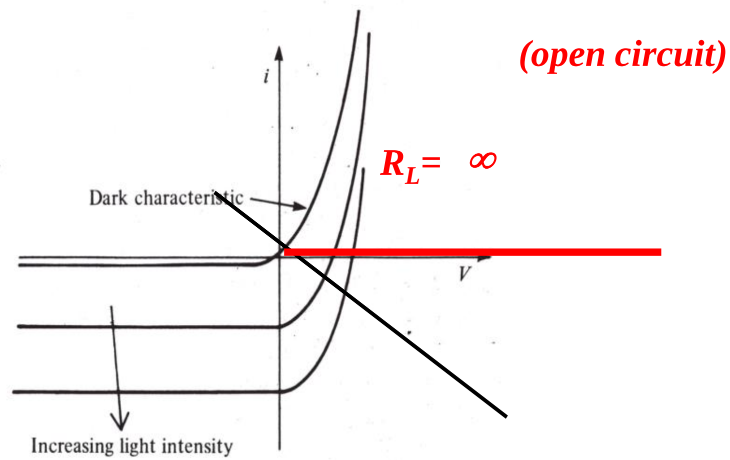


Photovoltaic mode (open circuit)

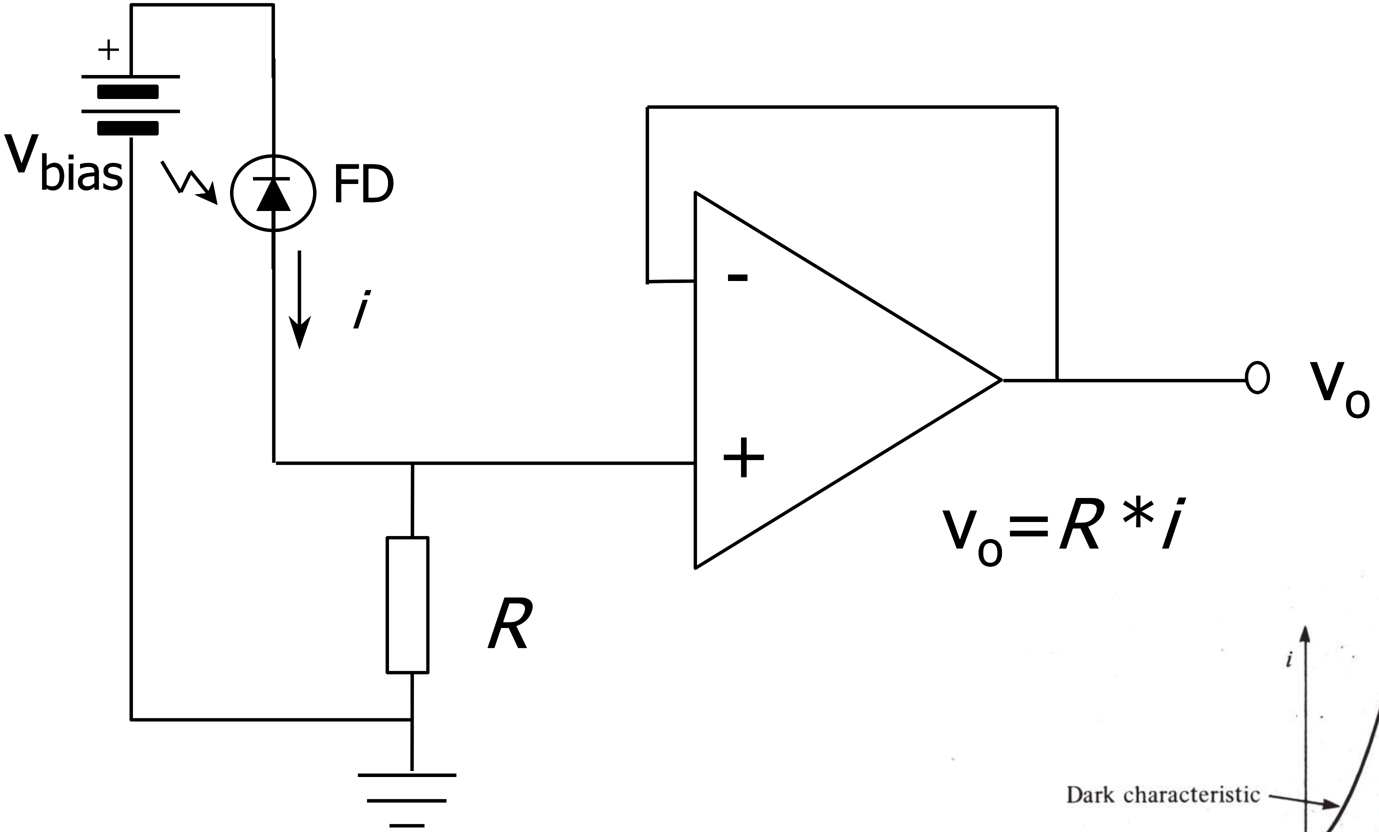
it's an open circuit because of the "infinite" resistance, with 0 amperes. This circuit is non inverting amplifier

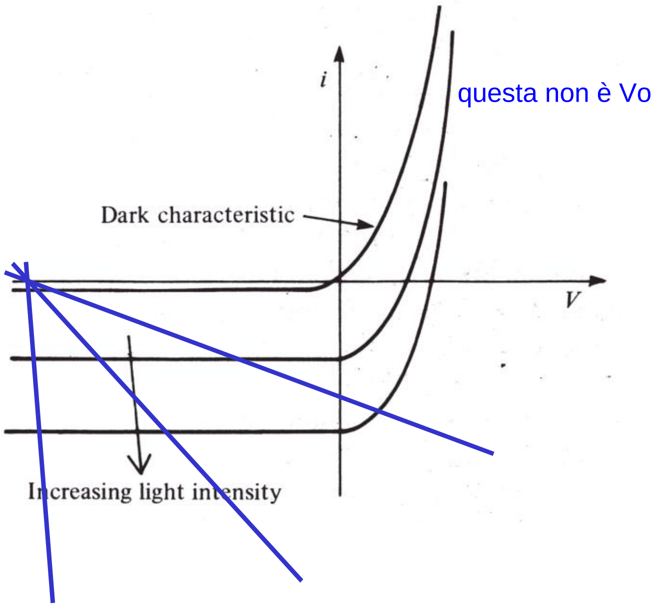


$$v_o = v_{fd} * (1 + R_f / R_d)$$



Photoconductive mode

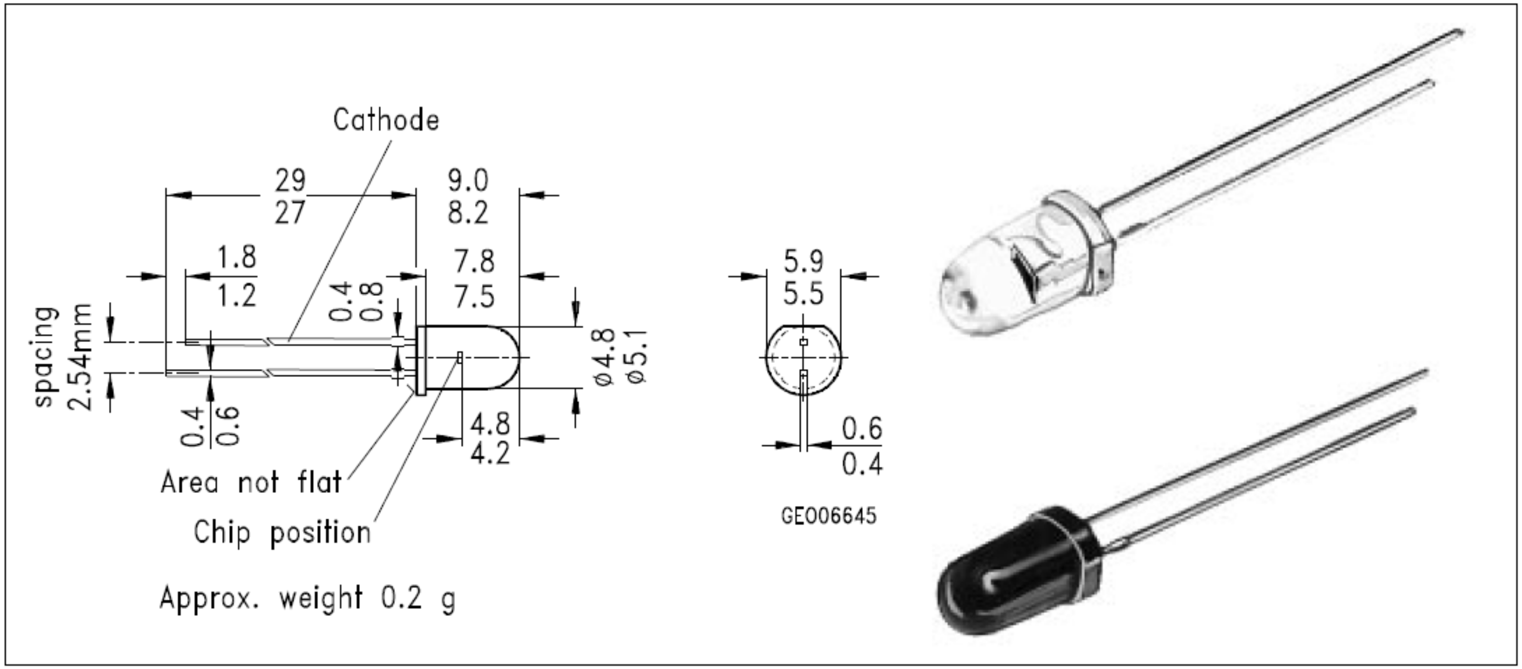




SIEMENS

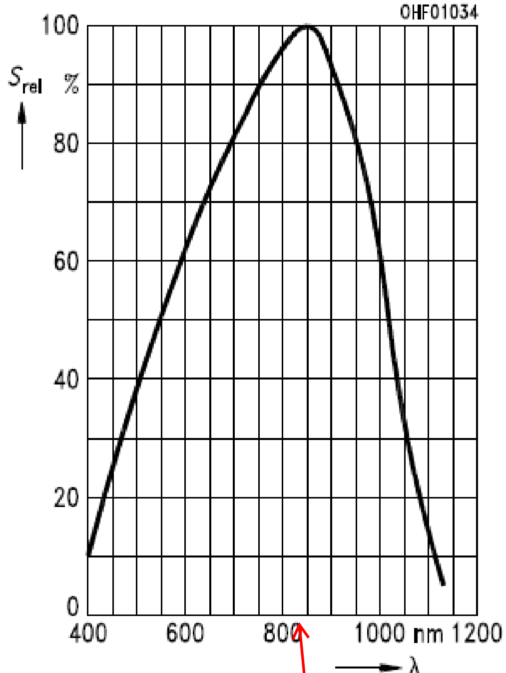
Silizium-PIN-Fotodiode mit sehr kurzer Schaltzeit **SFH 2030**
Silizium-PIN-Fotodiode mit Tageslichtsperrfilter **SFH 2030 F**

Silicon PIN Photodiode with Very Short Switching Time
Silicon PIN Photodiode with Daylight Filter



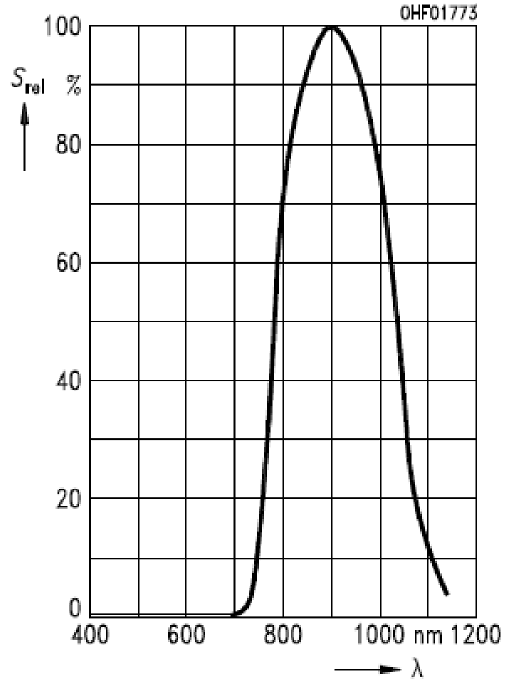
fixed voltage, how does the current changes with change in light

Relative spectral sensitivity SFH 2030
$S_{rel} = f\ (\lambda)$



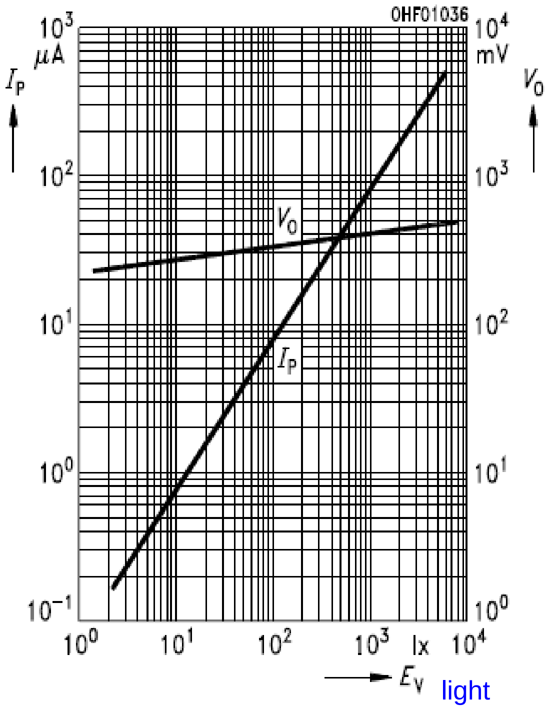
maximum sensitivity, at 800nm is NIF

Relative spectral sensitivity SFH 2030 F
$S_{rel} = f\ (\lambda)$



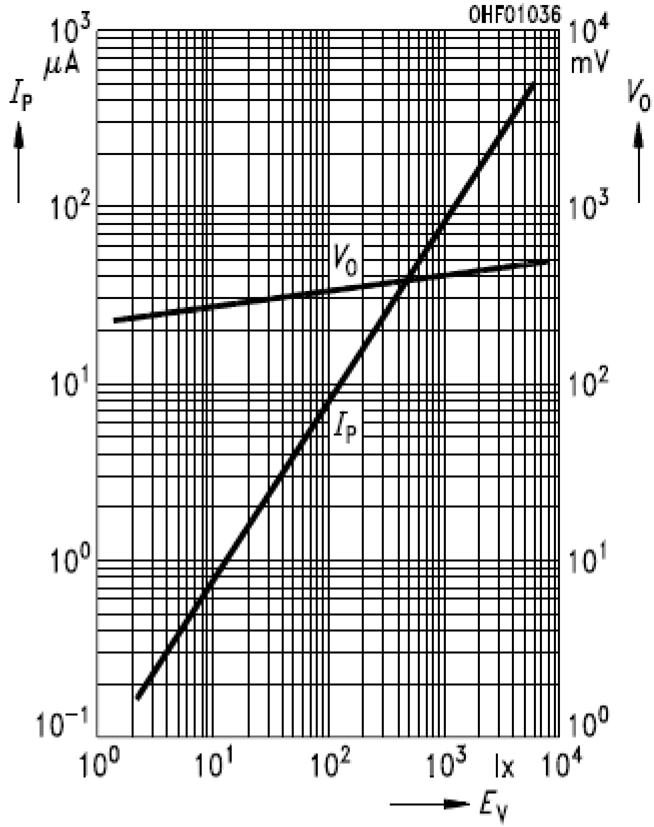
Photocurrent $I_P = f\ (E_V)$, V_R = 5 V
Open-circuit-voltage $V_L = f\ (E_V)$
SFH 2030

how voltage varies as a function of light

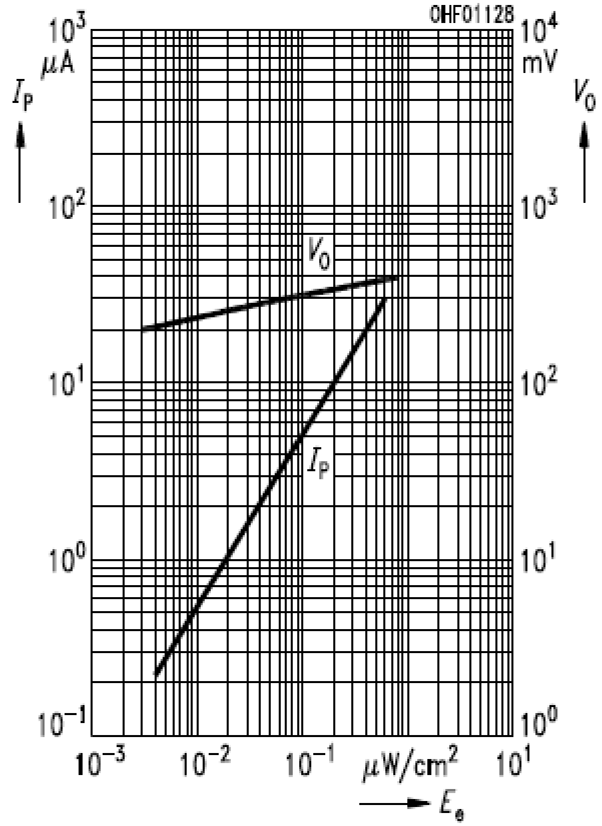


light (actually power per squared meter)

Photocurrent $I_P = f\ (E_v)$, V_R = 5 V
Open-circuit-voltage $V_L = f\ (E_v)$
SFH 2030



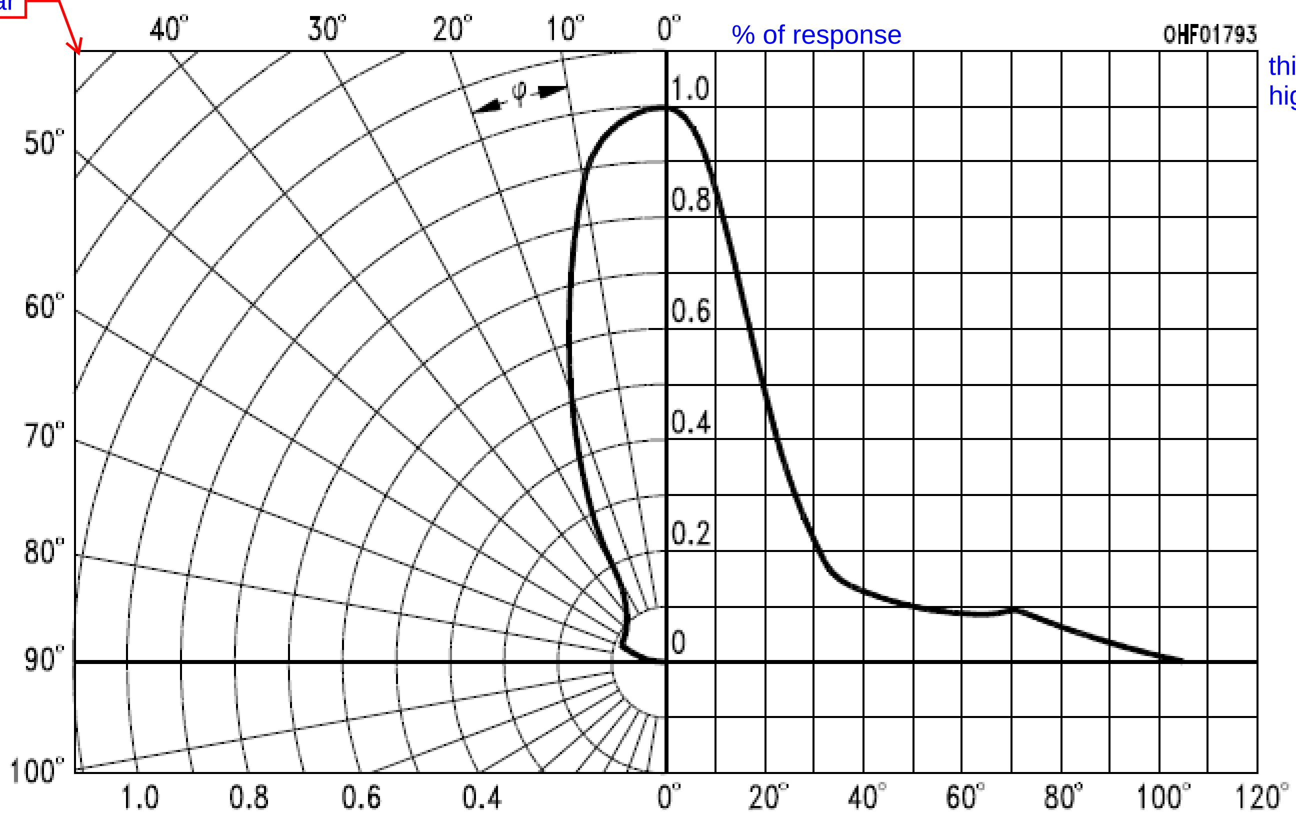
Photocurrent $I_P = f\ (E_e)$, V_R = 5 V
Open-circuit-voltage $V_L = f\ (E_e)$
SFH 2030 F



change in sensor's response depending on the angle of the source

Directional characteristics $S_{rel} = f\ (\varphi)$

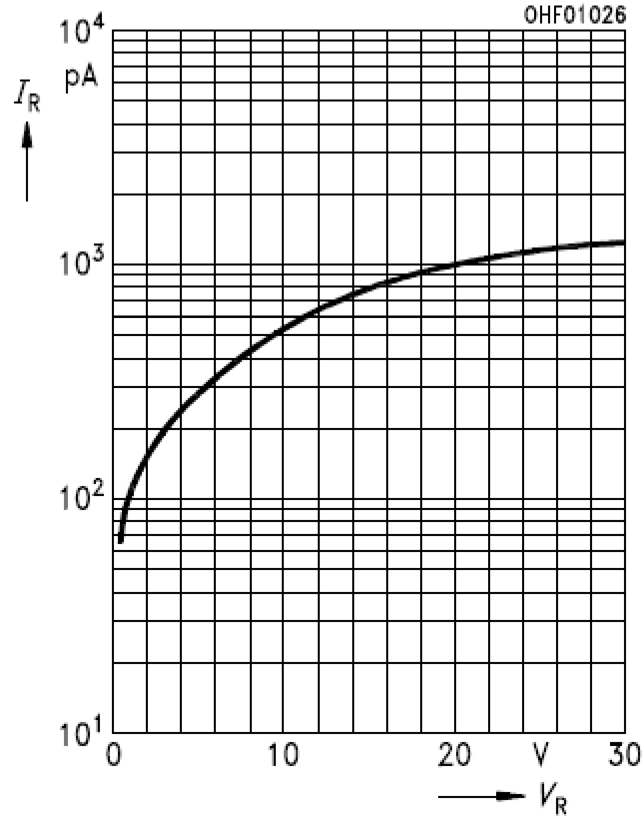
Polar plot, from the radar



this is designed to be highly directional how much is the current when there's no light

Dark current

$I_R = f\ (V_R),\ E = 0$



reverse voltage applied in photoconductive mode (so actually positive means negative, and you move to the left in the V/I curve, the dark current increases) only the idea

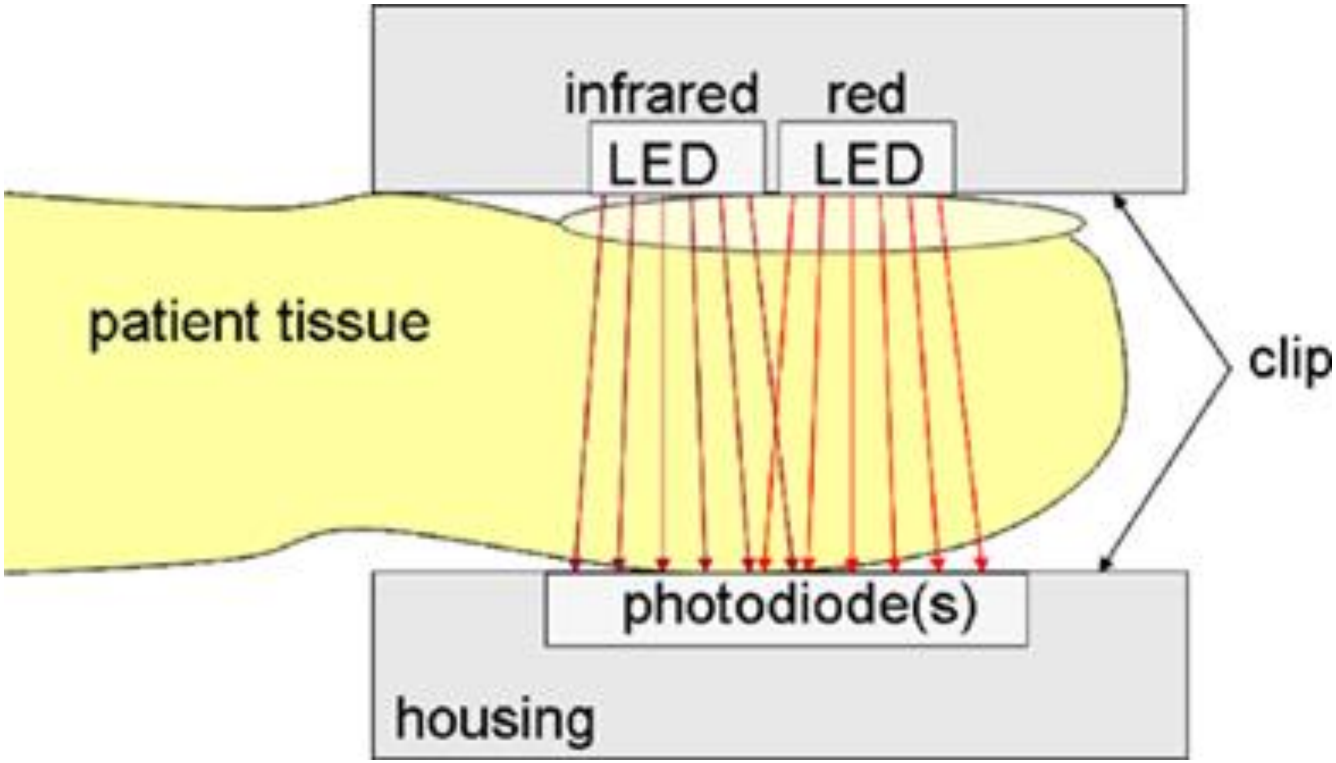
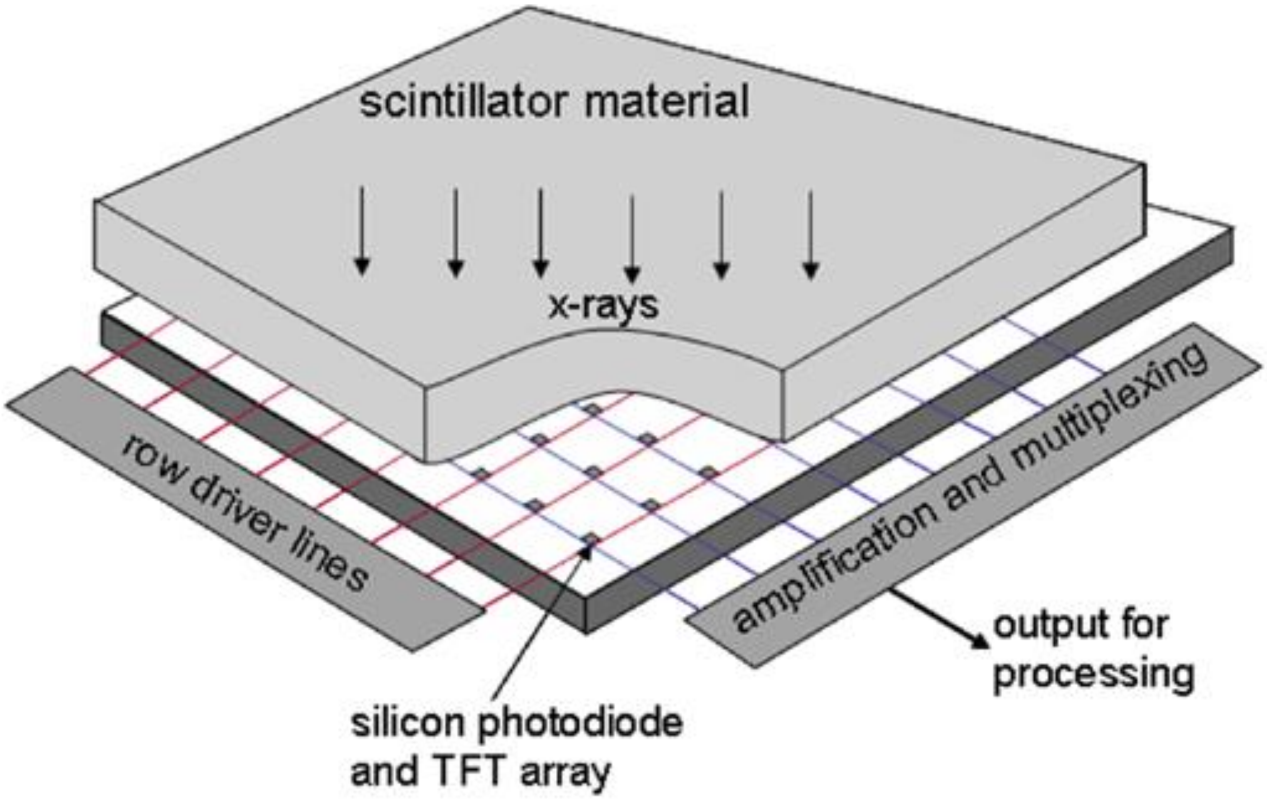


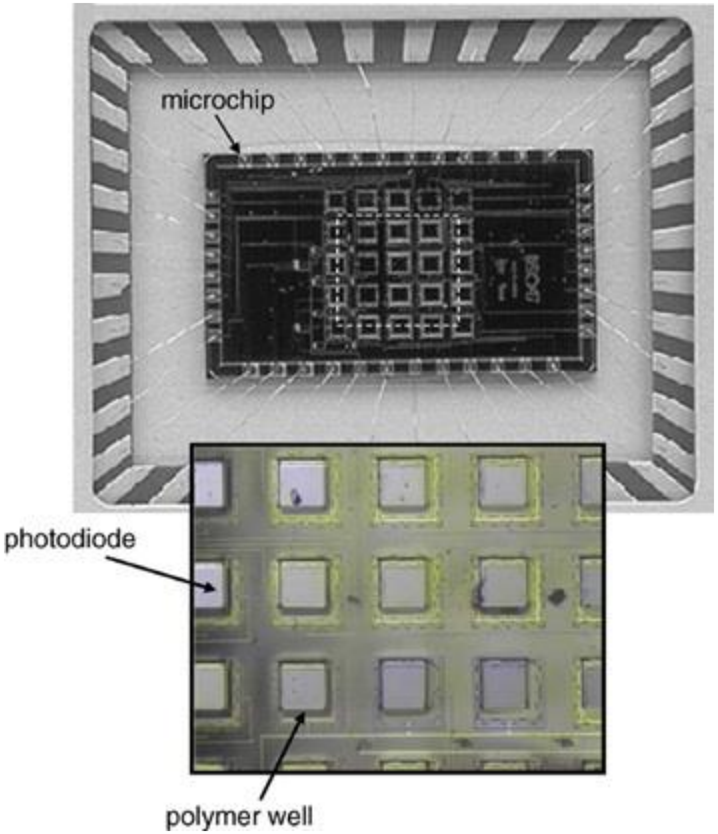
Illustration of pulse oximeter. Blood oxygenation is calculated by determining the ratio of absorption of the red and infrared spectrum caused by the difference in color between oxygen-saturated and unsaturated hemoglobin. The photodiode(s) is used to collect the red and infrared light.

Example of application: x-ray imaging

only the idea



Flat panel x-ray imaging. A scintillating material is necessary to convert the x-rays not absorbed by the target tissue into visible light photons (usually green or blue), which can then be detected by an array of photodiodes. These photodiodes in turn activate pixels (thin-film transistors or TFTs) in another silicon layer that is then coupled to a computer to produce high-quality images of the target.



you have to have very similar sensors and opamps

Integrated high-speed screening microchip. Each nanoliter volume well contains a photodiode at the bottom for fluorescence monitoring of reactions inside the well. The photodiodes are covered by a thin film for filtering out excitation light.

The absorbance is also related to different parameters (optical length, concentration of the susbstance, ..)

Array of photodiodes

very often are used arrays of photodiods instead of alone. several all equal to eachothers, in this case COMMON CATHODE.

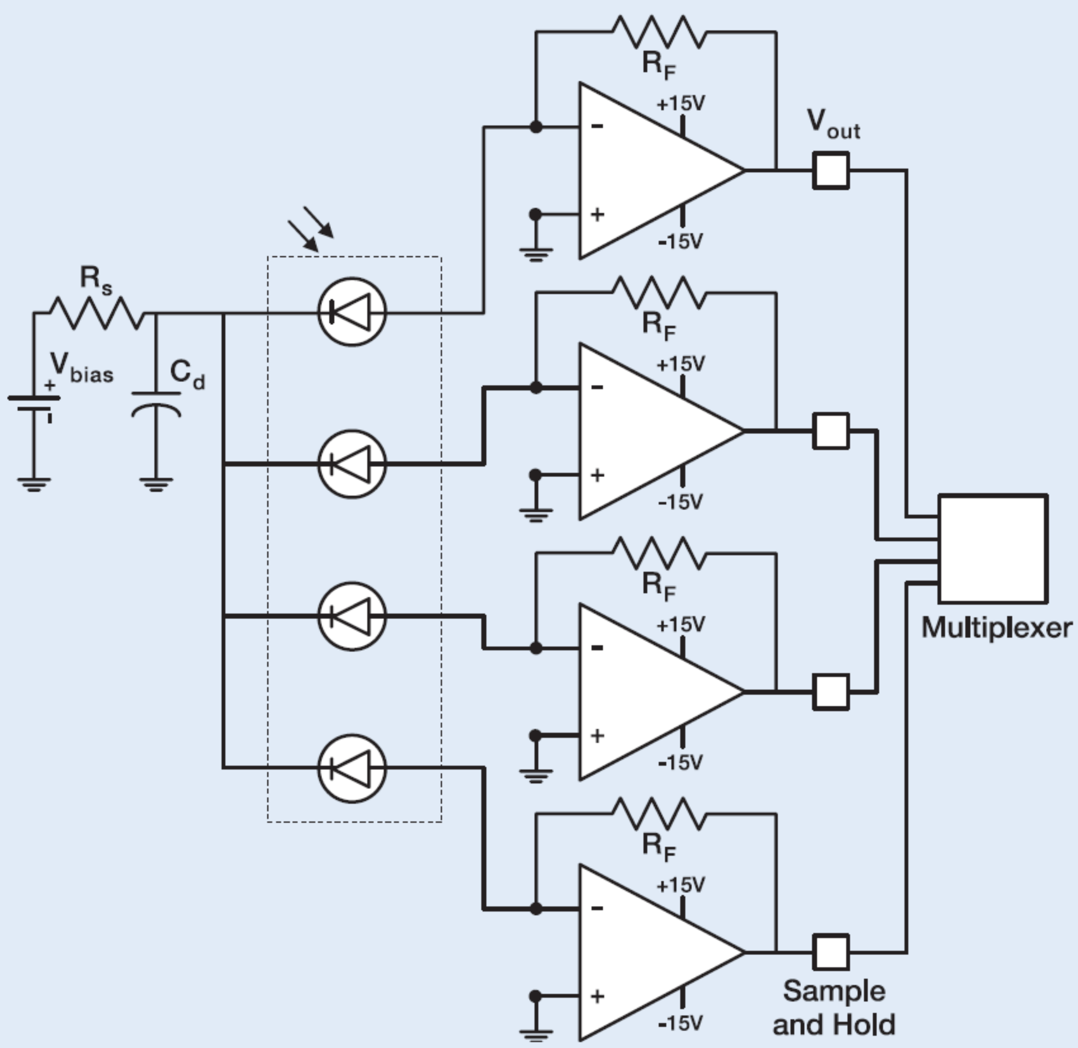


Figure 11. Circuit example for a multi-element, common cathode array

this is photoconductive mode, with a reverse bias, and the signal is A CURRENT signal

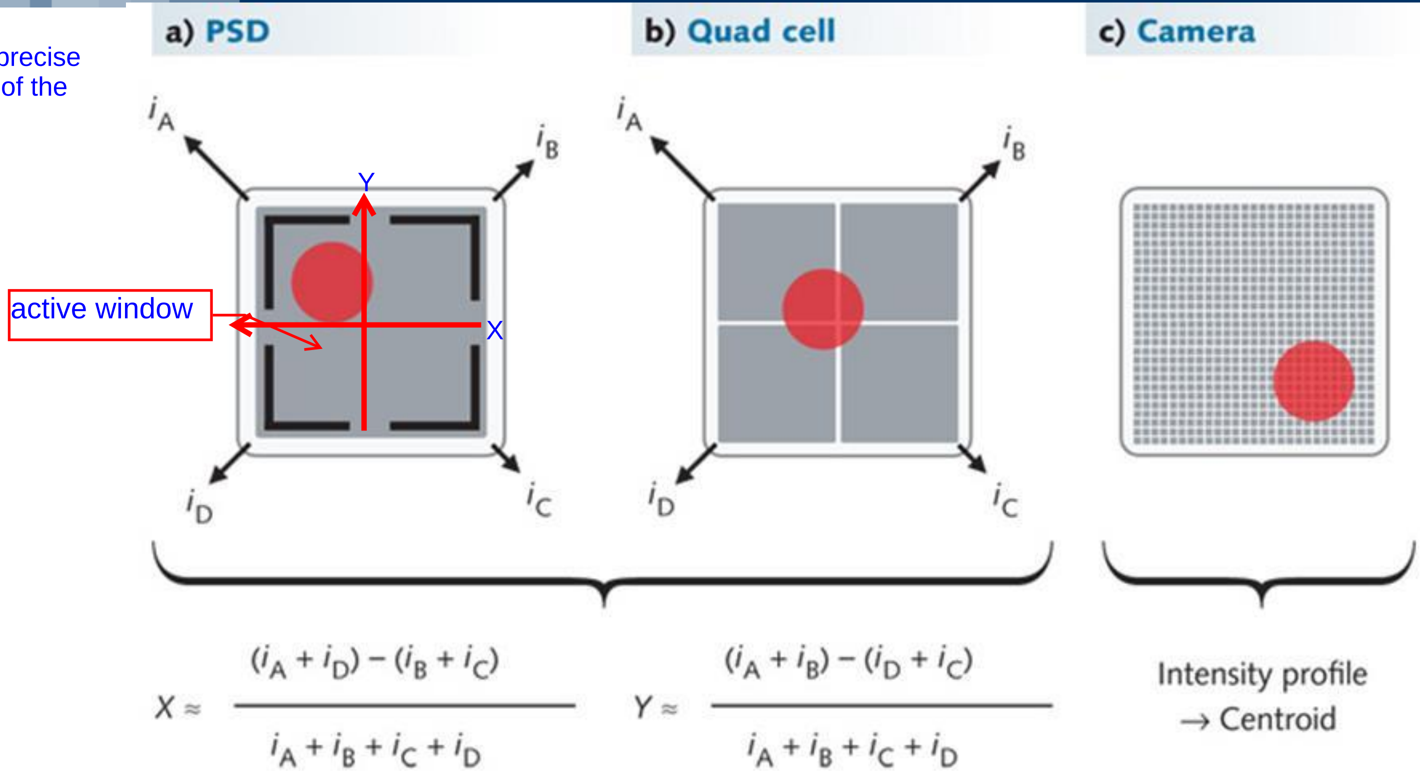
PSD: Position Sensing Detectors

Detectors based on optical sensors, able to measure SMALL displacement, microbending, small displacement of a laser (like in the AFM), alignment!

Optical position sensors, widely referred to as Position Sensing Detectors (PSD) utilize silicon photodetectors as **optical position sensors**. The applications vary from human eye movement monitoring, 3-D modeling of human motion to laser, light source, and mirrors alignment. They are also widely used in ultrafast, accurate auto focusing schemes for a variety of optical systems, such as microscopes, machine tool alignment, vibration analysis and more. Using PSD's, the position of a beam within fractions of microns can be obtained.

PSD: Position Sensing Detectors

This is a very precise measurement of the coordinates



3 typical structure of PSD, the red circle is like a spotlight (still like in the example of AFM). ia, ib, id, ic: 4 electrodes providing the photocurrent signal in a given corner of the device. You have like a common cathode and 4 different anodess displaced in 4 different corners. So if the light is in the center we have signals in 4 different anodes and it's the same. But if the spot is displaced and it's not in the center, could be like in the image at the top left: there's going to be much more current in iA compared to the other 3. There's an asimmetry of the current

Devices for detecting the position of a light source (e.g., laser beam):

a) position-sensitive detector (PSD),
b) quadrant-cell detector (quad cell) the quad cell is formed by 4 different photodiodes
c) CMOS camera. Image sensors. Camera. We have a very high number of image elements (pixel), each element is not exactly a photodiode

The X and Y beam position on both the PSD and quad cell can be calculated from the detectors' current outputs i_A, i_B, i_C, and i_D. The beam position on the camera is determined by finding the beam's centroid.

Quad cell (segmented photodiodes): position calculation

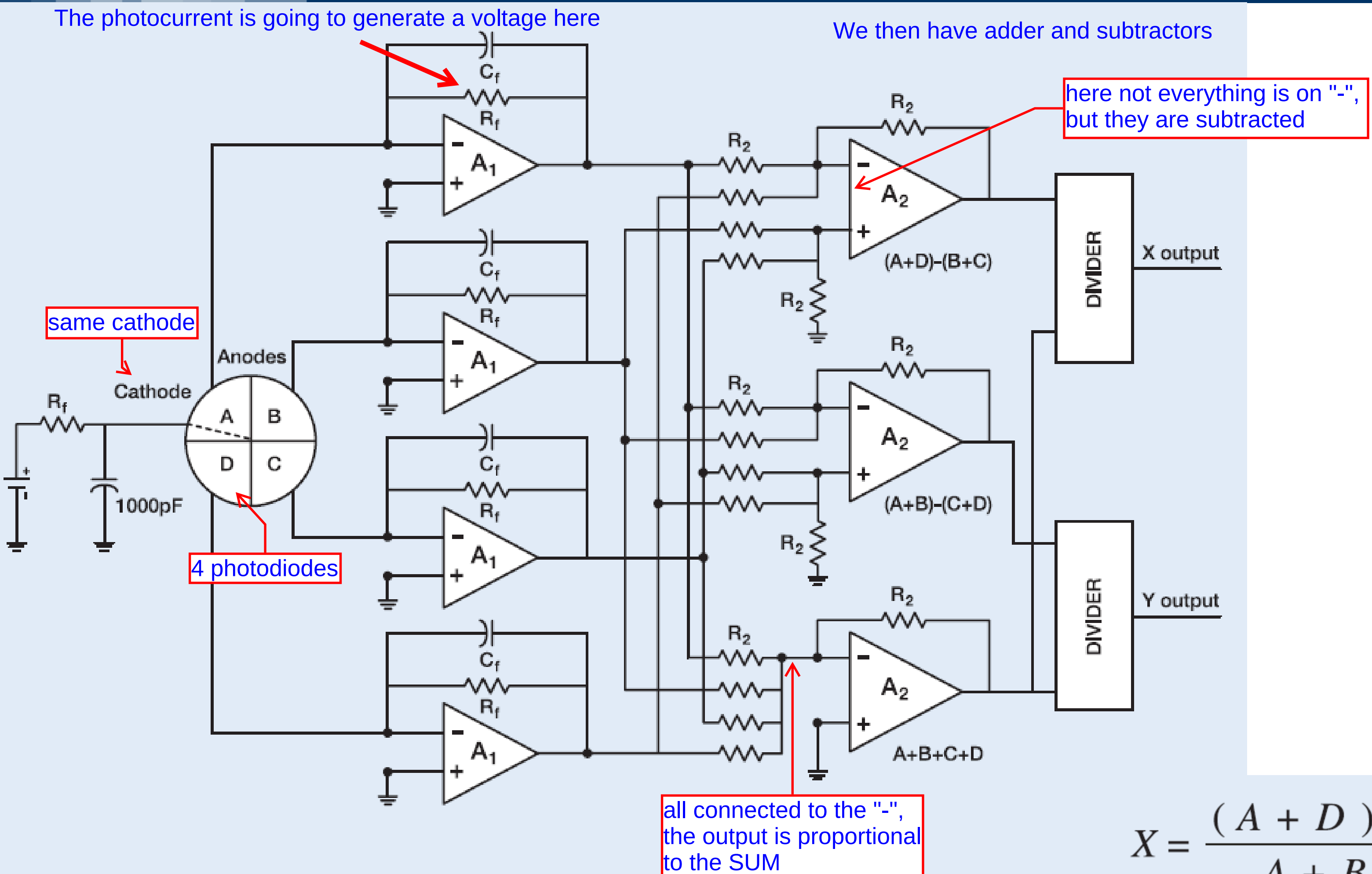
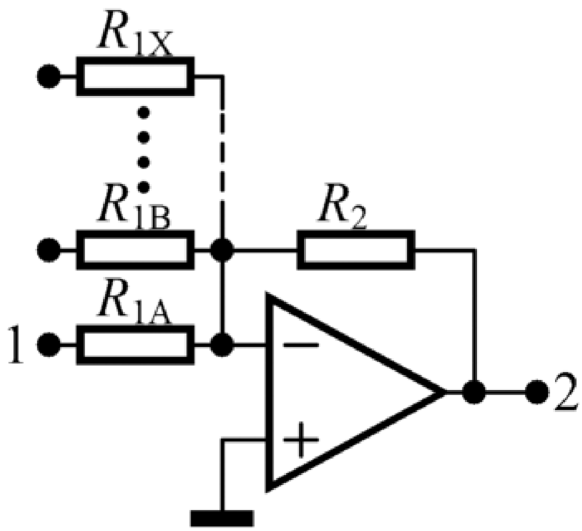


Figure 12. Typical circuit used with segmented photodiodes

$$X = \frac{(A+D)-(B+C)}{A+B+C+D}$$

$$Y = \frac{(A+B)-(C+D)}{A+B+C+D}$$

Summing amplifier



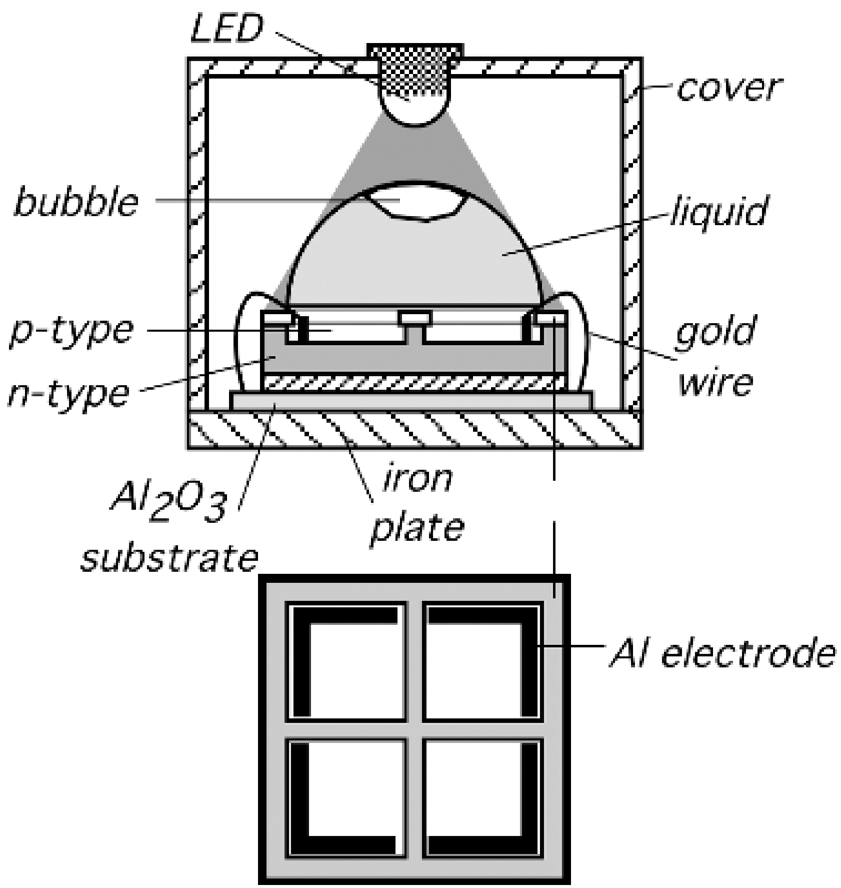
This circuit is able to sum the voltages applied at the input (*summing circuit*). Each applied input voltage V_{ix} contribuites to the output as:

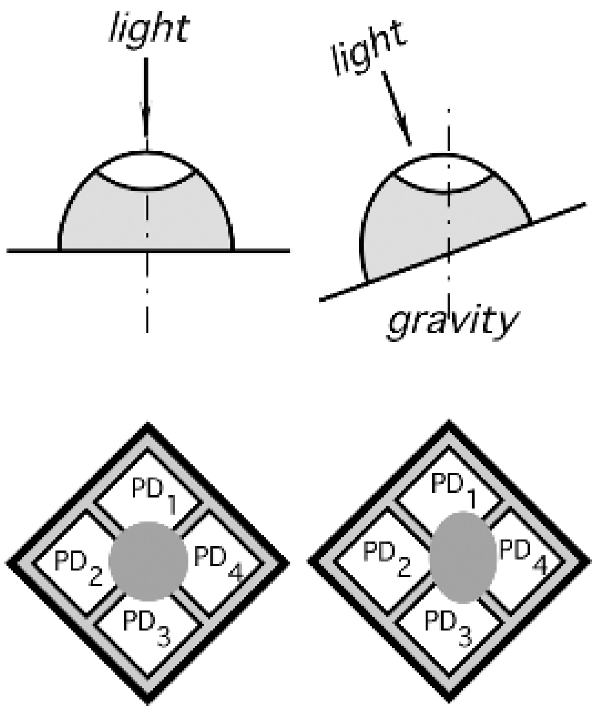
$$V_{ux} = -V_{ix}\frac{R_2}{R_x}$$

Choosing all resistances equal to *R*:

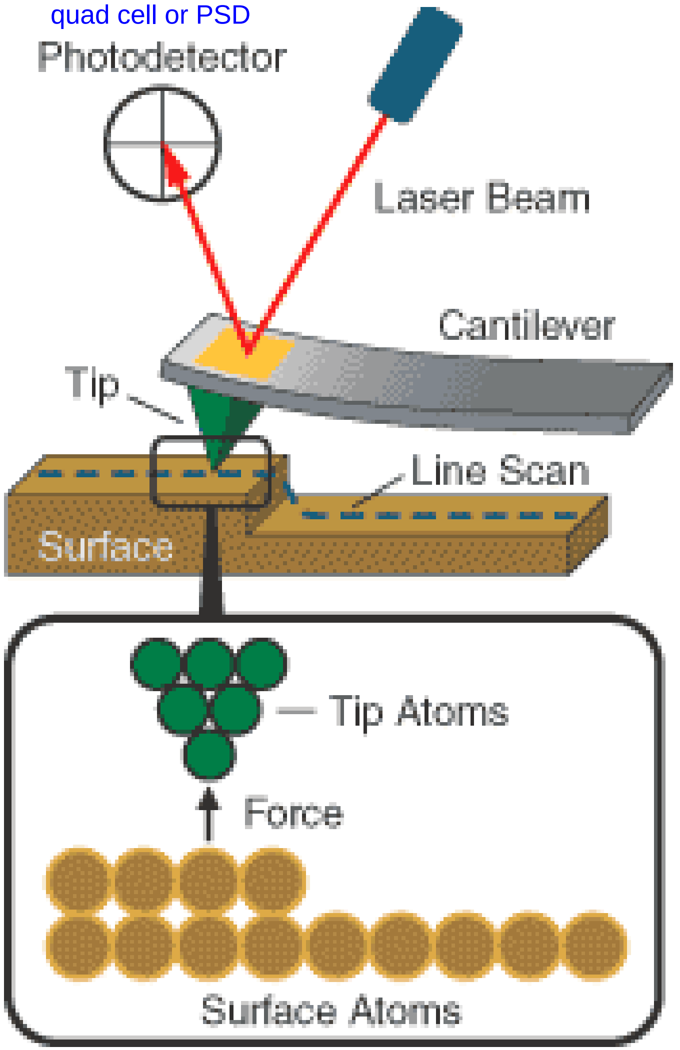
$$V_u = -\frac{V_{ia}R}{R} - \frac{V_{ib}R}{R} \ldots - \frac{V_{ix}R}{R} = -(V_{ia} + V_{ib} \ldots + V_{ix})$$

System to detect the alignment of an object to respect the horizontal plane (in a gravitational system). "Sistema a bolla". If it's not aligned the bubble can create highly asymmetrical current.



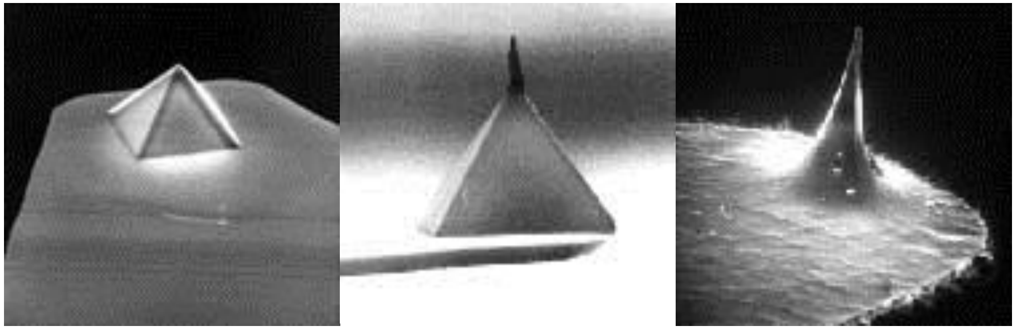


Atomic force microscope (AFM)



http://www.molec.com/what_is_afm.html

- Invented in 1986
- Cantilever
- Tip
- Surface
- Laser
- Multi-segment photodetector



Three common types of AFM tip. (a) normal tip (3 μm tall); (b) supertip; (c) Ultralever (also 3 μm tall).
Electron micrographs by Jean-Paul Revel, Caltech. Tips from Park Scientific Instruments; supertip made by Jean-Paul Revel.

http://stm2.nrl.navy.mil/how-afm/how-afm.html#imaging%20modes no

The AFM was originally designed as an **imaging** tool.
It acquires topographic images by methodically scanning a sample with a flexible probe, called a cantilever, which bends according to the contours of the sample's surface.

The bending of the cantilever is translated into an image map, which reveals the height differences in the surface being scanned.

It is possible to image biological samples under physiological conditions as imaging can be done in both air and liquid. The resulting resolution of such maps is at the atomic level.

Atomic force microscope (AFM)

no

The AFM can also be operated in the **force scan mode**, which allows for the measurement of adhesion forces between receptors and their corresponding binding partners, or ligands.

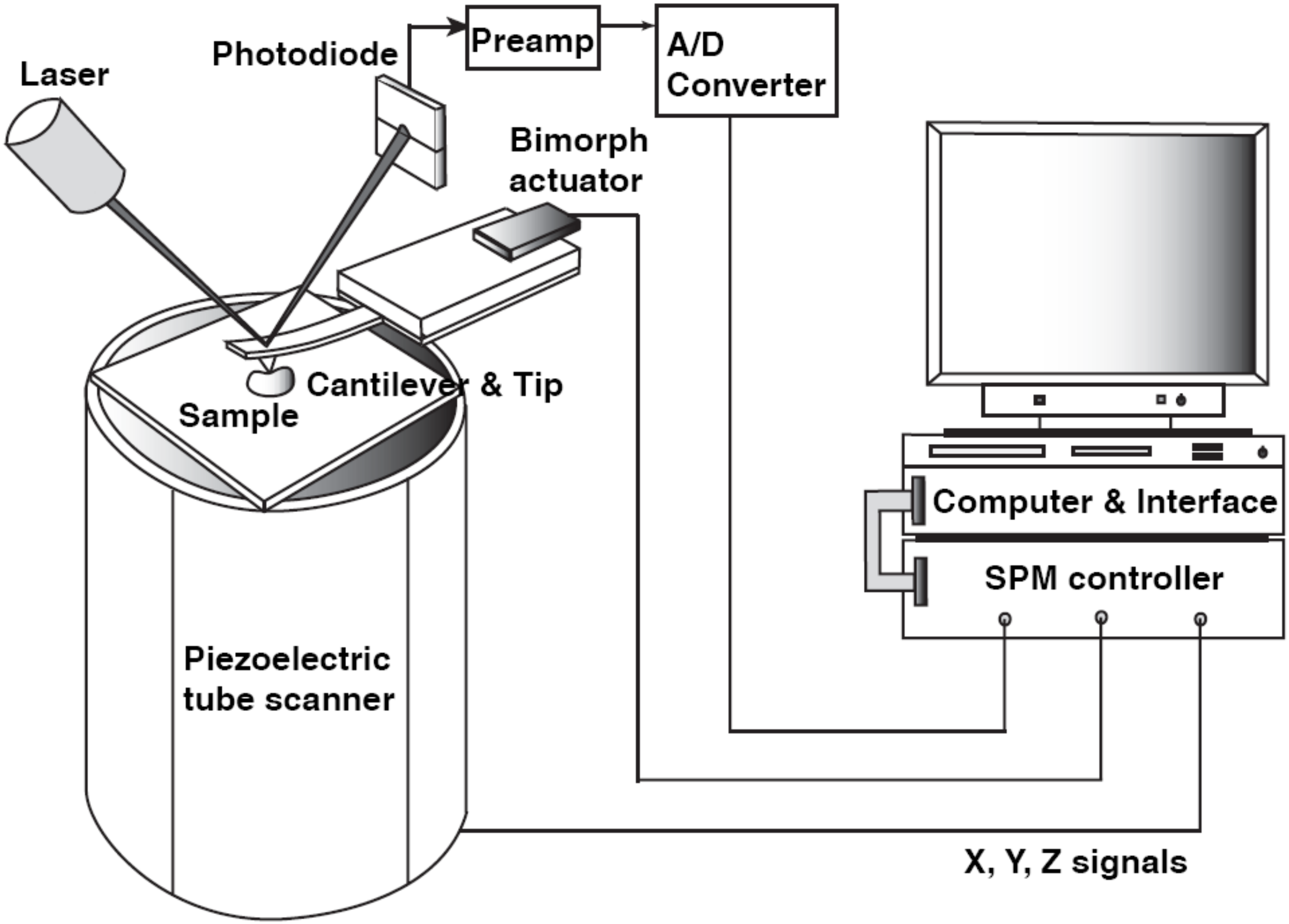
In studies of ligand-receptor forces, the receptor is immobilized on the surface of a flexible AFM cantilever whereas the ligand is attached to a suitable substrate.

The deflection of the cantilever during the approach and withdrawal of the cantilever from the substrate allow for the force of the interaction to be measured.

no

The AFM can also serve as a micro-indenter that probes soft samples, including cells revealing information about their **mechanical properties**.

The mechanical properties of cells play an important role in such essential physiological
processes such as cell migration and cell division.



Schematic illustration of an AFM. A force sensor consists of a flexible cantilever with an extremely sharp tip at its end. A ceramic (Si3N4) or semiconductor (Si) tip on the cantilever can be brought into close proximity to a sample surface. As the tip is close to the sample surface, it either continuously touches or periodically vibrates on the surface, and bends or changes in its vibration amplitude and frequency. A laser spot is reflected off the top of the cantilever. When the cantilever bends, the laser light is deflected onto a two-panel photodiode. The detected signals are amplified and transformed by electronic circuits and sent to an SPM controller. The SPM controller, the computer, and their interfaces generate an image.