POLITECNICO
MILANO 1863

Light sensors

SENSOR SYSTEMS

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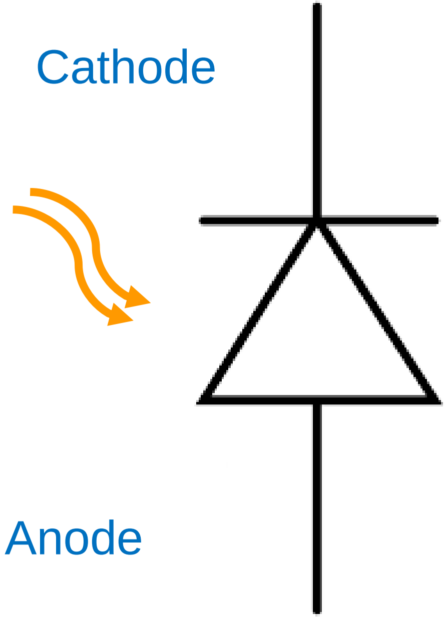
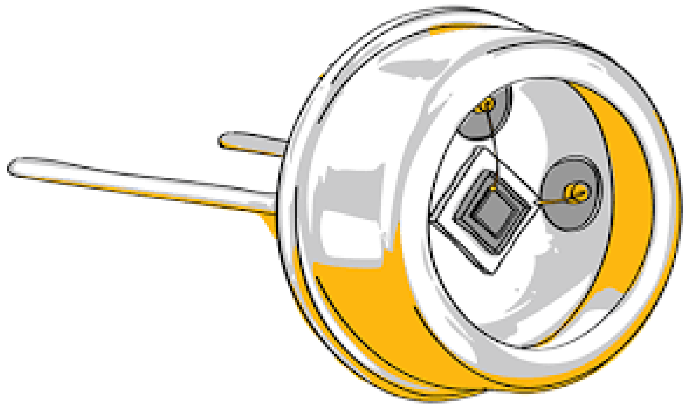
- Photodiode
- APD, SPAD and SiPM
- Light Dependent Resistor (LDR)

Photodiode





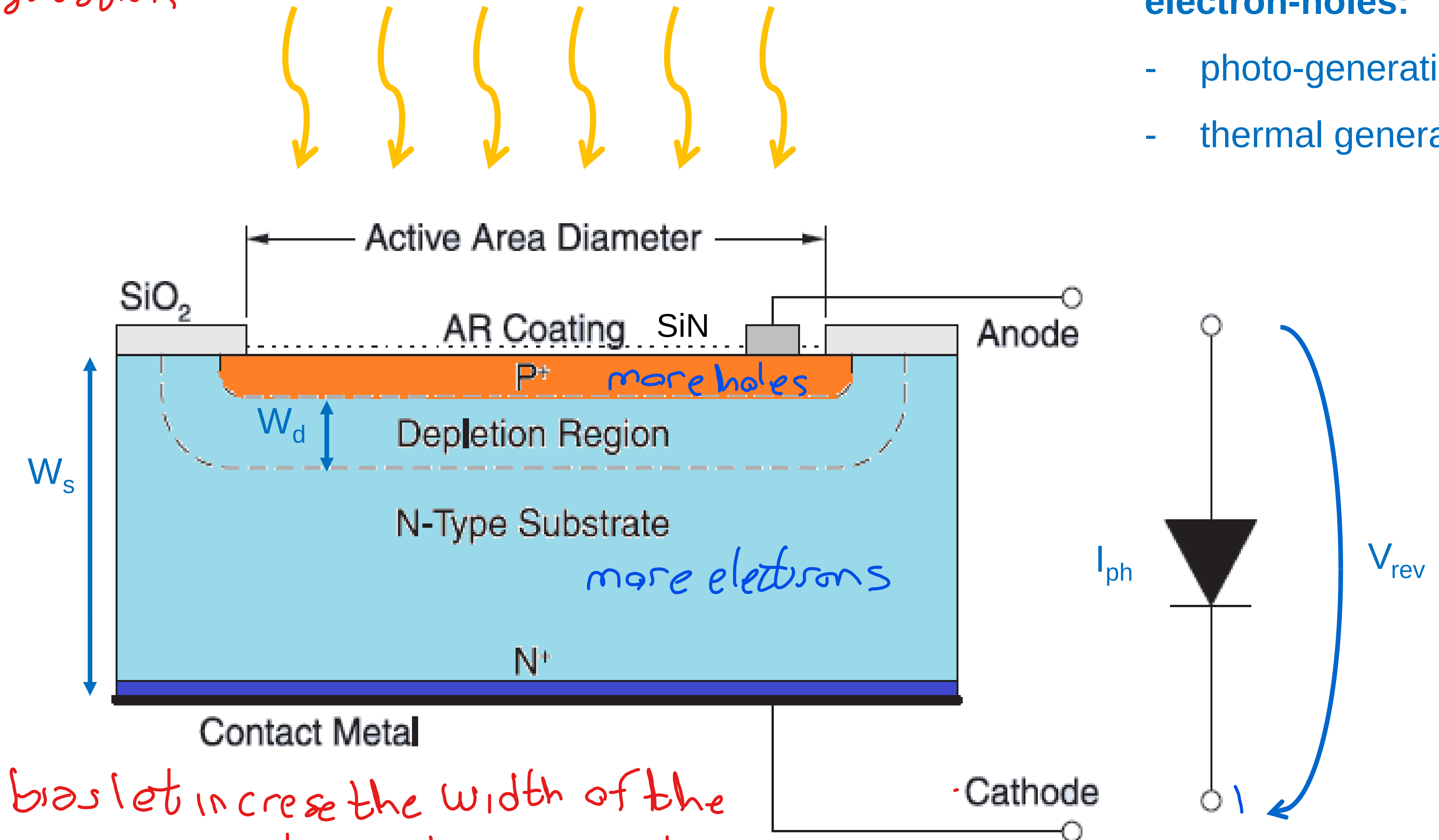
WeBeep: 05 - Photodiode

Silicon Photodiode cross-section

noise: thermal generation

electron-holes:

- photo-generation
- thermal generation



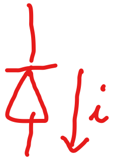
reverse bias let increse the width of the depletion region and absorbes more photons

Operation mode

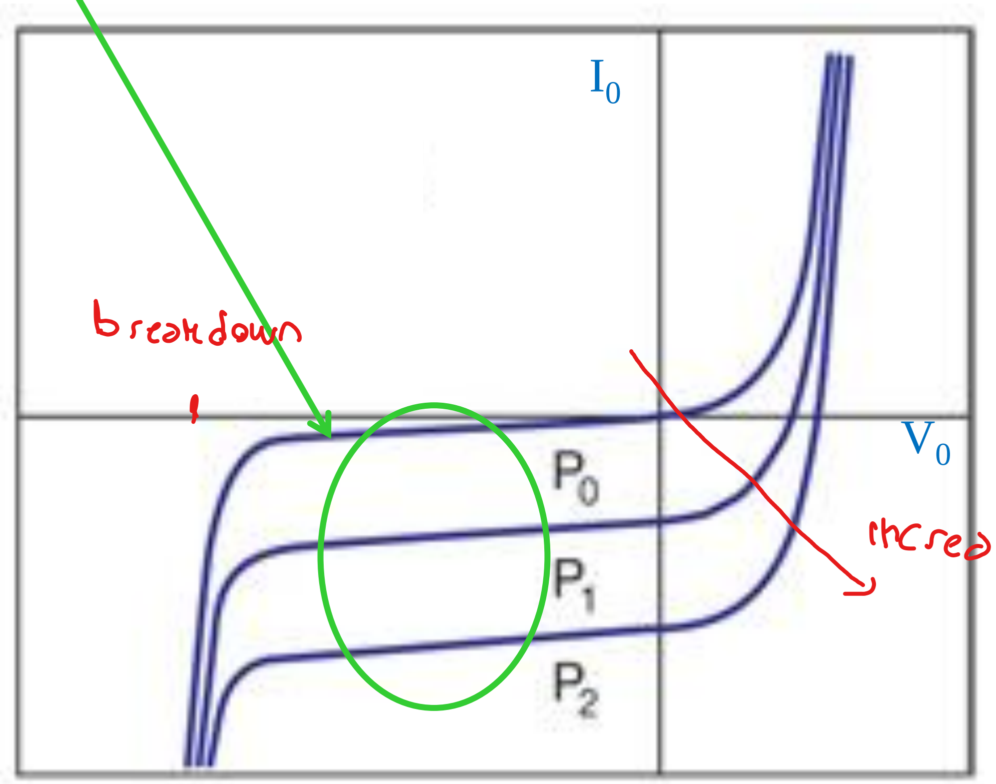
Photoconductive linear mode:

- Reverse bias
- Below break-down voltage

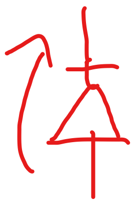
P = impinging optical power



i reverse current

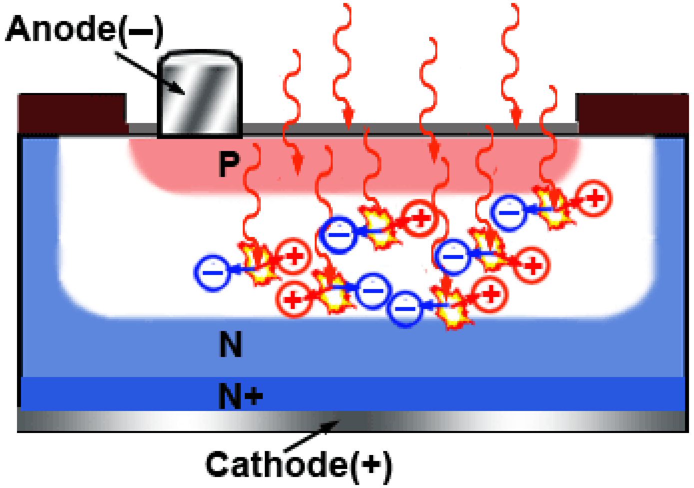


Photodiode Operation

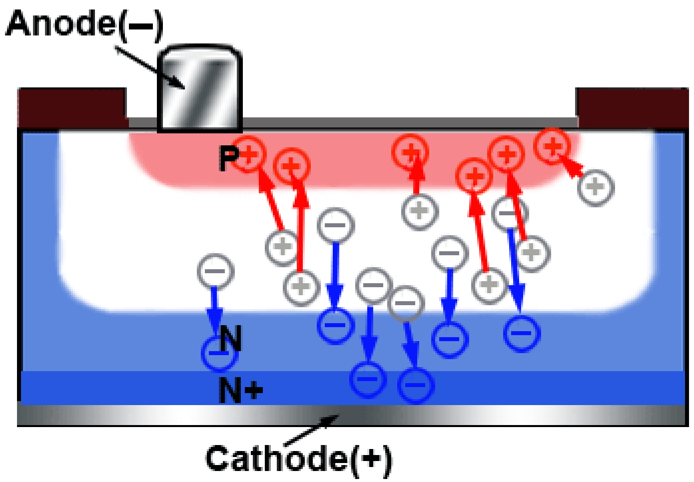


reverse bias

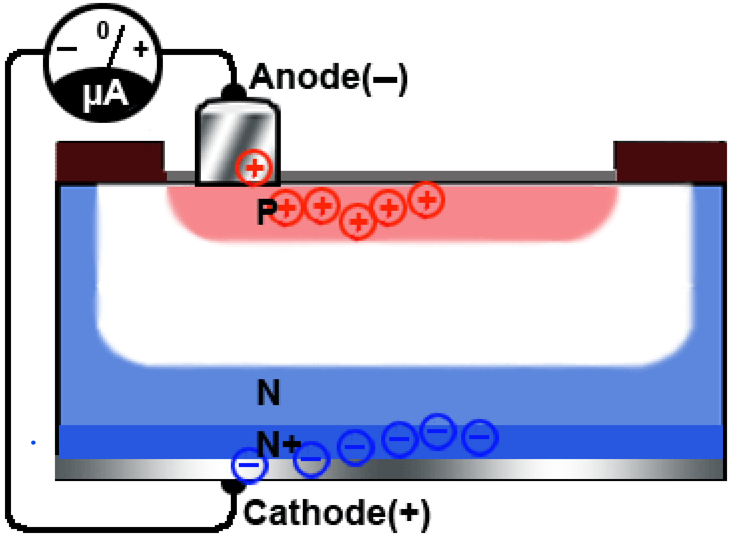
separation of ~~currents~~ charges => current



1 - Electron/Hole pairs generation



2 - Carriers are attracted by reverse bias

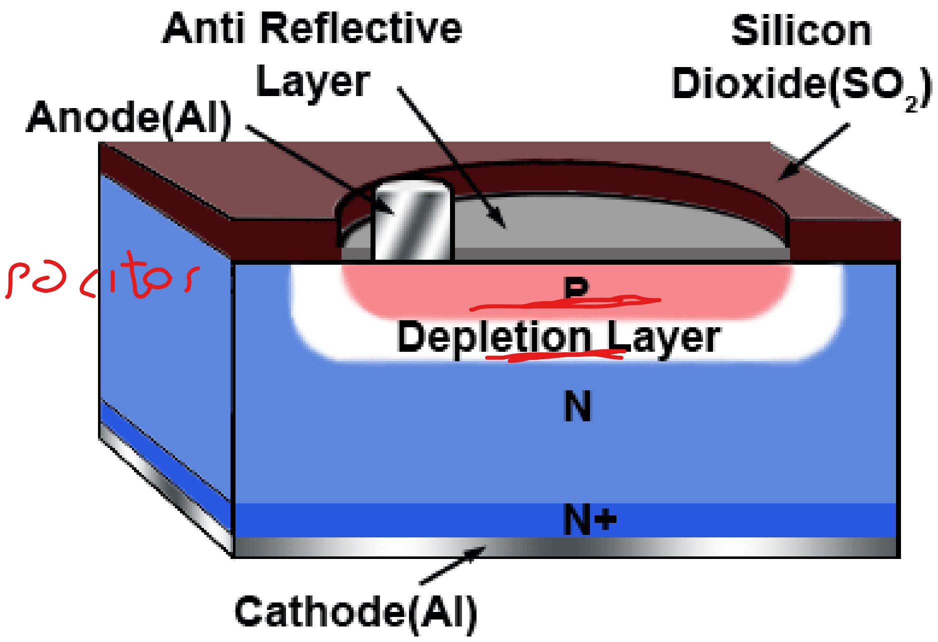


3 - Carriers form a photoelectric current

if light absorbed on N region, + and - generates but they can recombine

p-n vs p-i-n

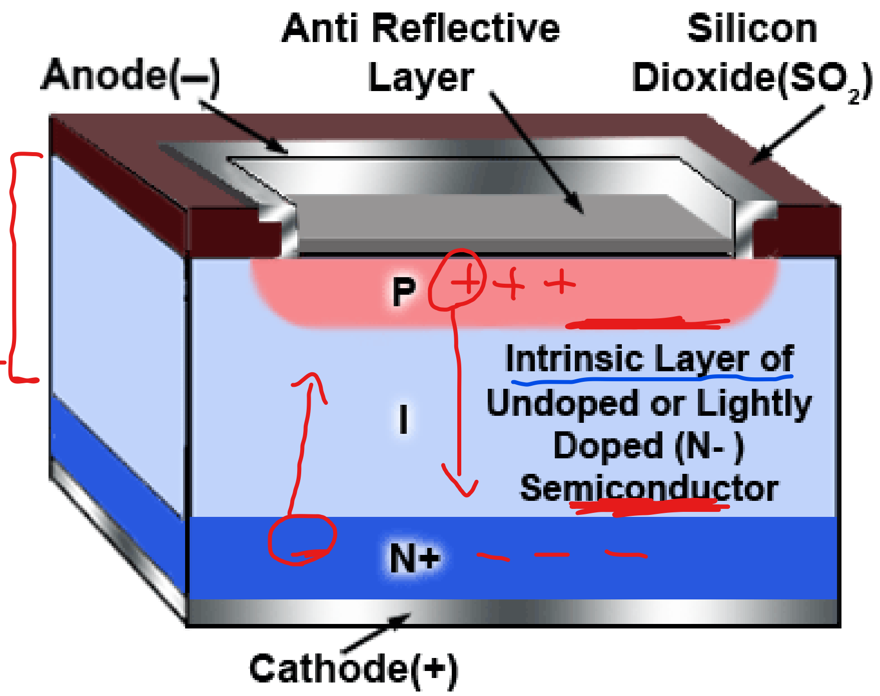
capacitor



Slightly open

No free e^- or p^+

depleted region is wide



it's nice because:

- high probability to detect photon
- higher capacitance, higher instability.

In PIN is more stable

P-I-N photodiod

p-i-n photodiode has larger depletion region

→ reduced capacitance

→ responsivity in a wider spectrum

↳ Probab. to detect Photons

Penetration depth = depth at which the intensity of the radiation inside the material falls to 1/e (about 37%) of its original value at the surface.

In silicon

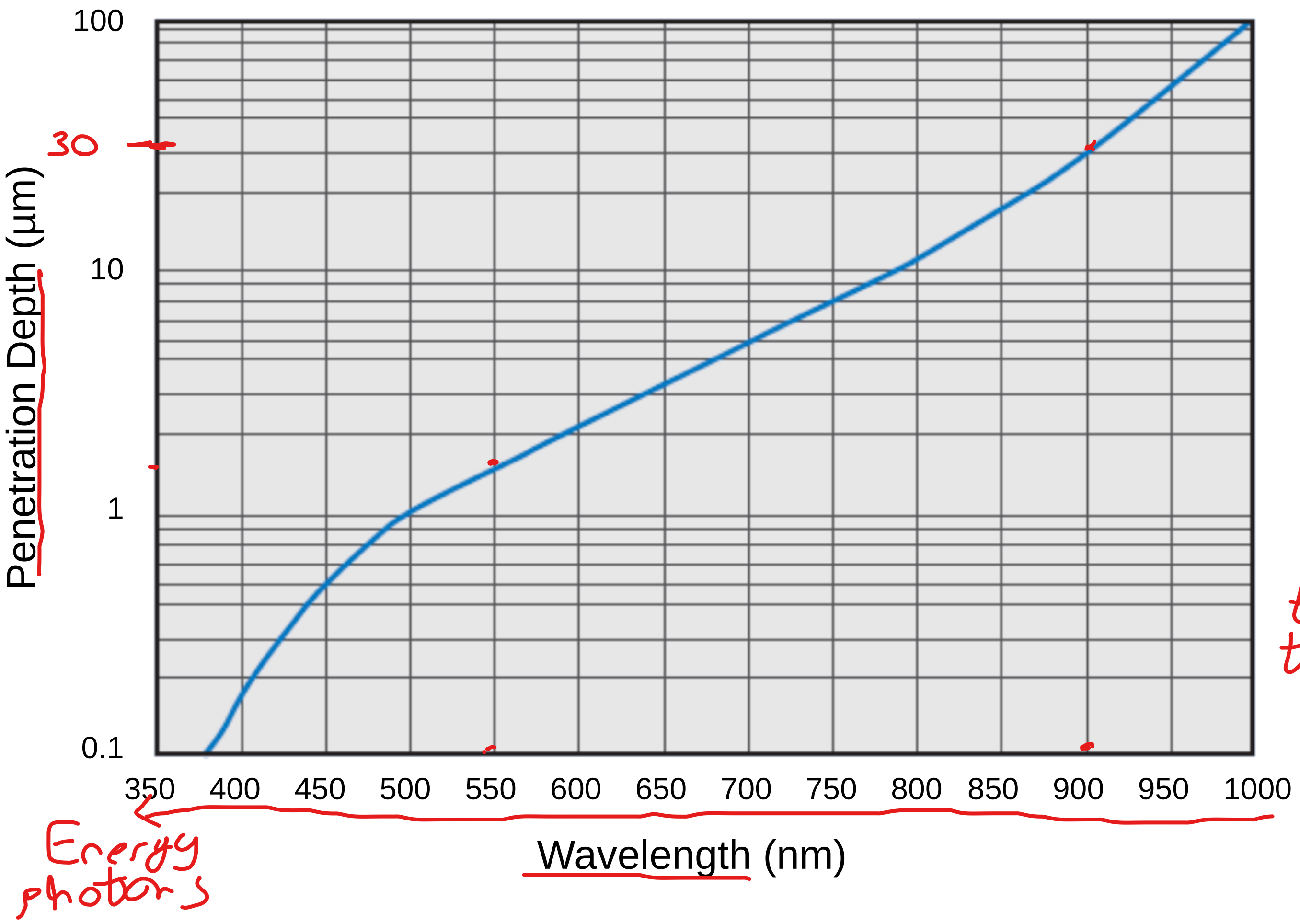


Photo-generation:

Eph > Eg

(Si: Eg = 1.12 eV)

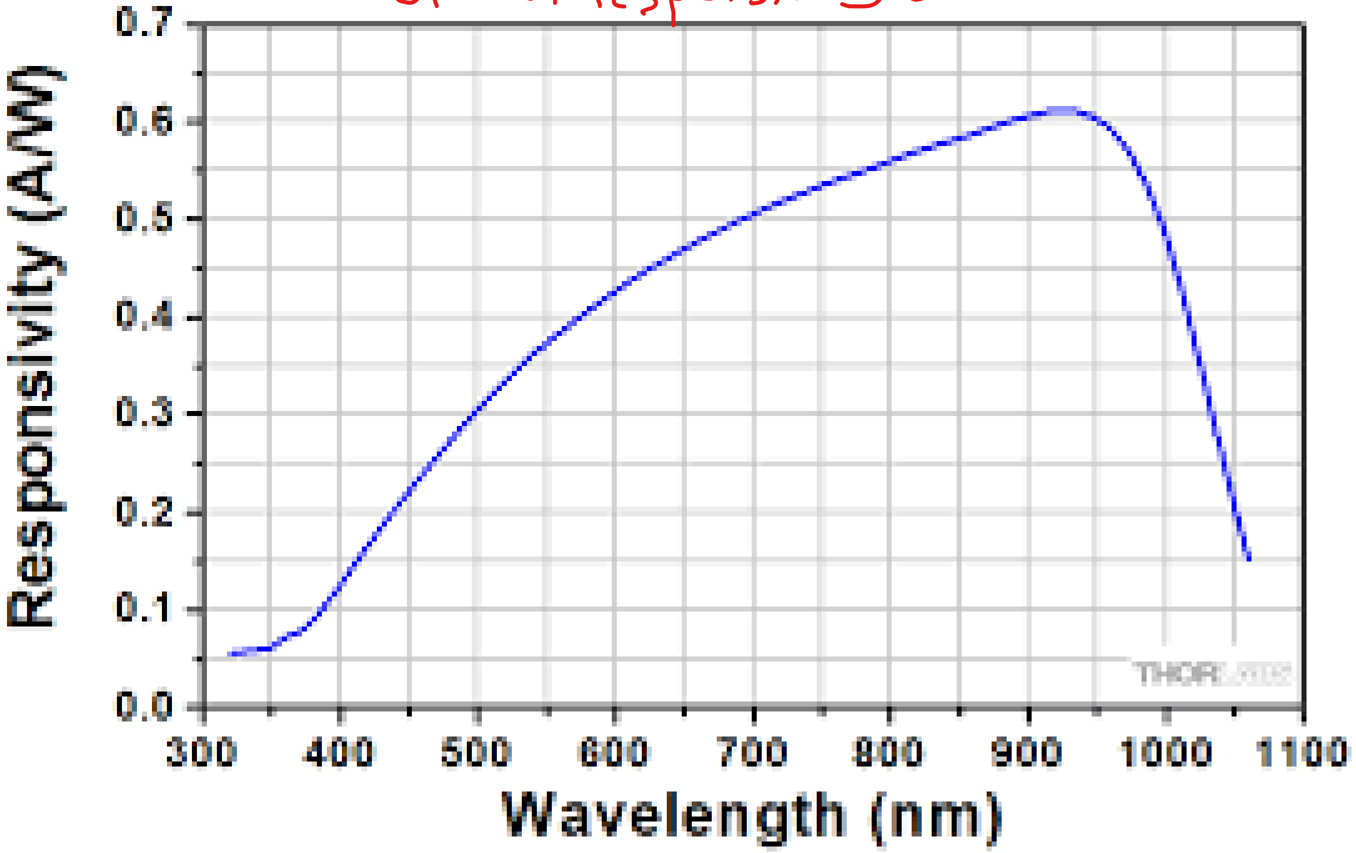
energy gap: energy to provide to the photons to go ~~to~~ from the valens to the energy gap

Photocurrent generated
Power

Photodiode Responsivity (sensitivity) =
ratio of the photocurrent I_{ph} to the incident light power P at a given wavelength:

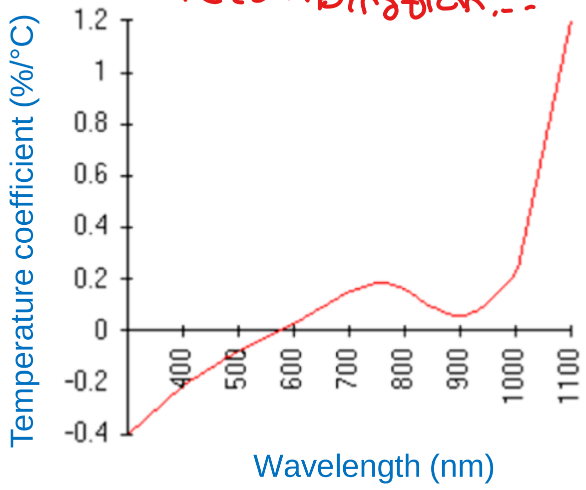
$$R_\lambda = \frac{I_{ph}}{P}$$

shape of responsivity of detector.



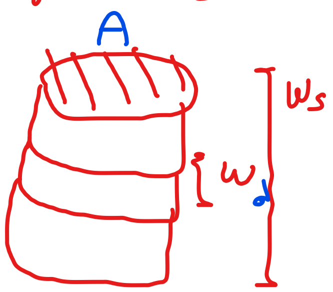
R_λ depends on:

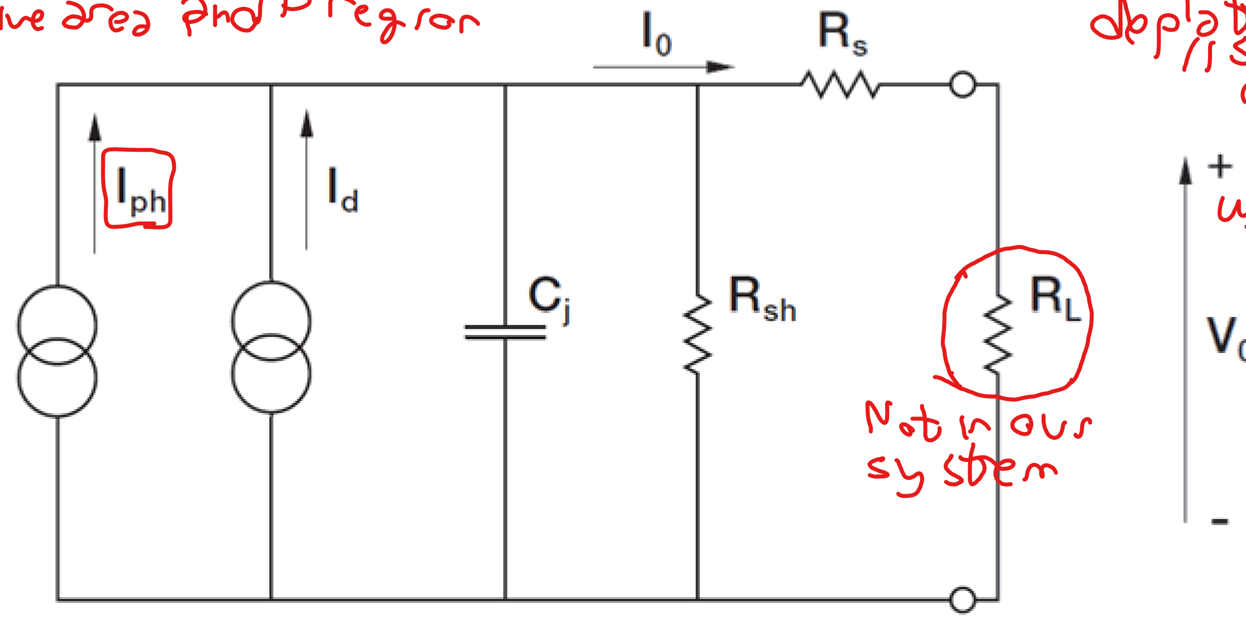
- Incident light wavelength
- Applied V_{rev}
- Temperature (not straight forward
↳ impact on depletion region, recombination...



Photodiode electrical model (Readout circuit)

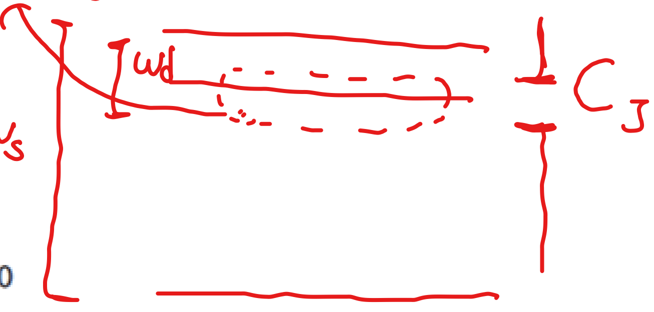
difference between active area and D region





Not in our system

depletion with no charges (isolates)



I_{ph} = photo- generated current — current generated by photon absorbed

I_d = current of the ideal pn-junction (dark current) — current with no photons (thermal generation?)

C_j = junction capacitance: $C_j = \frac{\varepsilon \cdot A}{W_d}$ — capacitance of depletion region

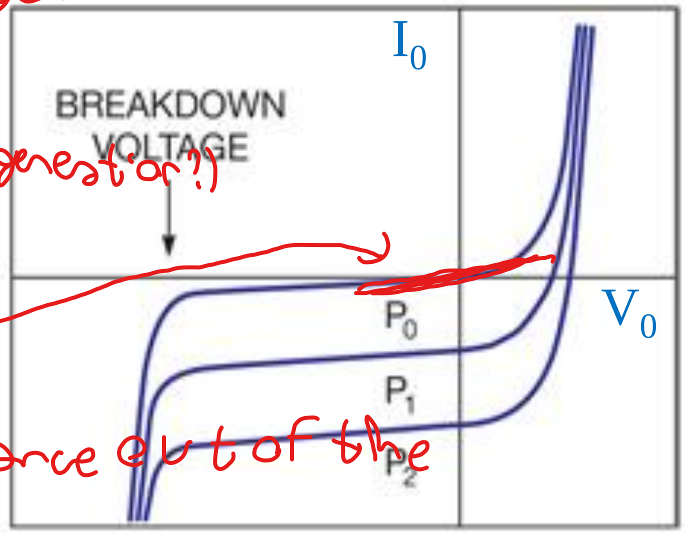
(non physical resistance)

R_{SH} = shunt resistance: slope at 0V — Parameter that models the slope at 0V

very big

R_s = series resistance: $R_s = \frac{(W_s - W_d) \cdot \rho}{A} + R_c$ — Physical, represents resistance out of the depletion area.

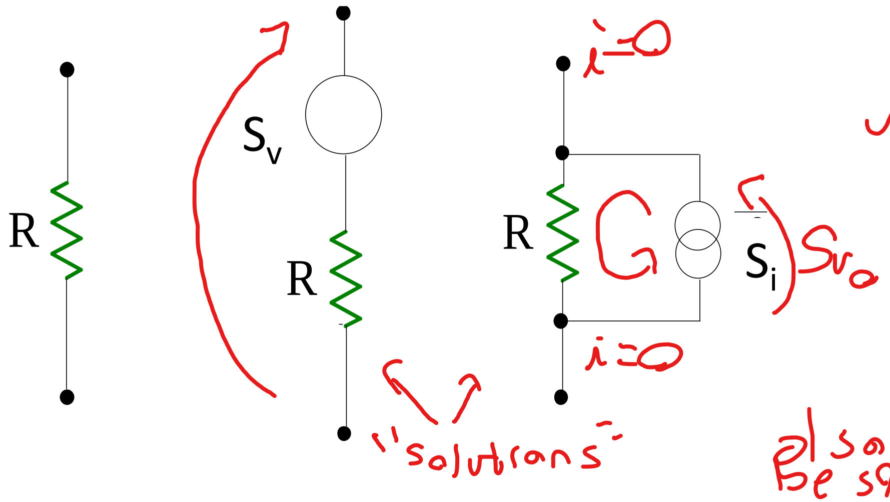
very small



Sources of noise (Present in additional material)

Thermal (Jhonson) noise → Brownian motion of charges

In Resistors, non biased but if you have more e^- in a region, a current could be generated



Spectral density

voltage

$$S_v = 4KT \cdot R \quad \left[\frac{V^2}{Hz}\right]$$

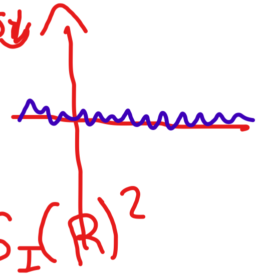
flat on frequency

$$4kT = 1.66 \cdot 10^{-20} \frac{V^2}{Hz \cdot \Omega}$$

also the transport function have to be squared when working with power

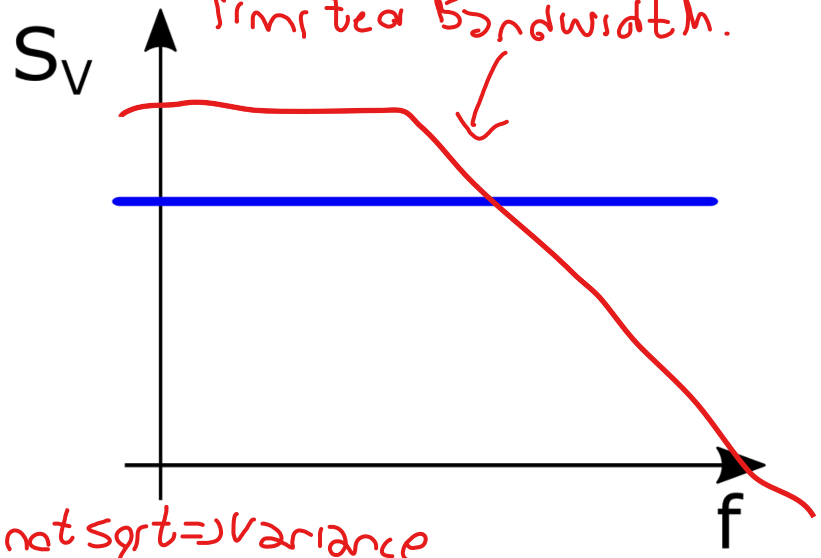
current spectr. density

$$S_i = \frac{4KT}{R} \quad \left[\frac{I^2}{Hz}\right]$$



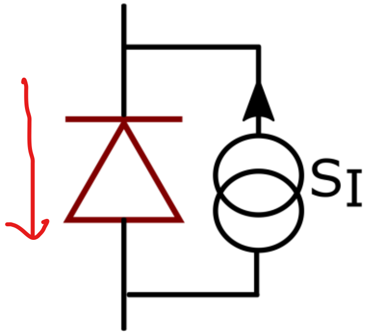
$V_o = IR \Rightarrow S_{V_o} = S_I (R)^2$

usually real are limited bandwidth.

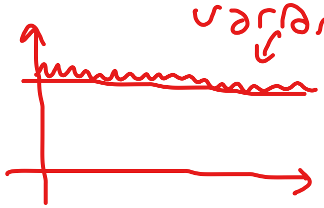


Shot noise → "granularity" of charge crossing a junction

→ PN Junctions



variance



Spectral density

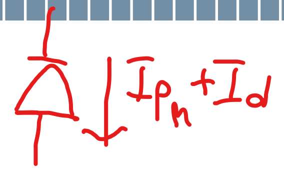
$$S_i = 2q \cdot I$$

flat on frequencies

Noise standard deviation: $V_n = \sqrt{S_v \cdot \Delta f}$ and $I_n = \sqrt{S_i \cdot \Delta f}$

if not sqrt ⇒ variance.

Photodiode noise



- **Shot noise**

  = statistical fluctuation in both the photocurrent and the dark current:

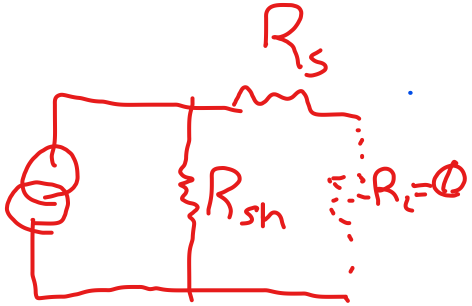
$$I_{sn} = \sqrt{\underbrace{2q\left(I_{ph}+I_d\right)}_{S_i}\cdot\Delta f}$$

- **Thermal (Jhonson) noise**

  = thermal generation of the shunt resistance:

transfer function

$$I_{jn\_Rsh} = \sqrt{\frac{4kT\Delta f}{R_{sh}}\cdot\frac{R_{sh}^2}{(R_{sh}+R_s)^2}} \approx \sqrt{\frac{4kT\Delta f}{R_{sh}}}$$

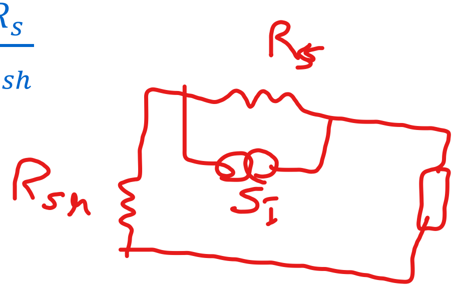


  Thermal noise of the series resistance is negligible:

Remember $R_s \ll R_{sh}$

$$I_{jn\_Rs} = \sqrt{\frac{4kT\Delta f}{\cancel{R_s}}\cdot\frac{R_s^{\cancel{2}}}{(R_{sh}+\cancel{R_s})^2}} \approx \sqrt{\frac{4kT\Delta f}{R_{sh}}\cdot\underbrace{\frac{R_s}{R_{sh}}}_{\ll 1}} = I_{jnRsh}\cdot\sqrt{\frac{R_s}{R_{sh}}}$$

SPICE simulation in additional material

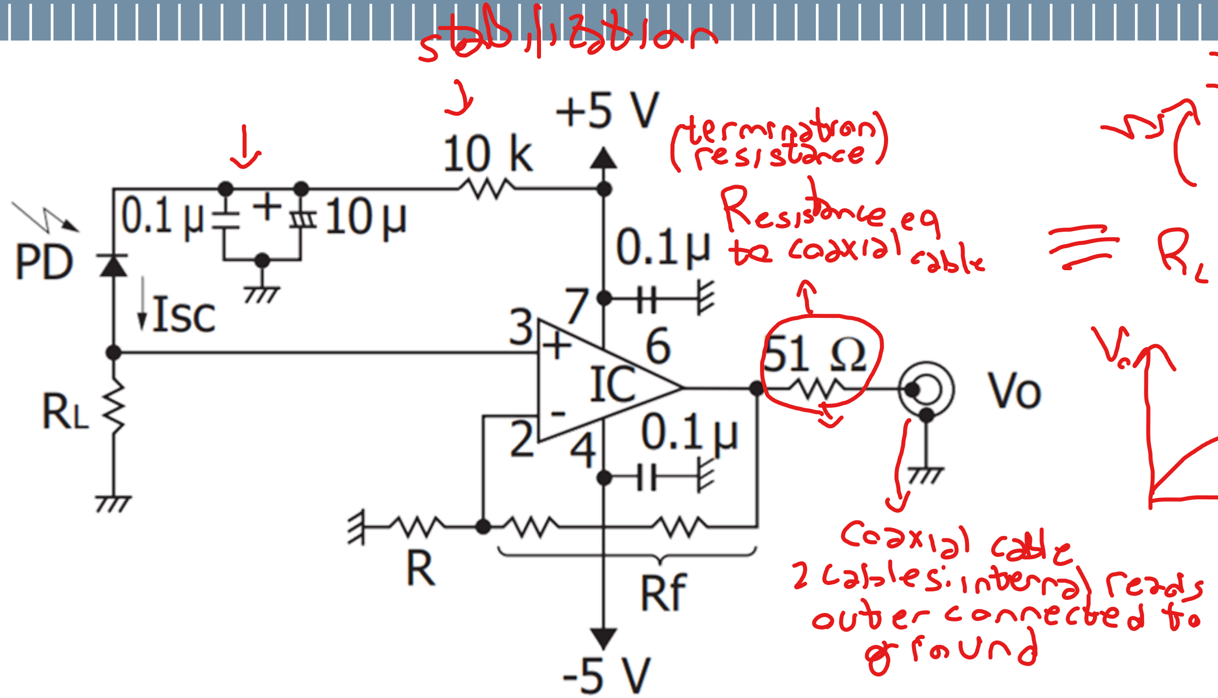


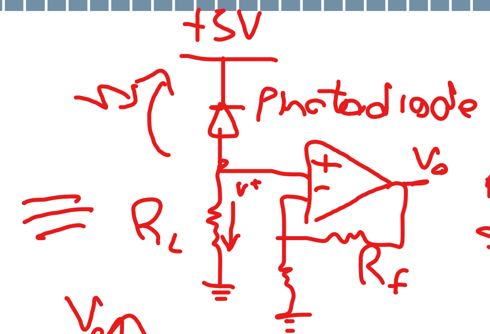
→ **Noise Equivalent Power (NEP)**

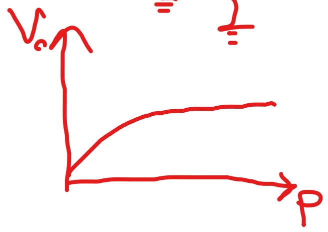
  = amount of incident light power on a photodetector, which generates a photocurrent equal to the noise current.

$$NEP = \frac{I_n}{R_\lambda}$$

amount of light to have a signal equal to the noise current



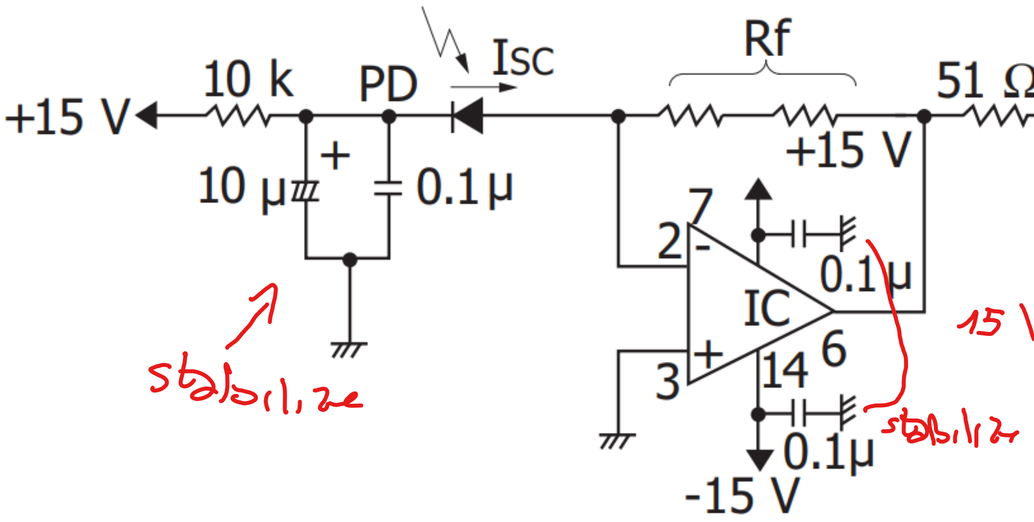


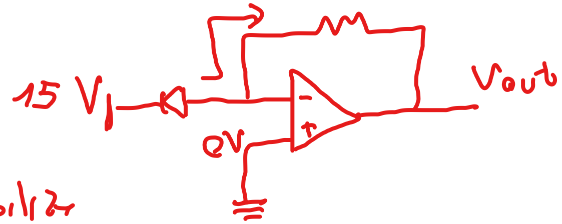


Non-inverting configuration

negative feedback: you go to a saturation

$$V_o = \underbrace{I_{SC} \cdot R_L}_{V_+} \cdot \underbrace{\left(1 + \frac{R_f}{R}\right)}_{\text{Gain}}$$



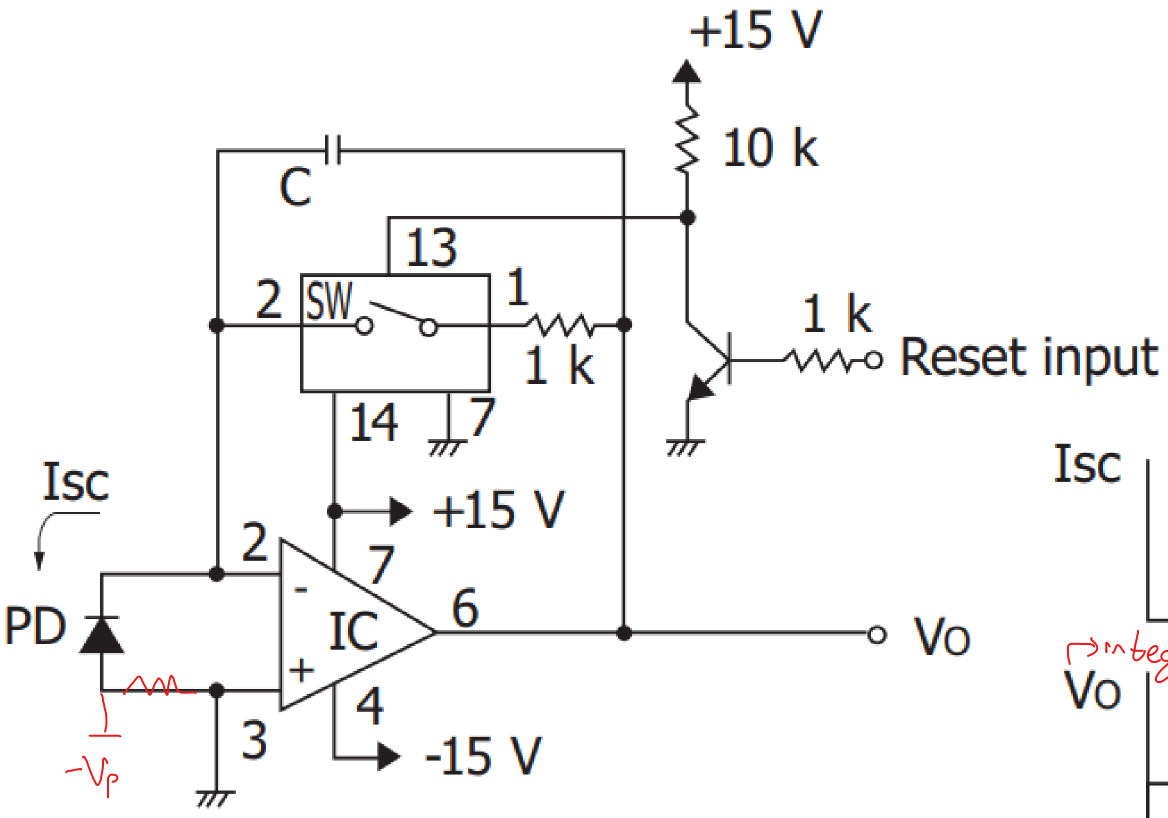


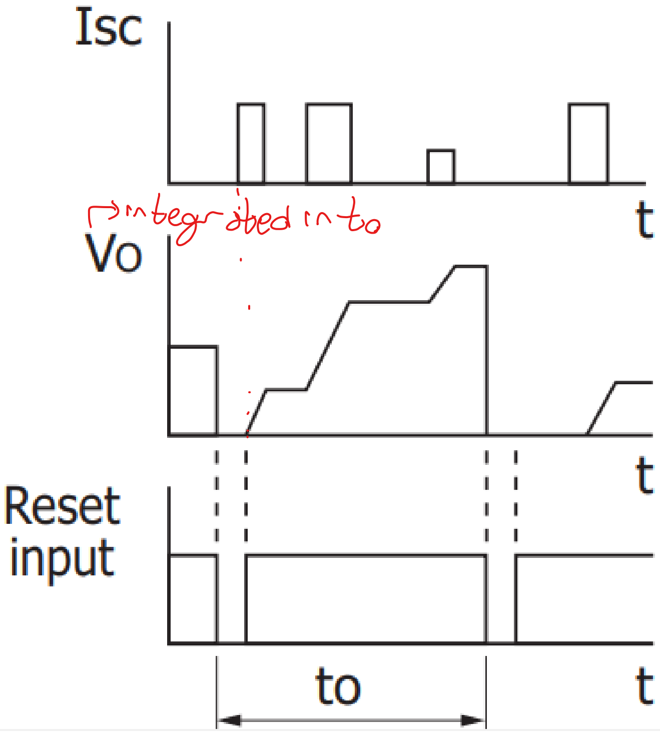
Transimpedance Amplifier

$$V_o = - I_{SC} \cdot R_f$$

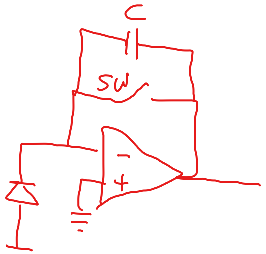
Typically, must be compensated!

Light integration





$$V_o = \frac{\overline{I_{SC}} \cdot t_o}{C}$$



closed sw: discharging C

Photodiode applications

Camera
- Light Meters
- Automatic Shutter Control
- Auto-focus
- Photographic Flash Control

Medical
- X ray Detection
- Pulse Oximeters
- Blood Particle Analyzers

Safety Equipment
- Smoke Detectors
- Flame Monitors
- Security Inspection Equipment
- Intruder Alert - Security System

Automotive
- Twilight Detectors
- Climate Control - Sunlight Detector

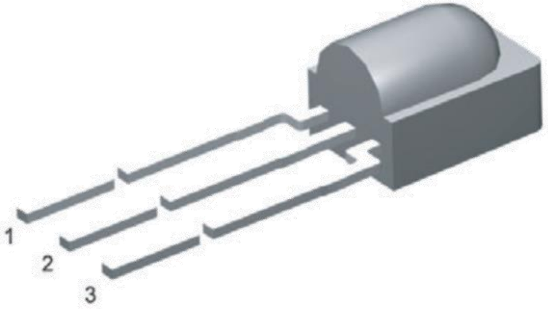
Communications
- Fiber Optic Links
- Optical Communications

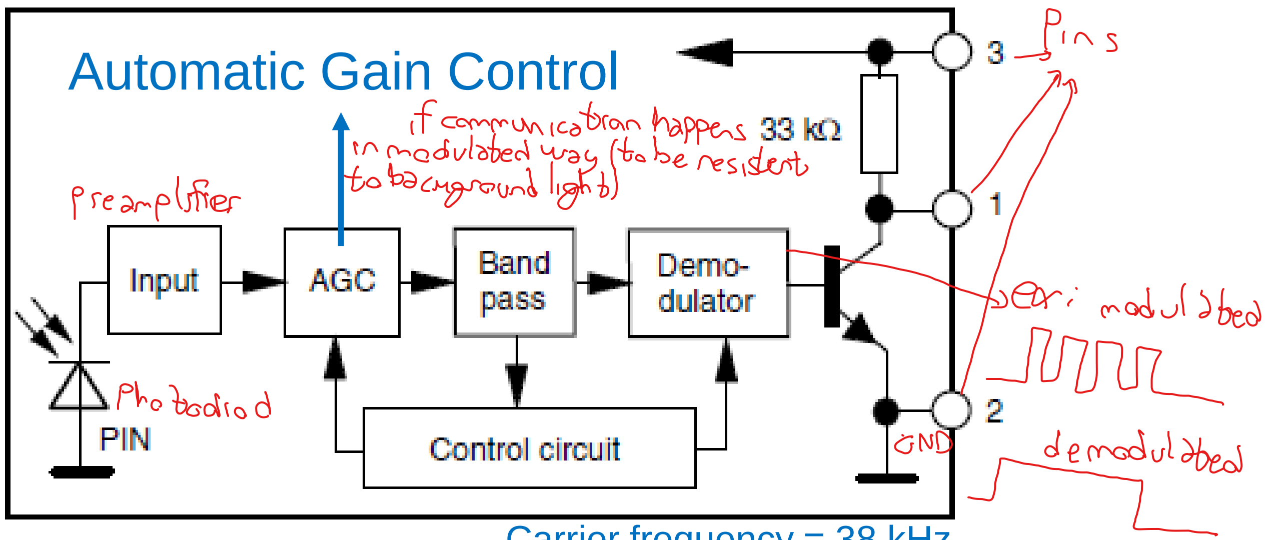
Industry
- Bar Code Scanners
- Light Pens
- Brightness Controls
- Rotary Encoders
- Position Sensors
- Surveying Instruments
- Copiers - Density of Toner

in our Nucleo Board

IR Receiver Module: TSOP58238

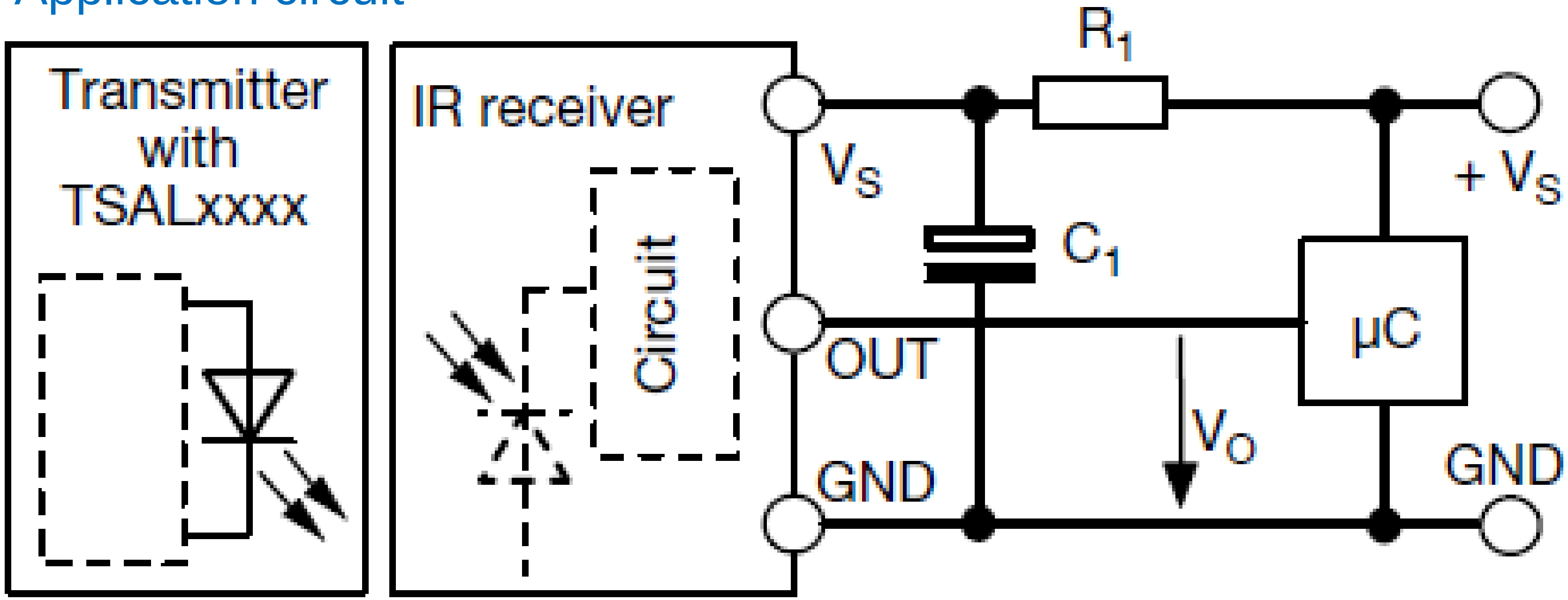
Used for communication (like for the tv control)



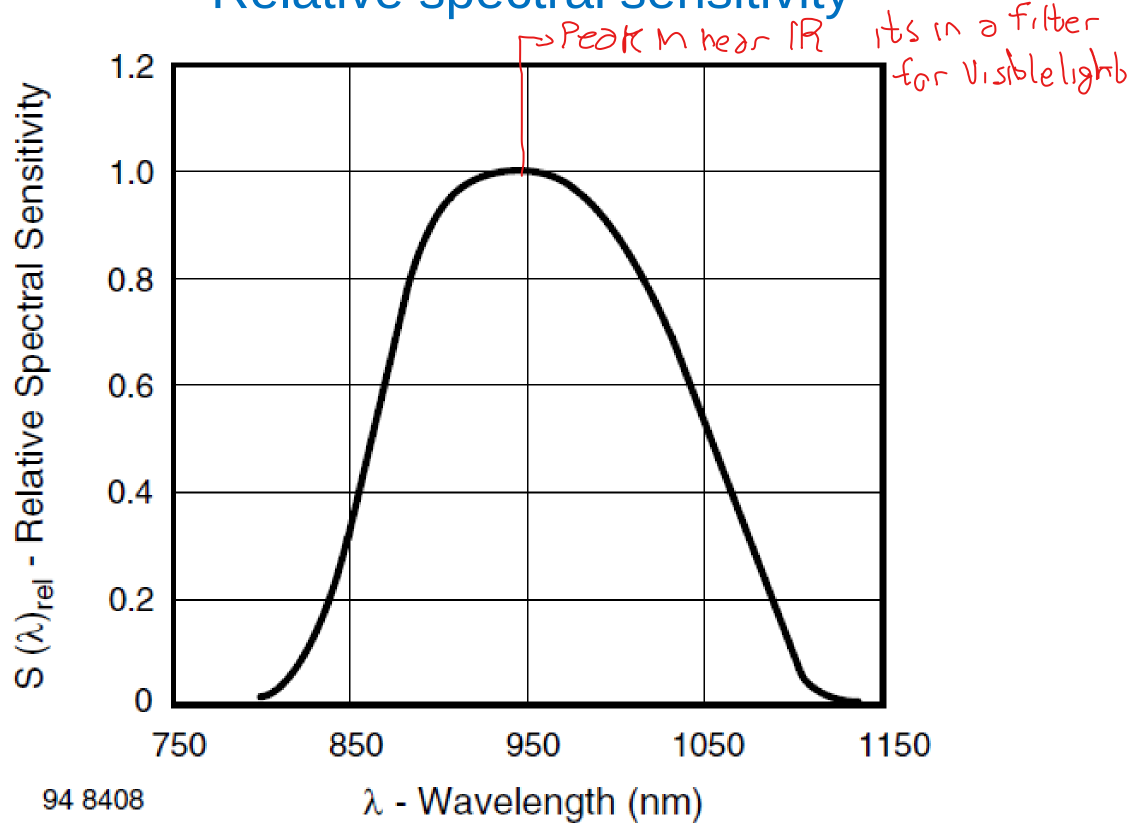


Carrier frequency = 38 kHz

Application circuit

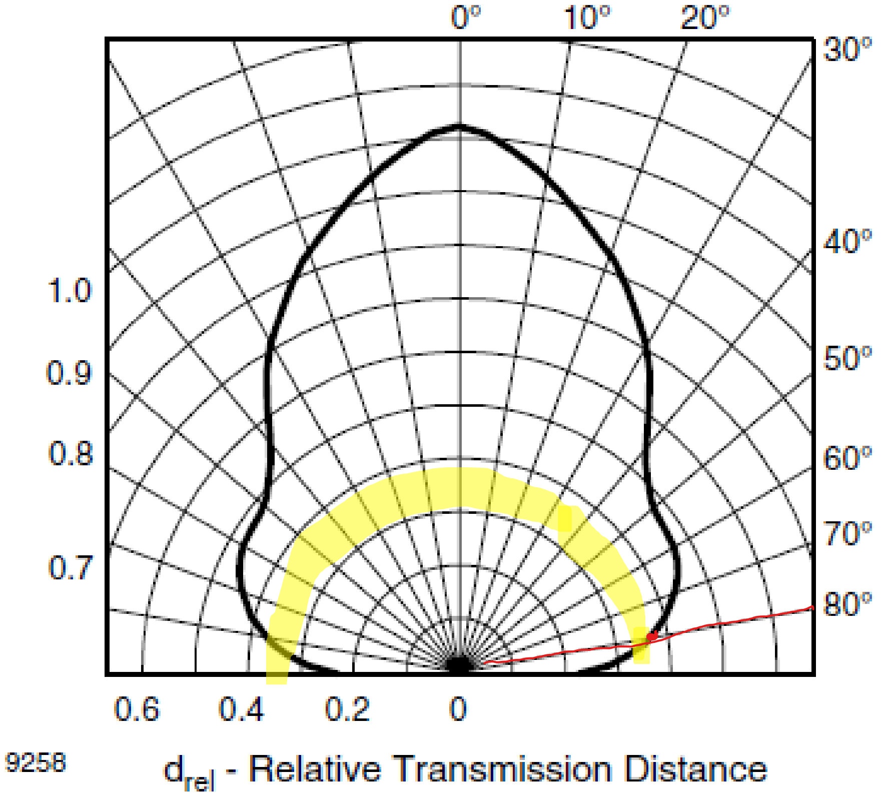


Relative spectral sensitivity



how much light will be absorbed relative to angle

Relative transmission distance



The peak sensitivity is at 950 nm
→ Near Infra-Red (NIR)

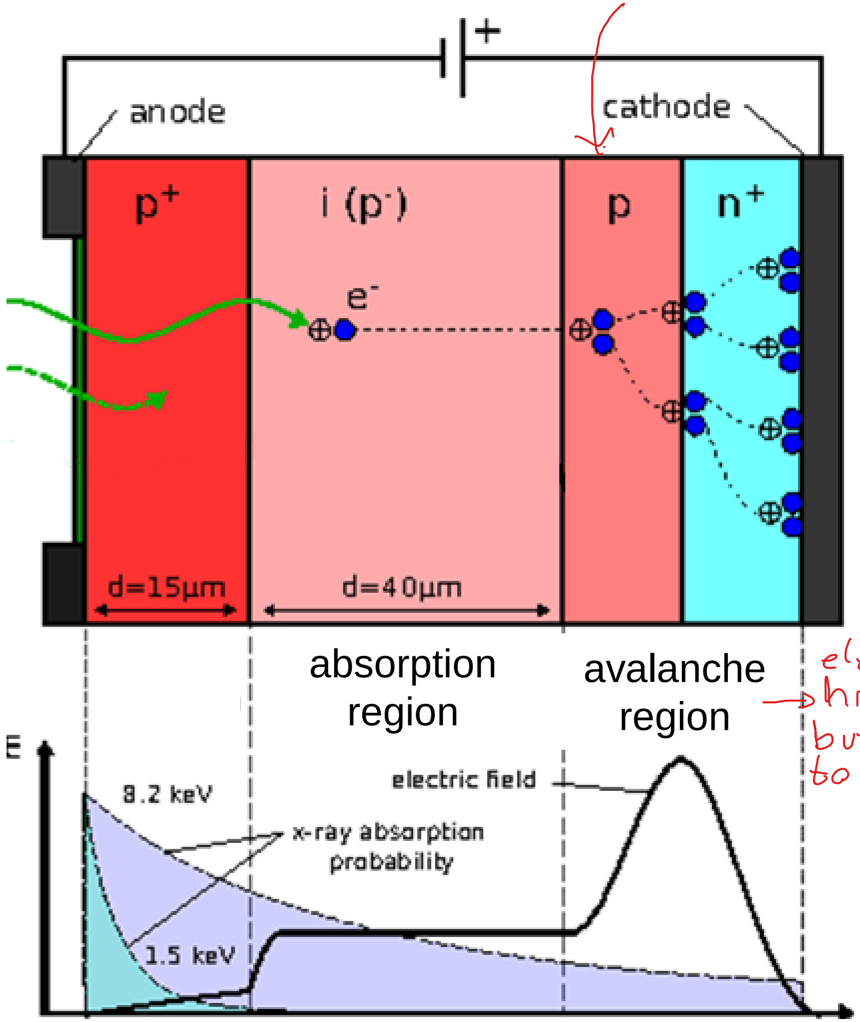
The sensitivity for light beam with 0° angle is the highest

The same sensitivity for a light beam with 80° angle is obtain at 0.35 relative distance.

Avalanche Photodiode (APD)

→ doesn't have advantages on the noise (it is multiplicated too)

e^- fast → for impact ionization another electron-hole pair.



- P-i-N junction
- Bias: below but close to breakdown
- Analog output proportional to incoming light
- Internal multiplication (gain: M ≈ 100)

→ an e^- usually generates 100 pairs

Used when there isn't so much light (5 photons)

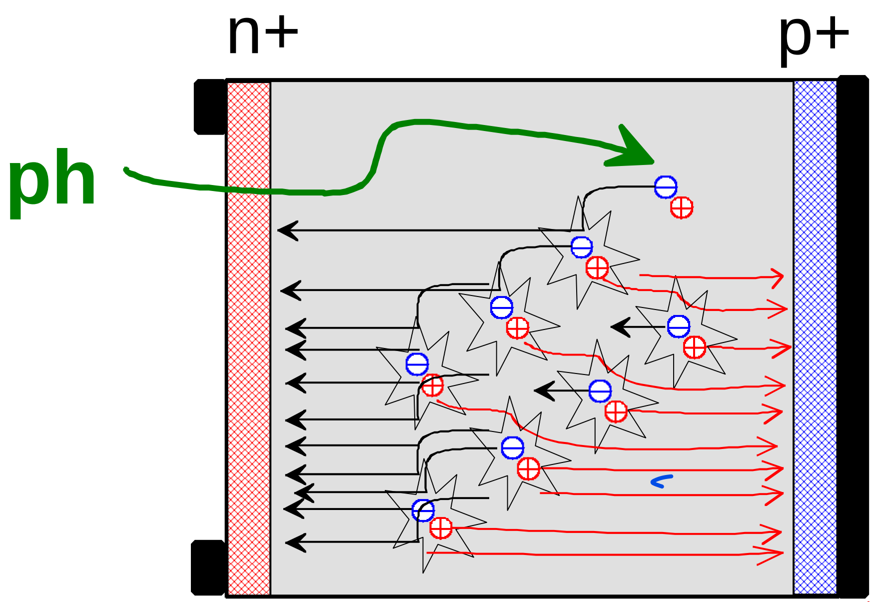
electric field → high to accelerate but not that high to have breakdown

Basic structure:

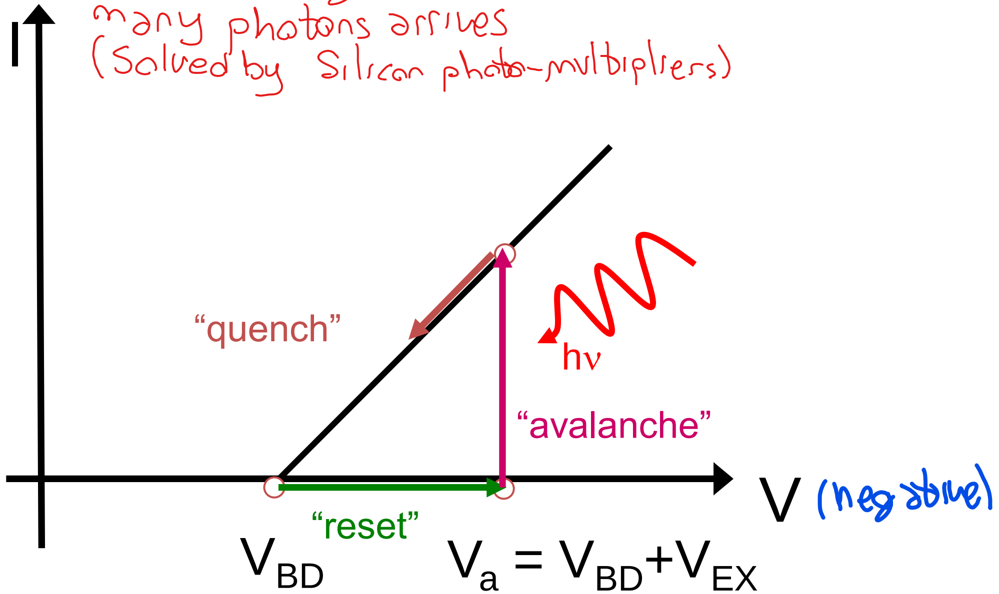
- absorption region = separate photo-generated holes and electrons
- multiplication region = high electric field to provide internal photo-current gain by impact ionization

disadvantage: another source of noise (uncertainty of the gain)

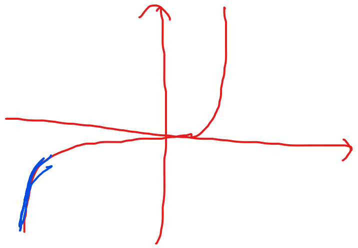
Single-Photon Avalanche-Diode (SPAD)



limitation: you don't know how many photons arrives (Solved by Silicon photo-multipliers)



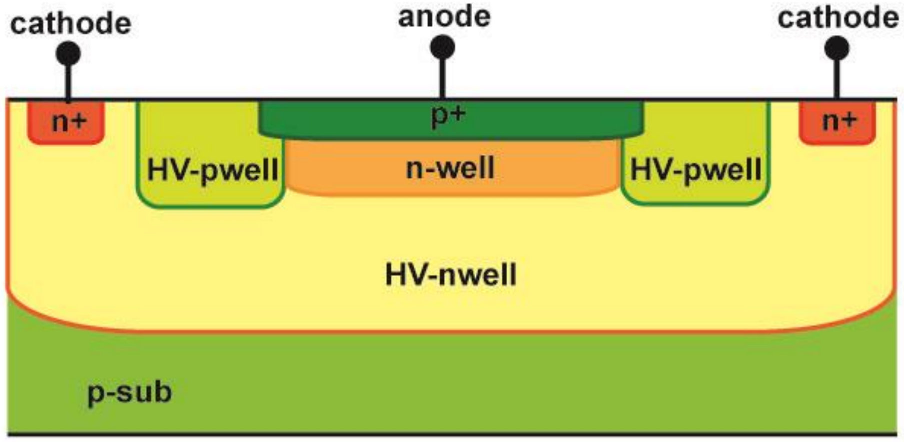
- P-N junction reverse biased
- Bias: well *ABOVE* breakdown
- **digital output**
- single photon sensitivity
- no read-out noise
- output: >10mA current for every photon

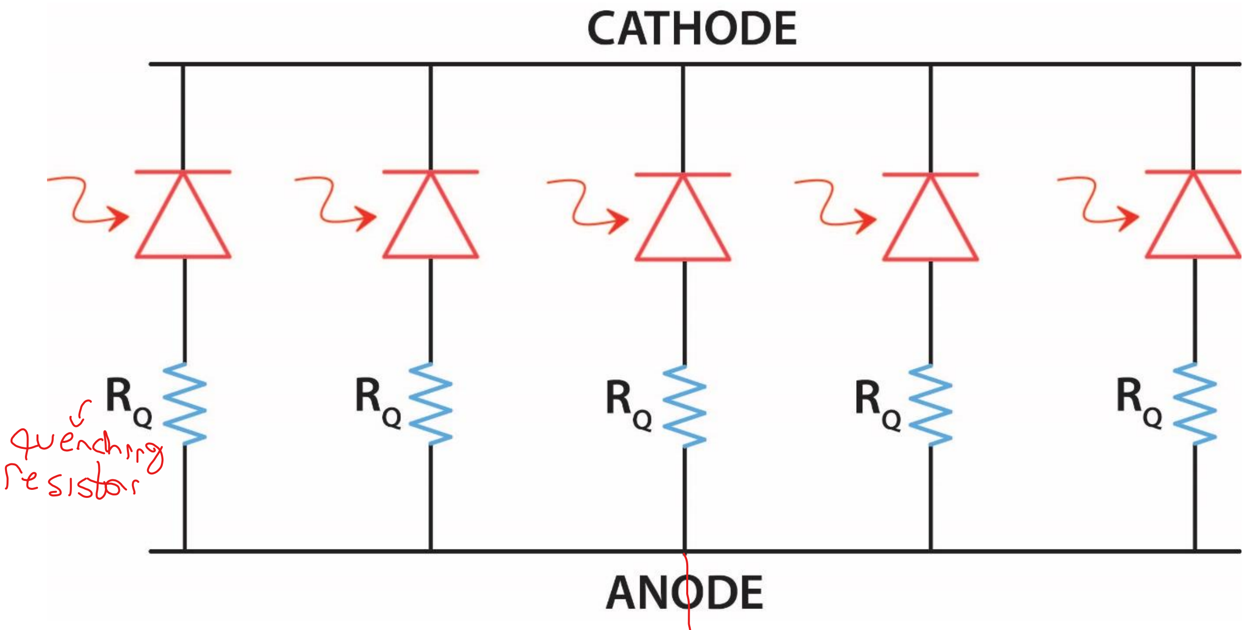


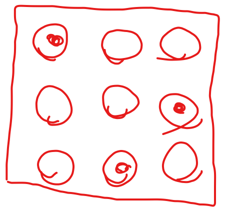
metastable state: No current but above breakdown when photon detected a positive feedback is initialized and generates current.

solid-state device:
can be integrated together
with electronics
(counter & TDC)

Must be stopped with quenching circuits (like a single resistor)

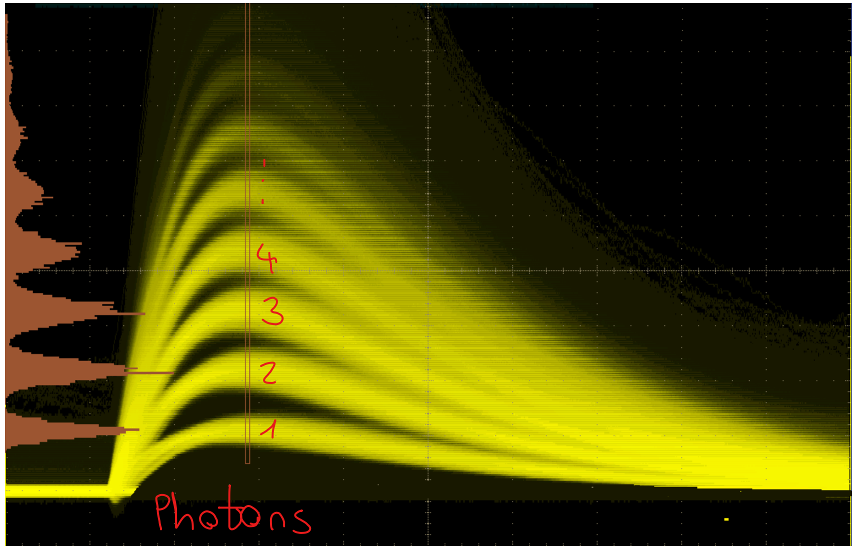






(of course if two photons impacts on same SPAD, detected only one photon)

Hundreds / thousands **SPADs**
+ quenching resistance in parallel



- ✓ Single photon sensitivity
- ✓ Photon number resolving capability
- ✓ Large active area

used for On/Off switches

light generates carriers within the resistor
So that resistance decreases

In the dark → R very high (up to 1MΩ)
Exposed to light → R drops dramatically (few ohms)

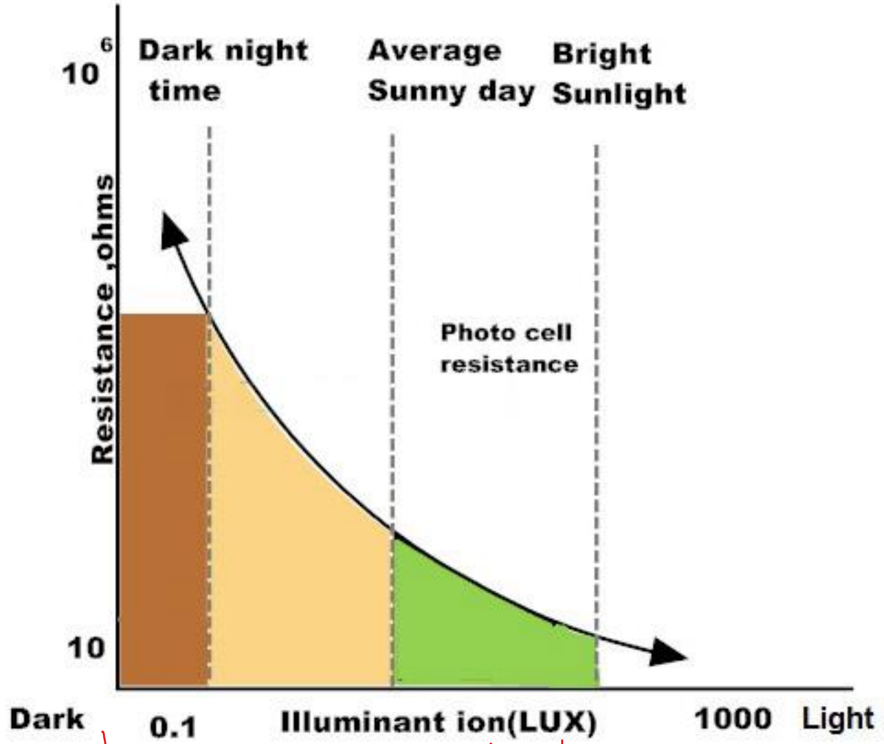
Working principle:

Photons excite electrons from the valence band to the conduction band

→ more free electrons in the material

→ lower resistance

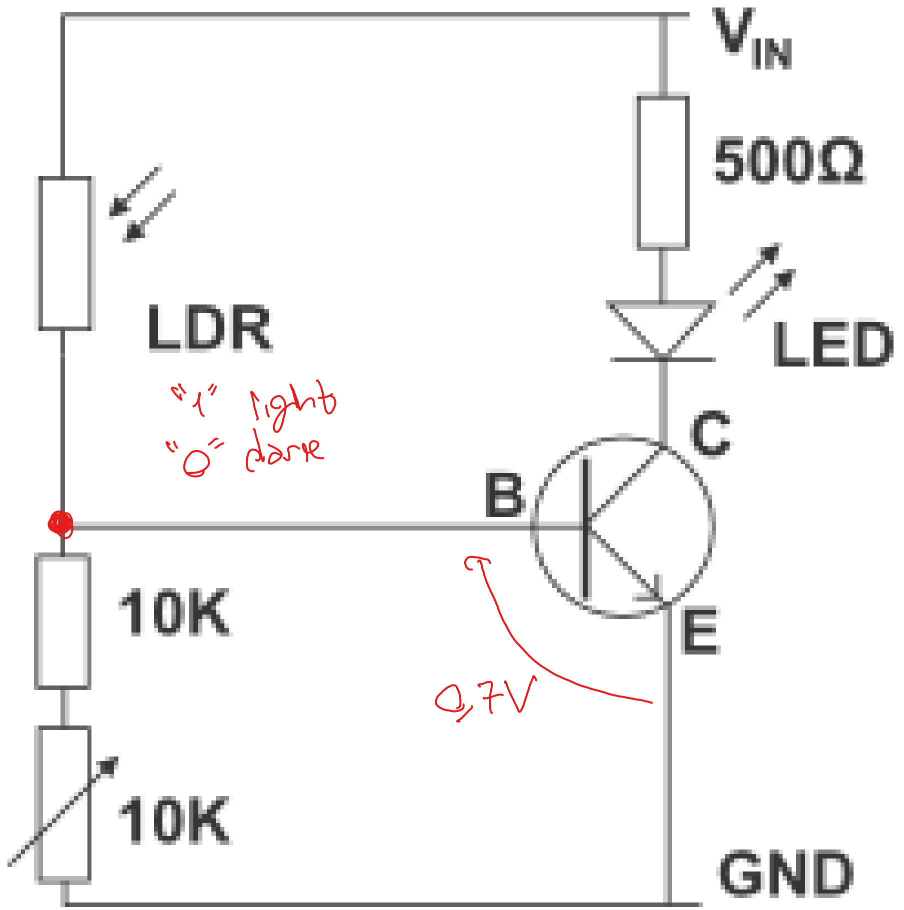
But…
- low sensitivity
- non-linear characteristic
- sensitive to temperature changes



non linear and low sensitivity

Typical application

We will read this node with the ADC integrated in our board



WITHOUT LIGHT

High LDR

$V_{BE} < 0.7$ → BJT off

→ LED off

WITH LIGHT

Low LDR

$V_{BE} = 0.7$ → BJT on

→ LED on