Introduction to Photodetectors (Part II)

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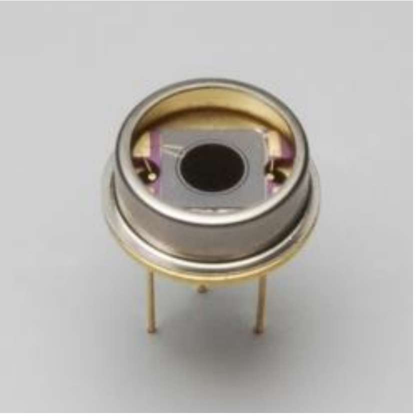
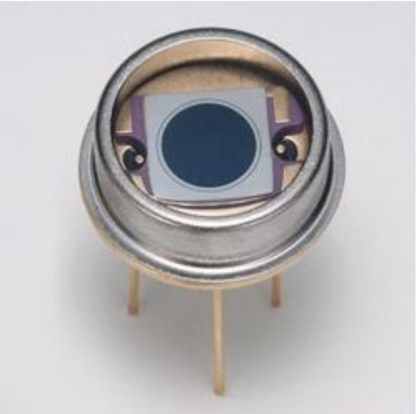
Index

- Structure and operation of point photodetectors
- Applications of photodetectors
- Selection of a photodetector

Structure and operation of photodetectors

Point photodetectors





PMT PD APD SiPM

PMT – photomultiplier tube

PD – photodiode

APD – avalanche photodiode

SiPM – silicon photomultiplier

PMT

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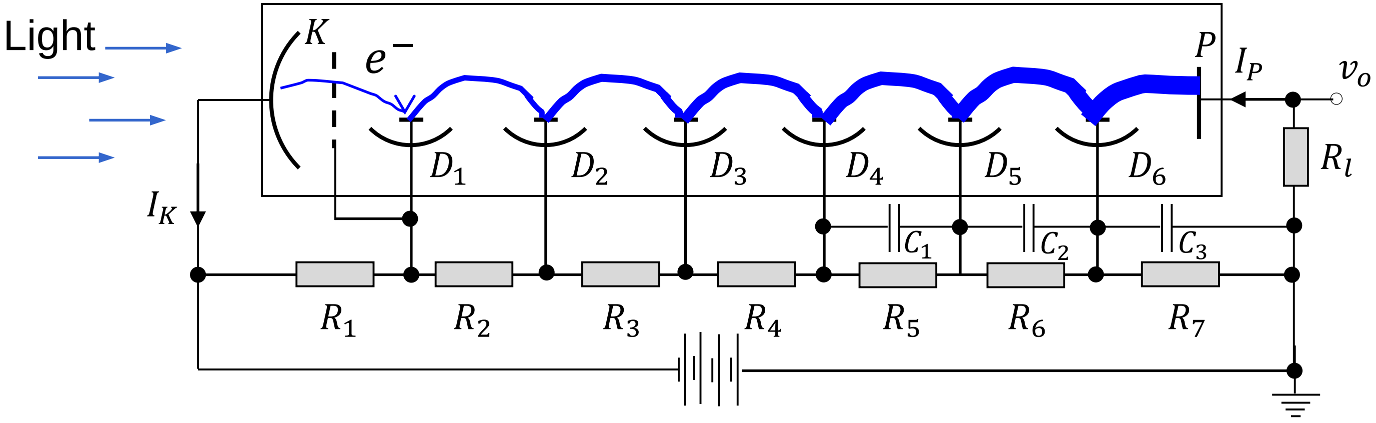
K – cathode $D_1, \dots D_6$ – Dynodes P – anode



$V \sim 1000$ V

There are two essential phenomena involved in the operation of a PMT: *extrinsic photoelectric effect* and *electron secondary emission*.

Side-on PMT

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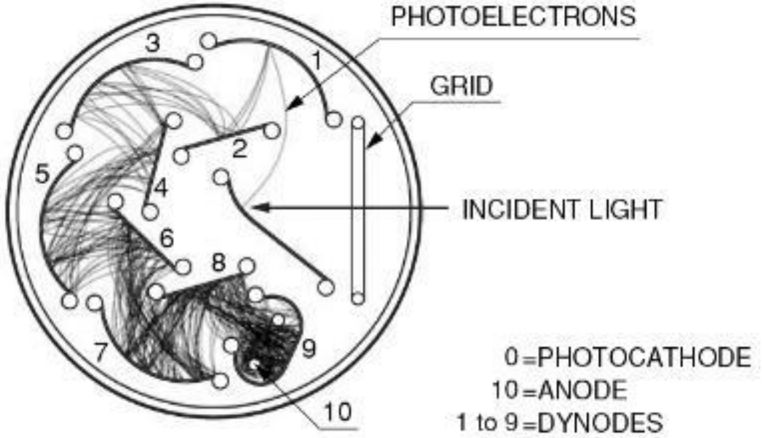
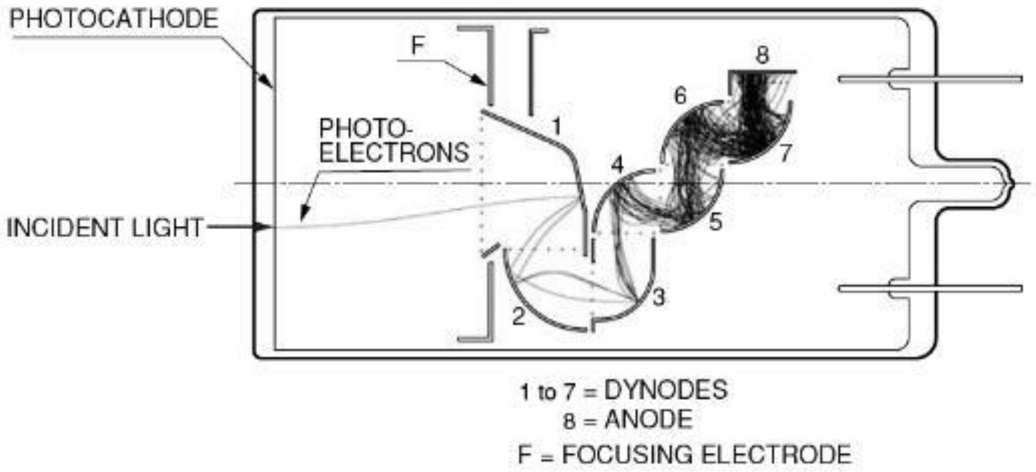
“side on” or “opaque” PMT

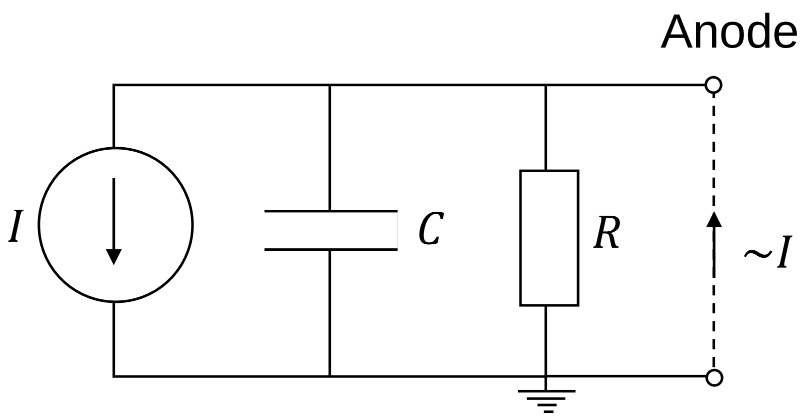


Head-on PMT

“head on” or “semi-transparent” PMT



Equivalent circuit of a PMT



$$I = P_0 S_K \mu = P_0 S_P$$

I – Anode current

P_0 – Incident light power

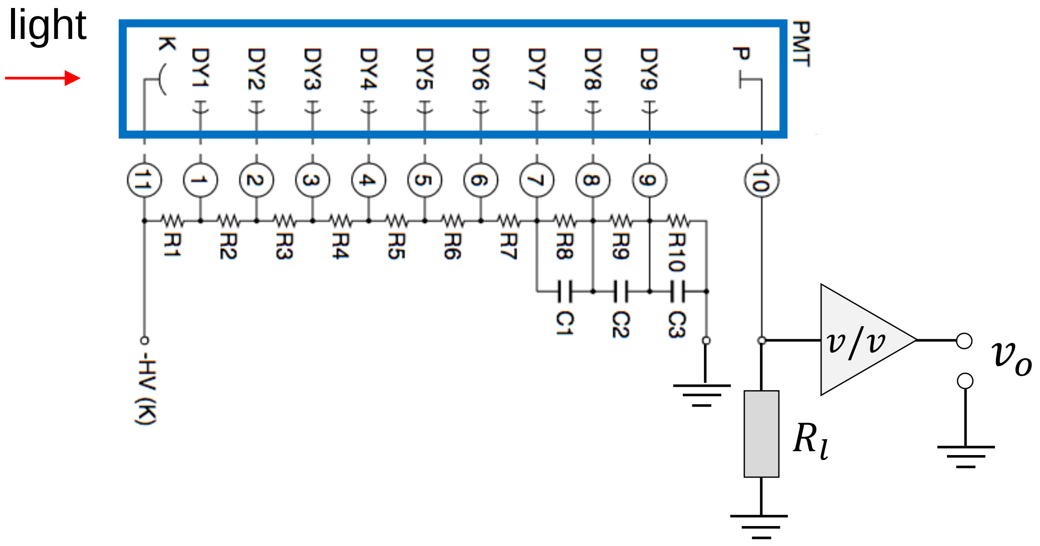
S_K – Photocathode spectral sensitivity

S_P – Anode spectral sensitivity

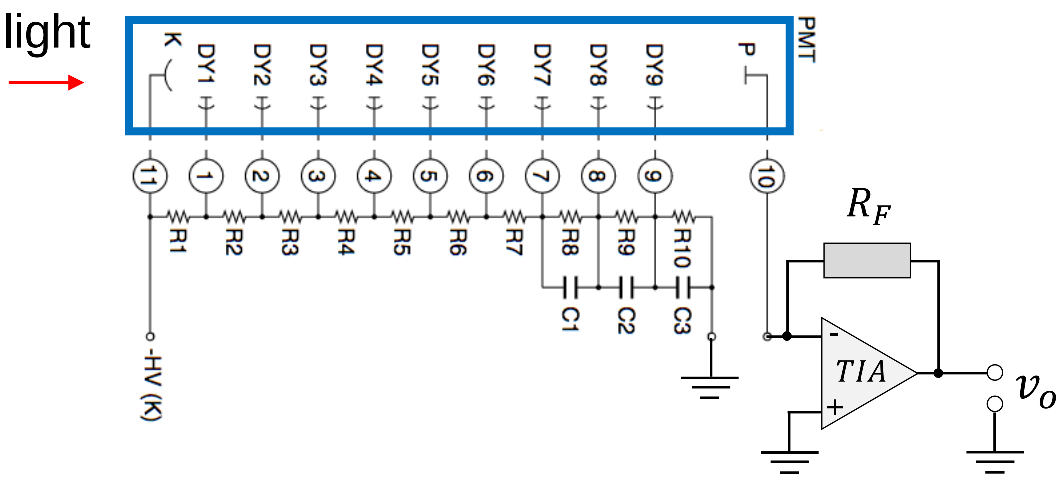
μ – Gain

Terminal capacitance C does not depend on the size of the active area; it is on the order of tens of pF. The value of R is very high, $\sim 10^8\ \Omega$ and more.

Anode-grounded operation

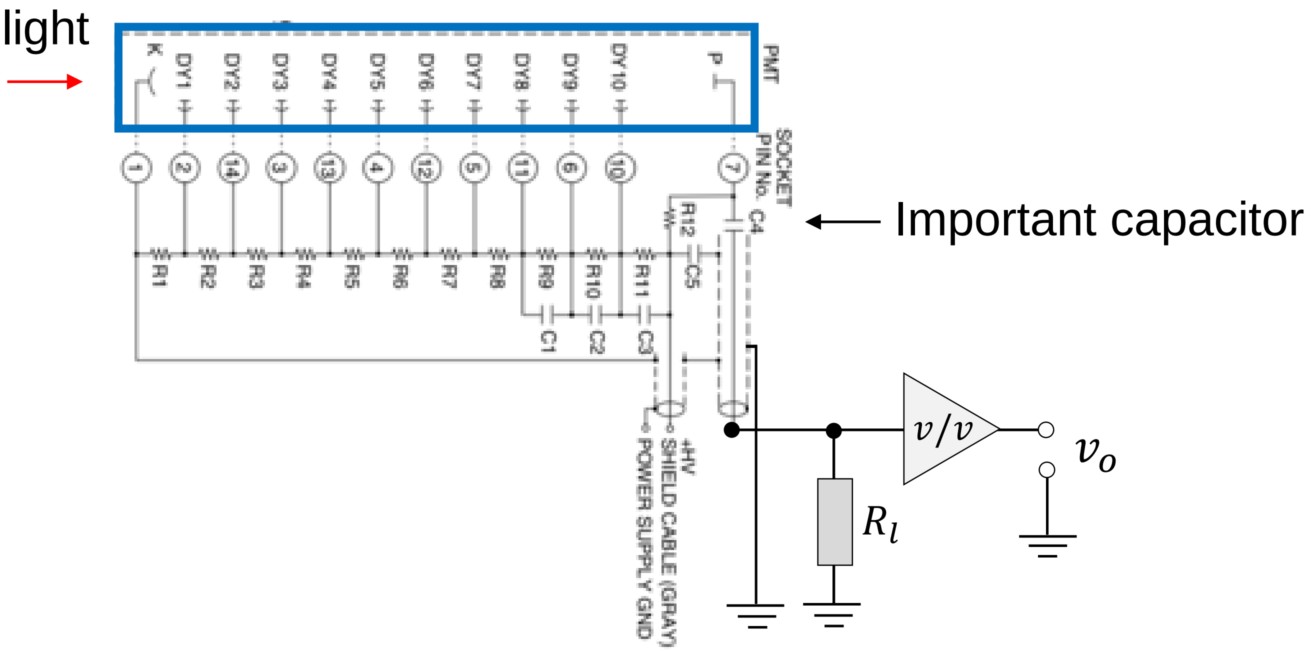


Anode-grounded operation with a resistive termination and voltage-to-voltage amplifier



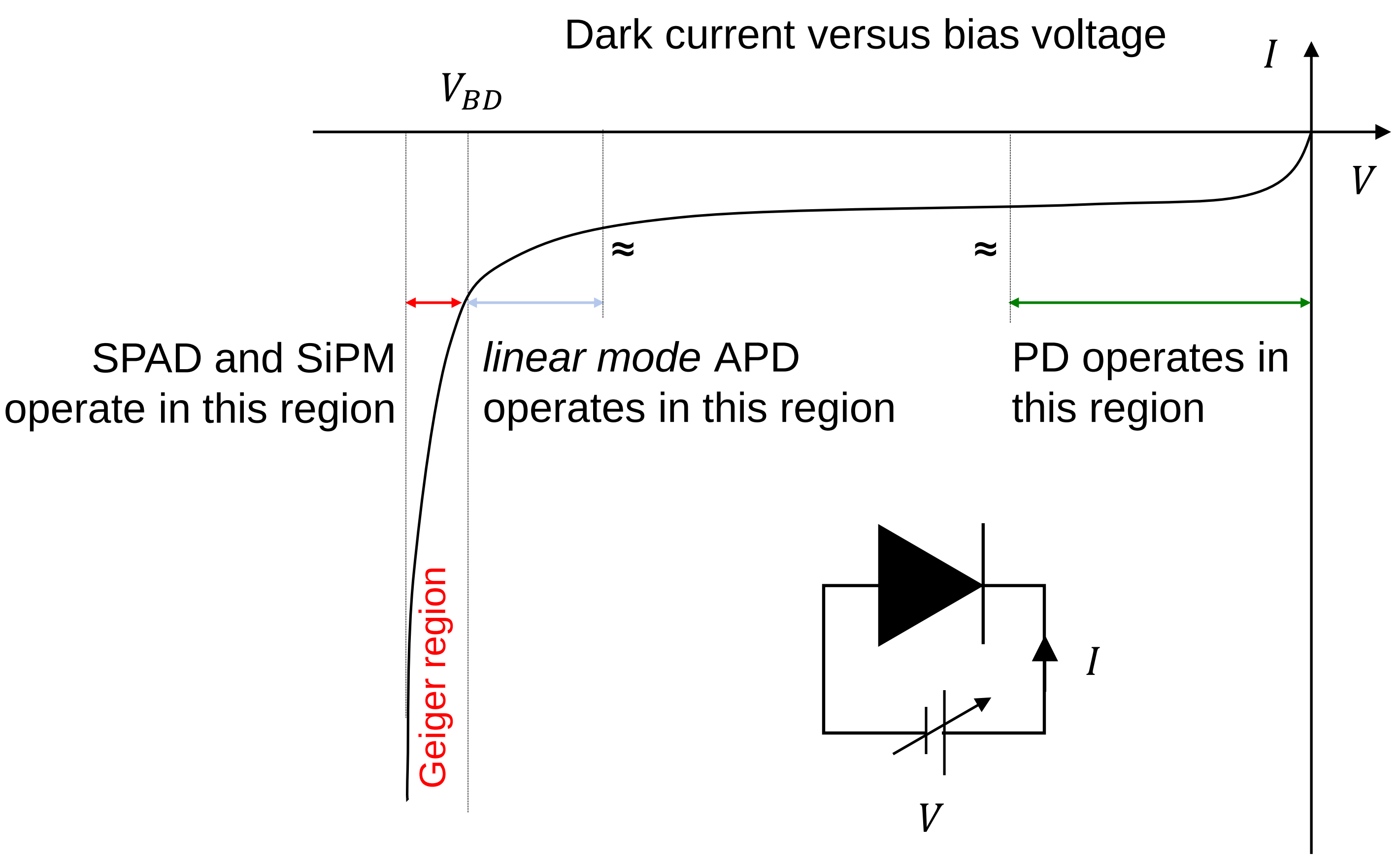
Anode-grounded operation with a transimpedance amplifier

Cathode-grounded operation

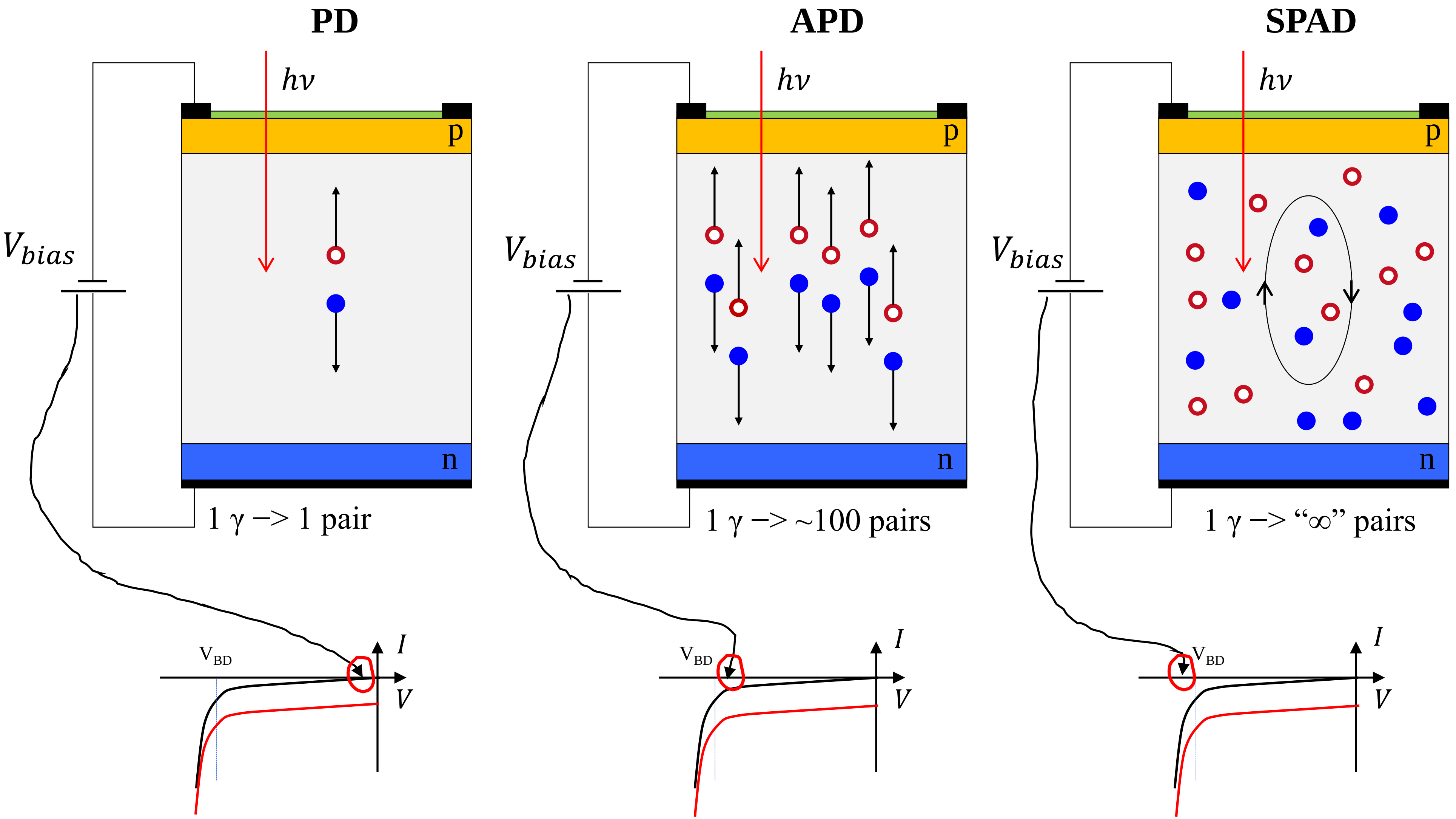


Cathode grounded operation, common in scintillation-based applications.

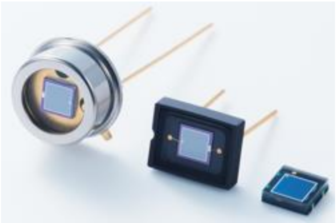
Generic PN junction: regimes of operation

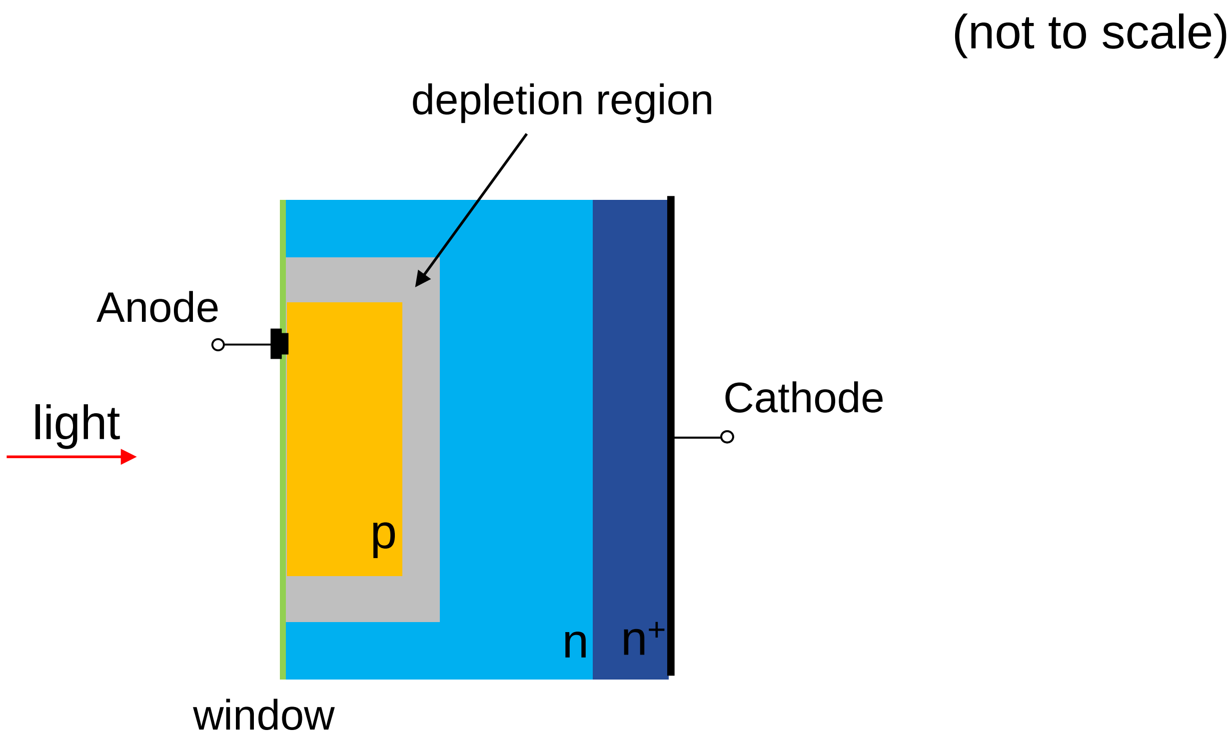


Impact ionization



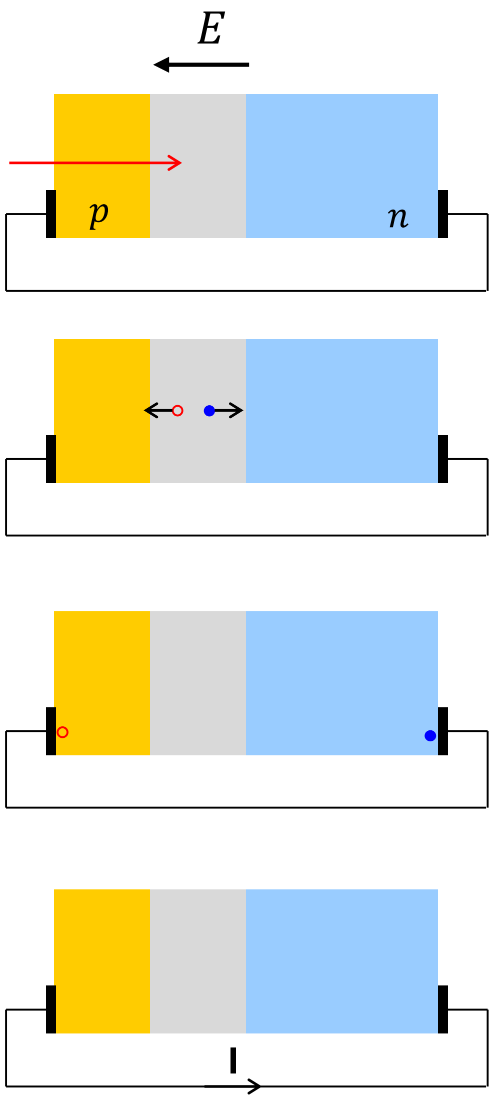
Photodiode





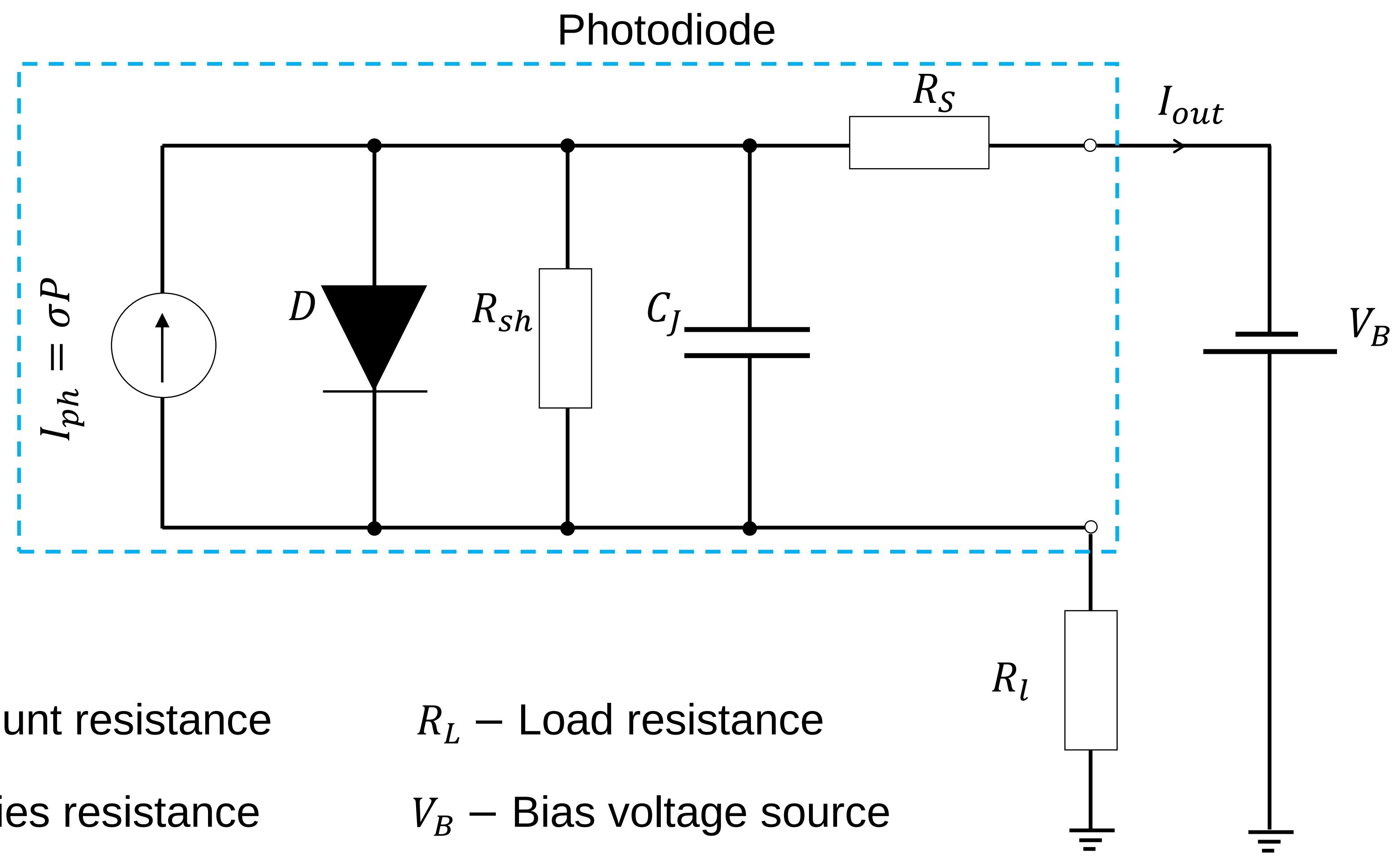
The basic structure of a photodiode.

Photodiode



1. An incident photon is absorbed in the depletion region resulting in mobile electron and hole
2. The built-in electric field causes the hole to drift towards the p region and the electron towards the n region
3. The hole has migrated to the p region and the electron to the n region
4. The electron flows through the connecting wire to recombine with the hole

Equivalent circuit



R_{sh} – Shunt resistance

R_S – Series resistance

C_J – Junction capacitance

R_L – Load resistance

V_B – Bias voltage source

I_{ph} – Photocurrent

Photodiode modes of operation

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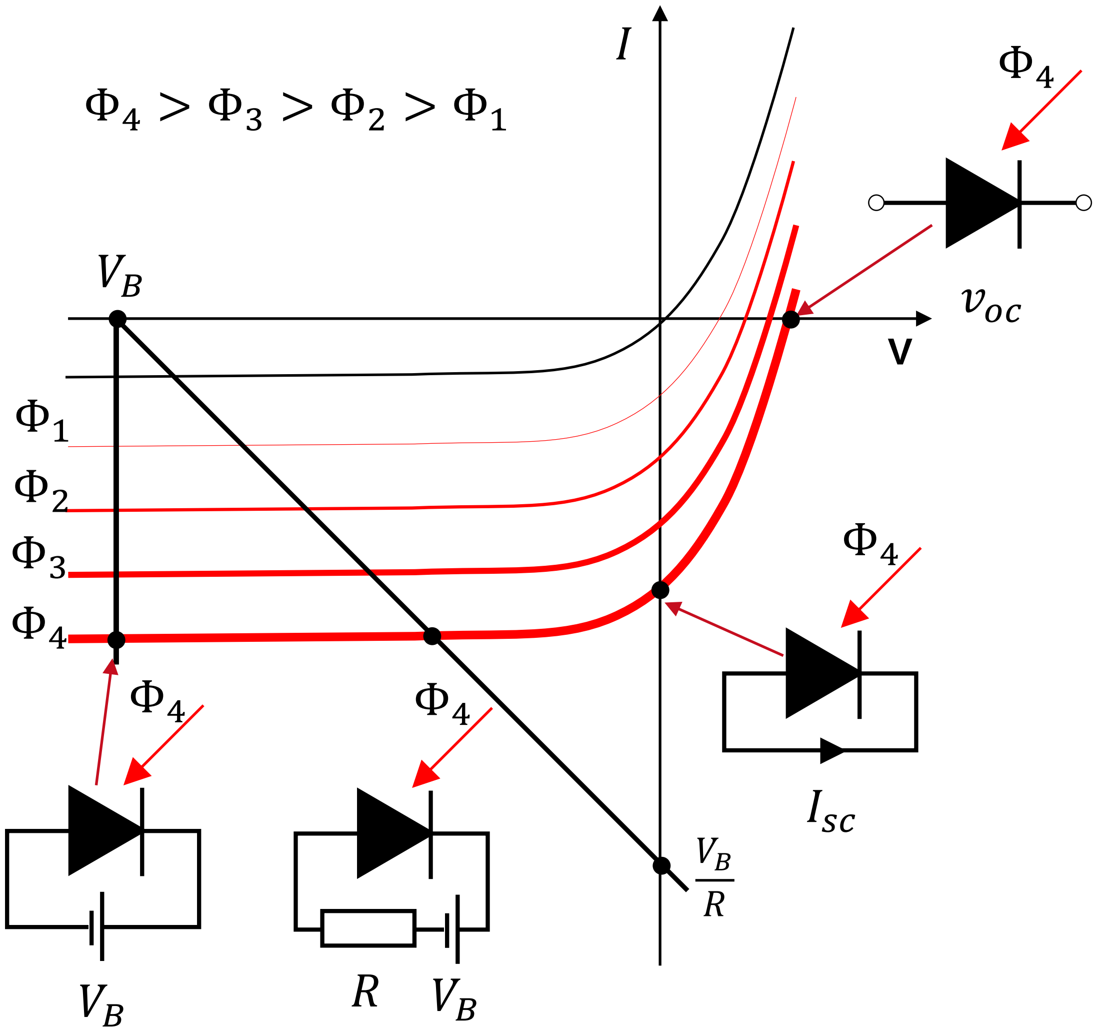


$$I = I_0\left[\exp\left(\frac{qV}{kT}\right) - 1\right] - I_{ph}$$

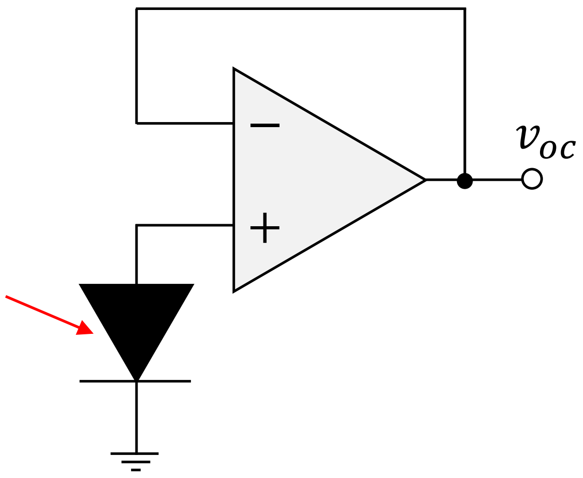
(photodiode equation)

$$v_{oc} = \frac{kT}{q}\ln\left(\frac{I_{ph}}{I_0} + 1\right)$$ (open circuit voltage)

$$I_{sc} \approx I_{ph}$$ (short-circuit current)

$$I_{ph} = \sigma P$$

Open circuit operation

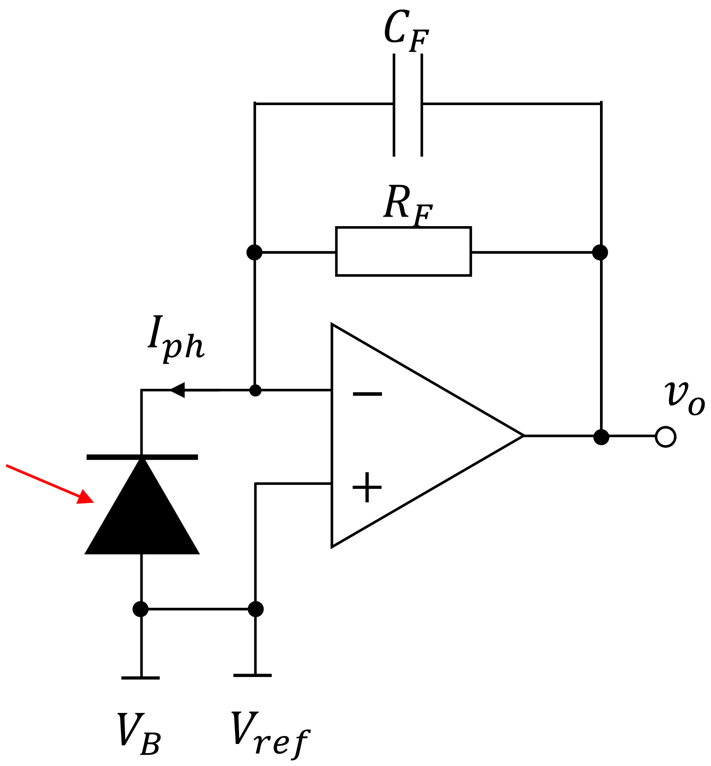


1. Output voltage logarithmically proportional to the incident power
2. Wide dynamic range
3. No dark voltage
4. Small bandwidth (large terminal capacitance)

Open-circuit configuration is often used in absorbance measurements.

$$v_{oc} = \frac{kT}{q} \ln\left(\frac{\sigma P}{I_0} + 1\right)$$

Short-circuit operation



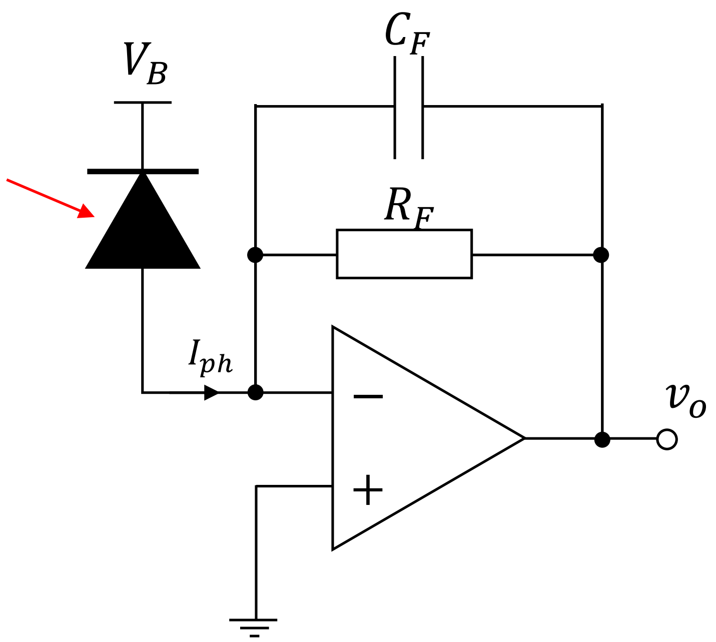
$$V_B = V_{ref}$$

Short-circuit configuration; anode and cathode are at the same potential. One can make $V_B = V_{ref} = 0 =$ ground.

1. Output current/voltage is linearly proportional to the input light power
2. No dark current
3. Limited bandwidth

Short-circuit operation is commonly used in light power meters.

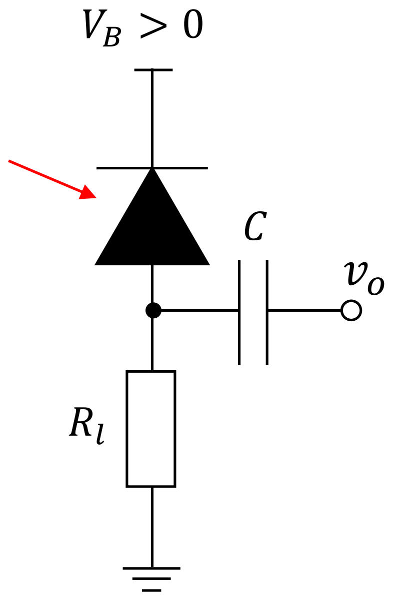
Biased operation with TIA



1. Bandwidth increases with V_B
2. Linear response but dynamic range limited by amplifier saturation
3. Dark current
4. At high-frequency operation, the TIA may exhibit gain peaking and instabilities.

This is one of the most popular configurations.

Biased operation with a resistive load

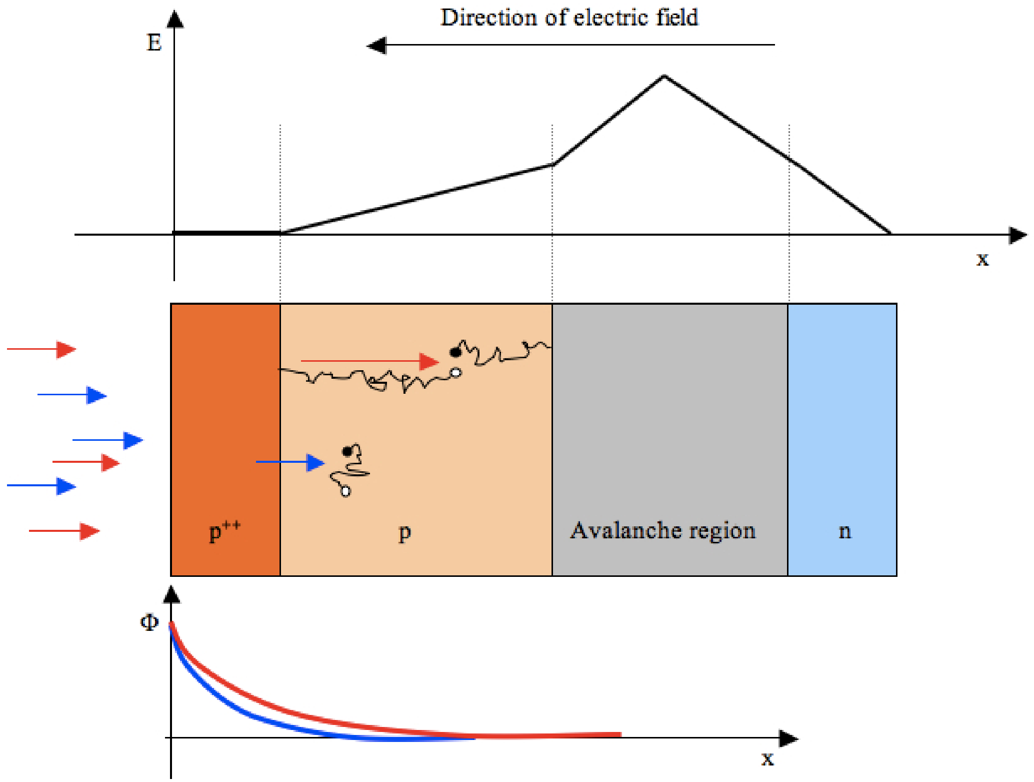


Capacitor for AC/pulse operation

1. Simpler noise behavior compared to TIA
2. No amplifier saturation
3. Bandwidth/signal amplitude tradeoff (as R_l increases)
4. Linearity/signal amplitude tradeoff (as R_l increases)

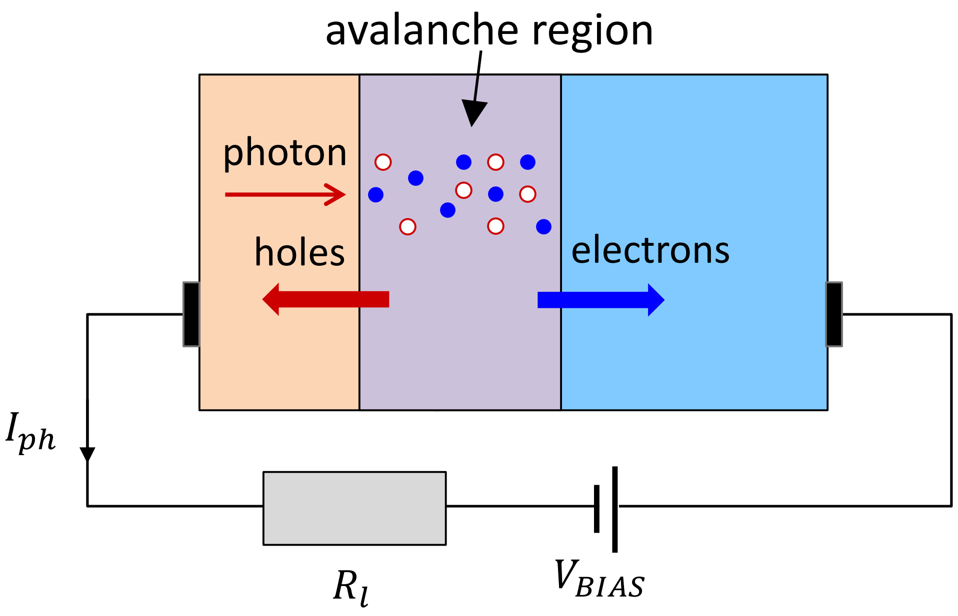
Avalanche photodiode

Not to scale

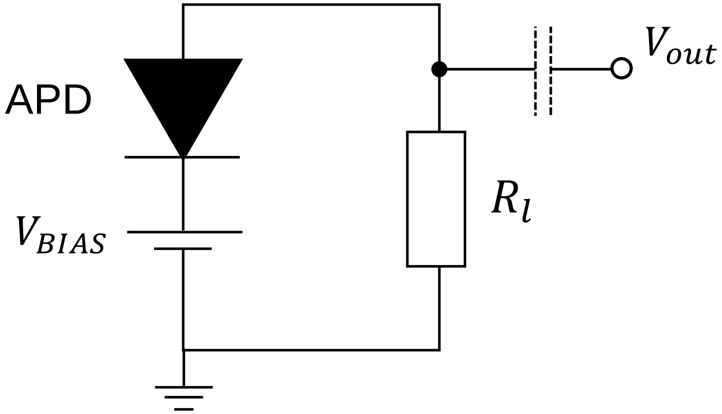


A possible structure of an APD

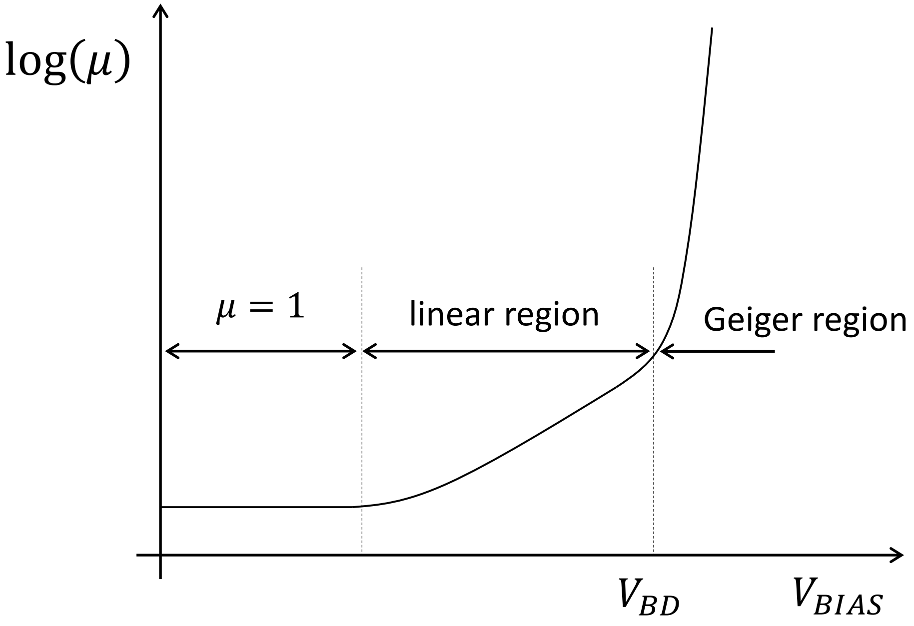
Avalanche photodiode

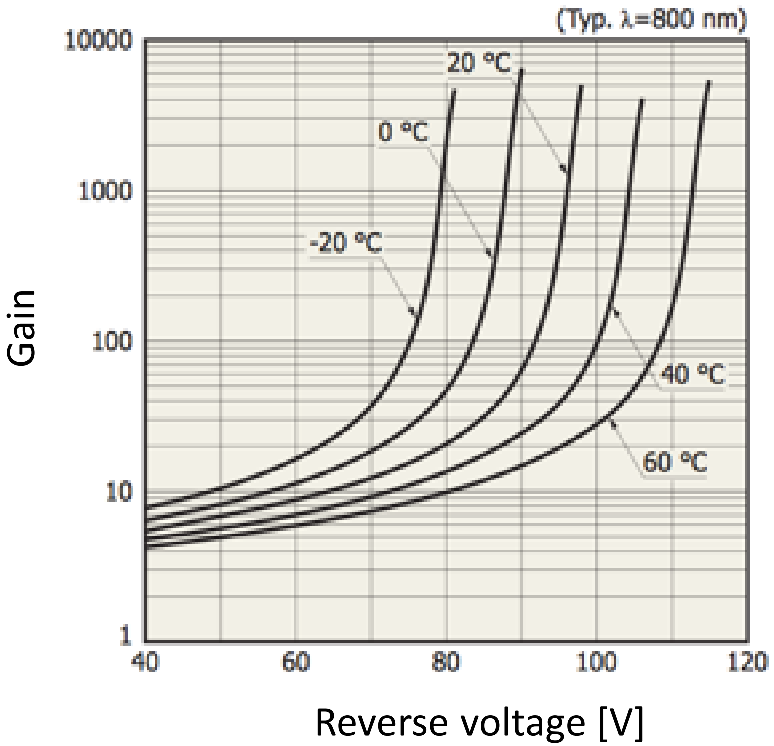


- APD is biased below breakdown voltage
- Single photon can lead up to about 100 electron-hole pairs
- Avalanche is self quenching
- Excess noise factor, $F \approx \mu^{x}$, where $x \approx 0.3 - 0.4$



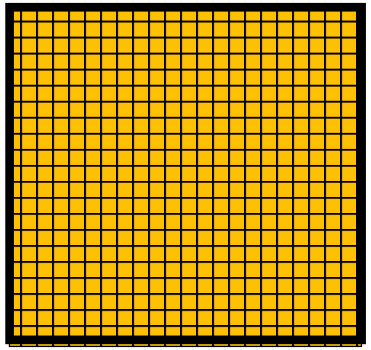
Modes of operation



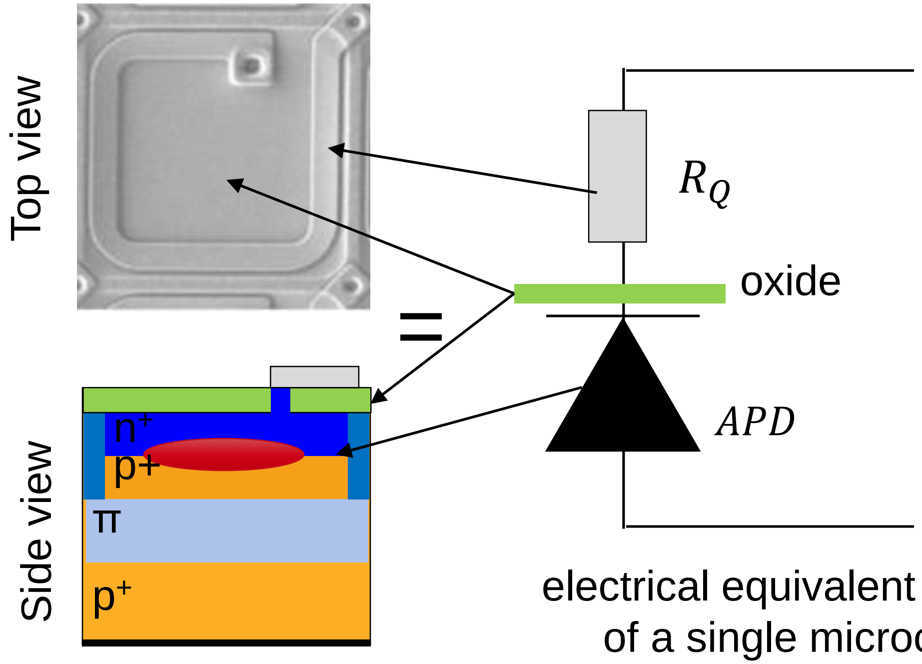


Note how the gain depends on reverse voltage and temperature

Silicon Photomultiplier

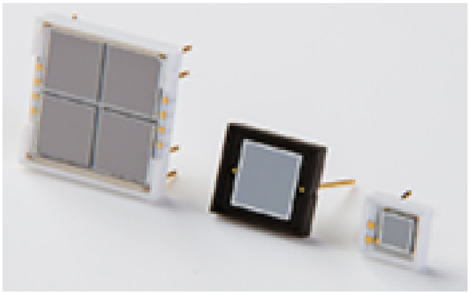


SiPM is an array of microcells



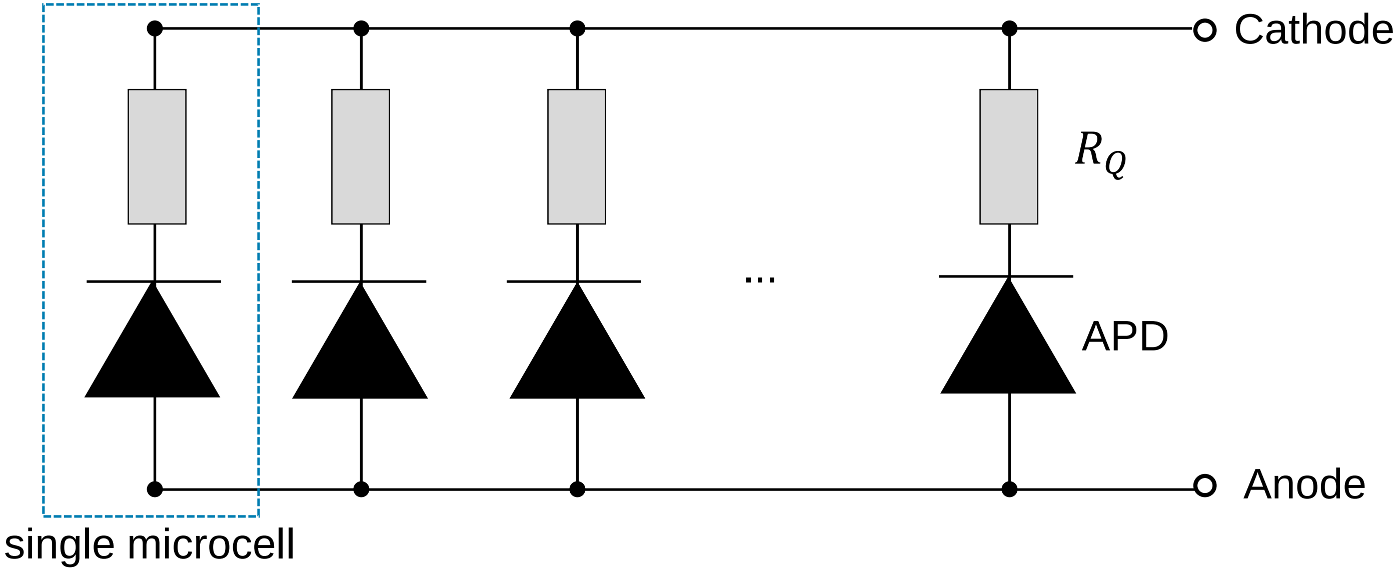
Single microcell

electrical equivalent circuit
of a single microcell



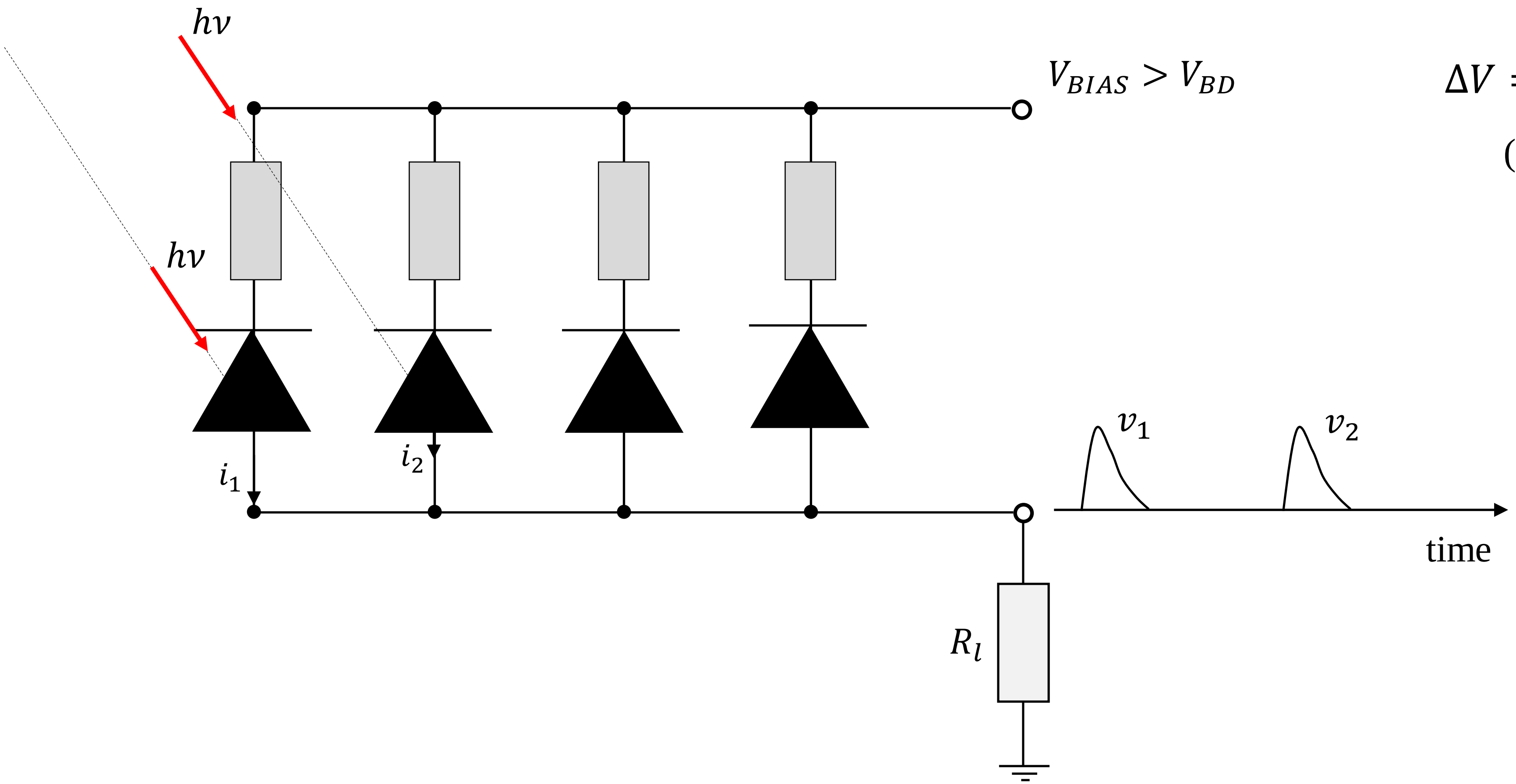
Also known as multi-pixel photon counter (MPPC)

SiPM: Structure



All of the microcells are connected in parallel.

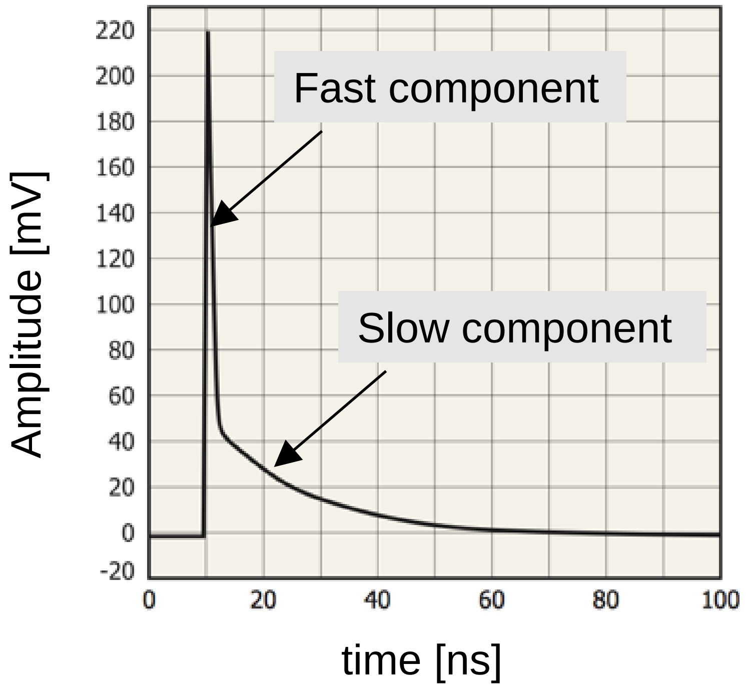
Operation



$$\Delta V = V_{BIAS} - V_{BD}$$

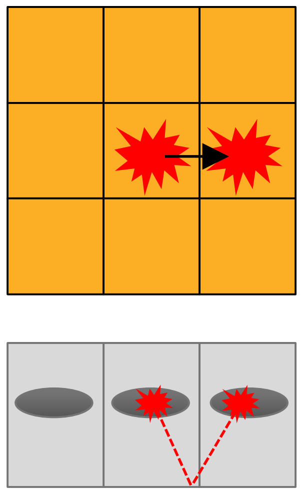
(overvoltage)

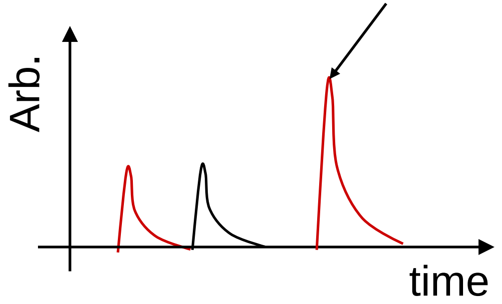
Anatomy of a pulse



- The RC time constant of the slow component depends on microcell size (all else being equal)
- The recovery time $t_r \approx 5 \times$ the RC time constant
- t_r is on the order of 10s to 100s of ns but in practical situations it is also a function of the detection bandwidth

Crosstalk

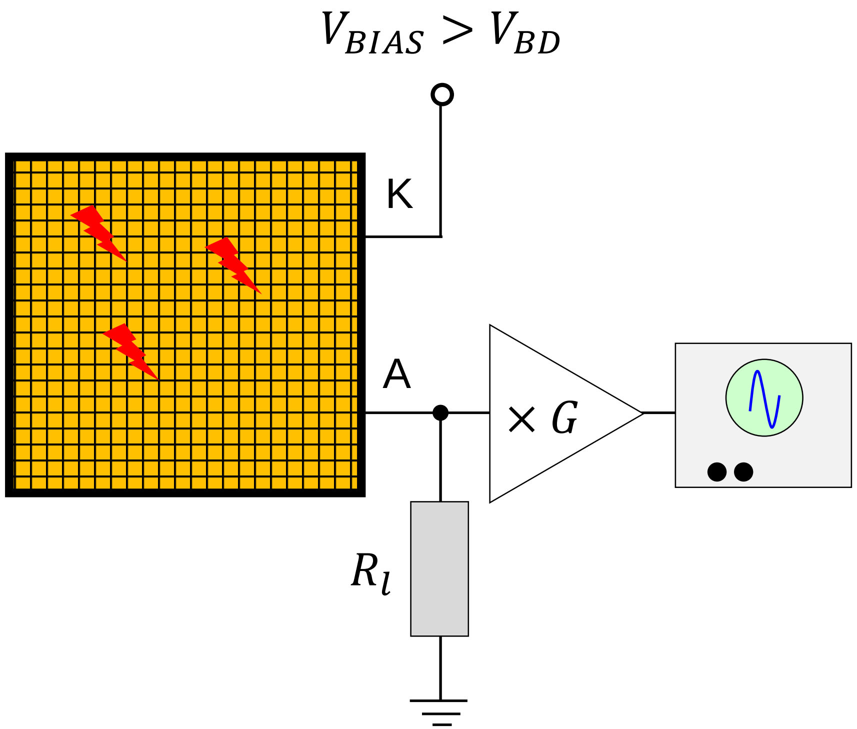


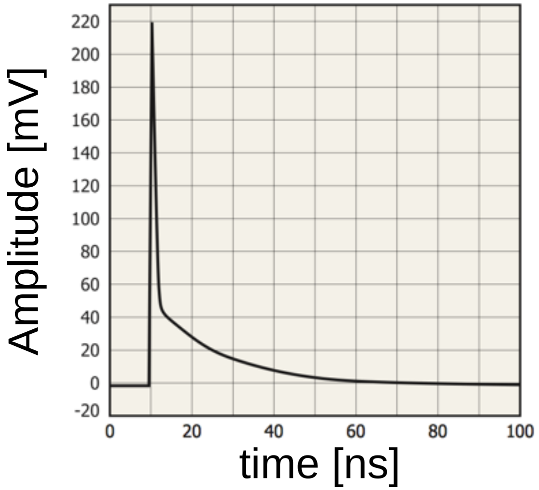


Primary discharge can trigger a secondary discharge in neighboring microcells. This is crosstalk.

Crosstalk probability depends on overvoltage.

SiPM: Gain





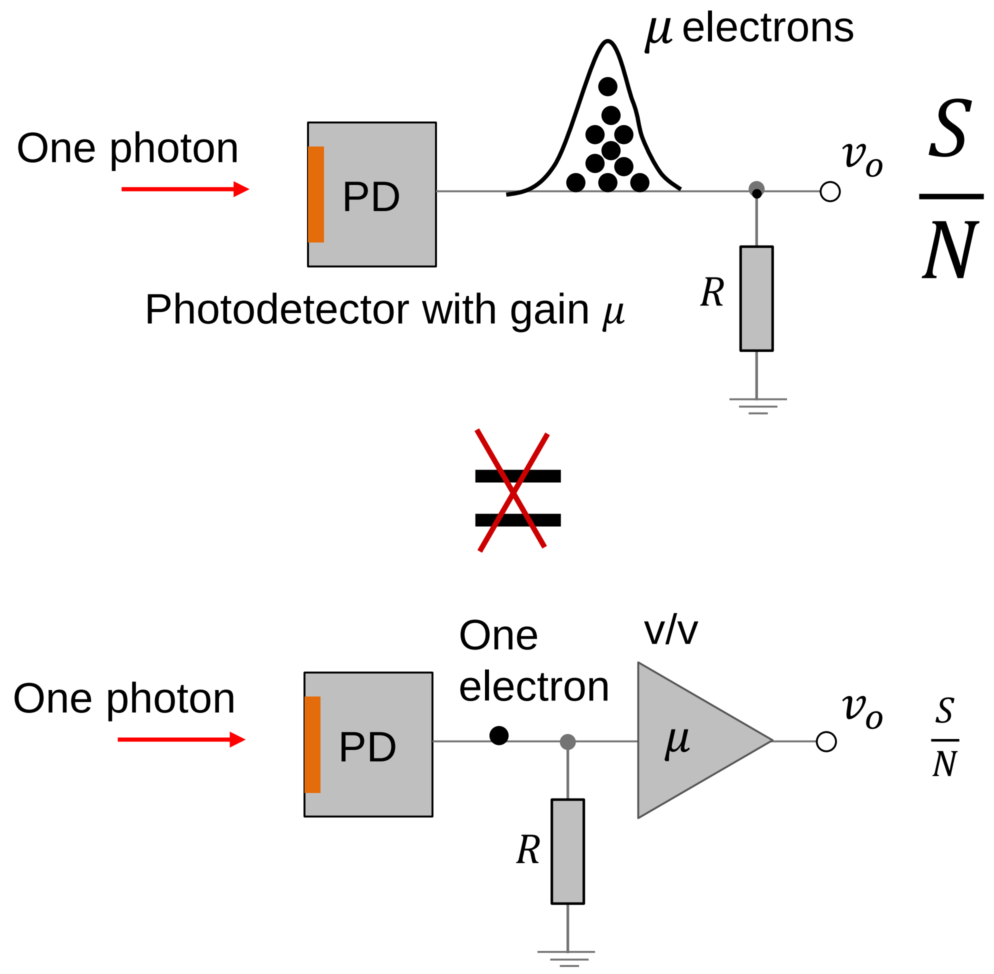
Example of single-photoelectron waveform (1 p.e.)

Gain = area under the curve in electrons

$$\mu = \frac{(V_{BIAS} - V_{BD})C_J}{e} = \frac{\Delta V \cdot C_J}{e}$$

$$F \approx 1 + P_{ct}$$

Importance of intrinsic gain



Importance of intrinsic gain

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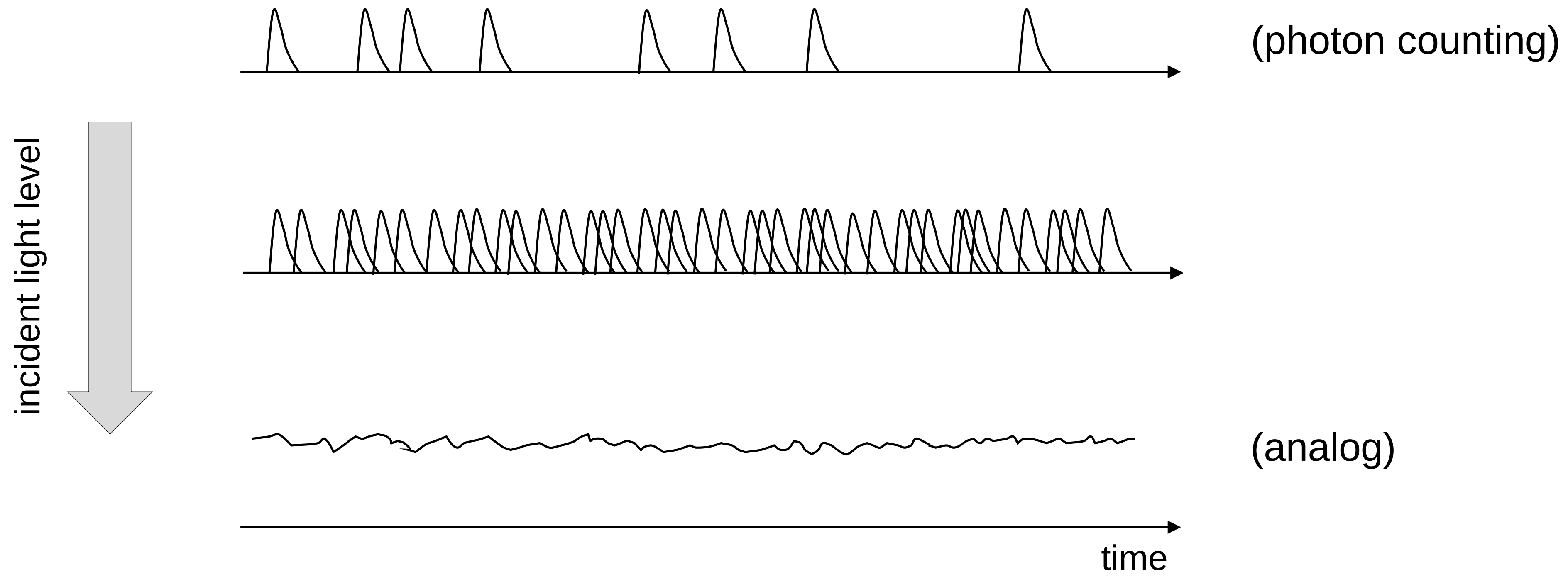
$$\frac{S}{N} = \frac{P \cdot \sigma \cdot \mu}{\sqrt{2eB[(P + P_B)\sigma + I_D]F\mu^2 + \frac{4kTB}{R}}} = \frac{P \cdot \sigma}{\sqrt{2eB[(P + P_B)\sigma + I_D]F + \frac{4kTB}{R\mu^2}}}$$

If μ is very large

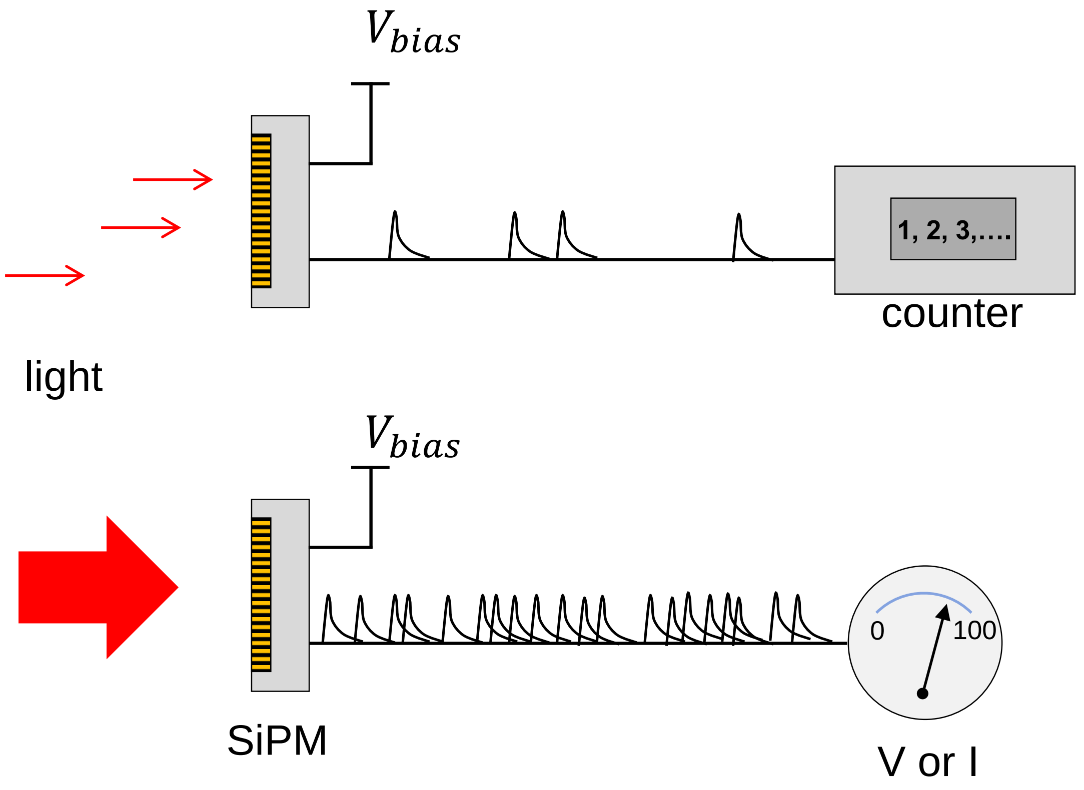
$$\frac{S}{N} = \frac{P \cdot \sigma}{\sqrt{2eB[(P + P_B)\sigma + I_D]F}}$$

Intrinsic gain suppresses noise contribution to $^{S}/_{N}$ from the front-end electronics.

Modes of operation



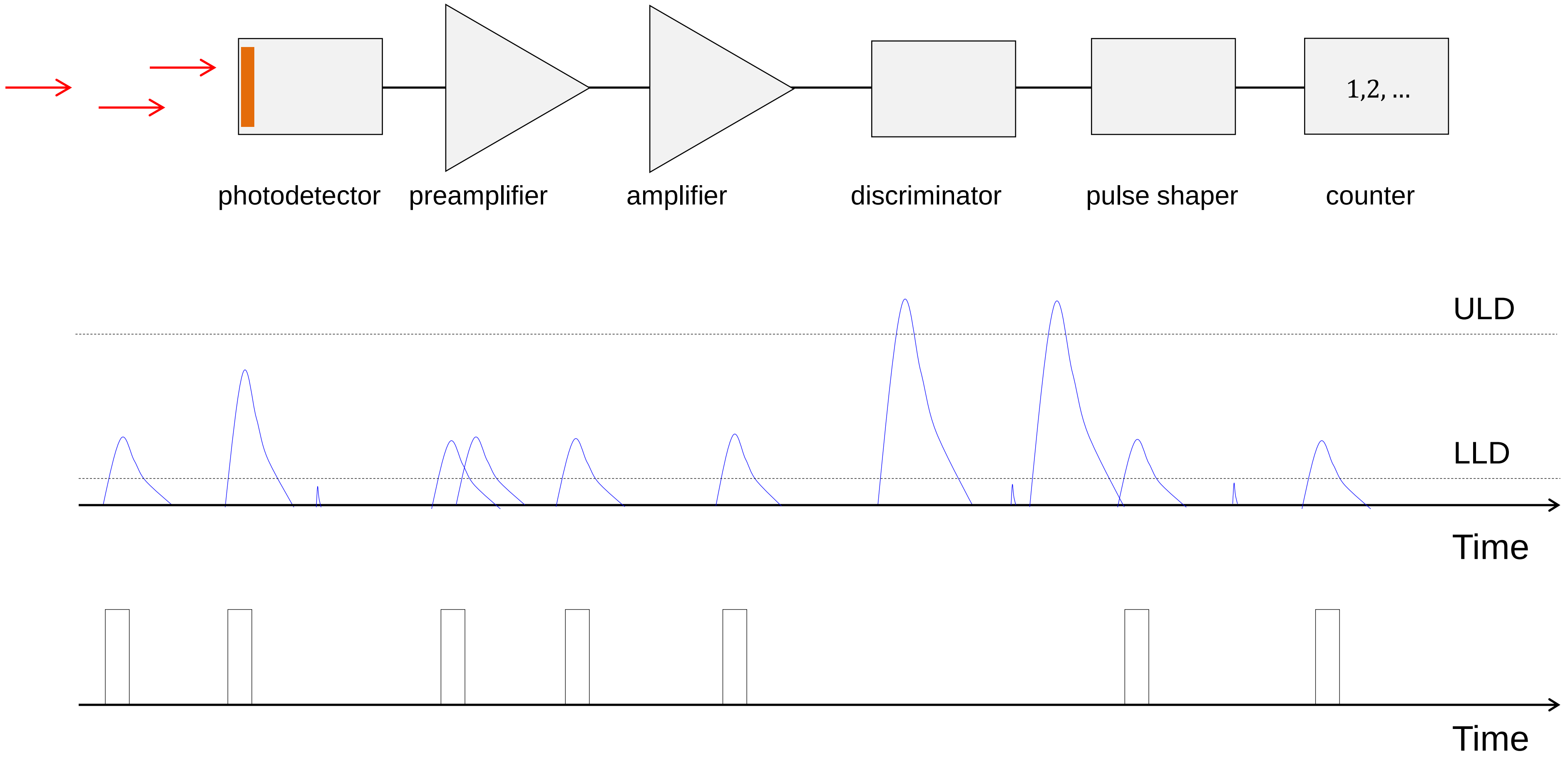
Modes of operation



If the pulses are distinguishable, SiPM can be operated in a **photon counting** mode.

If the pulses overlap, the SiPM can be operated in an **analog mode**. The measured output is voltage or current.

Photon counting



Photon Counting: signal to noise ratio

$$\frac{S}{N} = \frac{n_S\sqrt{T_{exp}}}{\sqrt{n_S + 2(n_B + n_D)}}$$

T_{exp} – measurement time

$n_S = n_{tot} - (n_B + n_D)$

n_{tot} – number of counts per unit time due to “science” light, background light, and dark counts

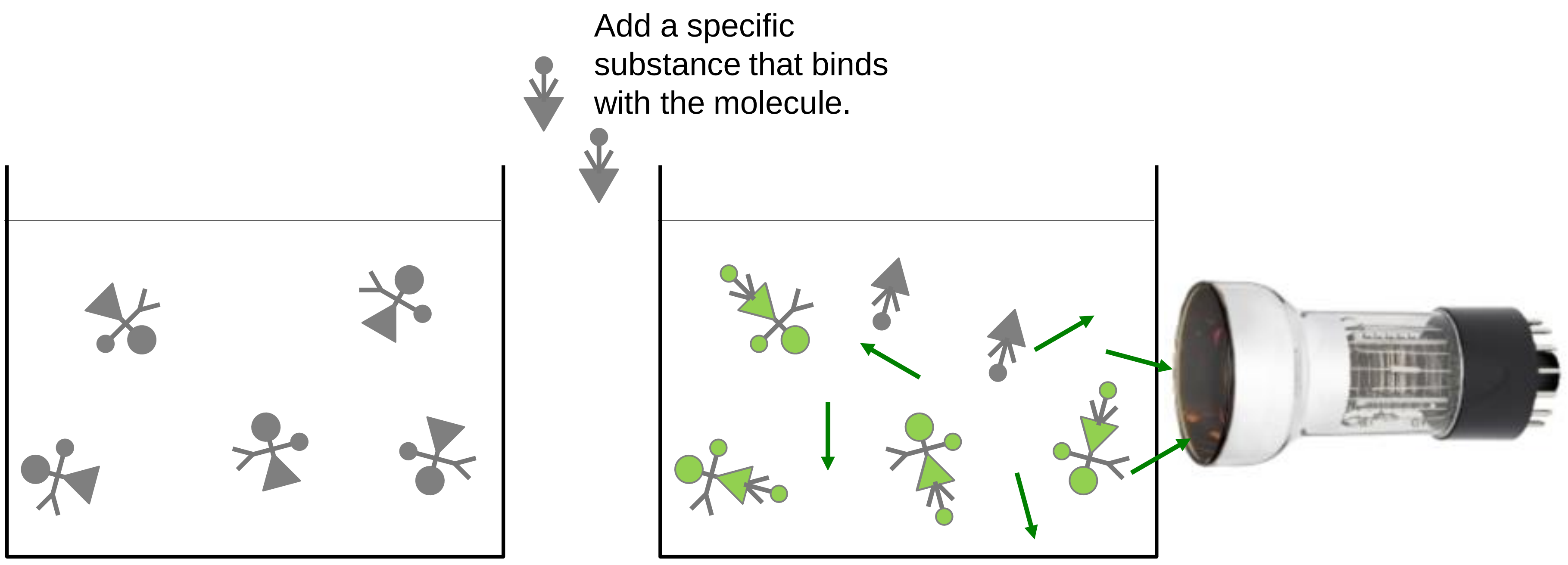
n_B – number of counts per unit time due to background light

n_D – number of counts per unit time due to dark current

All rates are measured with the same exposure time T_{exp}

Applications of photodetectors

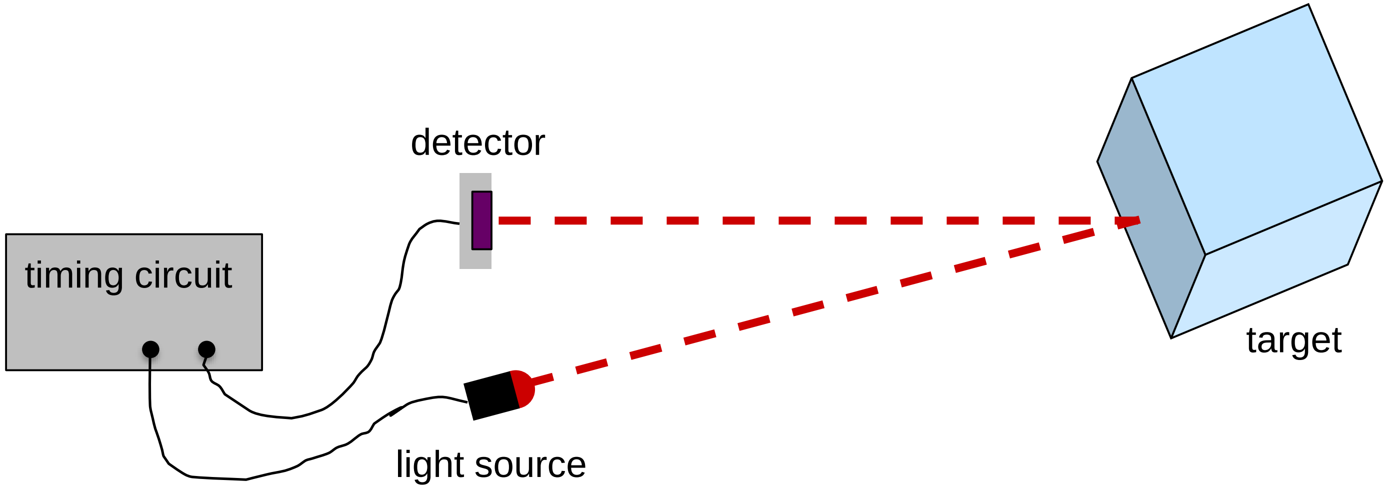
Application where a PMT Excels: bioluminescence



Emitted light is slowly-varying, weak, and diffuse

- PMT's large active area, low dark current, and high gain make it suitable for this application

Application where a PMT is not Ideal: time of flight LiDAR



$$d = \frac{c\Delta t}{2n}$$

Δt – round-trip time of flight

d – distance to the target

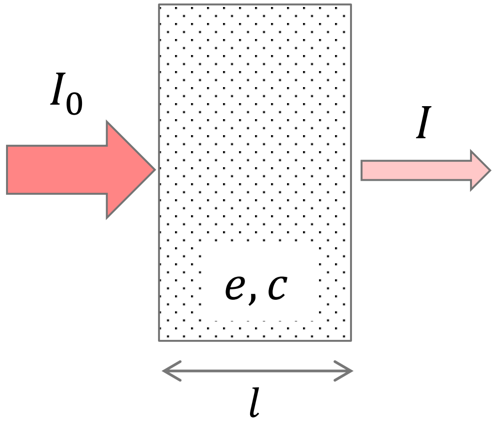
c – speed of light

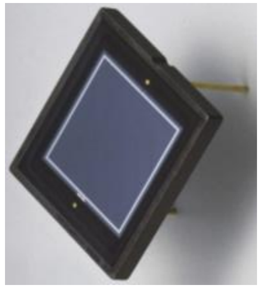
n – index of refraction

- PMT is not ideal because it is mechanically fragile* and has limited dynamic range.

* Ruggedized models of PMTs exist and are used in oil logging

Application where a Photodiode Excels: absorbance





$$A = -log_{10}\left(\frac{I}{I_0}\right) = ecl$$

High intensity DC light

A – Absorbance; the Beer-Lambert Law

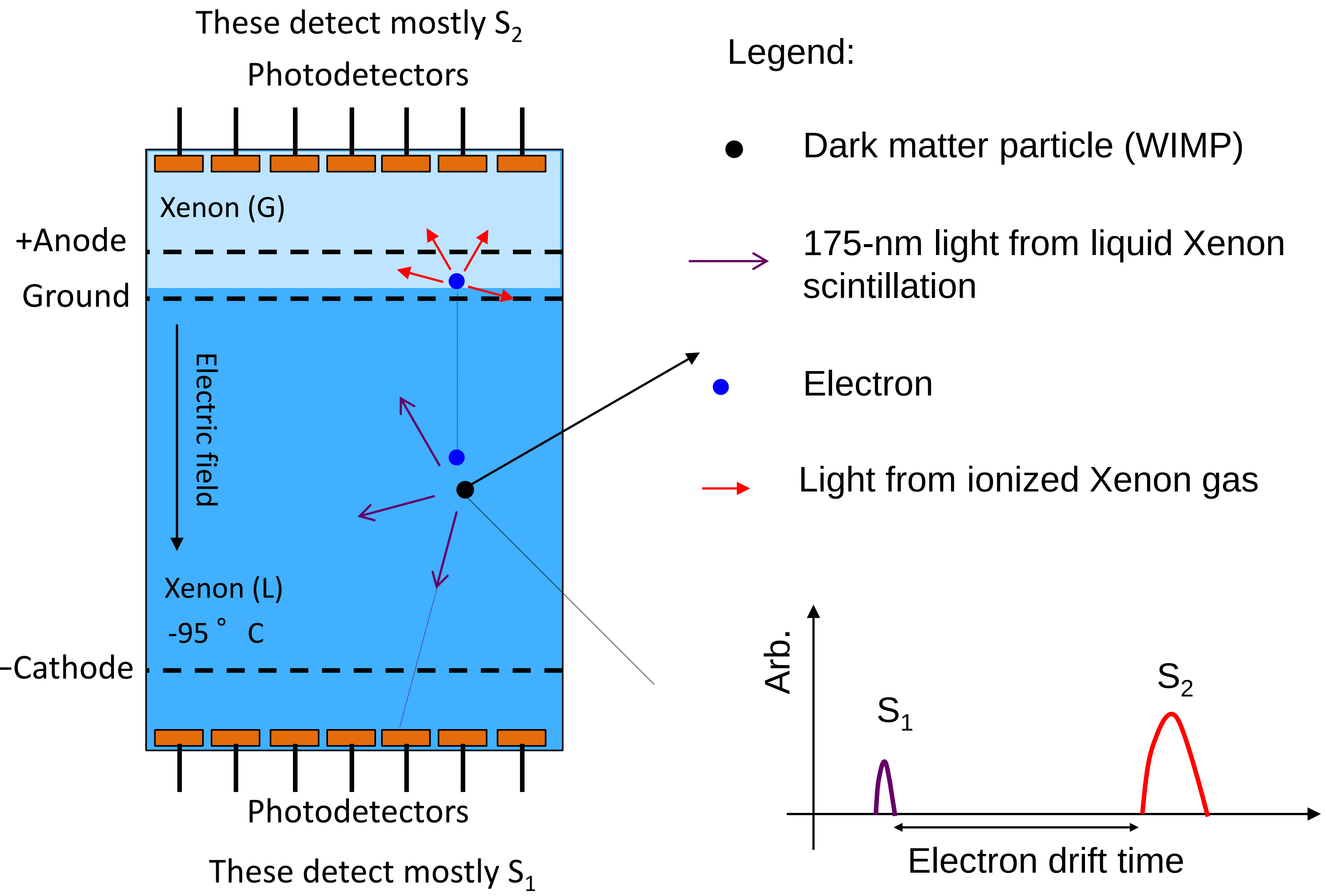
e – Molar absorptivity in L mol^{-1} cm^{-1}; wavelength dependent

c – Concentration of the compound in mol L^{-1}

l – (Path length of light in the sample in cm)

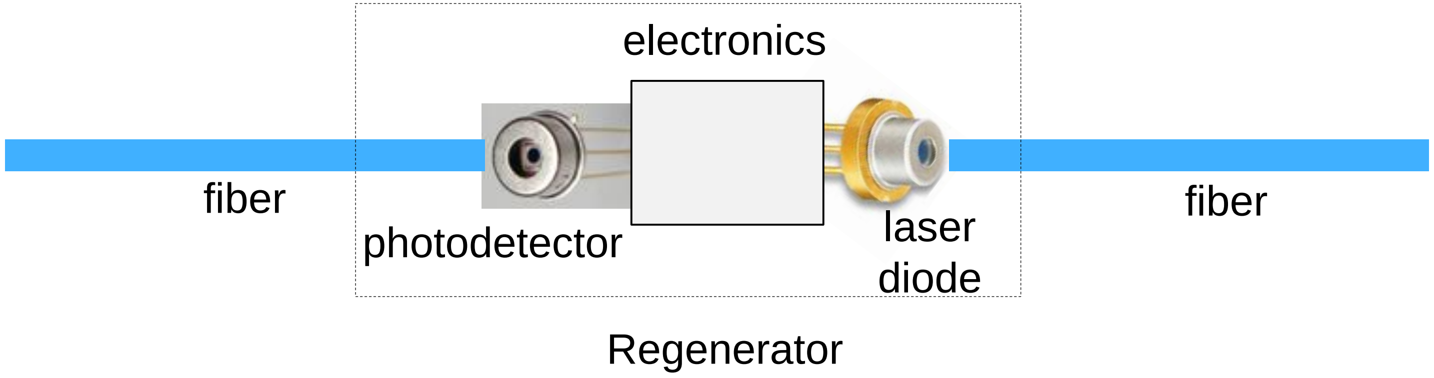
- Low cost and very high dynamic range make a photodiode a good choice for this application.

Application where a Photodiode is not ideal: dark matter detection



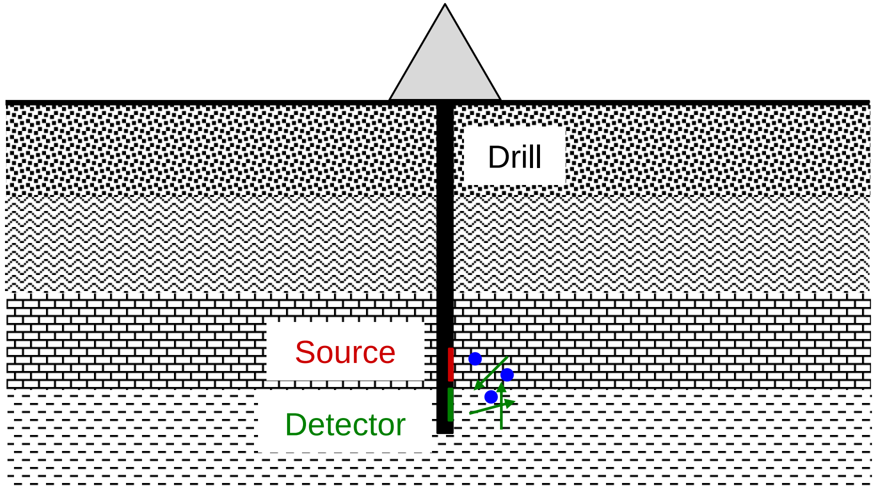
- A photodiode doesn't have intrinsic gain, which is an advantage in low-light detection.

Application where an APD Excels: optical fiber communication



- High dynamic range, intrinsic gain, and wide bandwidth make an APD a good choice for this application

Application where an APD is not Ideal: Oil Logging



1. The source emits radiation (e.g., gamma rays or neutrons) into the surrounding rock
2. The radiation interacts with the surrounding rock
3. The detector detects scattered radiation
4. The nature of the radiation provides information about the rock's density, porosity, or chemical composition

- Gain of an APD is very sensitive to changes in temperature, which is a negative for this application.

Application where a SiPM Excels: PET

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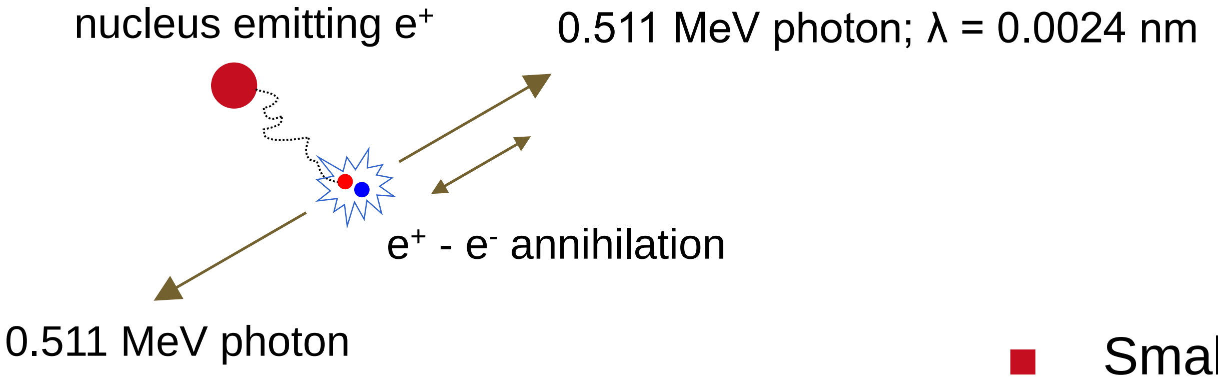
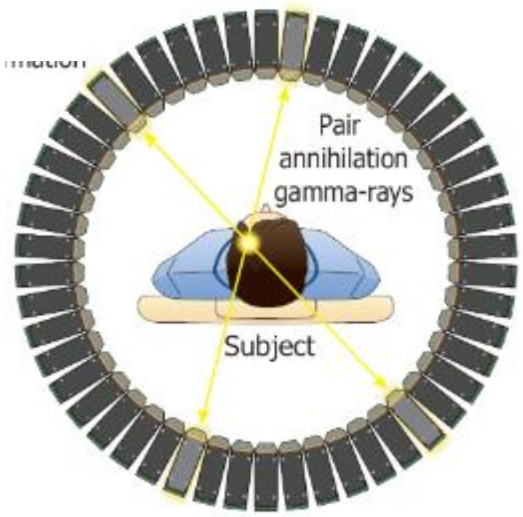
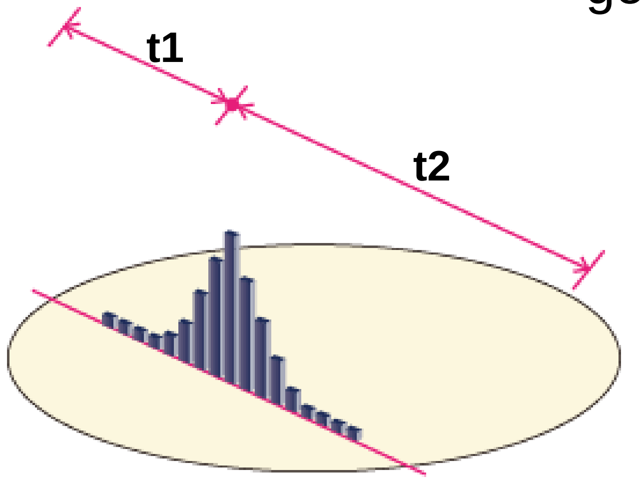
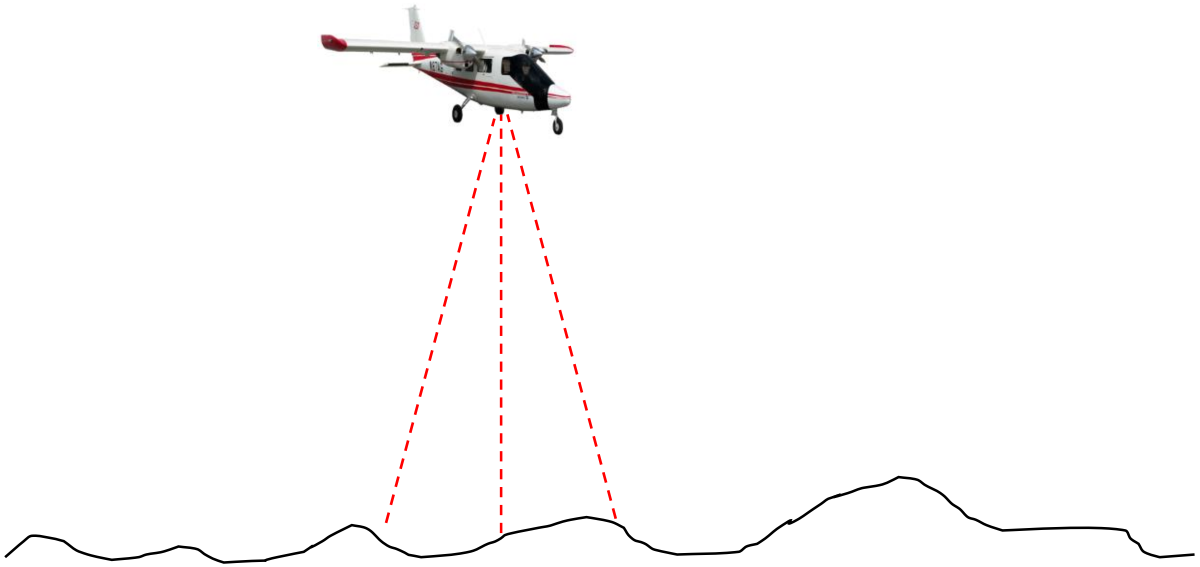


- Small active area, high intrinsic gain, and good response in blue make a SiPM a good choice for this application.





Application where a SiPM is not Ideal: Survey LiDAR



1. Infrared lasers are used for better transmittance through the air
2. Knowing the location of the airplane (GPS) and measuring the distance between the plane and the ground, the ground's topography can be determined
3. The distance can be measured using the time-of-flight technique

- SiPM has a limited to no response in IR

Selecting a photodetector

WIT$

- Many factors can play a role in the selection process of a photodetector. However, in many cases, the selection can be made using five basic, albeit crucial, criteria: W, I, T, S, and $.

W – wavelength of light

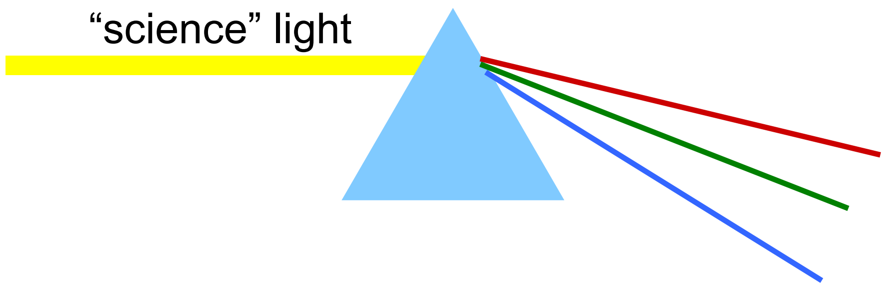
I – intensity (amount of light or light power)

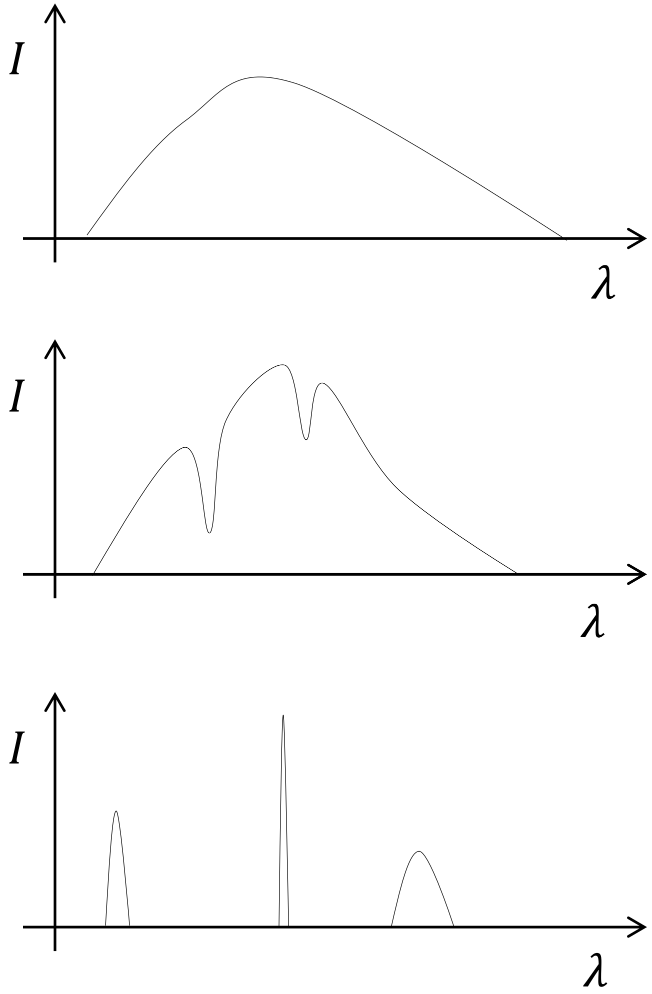
T – temporal (time characteristic of light: DC, AC, pulse)

S – spatial (spatial distribution of light: diffuse, collimated)

$ – price

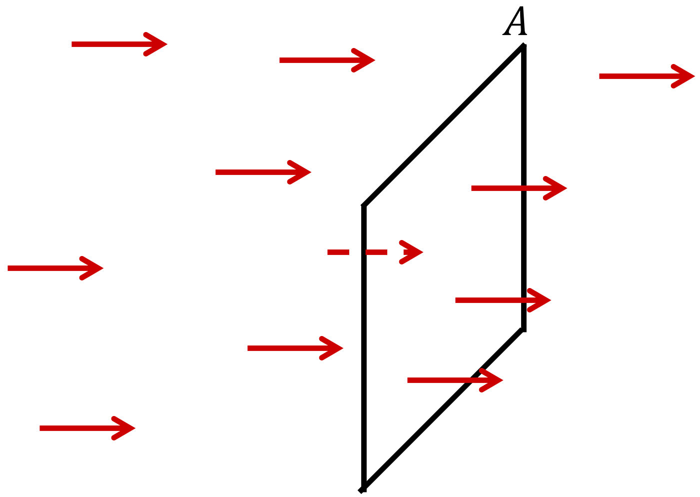
Characteristics of Light: Spectral Composition





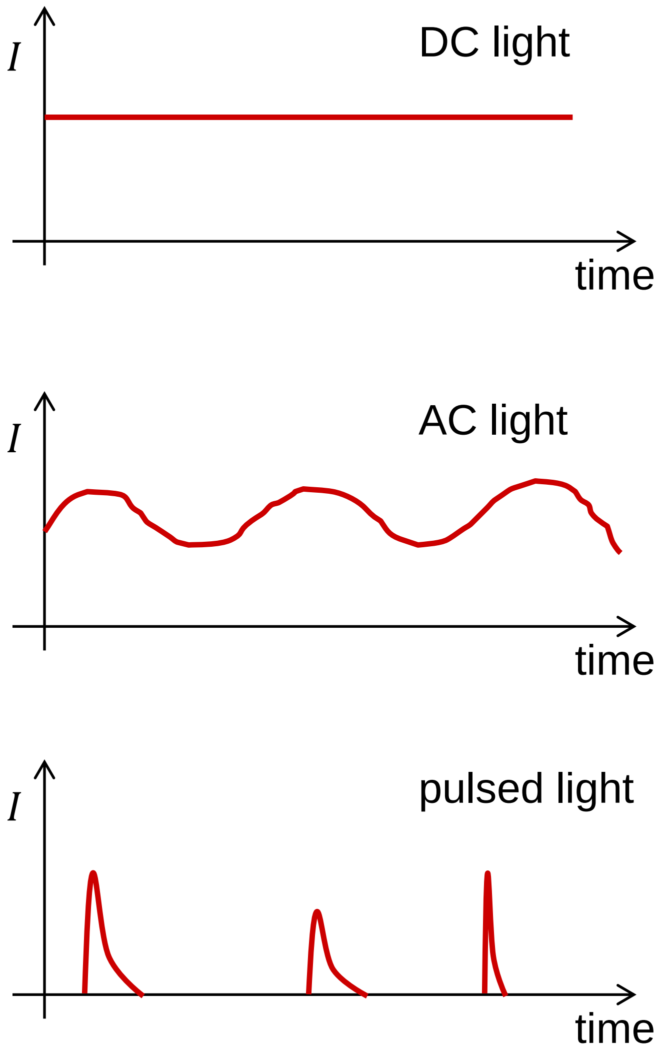
In many applications we often deal with monochromatic light.

Characteristics of Light: Intensity

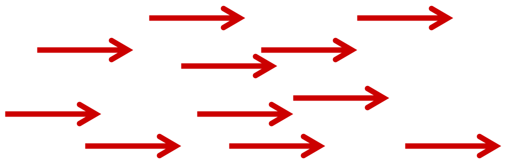


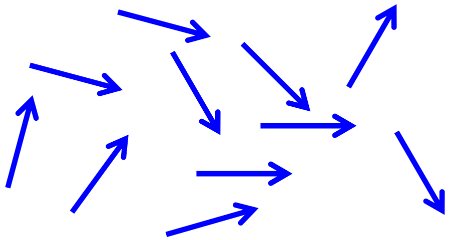
Intensity or irradiance is a measure of the amount of light passing through a unit area A. It can be expressed in number of photons per unit area per unit time or in Watts per unit area.

Characteristics of Light: Temporal



Characteristics of Light: Spatial

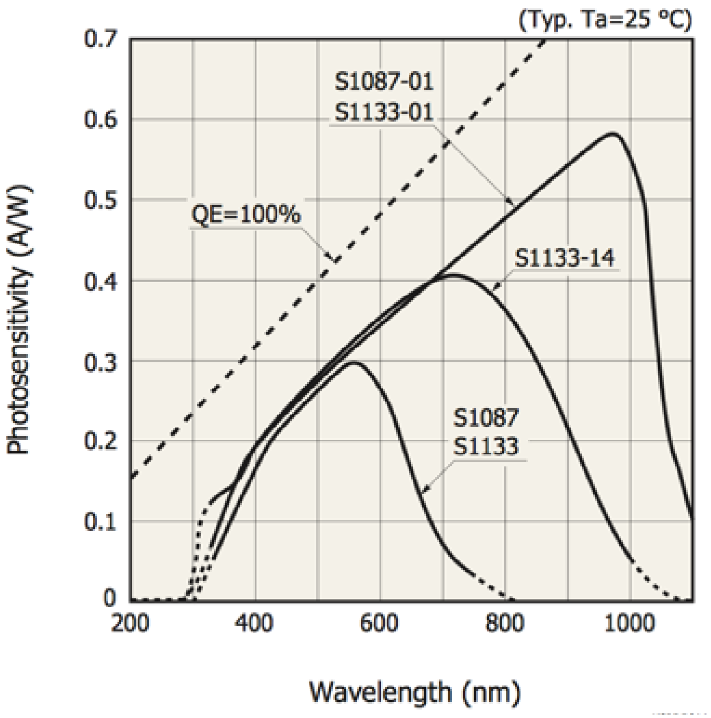

collimated light

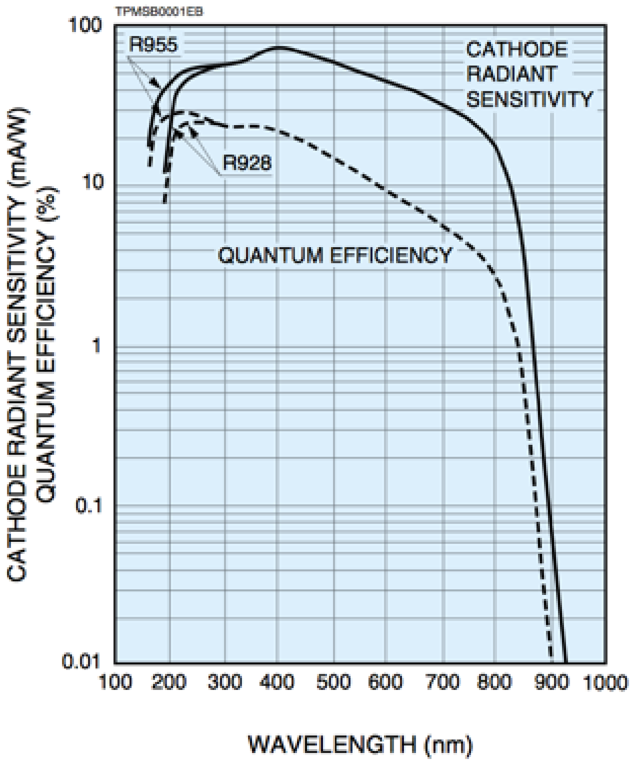

diffuse light

Collimated light can be focused with a lens, while diffuse light cannot be.

Selection Based on Wavelength

Photodetector must have photosensitivity at the “science” wavelength.





Examples of spectral sensitivity curves for a photodiode (left) and a PMT. Manufacturers provide such information for a photodetector (type and family).

Selection Based on Intensity

- Given the amount of input science light, the photodetector together with front-end electronics must produce $\frac{S}{N} > 1$. One needs to estimate the expected $\frac{S}{N}$.

<u>Some points to consider:</u>

1. A complete estimate of *S/N* should include contribution to noise from the detection circuit (e.g., a resistor or transimpedance amplifier). This contribution becomes less significant for a photodetector with internal gain, and this fact alone is the reason for a gain in a photodetector

2. The minimum detectable power is a function of detection bandwidth. Higher bandwidth increases noise and, therefore, increases the minimum detectable power. Alternatively, higher bandwidth lowers *S/N* for a given power of input light.

3. Large bandwidth is desirable if high fidelity is required: the output electrical signal accurately reproduces the input light signal.

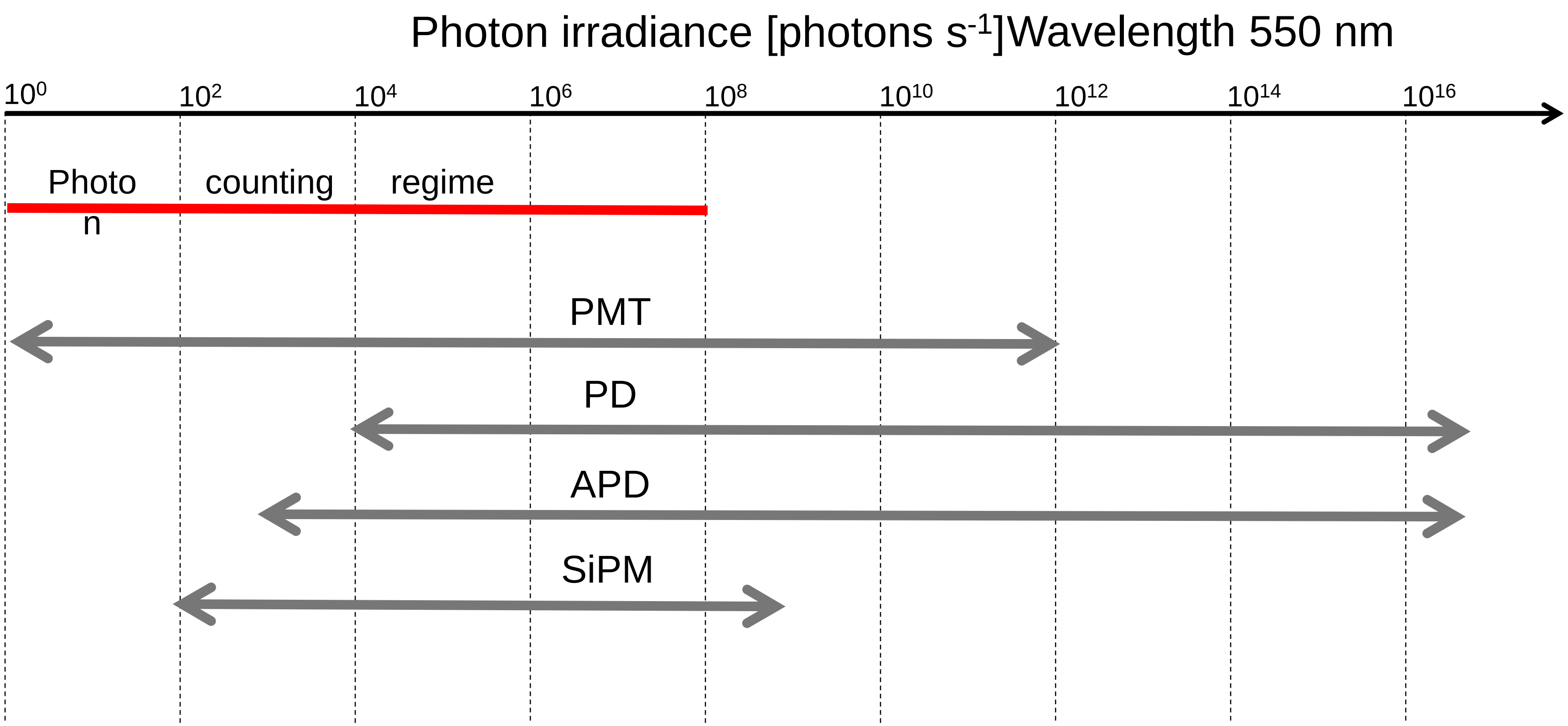
Selection Based on Intensity

4. The minimum detectable power for a given bandwidth is always larger than NEP for the same bandwidth.

5. Terminal capacitance of the photodetector affects the detection bandwidth: the higher the capacitance, the smaller the bandwidth.

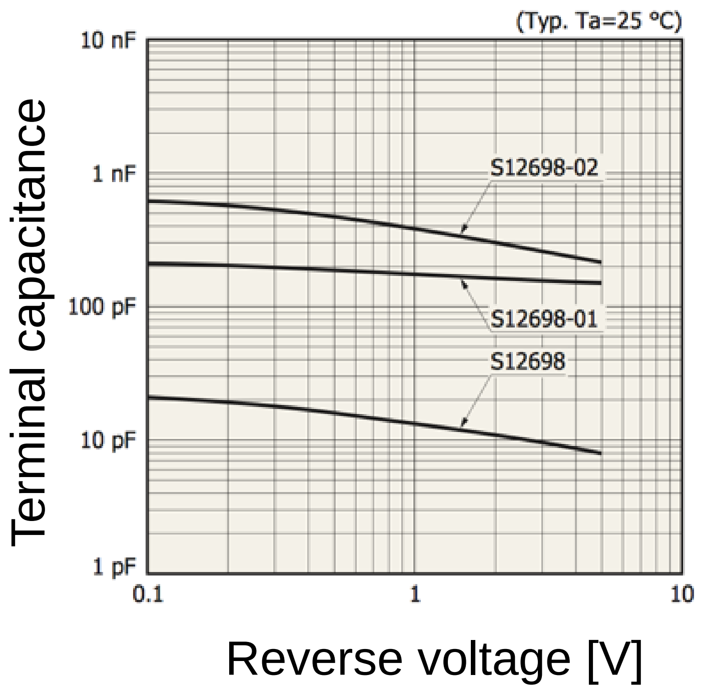
6. For the solid-state photodetectors (but not for PMTs), a larger active area causes a larger terminal capacitance, which decreases the detection bandwidth. Consequently, there is a tradeoff between sensitivity and bandwidth or sensitivity and signal fidelity.

Selection Based on Intensity



For each photodetector, the double arrow gives an approximate range of measurable the incident photon irradiance.

Selection Based on Temporal Characteristics



Terminal capacitance as a function of voltage for a photodiode.

1. DC light poses no additional restrictions on the photodetector
2. For AC and pulsed light, capacitances – junction, parasitic, or terminal – matter: their values affect the output signal rise time, time jitter, and detection bandwidth.
3. Except for PMTs, terminal capacitance increases with an active area.

Selection Based on Spatial Characteristics

1. If the level of incoming light is low but the light is nearly collimated, employing focusing optics can increase the incident light power on the detector, and, thus, improve the $\frac{S}{N}$. If, however, the incoming light is diffuse, focusing optics will not increase the incident power (diffuse light cannot be focused); the only other option is to use a detector with a larger active area.

2. The tradeoff is a higher dark current in the photodetector, which increases noise and, therefore NEP. As discussed above, in the case of a PD, APD, and SiPM (but not PMT), a larger active area reduces the detection bandwidth due to a larger junction capacitance.

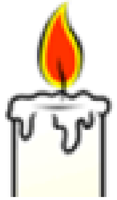
Selection Based on Price

1. If the selection process based on WIT$ did not yet produce a unique and outstanding choice (unlikely but possible), the price may be able the break the tie.

2. The prices can vary greatly among the different models of a photodetector in a given family; however, when the typical representatives of the families are compared, the highest to lowest prices are for a PMT, SiPM, APD, and PD.

3. This is a price for a stand-alone photodetector. If the potential user needs to design the detection setup from "ground up," the cost of auxiliary equipment such as power supplies, amplifiers, etc. should also be considered

Other Considerations



temperature stability

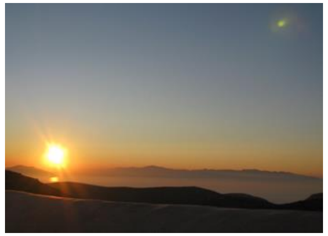
magnetic immunity

radiation immunity/damage

power consumption

ruggedness; resistance to shock and vibrations

size, geometrical constraints



dynamic range

time jitter

environmental: humidity, helium rich, corrosive, vacuum, ambient light, etc.

Thank you

Thank you for listening

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1 Weeks Break				
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5	Introduction to Image Sensors	2	30-Jun-20	02-Jul-20
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