Developments in photon detection: Silicon Photo-Multipliers and their applications

PhD in Experimental Physics
XXXIV ciclo

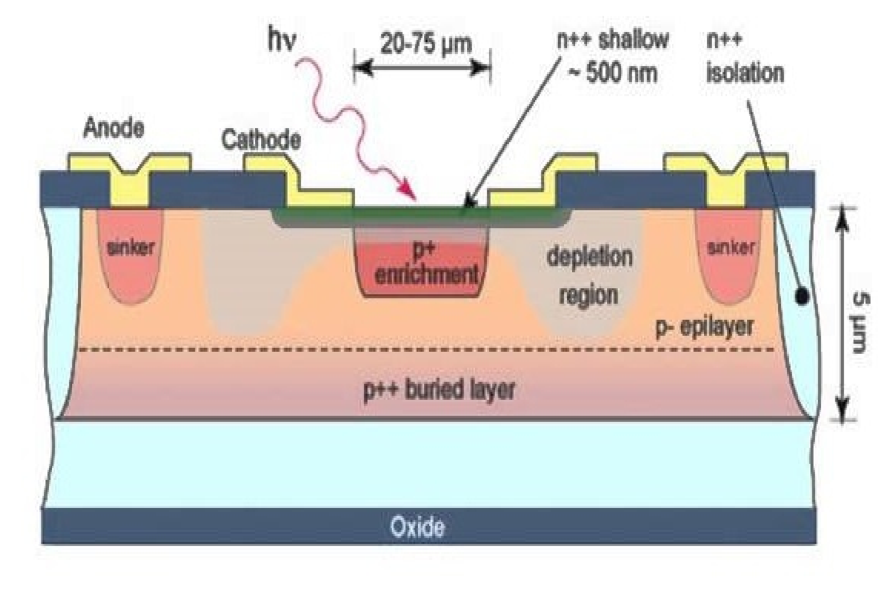
Professor:
Pier Simone Marrocchesi

Student:
Andrea Vanella

Single Photon Avalanche Photodiode

SPADs are semiconductor devices based on a p–n junction reverse-biased at a voltage V_{bias} greater than breakdown voltage V_{BD}, Geiger mode.

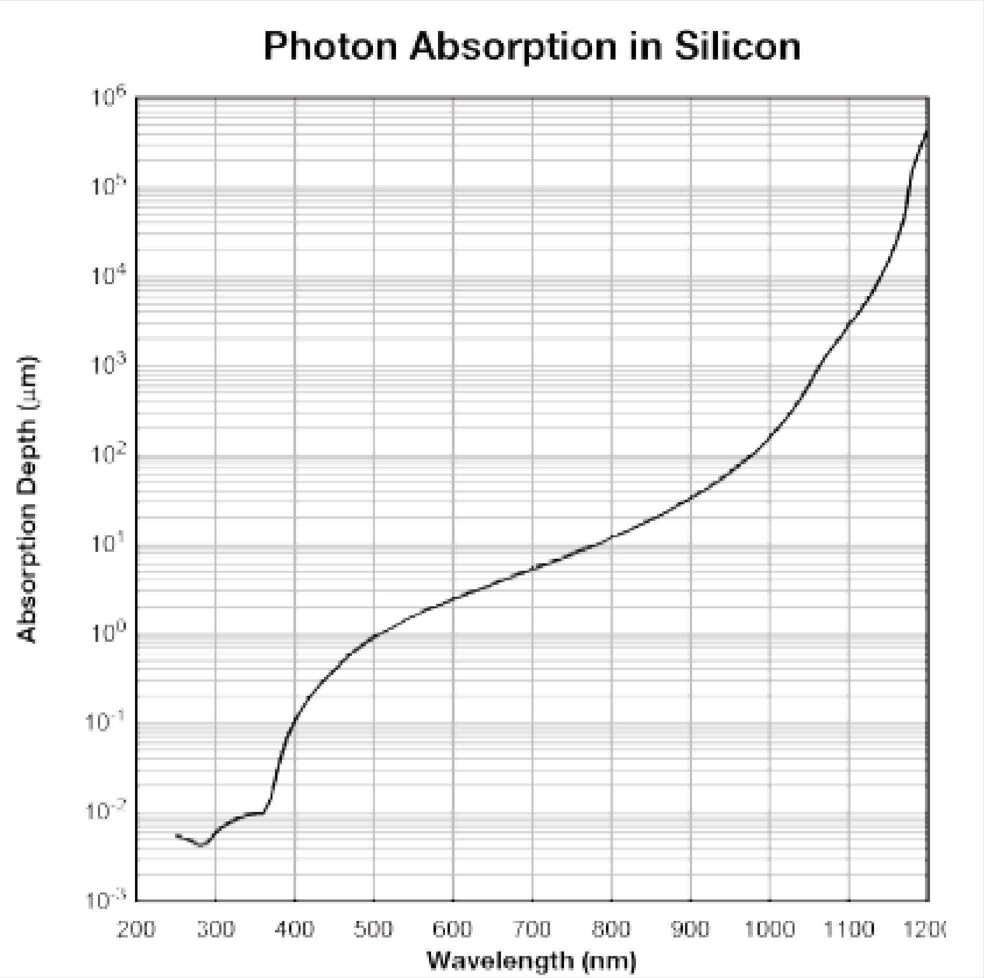
The Si p-n junction creates a depletione region which is free of mobile charge carriers.



Single Photon Avalanche Photodiode

When a photon is absorbed in Si it will create an electron-hole pair. Because of the reverse bias applied, the electric field ($>5\cdot10^5$ V/cm) generated across the depletion region will accelerate the charge carriers towards the anode (holes) or cathode (electrons).

Therefore an absorbed photon will result in a net flow of current.

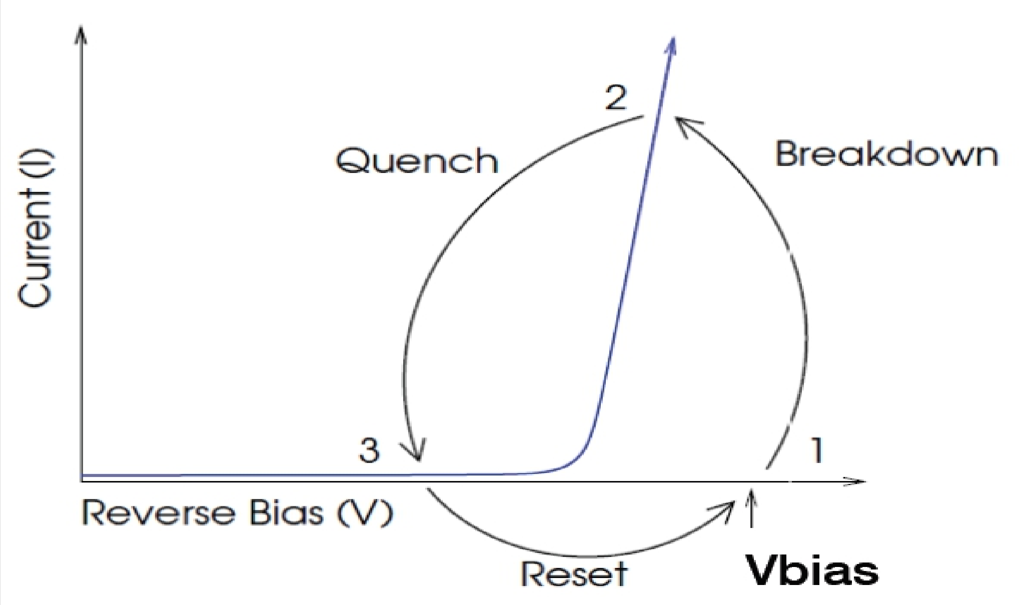


Single Photon Avalanche Photodiode

With high V_{bias} the charge carriers carry enough E_K to create secondary electron-hole pairs, impact ionization. A single photon creates an avalanche ionization, amplifying the original pair into a macroscopic current flow.

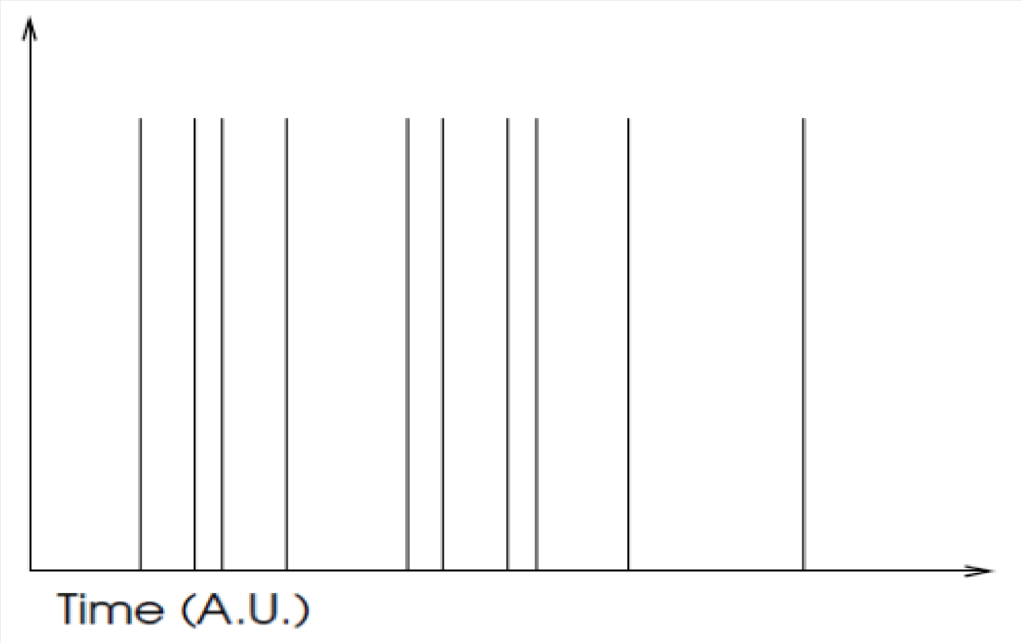
The current must be 'quenched', achieved with a resistor R_Q.

Recovery time: time needed to recovery the bias value



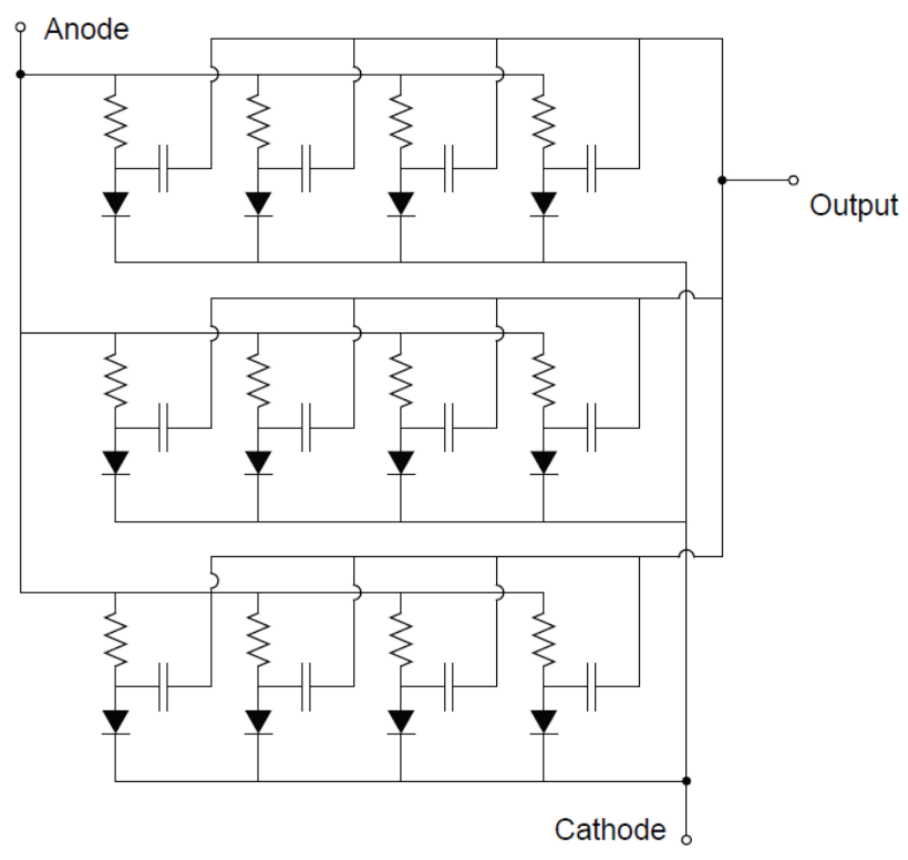
SPADs Drawbacks

- Binary device, on-off state
- No proportionality
- Same amount of charge regardless the number of incident photons



Silicon Photomultiplier

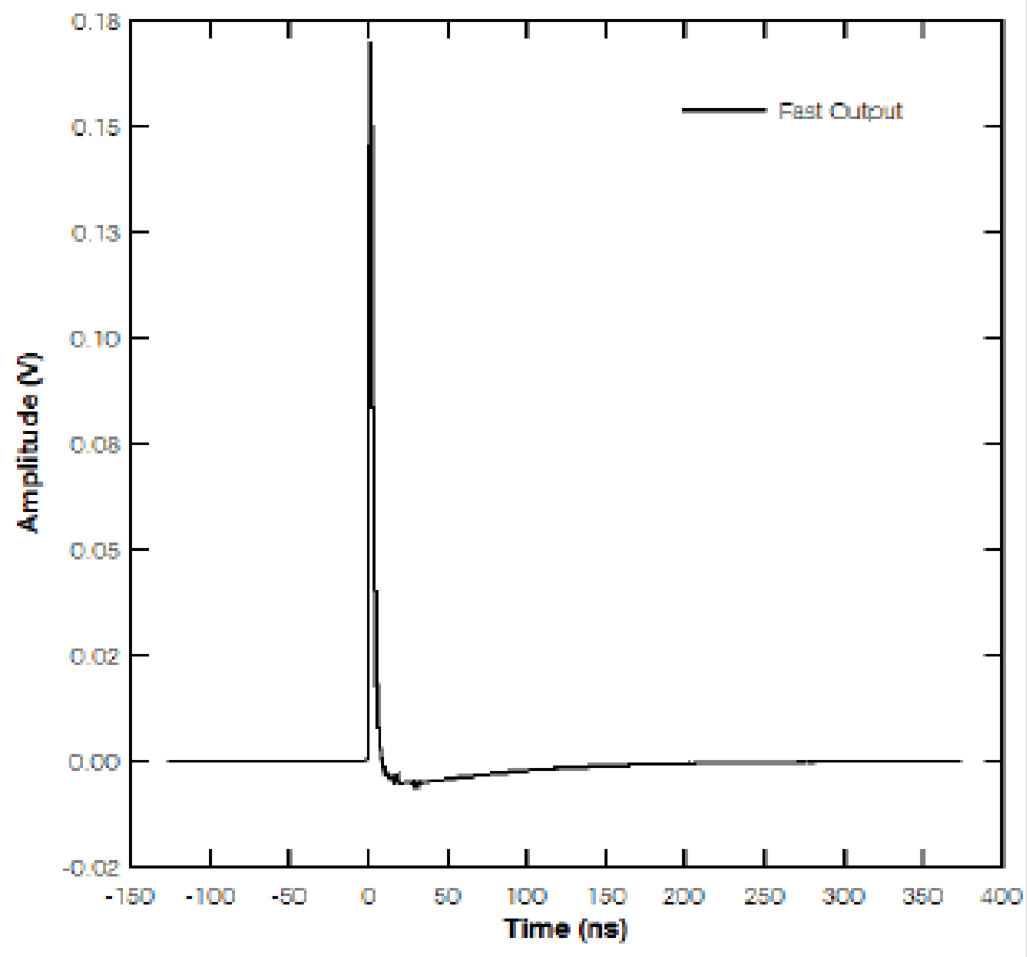
- Dense array of indipendent SPAD connected in parallel
- Summing over all the pixels one can know how many pixels are fired ⟶ # incident photon
- Proportionality
- Densities between 100 and 1000 microcells/mm^2



Recovery Time

$$T_{RC} = C_{pixel}(R_q + R_s N)$$

- C_{pixel} capacitance of a microcell
- R_Q quenching resistor
- R_S other resistances in series with detector
- \# of microcells



Gain and Fill Factor

The **gain** depends on the pixel capacitance and the operation voltage

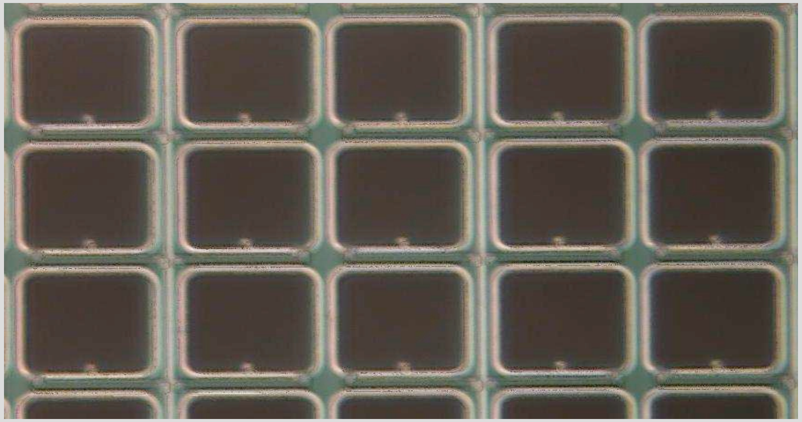
Q is the output charge of a single pixel

$$G = \frac{Q}{q}$$

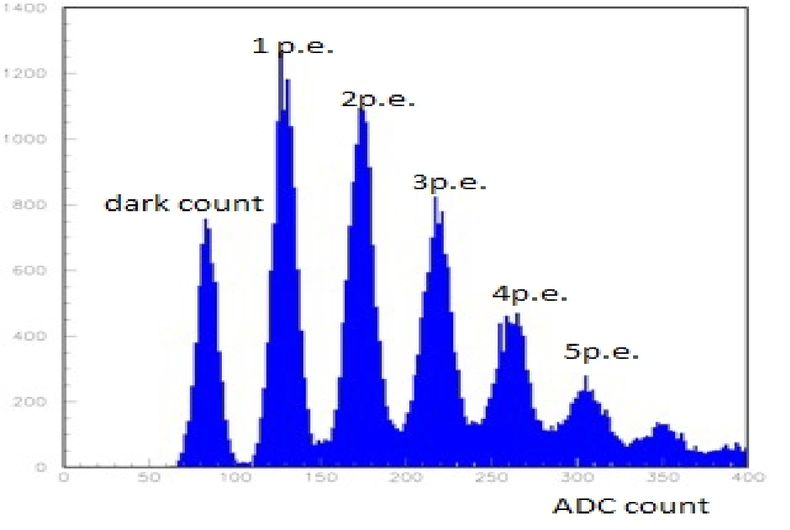
$$Q = C_{pixel}(V_{bias} - V_{BD}) = C_{pixexl} \Delta V$$

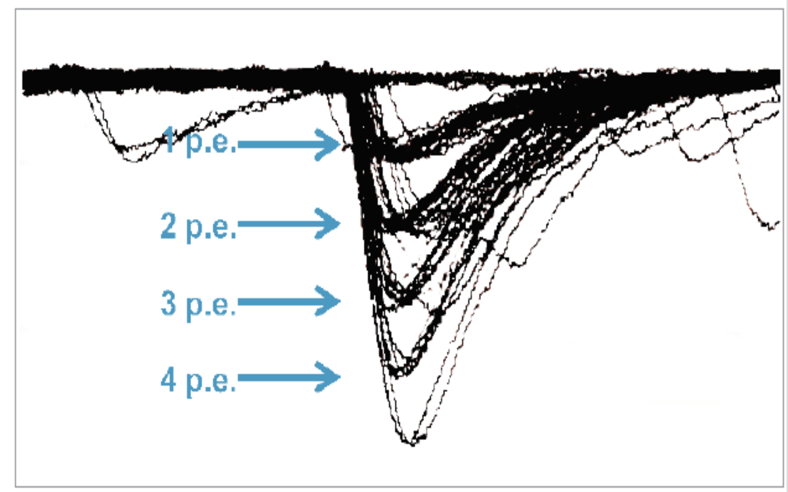
Fill Factor: Active surface/Total surface

- ***Larger fill factor***: higher PDE (wavelegth dependent) and gain, higher capacitance, larger recovery time
- ***Smaller fill factor***: lower PDE and gain, lower capacitance, shorter recovery time



Advantages and drawbacs





Advantages

- High gain (10^5-10^6)
- Low voltage operation (<100V)
- Insensitive to magnetic fields
- High PDE

Drawabcks

- Only small size available (~mm^2)
- High dark count rate (100kHz-1MHz/mm^2)

SiPM in medical field

Application for medical imaging: i.e. detecting cancer cells

- Compactness
- Low operating voltage

PET/MRI

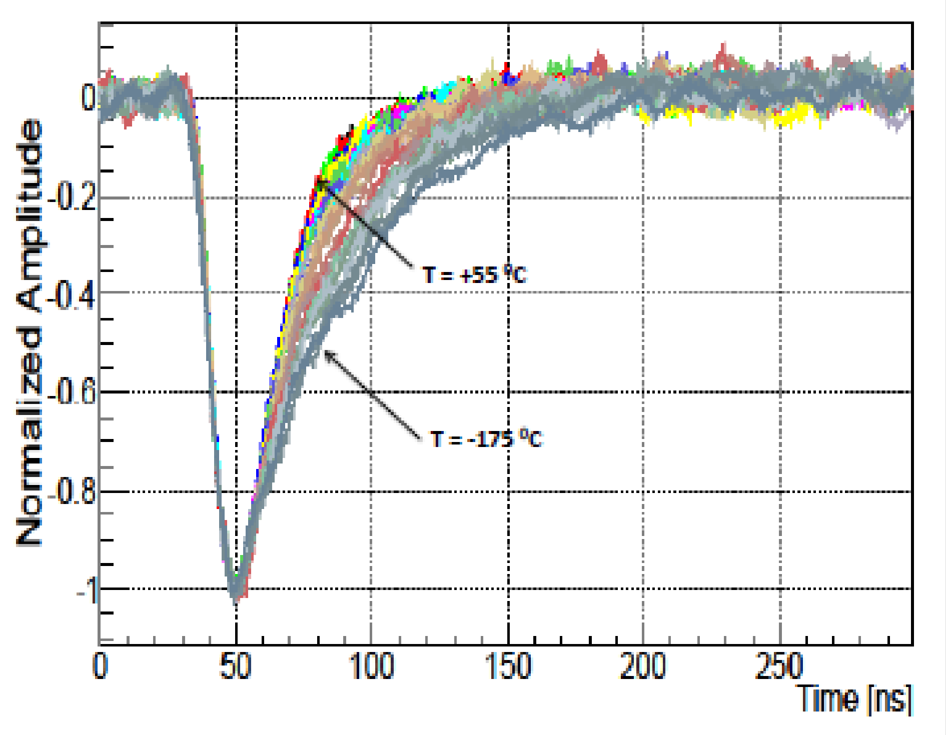
- Insensitive to magnetic field

Analysis of SiPM characteristics

Nagai et al. presented a Data Analysis based on ROOT

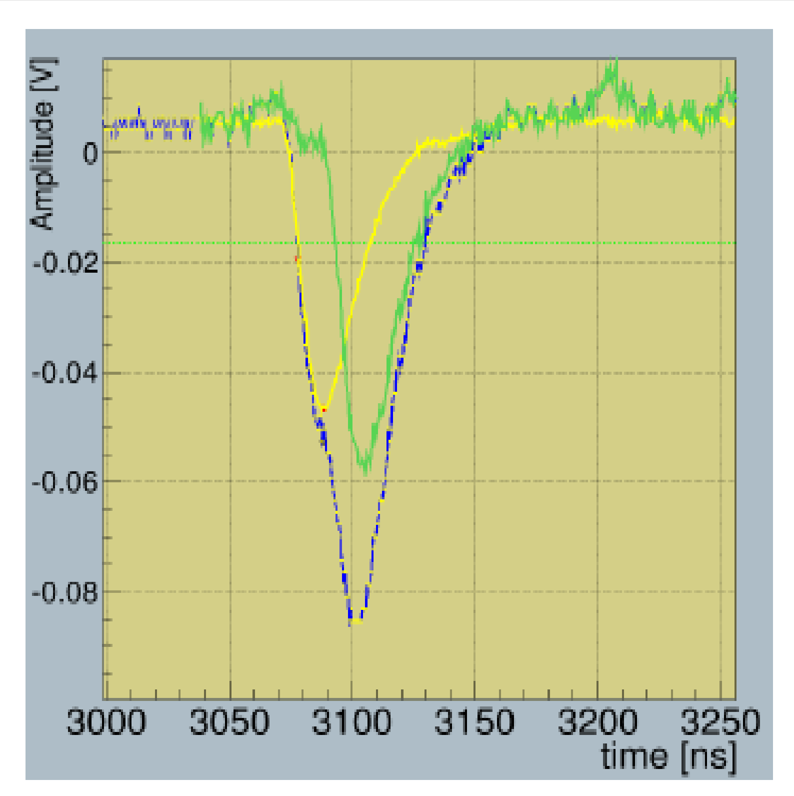
SiPM in N_2 atmosphere and controlled T from -175°C to 55°C

Attenueted laser to have few photons per pulse



Analysis of SiPM characteristics

- *Template creation,* find the typical SiPM pulse
- *Pulse finding procedure,* determine time intervals containing pulses
- *Template substraction,* reconstruct pulses in “train of pulses“
- *Pulse characterization,* calculate SiPM pulses parameters



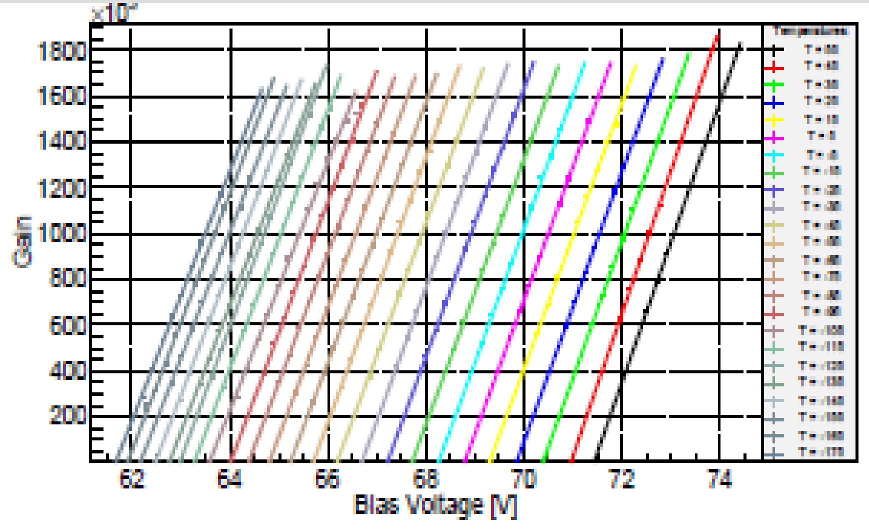
Analysis of SiPM characteristics

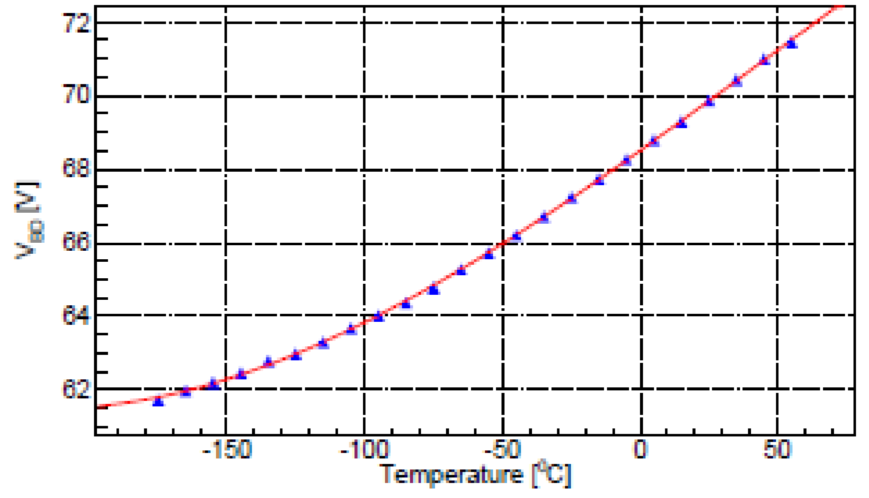
- *Time position,*
- *amplitude*
- *rise time*
- *recovery time*
- *charge Q*

$$f(t, a, \tau) = a \exp - t/\tau$$

$$Q = \int I(t)\, dt = \frac{1}{R \times G_{amplifier}} \int V_{pulse}(t)\, dt$$

Gain: G=Q/e





SiPM in Medical Field

Molecular imaging → PET/MRI combination

i.e. decting cancer cells

SiPM:

- **Insensitive to magnetic field**
- Low operating voltage
- Compactness

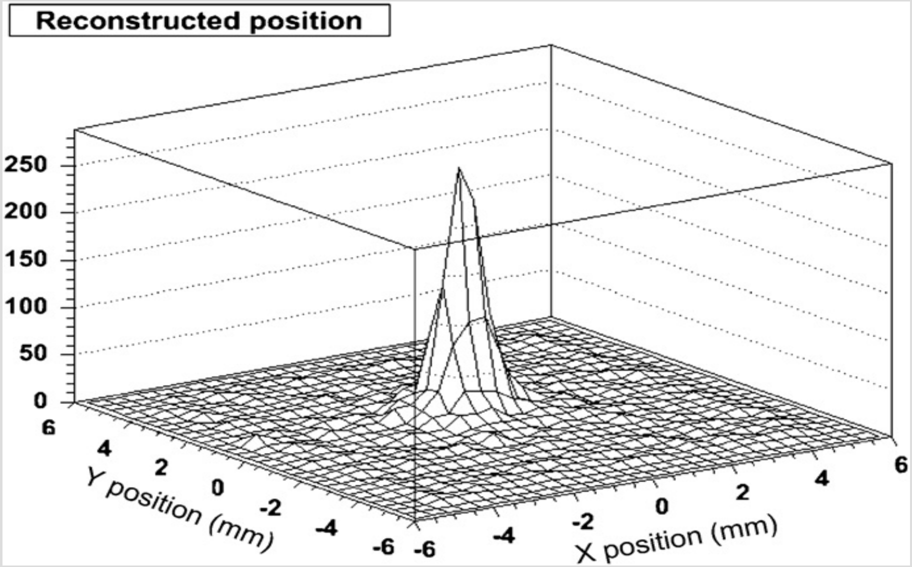
SiPM for PET

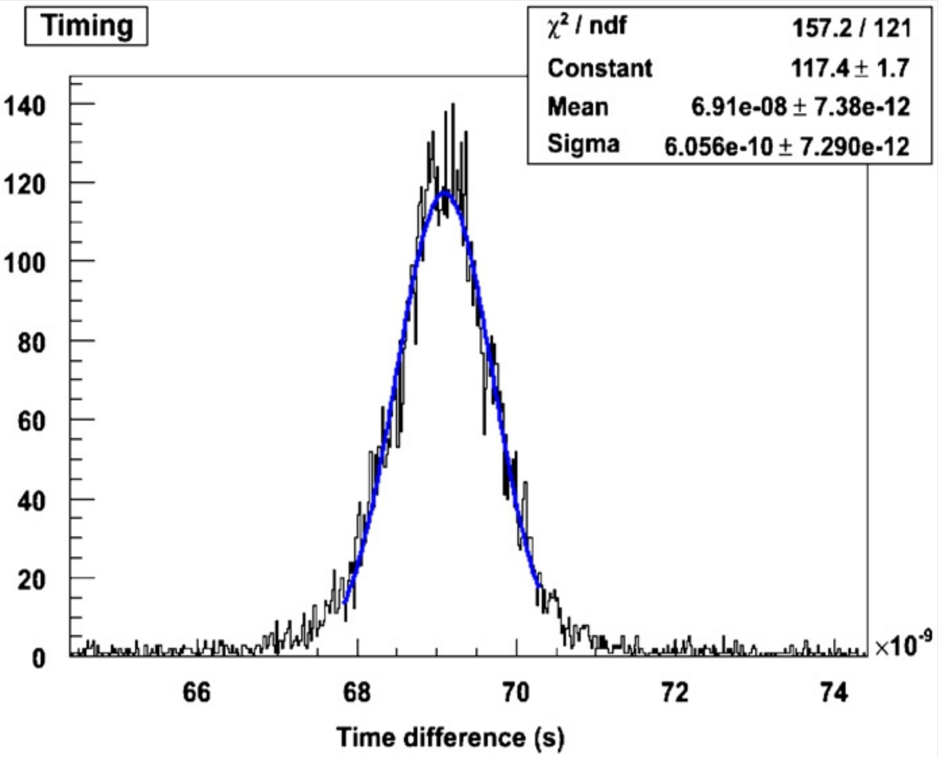
SiPM high dark count rate (1-3 Mhz/mm^2)

but PET is NOT a single p.e. technique

The dark count rate at 3-4 p.e.at T_R goes down at ~kHz

Time coincidence of two 1mm SiPM coupled with a LSO scintillator for 511 keV photons





Advantages and Pitfalls

- High gain: no need of pre-amplifier
    - Fast time properties
    - Low noise
    - More flexible design
- PET/MRI simultaneous imaging

- High number of channels, needing of high performance electronics
- Dependence of V_{BD} with T, and so Gain and PDE
- Cost (10 times PSPMT per mm^2)

SiPM in VHE astrophysics

Imaging Atmospheric Cherenkov Telescopes:

Changelling

- Short duration (~ns)
- Low light intensity (few p.e. per pixel)

SiPM vs PMT

- Higher PDE
- Better time resolution
- More compact
- Lower operation voltage

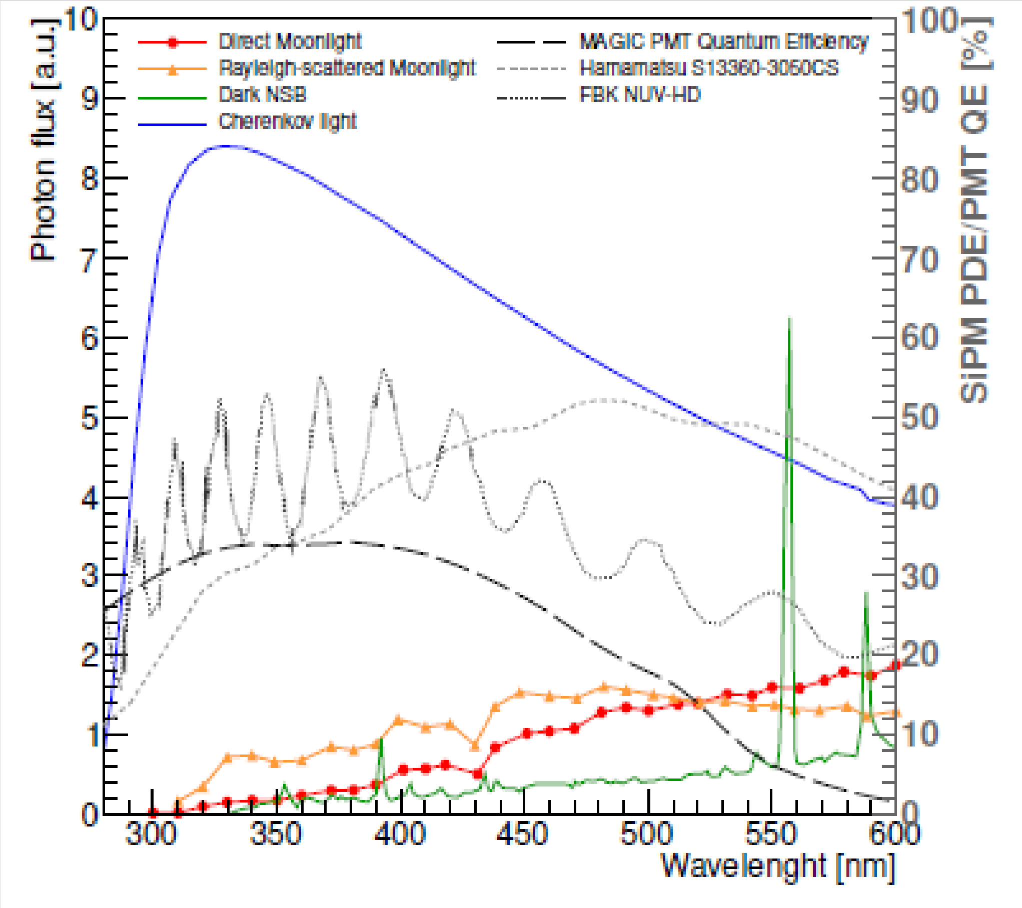
SiPM in VHE astrophysics

Peak of Cherenkov light at 350nm

Night Sky Background peak at about 550nm

Higher PDE of Sipm in red part BUT new SiPM enhanced in NUV band with a PDE ~50% around 350nm (FBK NUV-HD) and optical cross-talk ~5%

T variation <1.5°C during a night



SiPM in VHE astrophysics

Limited physical size

Pixels made of several SiPM, output summed with operational amplifiers as well the noise

- Reduction in capacitance but still increase with number of SiPM

Light-Trap pixel: SiPM coupled with a PMMA doped with WLS

Isotropically emitted red-shifted photons

- Low cost
- Capacitance does not

  increase with size

- Degradation in detection efficiency
- Time properties

CONCLUSION

Advanteges:

- High gain
- Low V_{op}
- Insensitive to magnetic field
- High PDE

Drawbacks:

- Small size
- Cost
- Dark count rate

References

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[5] Ahnen, M. L. et al. (2017). Astroparticle Physics, 94, 29–41.

Thanks for your attention!!!