LIGHT SENSORS

Antonino Pietropaolo
Consiglio Nazionale delle Ricerche
Istituto di Fisica del Plasma “P. Caldirola”
Milano Italy

Outline

- ✓ ***PHOTOMULTIPLIER TUBES***
- ✓ ***SILICON PHOTOMULTIPLIERS***

PHOTOMULTIPLIERS TUBES

Convert extremely weak light output of a scintillation pulse into a corresponding electrical signal

INSIS

BASIC STRUCTURE

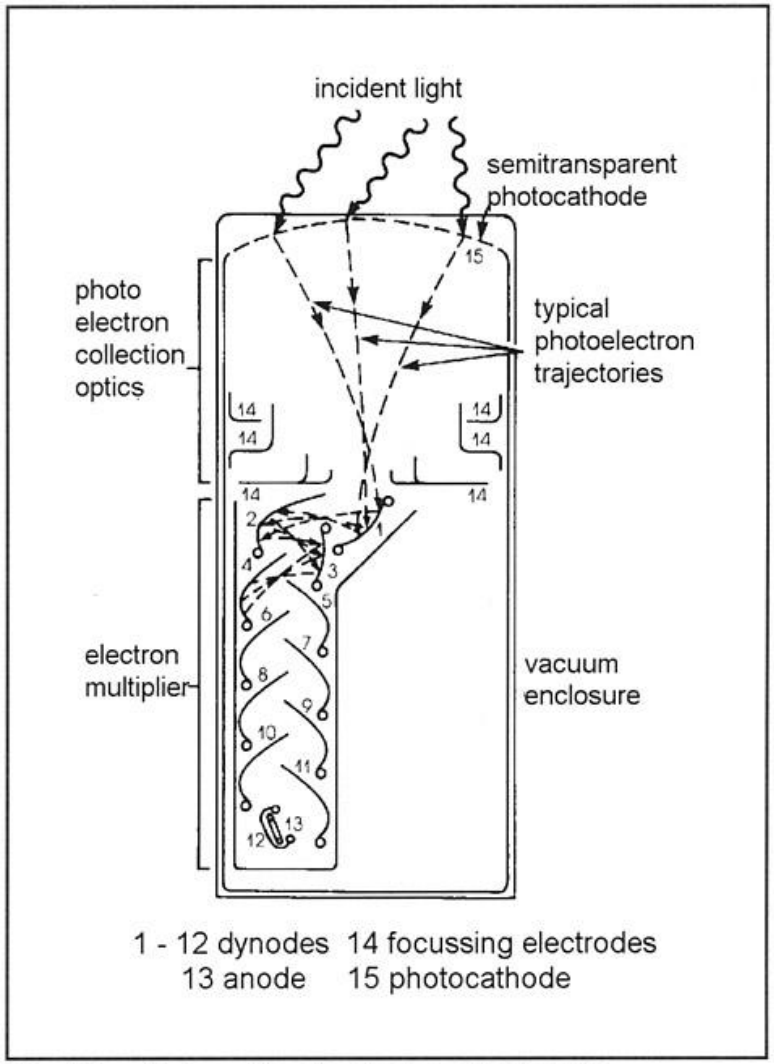
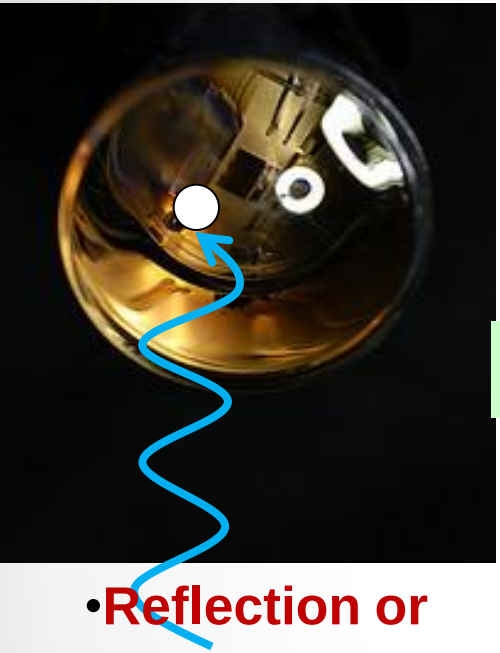


Fig. 4.1 Schematic of a photomultiplier tube.

Let see now the different elements in some detail

THE PHOTOCATHODE

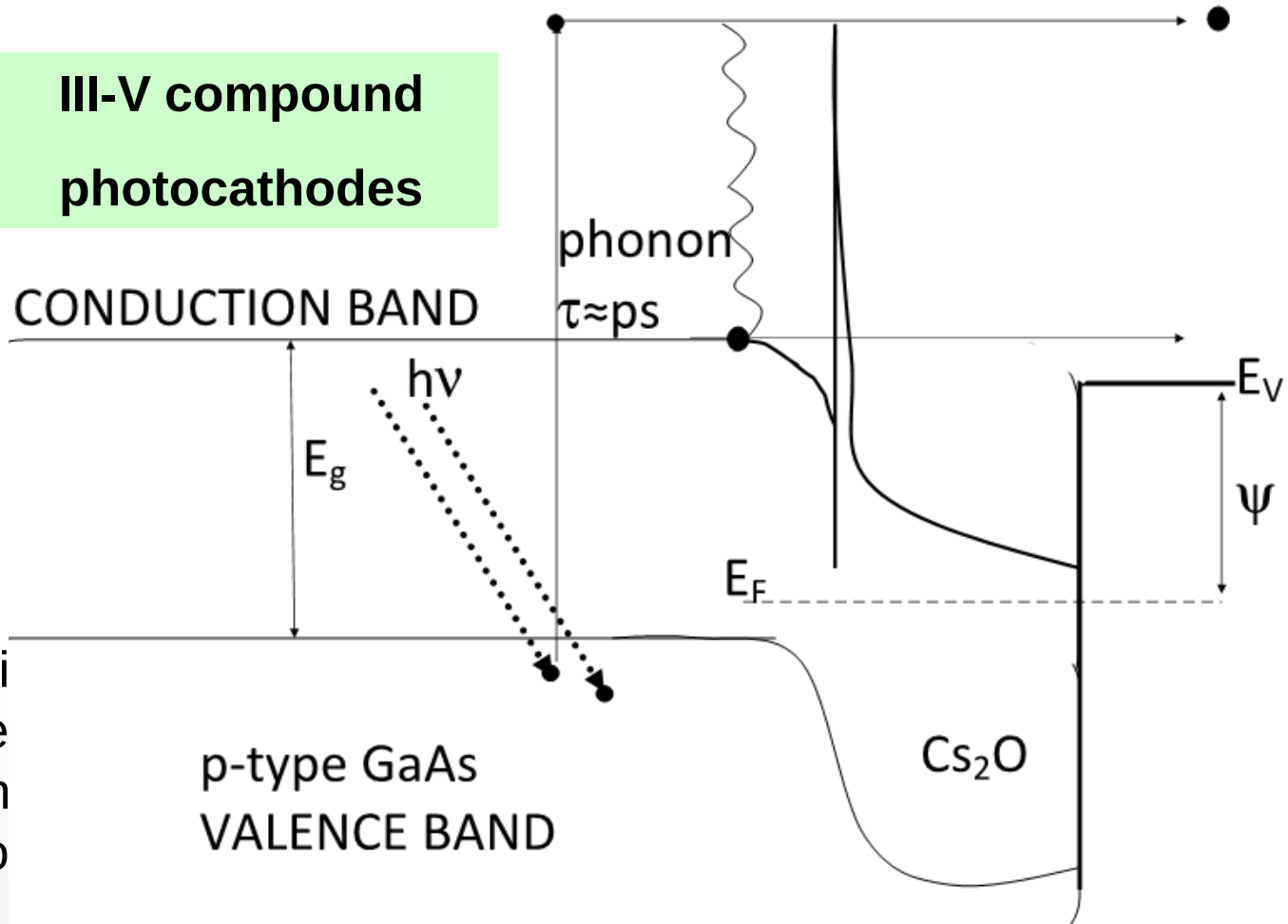


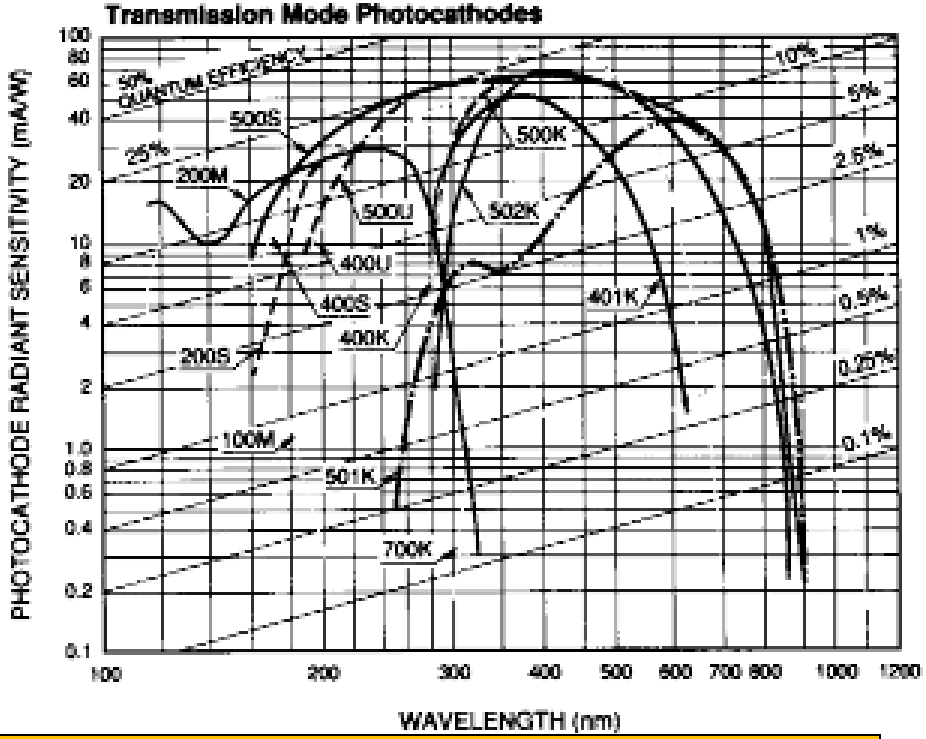
The photocathode is a semiconductor material coated (typically) onto a glass surface (window).

III-V compound photocathodes

- **Reflection or**
- **transmission type**

E_g: Energy gap
E_F: Fermi level
EA: electron affini
E_V: vacuum leve
ψ: work function
τ: e^--phonon interactio

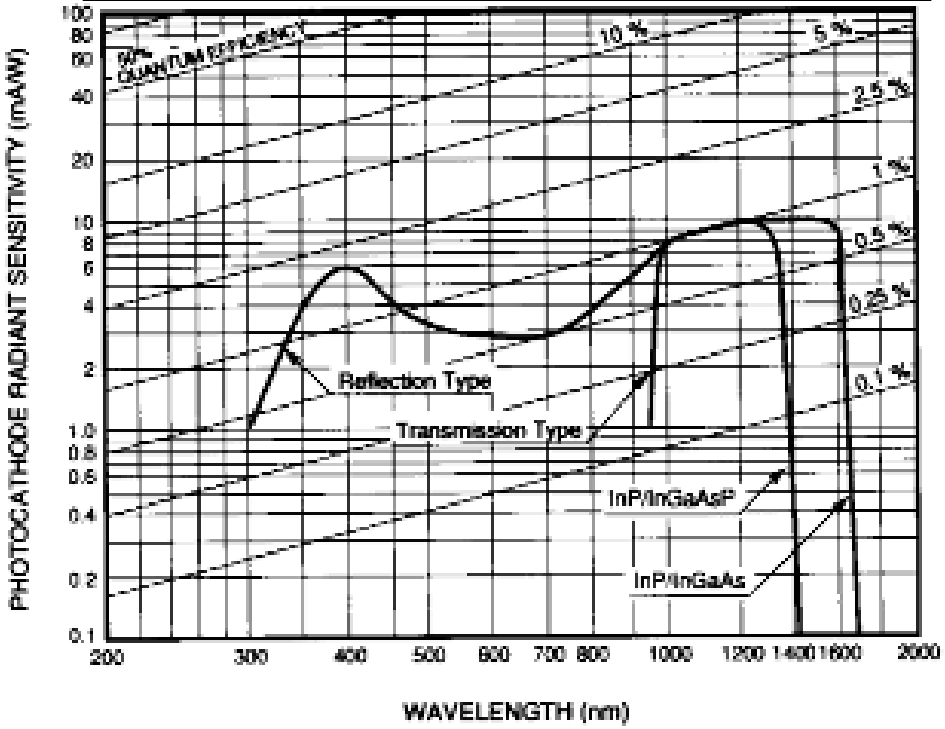




Typical spectral response

for InP/InGaAs and

InP/InGaAsP



- **Photocathode materials**

CsI

CsTe

SbCs

Bialkali (SbRbCs,SbKCs)

Hight T Low Noise Bialkali (SbNaK)

Multialkali (SbNaKCs)

AgOCs

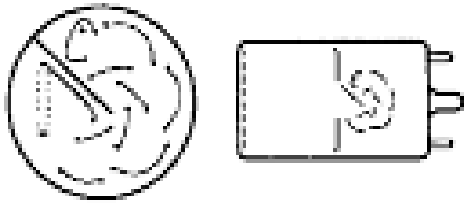
THE DYNODES

The multiplier portion of a PMT is based on the secondary electron emission effect: e^- from the photocathode are accelerated and strike the surface of an electrode called **dynode** whose material is properly chosen to result in more than one electron emission.

E_{e-} about 1 eV from the photocathode

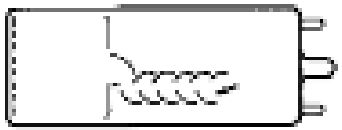
V_{fd} several hundreds volt (photocathde-first dynode applied voltage)

K_e at the dynode surface almost entirely determinded by the V_{fd}

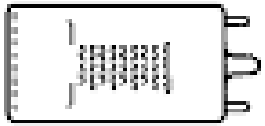


(1) Circular-cage Type

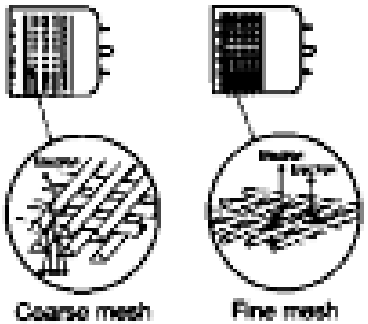
(2) Box-and-grid Type



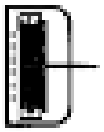
(3) Linear-focused Type



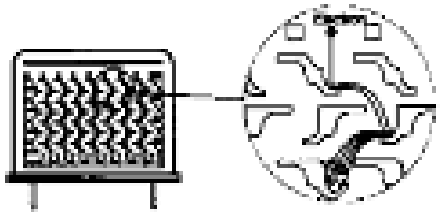
(4) Venetian Blind Type



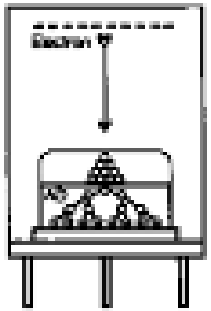
(5) Mesh Type



(6) Microchannel Plate Type



(7) Metal Channel Dynode Type



(8) Eelectron Bombadment Type

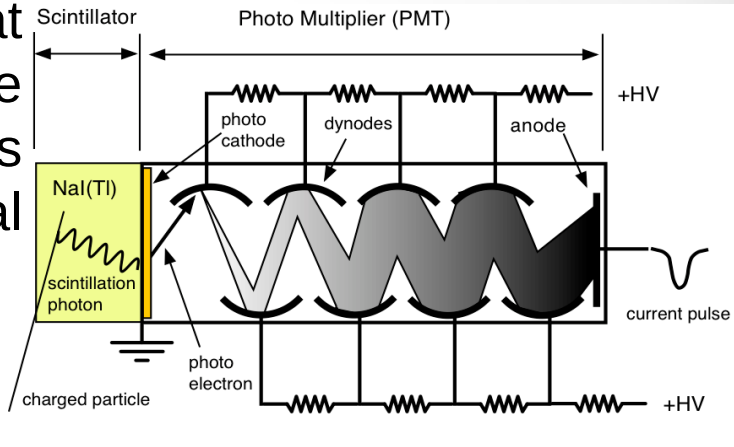
THE DYNODES

When the photolectron from photocathode strikes the first dynode it produces secondary electrons (gain). The overall gain is given by the number of multiplication stages used (number of dynodes):

$G = \alpha\delta^{N}$ α being about1 and $\delta \approx 5$ typically. With 10 stages one avhieves an overall gain of about 10^7. Also for dynodes, if NEA materials are used δ can be around 50 so that less stages (four/five) may be sufficient to achieve high gains with bestter time performances.

THE ANODE

The anode of a PMT is an elctrode that collects secondary electrons multiplied in the cascade process through multistage dynodes and send the electron current to an external circuit.



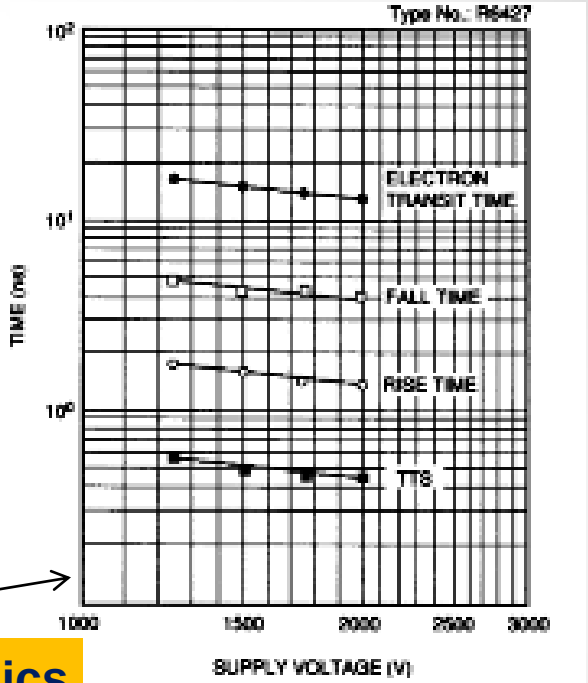
Anodes are carefully designed to be optimized with respect to seconday electrons trajectories.

Typical forms are **rods**, **plate** or **mesh** electrodes.

One important parameter is the potential between last dynode and anode to prevent space charge effect and obtain a large output current

FURTHER KEY CHARACTERISTICS

•**PMT have fast response** primarily determined by the time required for the photolectrons from the photocathode to reach the anode after being multiplicated in the muti-dynodes stage, as well as the differences in the transit time between each photoelectron. These characterisics times are proportional to $V^{-0.5}$

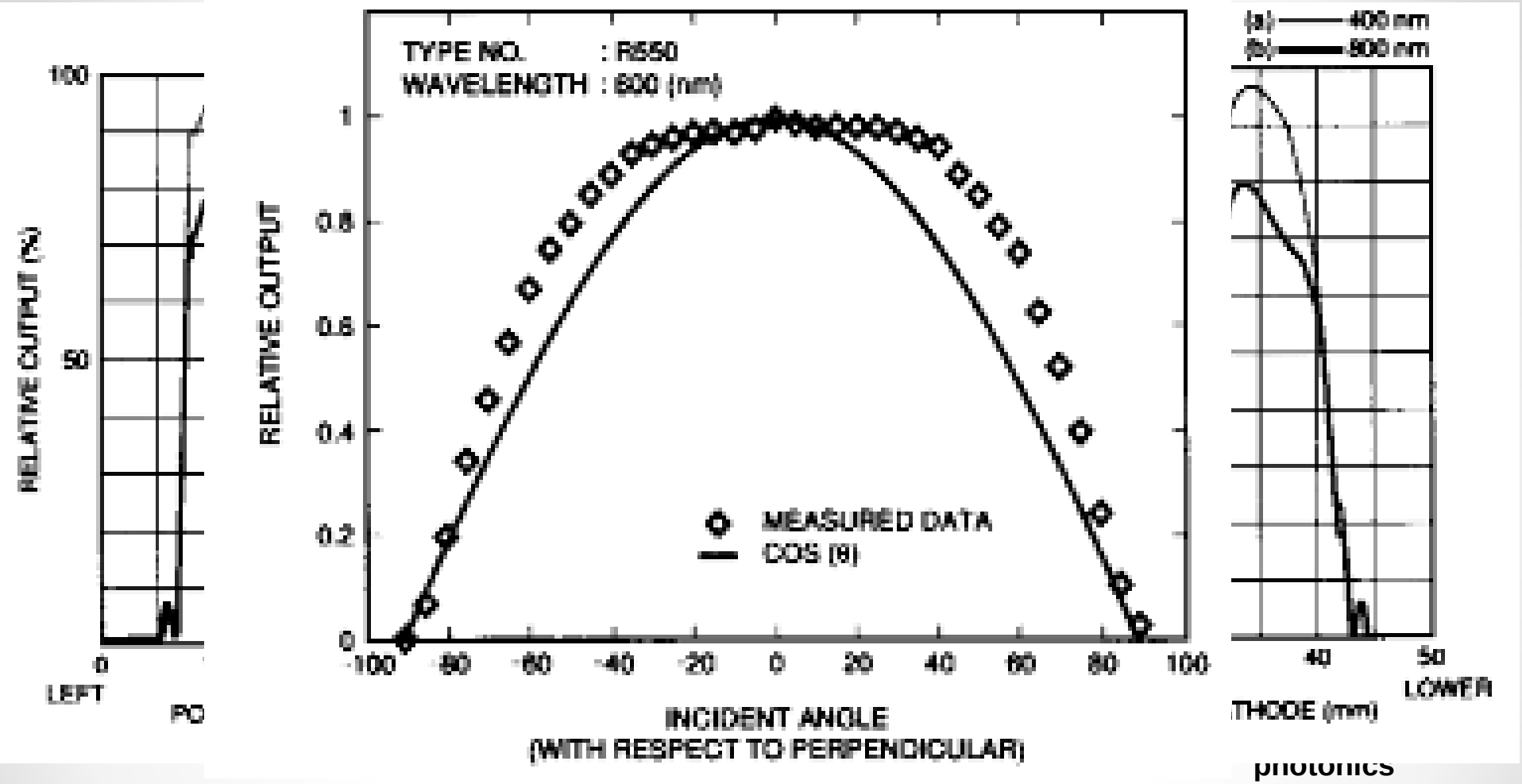


•**Source: Hamamatsu photonics**

Unit : ns

Dynode Type	Rise Time	Fall Time	Pulse Width (FWHM)	Electron Transit Time	TTS
Linear-focused	0.7 to 3	1 to 10	1.3 to 5	16 to 50	0.37 to 1.1
Circular-cage	3.4	10	7	31	3.6
Box-and-grid	to 7	25	13 to 20	57 to 70	Less than 10
Venetian blind	to 7	25	25	60	Less than 10
Fine mesh	2.5 to 2.7	4 to 6	5	15	Less than 0.45
Metal channel	0.65 to 1.5	1 to 3	1.5 to 3	4.7 to 8.8	0.4

Table 4-3: Typical time characteristics (2-inch dia. photomultiplier tubes)



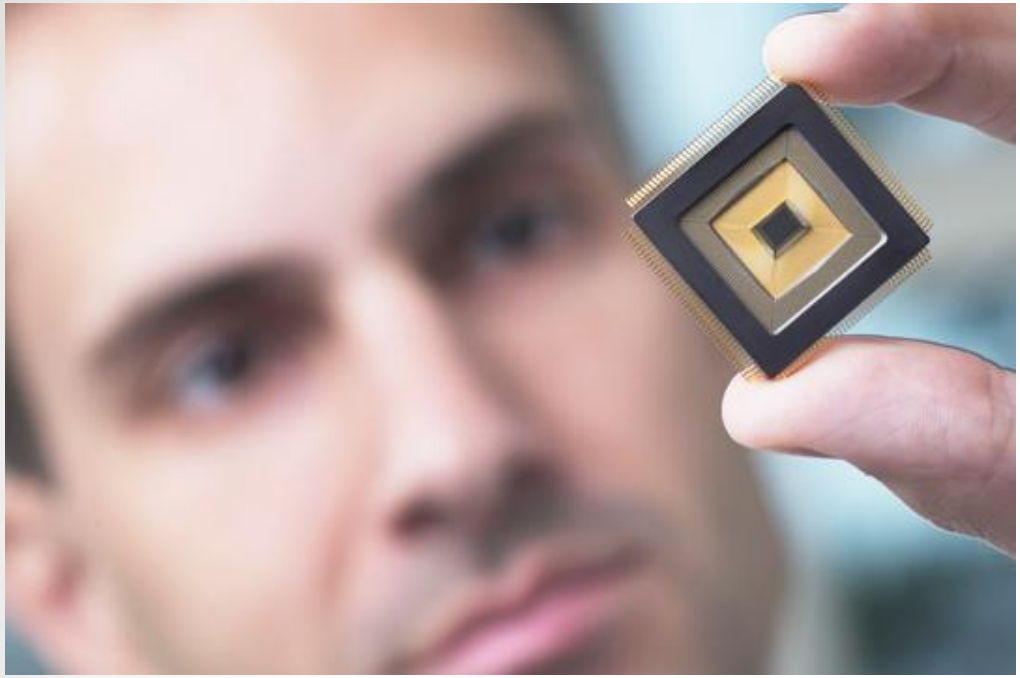
Uniformity: variation of the output signal with respect to the photocathode position = **photocathode uniformity x anode uniformity**

FURTHER READINGS

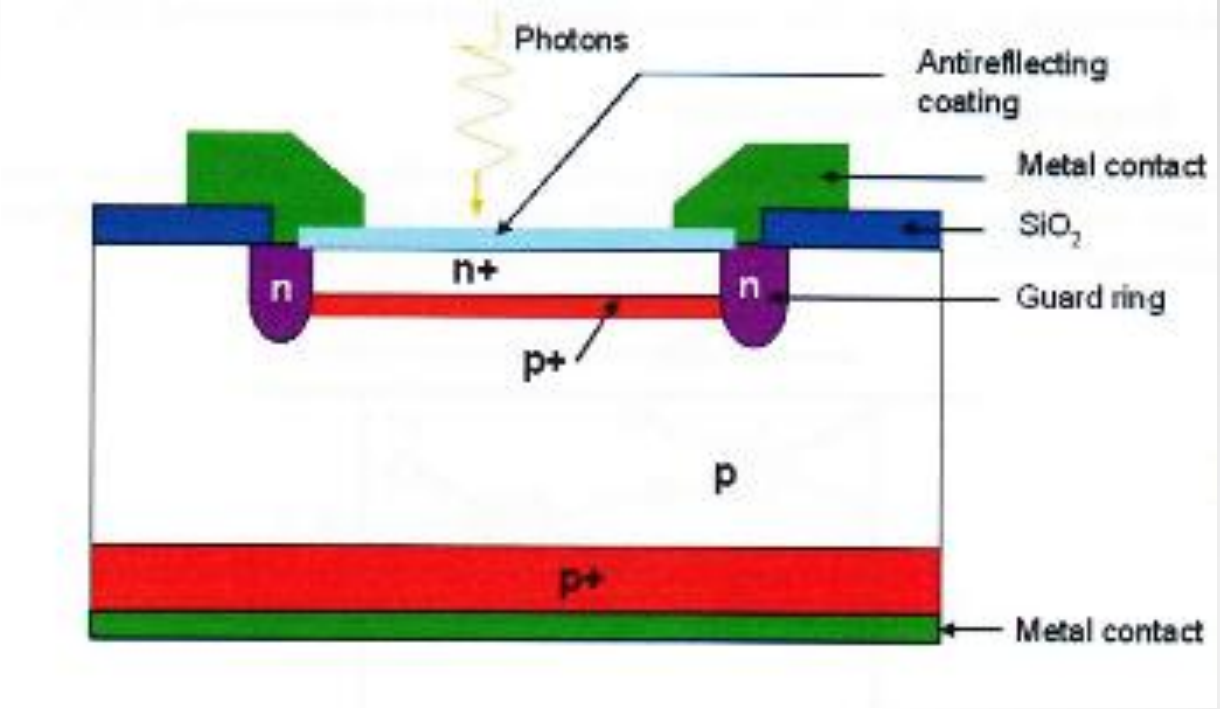
1- Glenn F. Knoll, in Radiation Detection and Measurements, John Wiley&Sons, Inc. Ed (1999) and references therein.

2- Hamamatsu Photonics: Photomultiplier Tubes (III edition) and references therein.

THE SILICON PHOTOMULTIPLIERS



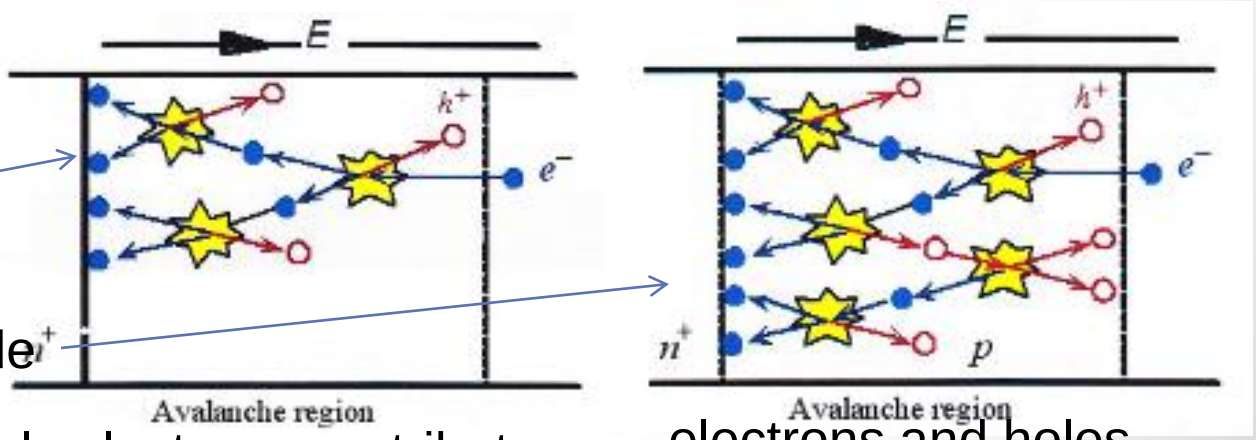
Matrix of avalanche photodiodes (APD), basically a p-n junction, operated at large reverse bias



Impact ionization

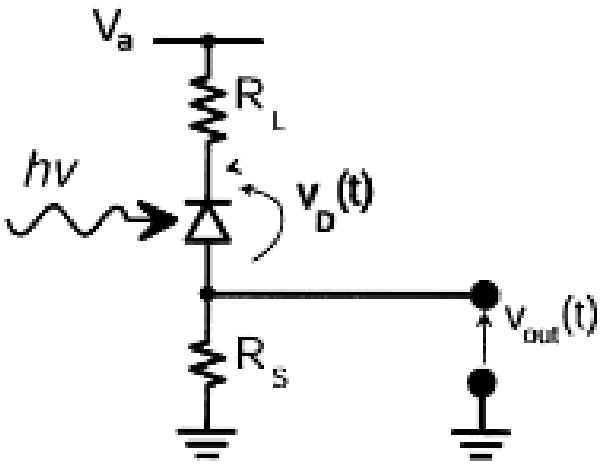
proportional or

(**SiPM case**) Geiger mode



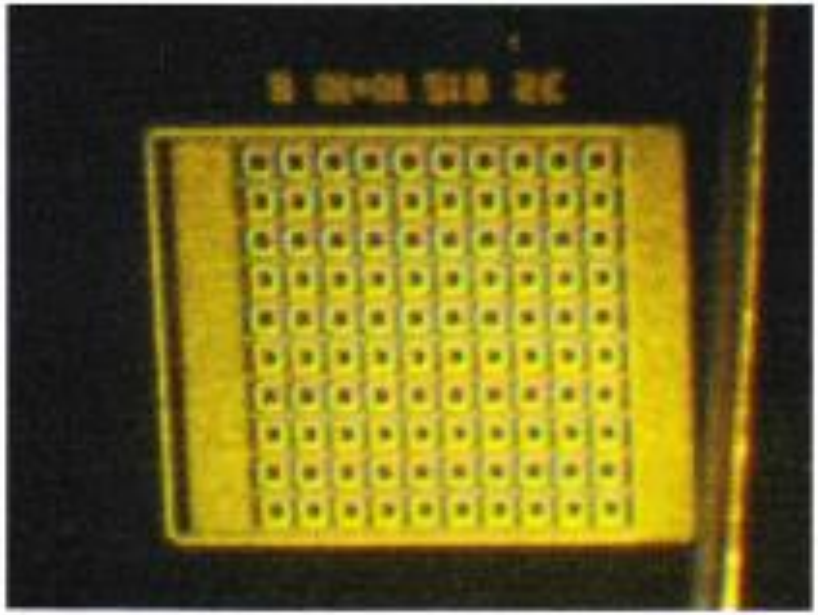
Only electrons contribute

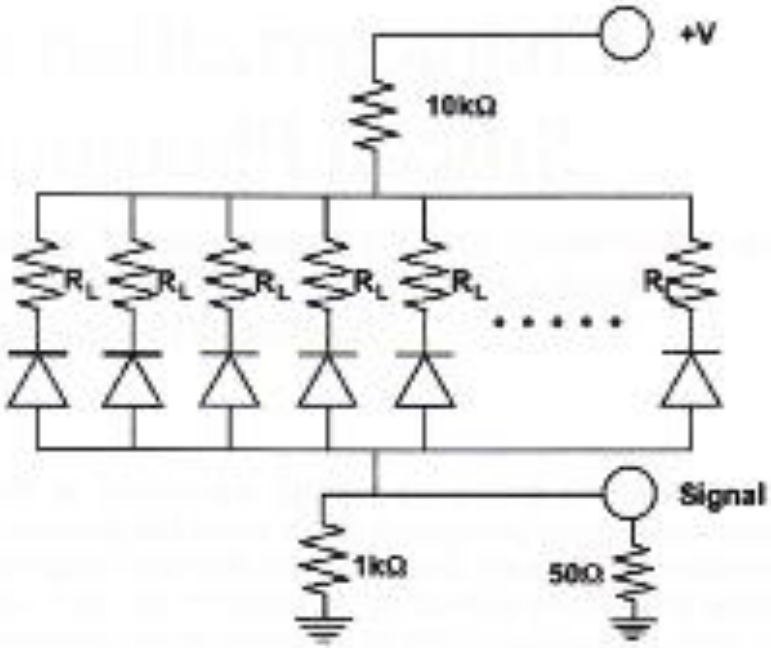
electrons and holes contribute

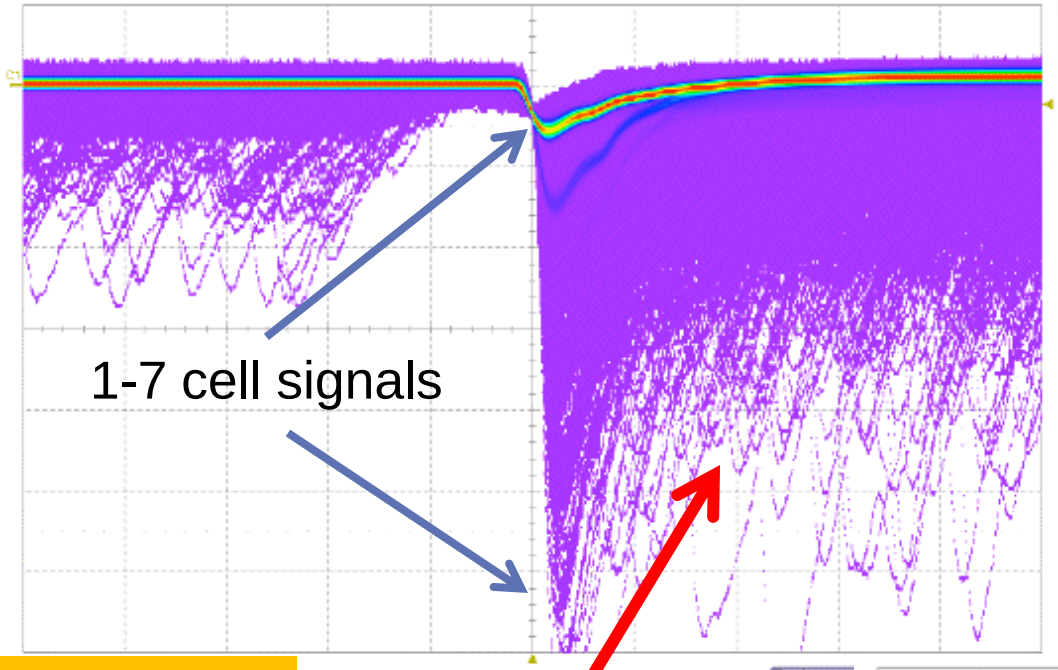


Passive Quenching:
each pixel (APD) of the SiPM is connected to the power supply through a large resistor (R_S=100-400 kΩ typically). During the breakdown R_S limits the current drawn and after the discharge richarges the diode to accept a new event.

The single pixels are binary units (Yes/No) as these are conceived, but the overall output is analog. The pulse is related to the number of pixels illuminated



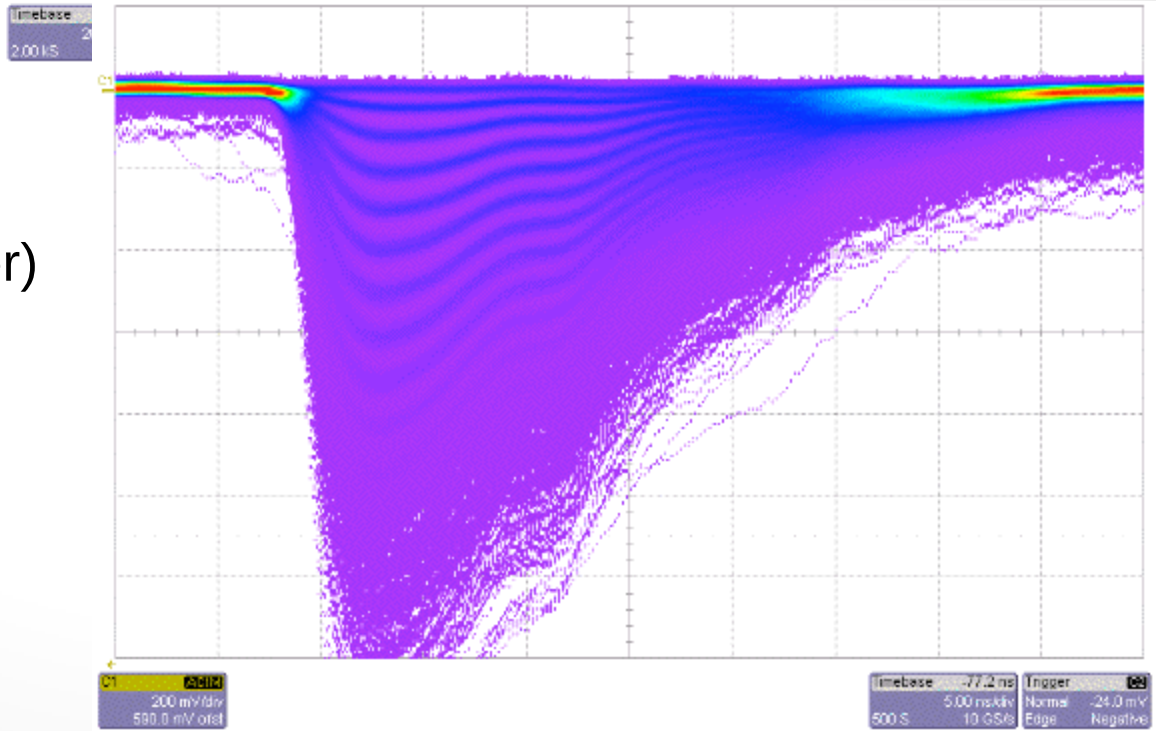




Typical output signals recorded on a digital scope

Dark noise

With irradiation

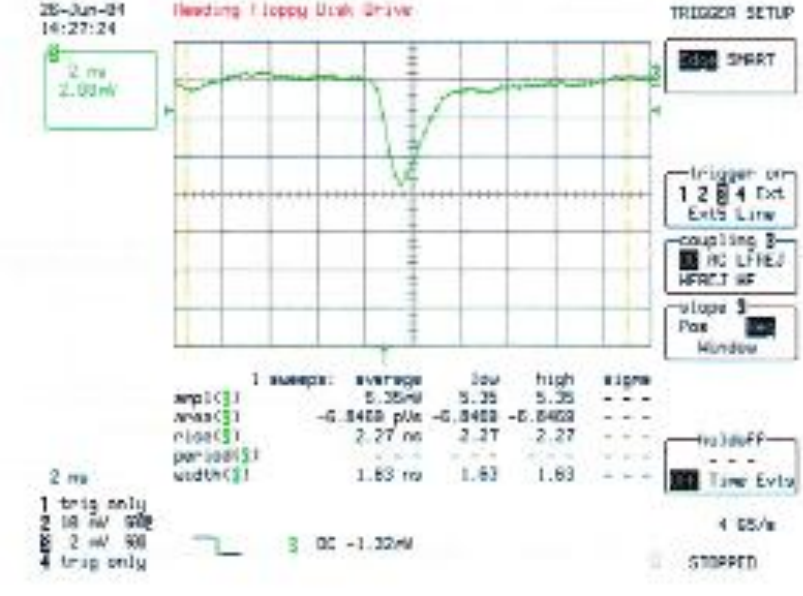


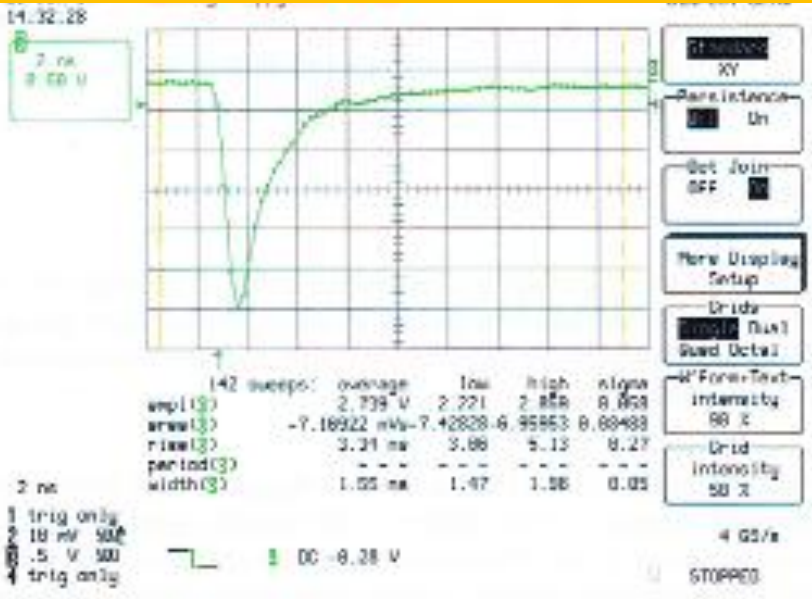
Afterpulses (we will se later)

TIMING CHARACTERISTICS

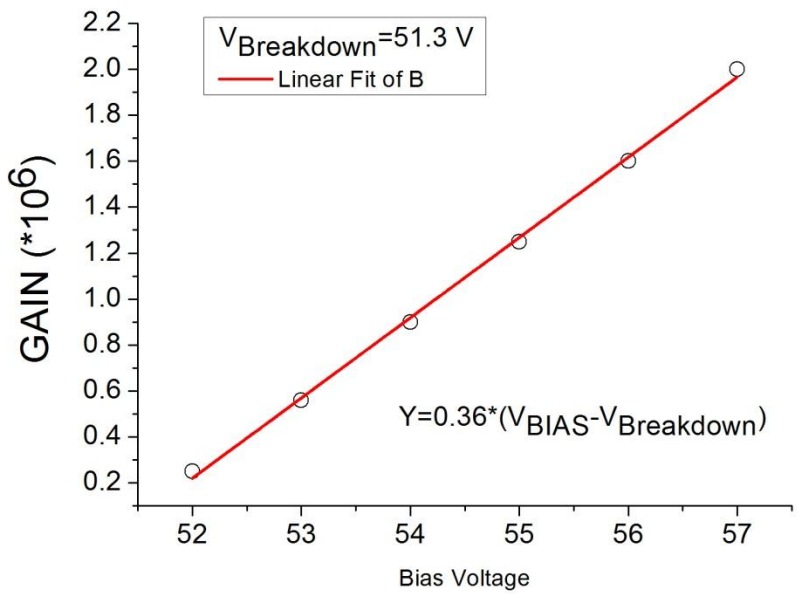
The avalanche process starts when the first impact ionization due to the photo-generated e-h pair, takes place. The typical rise time of a SiPM is around 1 ns whatever the number of pixels fired might be. A time jitter depends on the the difference between the position of the photon absorption point and the high field impact ionization region where the avalanche starts

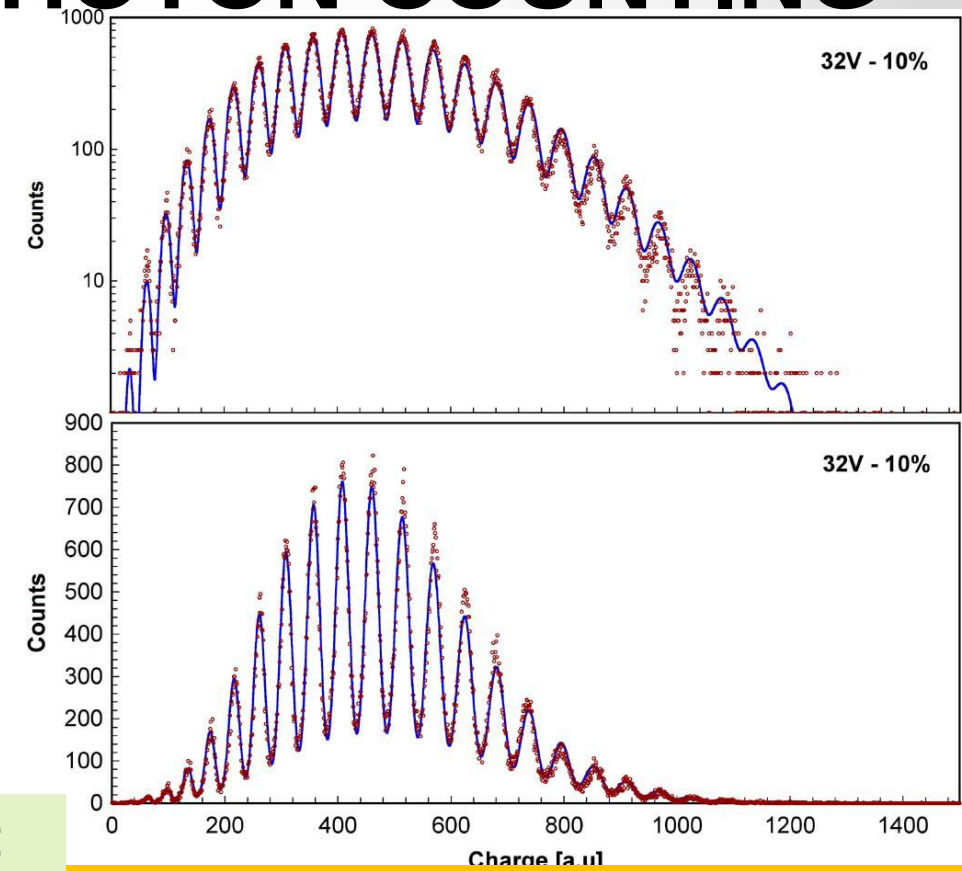
$\tau_J = d/v_S$ where **d** is the thickness of the depletion layer and v_S the saturation carriers speed . Time resolution depends on the number of fired pixels: typically it ranges between 20 ps (tseveral tens of pixels fired) to 250 ps (one pixel fired)





GAIN and SINGLE PHOTON COUNTING





The single pixel signal is determined by:

$$GAIN_{pixel} = \frac{Q_{pixel}}{|e|} = C_{pixel}\frac{(V_{BIAS} - V_{Breakdown})}{|e|}$$

Where Q_{pixel} is the total charge collected durining the Geiger discharge into the pixel capacitance. C_{pixel} in the order of 10fF and the overvoltage is about 10% of the Breakdown voltage.

Charge spectrum collected with a laser at 10% of its nominal intensity Poisson distrubtuion with gaussian peaks due to overall electronic noise and combination of non-uniformities and fluctuactions among unit cells

EFFICIENCY and DYNAMIC RANGE

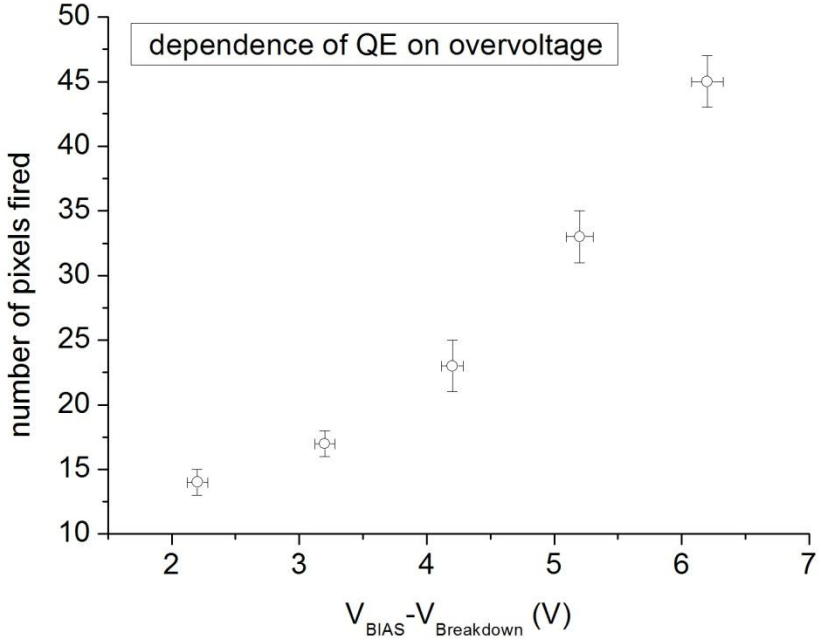
The efficiency is given by:

$$\varepsilon = QE \cdot \varepsilon_{Geiger} \cdot \varepsilon_{geom}$$

QE: quantum efficiency (probability for an incident photon to be absorbed) For Si @ λ=400 nm QE=70%

E_{geom}: geometrical efficiency A_{pixel}/A_{tot}

ε_{Geiger}: probablity for an e^- to trigger a discharge



As the number of pixels *m* is finite the maximum number of photons simultaneously detectable is limited. The number of pixels fired depends on the number of photons N_{phtons} impinging onto the detector

$$N_{pixelsfired} = m \cdot \left(1 - e^{-\frac{N_{photons} \cdot \varepsilon}{m}}\right)$$

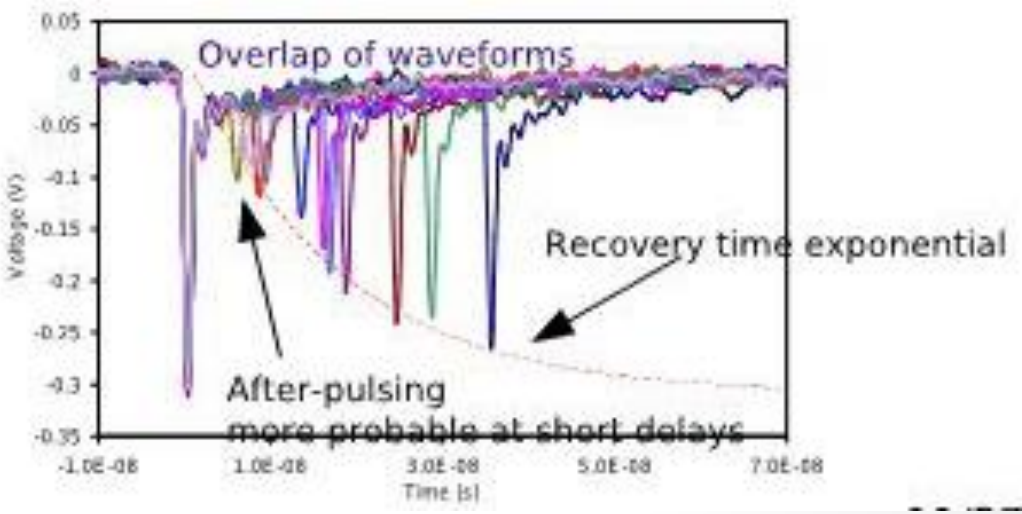
NOISE

Dark-counting rate souces

(a) Optical e-h generaiom

(b) Thermal e-h generation

(c) Impact ionization



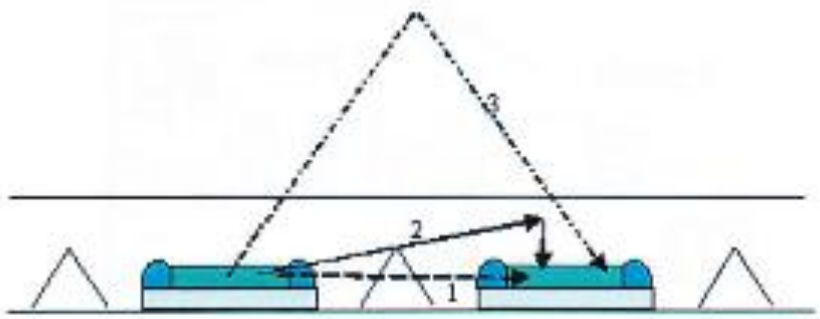
Afterpulsing

Increases with bias as Geiger discharge probability increases and so the charges that can be trapped and then released.

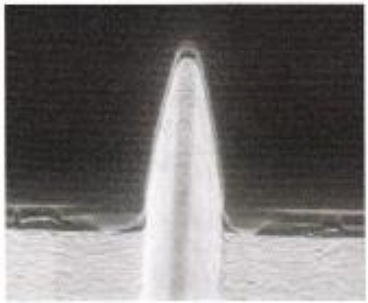
There is an afterpulse if: $\tau_{delay} > \tau_{dead}=R_{pixel}xC_{pixel}$ (about 10-20 ns)

Cross talk:

1-direct
2-inside the depletion layer
3-reflection

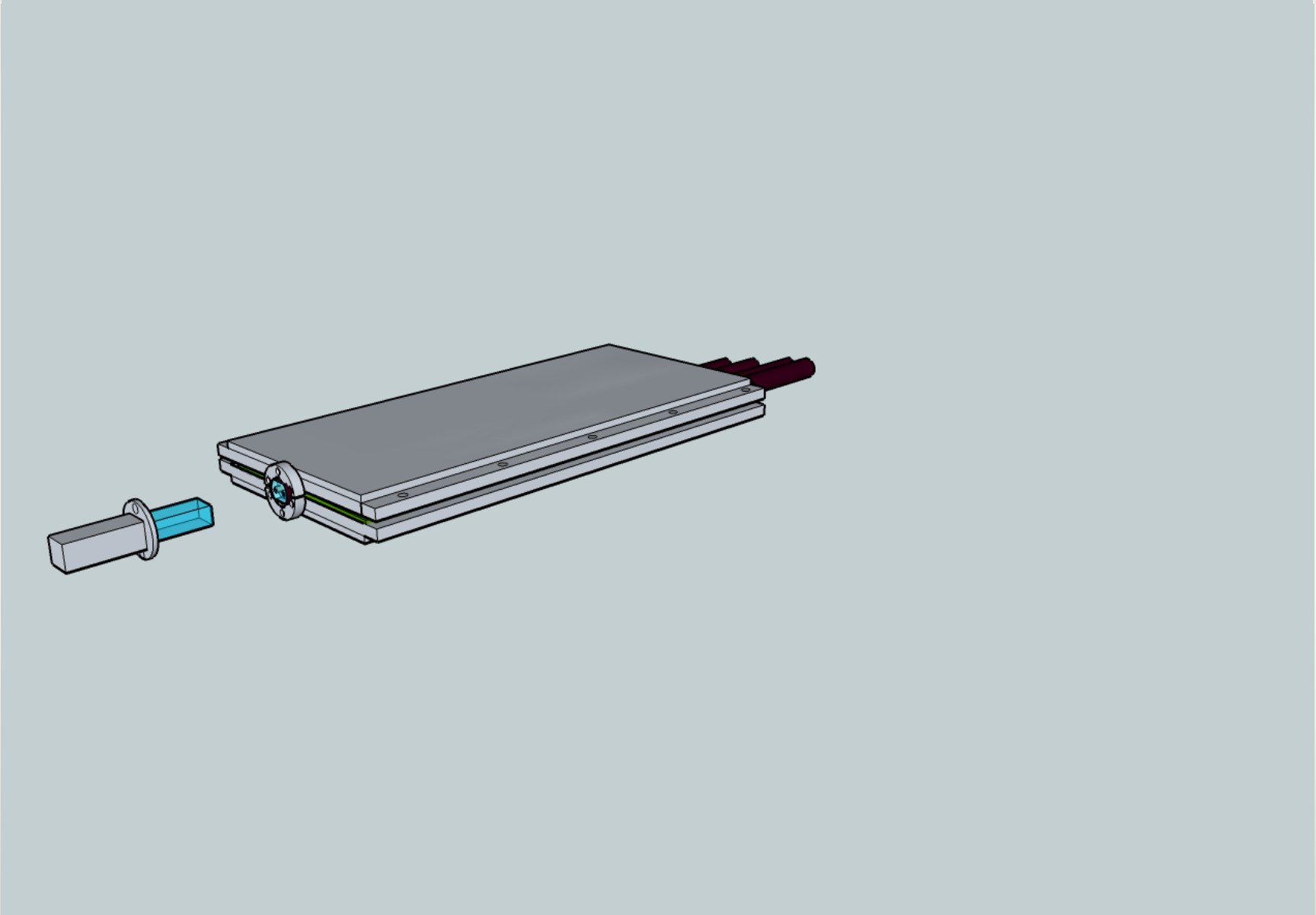


a way to reduce direct cross talk

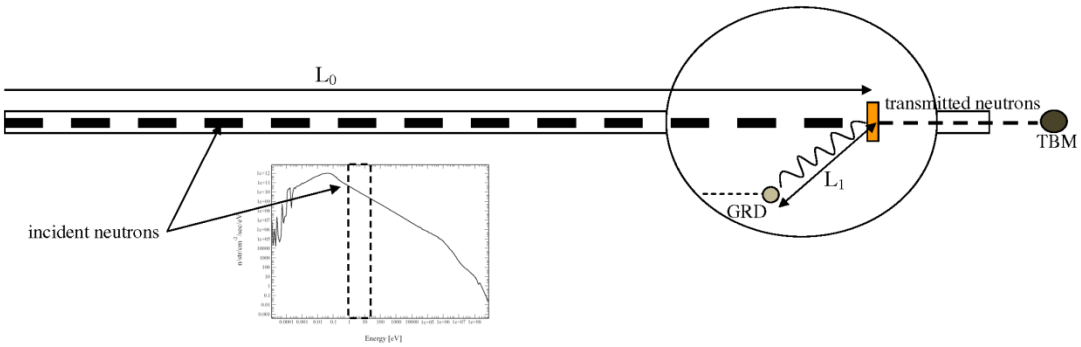


SiPM applications for neutrons:

A miniaturized NRCA detector

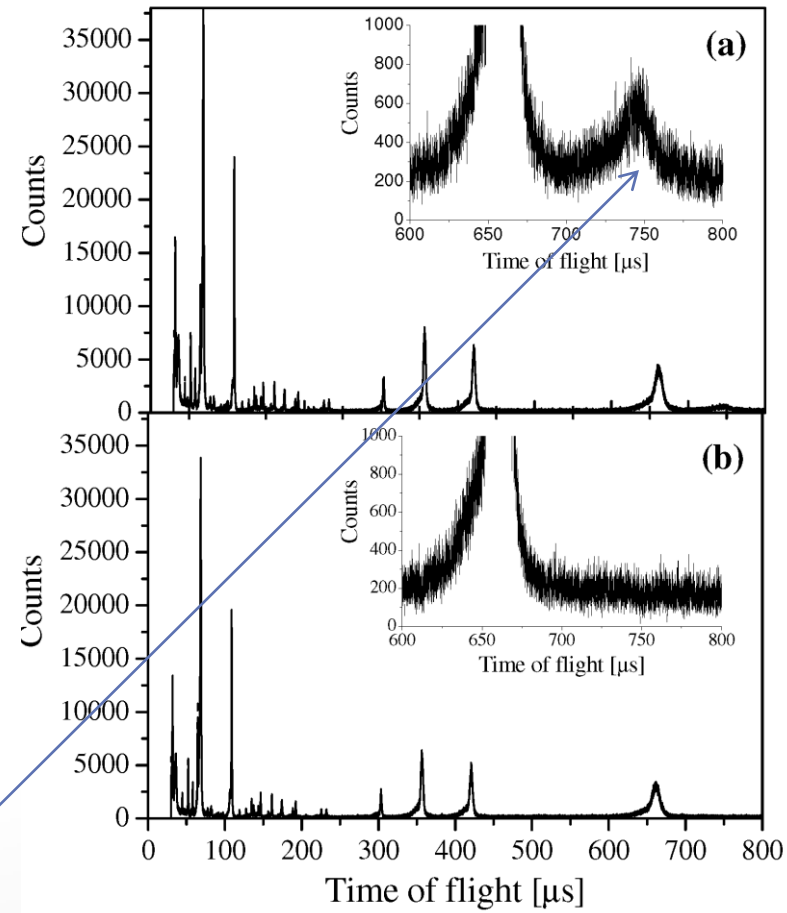


An example of SiPM application for neutrons



t_{exp} [μs]	t_{calc} [μs]	E_r [eV]	^{A}X
742.6±0.3	743.1	4.91	^{197}Au
662.5 ± 0.3	663.9	6.16	^{121}Sb
419.7± 0.3	420.1	15.37	^{121}Sb
355.1± 0.3	354.8	21.59	^{123}Sb
108.4± 0.3	108.9	228.65	^{65}Cu
68.4± 0.3	68.2	583.30	^{63}Cu
64.3± 0.3	65.1	640.66	^{63}Cu

•Au 40 ppm in weight



FURTHER READINGS

1- Hamamatsu Photonics, MPPC Manual.

2- P. Finocchiaro et al. IEEE trans. Electr. Dev. 55, 2757 (2008)

3- V. Golovin, Nucl. Instr. Meth. A 518, 560 (2004).

THANK YOU FOR YOUR ATTENTION