An Overview of SiPMs

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SiPM radiation workshop

Geneva, April 25th

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CONICET

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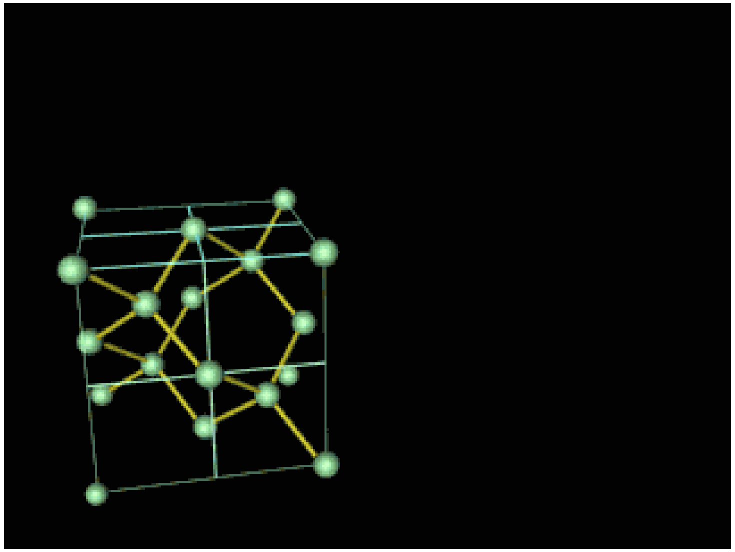
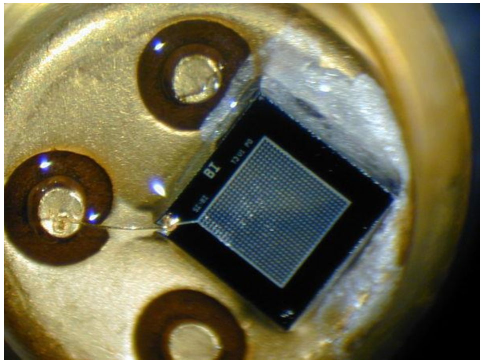
de San Martín

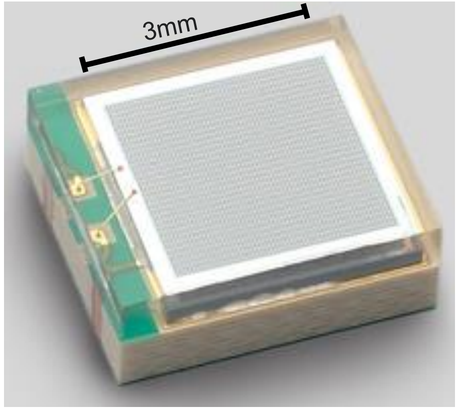
SiPM: Silicon Photomultiplier

- Also known as MPPC (Multi-Pixel Photon Counter)
- Key component for particle detection
  - Sensible component of instruments
- Converts light into electrical signals
- Must be very well studied
  - To design the detector in first place
  - To design the detector calibration procedure
  - To produce quality data
  - To understand the detector behavior





One of the first SiPM produced by FBK research center (formerly IRST) located in Trento, Italy. Src: wikipedia



Hamamatsu S13360-3025PE

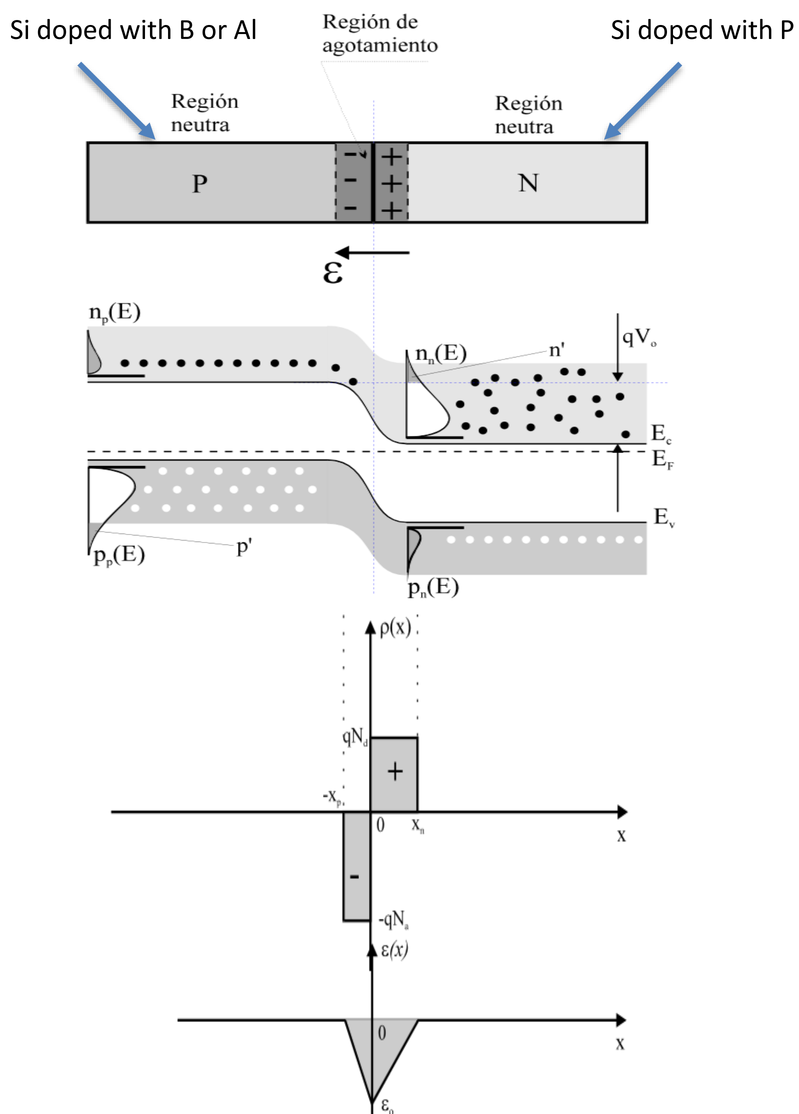
Introduction to Photodiodes

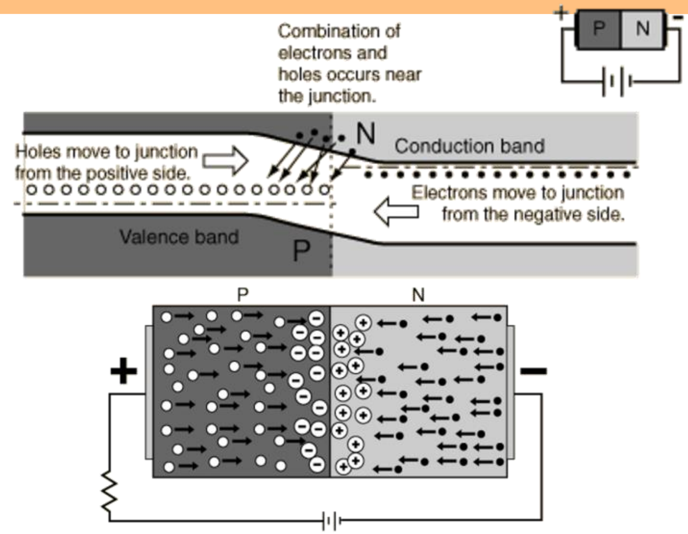
Diode bias

Forward bias:

$$I_{diff} + I_R > I_{drift} + I_G \qquad I_{tot} = +I_{forward}$$

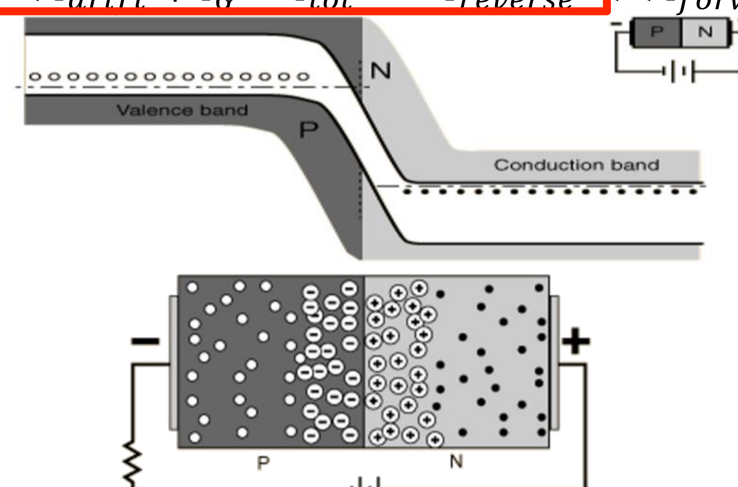
No bias: $I_{tot} = I_{diff} + I_R - I_{drift} - I_G = 0$



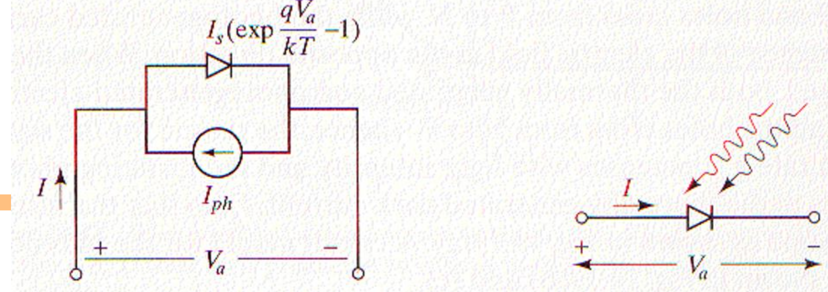


Reverse bias:

$$I_{diff} + I_R < I_{drift} + I_G \qquad I_{tot} = -I_{reverse} << I_{forward}$$



PhotoDiode:



- Core component of SiPMs
- Photons produce e-h pairs
- When reverse biased carriers contribute to inverse current

$$I_L = -qA(L_n + W + L_p)G_L$$

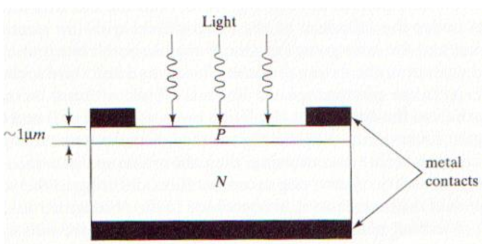
With: $G_L = f(PDE)$

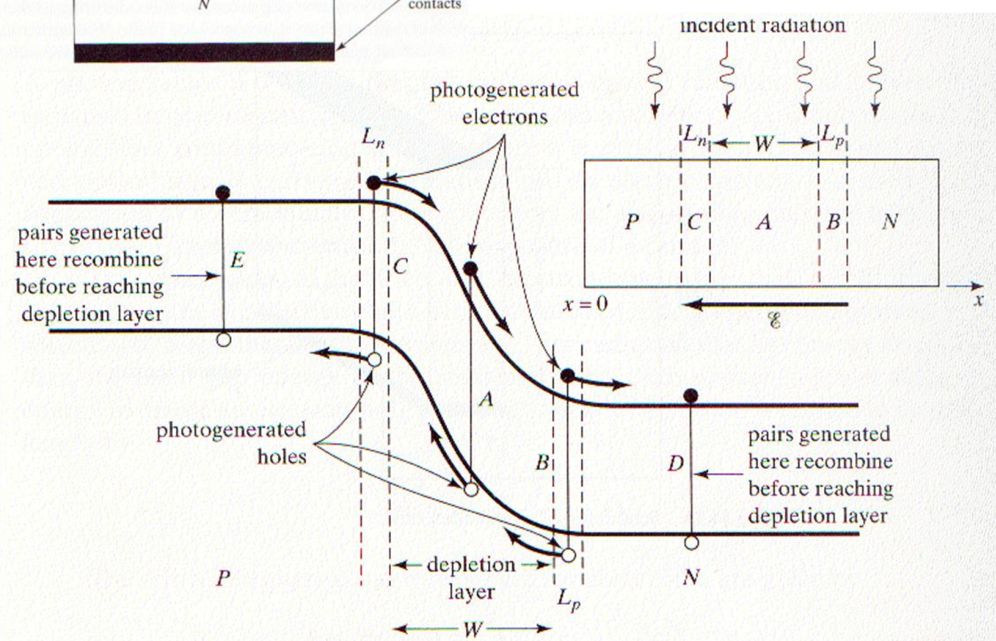
G_L = Photogeneration rate =

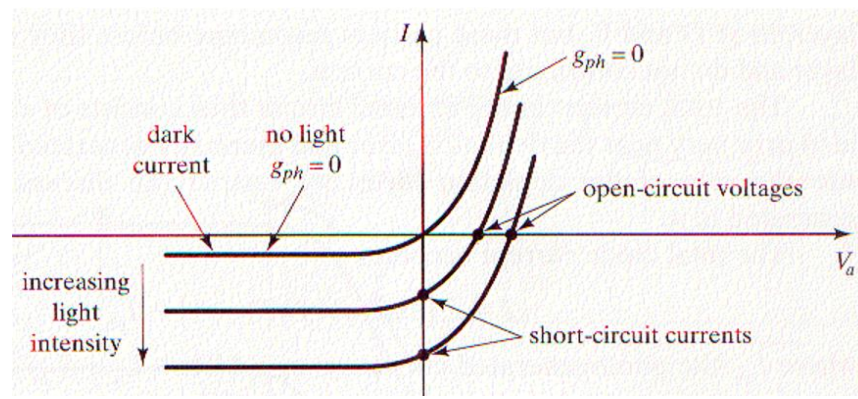
= #carriers s^{-1} cm^{-3}

$$I = I_0\left(e^{\frac{V}{V_T}} - 1\right) - I_L$$

Ideal dark-current







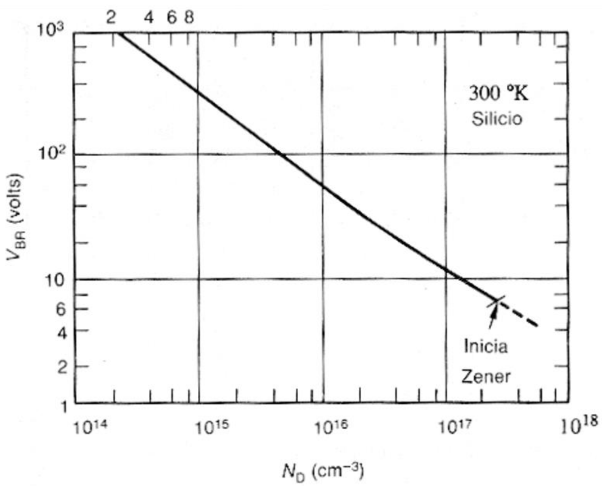
APD: Avalanche Photo Diode

Impact ionization produces avalanche in Junction (where maximum E field)

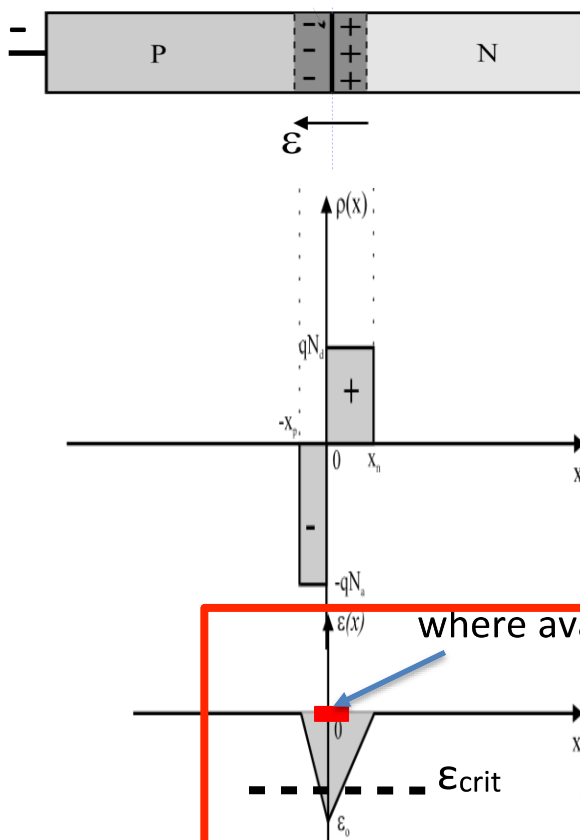
$$\varepsilon_{crit}^2 = \frac{2q(V_C - V_A)N_A N_D}{\varepsilon_0 \varepsilon_r (N_A + N_D)} \cong \frac{2qV_{BR} N_A N_D}{\varepsilon_0 \varepsilon_r (N_A + N_D)} \Rightarrow \quad V_{BR} = \frac{\varepsilon_{crit}^2 \varepsilon_0 \varepsilon_r (N_A + N_D)}{2qN_A N_D}$$

For P^+N:

$$V_{BR} = \frac{\varepsilon_0 \varepsilon_r}{2qN_D} \varepsilon_{crit}^2$$

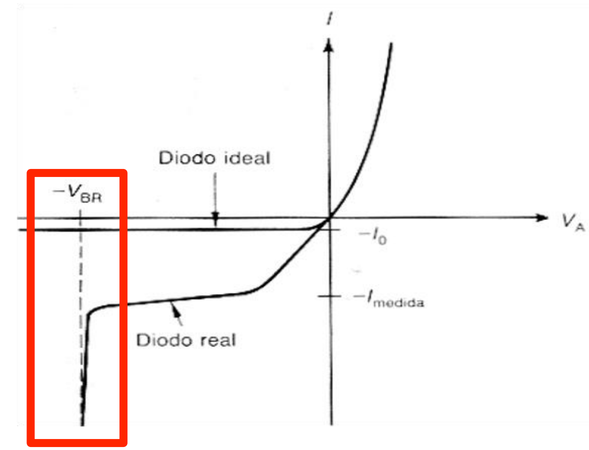


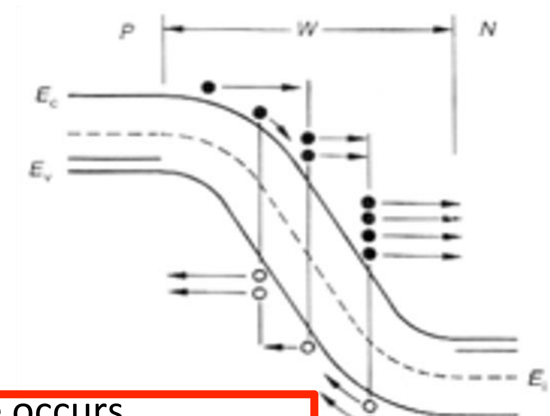
V_{BR} increases with T



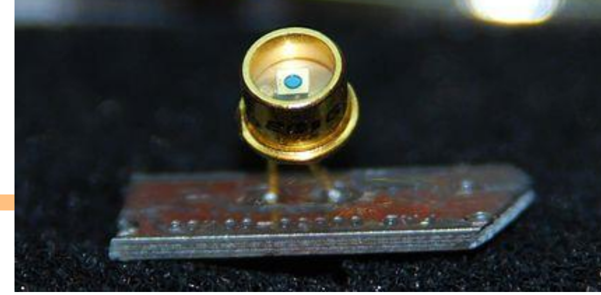
where avalanche occurs

ε_{crit} for e $1{,}75 \times 10^5$ V cm^{-1} and for h 2.5×10^5 V cm^{-1}





APD: operation modes



wikipedia

Linear mode: below V_{BR}

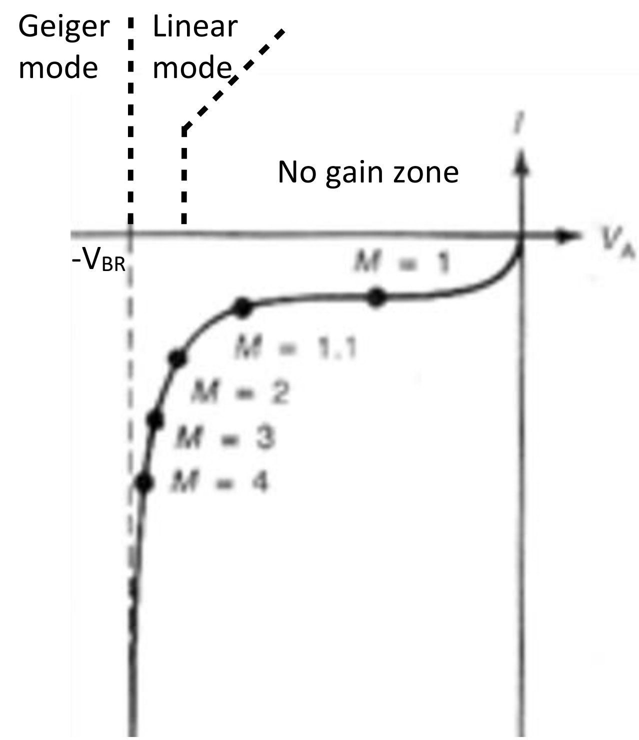
$$S_{out} \propto \#_{AbsorbedPhotons} \propto S_{in}$$

- Gain < 100
- Small avalanche is self-stopped

Geiger mode: above V_{BR}

$$S_{outmax} \forall \#_{AbsorbedPhotons} \propto S_{in}$$

- **Overvoltage is set above V_{BR}**
- Avalanche both initiated by e and/or h
- Single carrier injected in depletion region triggers self-sustained avalanche
- Carriers may be photo-generated (useful signal) or thermally generated (noise)
- Avalanche has to be stopped by external circuit

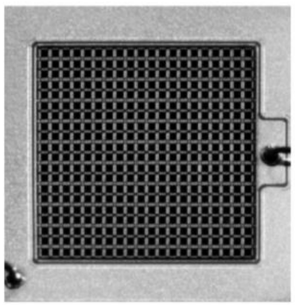


SiPM: Silicone Photomultiplier

SiPM: Silicone PhotoMultiplier

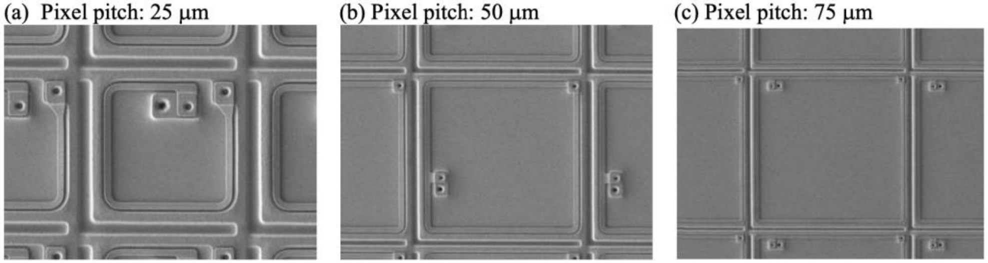
- Array of many integrated APDs+Rq in parallel

[Figure 1-18] An actual matrix implementation of MPPC microcells

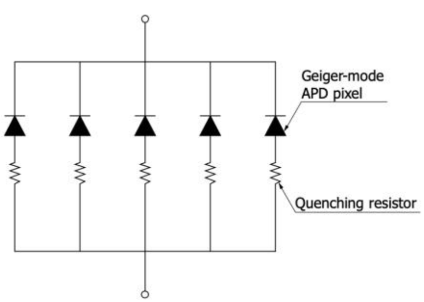


[Figure 1-16] Individual MPPC pixels (microcells) with a metal-composite quenching resistor fabricated around each microcell

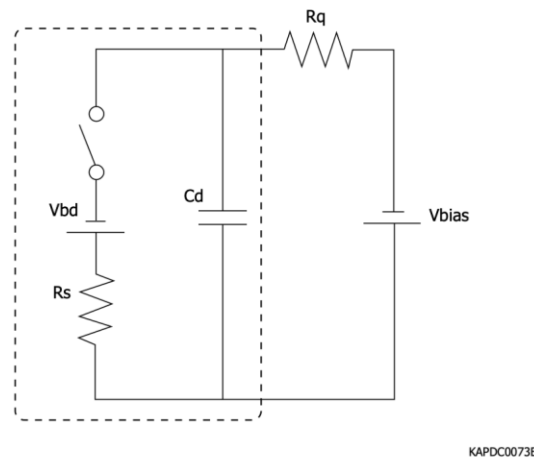
(a) Pixel pitch: 25 μm (b) Pixel pitch: 50 μm (c) Pixel pitch: 75 μm



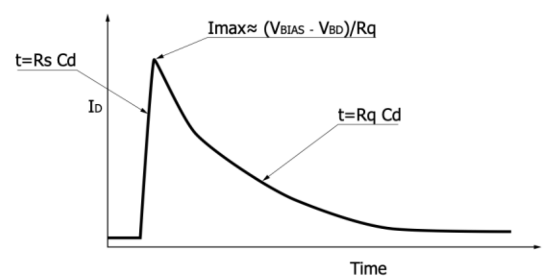
[Figure 1-17] Conceptual illustration of the MPPC as a matrix of GAPD pixels (microcells) connected in parallel



[Figure 1-12] Equivalent circuit of a Geiger-mode APD (GAPD)



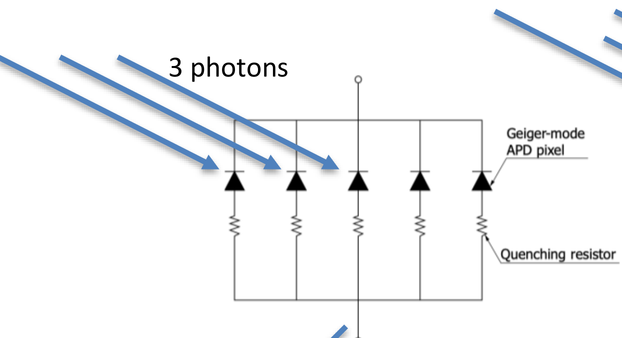
[Figure 1-13] Conceptual output pulse of the equivalent circuit

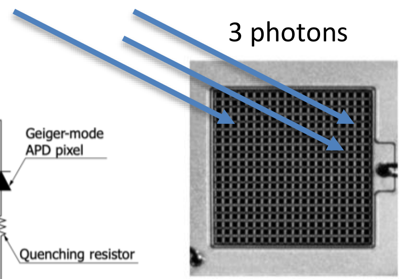


Src: Hamamatsu technical note

SiPM: Output signal

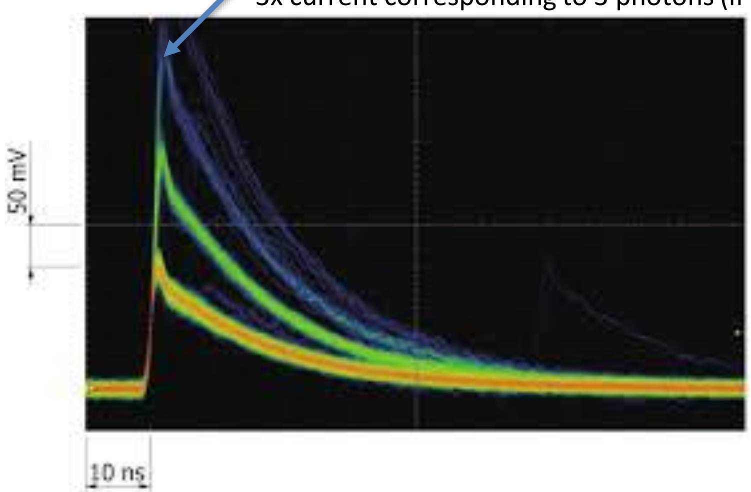
- Q_{out} and I_{peak} proportional to #photons hitting the microcells
  - unless >2ph hit same cell
  - light-pulse is a train of light sub-pulses spread in time

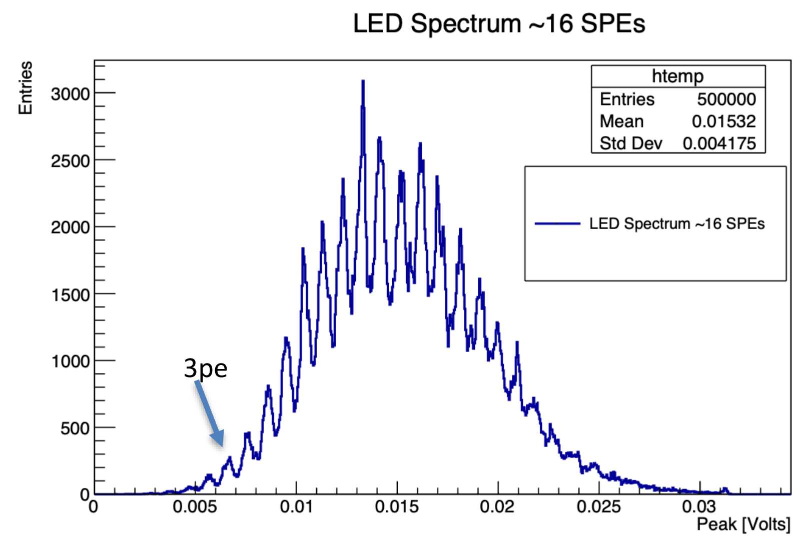




Tomorrow's talk

3x current corresponding to 3 photons (if eff. 100%)





Src: Hamamatsu

Parameters and non-ideal effects

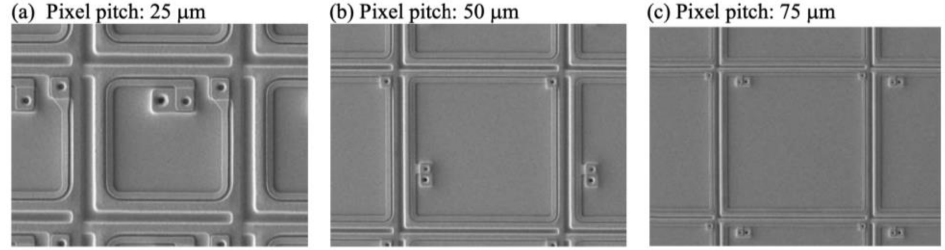
Physical shape

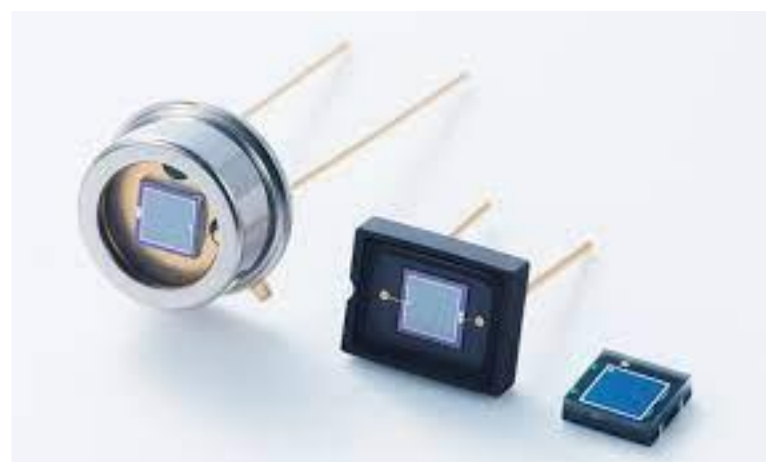
- Single SiPM
  - Pixel pitch / cell size
  - # of cells
  - Package type
- Array of SiPMs
- Custom designs

Selection guide

Type no.	Pixel pitch (μm)	Effective photosensitive area (mm)	Number of pixels	Package	Fill factor (%)
S13360-1325CS	25	1.3 × 1.3	2668	Ceramic	47
S13360-1325PE				Surface mount type	
S13360-3025CS		3.0 × 3.0	14400	Ceramic	
S13360-3025PE				Surface mount type	
S13360-6025CS		6.0 × 6.0	57600	Ceramic	
S13360-6025PE				Surface mount type	
S13360-1350CS	50	1.3 × 1.3	667	Ceramic	74
S13360-1350PE				Surface mount type	
S13360-3050CS		3.0 × 3.0	3600	Ceramic	
S13360-3050PE				Surface mount type	
S13360-6050CS		6.0 × 6.0	14400	Ceramic	
S13360-6050PE				Surface mount type	
S13360-1375CS	75	1.3 × 1.3	285	Ceramic	82
S13360-1375PE				Surface mount type	
S13360-3075CS		3.0 × 3.0	1600	Ceramic	
S13360-3075PE				Surface mount type	
S13360-6075CS		6.0 × 6.0	6400	Ceramic	
S13360-6075PE				Surface mount type	

(a) Pixel pitch: 25 μm (b) Pixel pitch: 50 μm (c) Pixel pitch: 75 μm





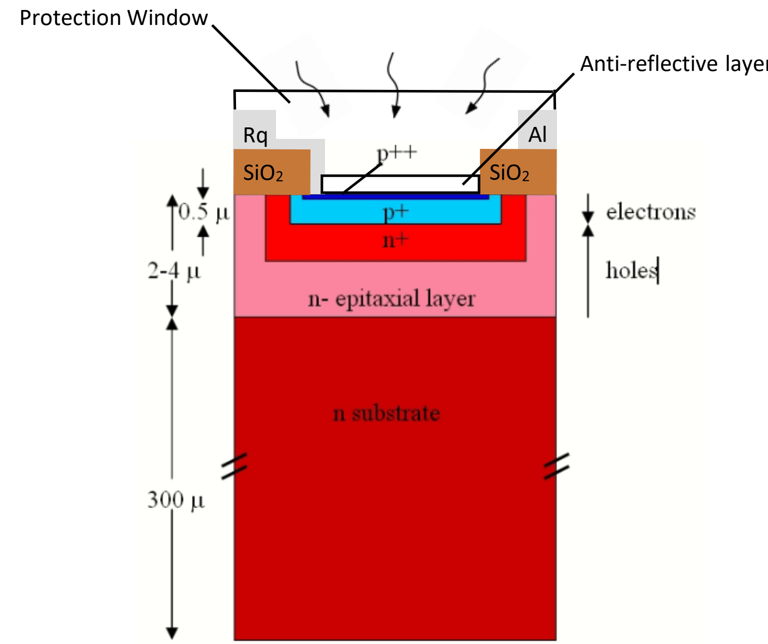
Detection efficiency

QE: Quantum efficiency (photon conversion rate) depends on:

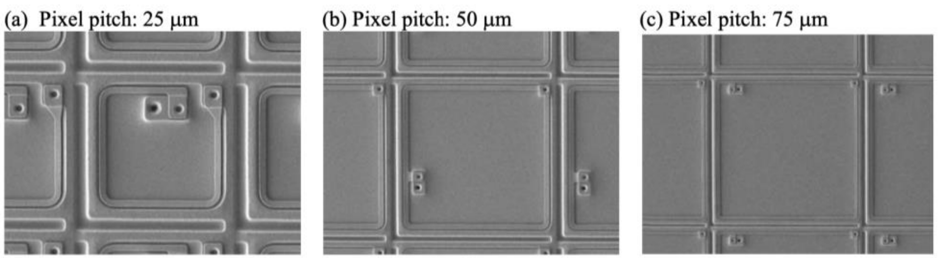
- λ and angle
- Material (Si, GaAs, GaN, GaP, etc.)
- Reflections

PDE: Photo-detection efficiency depends on:

- QE
- CE: Collection Efficiency
    - Fill factor (active area vs. total area)
    - Breakdown trigger probability (position of carriers generation)
    - Structure type (P on N or N on P) and layer thicknesses



Modified from D Renker and E Lorenz 2009 *JINST* **4** P04004



Parameters

PDE, Gain, Thermal pulses

$$S_{output}[e-] = (\underbrace{S_{input}[photons] \cdot QE \cdot CE}_{\text{PDE}} \cdot \underbrace{M}_{\text{Gain}}) + \underbrace{S_{dark}[e-]}_{\text{Thermal pulses}}$$

- Gain=Q_{out}/q_e
- Timing
  - Good timing resolution <25ps
  - Normally limited by electronics Frontend

$$\sigma_{Detector\ Jitter} \propto \frac{1}{\sqrt{N_{photon} \times PDE}}$$

- Dynamic range (defined by nonlinearity)
  - Limited by # of cells (*P*(>1pe) hitting cell)

$$Linearity = \frac{\frac{A_{output}(t_2) - A_{output}(t_1)}{A_{output}(t_1)}}{\frac{A_{input}(t_2) - A_{input}(t_1)}{A_{input}(t_1)}} \mid t_2 > t_1$$

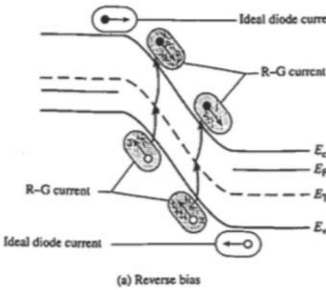
$$Nonlinearity\ [\%] = 100 - Linearity\ [\%]$$

- Dispersion of parameters:
  - non-uniformity among SiPMs of same series

A. Lucero today afternoon

Parameters cont': Noise

Pierret, Semiconductor Device Fundamentals



Dark-current

- continuous regime $I_{dark} = I_{drift} + I_{Generation} + I_{Surface} + I_{ThermalAvalanches}$

Hampel et al. NIM-A 976 (2020) 164262

DCR (Dark-count rate)

- dynamic regime

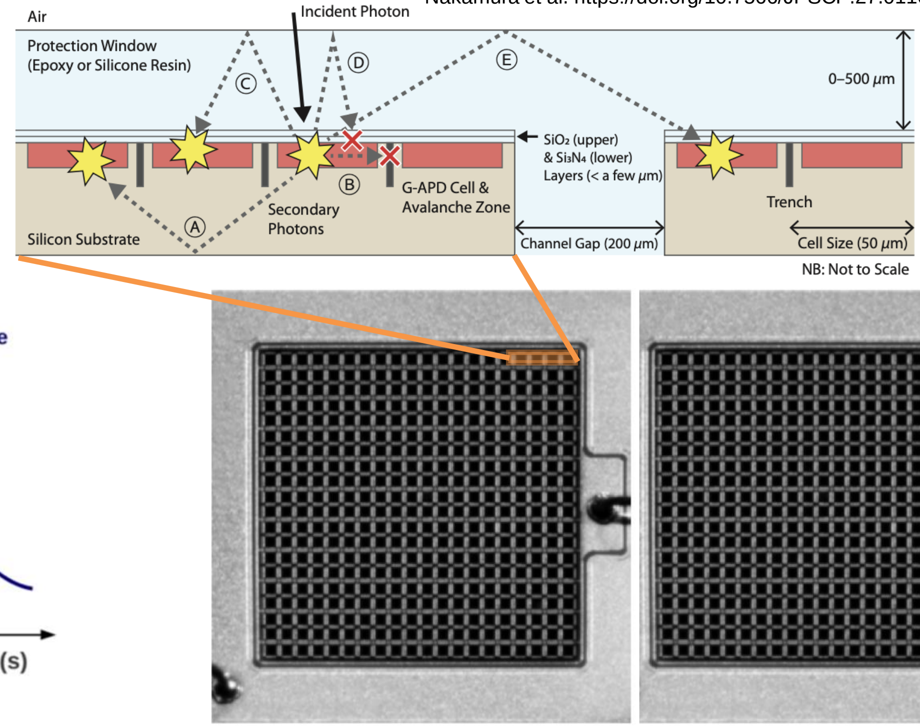
$$SNR = \frac{N_{photon} \times PDE}{\sqrt{(N_{photon} \times PDE) + N_{dark}}}$$

Cross-talk

$$CT = \underset{B)}{ID_{CT}} + \underset{A)}{IR_{CT}} + \underset{C)}{EI_{CT}}$$

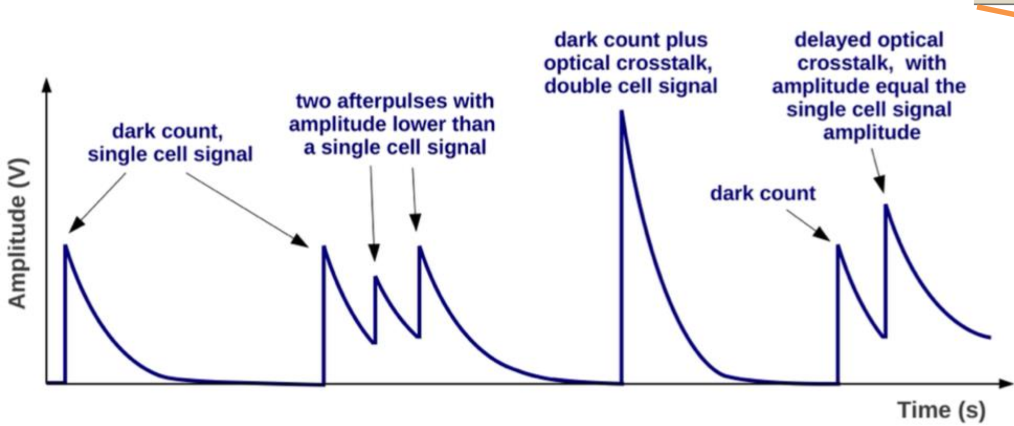
- ph or carriers from avalanche may trigger other cells
- reduced by manufacturing design with trenches and guard rings between cells

Nakamura et al. https://doi.org/10.7566/JPSCP.27.011



After-pulse

- Trapped carriers trigger cell



Stefan Gundacker *et al* 2020 *Phys. Med. Biol.*, *Reproduction from* Acerbi and Gundacker, 2019

Parameters cont': Noise???

- Useful for:
  - Detector diagnostics
  - Calibration

$$CT = \frac{CR_{>1.5PE}}{CR_{>0.5PE}}$$

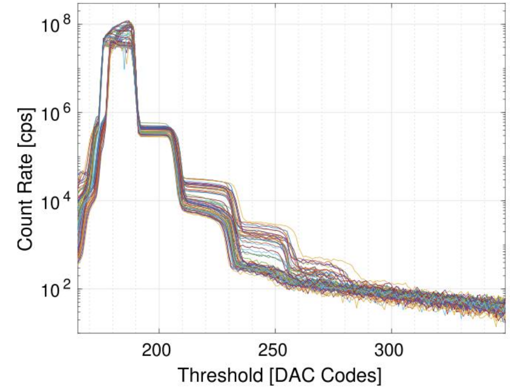
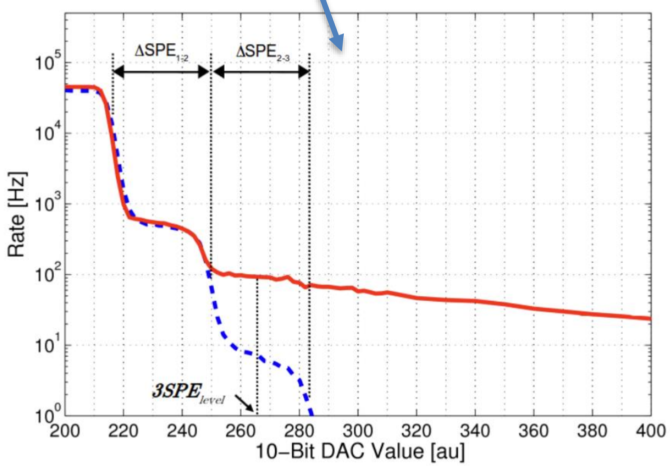
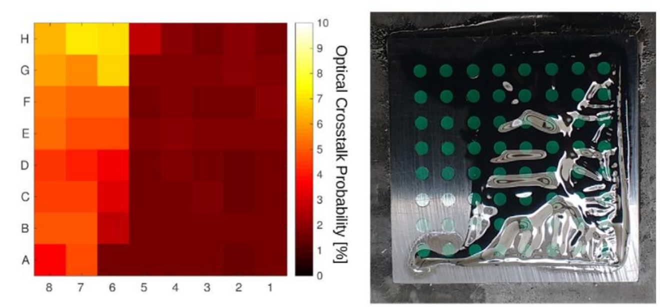


Fig. 8. Measurement of the average count rate over the threshold of the 64 SiPMs of the module after it first deployment. It can be seen that at 1.5 PE level there is a high dispersion of the count rate between channels, this is produced by a change in the CT of the devices due to a bad coupling of the SiPMs to the optical adapter.



Pierre Auger Collaboration FAL

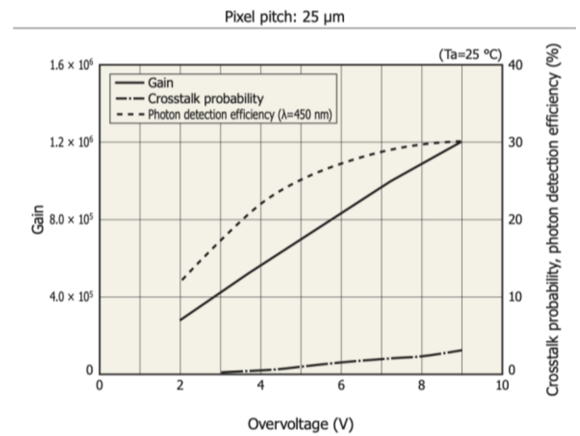


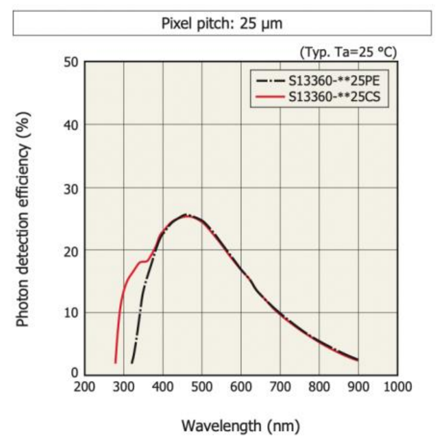
(a) (b)

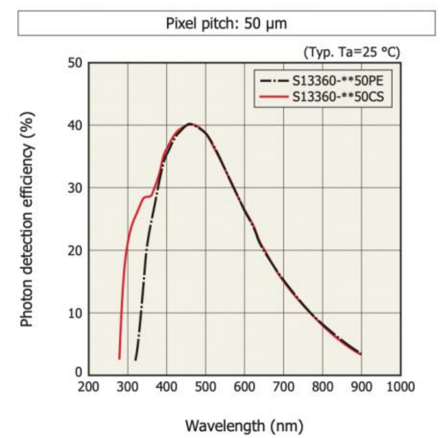
Fig. 9. (a) Plot of the optical crosstalk probability of each channel aligned with its position in the optical adapter. (b) Picture of the optical adapter after the extraction of the electronics. A high optical crosstalk probability correlates with the absence of optical silicone grease in the optical adapter.

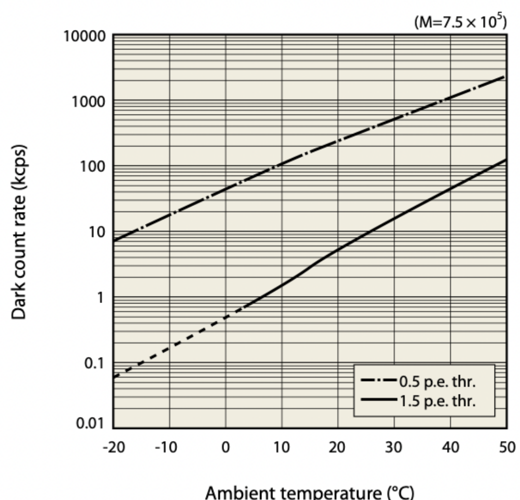
Parameters correlation and variations

- Gain vs. Overvoltage
- Gain and PDE vs. cell size
- Dynamic range vs. # of cells
- Gain/PDE vs. *T*
- DCR vs. *T*
- DCR/CT vs. Overvoltage
- many other…





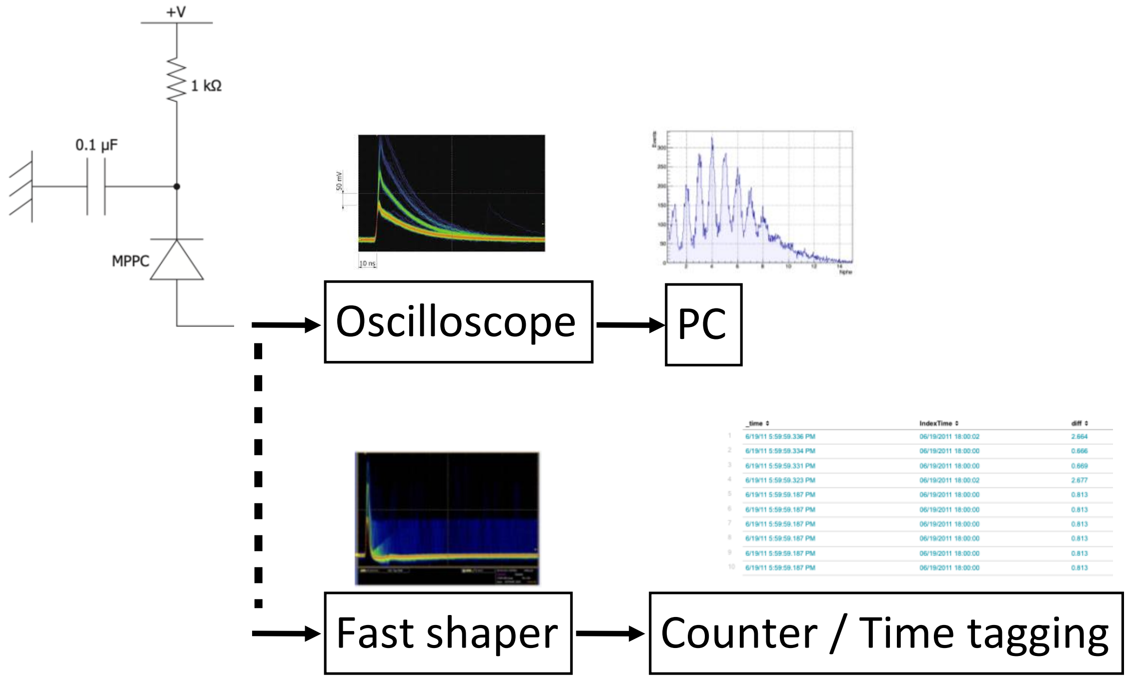




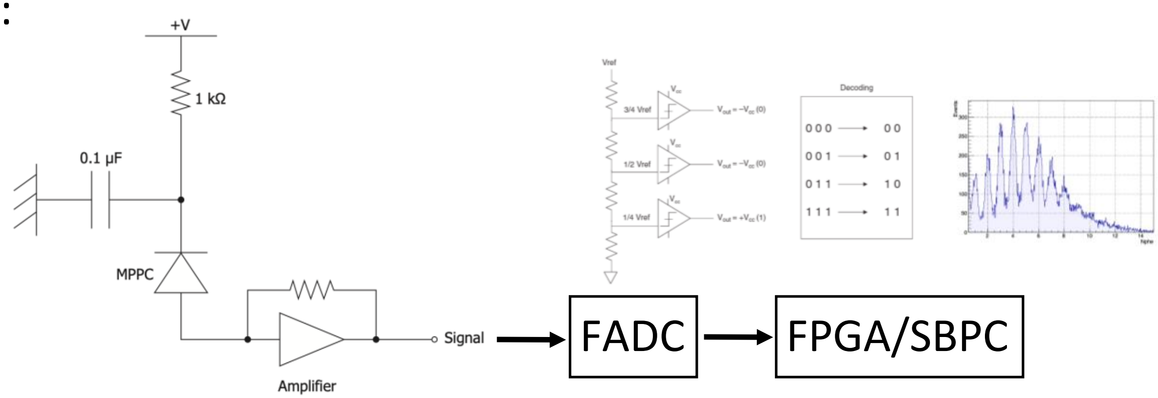
Signal Readout

Single SiPM: Readout

- Directly with
  a Oscilloscope
- Counter or Time
  measurements



- Readout circuit:



SiPM arrays

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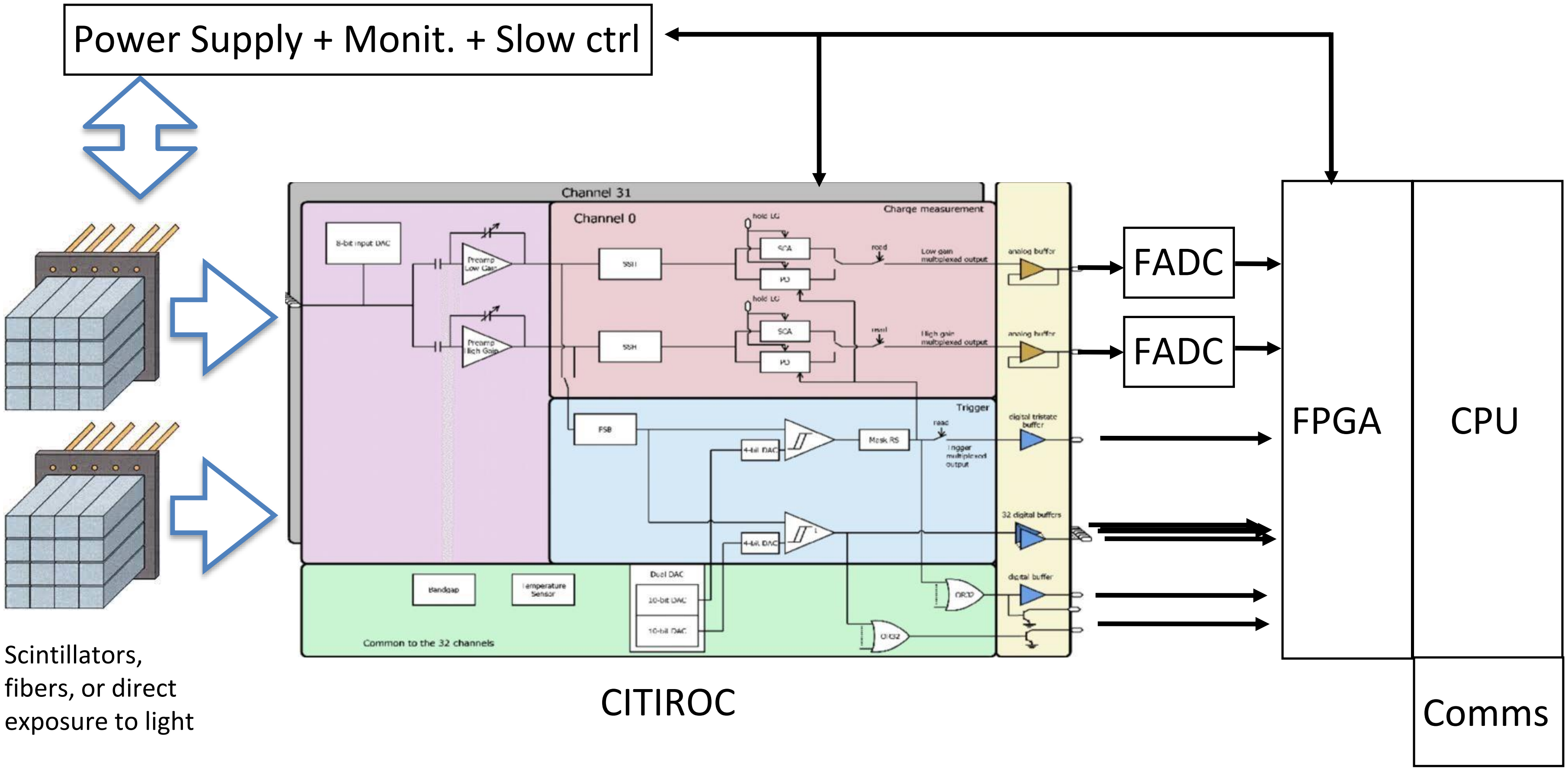
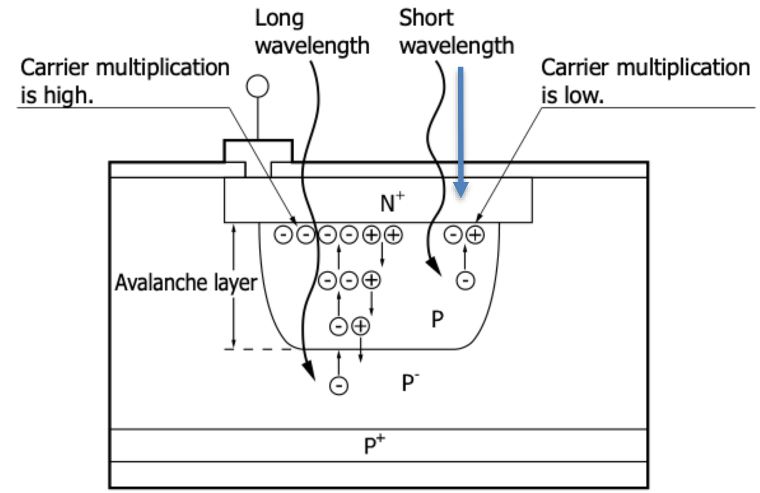


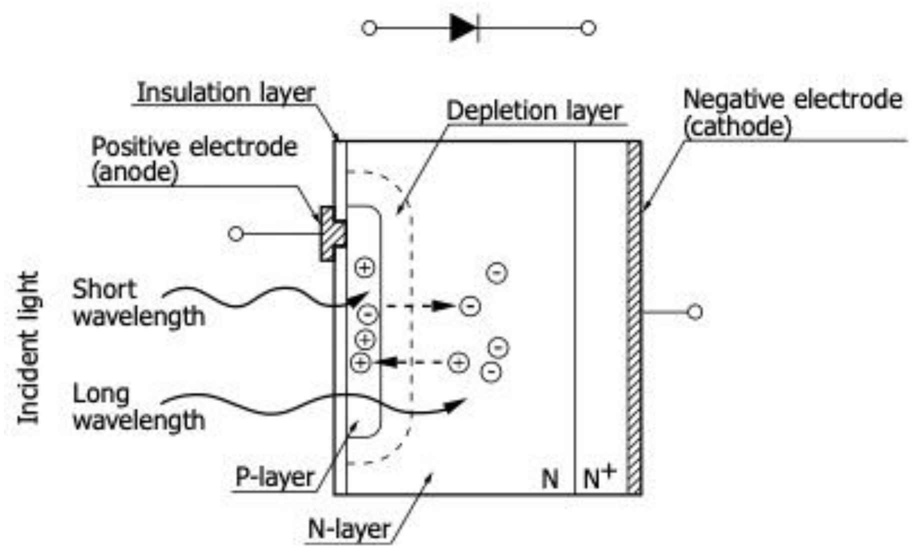
Muchas Gracias

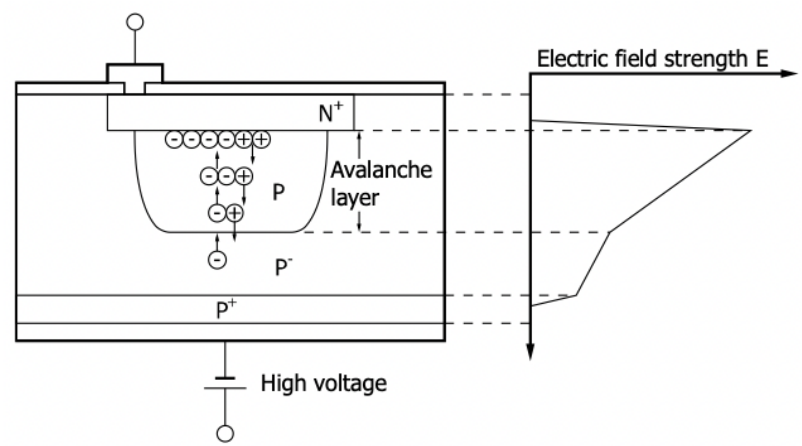
APD internal structure

N on P diode

- Equivalent to a SiPM cell (without Rq)
  - P on N better for blue λ

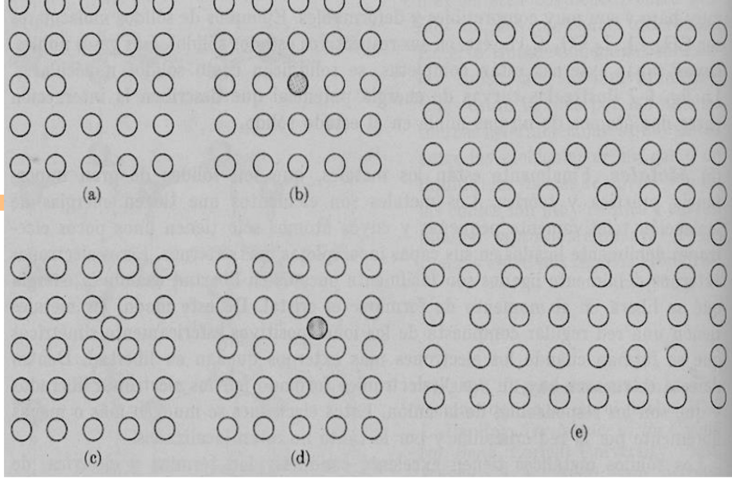






P on N diode

Harsh environments



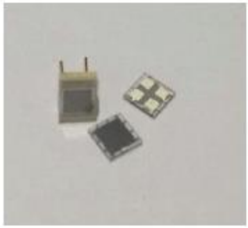
- Radiation damage produce defects
  - Bulk damage in the crystalline structure
    - From high energy particles (p, e, γ, π, n, ions)
    - Increases SiPM noise: dark-current, dark-counts, and therefore false triggering of detector
    - Also from low energy n through indirect processes
  - Surface damage in anti-reflective coating and maybe in first layer
    - Mostly from photons and low energy charged particles
    - Increases dark-current
  - Change of effective doping density
    - Low energy n produce transmutation doping in Si
    - Fast n produce Al/Mg but 2 orders of magnitude less likely)
    - Removal of some dopants (^{10}B capture and other processes)
- Annealing (damage recovery)
  - Reordering of displaced atoms
  - Somehow proportional to temperature

$$^{29}Si(n,\alpha)^{26}Mg$$

$$^{30}\mathrm{Si} + \mathrm{n} \rightarrow {}^{31}\mathrm{Si} \rightarrow (\beta^-)\ {}^{31}\mathrm{P}$$

$$^{10}\mathrm{B}(\mathrm{n},\alpha)\mathrm{Li}$$

SiPM vs PMT



Advantages

Compact and light

Very robust, mechanically and opto-electronically

More deterministic gain

Low ENF

Cheap and with multiple vendors

V_{Bias} 10-100x lower => simpler electronics, more reliable, low maintenance and costs

Higher red to near-IR QE

Almost not sensitive to magnetic fields

Low cross-talk between channels in SiPM arrays

Disadvantages

High Dark-current and Dark-counts

May require cooling => increased complexity and cost

No large active areas => higher dark counts per area, and high cost

High dependence of gain with temperature => Compensation also requires additional complexity and costs.

Output signal is complex and slow => requires more analog filtering and pulse shaping