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Introduction to SiPMs

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IRIS
INTEGRATED RADIATION
AND IMAGE SENSORS

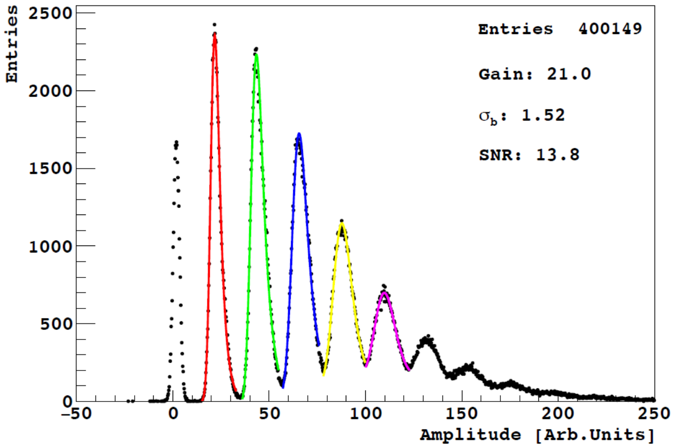
SiPM working principle

The Silicon Photomultiplier

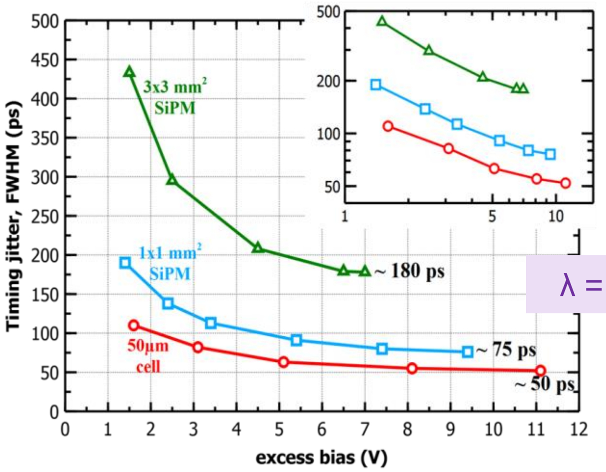
A SiPM is a single-photon detector, with internal signal amplification, fabricated on CMOS-compatible silicon wafers.

Capabilities of SiPMs:

- Detection of single photons in the visible / NIR range with simple (low power) readout electronics.
- Excellent timing performance: down to 50 ps FWHM.
- Few-photon or many-photon counting capabilities, depending on design.



Example of few-photon counting



λ = 425 nm

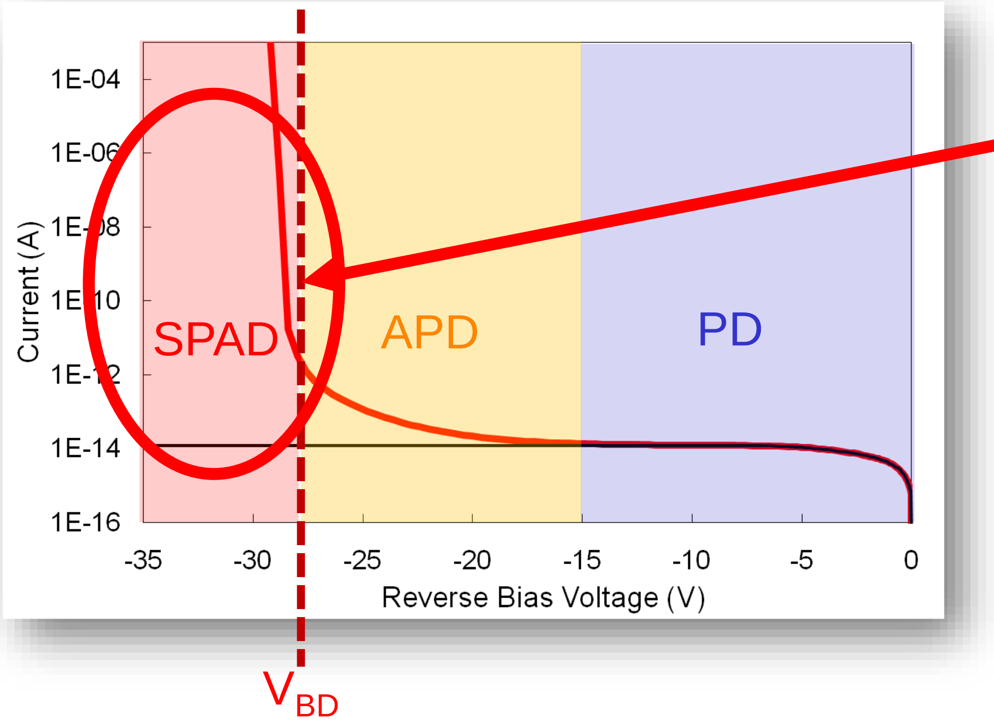
Single photon time resolution (SPTR)

Solid-state low-light detectors

SOLID-STATE DETECTORS WITH INTERNAL GAIN

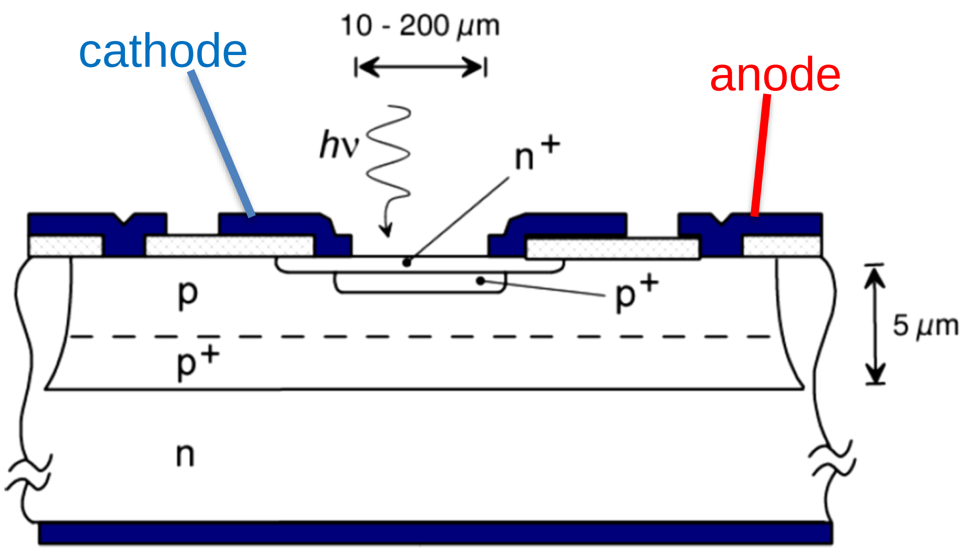
- process: multiplication of carriers via **impact ionization**

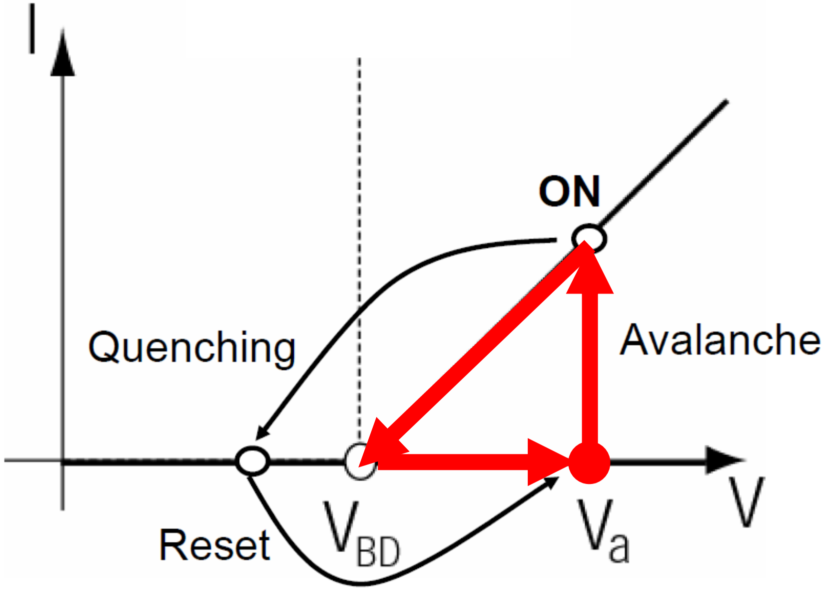
- **Advantages**: low-bias, compact, rugged, insensitive to magnetic field.



SPAD (Single-photon avalanche diode)
(GEIGER-MODE APD)
- Gain ~10^6 or more
- Timing ~ 20÷50 ps.
- Bias voltage <100V
- Sensitivity ~1 ph. e.

SPAD: working principle



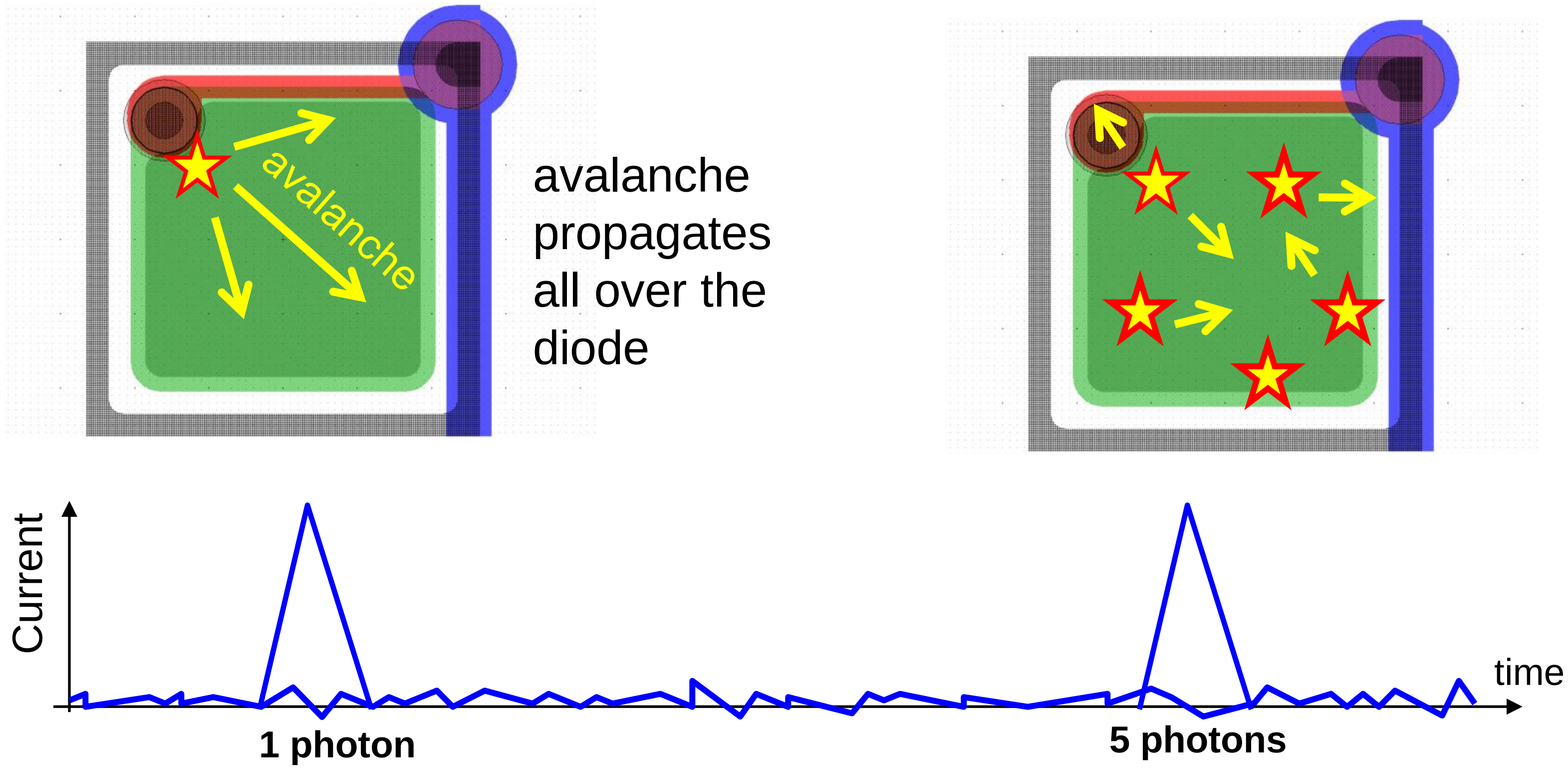


1. Biased (V_a) ABOVE breakdown voltage (with excess bias Vex)
2. Single photon or thermally generated carrier switches on avalanche process (with a certain probability) → macroscopic current
3. Avalanche has to be quenched by external circuit → quenching circuit:

   Passive quenching in SiPMs (large resistance: usually > 300 kOhm)
4. Bias reset above breakdown voltage → dead time.

SPAD: drawbacks

- **Limited active area: 20µm ÷ 200µm**
- **Cannot count the number of photons**

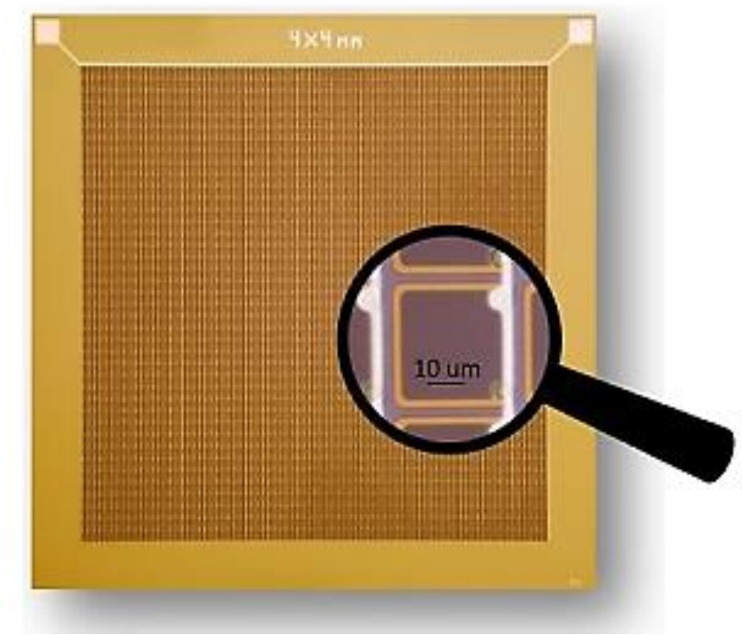


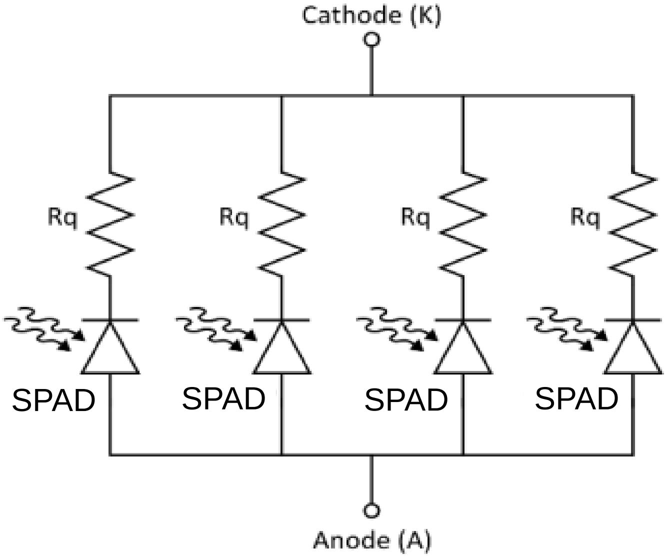
avalanche propagates all over the diode

The Silicon Photomultiplier (SiPM)

SiPMs are arrays of small SPADs connected in parallel.

Each SPAD employs a passive quenching mechanism.



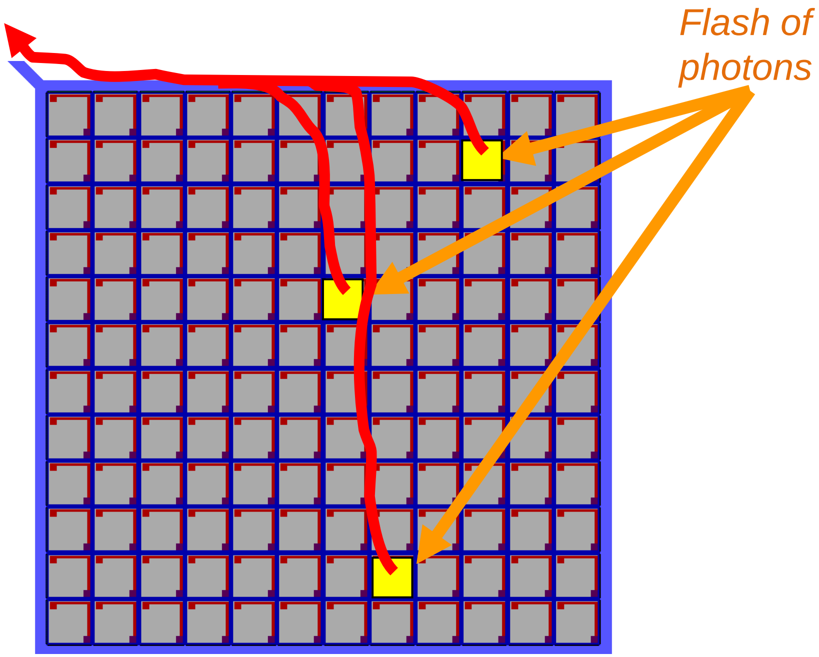


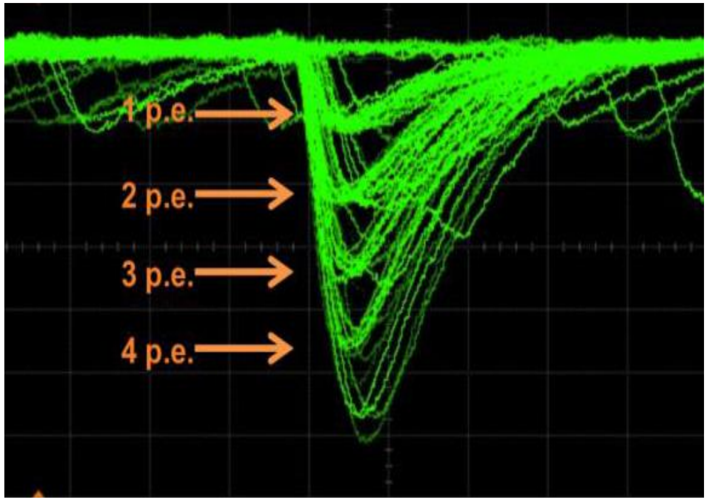
SiPM size:

1x1 mm^2 to 10x10 mm^2

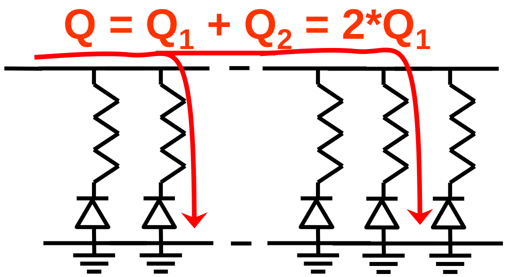
Microcell (SPAD) pitch:
12 um to 50 um
(typical)

The Silicon Photomultiplier (SiPM)



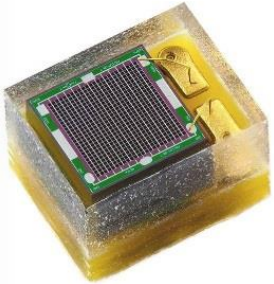


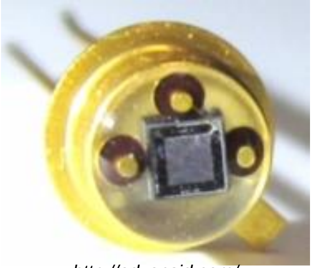
- Each element is independent and gives the same signal when fired.

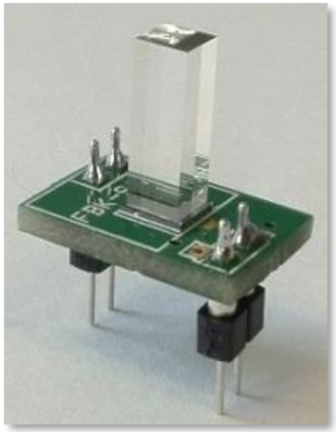


⇒ **Output amplitude (and charge) → proportional to the number of triggered cells → proportional to the number of photons.**

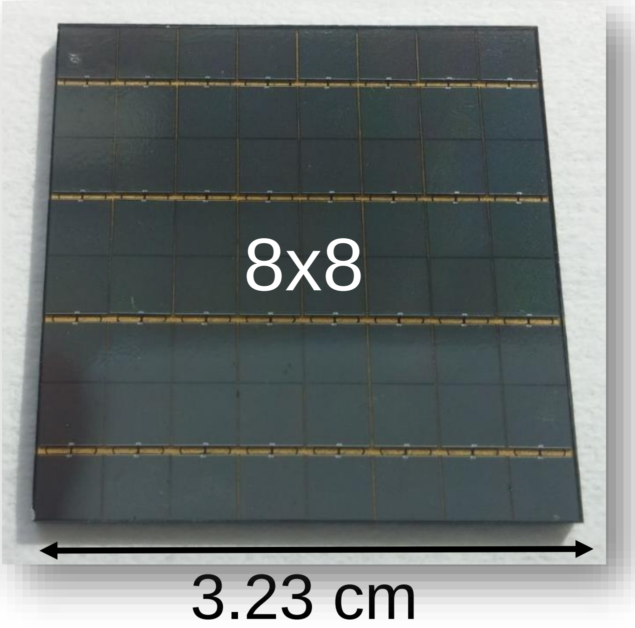
Silicon Photomultiplier (SiPM)


http://www.ketek.net/

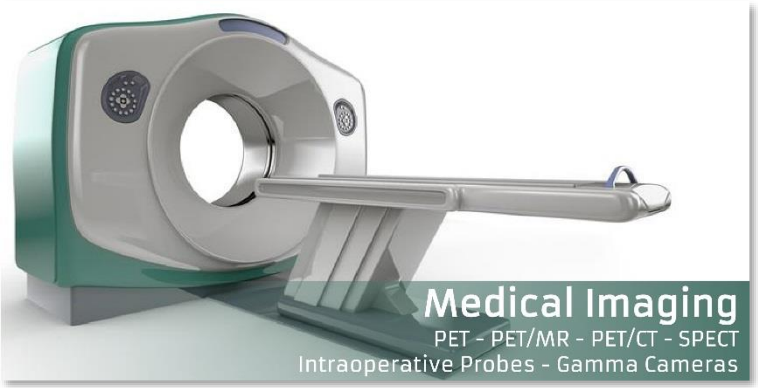

http://advansid.com/



- composed of square SPAD e.g. 40x40 μm^2
- Active area of 1x1mm^2 up to 10x10mm^2
- **Insensitive to magnetic fields**.
- **TILE of SiPMs** to cover big areas.
- Typically **coupled to scintillators** for gamma-ray detection   *(e.g. medical imaging, physics experiments)*



SiPM Markets and Applications



Medical Imaging

PET - PET/MR - PET/CT - SPECT
Intraoperative Probes - Gamma Cameras

High Energy Physics

Calorimeters - Particle Physics
Cherenkov light - LXe - LAr

Biotech & Life Science

PCR - Luminometers - Flow Cytometry
Spectroscopy - FLIM

Security & Safety

Homeland Security - Cargo Scanner
Radiation detectors - Dosimeter - Environmental monitoring

Analytical Instrumentation

SEM & Confocal Microscopy
Material Inspection

LiDAR

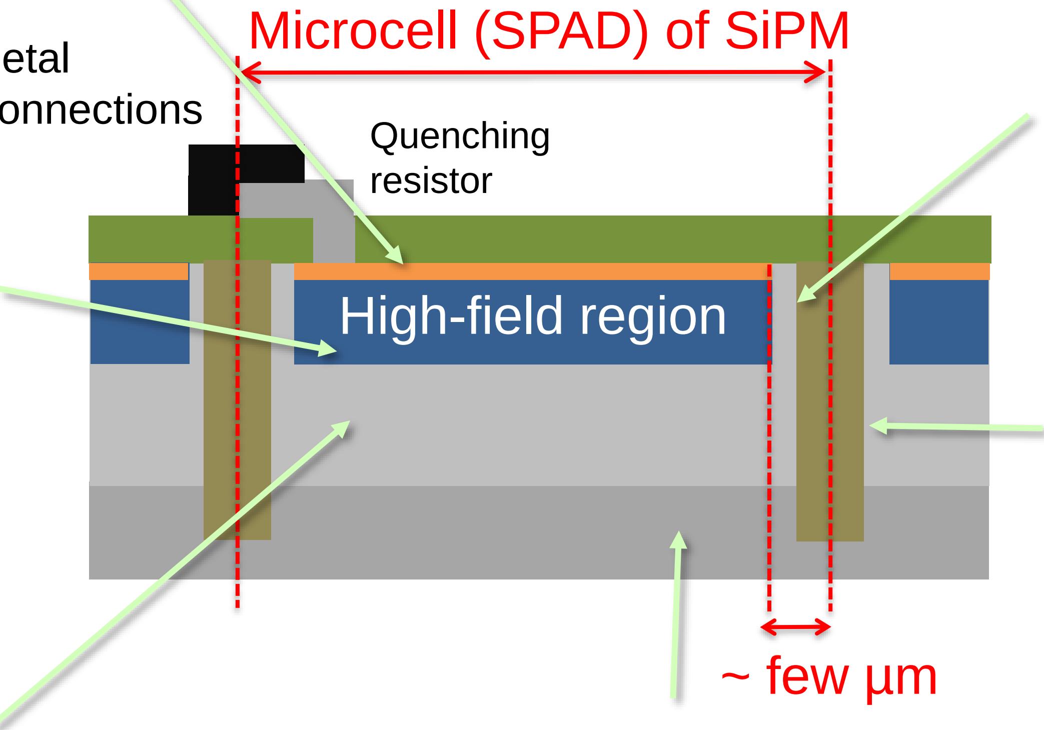
for autonomous driving

Typical SiPM Structures

Typical SiPM Structure with trenches

Superficial implant (SI):

Very thin, constitutes the entrance window for the light into the SPAD. High-dose, opposite dopant polarity compared to the epitaxial layer, partially undepleted. Constitutes one half of the diode.



Virtual Guard Ring:

Dead border around the high-field region, necessary to prevent edge breakdown.

High-field region:

is defined with a high-energy deep implant **(DI)** of the same type as the epi layer. Avalanche multiplication takes place here.

Deep trench Isolation:

are used to isolate adjacent microcells electrically. Optical isolation depends on filling material.

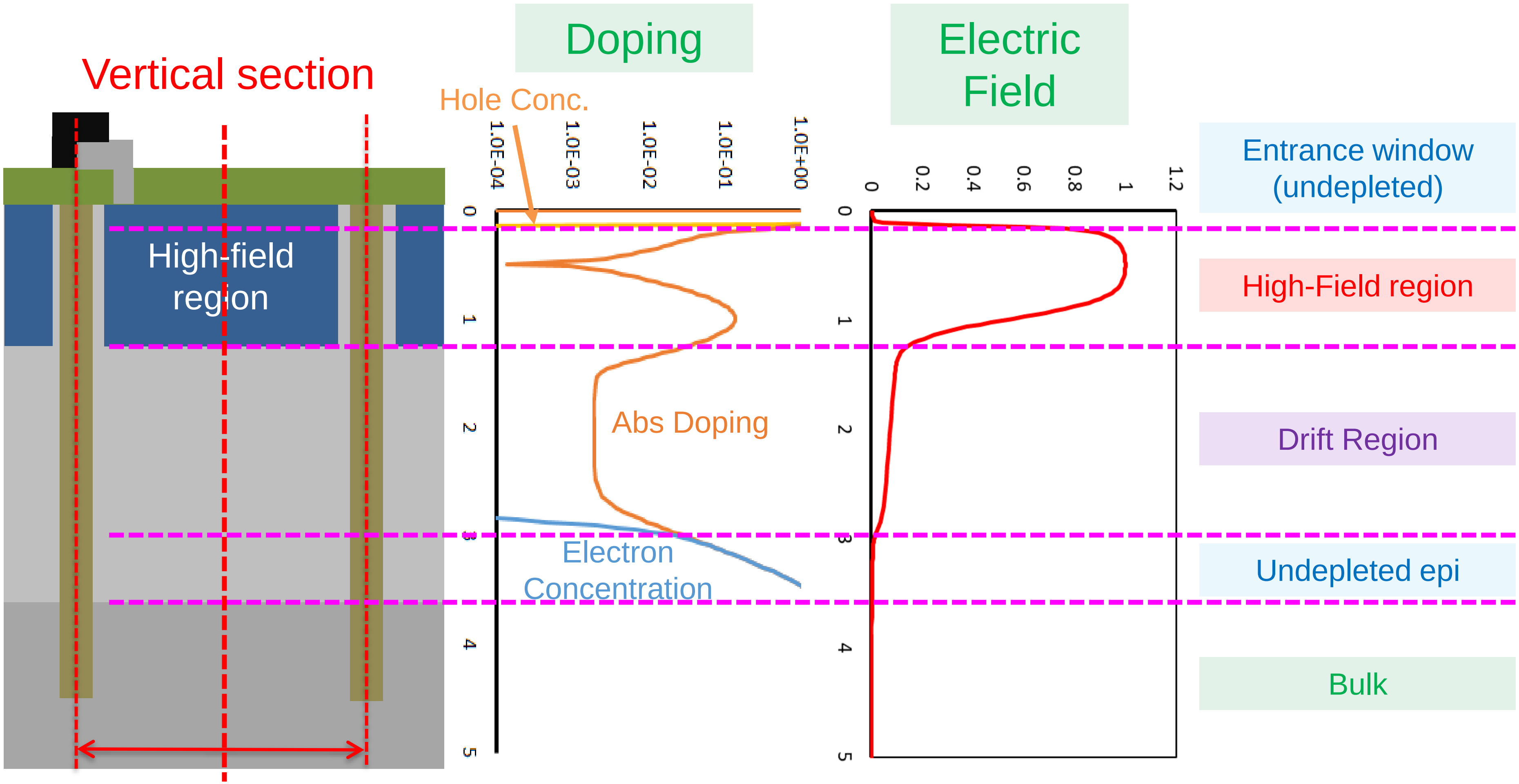
Epitaxial layer:

The high-resistivity region in which the SiPM cells are built. Few um thick. Almost fully depleted at breakdown. Close to the interface with the bulk, part of it is undepleted. Constitutes one half of the diode.

Bulk:

(Very) highly doped region upon which the epitaxial layer is built. Never depleted.

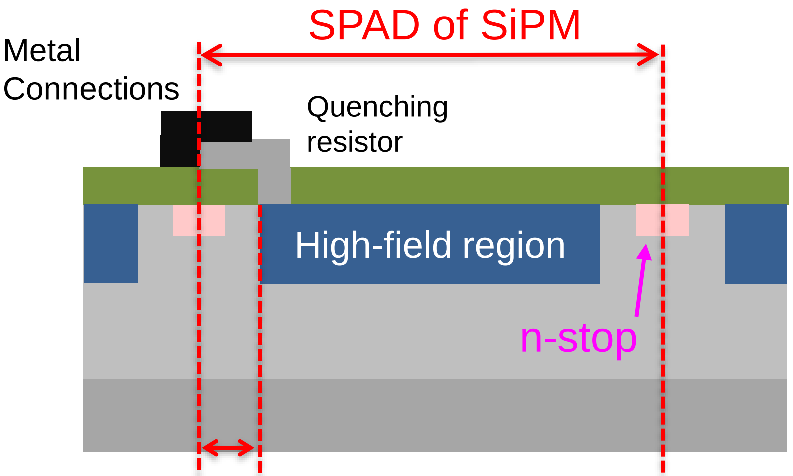
Typical NUV-SiPM structure with DTI



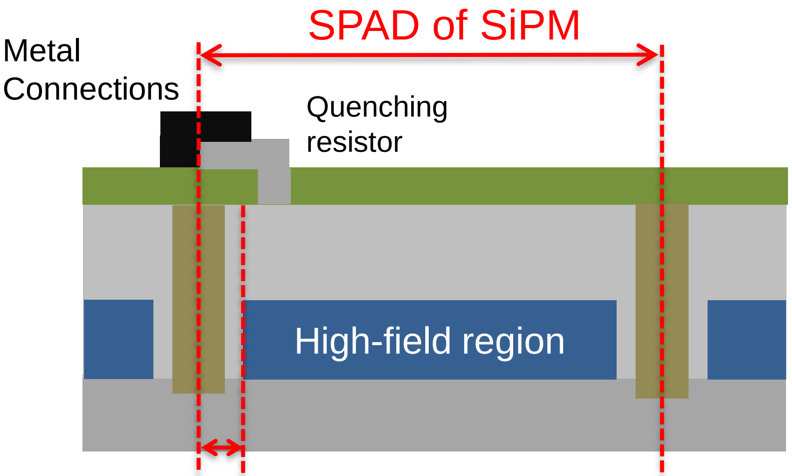
SPAD in a SiPM

Other SiPM Structures

Without DTIs



Deep Junction

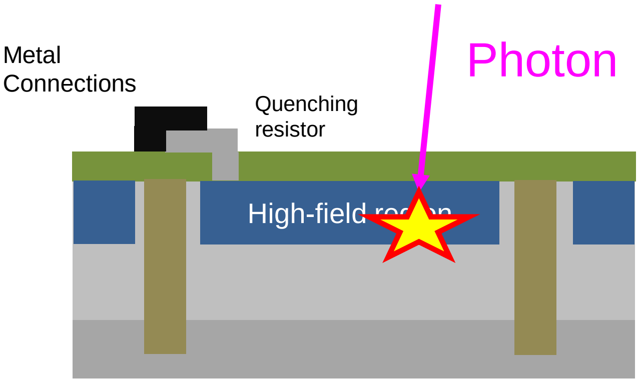


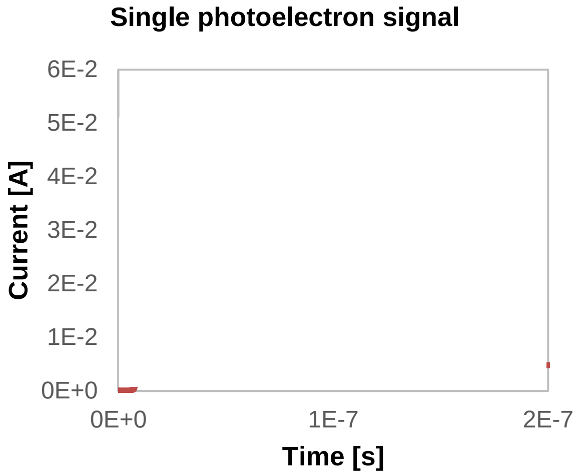
Single photoelectron signal and SiPM Gain

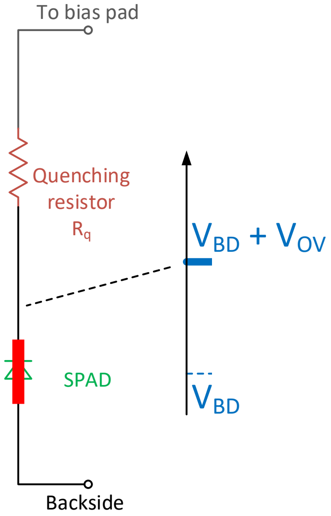
SiPM equivalent circuit

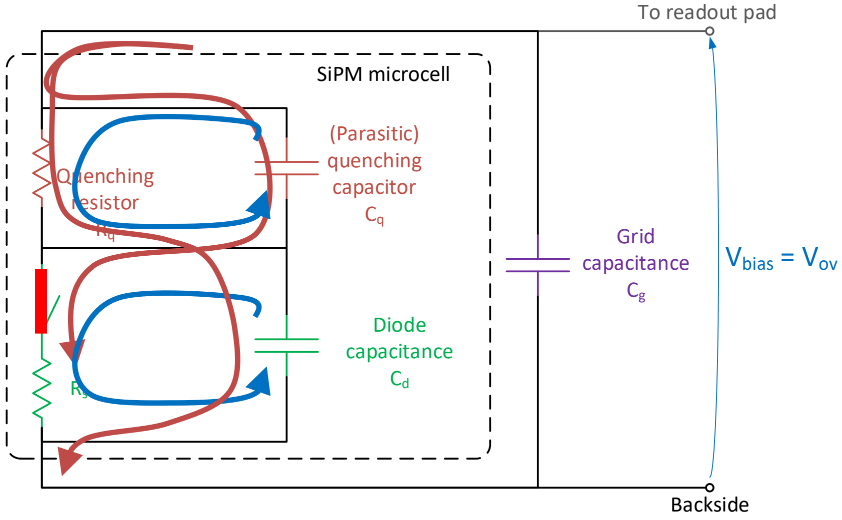
Corsi, F., et al. "Modelling a silicon photomultiplier (SiPM) as a signal source for optimum front-end design." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 572.1 (2007): 416-418.

The equivalent circuit is used to *simulate the current generated by the SiPM* when a photon or a thermally generated carrier triggers an avalanche.







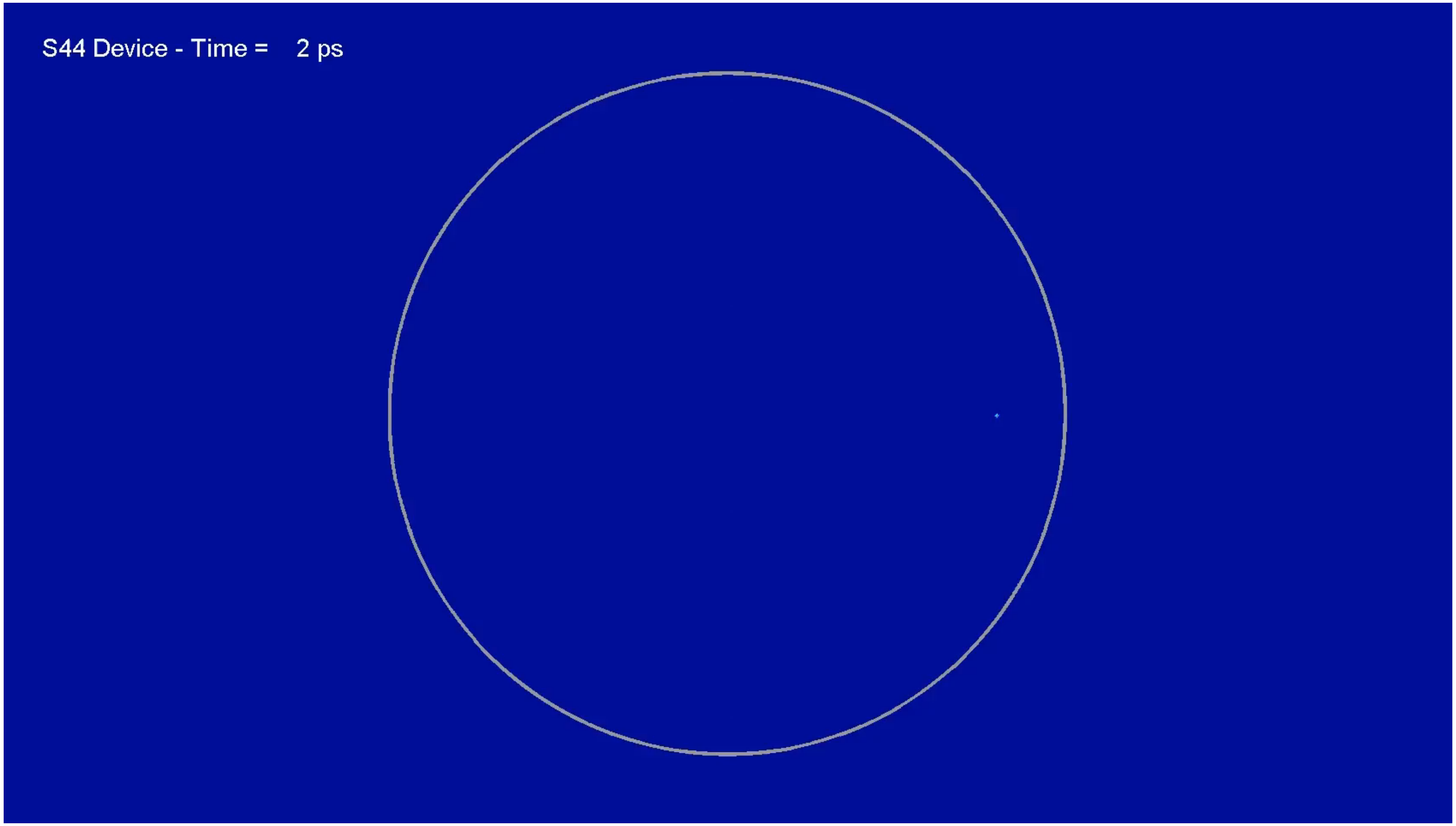


Avalanche Build-up

Avalanche build-up is a statistical process that depends on the over-voltage → higher V_{OV} means higher avalanche triggering probability.

If the avalanche is triggered, the avalanche current tends to diverge, although it is always limited by series resistors (either parasitic or placed on purpose).

The avalanche current grows over time both because of diffusion and inter-cell optical crosstalk.

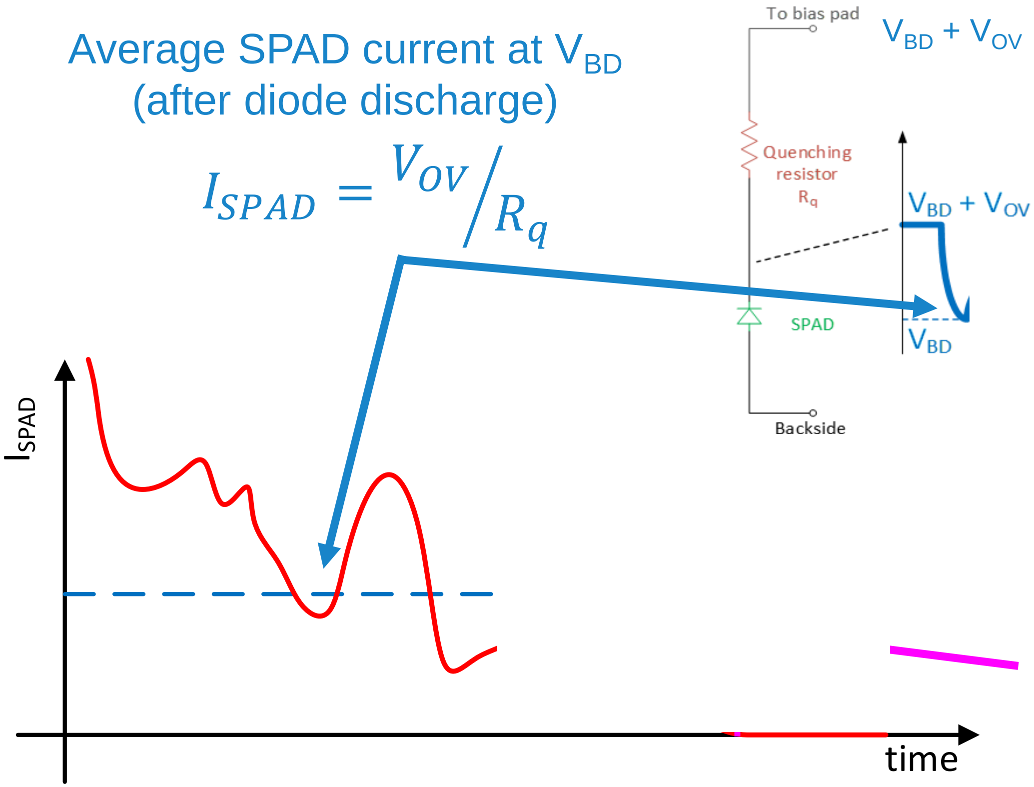


Simulated growth of the avalanche current over the SPAD active area

Passive Quenching

Passive quenching of the avalanche happens because of statistical fluctuations of the current flowing in the SPAD during the avalanche.

1. Diode current is limited by the quenching resistor (R_q)
2. If the current is sufficiently small, statistical fluctuations in the diode current bring it to a value equal to zero (even if for a brief amount of time)
3. Once the current is zero, no carriers are present in the high-field region and no further multiplication can take place → avalanche is quenched!



Average SPAD current at V_{BD} (after diode discharge)

$$I_{SPAD} = V_{OV}/R_q$$

Empirical limit for quenching:

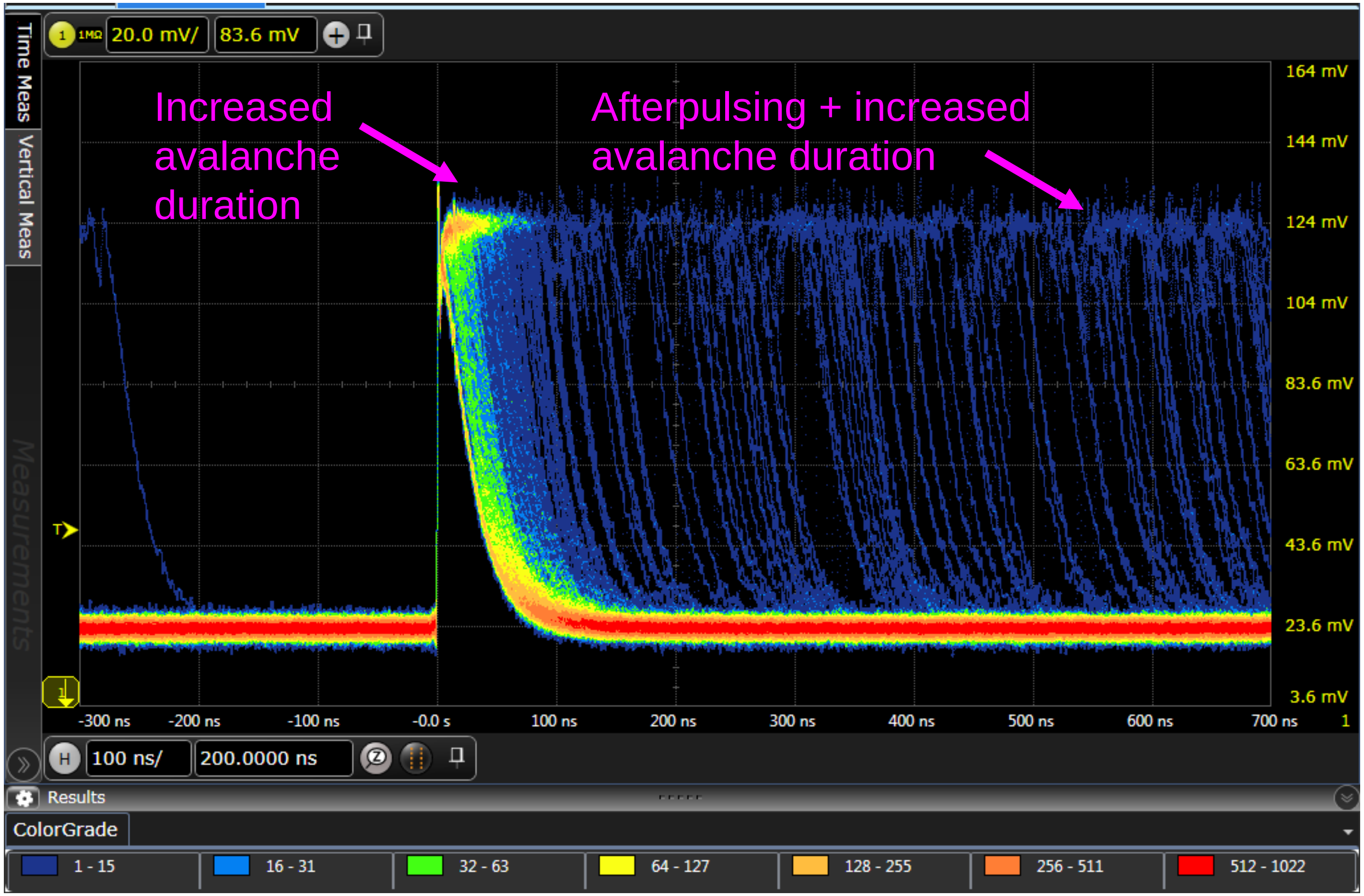
- 20 uA SPAD current at V_{BD}
- 50 kOhm / V_{OV} are necessary to achieve "good" quenching

Quenching of the avalanche!
(usually, very quick – ps range)

“Bad” quenching

If the value of the quenching resistor is not high enough (for the V_{OV} chosen), the SPAD avalanche is not quenched or takes a longer time to get quenched.

- Gain of the SPAD is increased and is no longer well defined, featuring large variations.
- Afterpulsing is also significantly increased, most likely due to the increased avalanche gain.



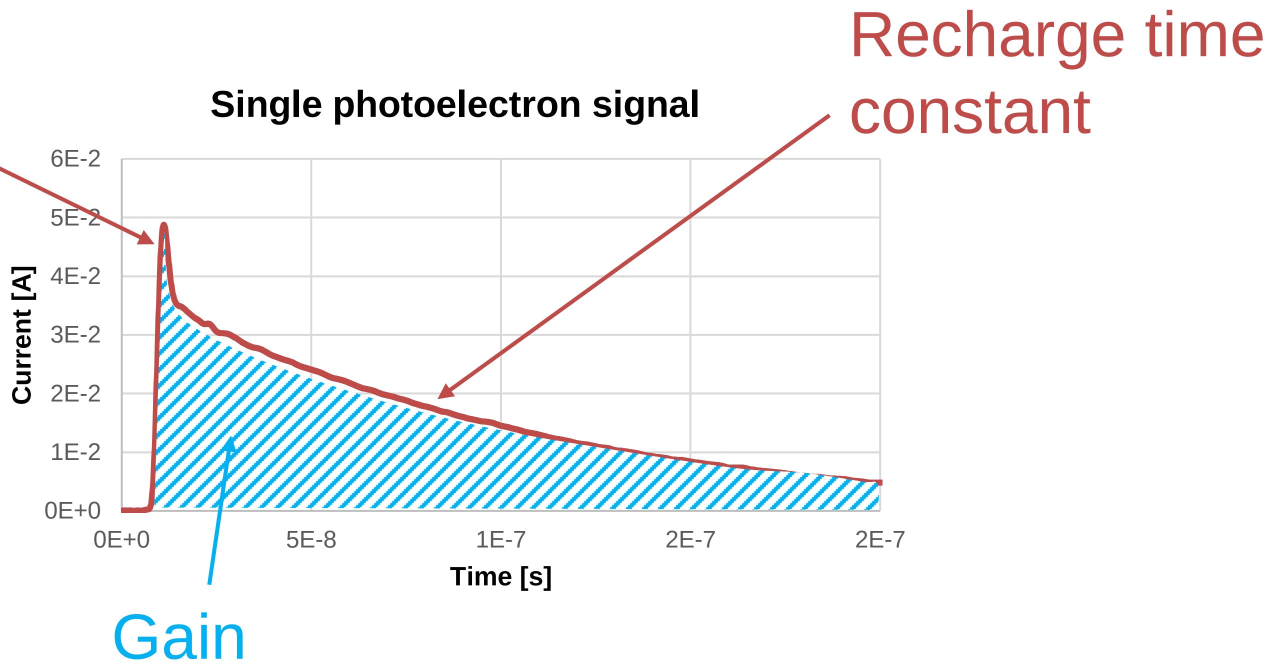
Increased avalanche duration

Afterpulsing + increased avalanche duration

SiPM Gain

The Gain in a SiPM is a measure of the *number of carriers that pass through the high field region of one microcell during an avalanche*.

It can be measured as the *integral of the output current of the SiPM* when an avalanche is triggered.



SiPM Gain and recharge time constant

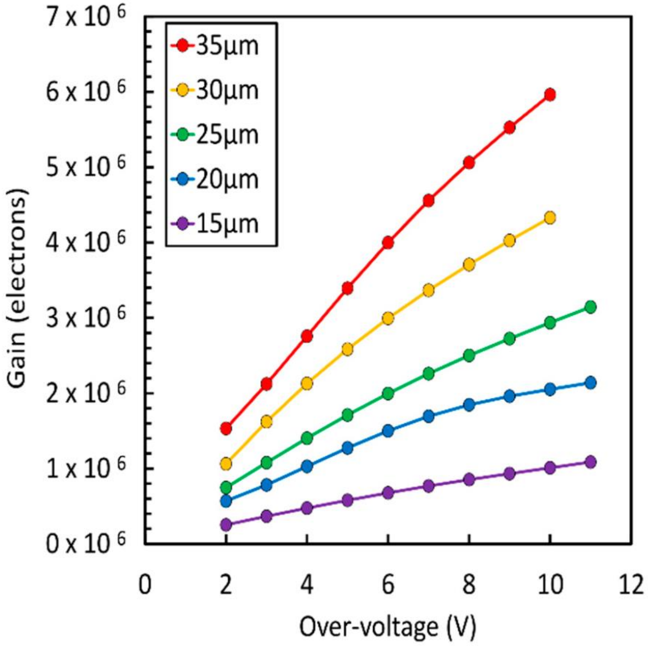
The Gain is *proportional to the microcell capacitance and to the over-voltage* applied, i.e. the bias in excess of the breakdown voltage.

- Larger microcells have higher gain at the same bias.
- Formula can be easily calculated from the charge balance on the different capacitors during transient.

$$Gain = OV \cdot (C_d + C_q)$$

$$\tau_{recharge} \approx R_q \cdot (C_d + C_q)$$

Parameter	Typical values
R_q	500 kOhm – 1.5 Mohm
C_d	15 fF – 150 fF
C_q	5 fF – 10 fF
Tau	8 ns – 100 ns



Example of the Gain measured on different cell sizes of the NUV-HD SiPM technology.

Photon Detection Efficiency

Photon Detection Efficiency

Photon Detection Efficiency (PDE) is a measurement of the *probability that a photon impinging on the SiPM surface starts an avalanche*.

$$PDE = FF \cdot QE \cdot P_t$$

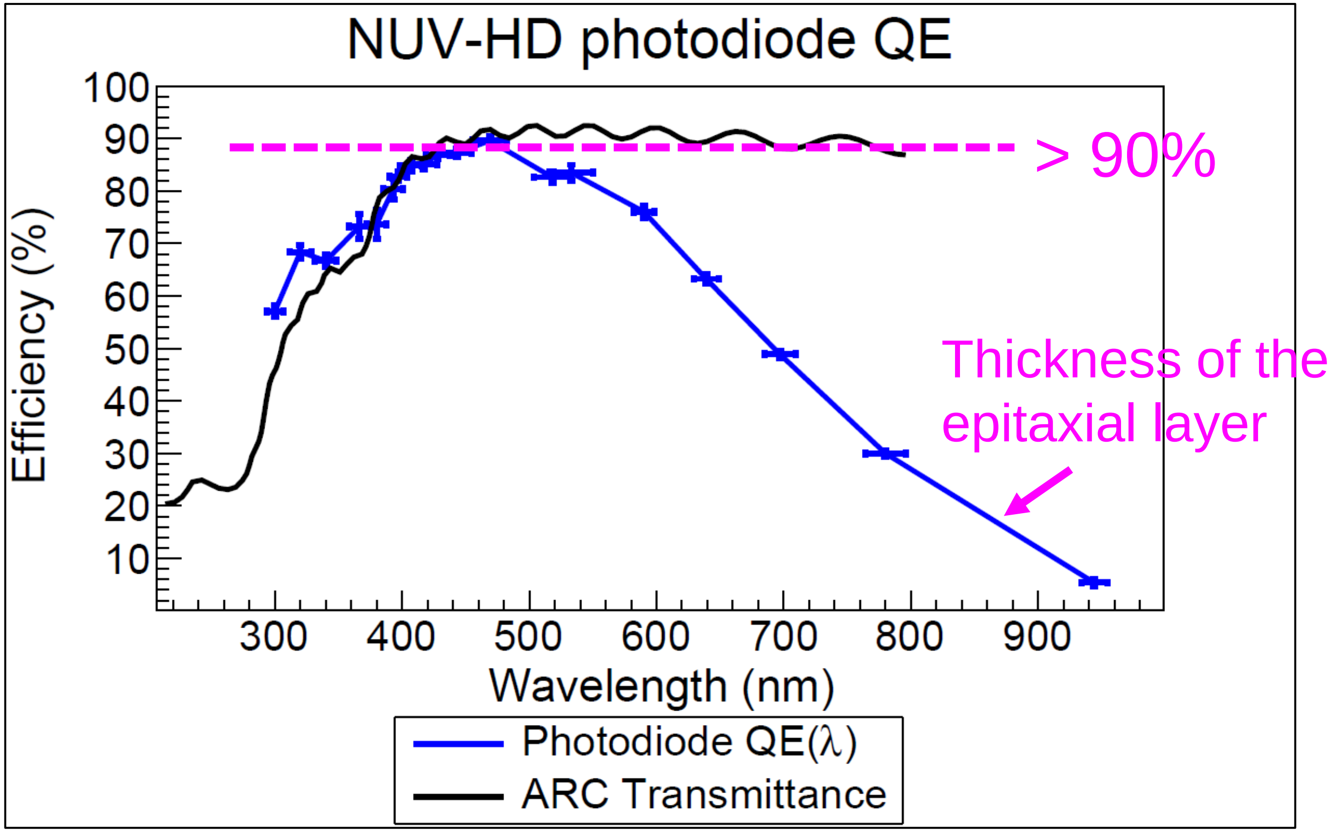
Fill Factor

Quantum Efficiency

Avalanche Triggering Probability

NUV-HD SiPM technology: QE

We use the NUV-HD SiPM technology as an example to show the different components of the PDE. NUV-HD SiPMs are based on a *p-on-n junction*.

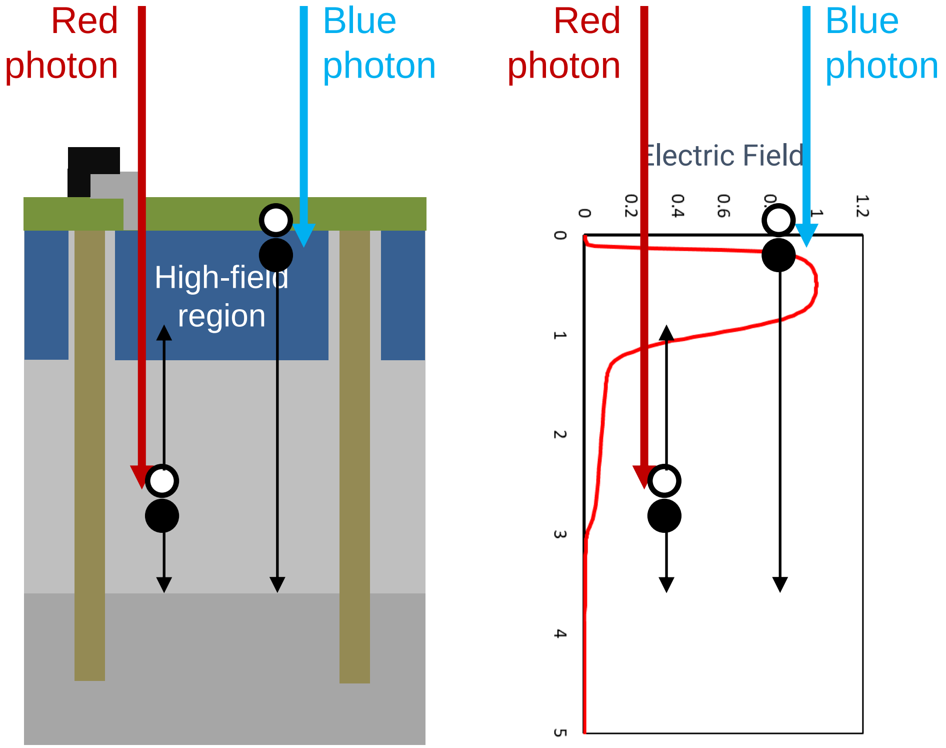


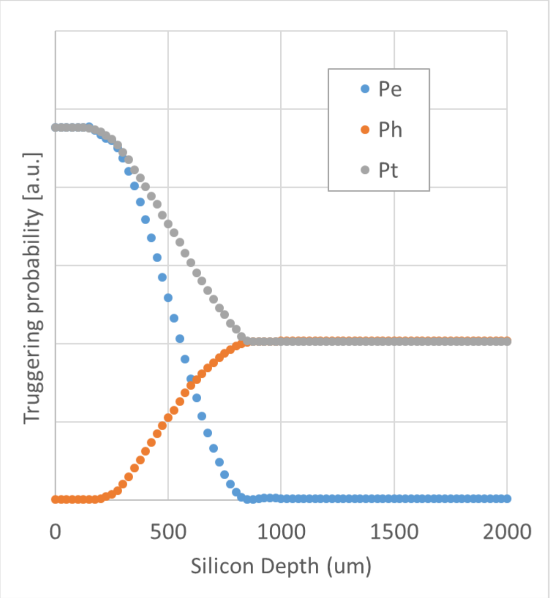
Measured on a photodiode with same layers as the SiPM

Avalanche triggering probability: Pt

Avalanche triggering probability increases with overvoltage, from zero at V_{BD} to 100% at high bias for both electron and holes.

At the same level of bias and peak electric field, *electrons have a higher probability of initiating* an avalanche compared to holes.

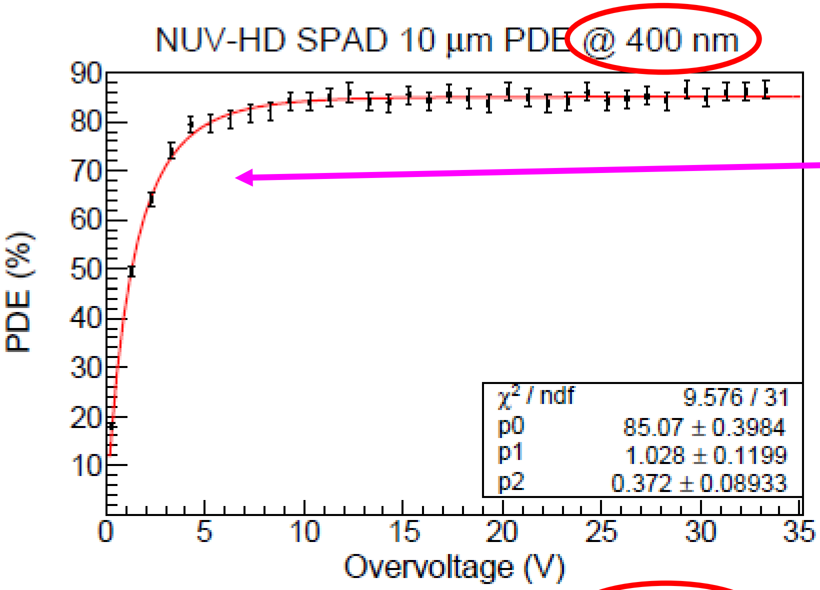




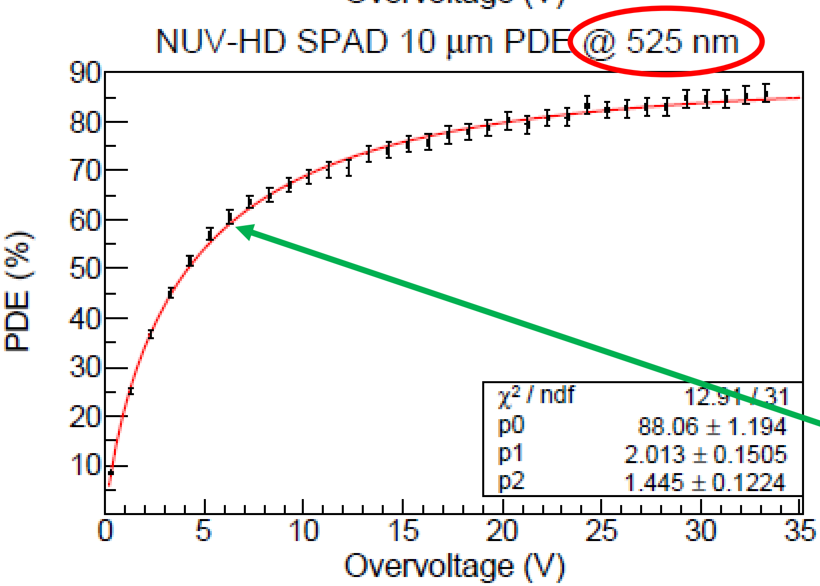
Qualitative plot of *avalanche triggering probability for holes, electrons and total vs. depth* in an p-on-n junction similar to the one used in NUV-HD SiPMs.

Oldham, W. G., Samuelson, R. R., & Antognetti, P. (1972). Triggering phenomena in avalanche diodes. IEEE Transactions on Electron Devices, 19(9), 1056–1060. doi:10.1109/t-ed.1972.17544

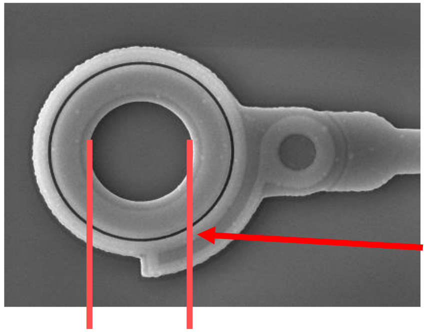
NUV-HD technology: QE*Pt



Fast increase with over-voltage:
→ avalanche is initiated by electrons



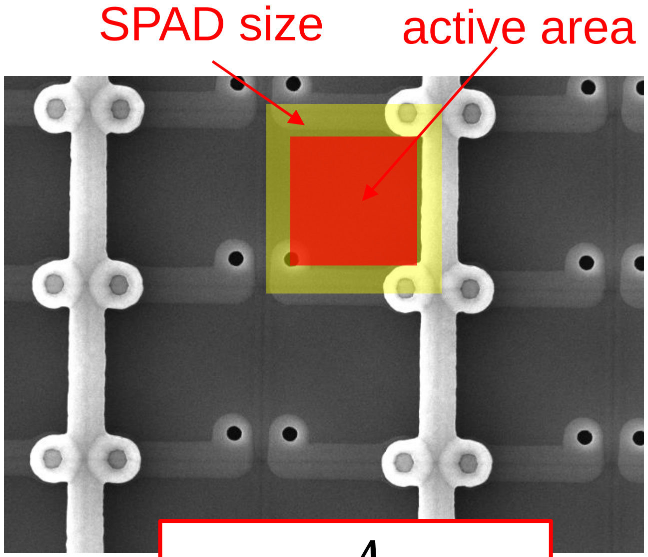
Measured on a SPAD with 100% FF



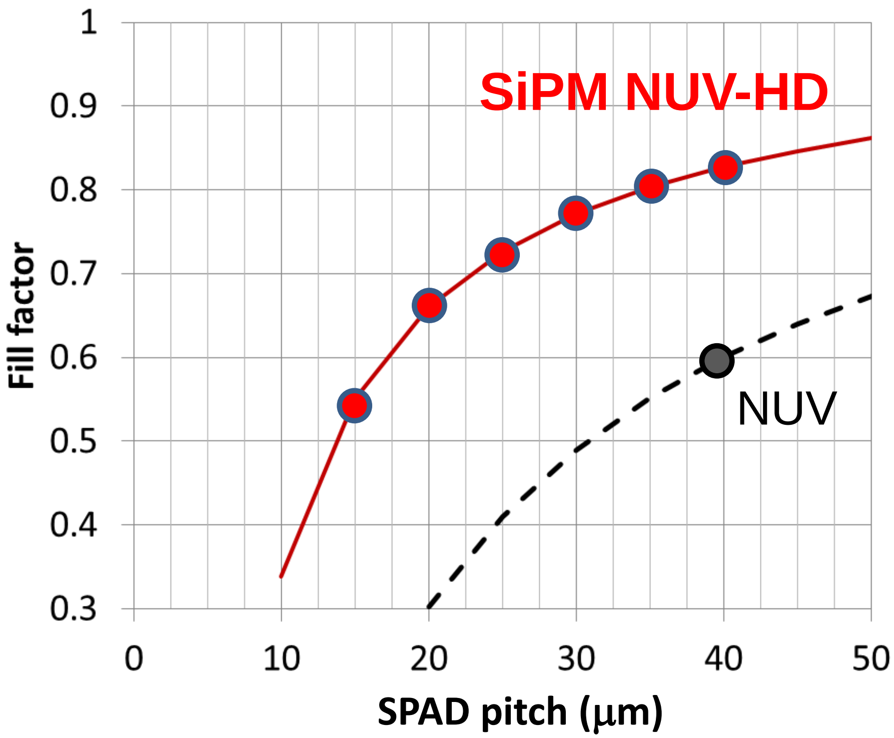
SPAD size is defined by metal opening which is within the high-field region

Slower increase with over-voltage:
→ avalanche is initiated by holes (and electrons)

NUV-HD: Fill Factor



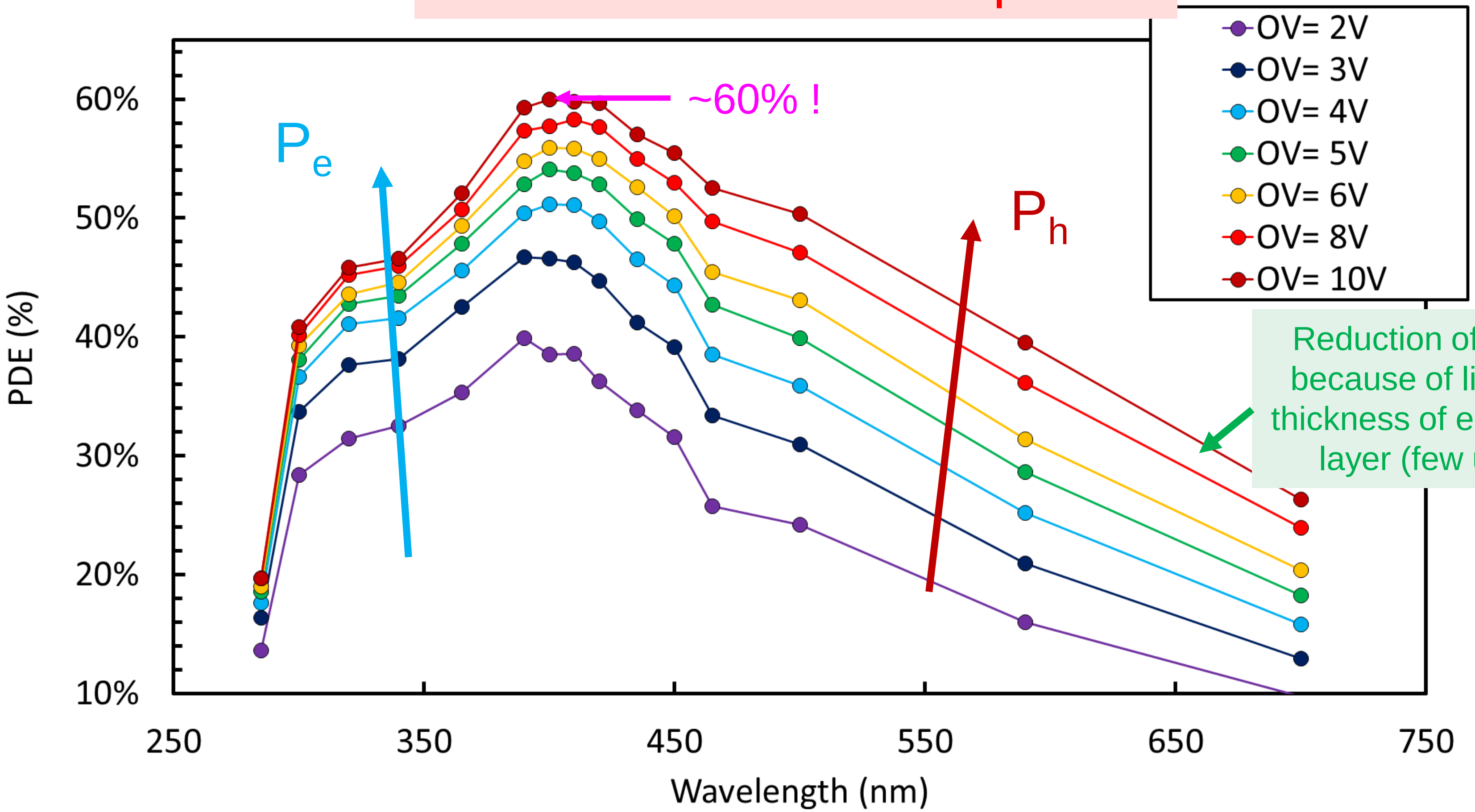
$$FF = \frac{A_{active}}{A_{total}}$$



SPAD Pitch	15 µm	20 µm	25 µm	30 µm	35 µm	40 µm
Fill Factor (%)	55	66	73	77	81	83
SPAD/mm^2	4444	2500	1600	1111	816	625

Photon detection efficiency

NUV-HD 35 um cell pitch



Reduction of PDE because of limited thickness of epitaxial layer (few um)

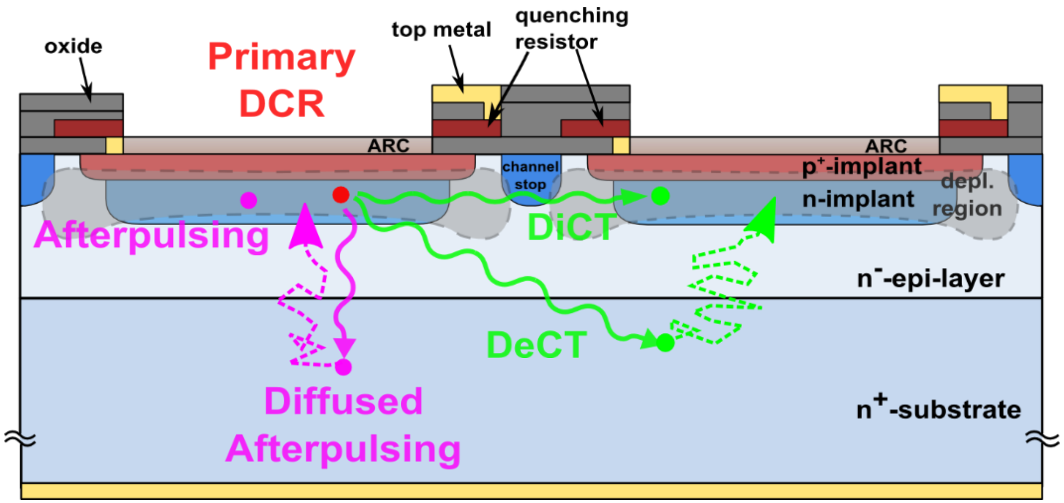
Gola, A et al. (2019). “NUV-Sensitive Silicon Photomultiplier Technologies Developed at Fondazione Bruno Kessler.” *Sensors*, *19*(2), 308.

Noise sources in SiPMs

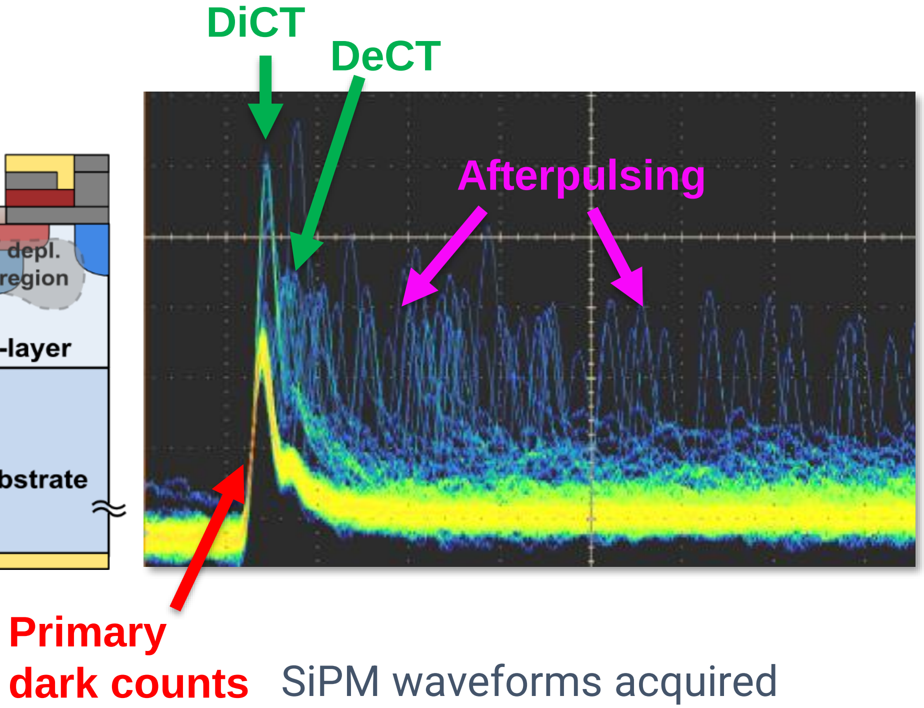
Noise in SiPMs

Different SiPM noise components are related to *different physical phenomena*.

$$\boxed{P(correlated) \propto Gain(OV)}$$



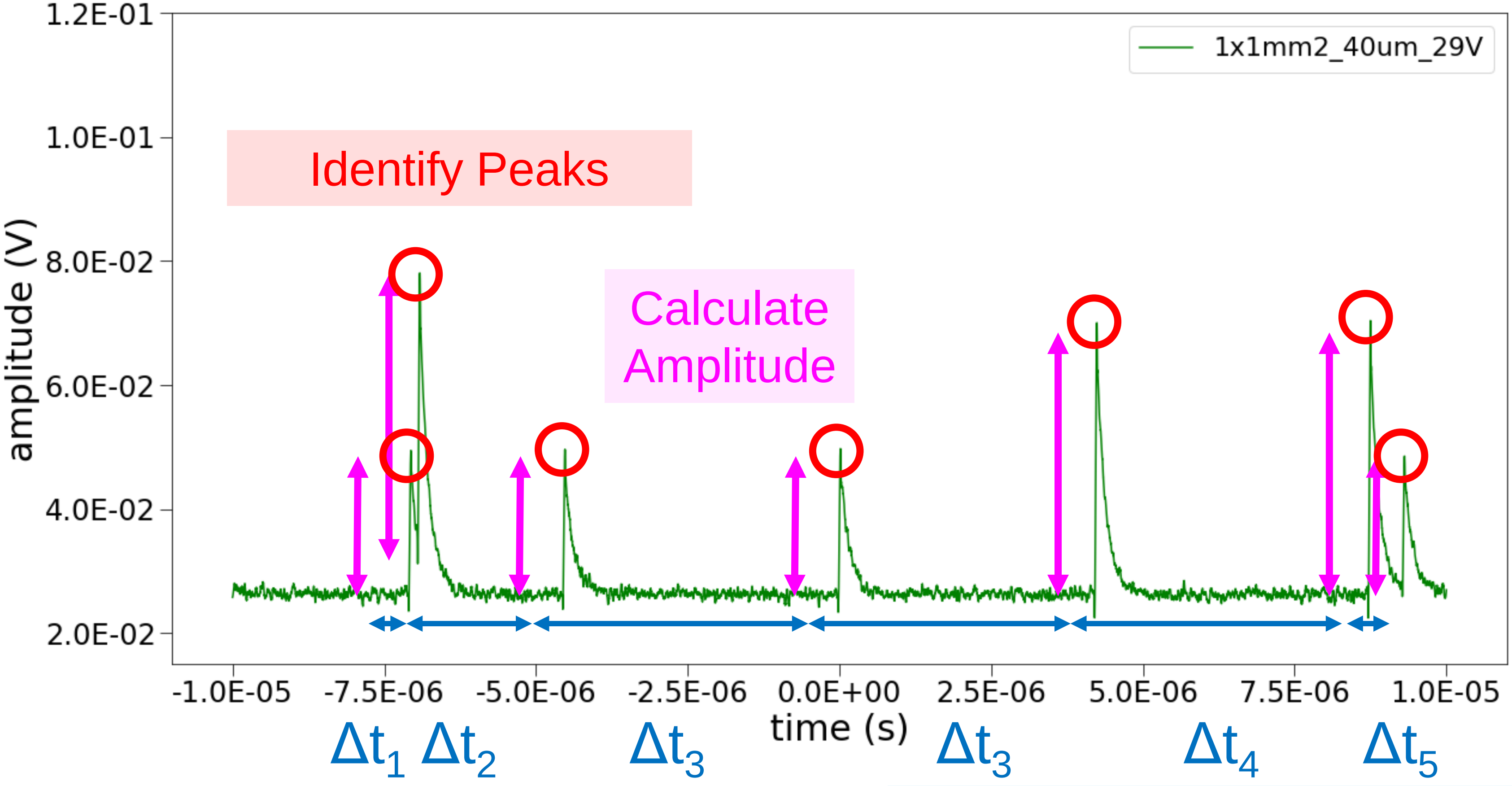
Cross-section of the SiPM microcells.



SiPM waveforms acquired with the oscilloscope

Typical Measurement Technique

Acquire *continuous waveform*, filter and post-process data to identify peaks corresponding to dark counts. Then calculate inter-arrival times.

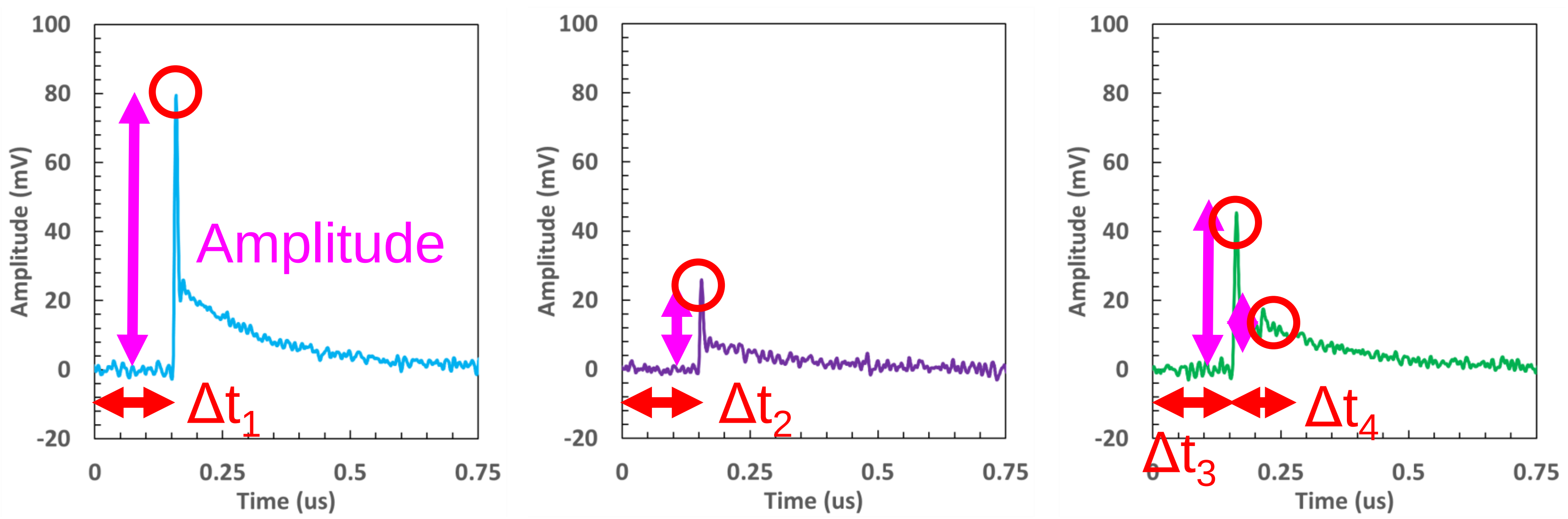


Calculate inter-arrival time

Segmented acquisition technique

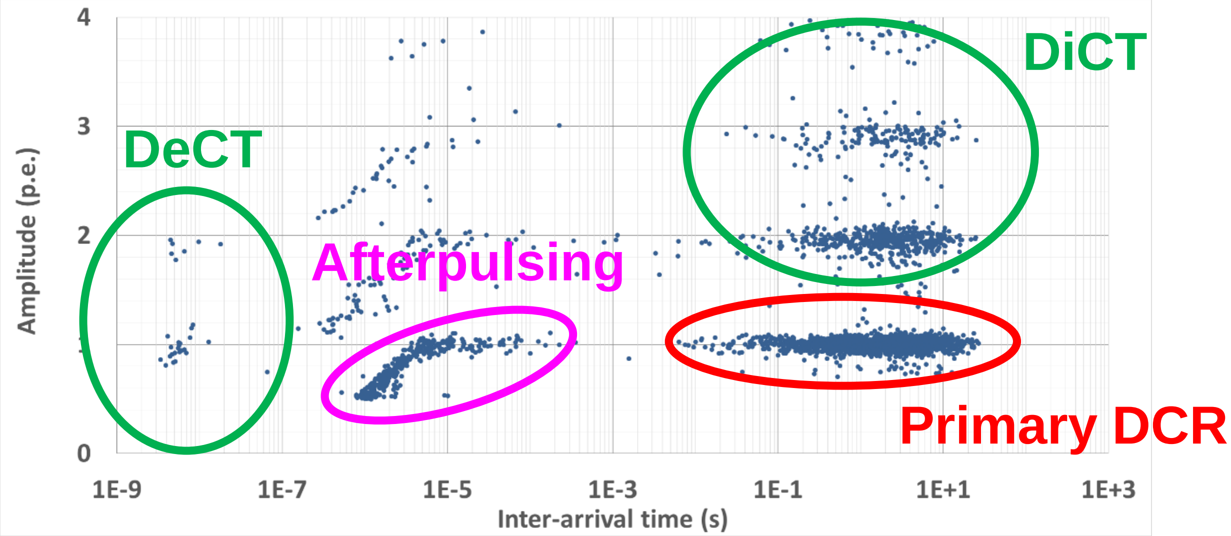
Memory segmentation is employed to avoid storing unnecessary large amount of “empty” data, when measuring very low DCR.

$$\Delta t_1^{tot} = TS_1 + \Delta t_1 \qquad \Delta t_2^{tot} = TS_2 + \Delta t_2 \qquad \begin{aligned} \Delta t_3^{tot} &= TS_3 + \Delta t_3 \\ \Delta t_4^{tot} &= \Delta t_4 \end{aligned}$$

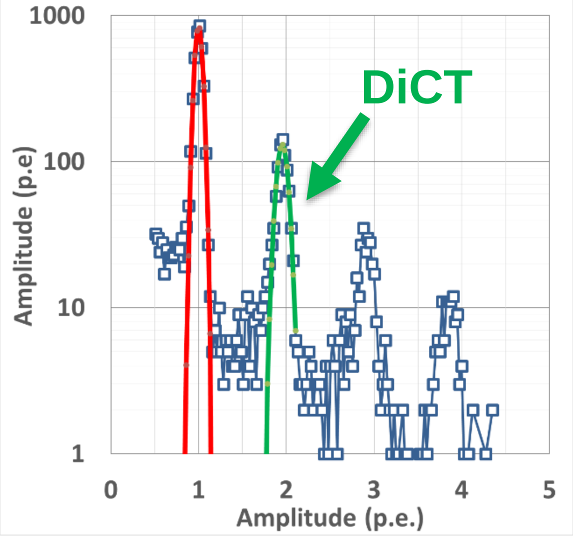


Example of noise measurement

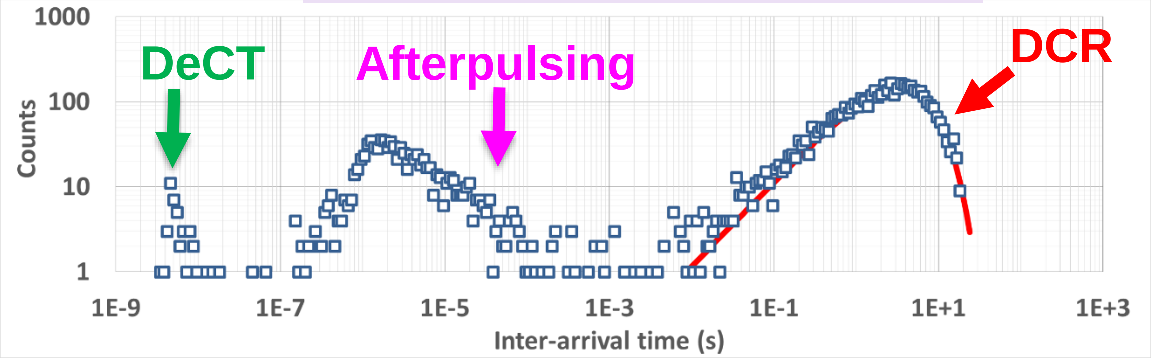
Scatter plot

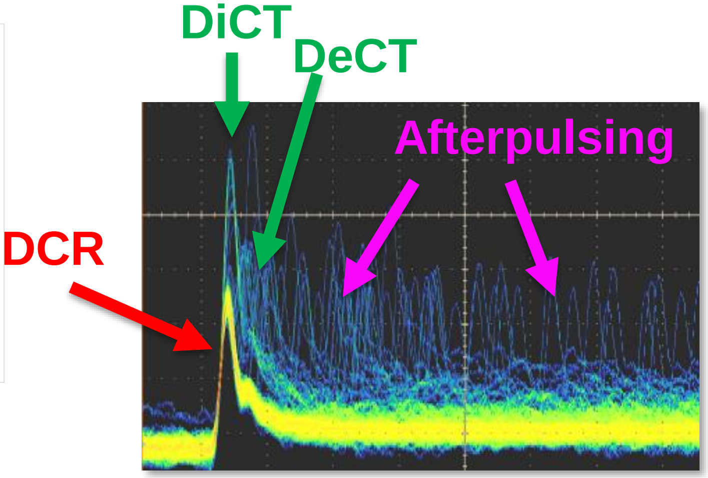


Amplitude histogram



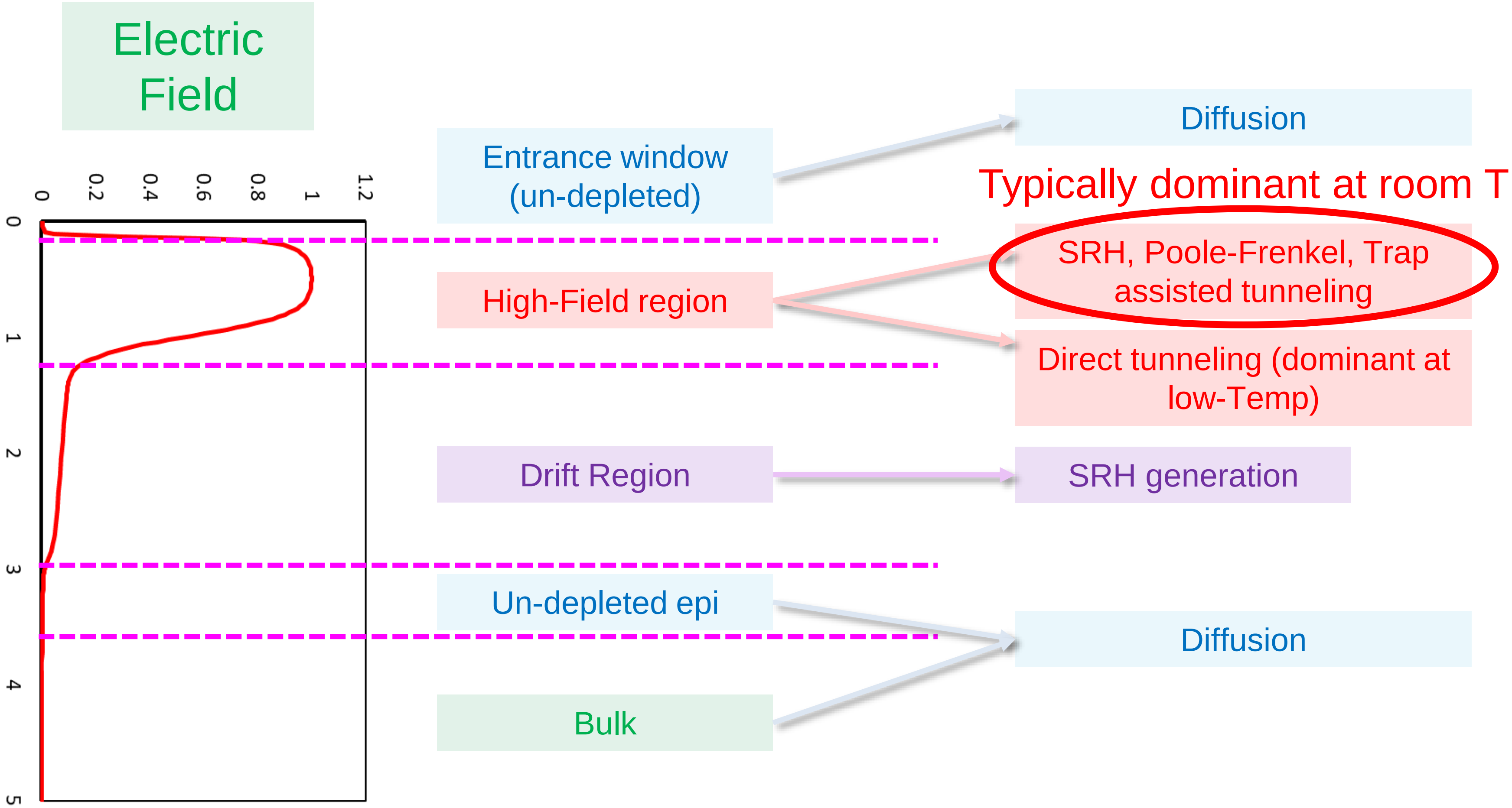
Inter-arrival time histogram





← Sensitivity ≥ 12 orders of magnitude! →

Sources of primary DCR



Entrance window (un-depleted) → Diffusion

Typically dominant at room T

High-Field region → SRH, Poole-Frenkel, Trap assisted tunneling

High-Field region → Direct tunneling (dominant at low-Temp)

Drift Region → SRH generation

Un-depleted epi → Diffusion

Bulk → Diffusion

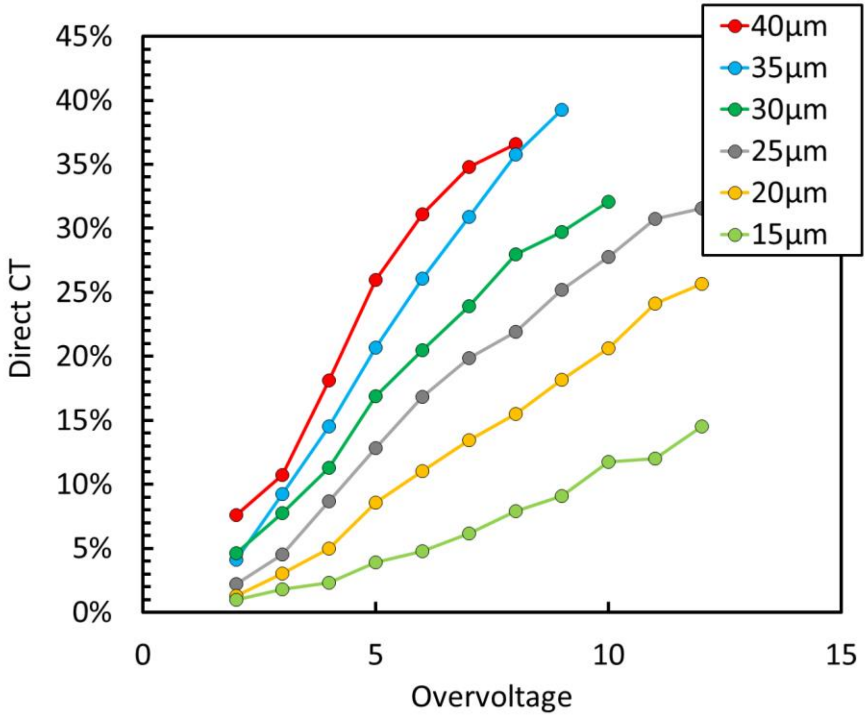
All these components have different dependence on device parameters and on temperature..

Ways of plotting Noise Sources

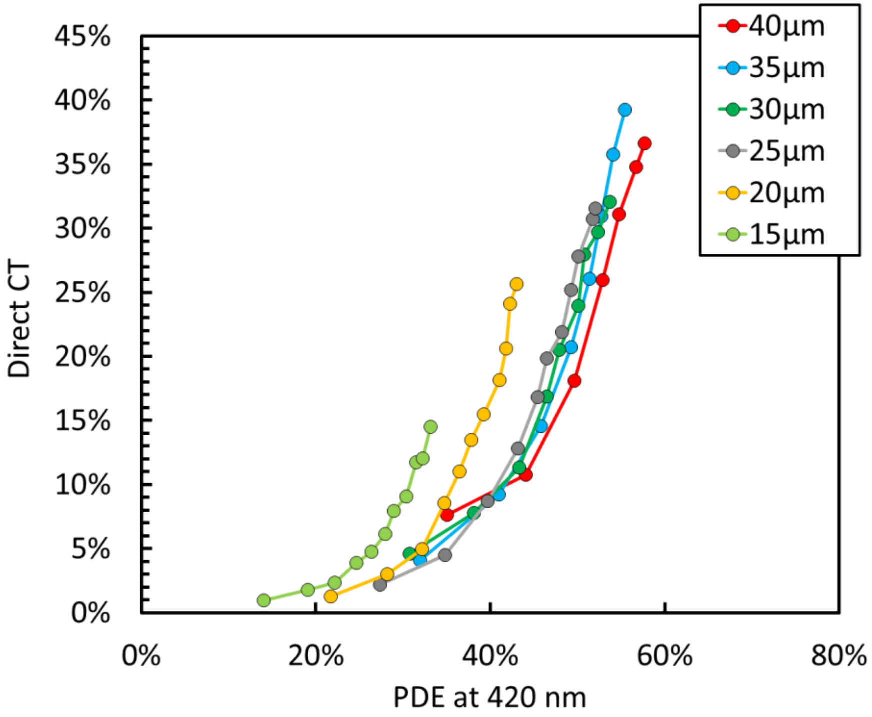
If the SiPM noise is plotted as a function of the over-voltage, it does not take into account that different cell-sizes / SiPM technologies also feature different PDE.

- Not easy to compare S/N (~ PDE / Noise)
- As an alternative, we can plot the Noise as a function of the PDE at the wavelength of interest.

CT vs. OV



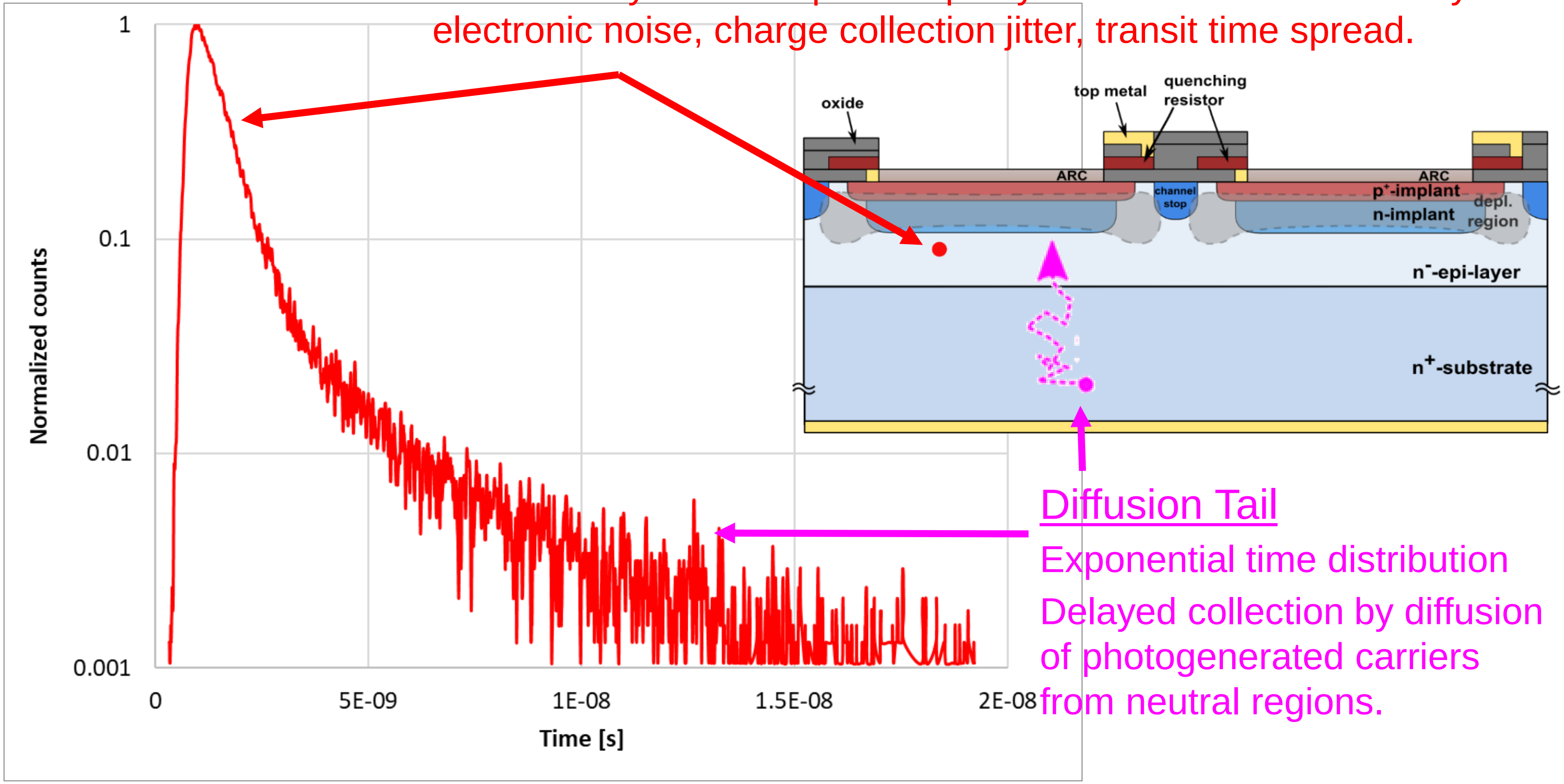
CT vs. PDE



Single-Photon Time Resolution
SPTR

Single-Photon Time Resolution

SPTR is a measurement of the precision of the SiPM/SPAD in detecting the time of arrival of a single photon.



Main SPTR peak

Quasi Gaussian distribution

Collection by drift in depleted epi-layer. Width is determined by electronic noise, charge collection jitter, transit time spread.

Diffusion Tail

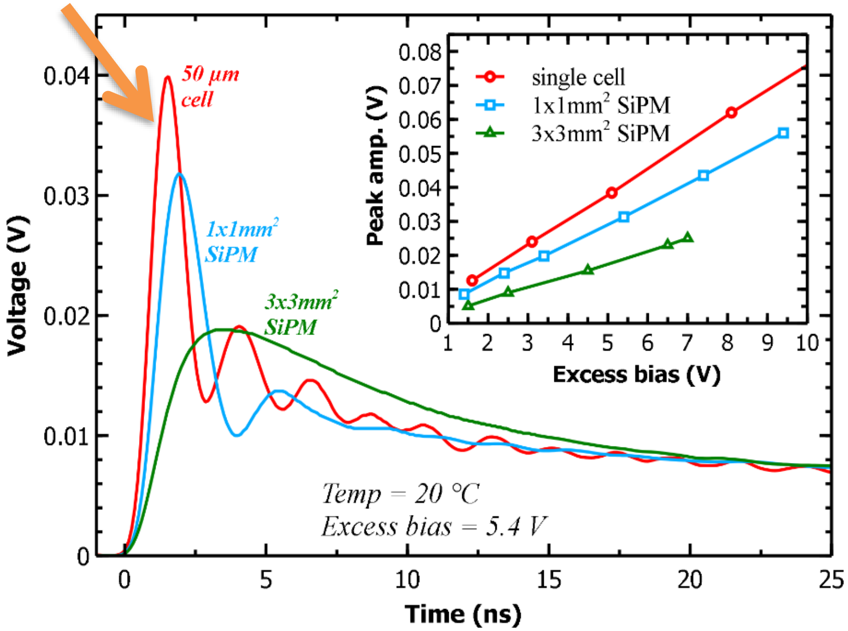
Exponential time distribution

Delayed collection by diffusion of photogenerated carriers from neutral regions.

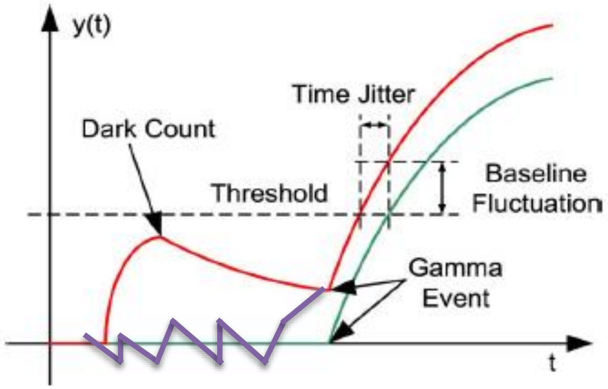
SPTR on SiPMs: effect of dimensions

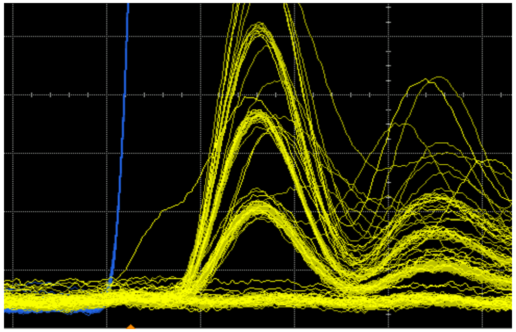
In most cases, SPTR is limited by the electronic noise of the front-end divided by the signal derivative at the pick-off threshold.

Output capacitance of the SiPM significantly slows down the rising edge of the single-cell response (pulse).



$$\sigma_n \propto \frac{\sigma_a}{f'_{th}}$$



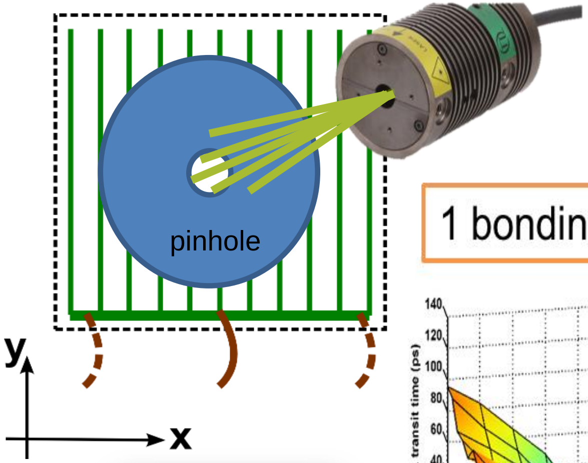


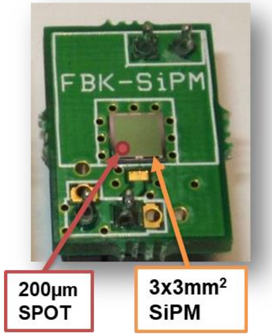
Larger active area
→ larger SiPM metal capacitance

Electronic noise effect on SPTR very important on medium / big area SiPMs

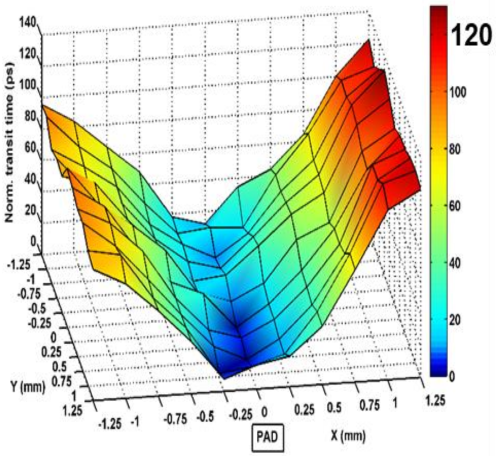
Acerbi, Fabio, et al. "Characterization of single-photon time resolution: from single SPAD to silicon photomultiplier." *IEEE Transactions on Nuclear Science* 61.5 (2014): 2678-2686.

SPTR on SiPMs: scan with focused light "transit time skew"

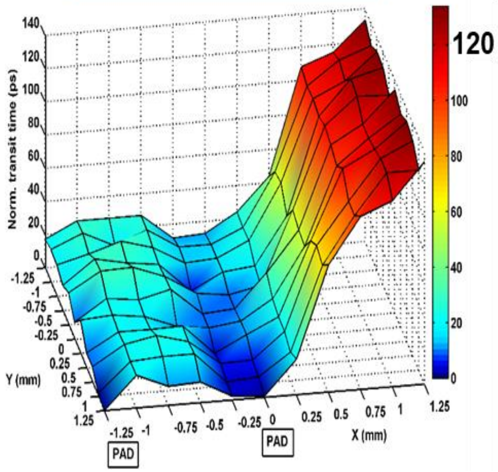




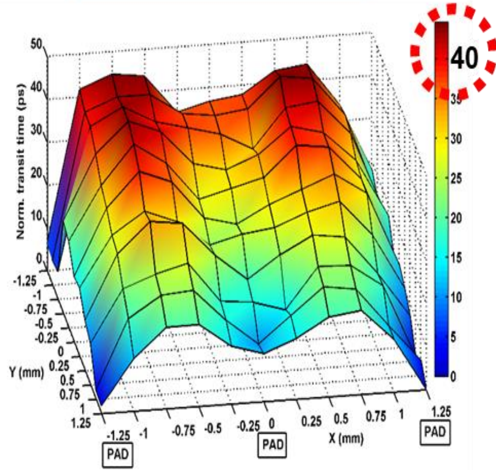
1 bonding wire (center)



2 bonding wires



3 bonding wires



With med./large area SiPMs
→ important also the effect of transit time skew
→ depend on metal grid and bonding pads

Efficient signal pick-up and improved metal grid layout needed.