Single-photon detectors in micro-electronics technology – part 2

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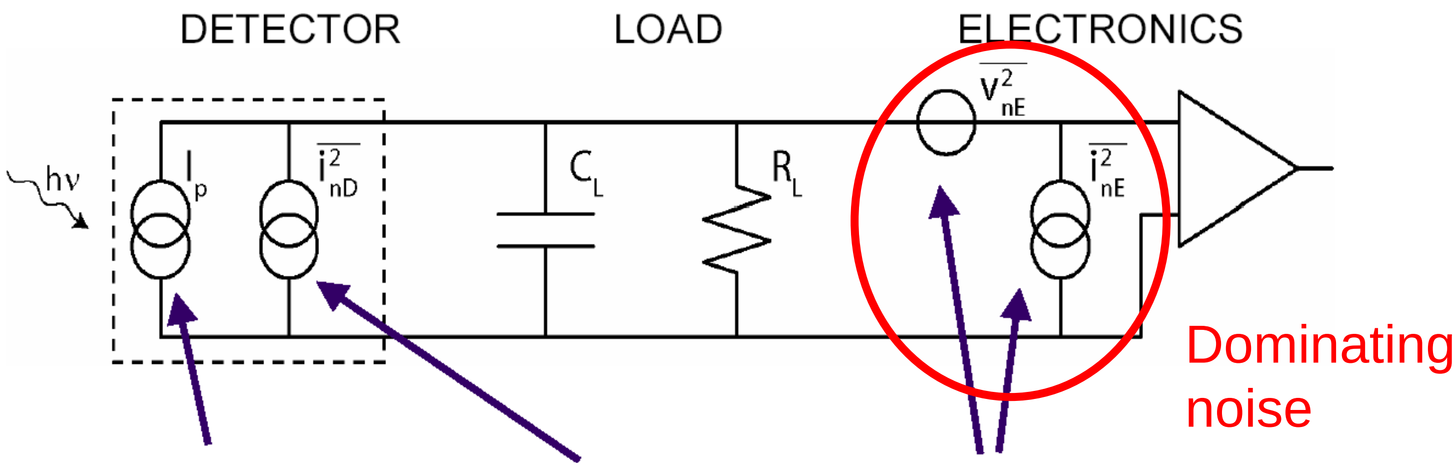
Low-level light detection technologies

Recap

The problem: processing of extremely weak signals



Current signal: 1 pair/photon

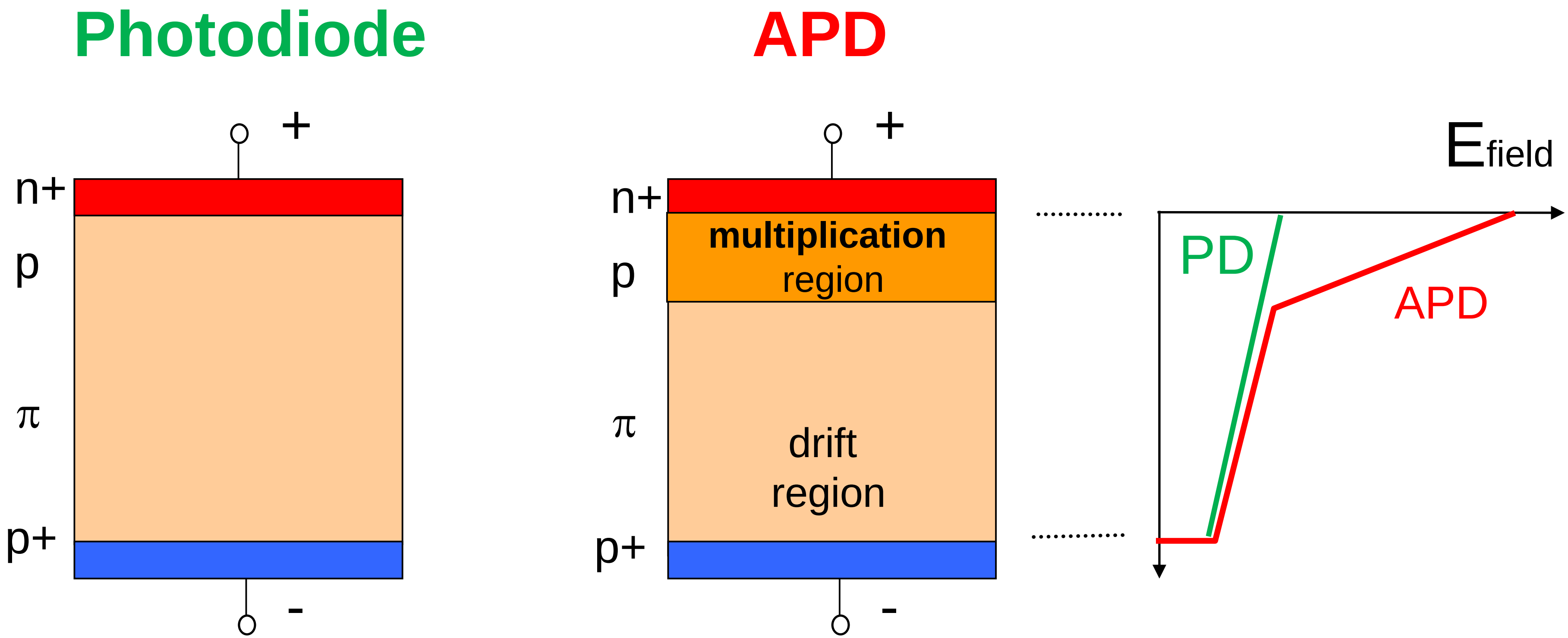
Detector noise: fluctuation of leakage current

Electronics noise: shot + thermal noise

Need of a detector with internal amplification to reduce the impact of electronic noise!

Solid-state photodetectors with internal gain.

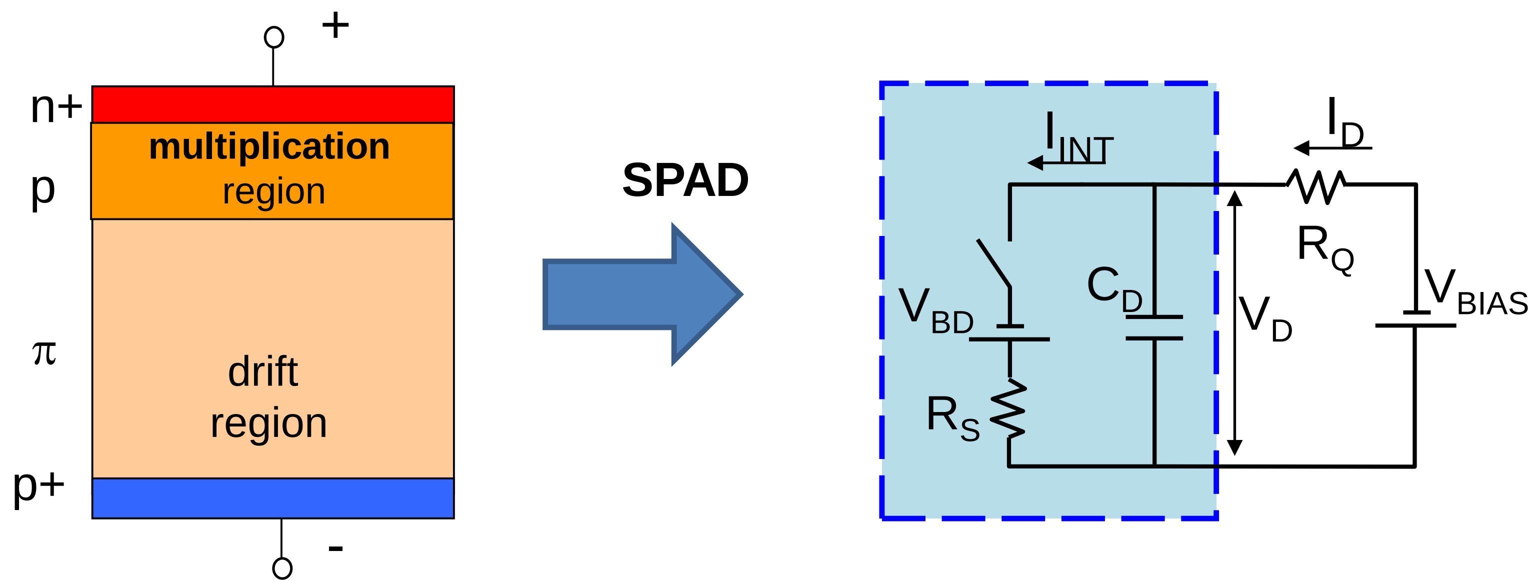
Detectors with gain



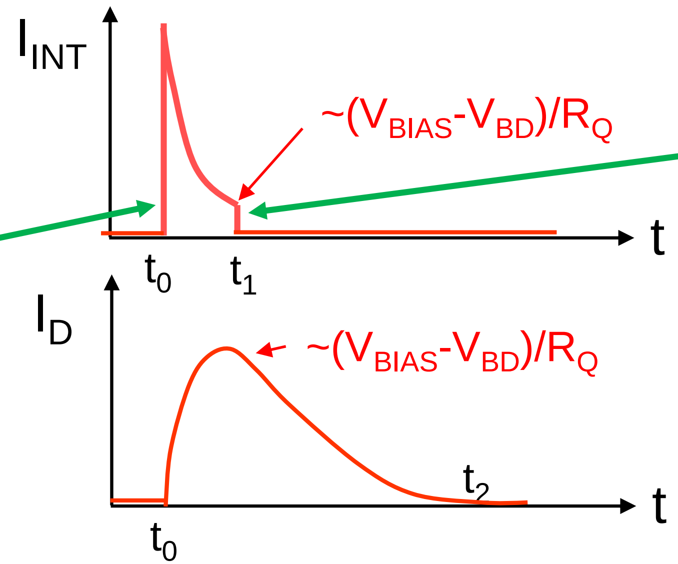
1 photo-carrier

Impact ionization:
- linear mode: gain M
- Geiger mode: avalanche

GM-APD/SPAD: model

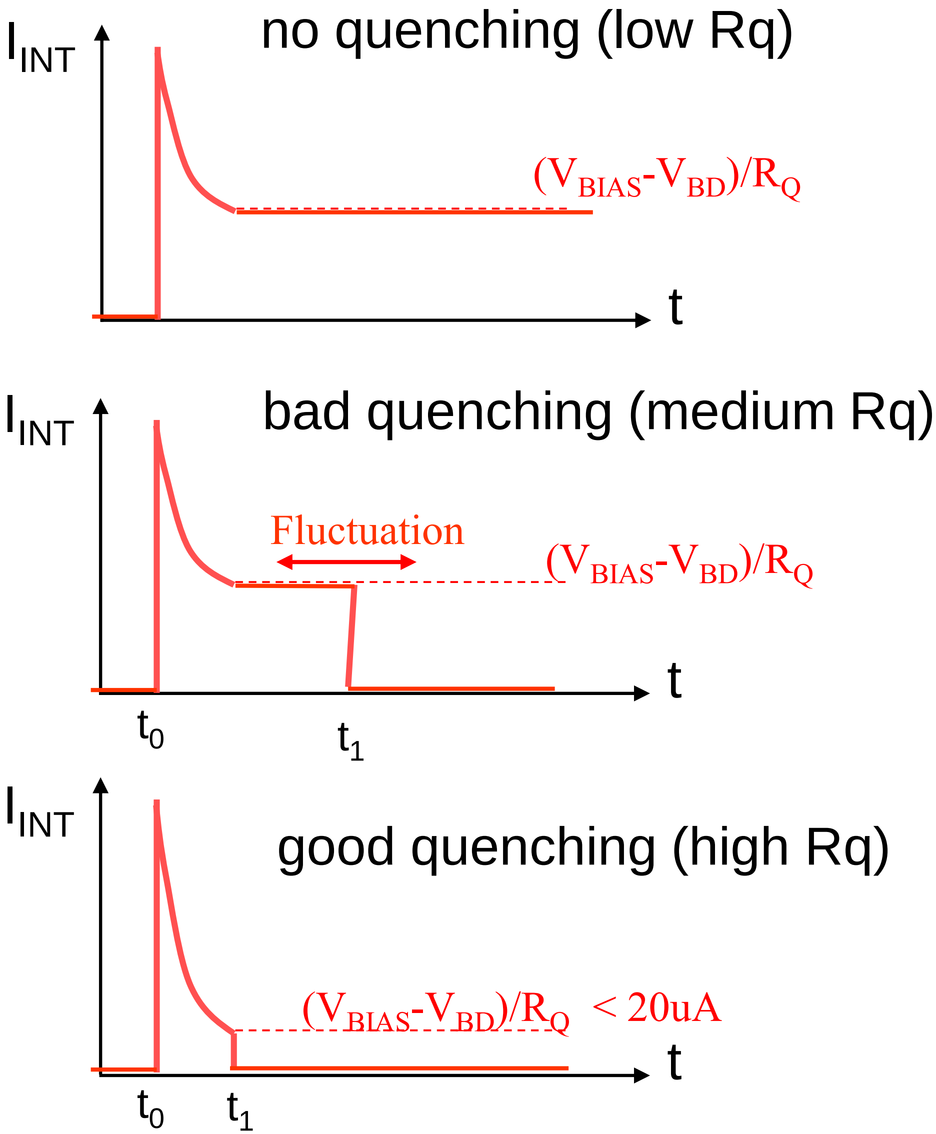


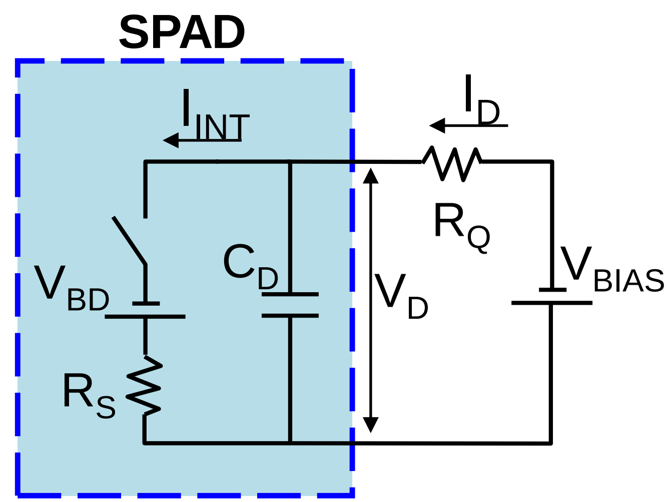
Photon detection:
Avalanche triggering probability



Turn-off probability

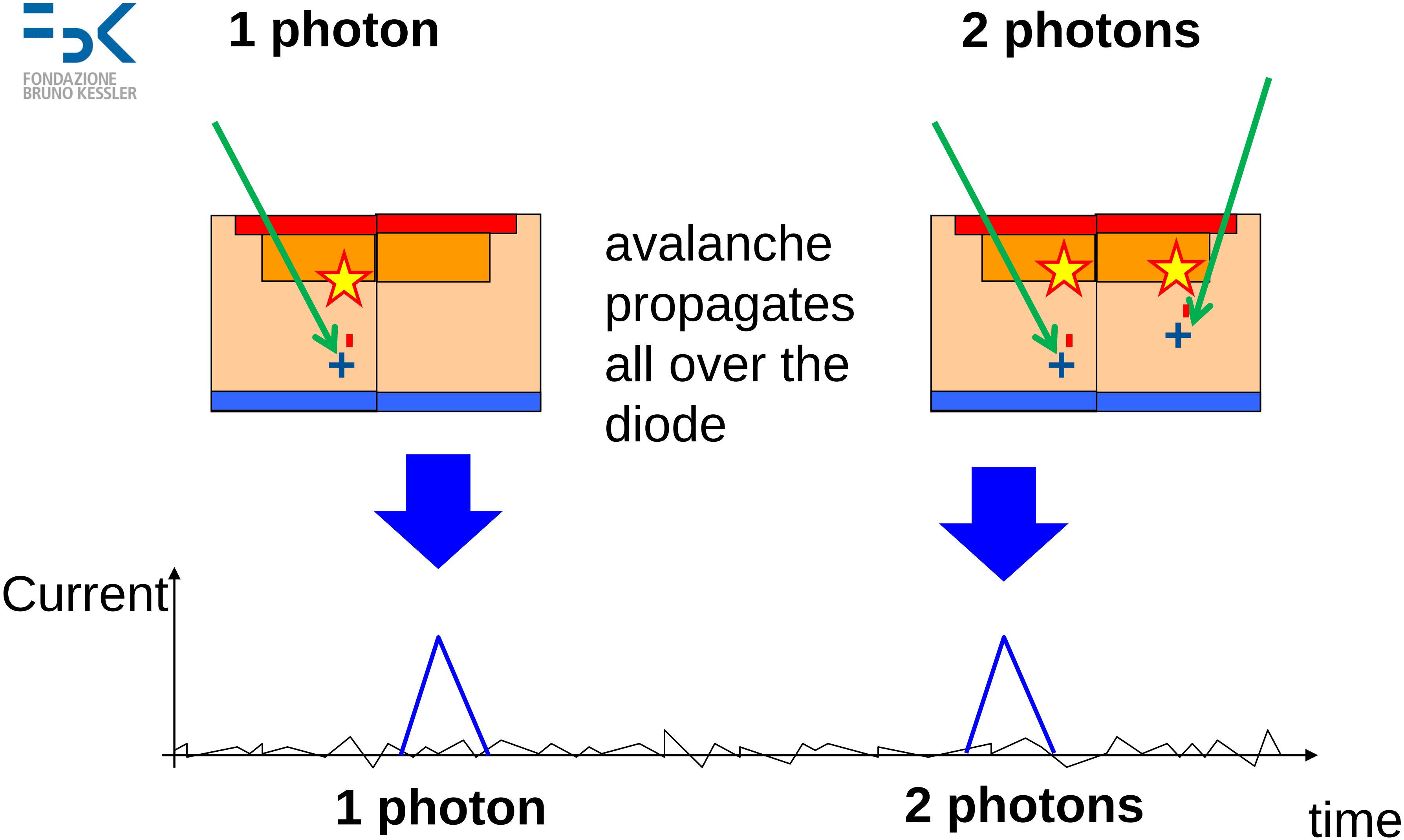
P_{10} – Turn-off probability





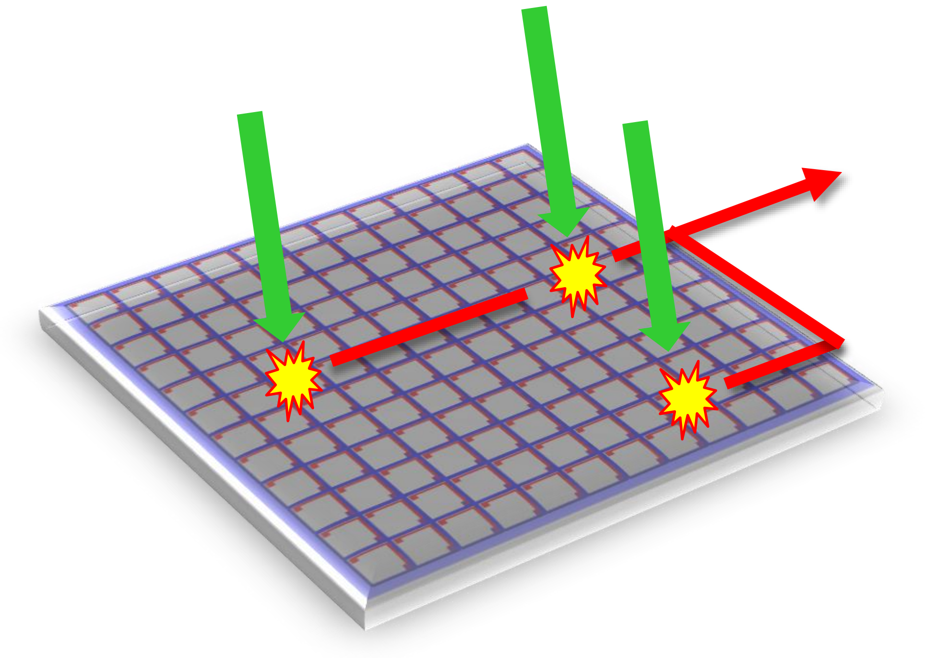
fast, efficient!

R_Q>~300kohm



The SPAD response is not proportional to light intensity (in flashes).

SiPM concept



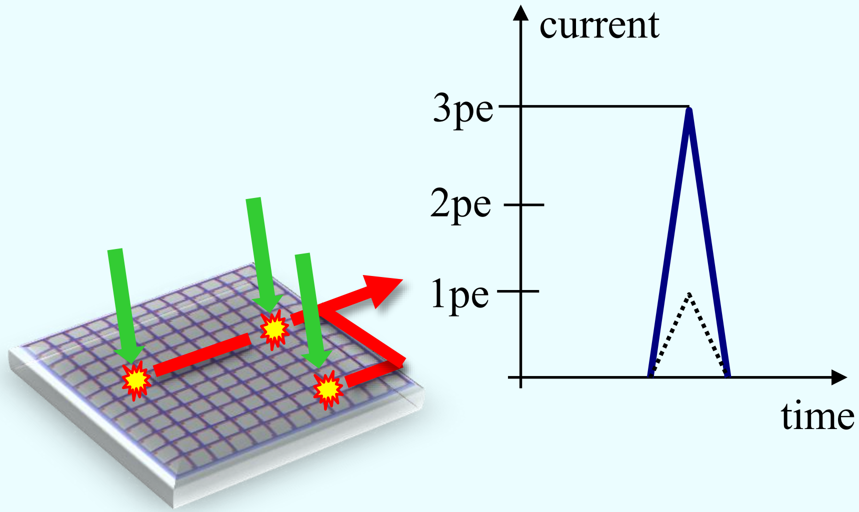
Array of tiny independent SPADs can provide a proportional information.

Analog SiPM

SPADs are connected in parallel.

Output analog signal is proportional to # of photons.

Very simple technology, fully custom, optimized.

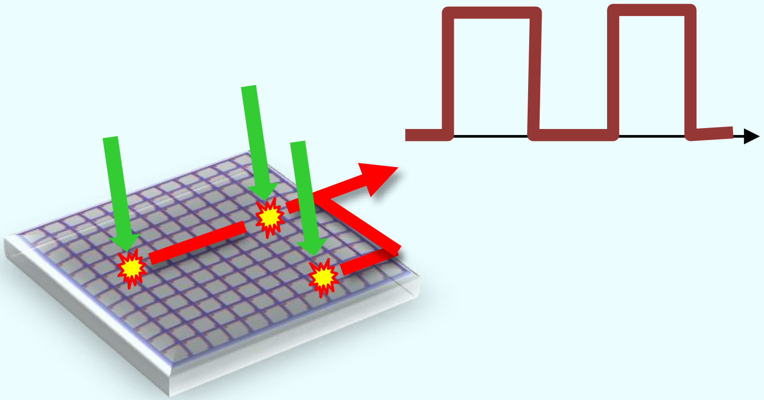


Digital SiPM

Signal digitized at SPAD level.

Integrated Digital architecture produces information on # of photons and time stamp.

Deep sub-mm CMOS technology required.



SPADs/SiPMs: when, where?

1960	1970	1980
Theory of Geiger-mode discharge in pn junctions Haitz, McIntyre…	Idea of SPAD exploiting G-M theory Various sources	First SPADs PoliMI EG&G, Canada

Some papers from 80-90s:

Towards picosecond resolution with single-photon avalanche diodes

S. Cova, A. Longoni, and A. Andreoni

Centro Elettronica Quantistica e Strumentazione Elettronica del C.N.R., Politecnico di Milano, Istituto di Fisica, Milano, Italy

(Received 5 August 1980; accepted for publication 17 October 1980)

Avalanche photodiodes and quenching circuits for single-photon detection

S. Cova, M. Ghioni, A. Lacaita, C. Samori, and F. Zappa

1956 APPLIED OPTICS / Vol. 35, No. 12 / 20 April 1996

Photon counting techniques with silicon avalanche photodiodes

Henri Dautet, Pierre Deschamps, Bruno Dion, Andrew D. MacGregor, Darleene MacSween, Robert J. McIntyre, Claude Trottier, and Paul P. Webb

3894 APPLIED OPTICS / Vol. 32, No. 21 / 20 July 1993

SPAD/SiPMs: when, where?

1995 — Analog SiPM concept
Russian researchers

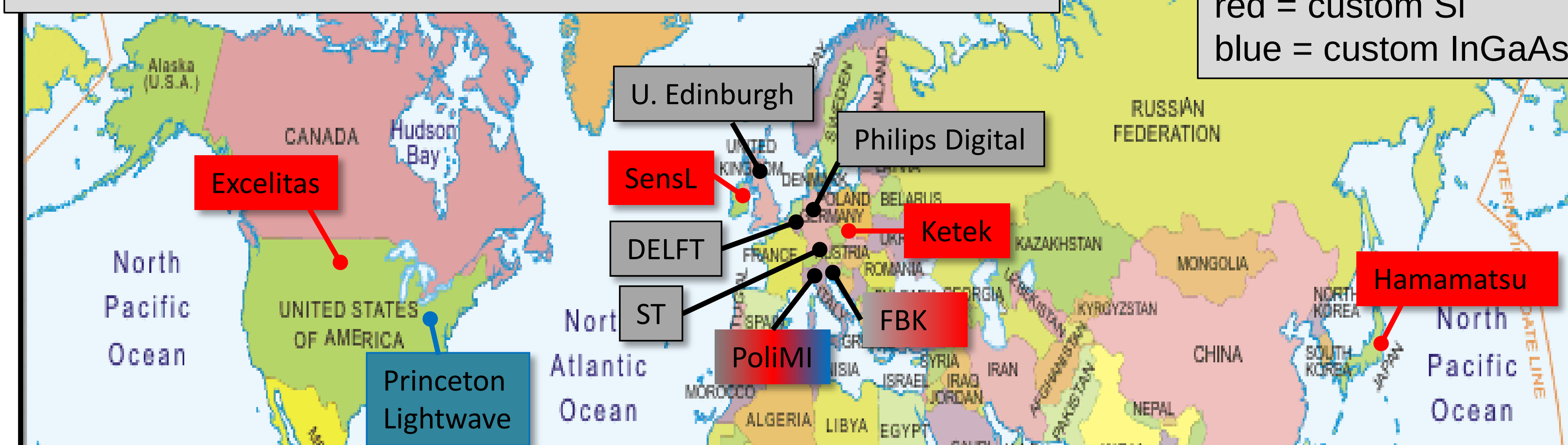
2000+ — SPAD & SiPM developments in custom and standard CMOS
few research centers

~2005 — First SiPM devices with good performance

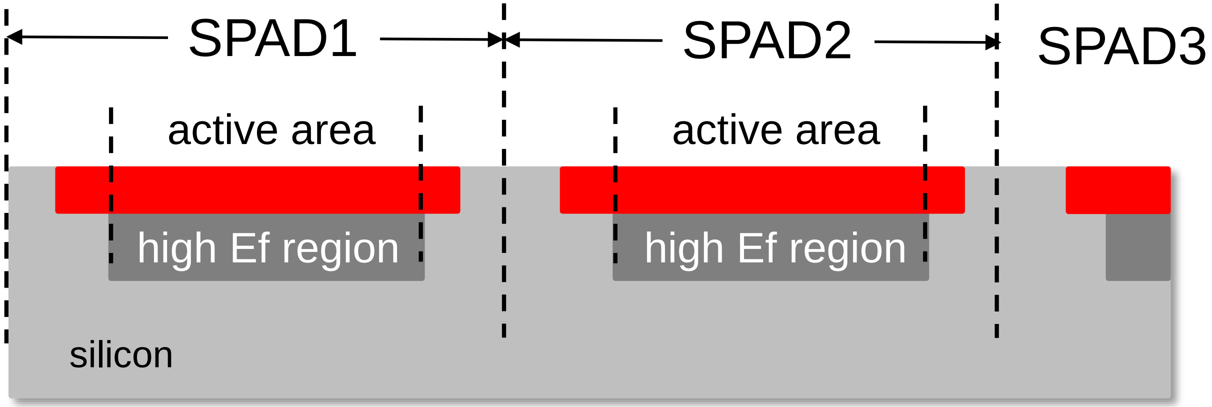
2010+ — Growing industrial applications

Some of the main actors in SPADs/SiPMs:

grey = CMOS
red = custom Si
blue = custom InGaAs



...from SPAD to SiPM



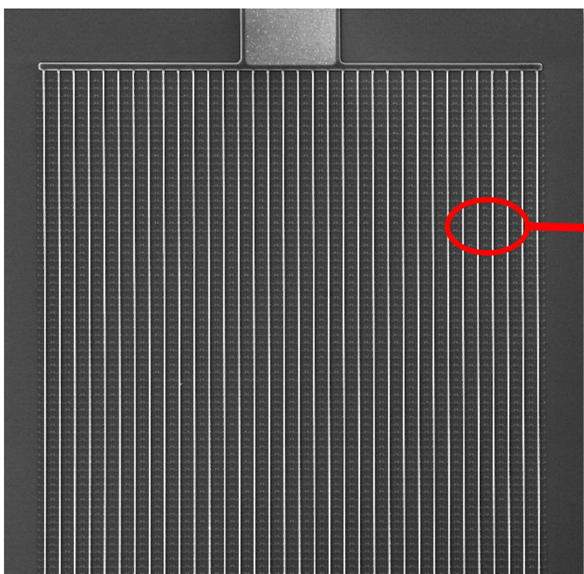
New issues:

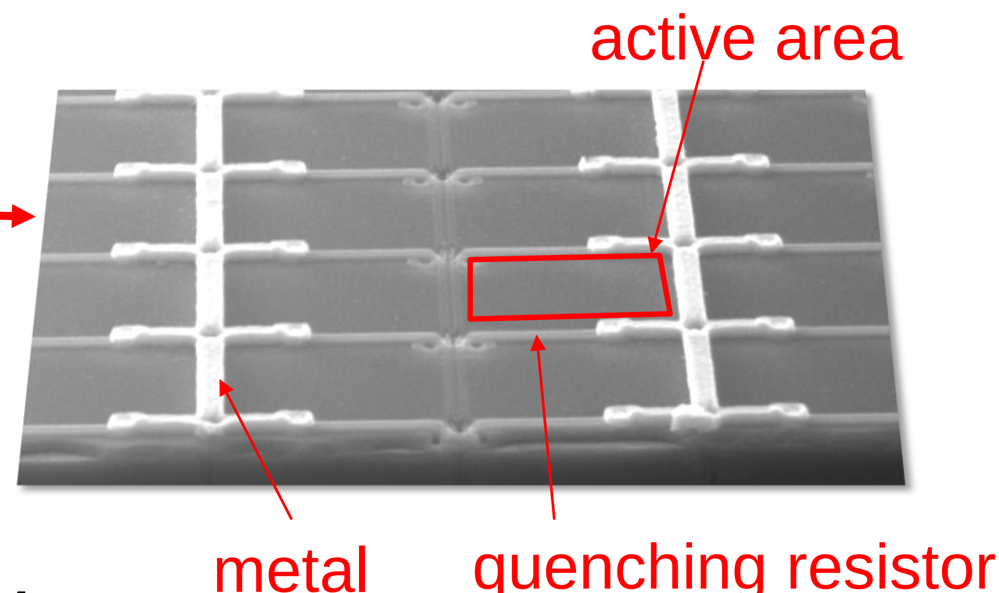
- SPAD fill factor limits the efficiency
- Interactions between SPADs
- Large area

Analog SiPM

Simple technology:

- ~10 lithographic layers layers
- passive quenching
- «easily» customizible to application

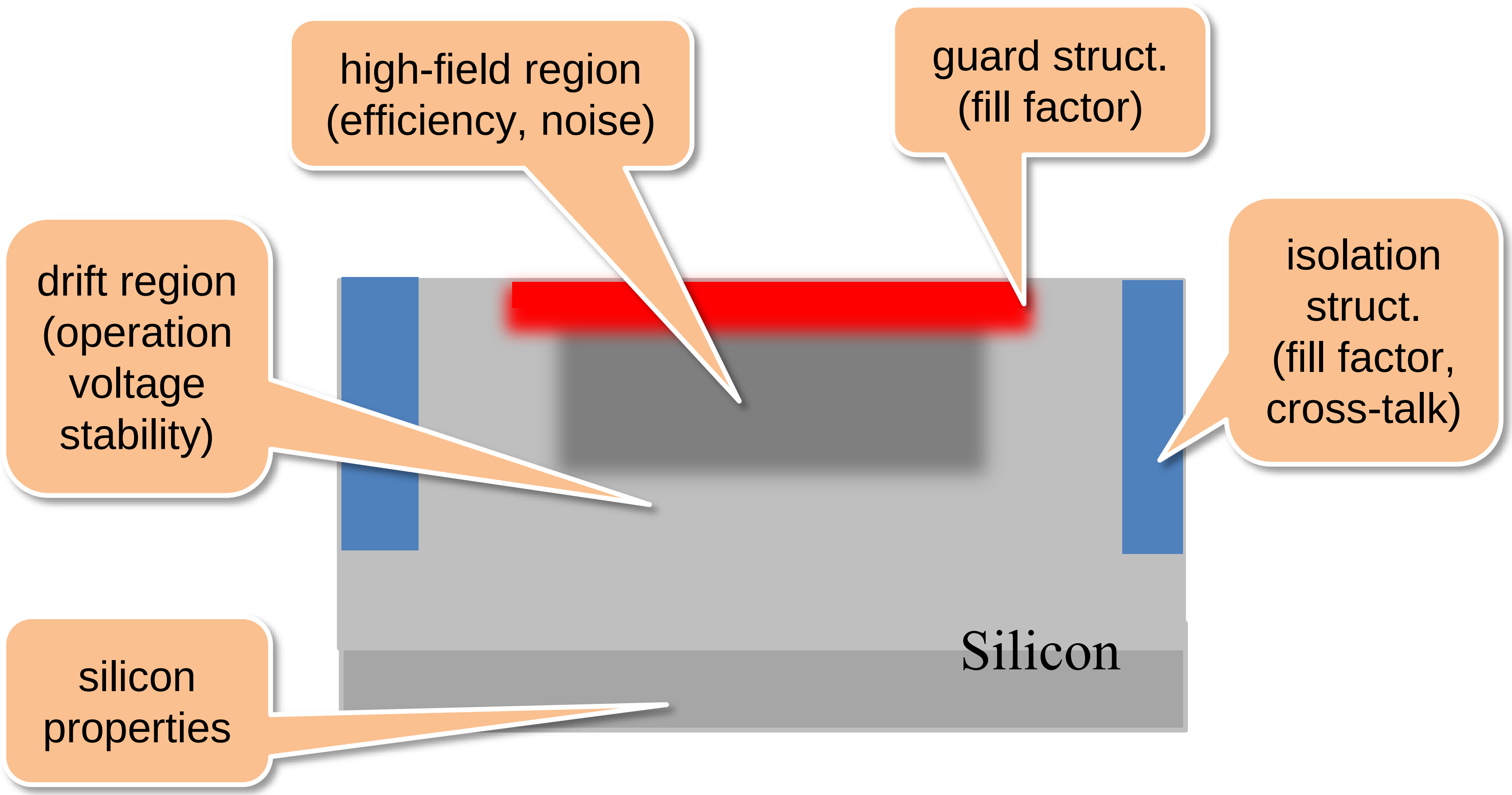




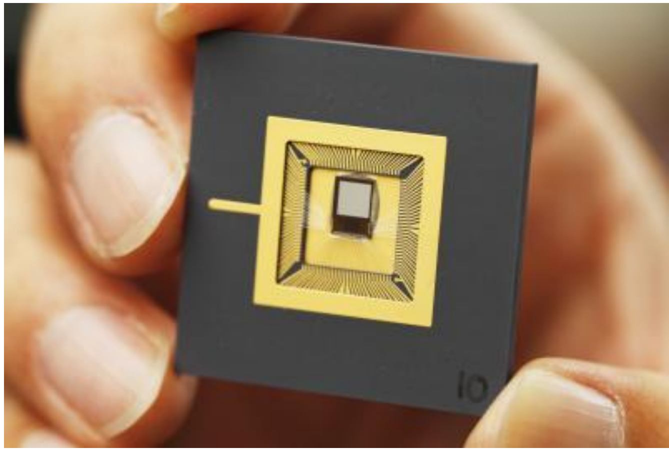
SEM picture of a $1x1mm^2$ SiPM

Analog SiPM

Technology can be optimized in all aspects to get an optimal SPAD.



Digital SiPM

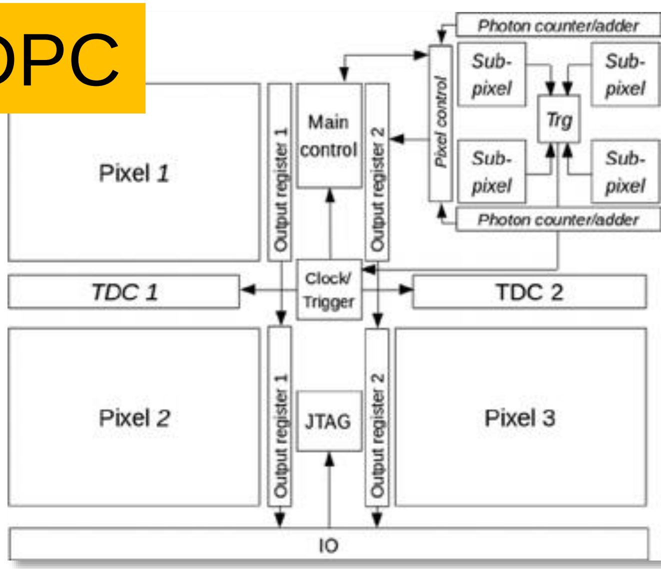


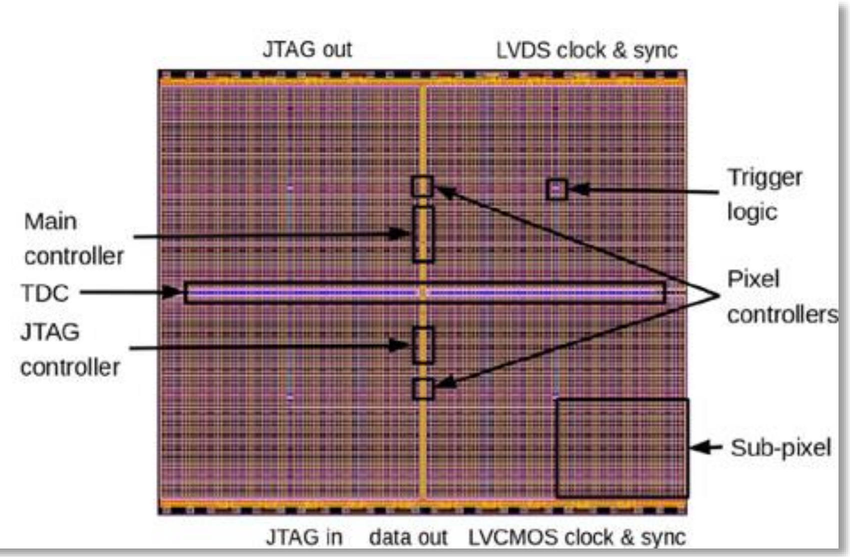
Main Features:

- standard CMOS technology
- integration of «intelligence» in the sensor
  - switch off noisy SPADs
  - distributed TDCs for better timing
  - smart validation systems
  - …
- architecture is usually customized to the application
- SPAD sensor is sub-optimal

Digital SiPM (for PET) - examples

Philips DPC

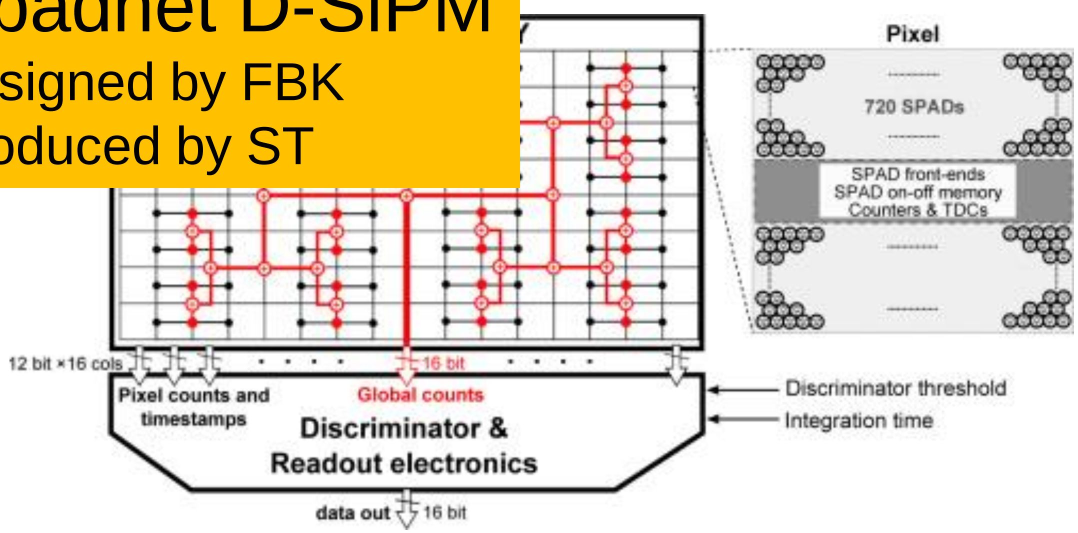


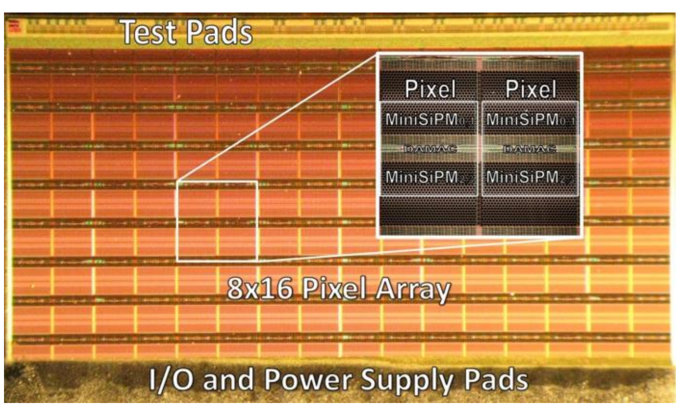


Spadnet D-SiPM

designed by FBK

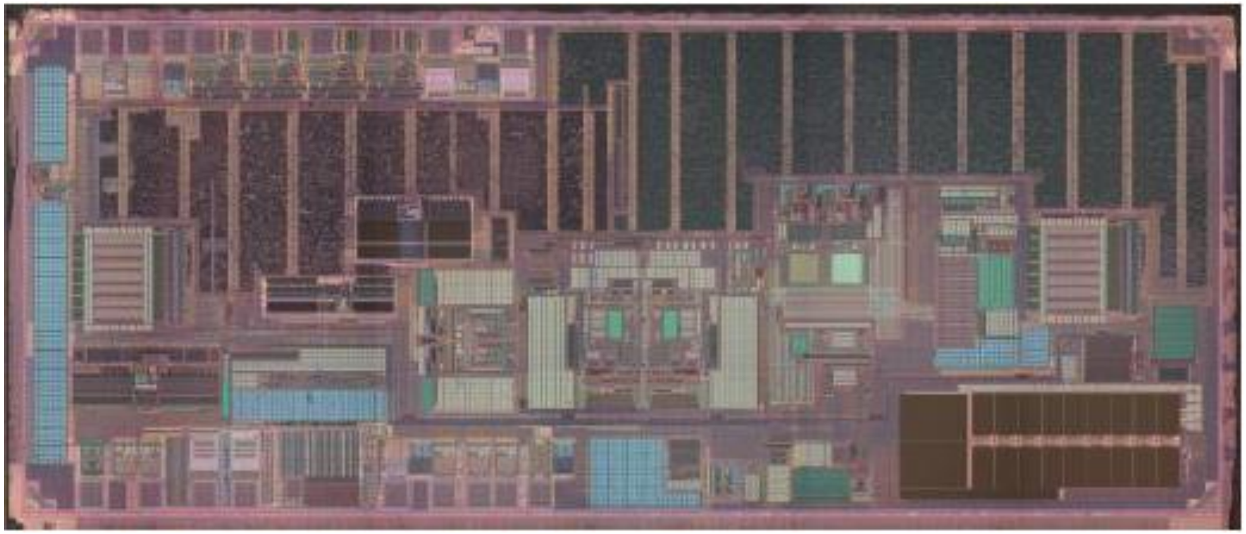
produced by ST





From high-end applications to consumer

- STM SPAD-based TOF Proximity Sensor



@Chipworks (http://ww2.chipworks.com/e/4202/6180-Time-of-Flight-Sensor-pdf/hwvfs/713665047)

Main characteristics of a SiPM

Parameters of a SiPM

1) Gain

Number of electrons produced per detected photon

2) Primary Noise (Dark Count Rate [Hz])

Cells firing spontaneously

3) Correlated Noise → excess noise factor (ENF)

after-pulsing, optical cross-talk

4) Photo-detection efficiency (PDE)

5) Single Photon Time Resolution (SPTR)

Description of each parameter with reference to an FBK technology: NUV-HD

FBK SiPM technology roadmap

Original technology — *2005*

Electric field engineering

RGB — *2010*

NUV — *2012*

New cell border (trenches)

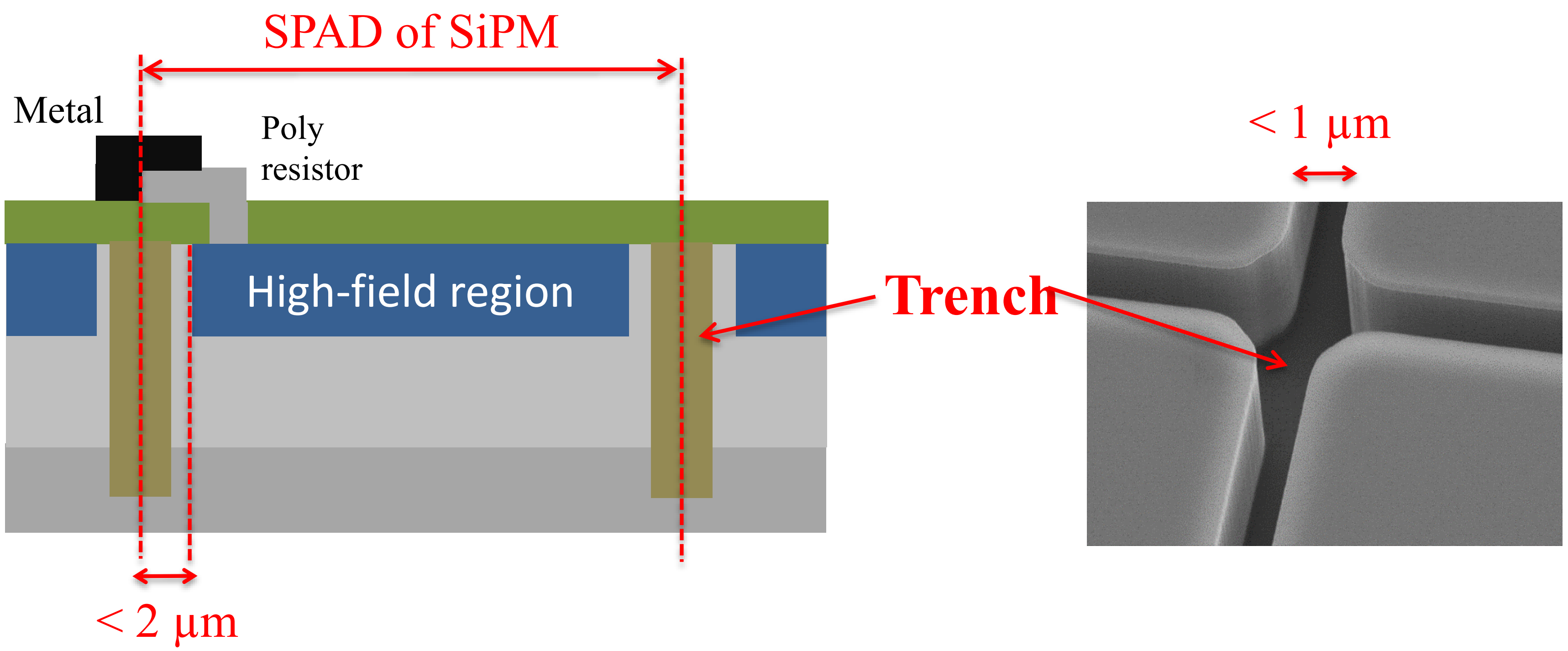
RGB-HD — *2012*

NUV-HD — *2015*

Ongoing developments

- NUV-HD optimization
- RGB-UHD
- VUV-HD
- NIR

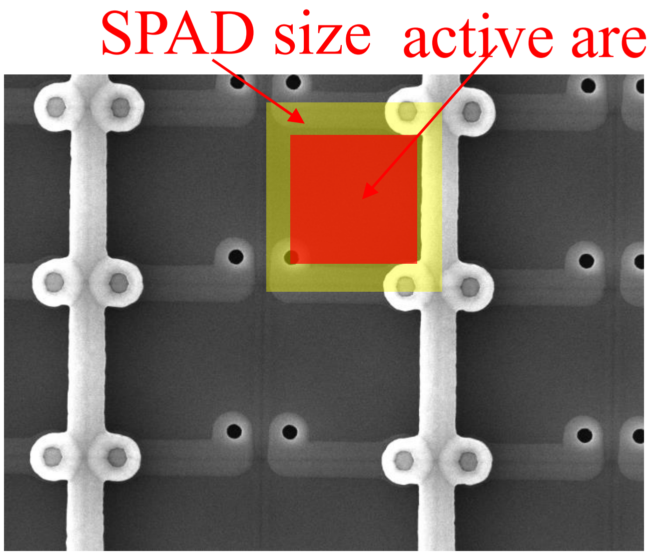
HD technology

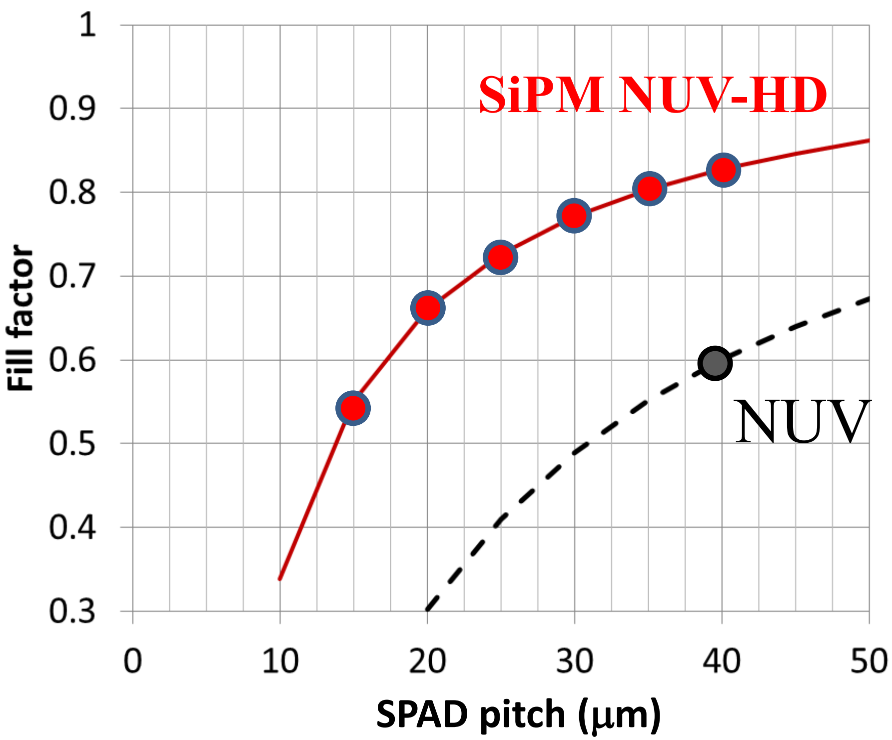


- Narrow dead border region → High Fill Factor
- Trenches between cells → Low Cross-Talk
- Make it simple: 9 lithographic steps

(C. Piemonte et. al., (2016) IEEE T. Electr. Dev., [10.1109/TED.2016.2516641](https://doi.org/10.1109/TED.2016.2516641))

HD: layout features





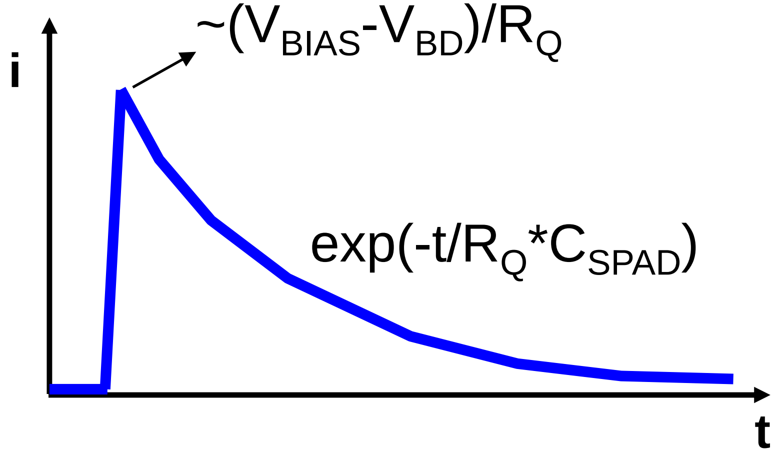
SPAD Pitch	15 µm	20 µm	25 µm	30 µm	35 µm	40 µm
Fill Factor (%)	55	66	73	77	81	83
SPAD/mm²	4444	2500	1600	1111	816	625

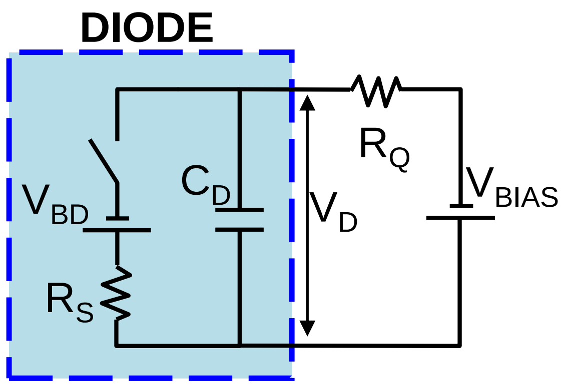
High Dynamic Range

High PDE

Gain of a SPAD/SiPM

Gain = number of electrons per photo-carrier generation



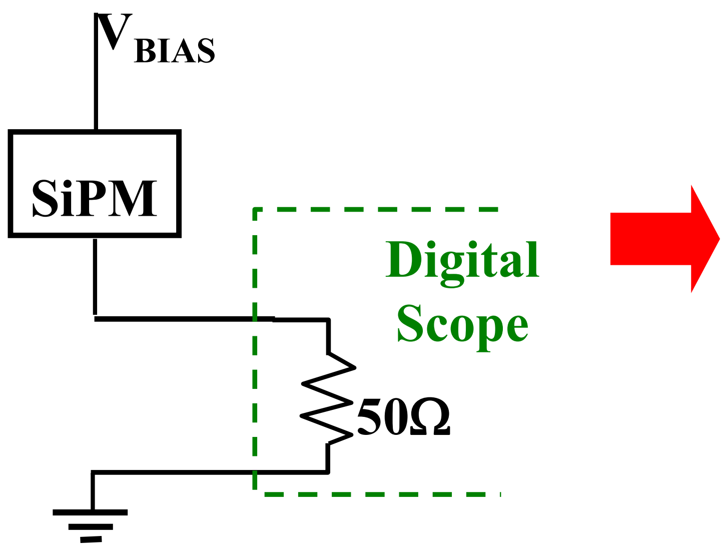


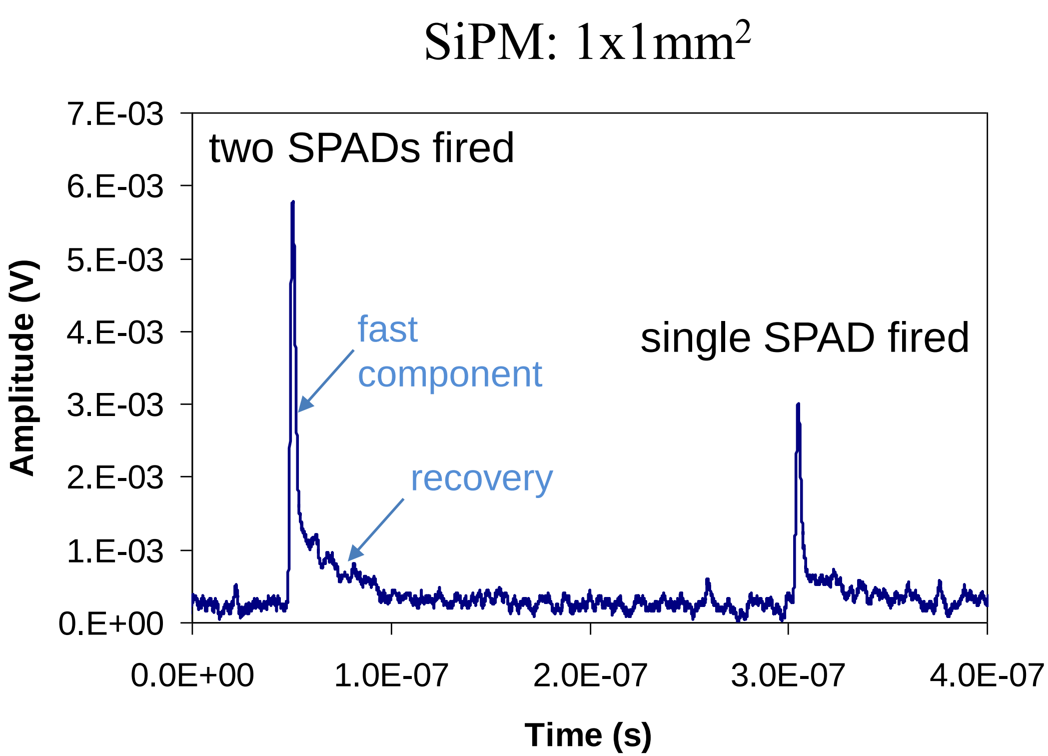
$$\textbf{Gain} = \frac{I_{MAX} \cdot \tau_Q}{q} = \frac{(V_{BIAS}-V_{BD})}{R_Q}\frac{\tau_Q}{q} = \frac{\mathbf{(V_{BIAS}-V_{BD}) \cdot C_D}}{\mathbf{q}}$$

Uniformity and stability of V_{BD} is crucial!

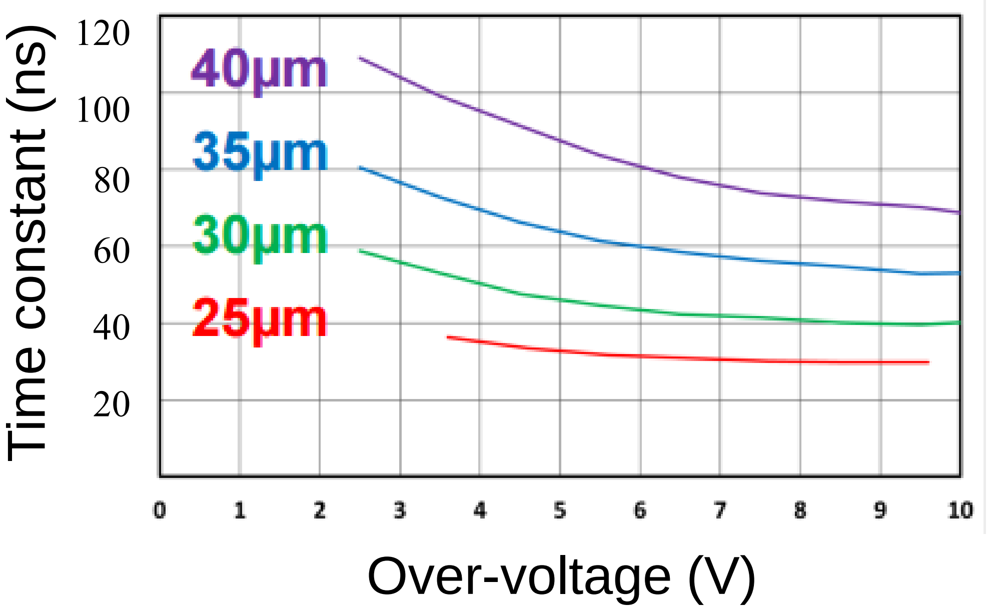
SiPM Signal – NO amplifier

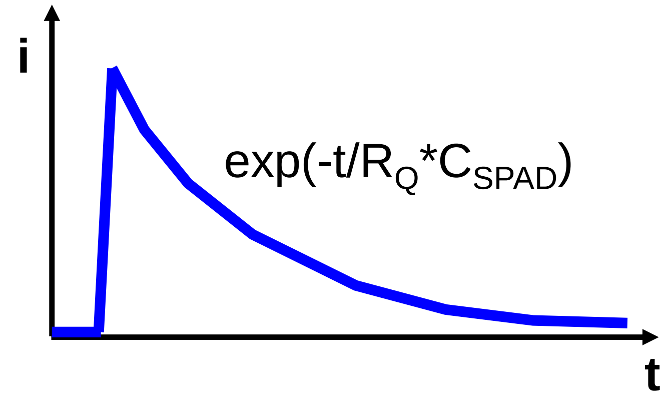
Thanks to the large gain it is possible to connect the SiPM directly to the scope

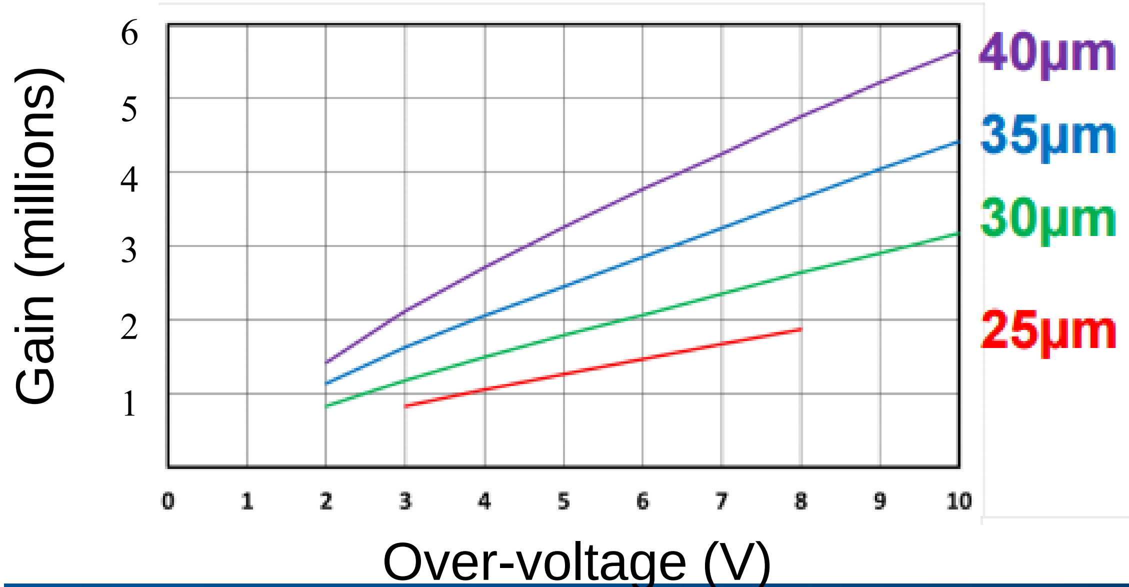


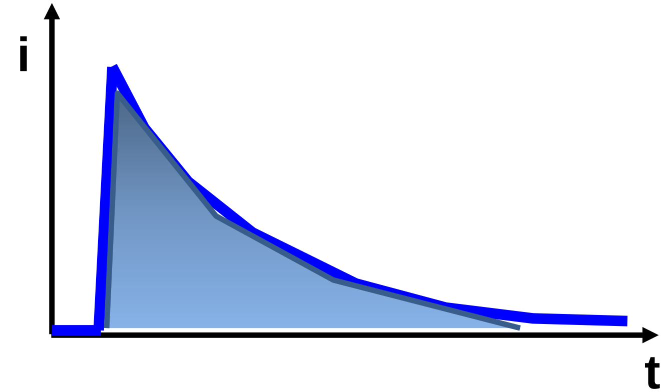


Gain of a NUV-HD SiPM





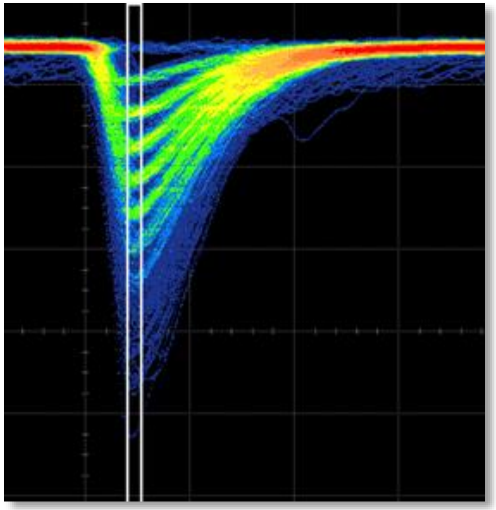




SiPM photon counting capability

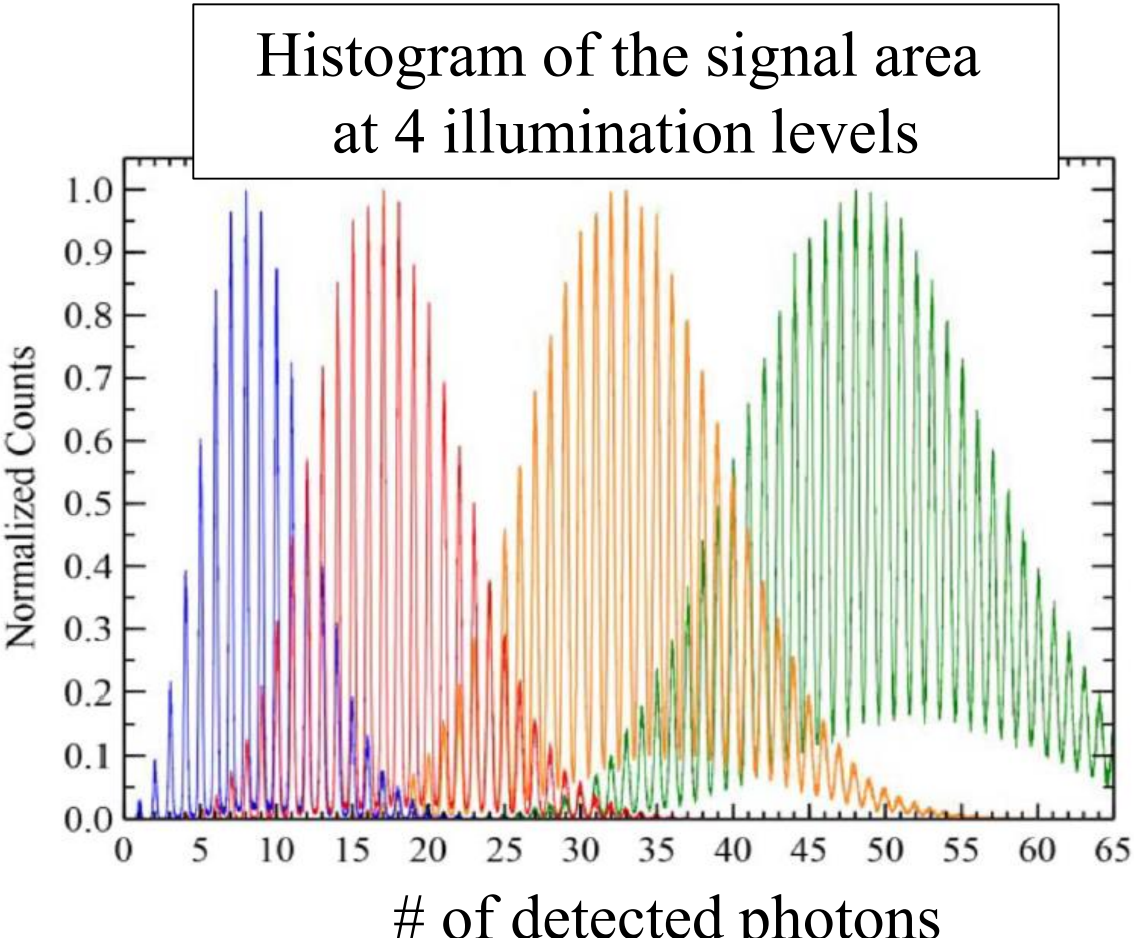
→ gain uniformity in SPAD and SPAD-to-SPAD

SiPM illuminated with weak pulses



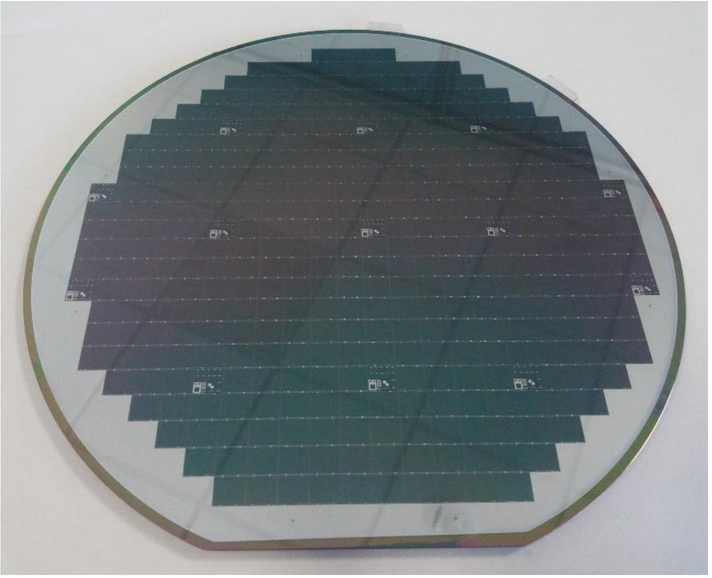
T = 20 C

SiPM area 1x1mm^2



V_{BD} Uniformity

Gain uniformity (intra- and inter- device) is mostly affected by Vbd. What is the V_{bd} uniformity?



6” Silicon wafer

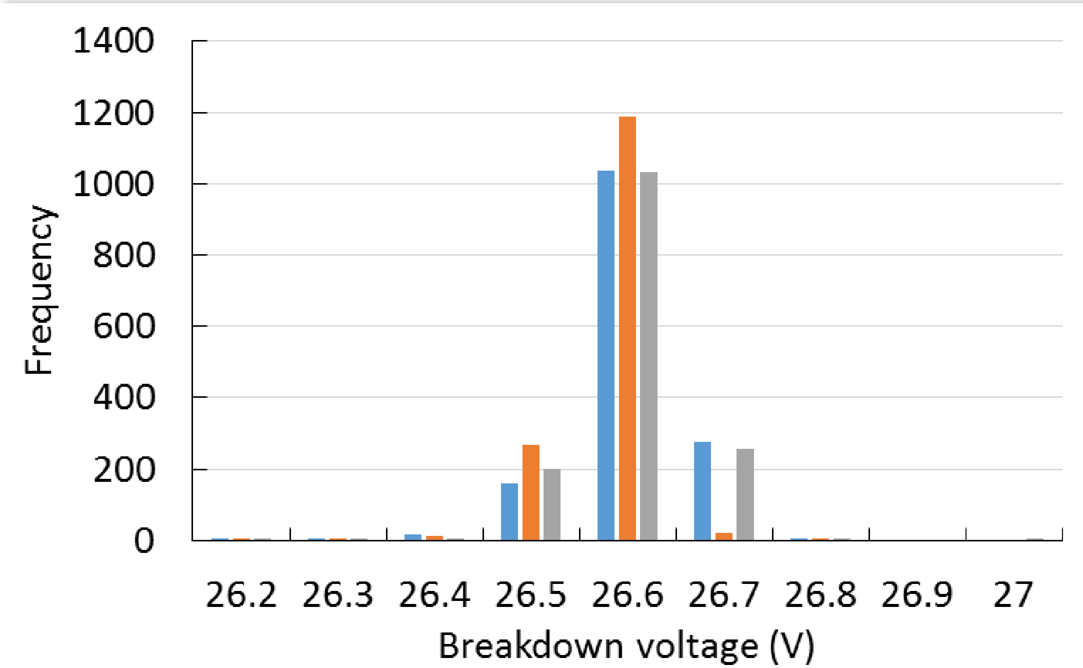
1532 3x3mm^2 SiPMs per wafer

SPAD pitch is **35mm**

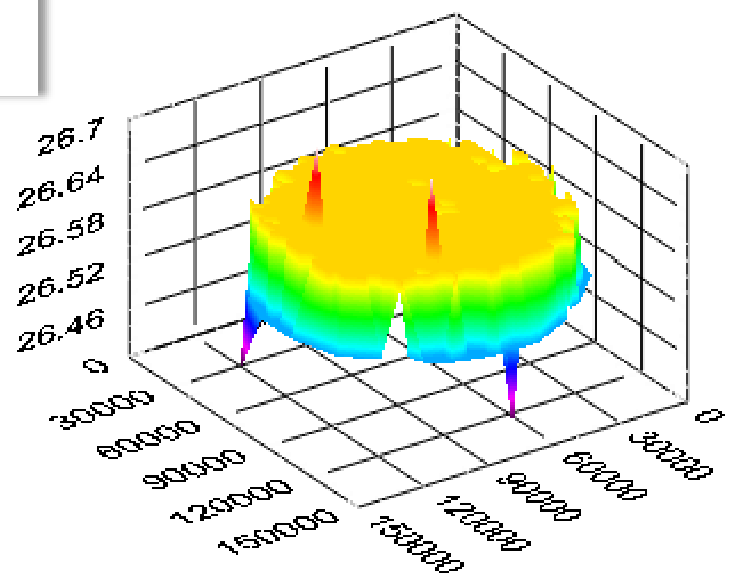
Each SiPM has **6295 SPADs**

Reverse IV measurement on all SiPMs on 3 sample wafers:
→ Breakdown voltage

V_{BD} Uniformity

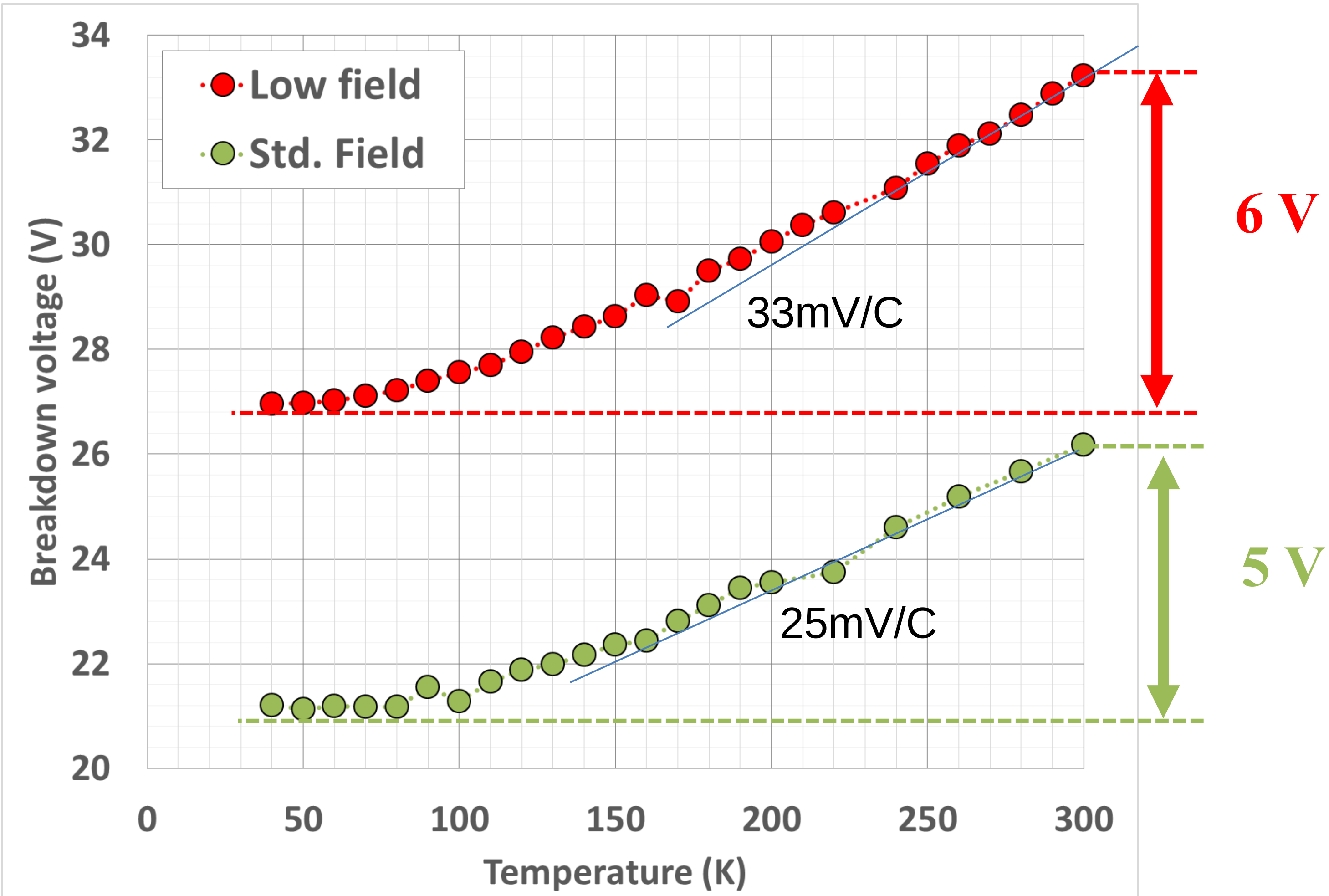


Distribution of V_{BD} on three wafers.
Max variation 200mV!



V_{BD} Temperature dependence

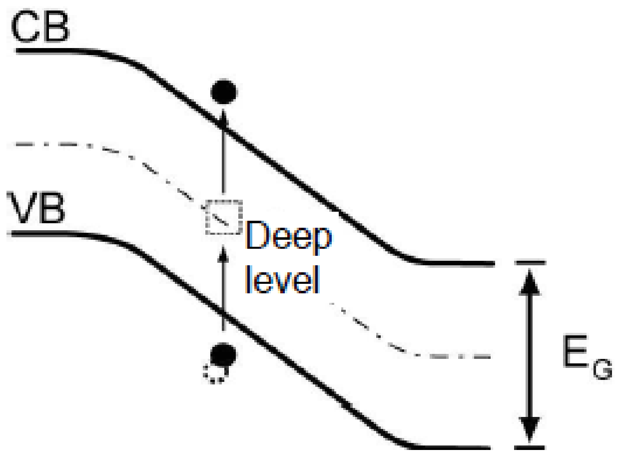
The mean free path of the carriers in the high-field region increases with decreasing temperature.



DOI: 10.1109/TED.2016.2641586

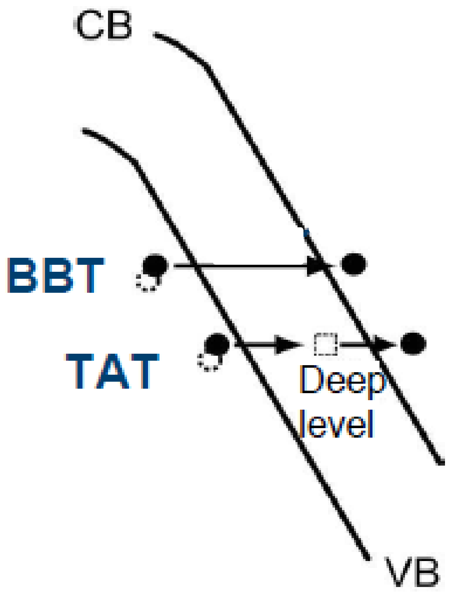
Dark count rate

Thermal generation (SRH model)



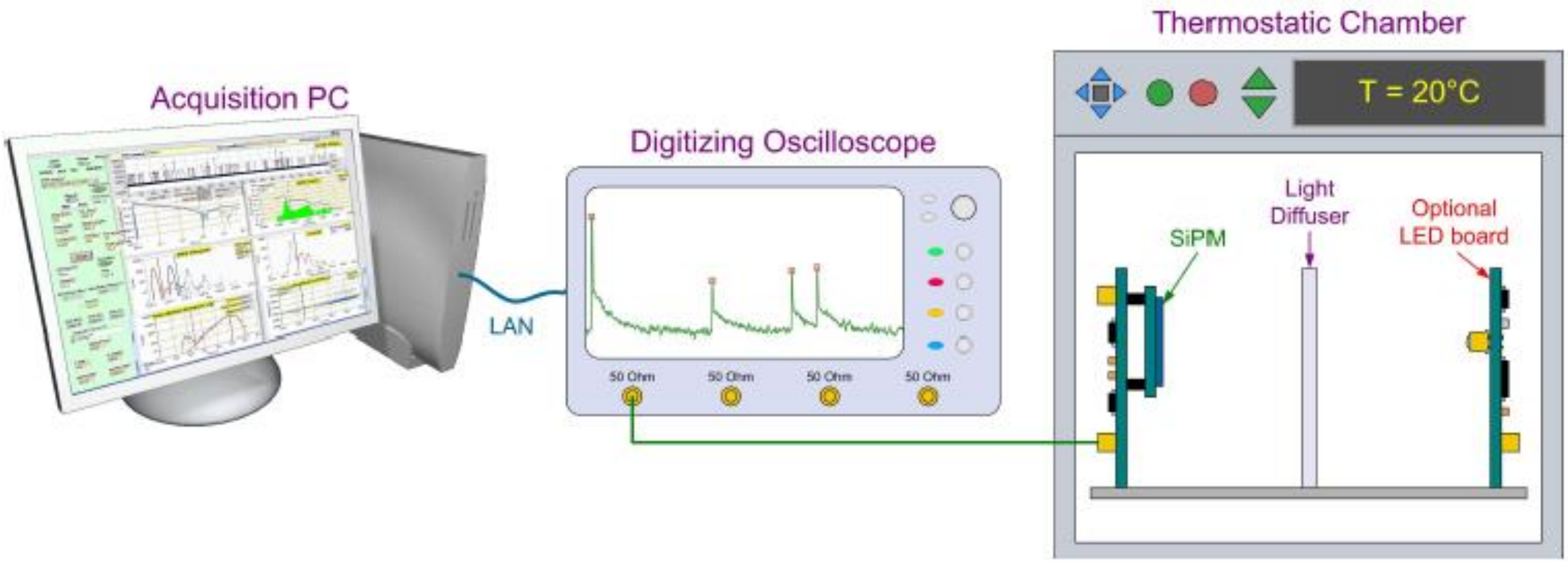
Main source of carrier generation in silicon at room T in standard photodiodes

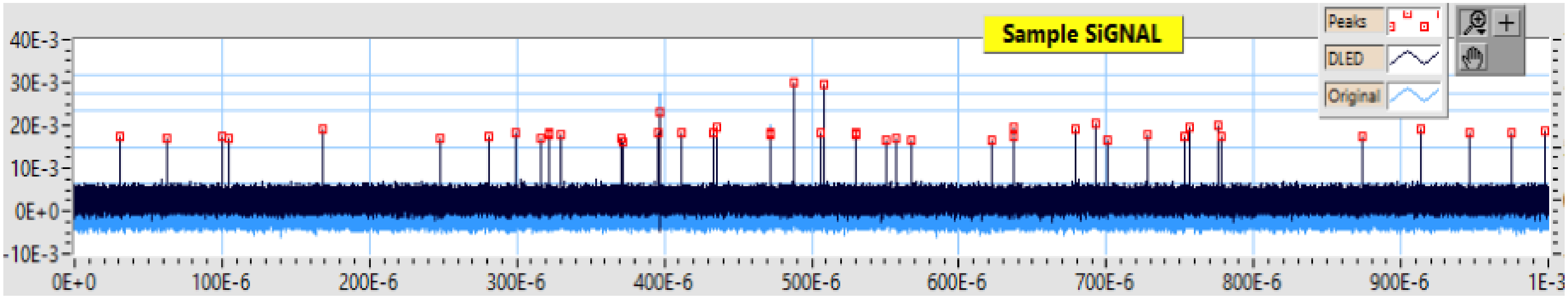
Tunneling generation



TAT is an important additional contribution in devices relying on impact ionization

DCR measurement



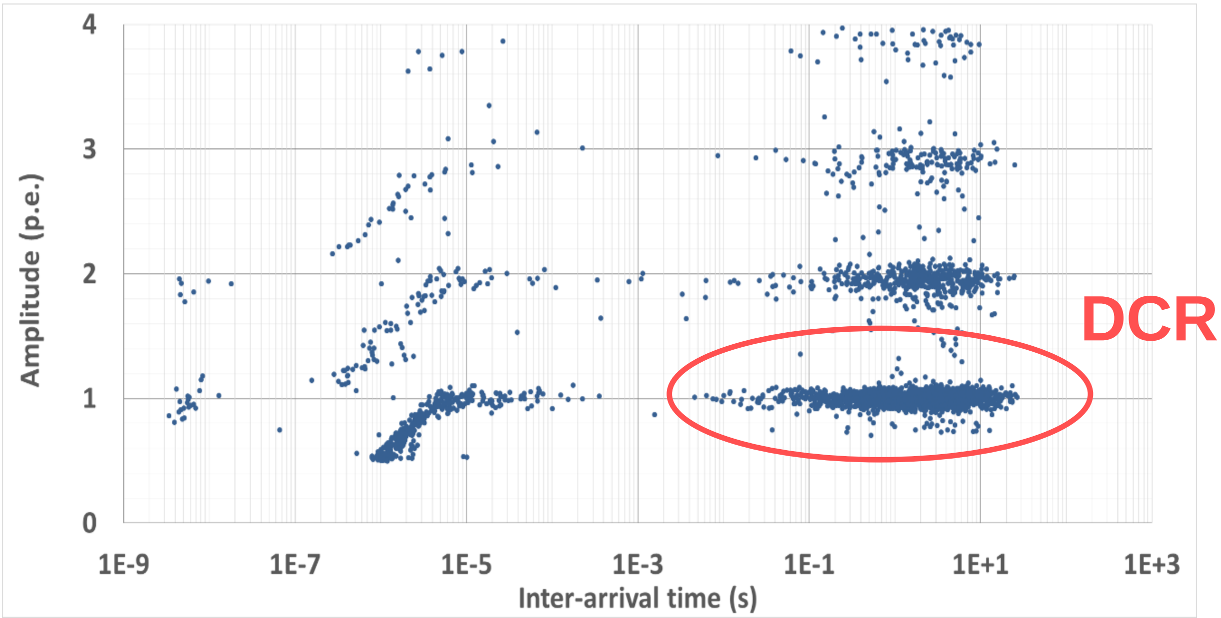


(C. Piemonte et. al., (2012) IEEE NSS/MIC Conf. Rec., N1-206)

DCR measurement

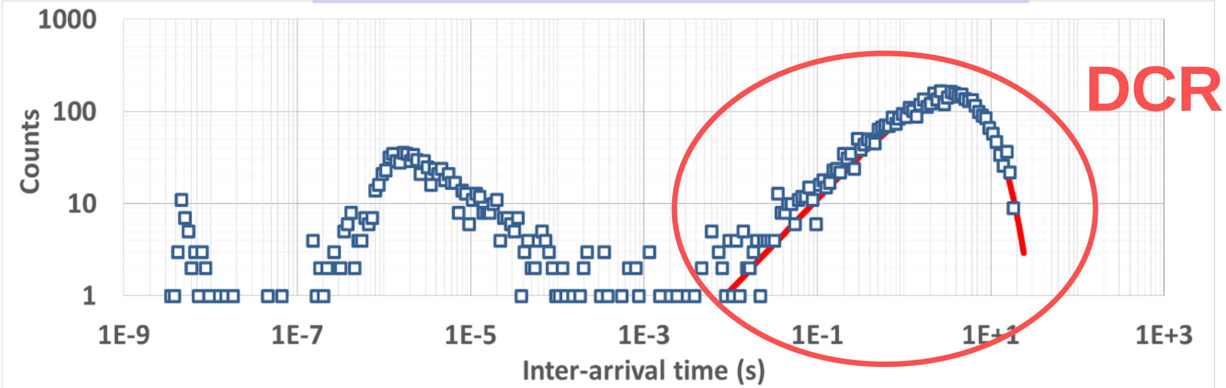
T=70K
(example to separate well the components)

Scatter plot



Scatter plot of amplitude vs inter-times

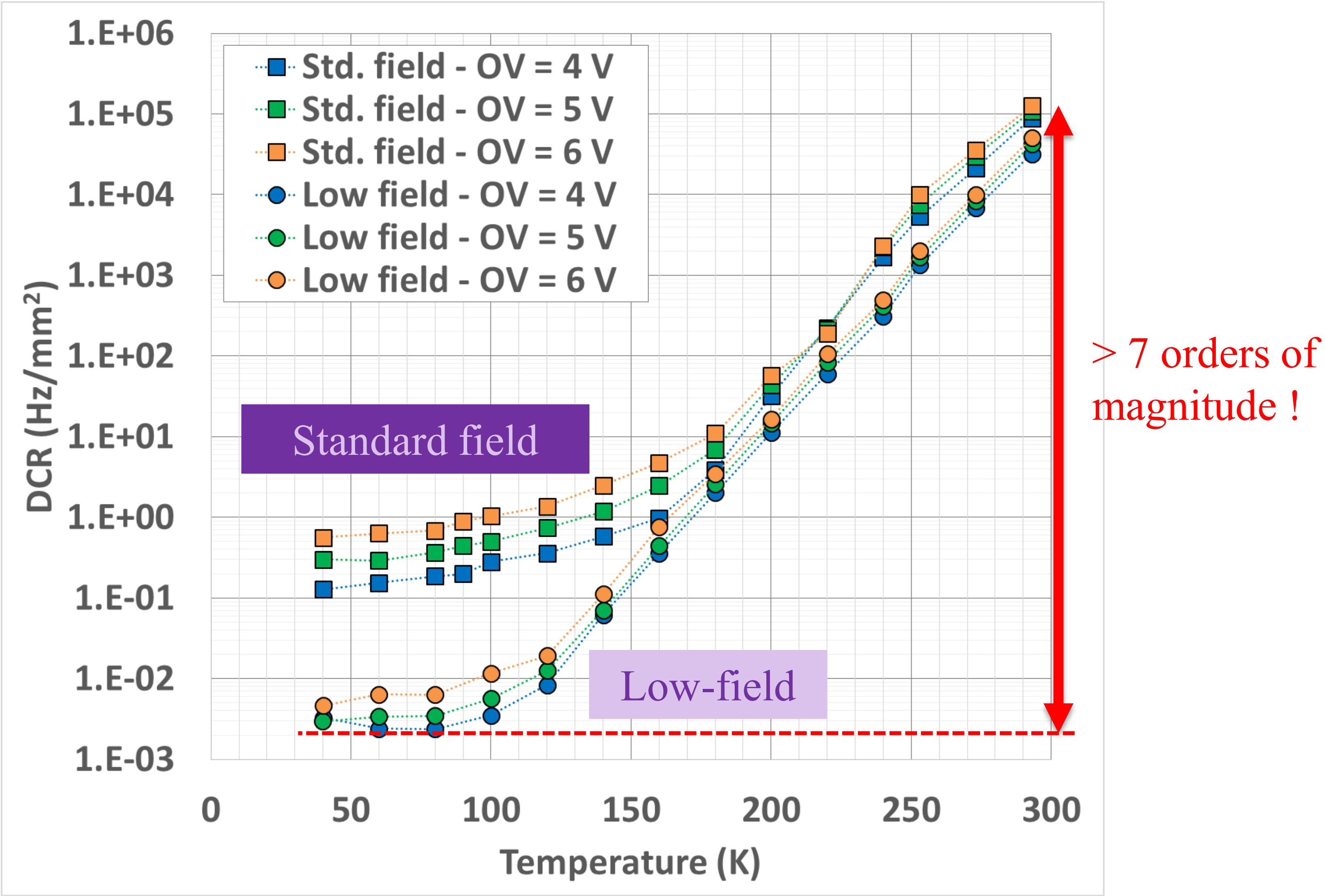
Inter-arrival time histogram



DCR event distribution with Poisson fit

DCR / mm² vs. Temperature

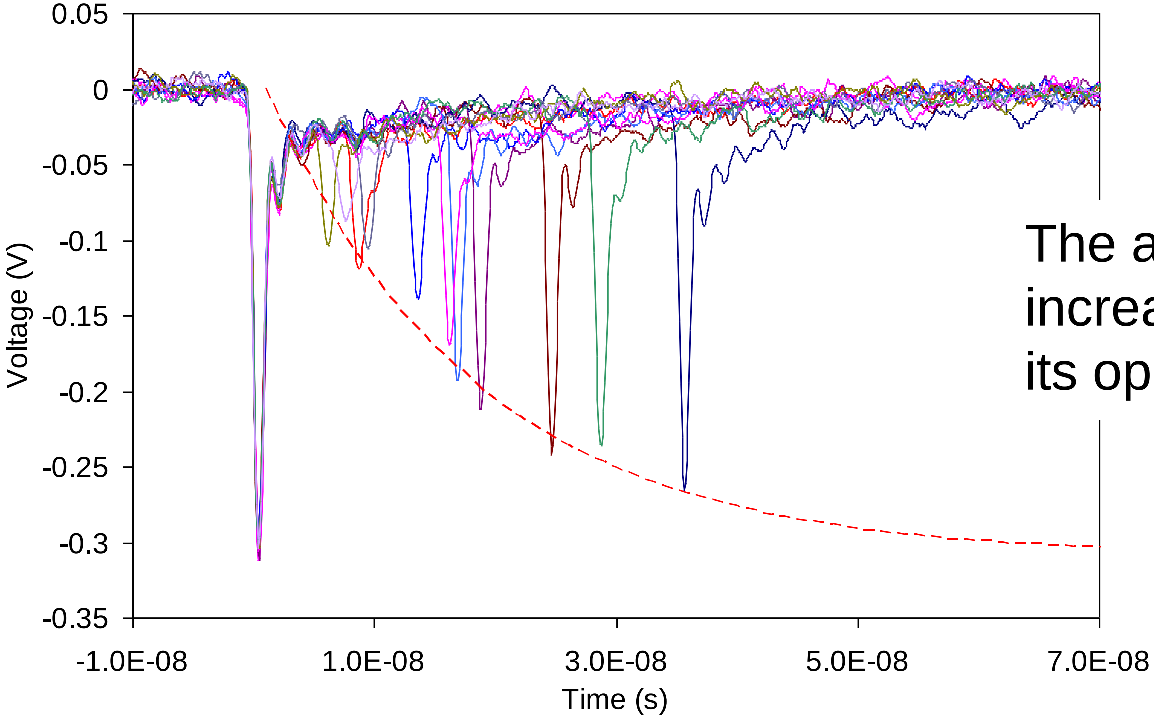
NUV-HD **4x4mm²** size **25µm** SPAD pitch (25600 SPADs)



After-pulsing Probability

Carriers may be trapped during an avalanche, released and may triggering another avalanche.

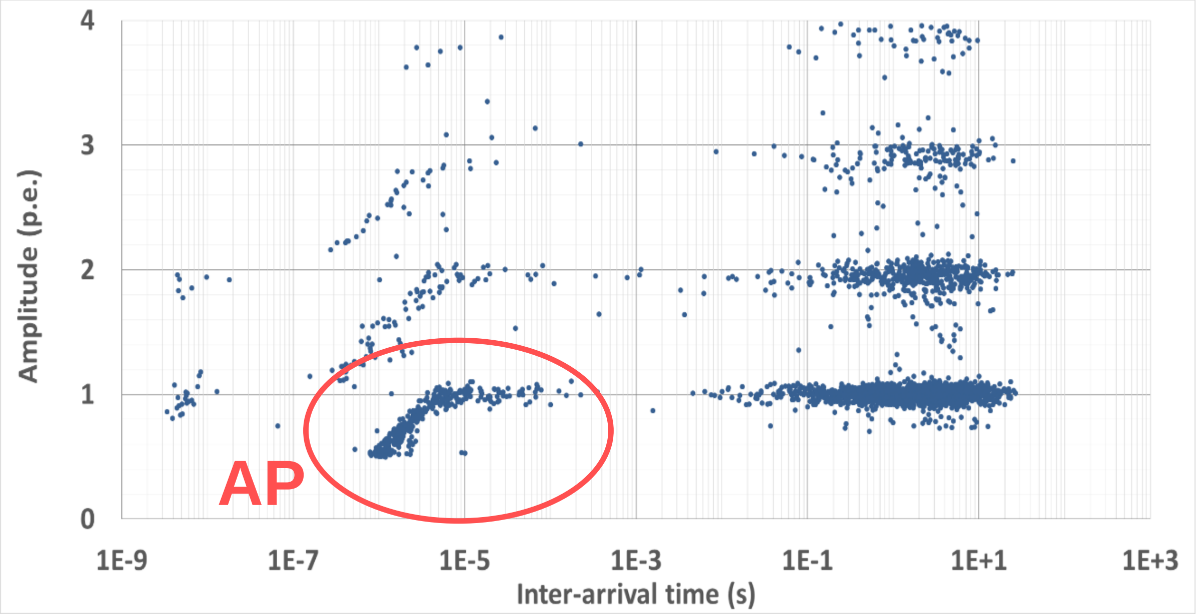
Collection of primary Events with after-pulse



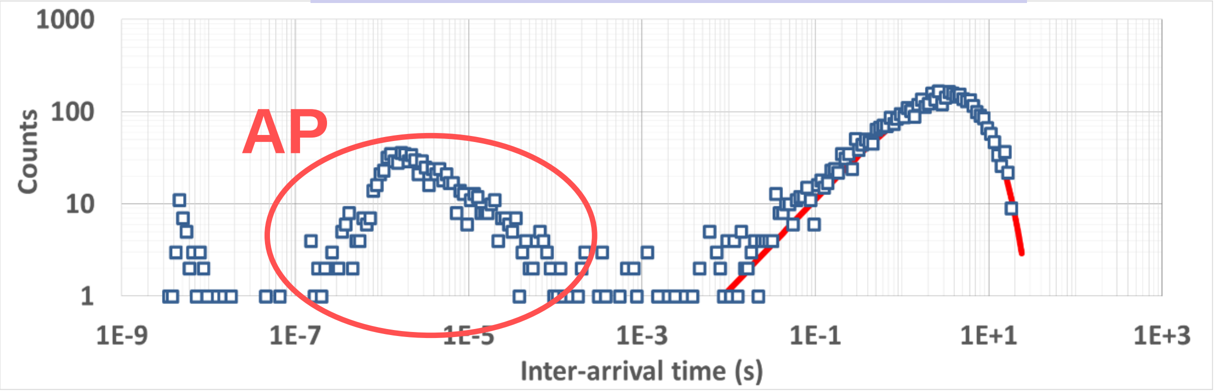
The amplitude of the after-pulse increases as the cell recovers to its opertional condition

AP measurement

Scatter plot



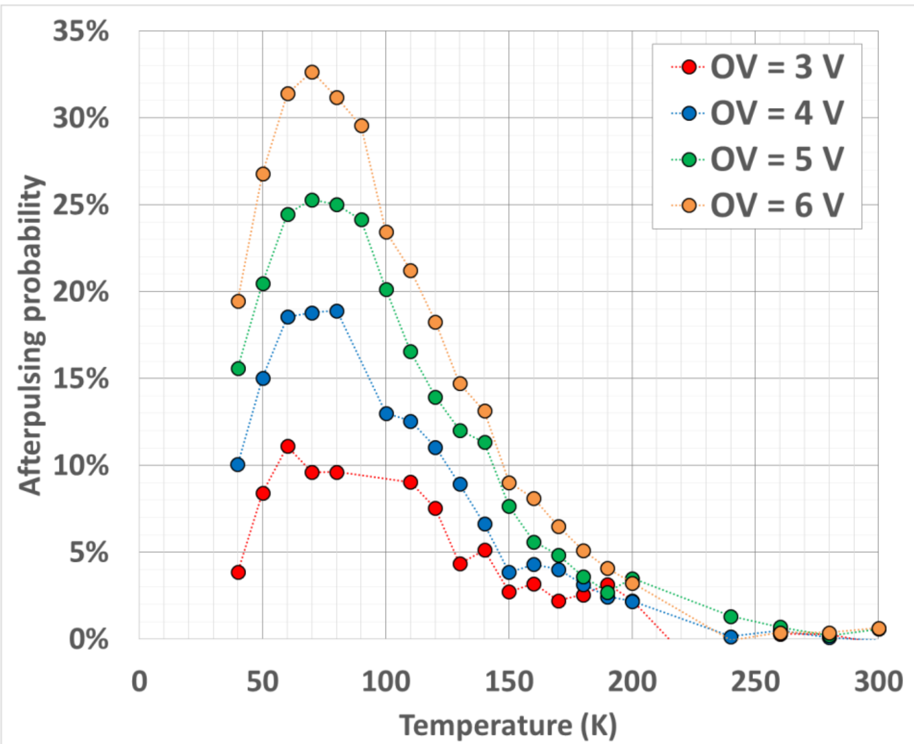
Inter-arrival time histogram



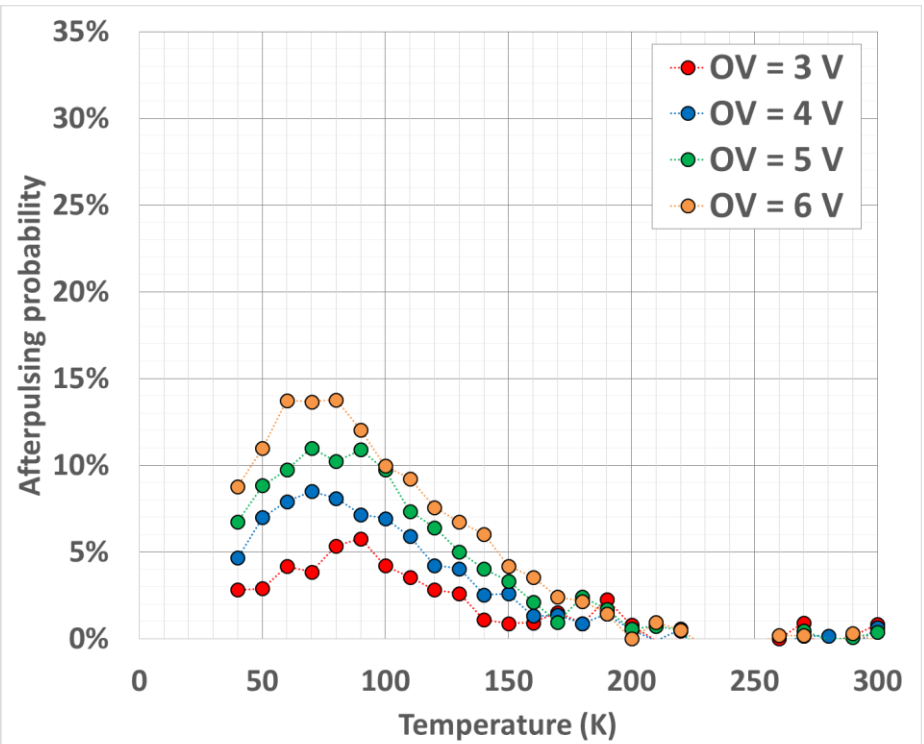
Scatter plot of amplitude vs inter-times

AP in NUV-HD

AP increases with decreasing temperature because the release becomes slower..



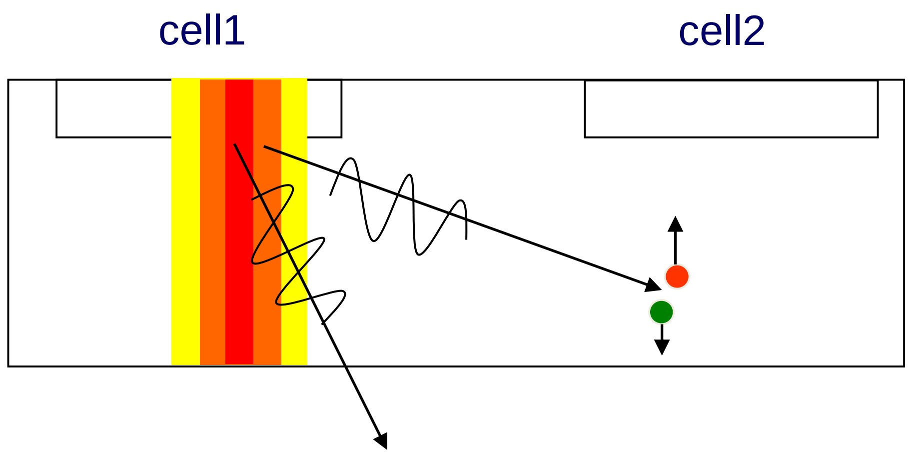
Standard field



Low-field

Optical cross-talk

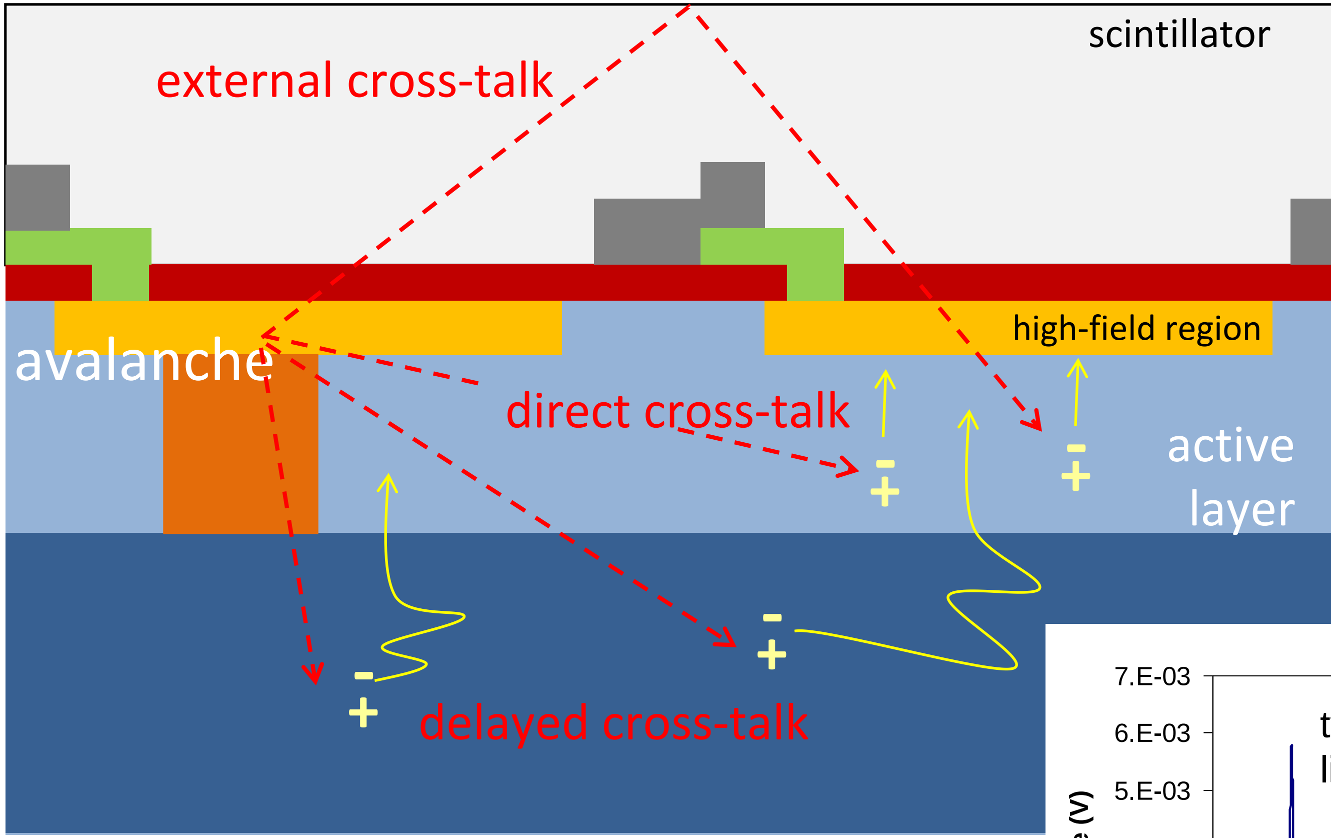
Photons are emitted during an avalanche which may trigger another avalanche in another SPAD

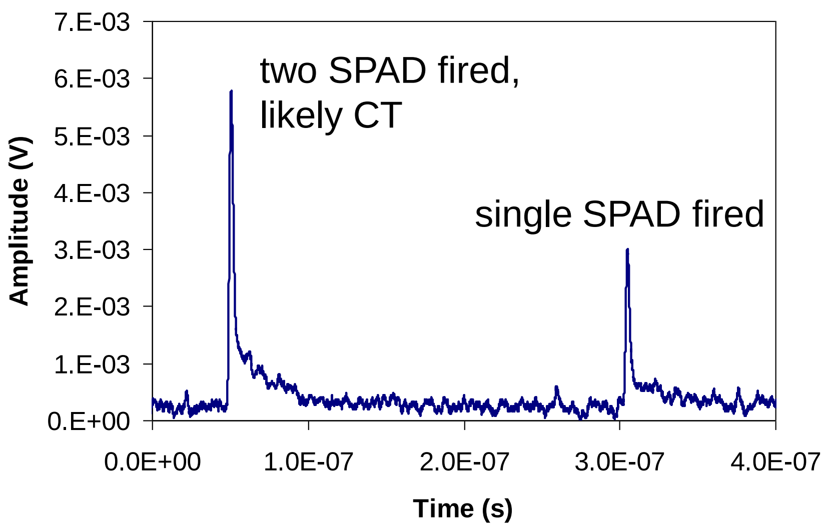


3x10^{-5} photons with energy higher than 1.14eV emitted per carrier crossing the junction.

[A. Lacaita et al., IEEE TED, vol. 40, n. 3, 1993]

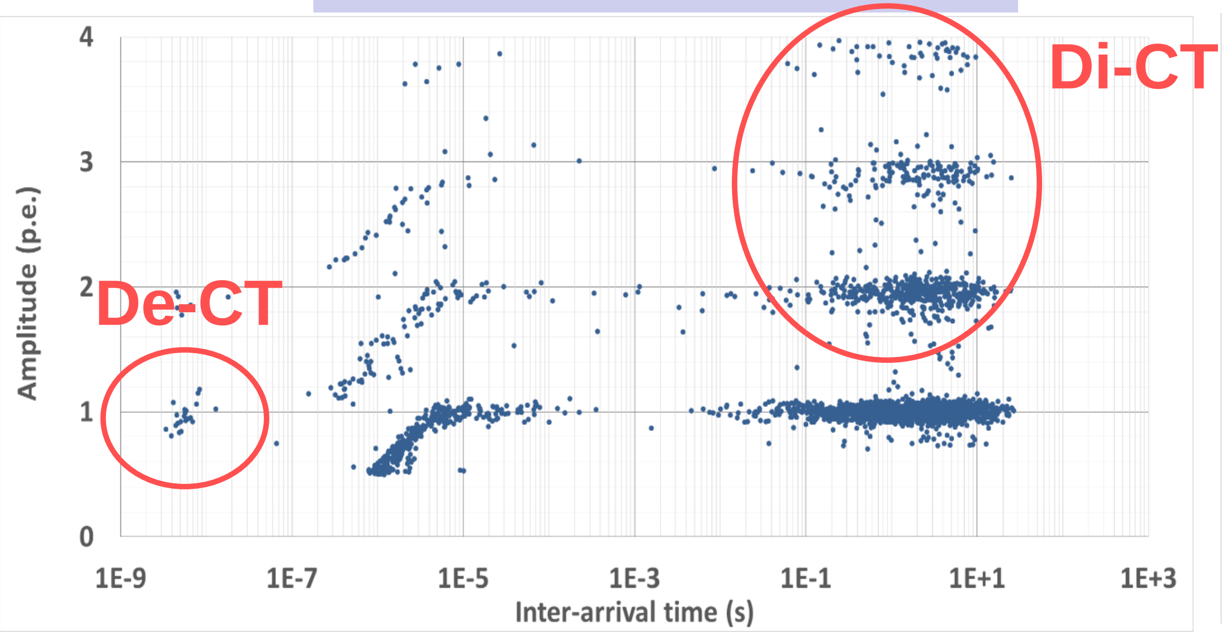
Optical cross-talk



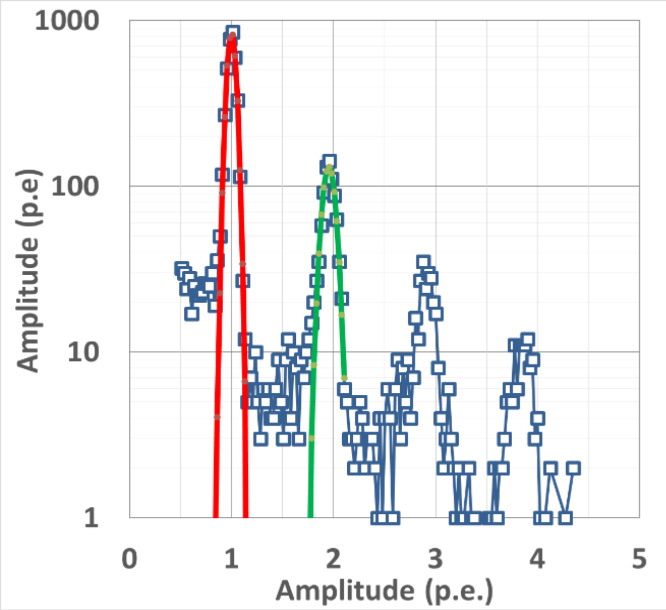


CT measurement

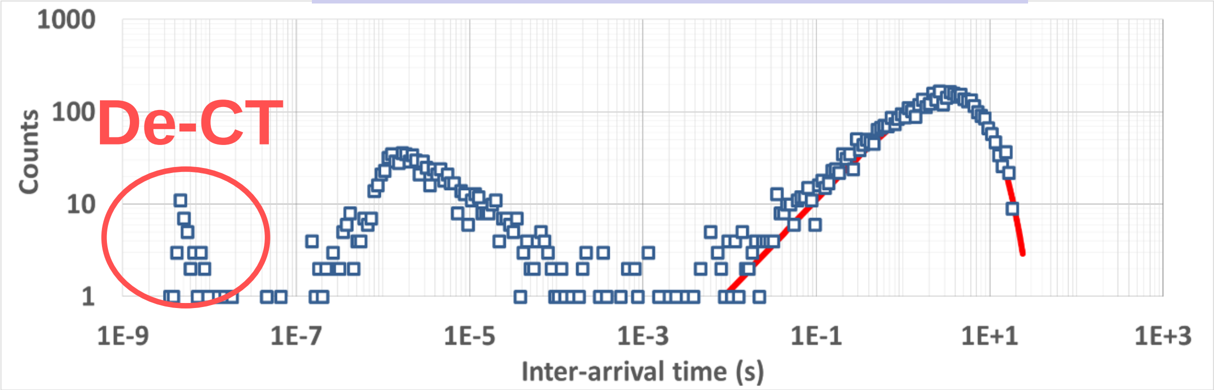
Scatter plot



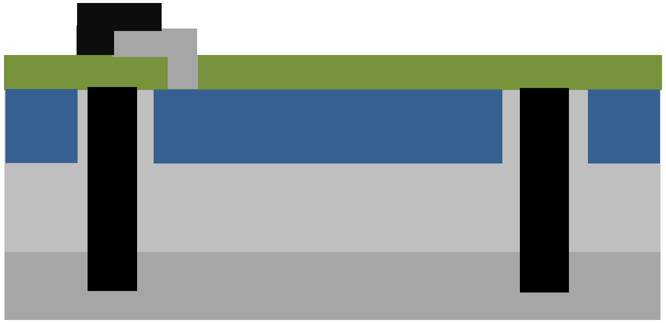
Amplitude histogram



Inter-arrival time histogram

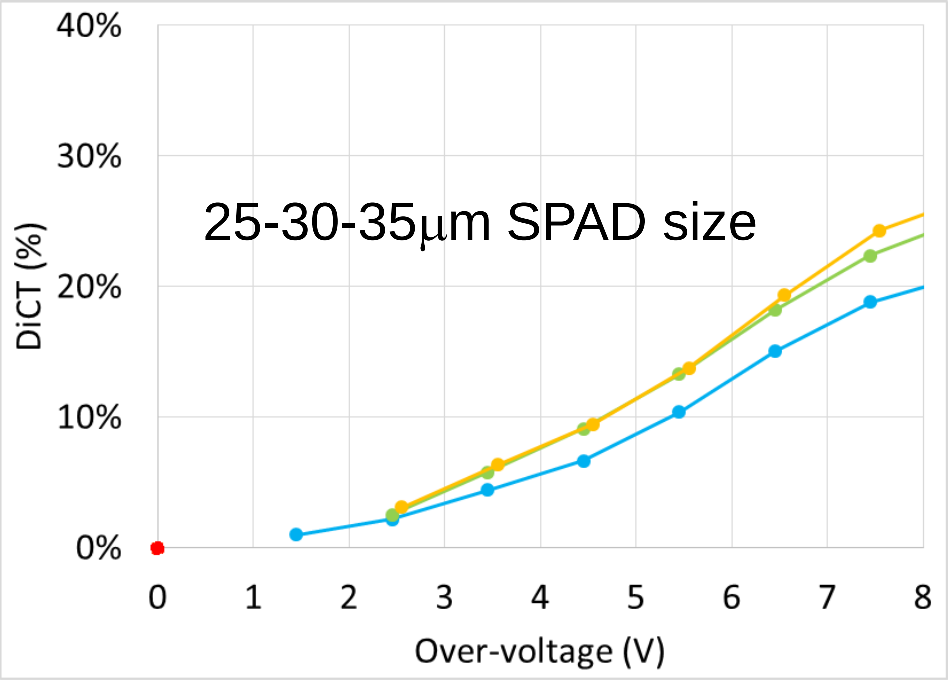


CT in NUV-HD



Direct cross-talk

Delayed events



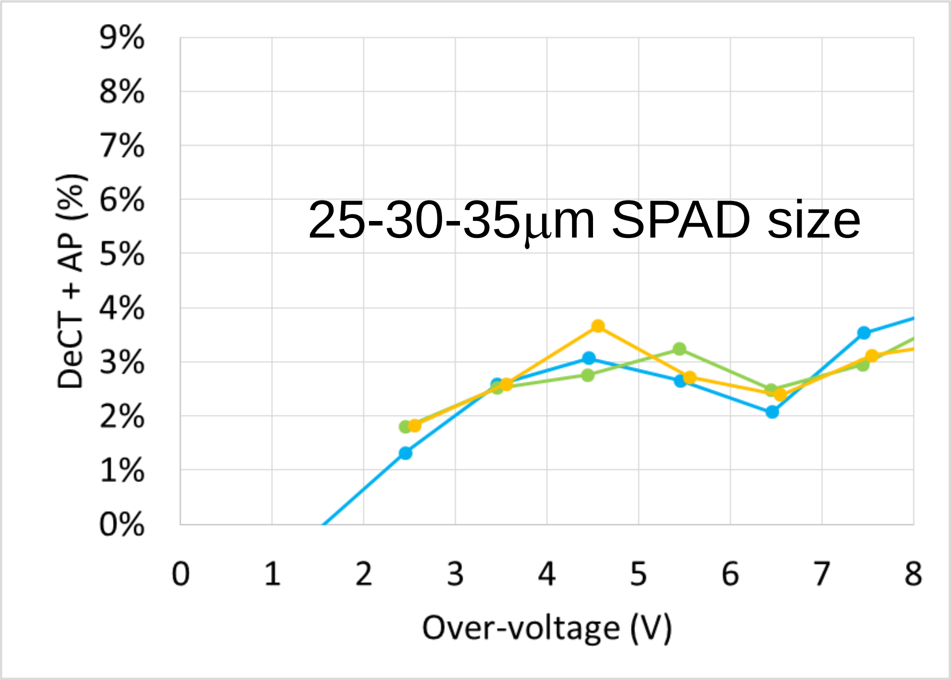


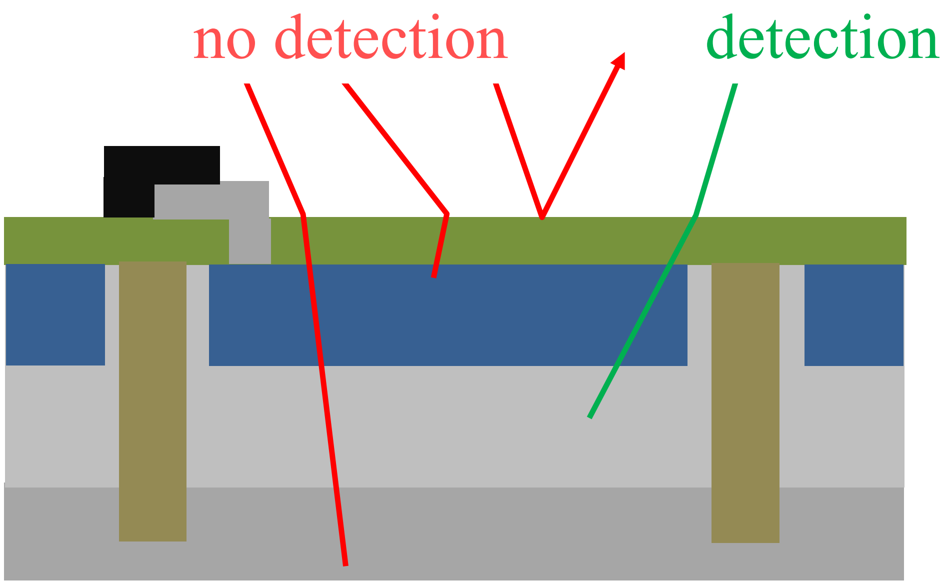
Photo-detection efficiency

$$\mathrm{PDE}(V,\lambda) = \mathrm{FF} \times \mathrm{QE}(\lambda) \times T_P(V,\lambda)$$

SPAD Fill Factor	Quantum Efficiency	Triggering Probability

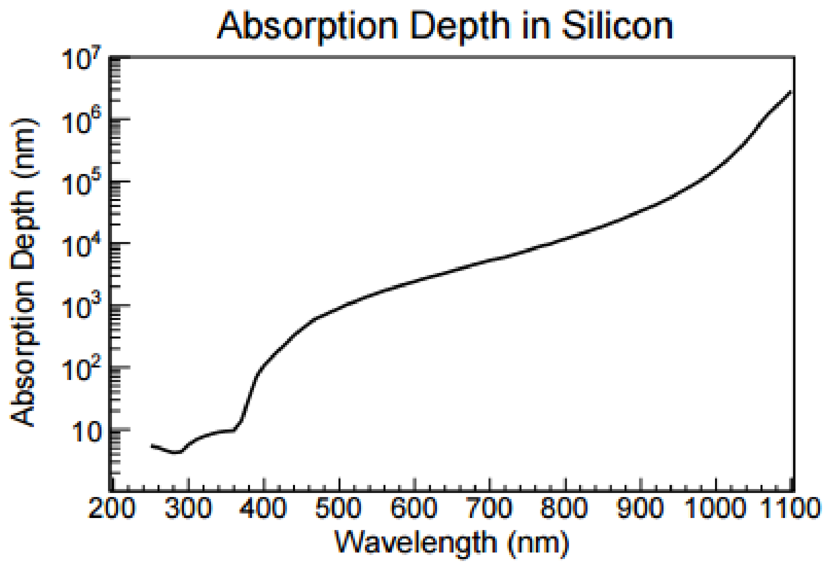
2016 JINST 11 P11010

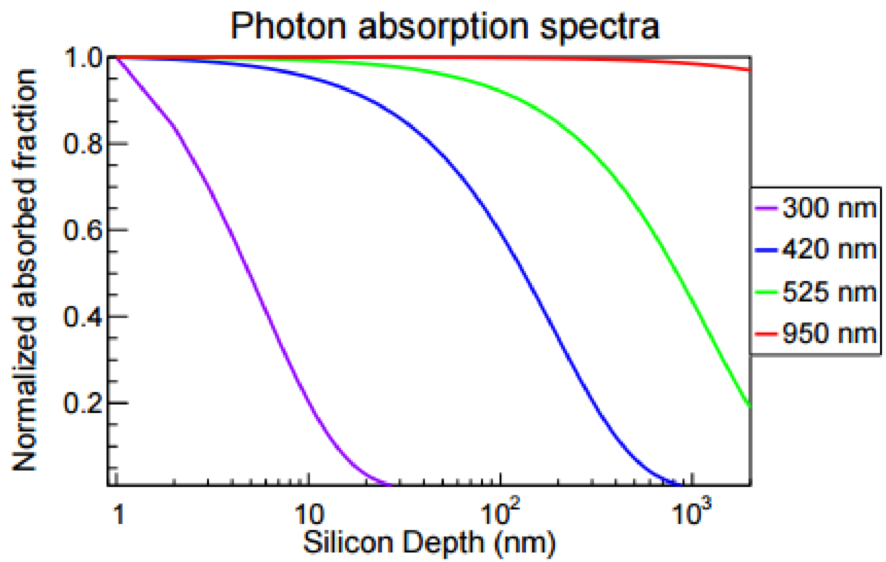
QE



It depends on:

- Anti-reflective coating
- active layer thickness
- junction depth



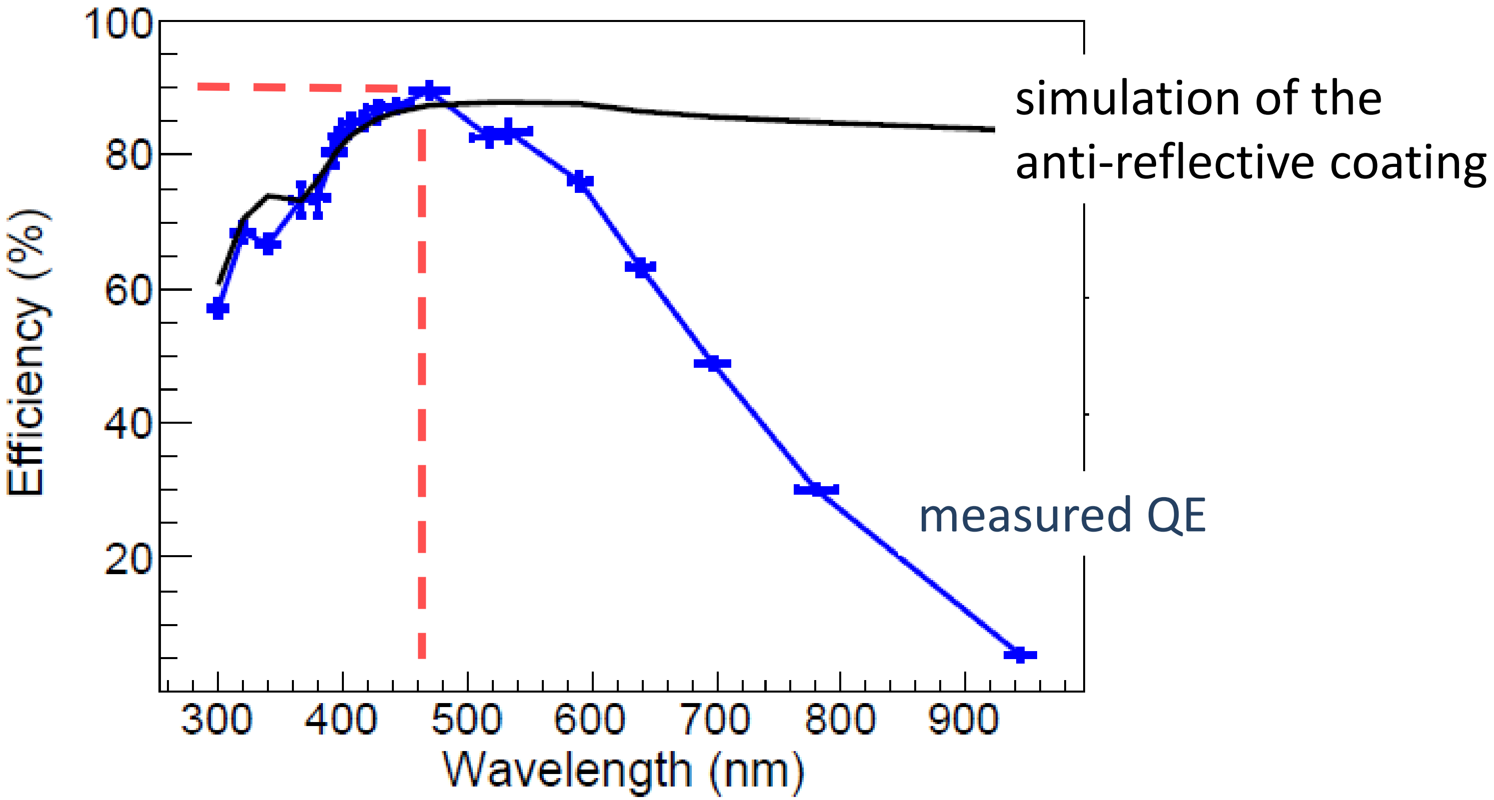


NUV-HD: QE

QE Measured on a photodiode produced with SiPMs

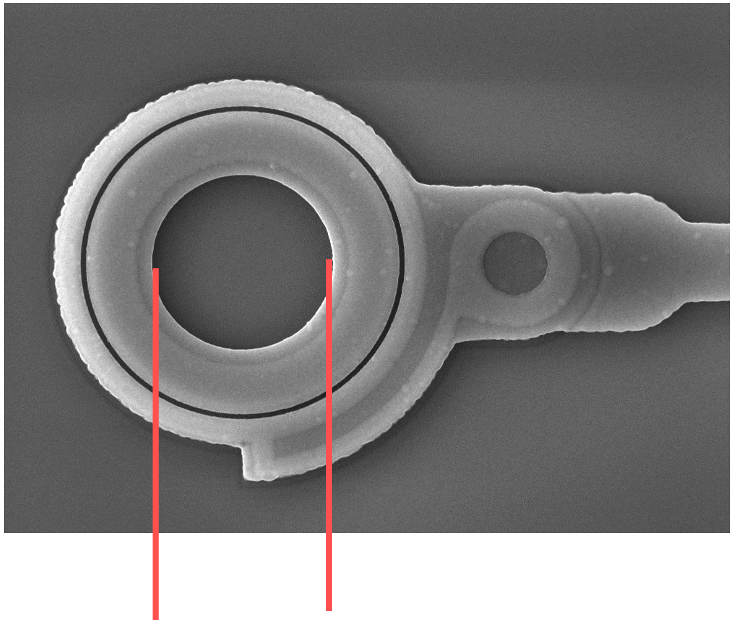
\+

Simulation of the anti-reflective coating

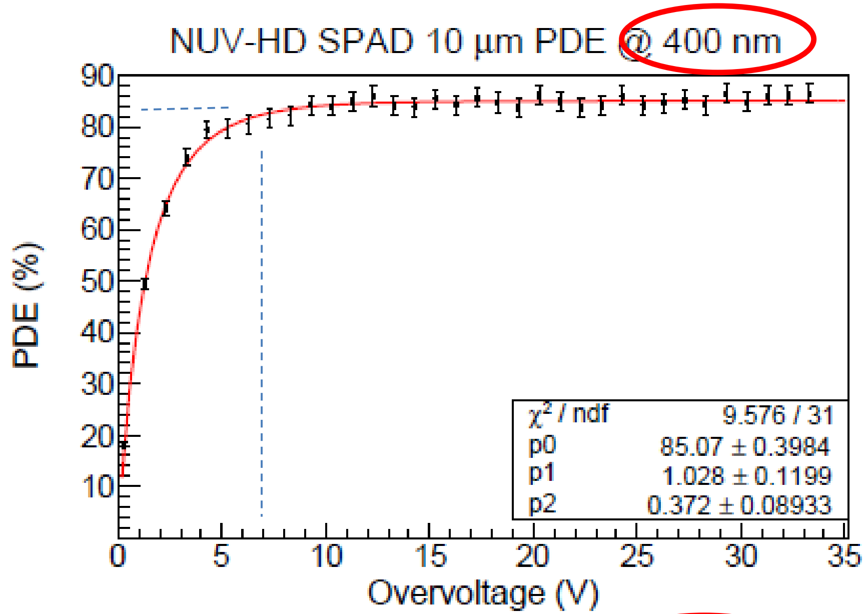


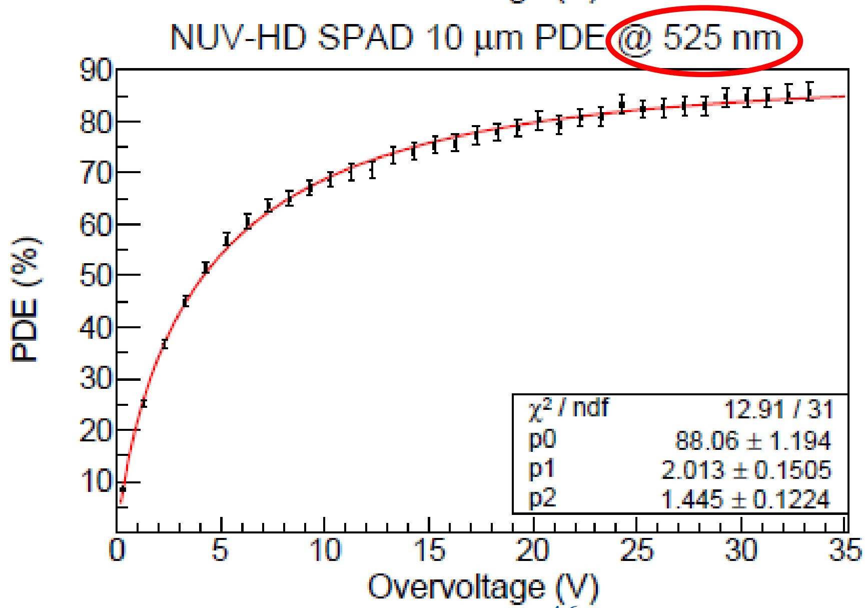
NUV-HD: QE*Pt

cSPAD (100% Fill Factor)



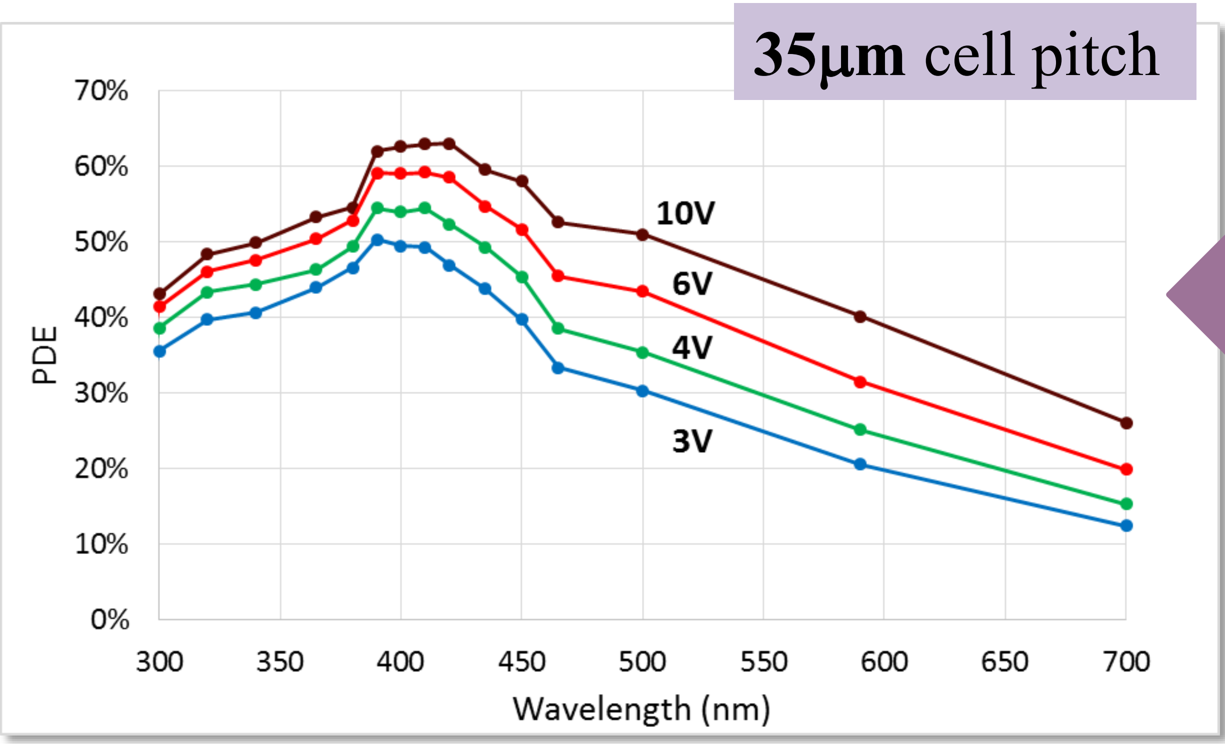
SPAD size is defined by metal opening which is within the high-field region





NUV-HD: PDE

SPAD Pitch	15 µm	20 µm	25 µm	30 µm	35 µm	40 µm
Fill Factor (%)	55	66	73	77	81	83
SPAD/mm²	4444	2500	1600	1111	816	625



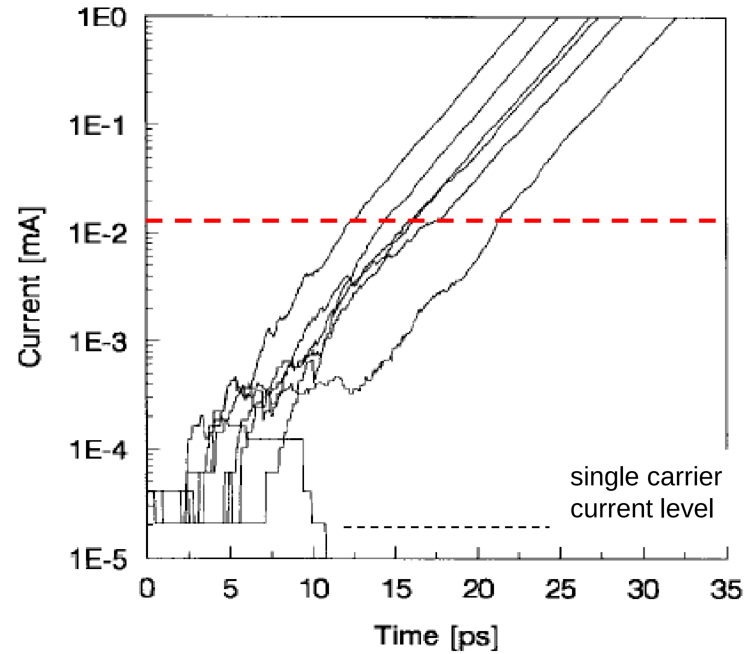
Intrinsic Time jitter

Statistical Fluctuations in the current growth:

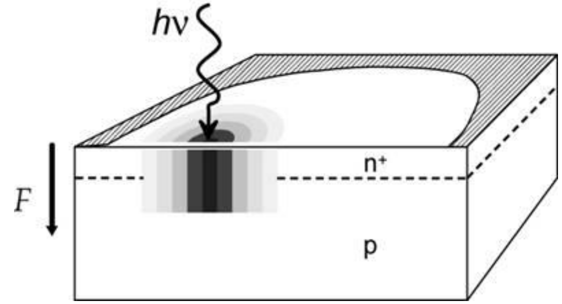
1. Photo-**conversion depth**

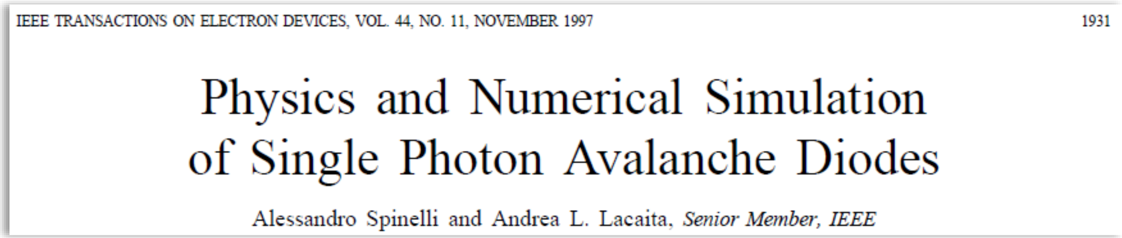
2. ***Vertical*** Build-up at the very beginning of the avalanche

   t=0 pair generation
   $0<t>t_1$ drift to the high-field region
   $t>t_1$ avalanche multiplication



3. ***Lateral*** Propagation

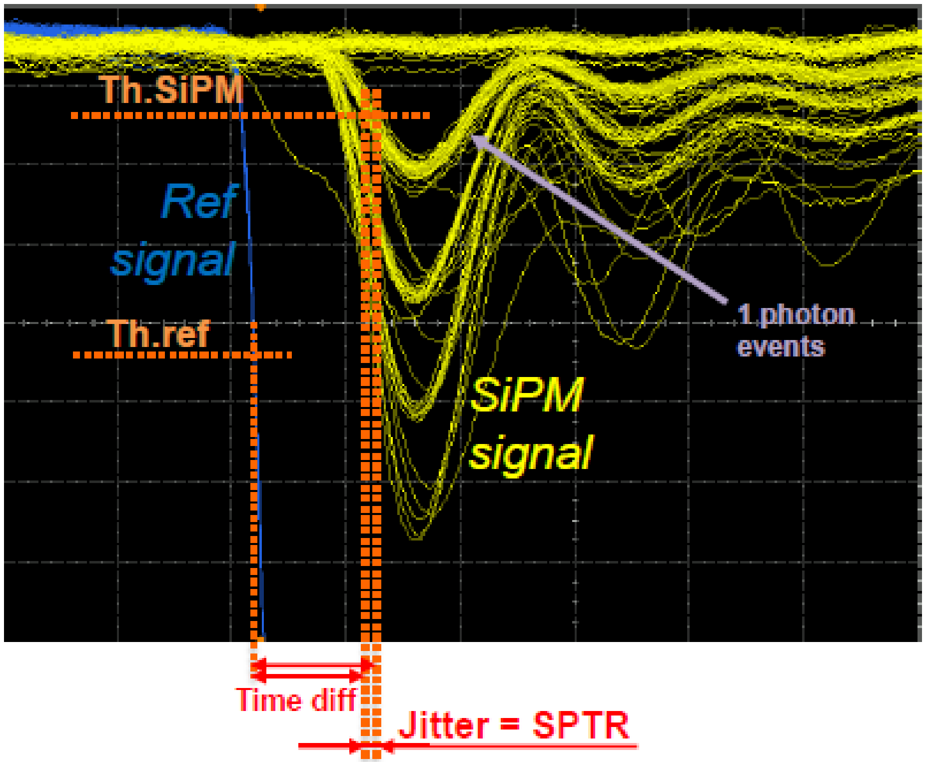


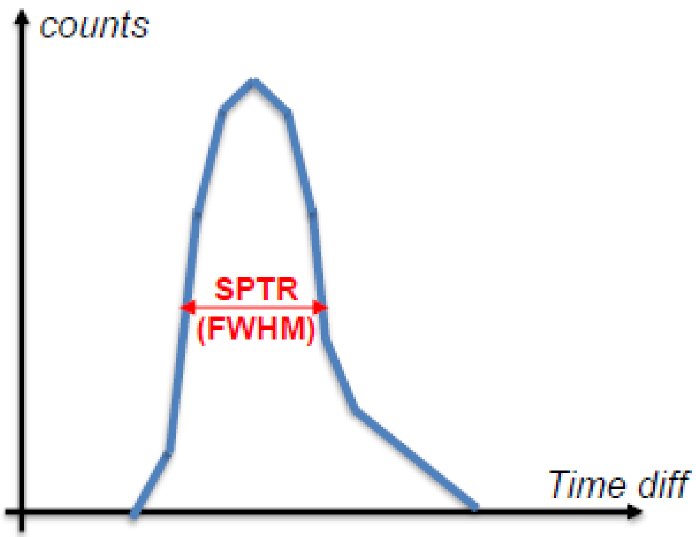

IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 44, NO. 11, NOVEMBER 1997 1931

Physics and Numerical Simulation of Single Photon Avalanche Diodes

Alessandro Spinelli and Andrea L. Lacaita, *Senior Member, IEEE*

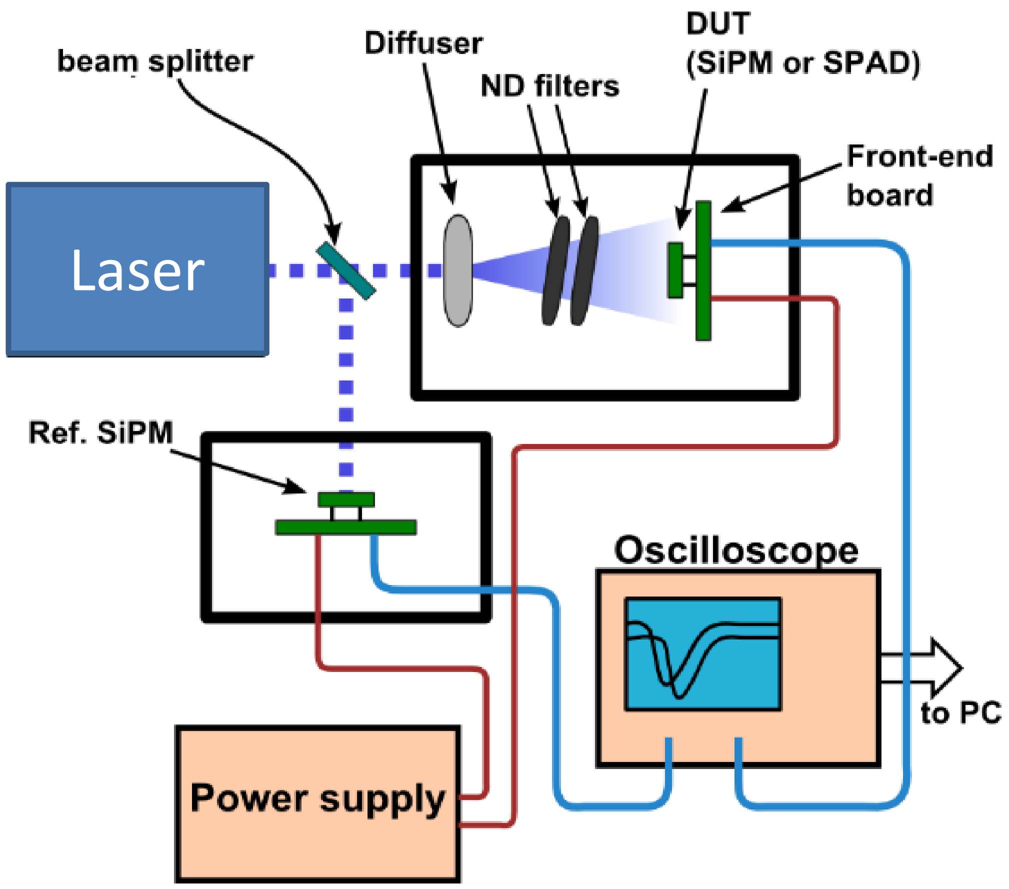
Single-photon time resolution (SPTR)



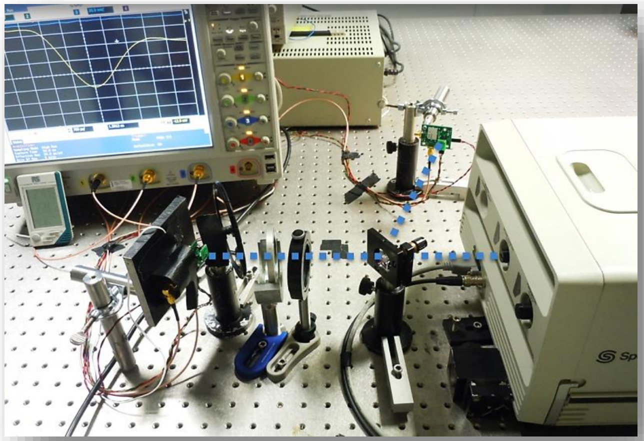


- **Single-photon time resolution: jitter in time between photon arrival on the SiPM and front end detection of the event**
- Typically measured FWHM

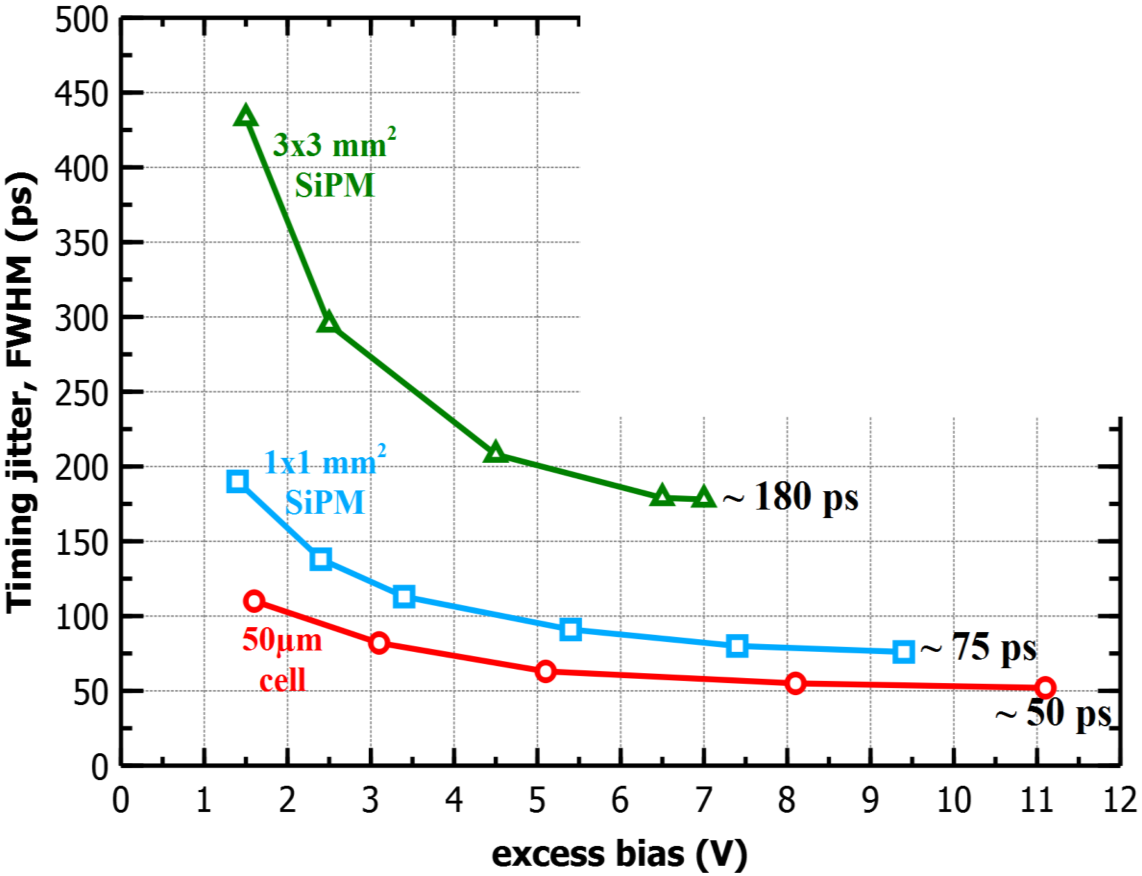
Measurement setup for SPTR



- **2-ps width pulsed laser (425nm)**
- **Set-up time resolution ~ 10ps FWHM**



Example of SPTR

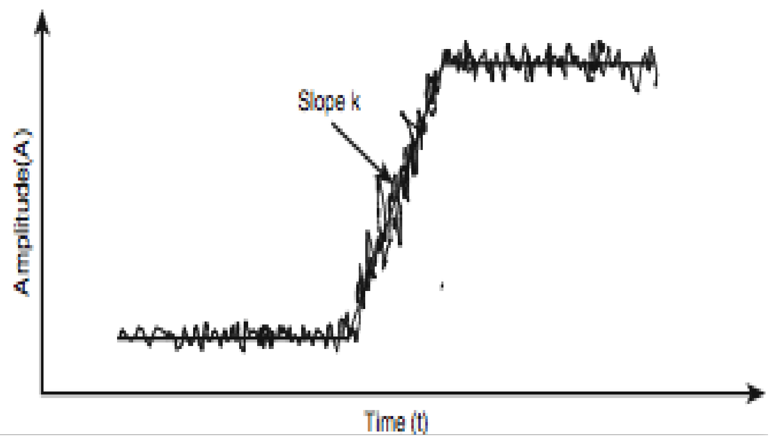


- SPAD (50x50um^2)
- 1x1mm^2 SiPM of 50x50um^2
- 3x3mm^2 SiPM of 50x50um^2

F. Acerbi, et al IEEE TNS vol. 61, n. 5, 2014 , pp. 2678 - 2686

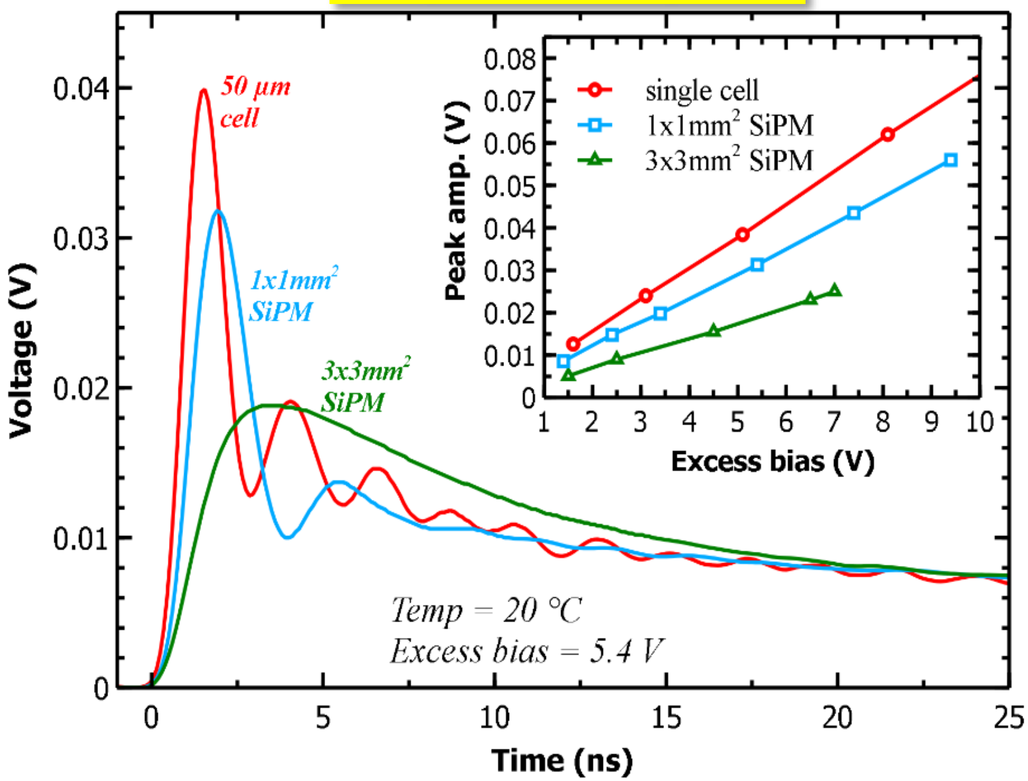
Noise contribution to SPTR

Is the electronic noise the origin of SPTR deterioration moving to large areas?

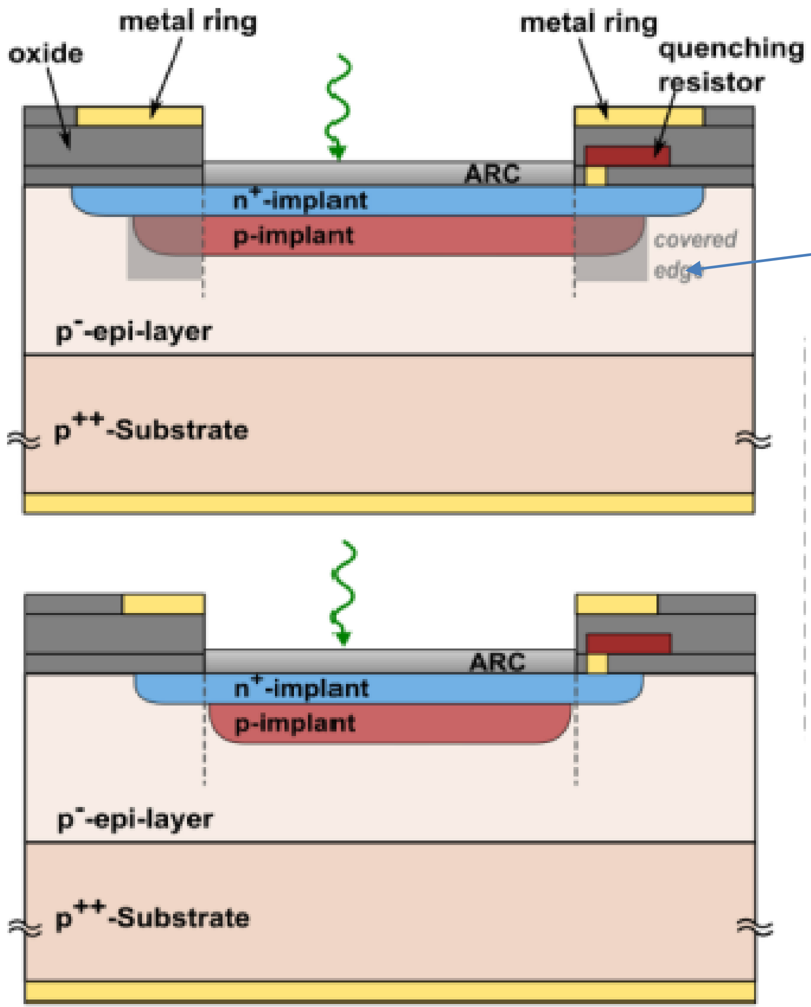


$$\sigma_t \propto \frac{\sigma_a}{f'_{th}}$$

Signal shape



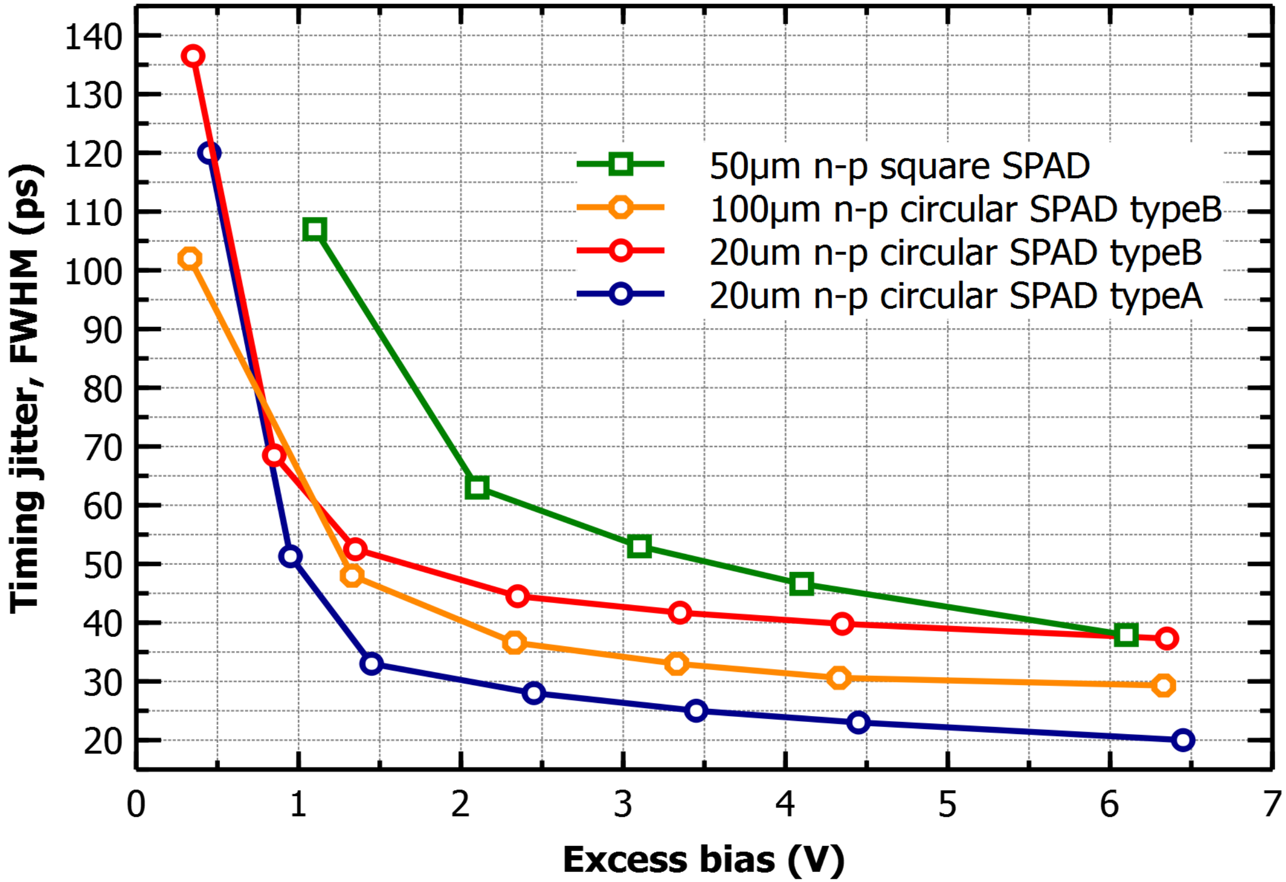
SPTR: ultimate limit?



We designed a small SPAD with masked edges.

IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS, VOL. 20, NO. 6, NOVEMBER/DECEMBER 2014

SPTR: analysis at a single SPAD level



uncovered edge
uncovered edge
uncovered edge
covered edge

20 ps FWHM!!!

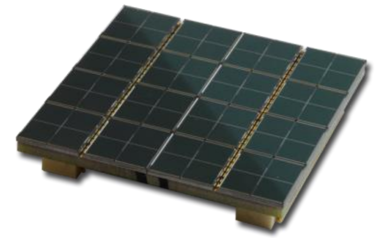
Metal ring all-around active area

- Better signal extraction
- more uniform signal shape

Main numbers in one table

Parameter	NUV-HD technology 1mm² 40µm SPAD
DCR (20C)	<100 kHz
Di-CT	<20%
De-CT	<5%
AP (20C)	<5%
PDE	60% (400nm)
SPTR	80 ps FWHM

PMT *vs* SiPM for NUV light



	PMT	SiPM
compactness	↓	↑
robustness	↓	↑
sensitivity to magnetic fields	↓	↑
low operating voltage	↓	↑
PDE	↑	↑
DCR	↑	↓
dynamic range	↑	↓
SPTR	↑	↑
cost	↑	~↑
market competition	↓	↑

Hot topics in SIPM/SPAD

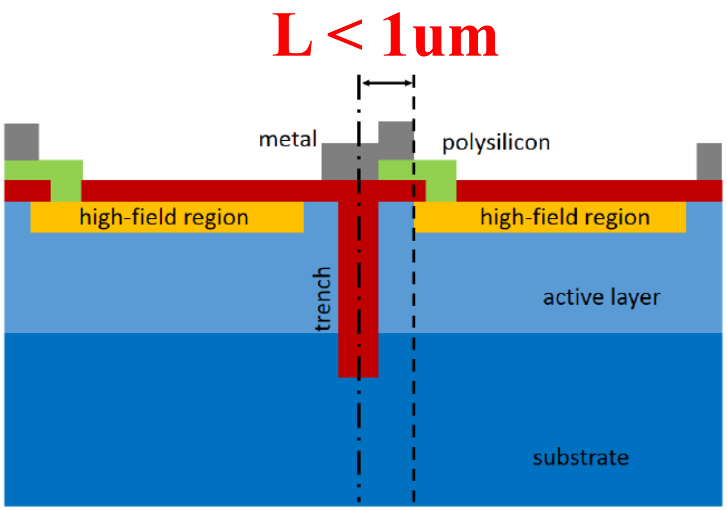
- High Dynamic Range
- NIR sensitivity

FBK is working on those aspects.
UHD technology is an example.

UHD Technology

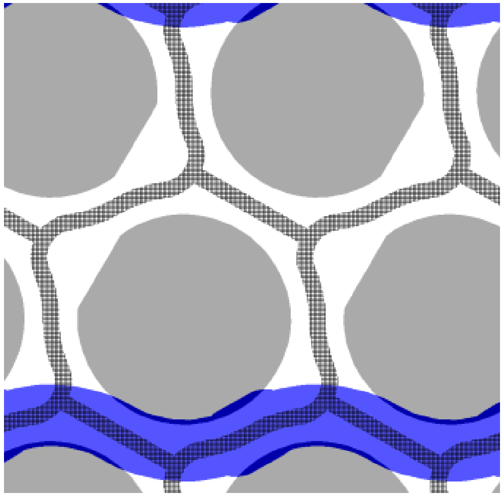
New design

Reduction of all the feature sizes

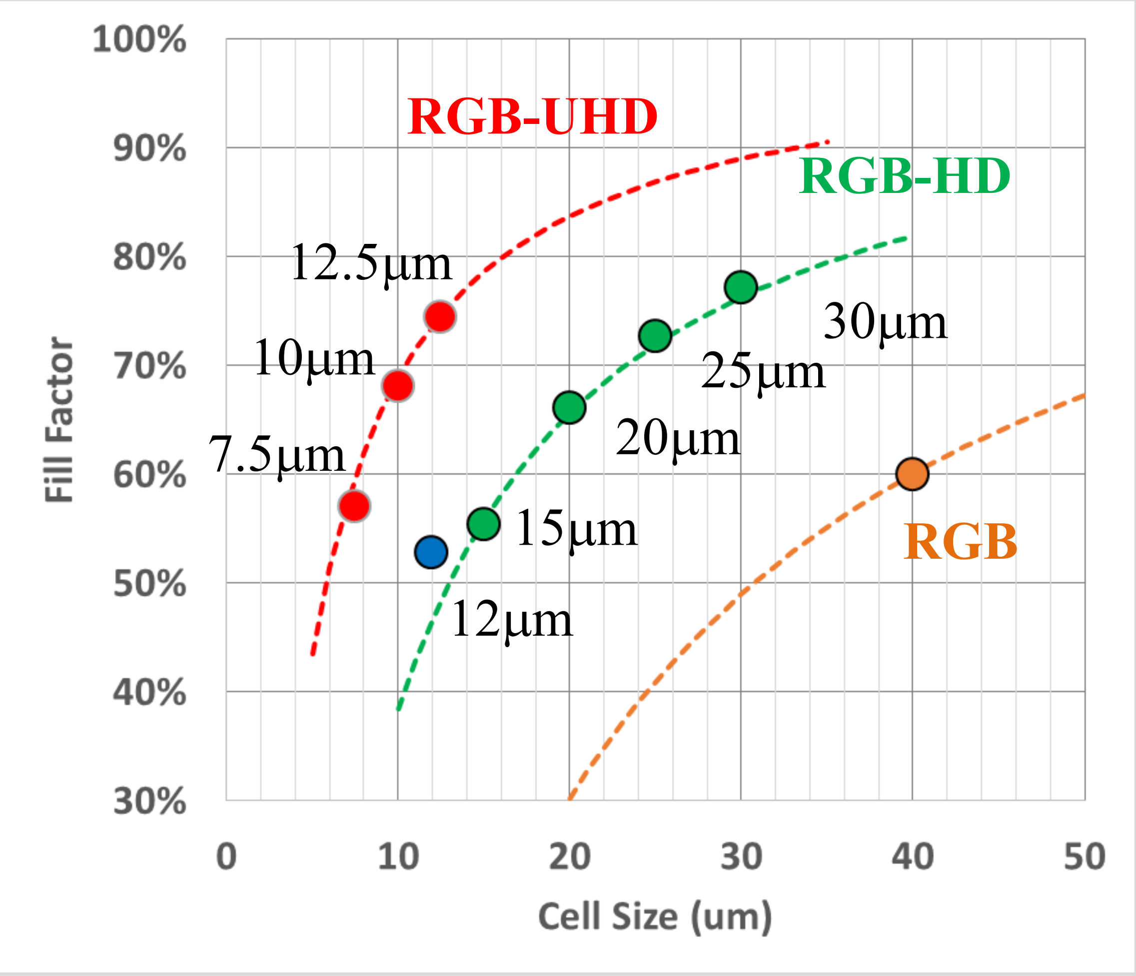


Circular active area (smallest cells)

- No corners (with lower field)
- Hexagonal cells arranged in honeycomb configuration



HD technology: small cells



RGB-HD

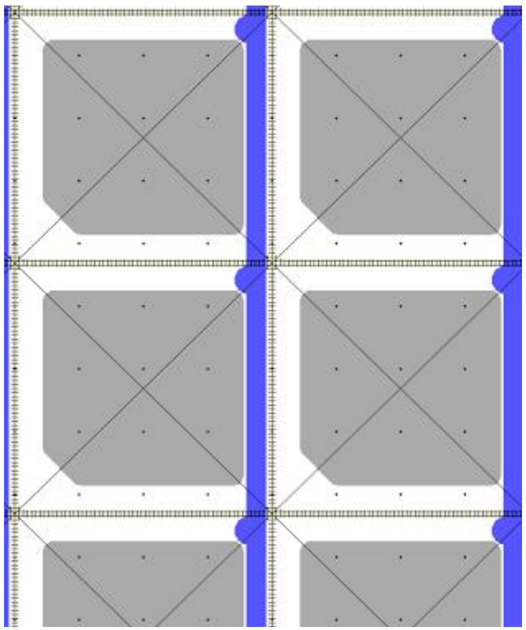
cell pitch (µm)	cells/mm^2
12	7000
15	4500
20	2500
25	1600
30	1100

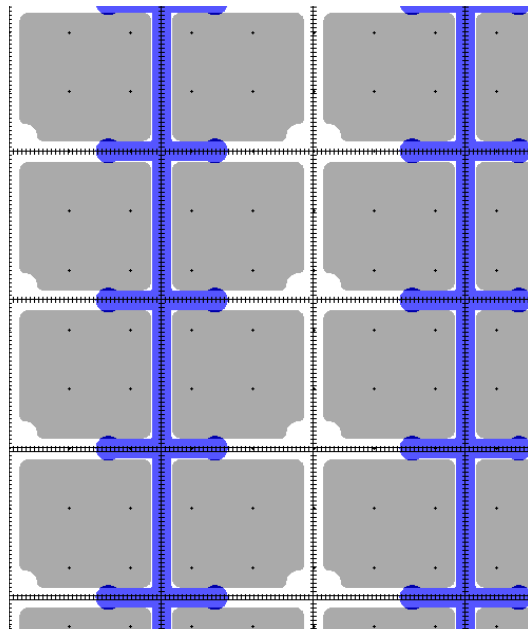
RGB-UHD

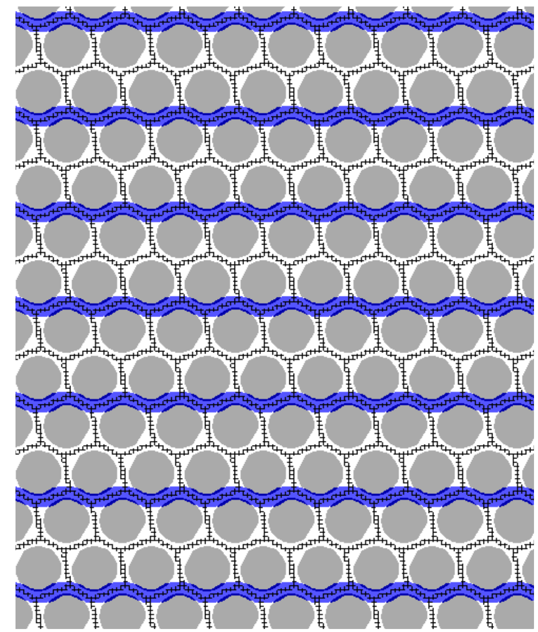
cell pitch (µm)	cells/mm^2
7.5	**20530**
10	**11550**
12	**7400**

Comparison to other technologies

40 um cell | **25 um cell** | **<7.5 um cell**







RGB SiPMs

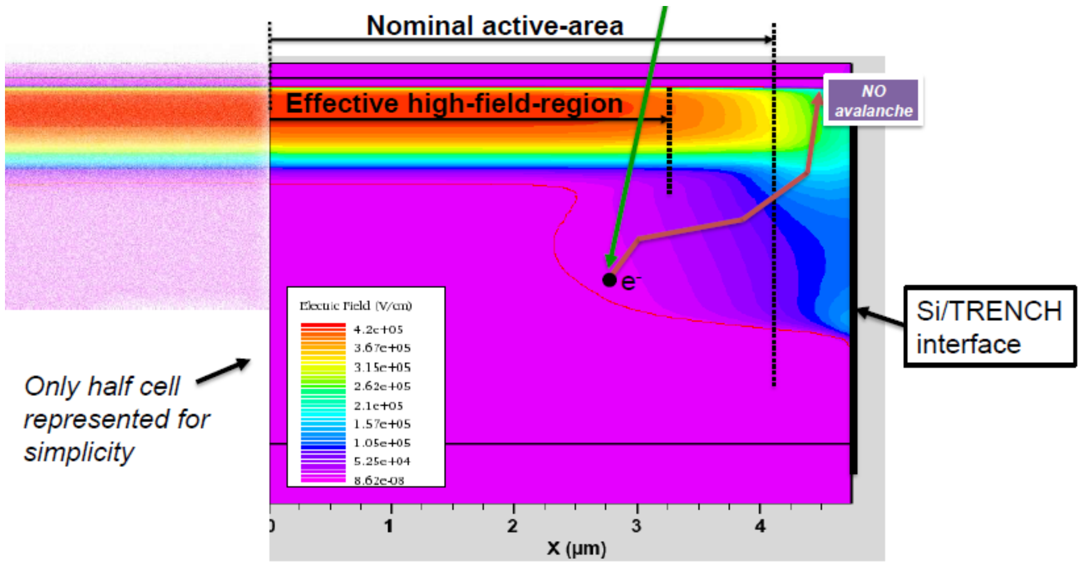
RGB-HD SiPMs

RGB-UHD SiPMs

![FBK logo]

…new design is not enough…

Border region plays an important role for small cells.

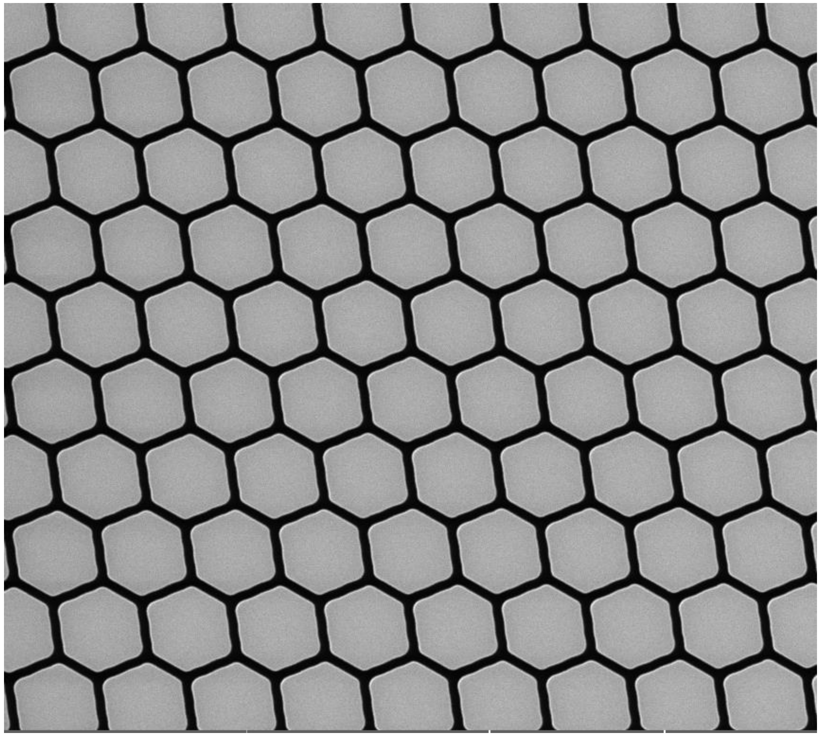


TCAD Simulation: Electric Field
10µm cell @ 2V excess bias

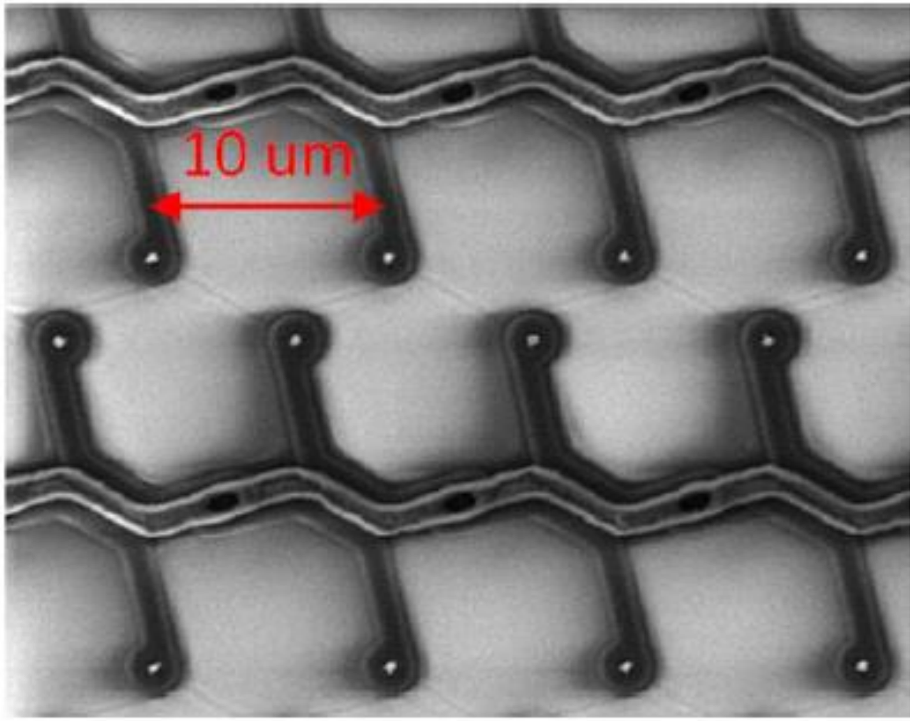
We have to develop a new guard ring (NGR) especially for the smallest SPAD (5um)

F.Acerbi et al., presented at IEEE NSS, Strasbourg 2016

SEM images



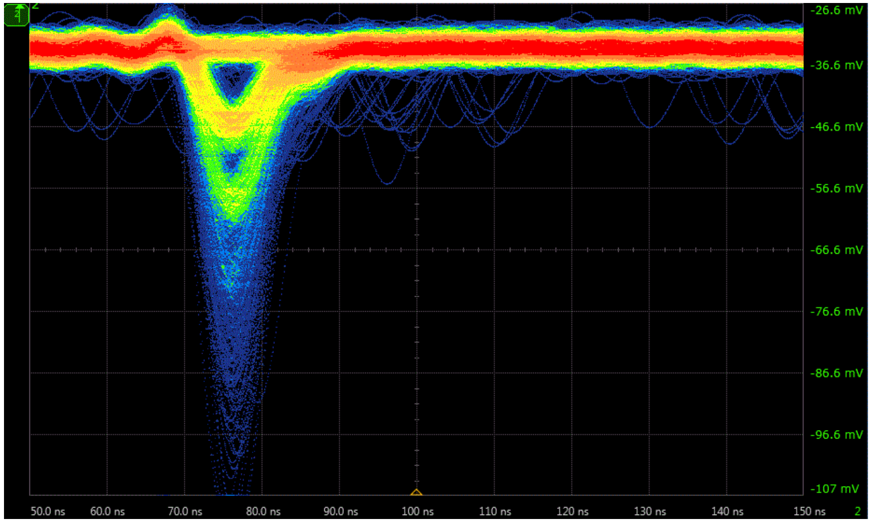
Microcells separated by trenches (picture taken during processing)



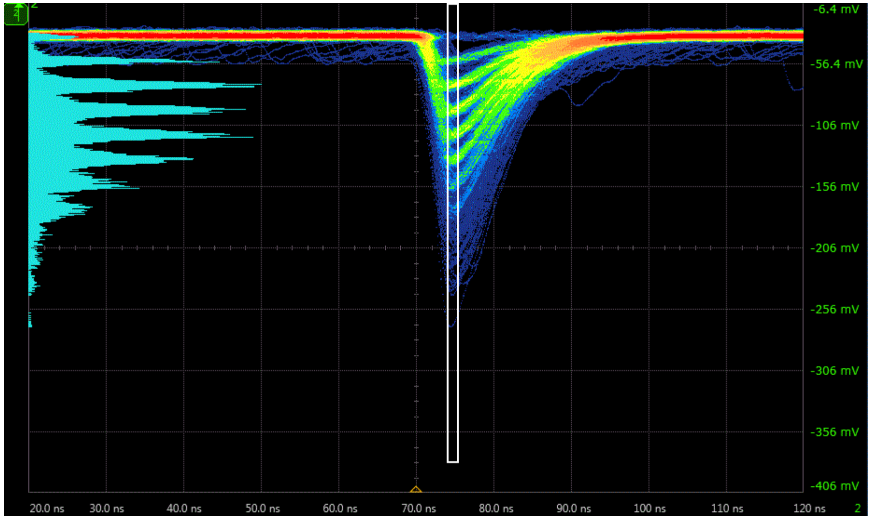
Finished SiPM (10 um)

Oscilloscope waveforms

7.5 um cell



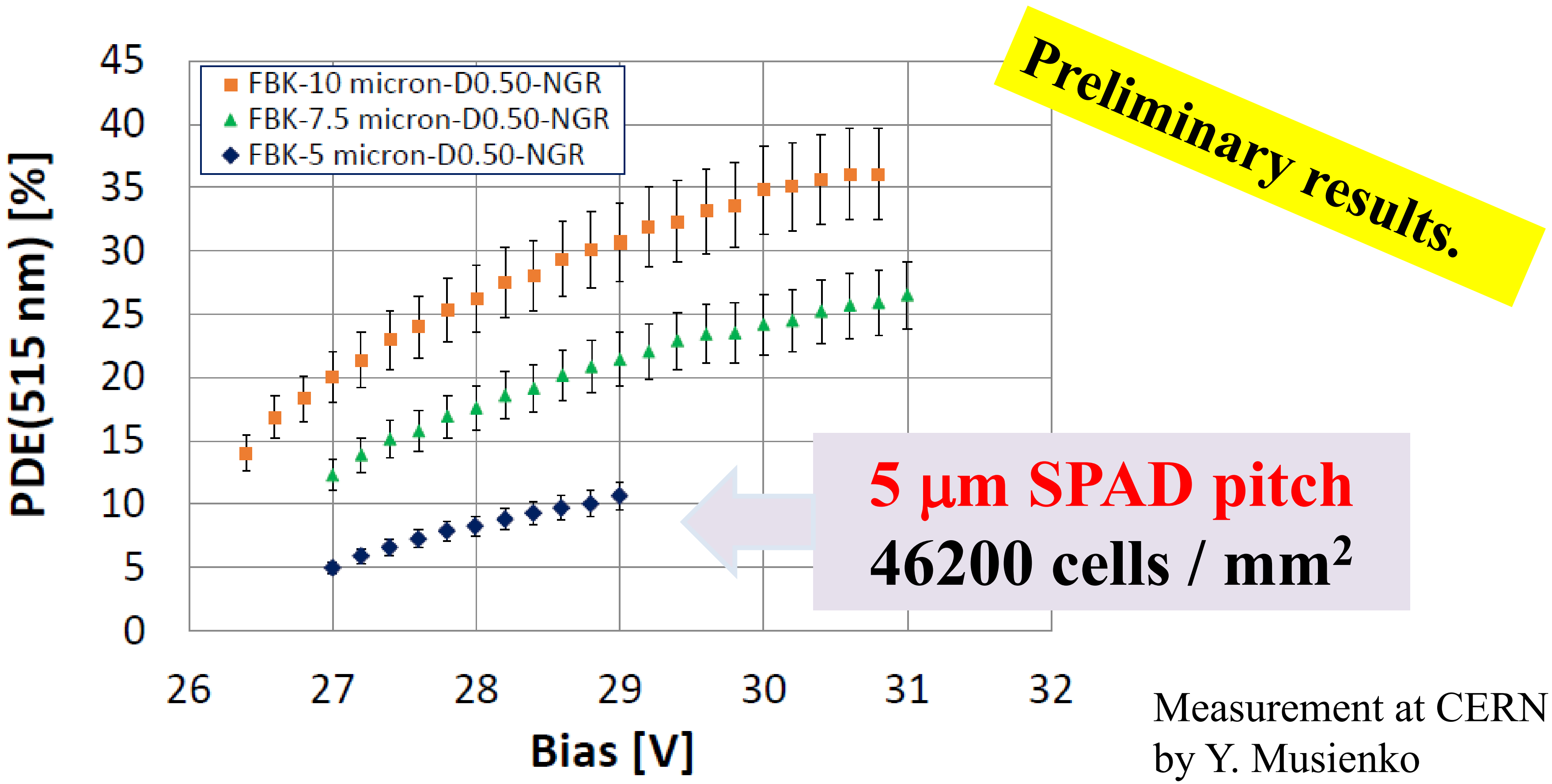
10 um cell



The 5um SPAD does not work with the standard guard ring while **it works with NGR!!**

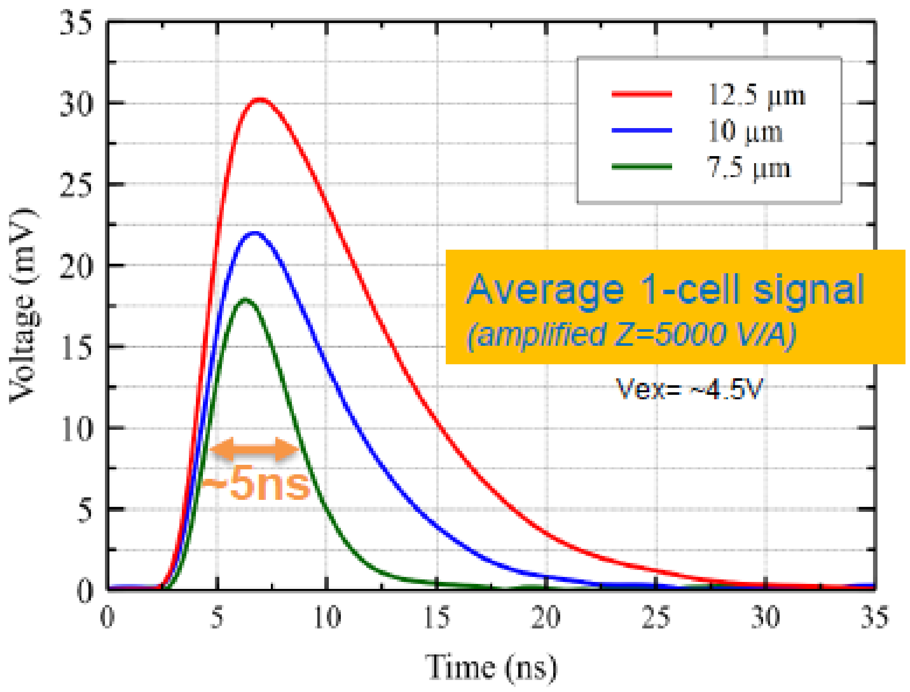
RGB-UHD: PDE

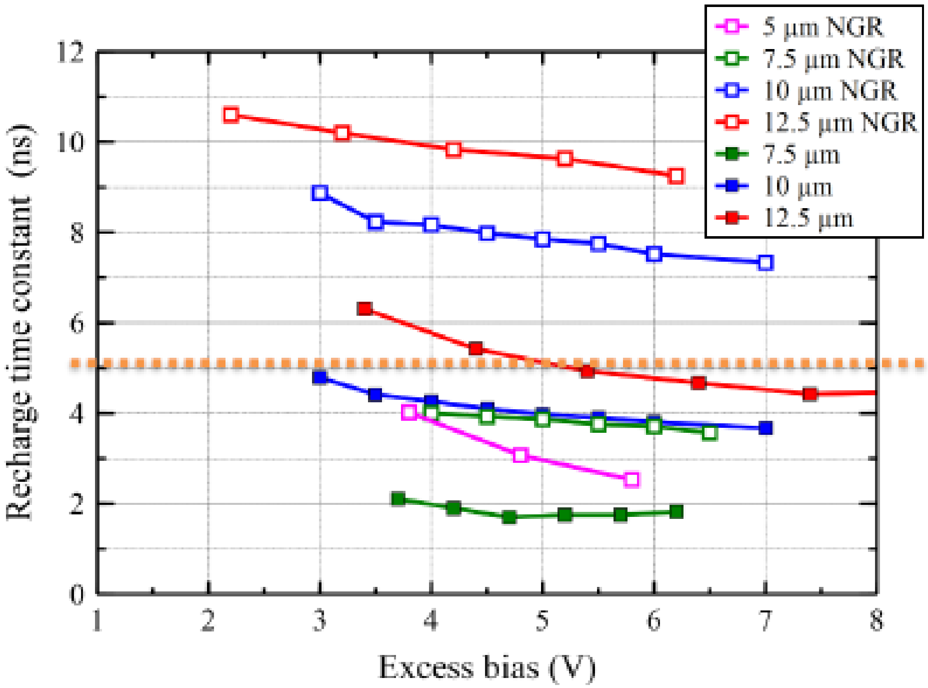
- Optimization of the technology
- Development of even smaller cell size



Measurement at CERN
by Y. Musienko

RGB-UHD: Signal





Thanks to all collaborators

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