FONDAZIONE BRUNO KESSLER

FUTURE BUILT ON KNOWLEDGE

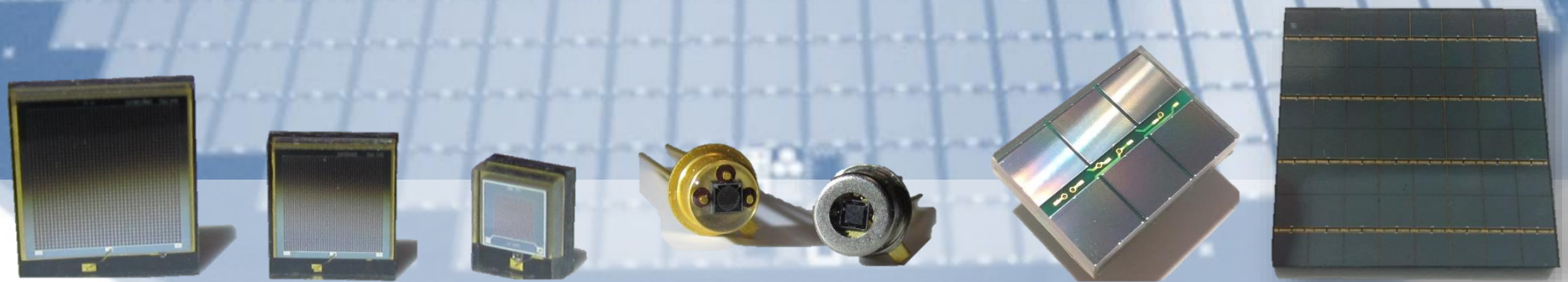
5th International Workshop on New Photon-Detectors
PD18
Nov. 27-29, 2018, The University of Tokyo, Tokyo, Japan

SiPM overview: status and trends

***Fabio Acerbi*, G. Paternoster, A. Gola**

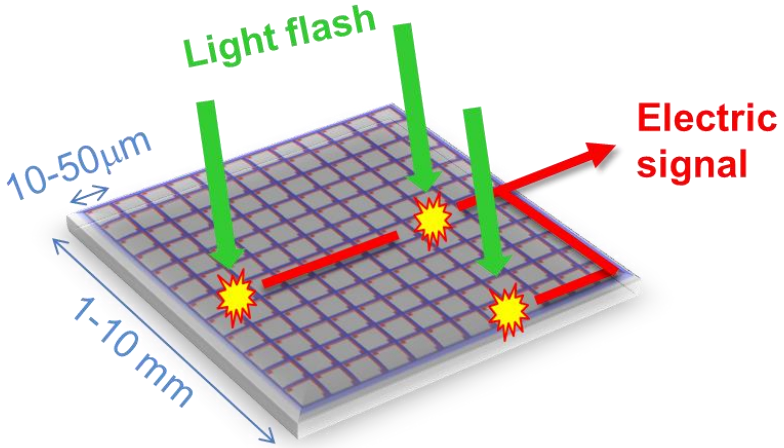
Fondazione Bruno Kessler (FBK), Trento, Italy.

acerbi@fbk.eu



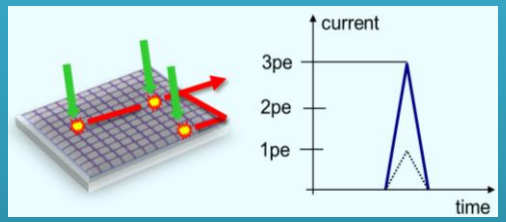
The silicon Photomultiplier (SiPM)

Silicon Photomultipliers:
array of compact independent SPADs, with integrated quenching circuit, outputting the sum of cell signal (analog sum or digital sum)



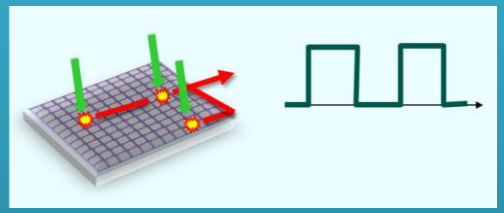
Analog SiPM

- SPADs are connected in parallel.
- Output analog signal is proportional to the number of photons.
- Custom technology (or CMOS).
- "Simple" technology, optimized SPAD performance.



Digital SiPM

- SPAD signal digitized at pixel level.
- Integrated digital architecture allows data processing on the sensor.
- CMOS technology.
- Optimized signal treatment, quenching/reset and processing.

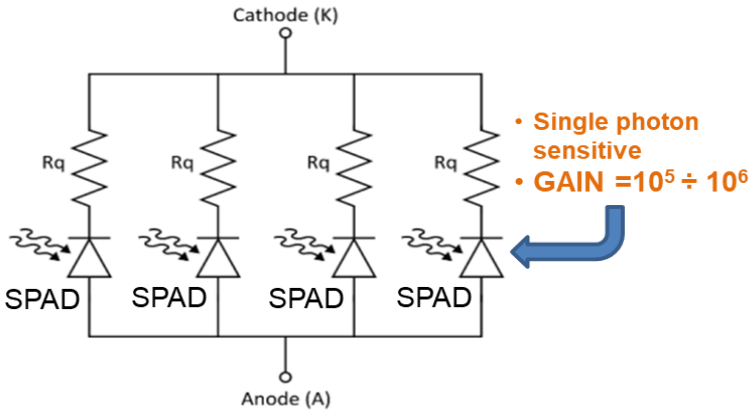


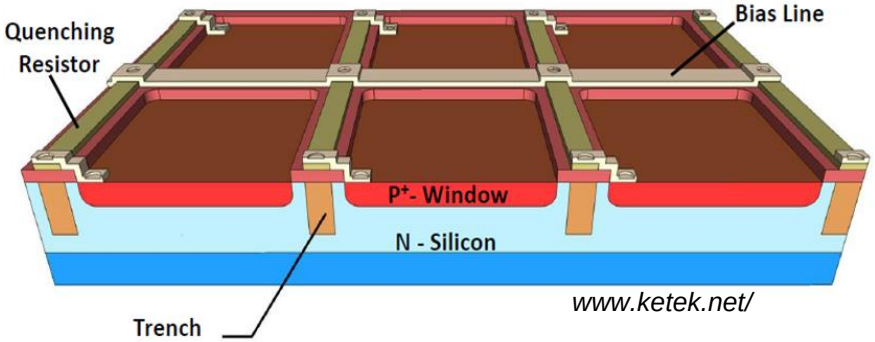
C. Piemonte – SENSE tech. forum 2018

Analog silicon Photomultiplier (aSiPM)

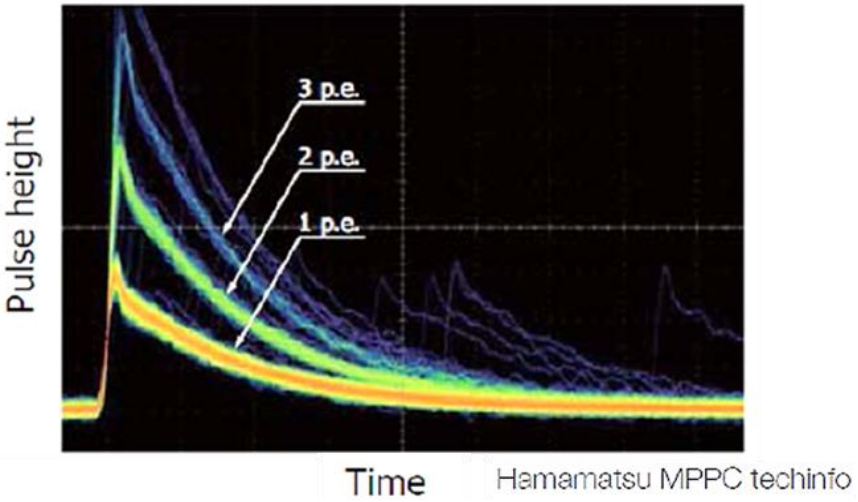
(Analog) Silicon Photomultipliers:

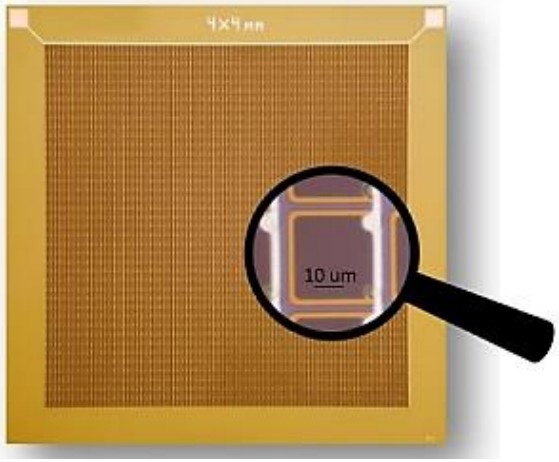
- integrated passive quenching
- SPADs connected in parallel
- Amplitude and gain proportional to the number of photons

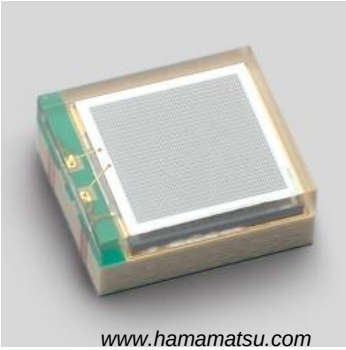




www.ketek.net/





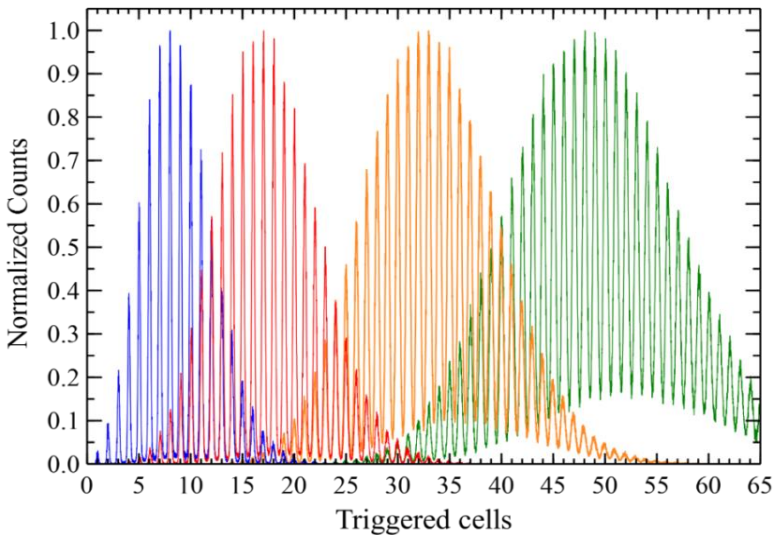


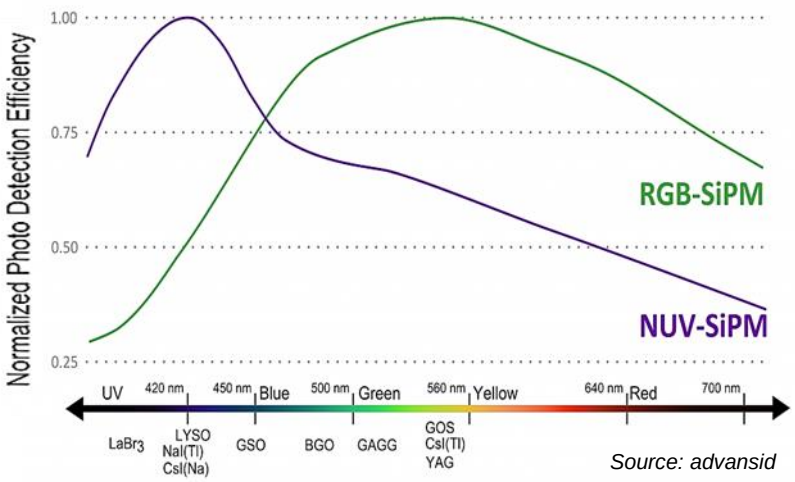
www.hamamatsu.com

When excited with faint light flashes, it gives fast, proportional signals with high internal gain. It is a solid-state PMT.

aSiPM: main characteristics

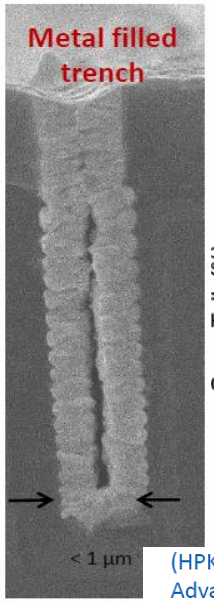
- ✓ Single photon sensitivity
- ✓ Good Photon number resolution (up to tens and even 100 photons distinguishable)
- ✓ High photon detection efficiency:
- ✓ High fill factor: ~50÷80% over the whole detector area
- ✓ Possibility high dynamic range: up to few or hundreds of thousands
- ✓ Good time resolution (SPTR, CRT)
- ✓ Compact and rugged
- ✓ Low bias voltage (25V÷80V)
- ✓ High gain (10^5 – 10^6)
- ✓ Insensitive to magnetic field
- ✓ Different optimization: PDE optimized for blue, green, VUV etc.



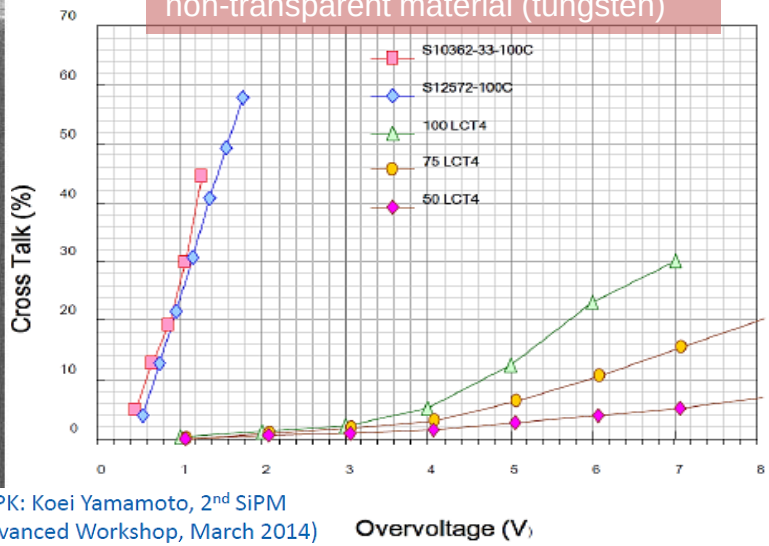


Source: advansid

aSiPM improvements over last years

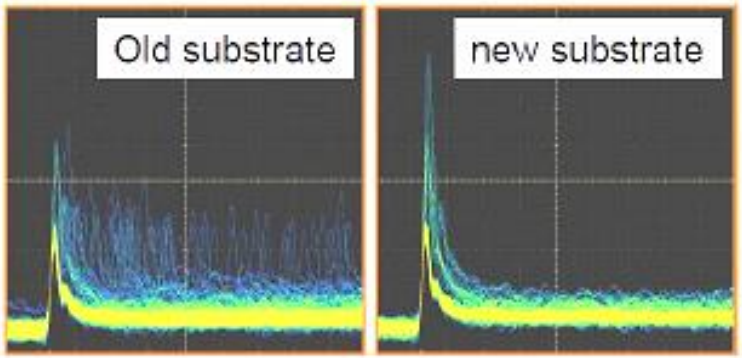


1) opt. CT reduction: trench filled with non-transparent material (tungsten)



(HPK: Koei Yamamoto, 2nd SiPM Advanced Workshop, March 2014)

2) Afterpulsing and delayed X-talk reduction



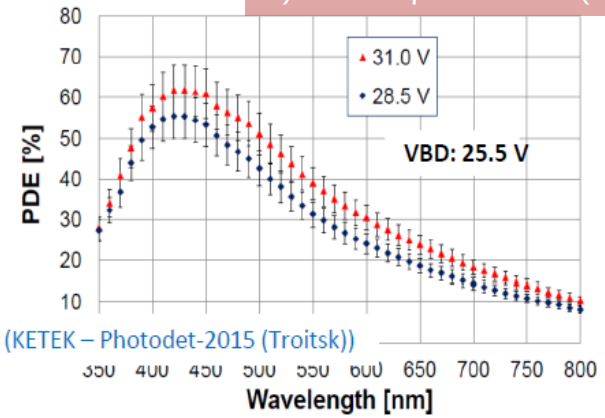
- Improved substrate

Minority carrier lifetime reduced ~ 2 order of magnitude

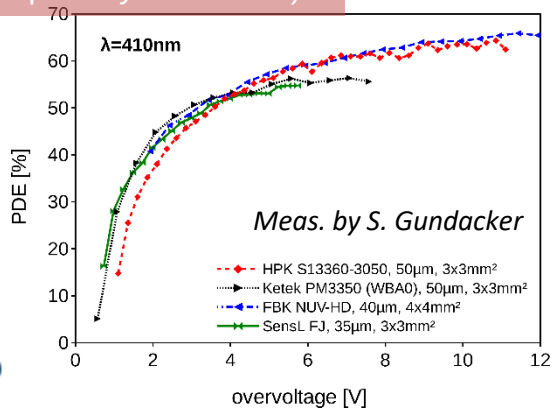
→ lower delayed correlated noise

source: Yu. Musienko, SENSE TechForum, Geneva, 21.06.2018

3) PDE improvement (especially in the blue)



(KETEK – Photodet-2015 (Troitsk))



Lower correlated noise → allow **operating SiPM at higher excess bias** → reach higher PDE
Combined with **structure improvement** → Higher FF → higher PDE

SiPM producers

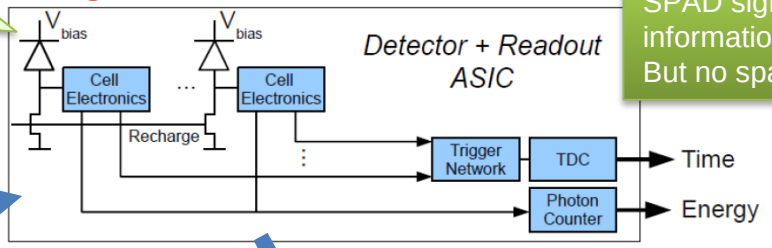
Source: W. Ootani, Special workshop on photon detection with MPGDs, (Modified)

CMOS SPADs and digital SiPMs

Digital SiPM

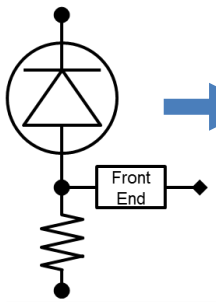
- First commercial dSiPM from Philips
- Individual pixels can be turned on/off

Digital SiPM

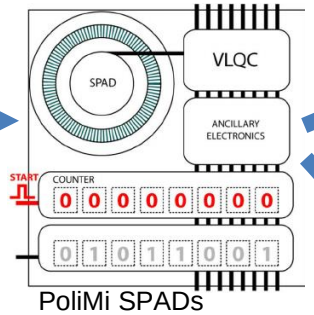


SPAD signal summed-up: information on number of photons, But no spatial information

SPAD



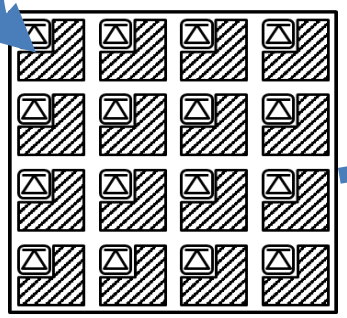
Pixel



SPAD + quenching circuit
→ basic block !

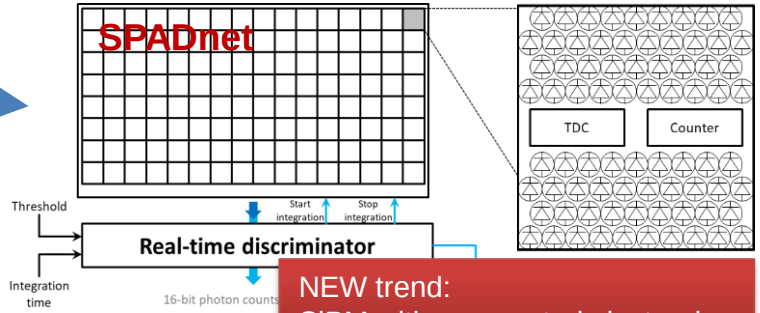
2) Addition of counting and ancillary electronic → smart pixel

SPAD imager



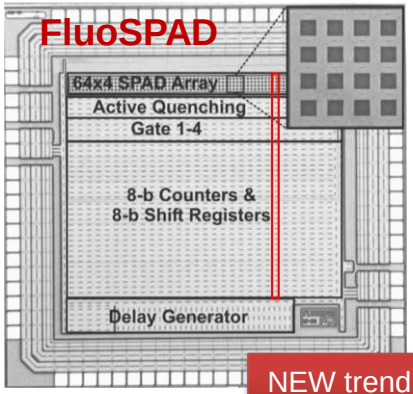
Counting & time-stamp of each SPAD
→ single-photon based image

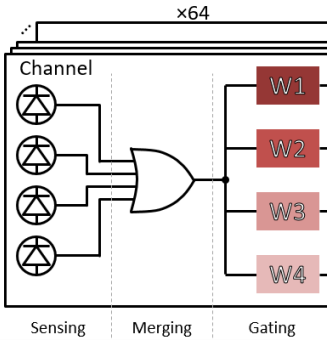
SPADnet



NEW trend:
SiPM with segmented electronics

FluoSPAD



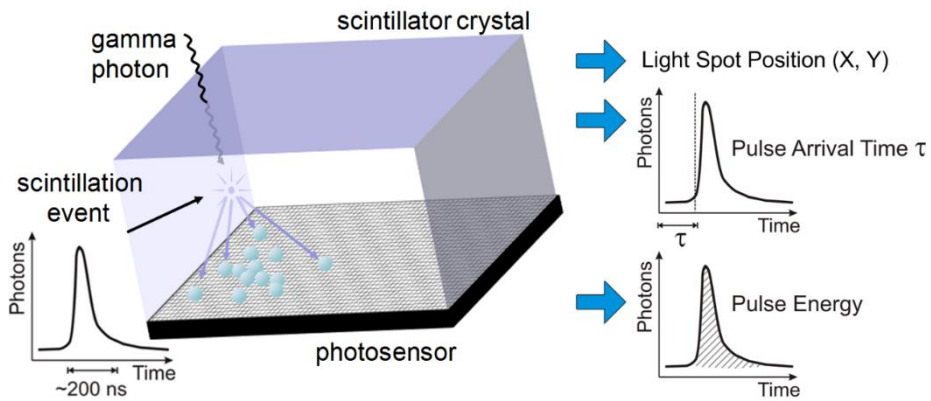


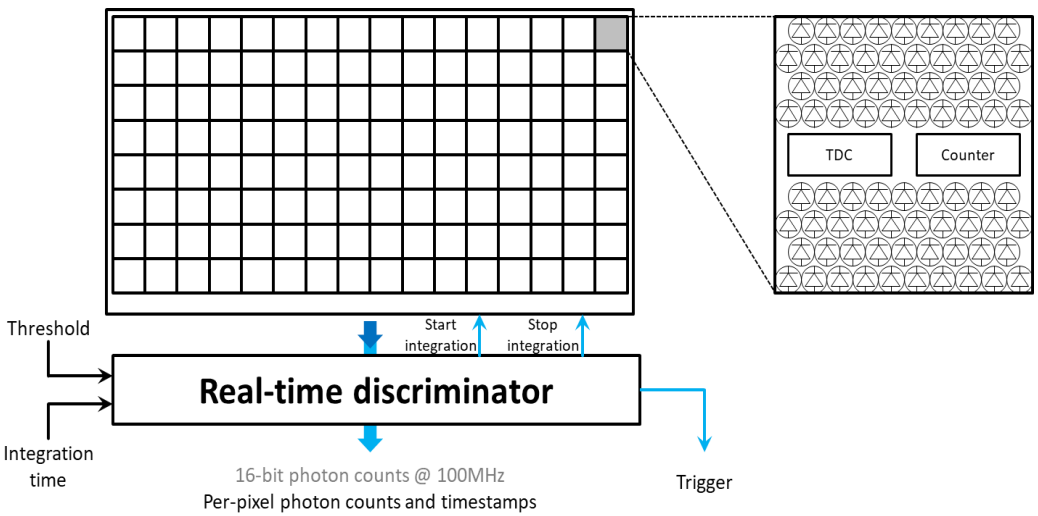
NEW trend:
imager with mini-SiPMs as pixels

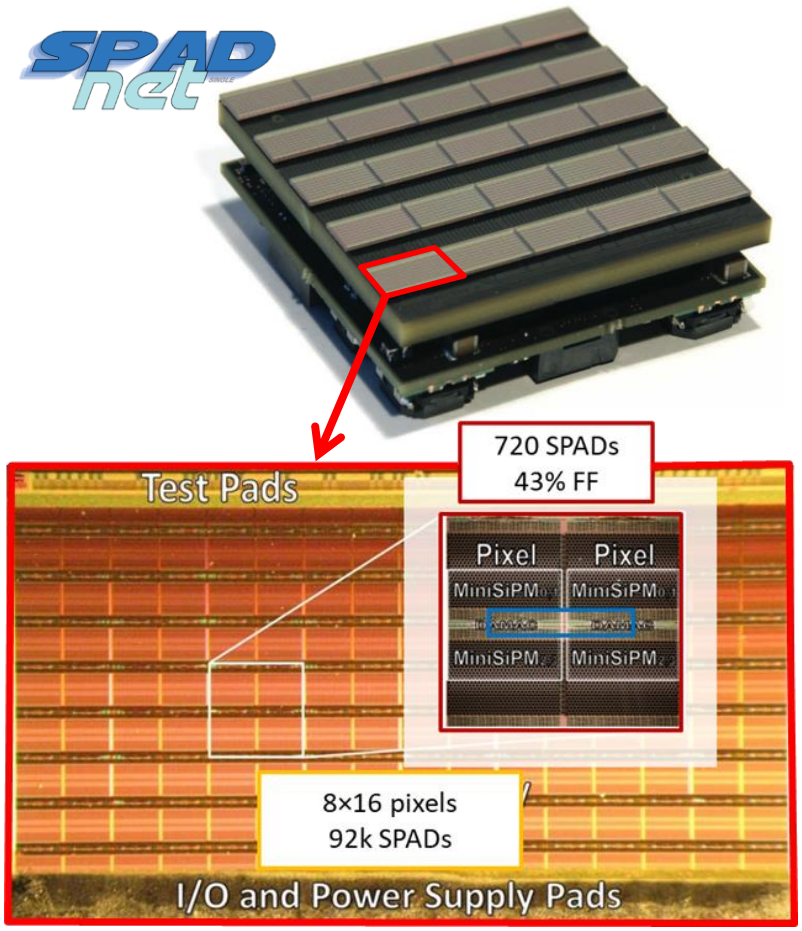
Example: SPADnet Photonic Module

Digital SiPM (D-SiPM) System-on-Chip (SoC)

Source: slides from L.Gasparini, presented at CERN 2018







2 acquisition phases → 2 operating modes

- *Before γ :* Single-channel D-SiPM with real-time discriminator
- *After γ:* 2D array of D-SiPMs with photon counters and TDCs

Example: Digital SiPM with 3D integration

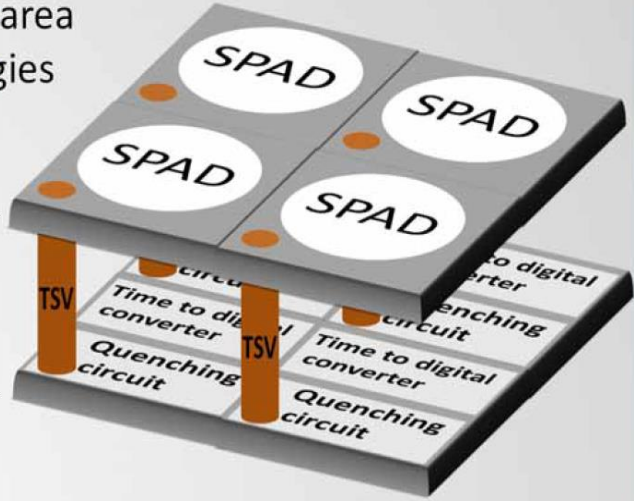
Uni. Sherbrook
3D stacked, with front-side illuminated SPADs

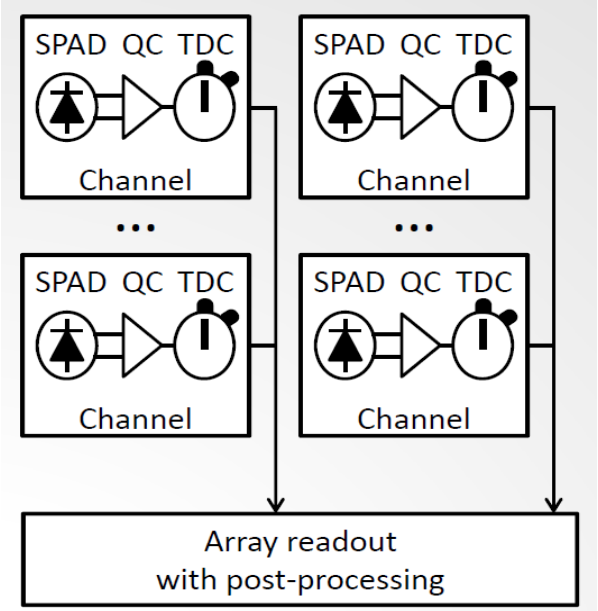
3D Integration

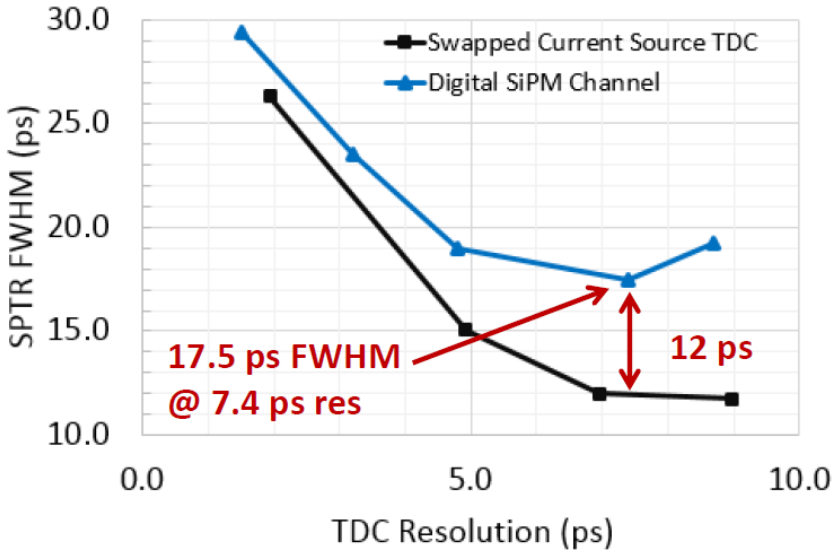
- Maximize photosensitive area
- Heterogeneous technologies integration

Custom process

TSMC CMOS 65 nm



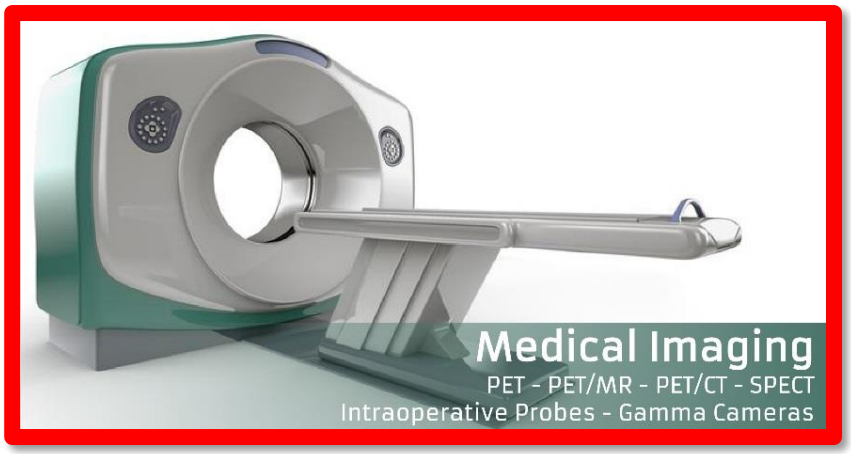




Optimized custom technology for SPADs
+
CMOS advanced tech. for quenching and processing.

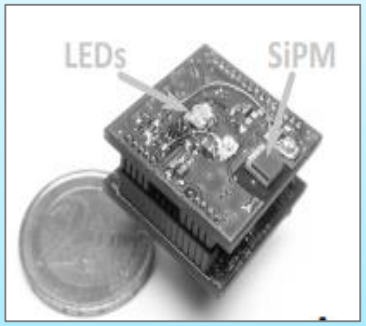
- **Focused on best TDC and timing performances**
  - Obtained <20ps FWHM single-photon time resolution on one channel.

SiPM typical applications

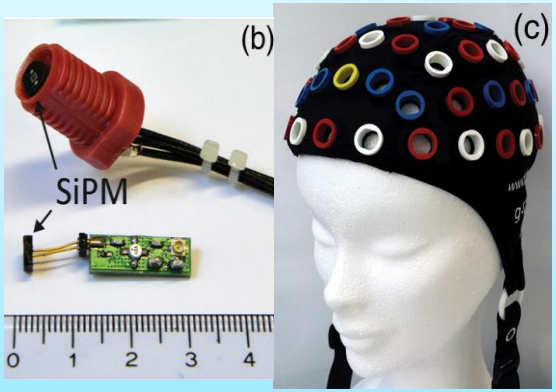


New applications

fNIRS (functional NIR Spectroscopy)

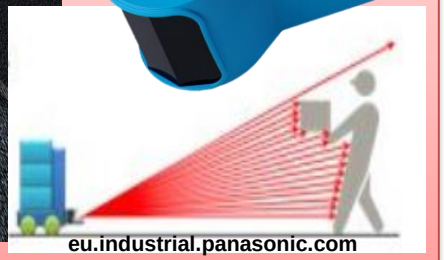


R. Zimmermann, et. Al. "Silicon photomultipliers for improved …"

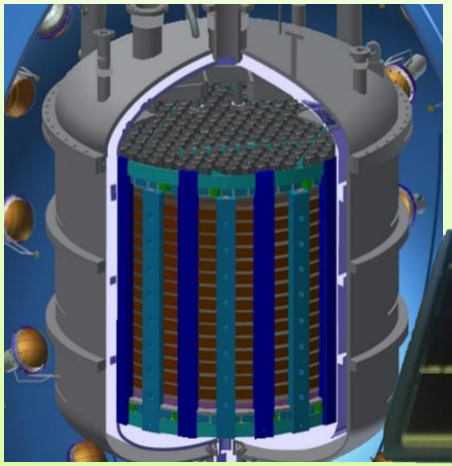


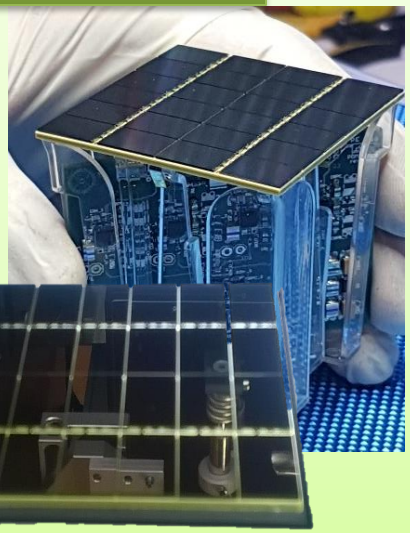
Re et al. Neurophoton. 3(4), 045004 (2016)

LIDAR (light detection and ranging): automotive & industrial

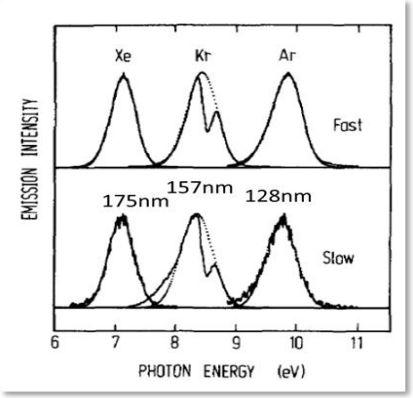


Experiments with liquid Noble-gas scintillators (Cryogenic Temperatures)





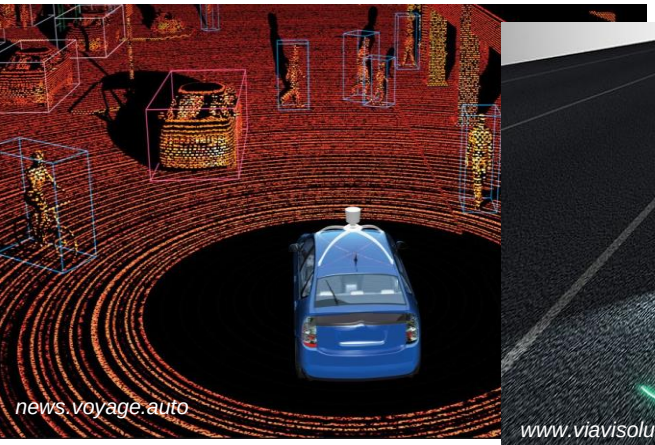
- VUV
- NUV
- NIR

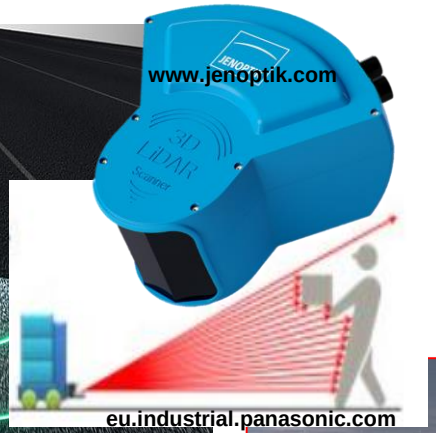


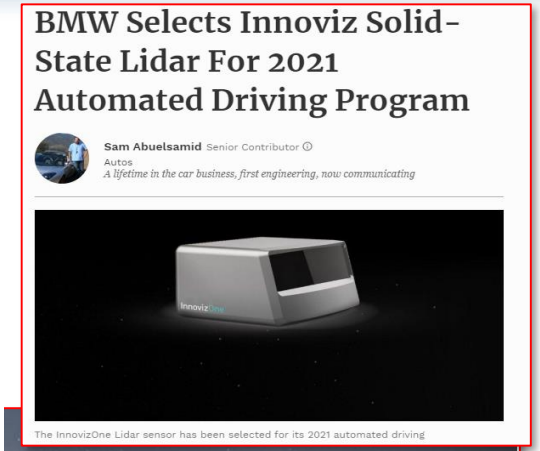
New trend:
NIR-sensitive SiPMs

(for LIDAR and others)

SiPM for LIDAR

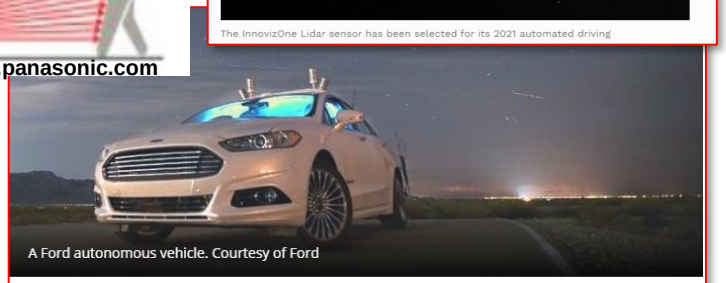





BMW Selects Innoviz Solid-State Lidar For 2021 Automated Driving Program

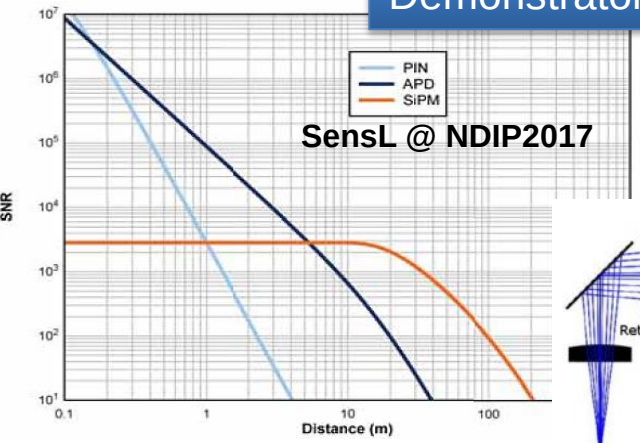
Sam Abuelsamid Senior Contributor
Autos
A lifetime in the car business, first engineering, now communicating

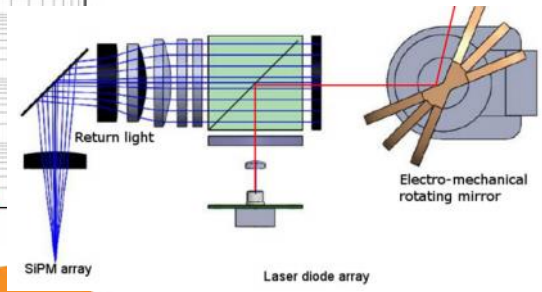
The InnovizOne Lidar sensor has been selected for its 2021 automated driving


A Ford autonomous vehicle. Courtesy of Ford

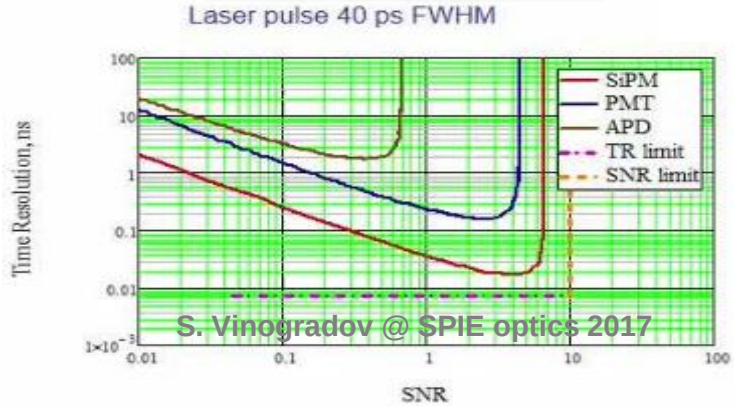
Ford buys Geiger-mode lidar firm Princeton Lightwave

Demonstrators available

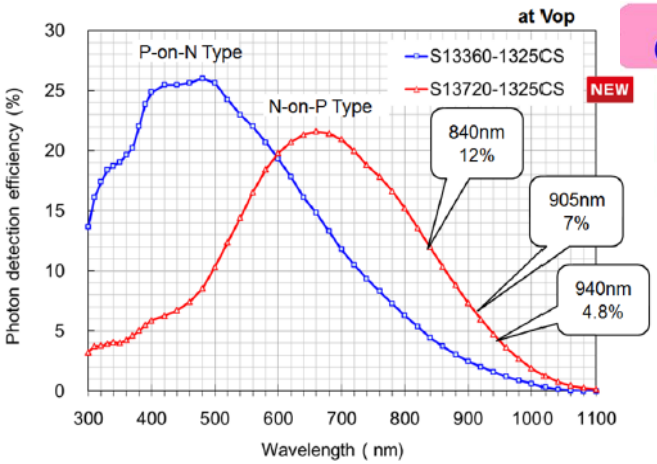




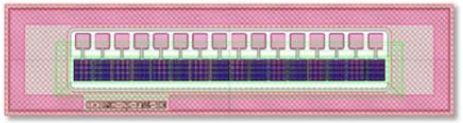
Theoretical studies



SiPM specifically developed (NIR sensitive)



S13720 series
(NIR measurement)

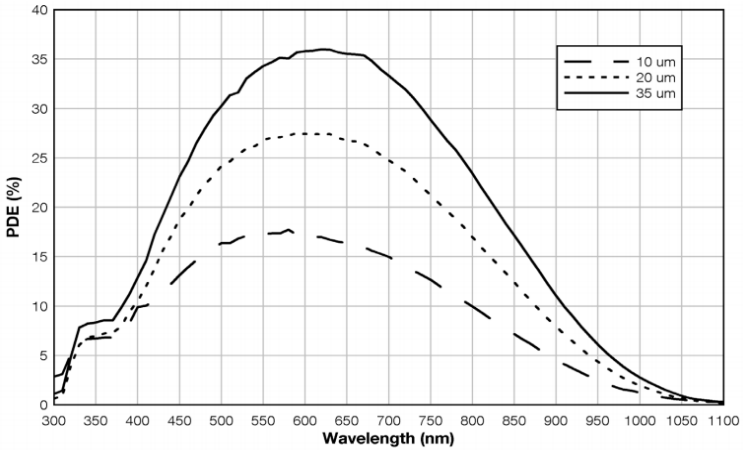


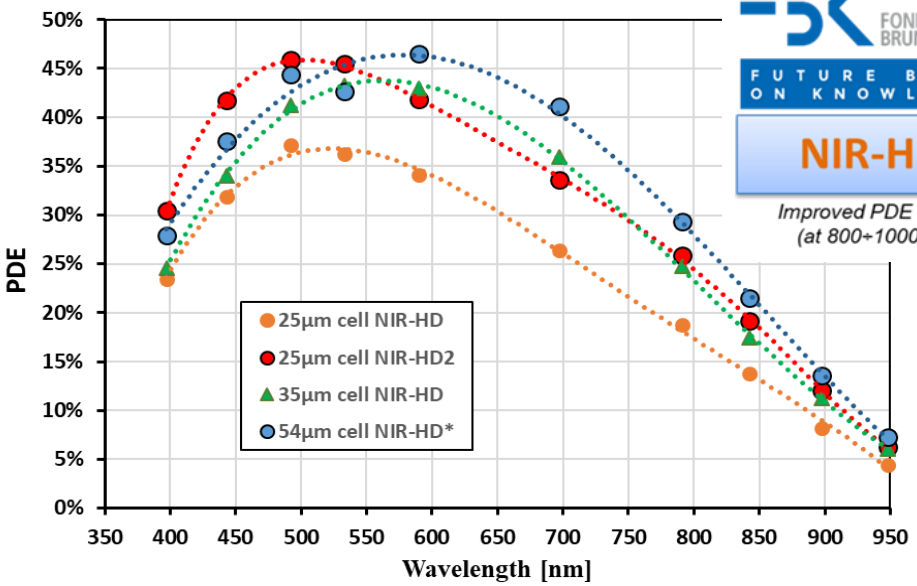
NIR Linear MPPC
16 channel
200umx175um
25um pixel

ON Semiconductor®
www.onsemi.com

RB-Series SiPM Sensors

Advance Information
Silicon Photomultipliers (SiPM), Red-Enhanced Second Generation





FONDAZIONE BRUNO KESSLER
FUTURE BUILT ON KNOWLEDGE

NIR-HD

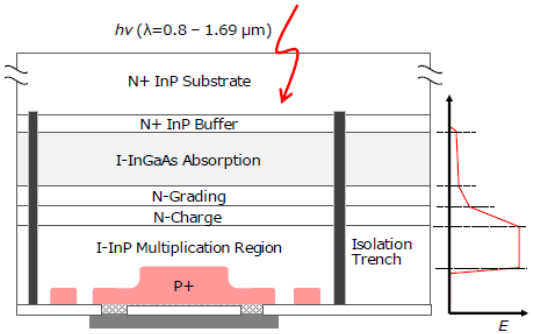
Improved PDE in NIR (at 800÷1000nm)

- **Active R&D for SiPM NIR-sensitive.**
- **Different producer introduced new product.**
- **Linear array already present.**
- **PDE @850nm and 900nm increased.**

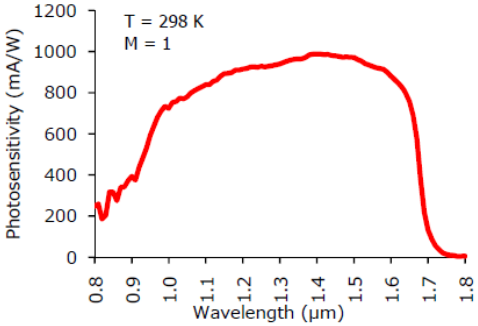
Interesting: InGaAs MPPC (800nm-1.6µm)

Development of InGaAs MPPC for NIR Photon Counting Applications

Yusei Tamura*, Yoshihito Suzuki, Takuya Fujita, Tomokazu Kurabayashi, Takashi Baba, Kenji Makino, Shigeyuki Nakamura, Koei Yamamoto
Hamamatsu Photonics K.K., 1126-1, Ichino-cho, Higashi-ku, Hamamatsu City, Shizuoka Pref., Japan, 435-8558

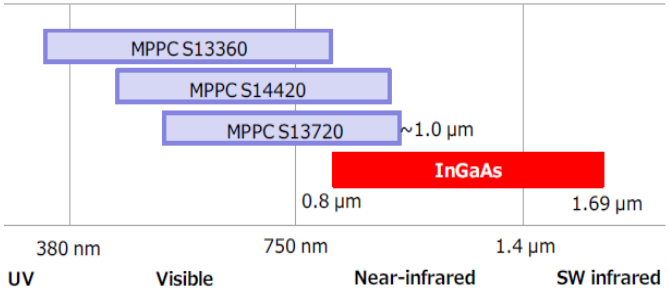


(a)

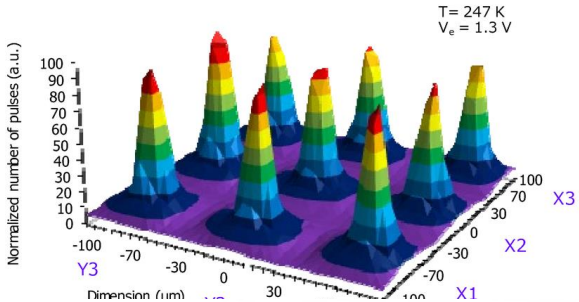


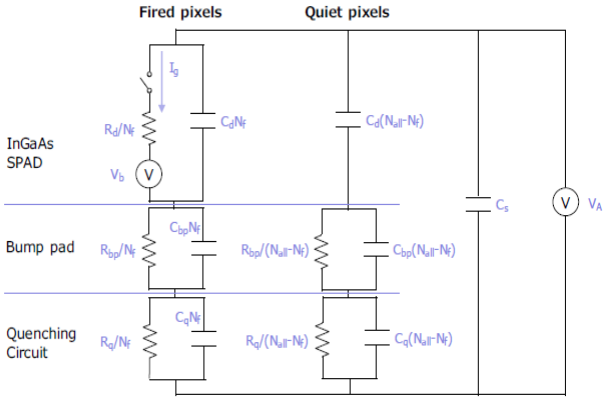
(b)

Figure 2. Structure of the developed InGaAs single-photon avalanche diode (SPAD). (a) Cross-section of a pixel. (b) Spectral response of the developed InGaAs SPAD. The measurement was performed in room temperature.

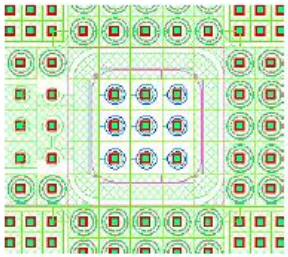


Product lineup of MPPC along wavelength regions and the wavelength sensitivity of InGaAs devices

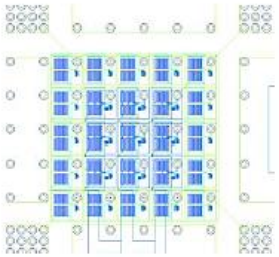




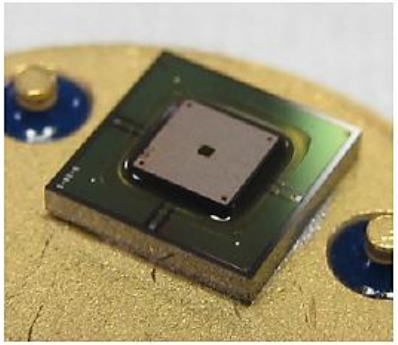
Circuit model for designing pixel circuits



(a)



(b)

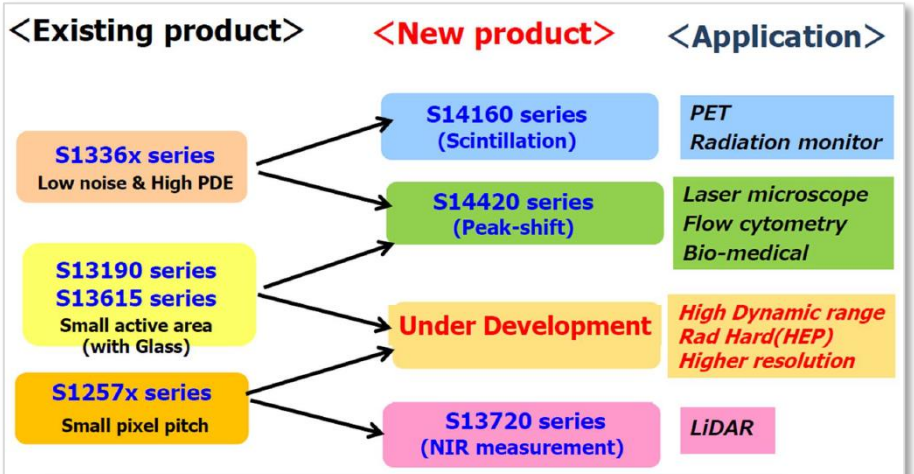


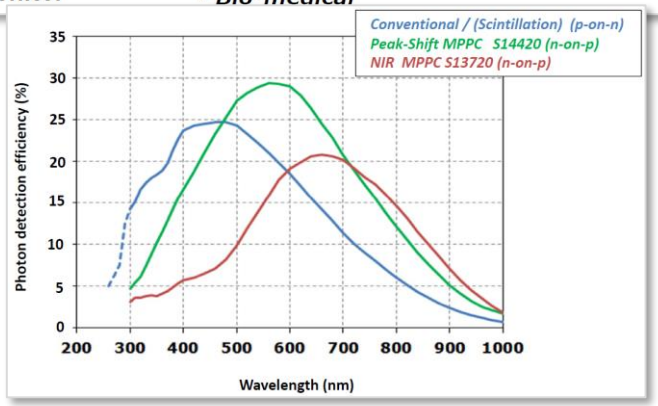
(c)

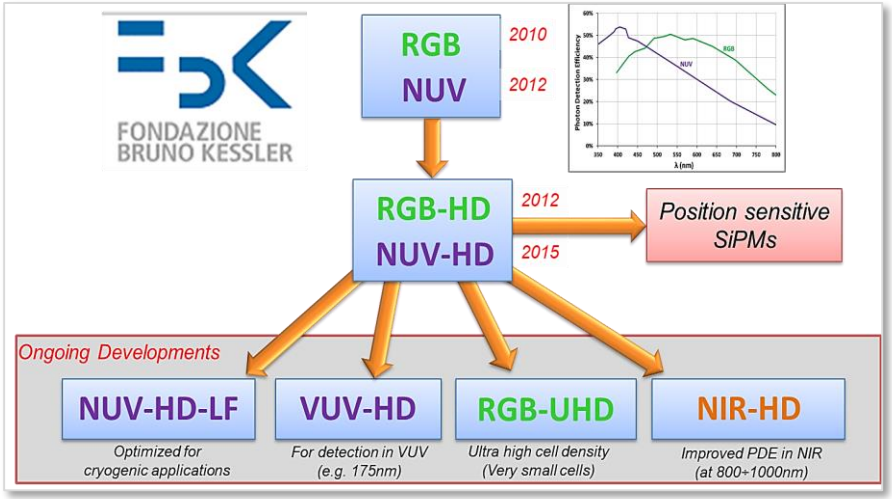
Figure 6. Implementation of the hybrid InGaAs MPPC. (a) Sensor layer. (b) CMOS circuit layer. (c) Assembled chip by a flip-chip bonding technique.

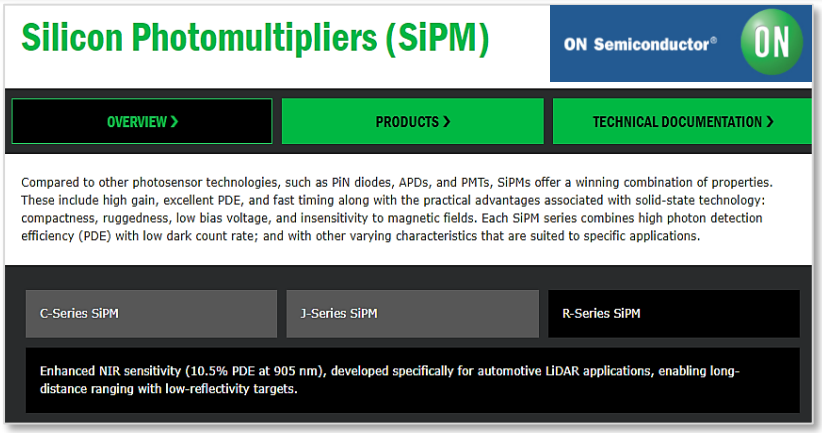
New product trends and developments

Trend1: product differentiation









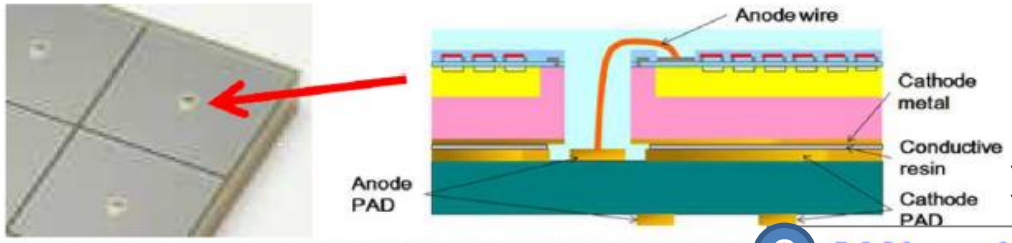
- **NIR in LIDAR, radiation harness, packaging simplification, spectral sensitivity optimized to application, optimal cell-size**

  → solution: differentiate the product

Trend2: Tech./packaging simplification & improvement

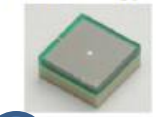
1 Technology : Hole Wire Bonding (HWB)

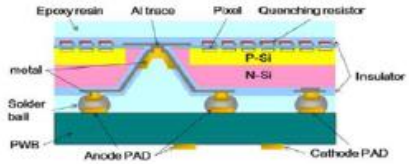
S14160 series achieves a low cost and small dead area by Hole Wire Bonding (HWB) technology. (Patent pending)



Source: Hamamatsu SENSE tech. forum 2018)

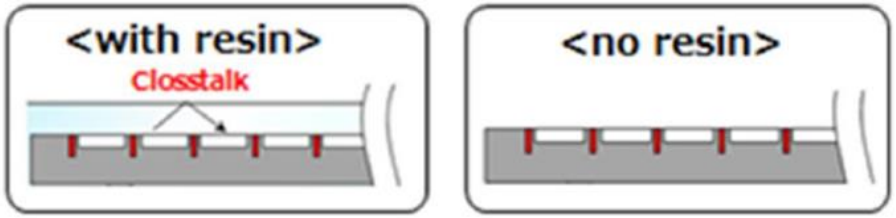
■ Reference
<S13360 TSV type>





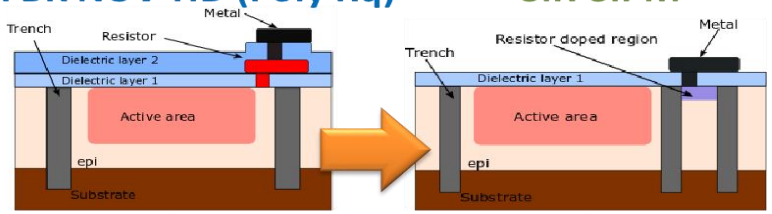
2 CAN package

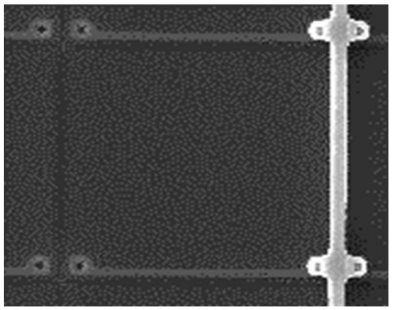
- Low crosstalk because there is no resin on the MPPC chip

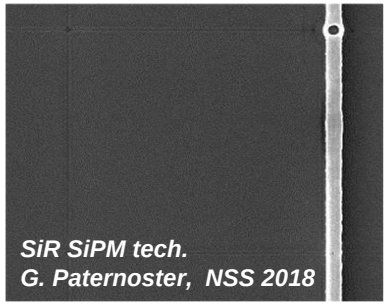


3 SiR - SiPM Technology

FBK NUV-HD (Poly Rq) **SiR-SiPM**





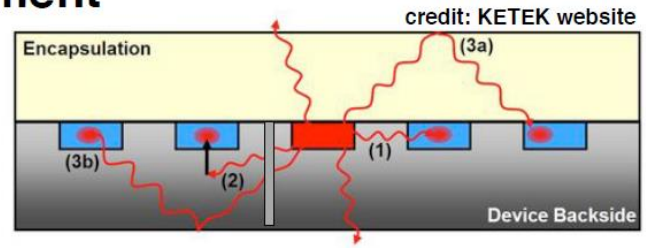


SiR SiPM tech.
G. Paternoster, NSS 2018

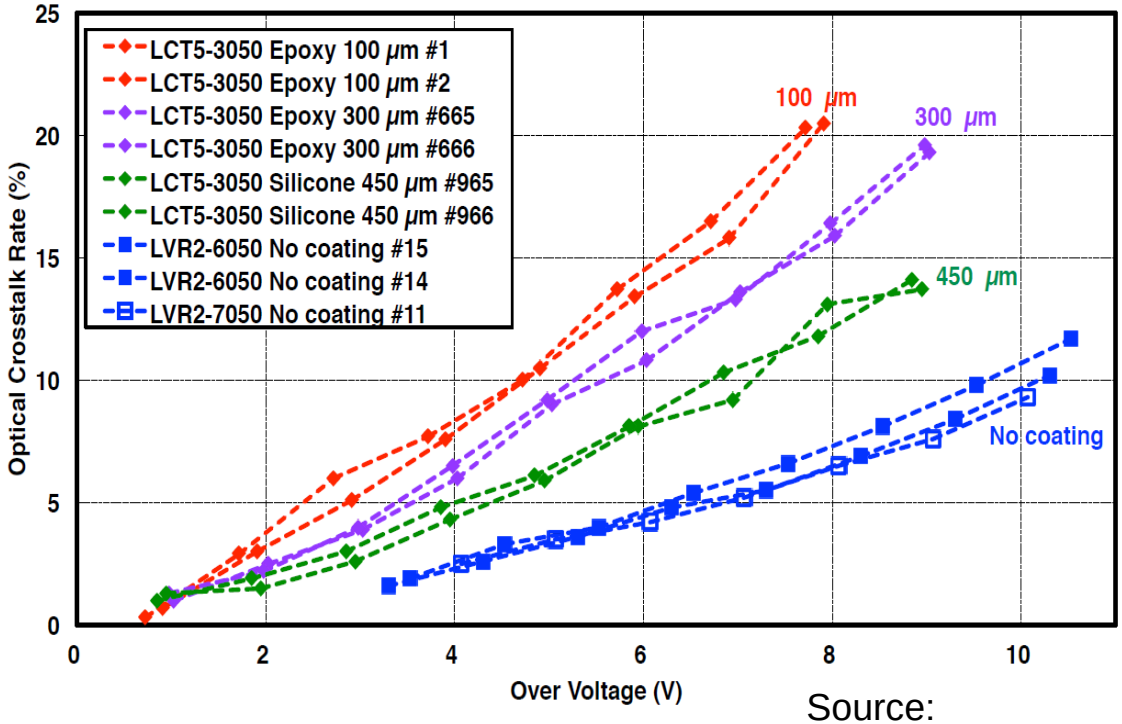
1. New solutions low-cost packaging. (e.g. hole wire bonding)
2. Top-resin removal for lower crosstalk.
3. New solutions for cheap and faster microfab. process. (e.g. SiR SiPM)

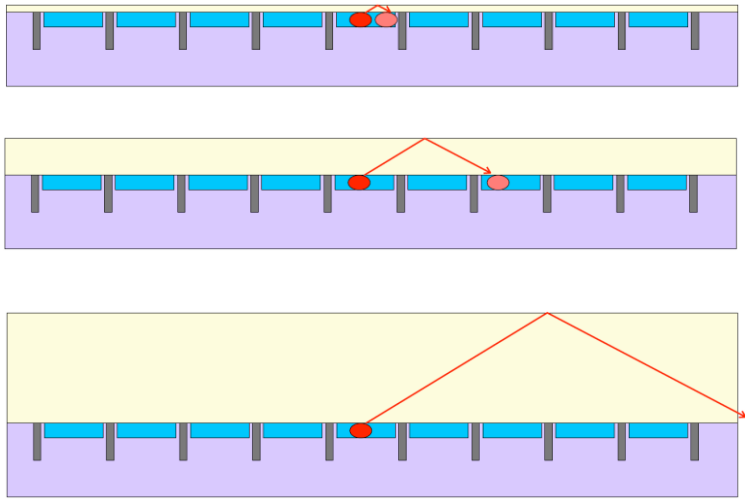
Effect of resin on external opt. CT

- Silicon Photomultiplier is chosen as a photon sensor for SST
  - Main objective of CTA SiPM development
    - Suppress OCT while retaining photon detection efficiency (PDE)



External Crosstalk





Source:
Suppressing Optical Cross Talk in Silicon Photomultiplier
ICASiPM, JUN 11–15, 2018, Schwetzingen Germany

SiPM: quenching resistor technologies

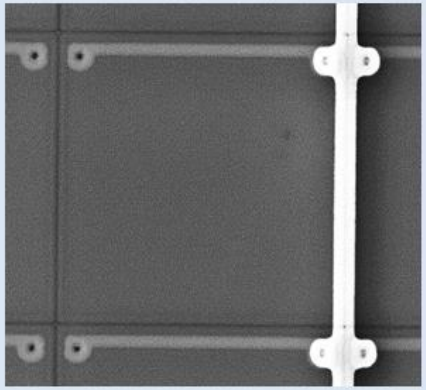
Integrated passive quenching Resistor is required to quench the avalanche current and reset the SPAD after an event

Typical R_q = 500 kOhm – 1 MOhm

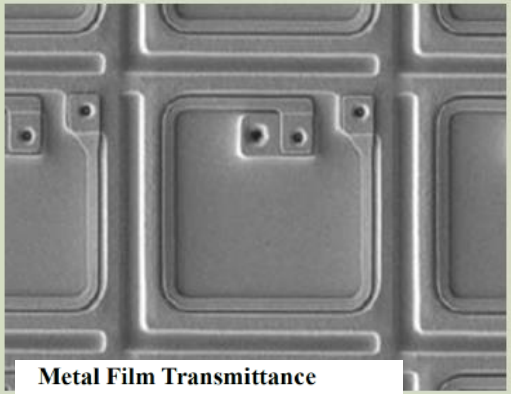
Different possible technologies….

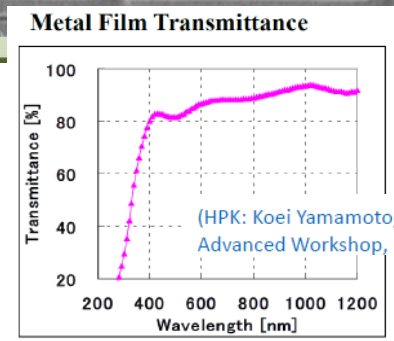
Poly Silicon Resistor

FBK, SensL, Ketek



Thin Metal Film Resistor

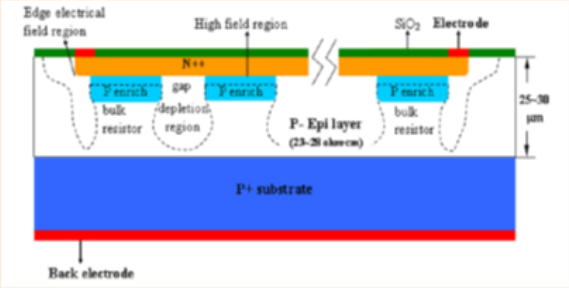




(HPK: Koei Yamamoto, 2nd SiPM Advanced Workshop, March 2014)

Bulk Silicon Resistor

Max Plank Institute, Beijing Normal University

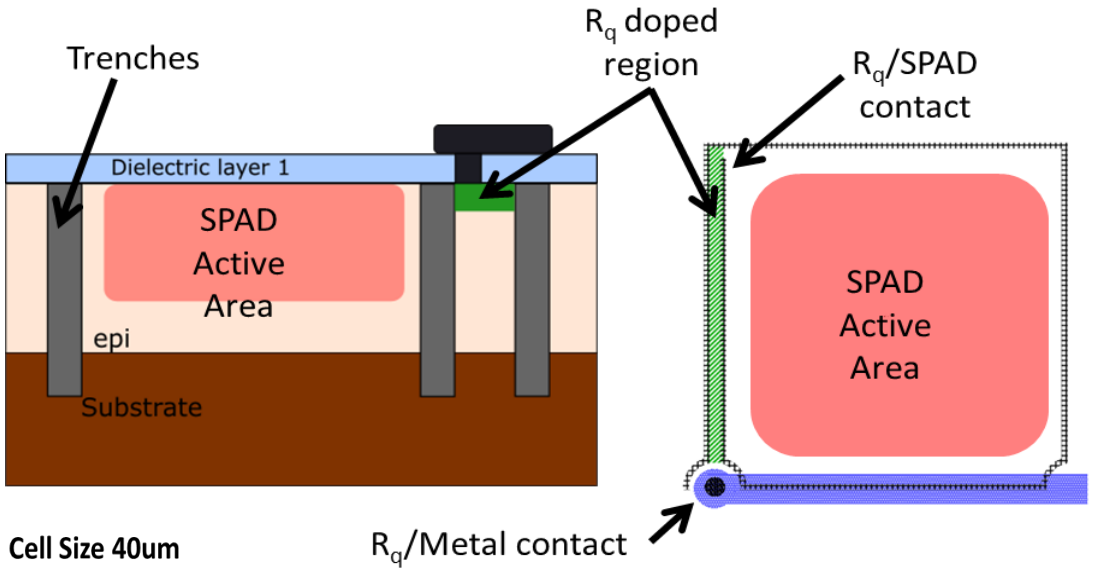


Cons.

- High temperature coefficient
- Additional microfab. process steps

SiR - SiPM Technology

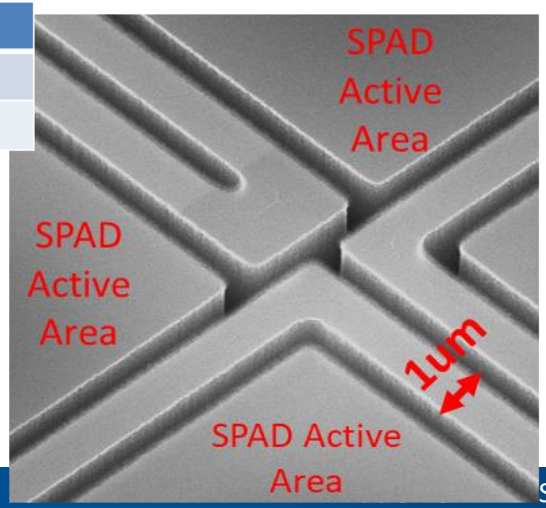
Silicon Resistor (SiR-SiPM): quenching resistor integrated in the silicon substrate by means of a semi-conductive channel



- The resistor is realized by means of a **shallow doped region** and **confined between two trenches.**
- The silicon resistor is connected to the device by overlapping the shallow doped layer

Cell Size 40um

Fill Factor	
NUV-HD	83 %
SiR	77 %



SiR-SiPM Advantages

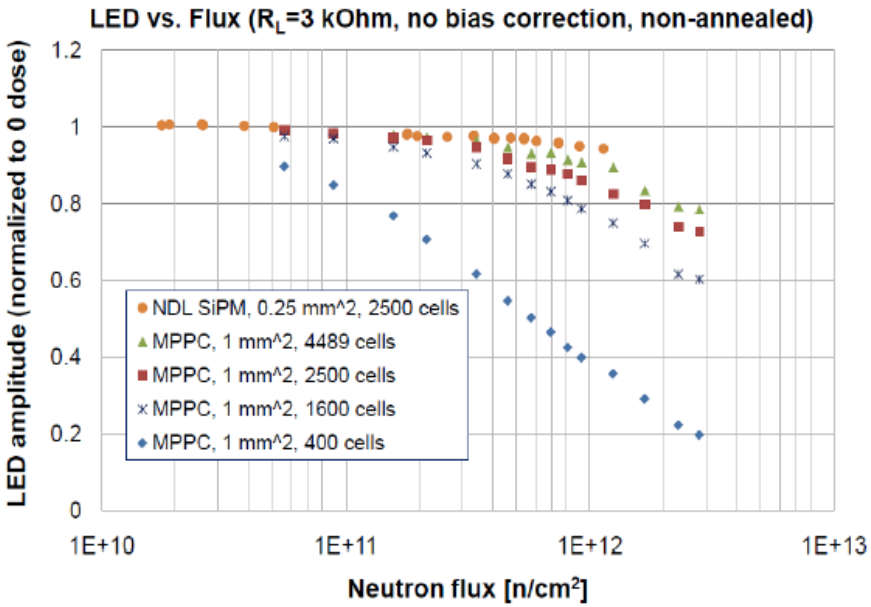
- **Faster and cheaper fabrication process (30% less steps)**
- Simpler and more reliable fabrication process (no poly deposition; no Si/Poly contact)
- **Significantly reduced R_q dependence on the temperature**
- Small FF reduction
- **ARC is easily customizable** (single layer of oxide, no poly, reduced surface morphology)

SiPM radiation hardness – studies and improvements

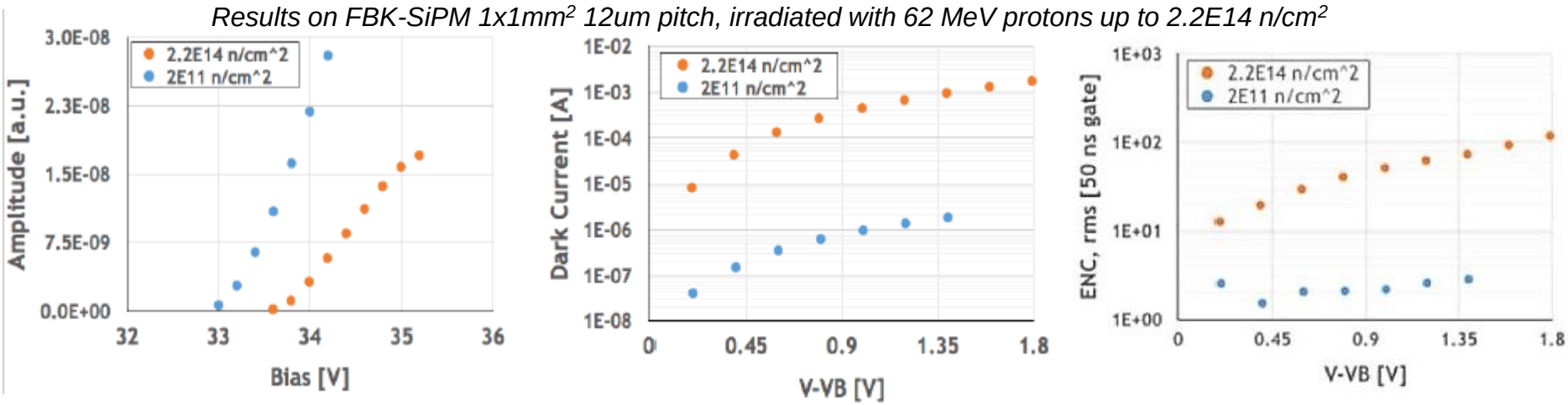
Studies from Y. Musienko

source: slides SENSE TechForum, Geneva, 21.06.2018

- SiPM are still working at 2E14 n/cm^2
- But, performance changes:
  1. Small increment of Vbd
  2. Reduction of PDE ~10%
  3. Significant increase of primary noise generation
  4. Correlated noise (ENC) increase



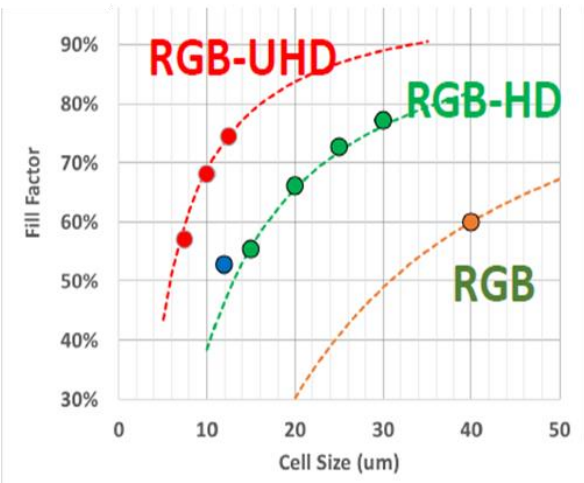
Results on FBK-SiPM 1x1mm^2 12um pitch, irradiated with 62 MeV protons up to 2.2E14 n/cm^2



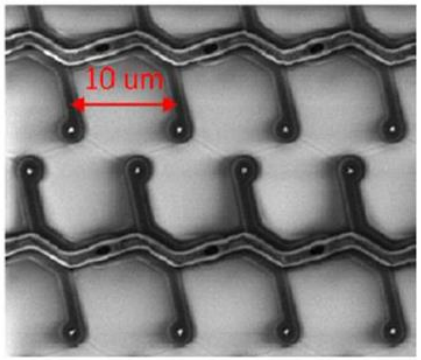
SiPM radiation hardness – studies and improvements

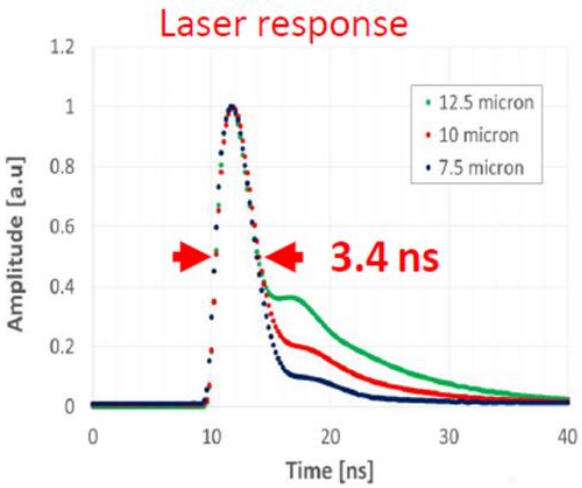
- **Trends to improve radiation hardness:**
  1. **Small (or very-small) cells**
     → reduced effect of noise cells,
     → lower gain and lower power consumption after irradiation
  2. **Low-electric-field**
     → Higher Vbd and DCR dependence on temperature
     → greater reduction of DCR with cooling, even after irradiation

Example UHD-SiPMs → very small cells

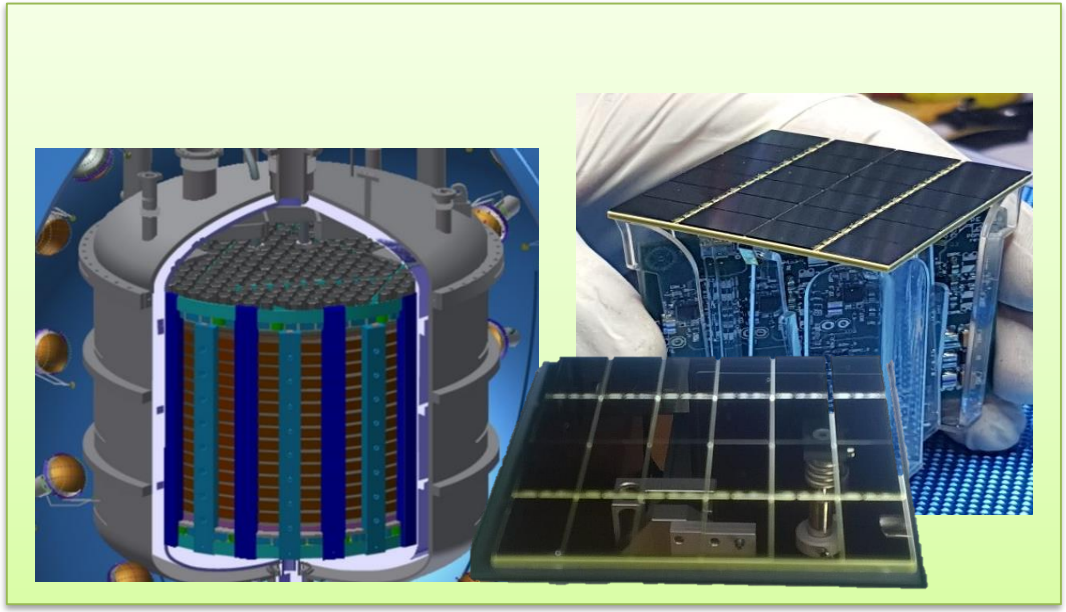


Finished 10 μm cell pitch SiPM





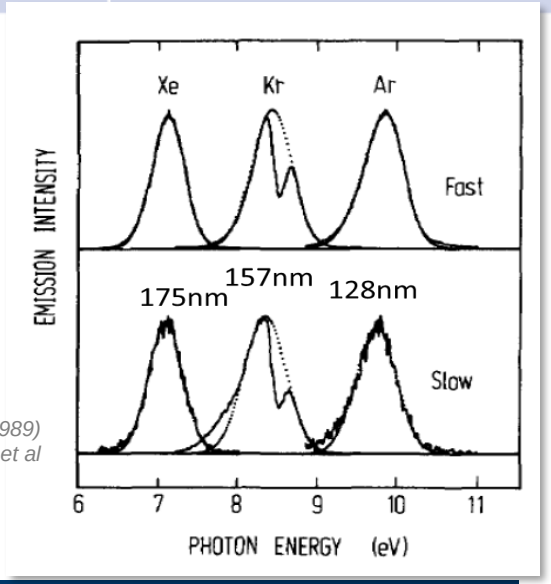
Big experiments with liquid Noble-gas scintillators



LXe and LAr experiments using SiPM

Experiment	Type	Photo-detector solution	Area
MEG-II	LXe	Hamamatsu VUV2	0.6 m2
nEXO	LXe	FBK, Hamamatsu, 3DdSiPM	~5 m2
DARWIN	LXe	SiPM is one option	~8 m2
DarkSide-20k	LAr	FBK NUV-HD triple dopant	15 m2
DEAP-300t	LAr	SiPM is baseline option	~200 m2
Proto-DUNE-SP	LAr	Light guide or trap + SiPM	
DUNE	LAr	Light guide or trap + SiPM	

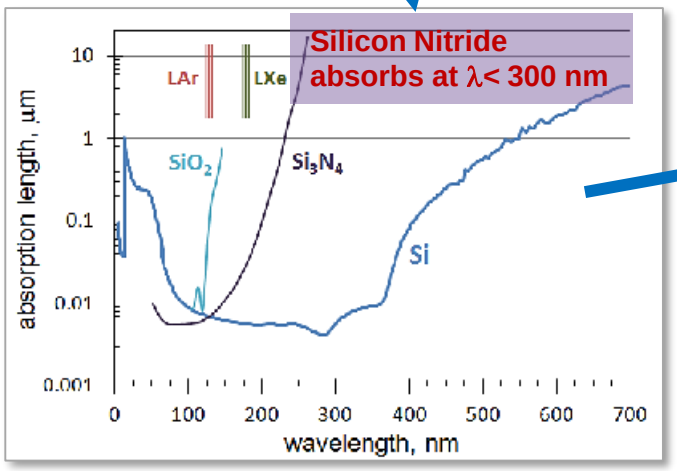
source: F. Retiere – ICASIPM 18

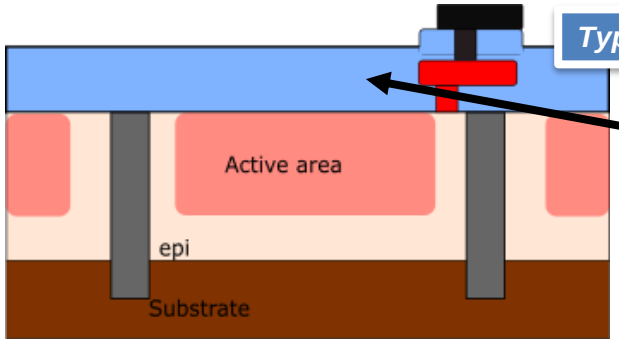


J Chem Phys vol 91 (1989) 1469 E Morikawa et al

LXe → VUV light detection challenge

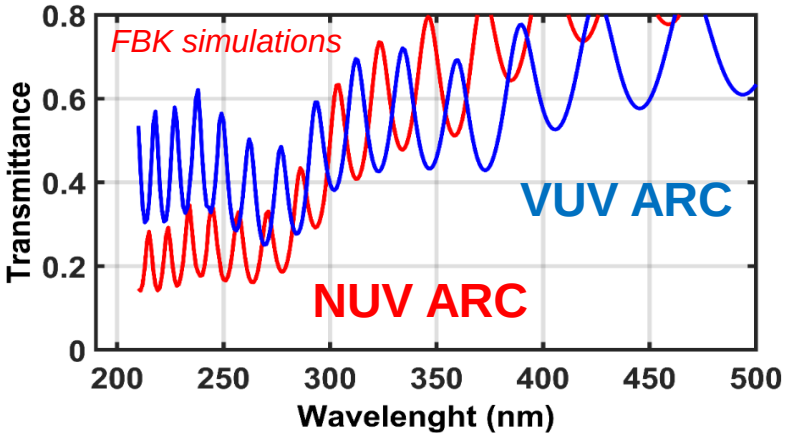
1. **Anti-Reflective Coating (ARC)**
   - VUV light can reflect on SiPM
   - **VUV light is absorbed in the dielectric layers** protecting the SiPM





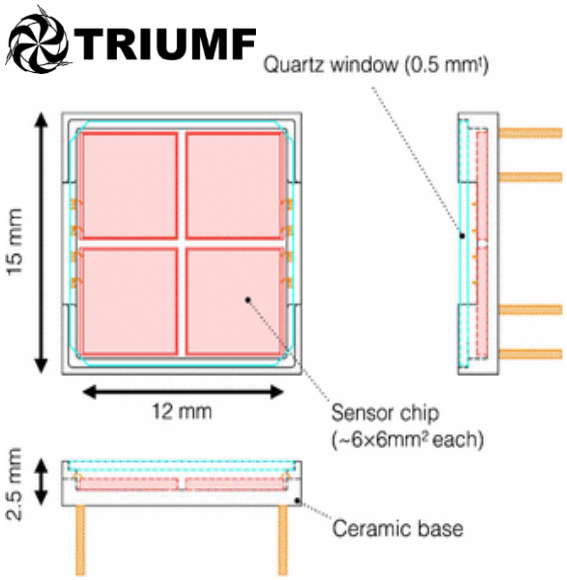
Multistack of Si_3N_4 and SiO_2 layers

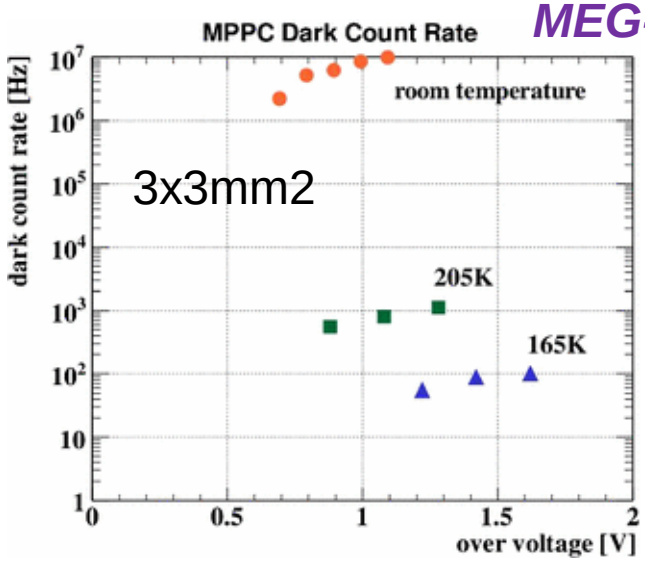
New VUV ARC:
- Elimination of SiN
- Preservation of the surface passivation quality



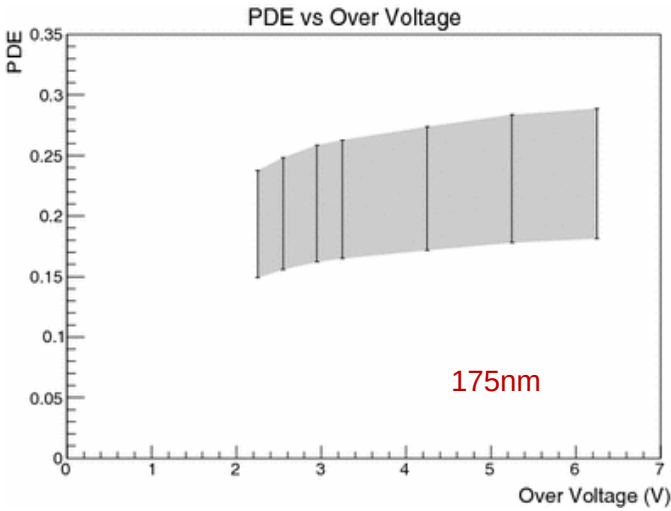
2. **Ultra-shallow interaction depth in Silicon** (possible QE losses due to surface recombination).

LXe → VUV SiPM performance

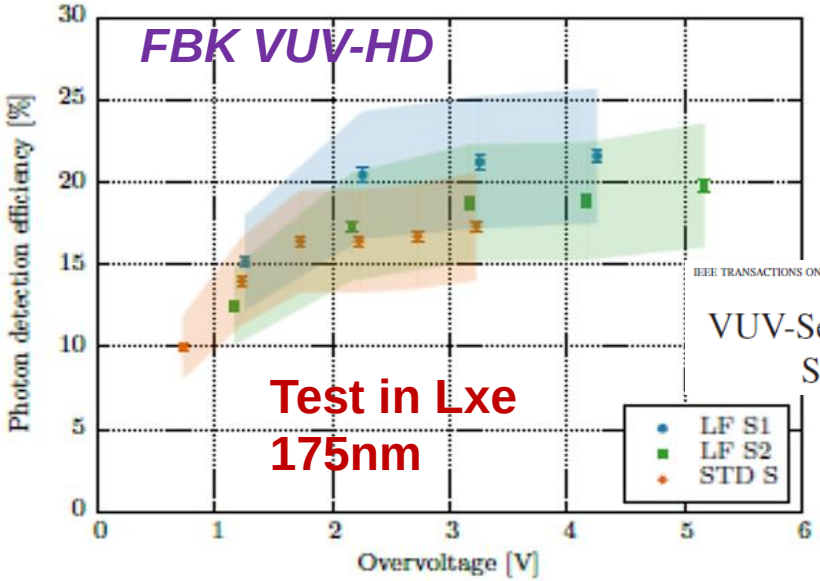




MEG-II MPPCs



Source: F. Retière – ICASIPM 2018



Good PDE in the VUV (@175nm): ~20% !

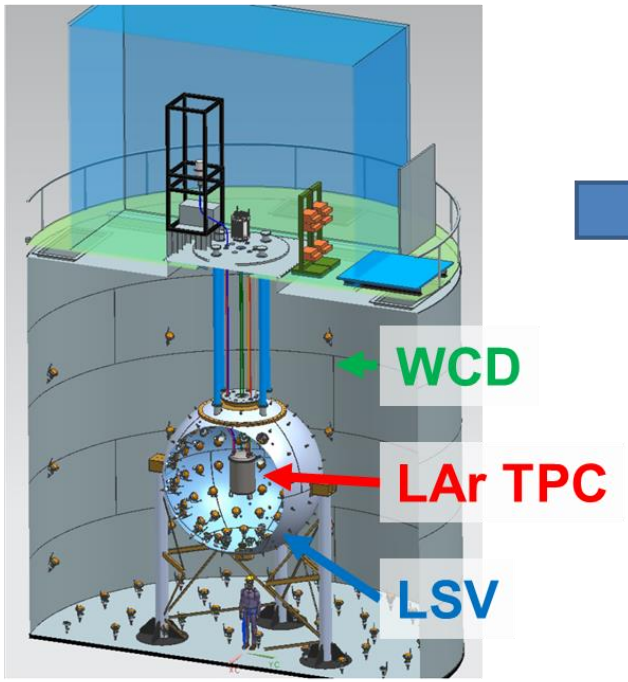
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 65, NO. 11, NOVEMBER 2018 2823

VUV-Sensitive Silicon Photomultipliers for Xenon Scintillation Light Detection in nEXO

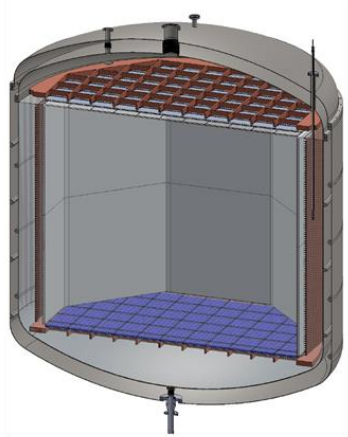
SiPM at Cryogenic Temperatures

There is a **growing interest in using SiPMs for the readout of liquid scintillators at cryogenic temperatures**.

Example: Darkside 20k experiment

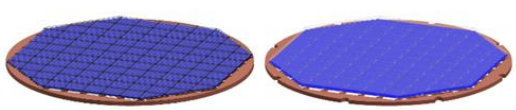


DarkSide-50
PMT-based TPC



~ 23t of UAr

LAr (λ=128nm)
↓
TPB WLS:
emission 400–450 nm

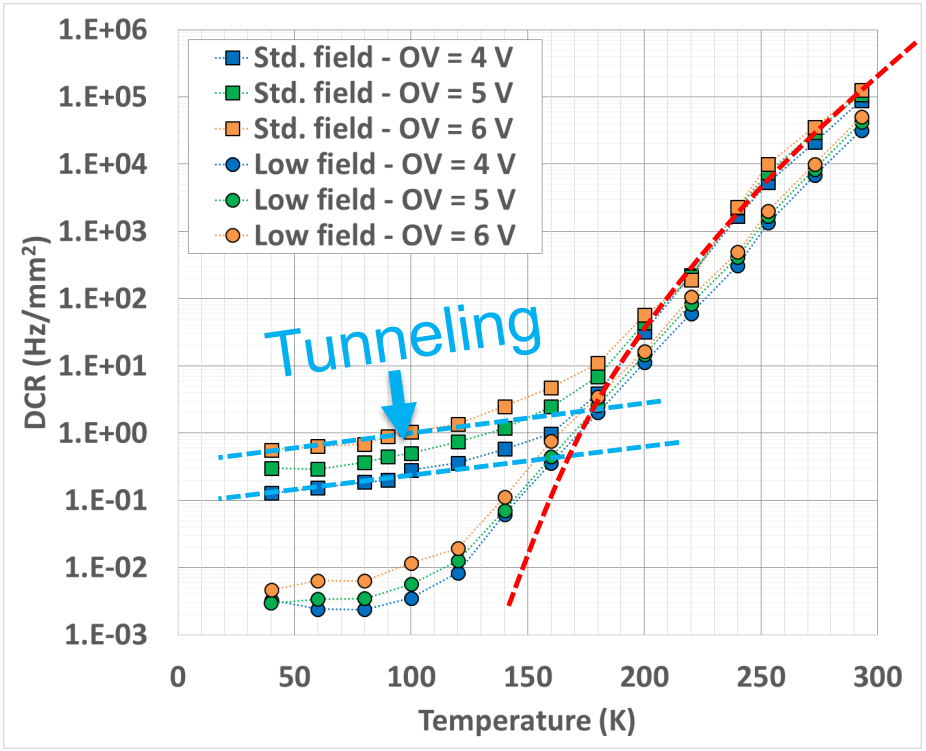


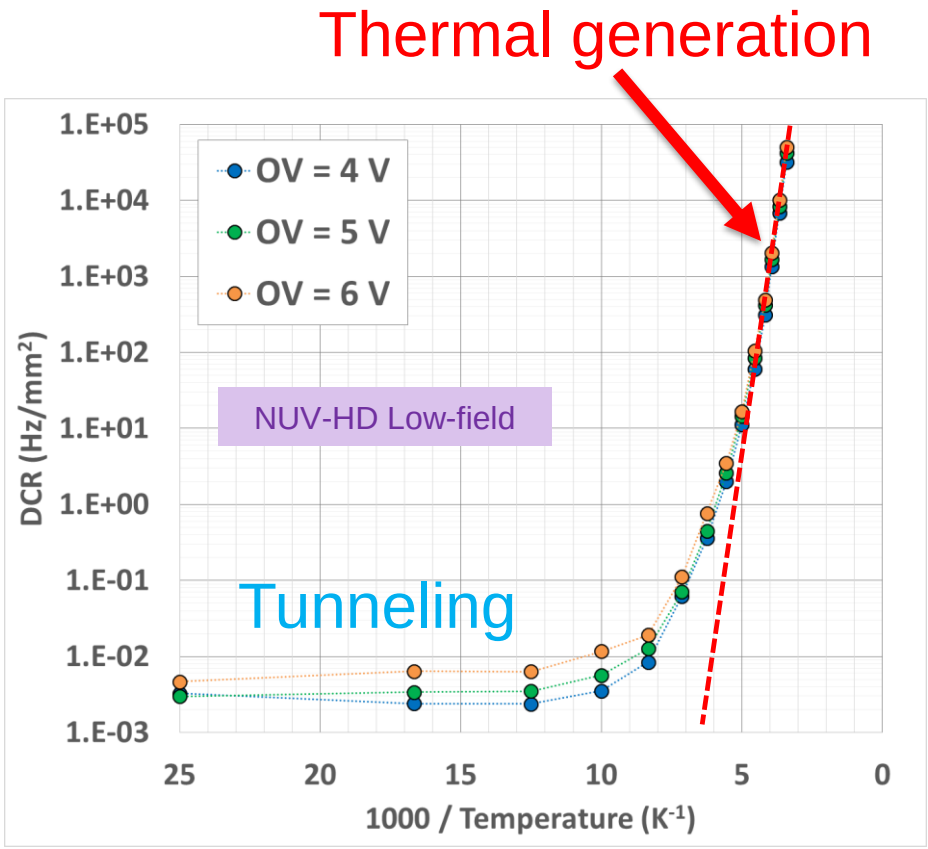
2 light readout planes: 15 m^2

SiPM tiles

DarkSide-20k
SiPM-based TPC

DCR: how scales with temperature?

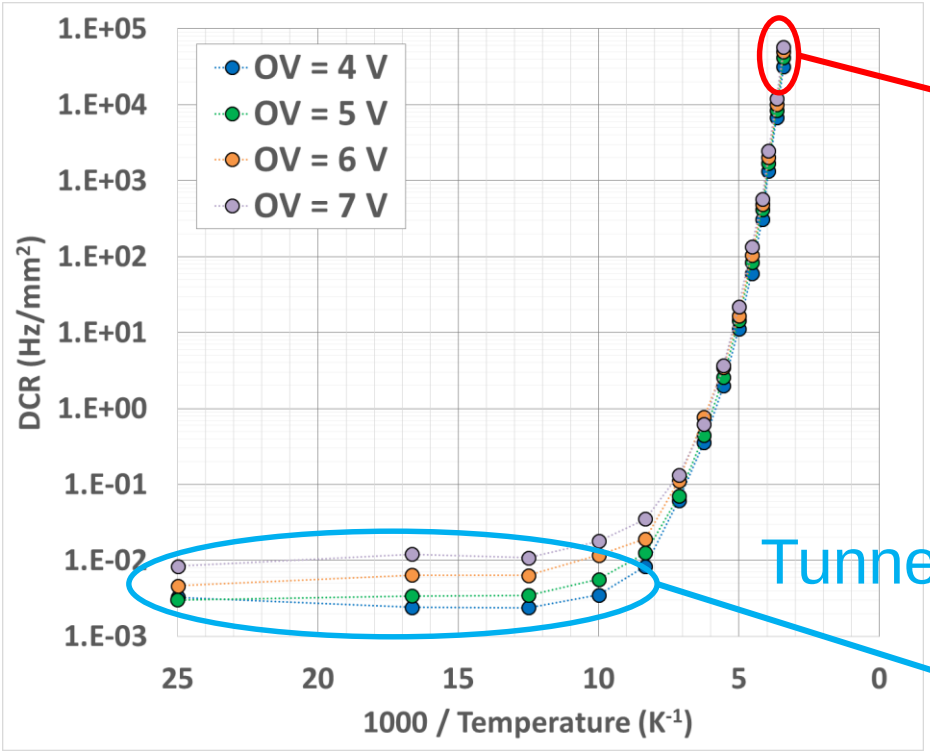




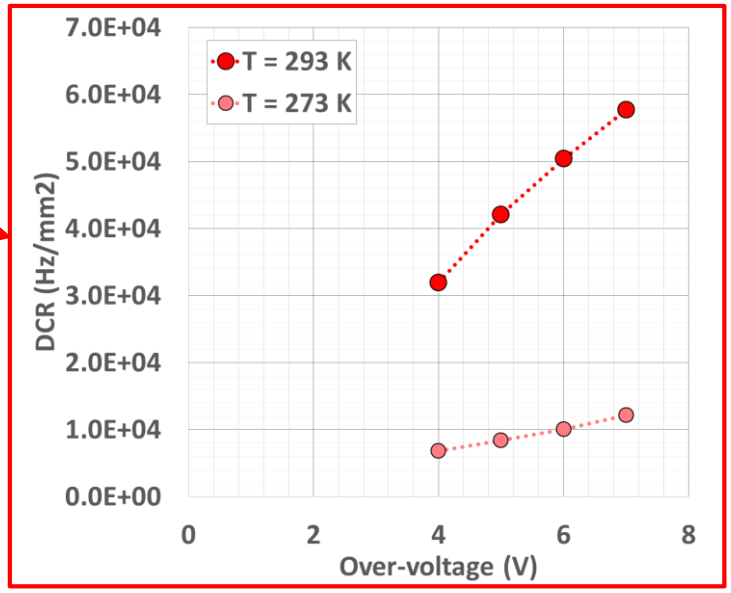
NOTE: thermal generation can be fitted with exp. curve in 1/T plot.
Tunneling can be approx. fitted with exp. curve in the plot DCR vs. Temp.

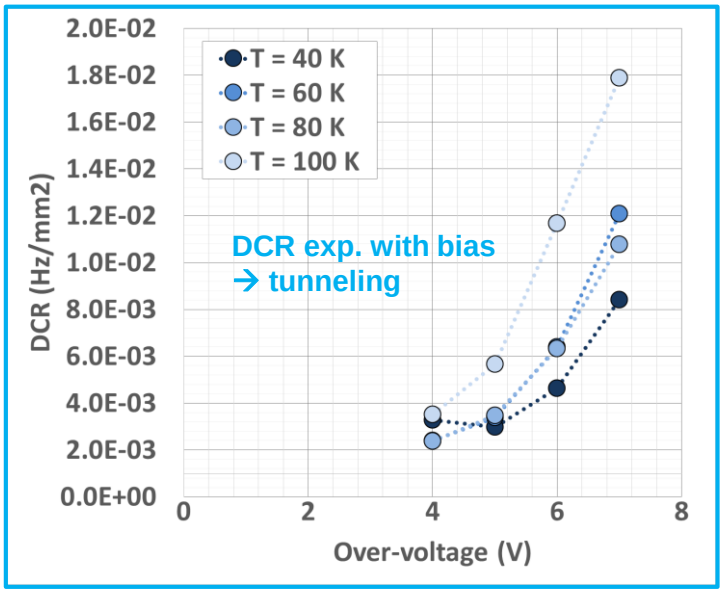
DCR: how scales with temperature?

Thermal generation

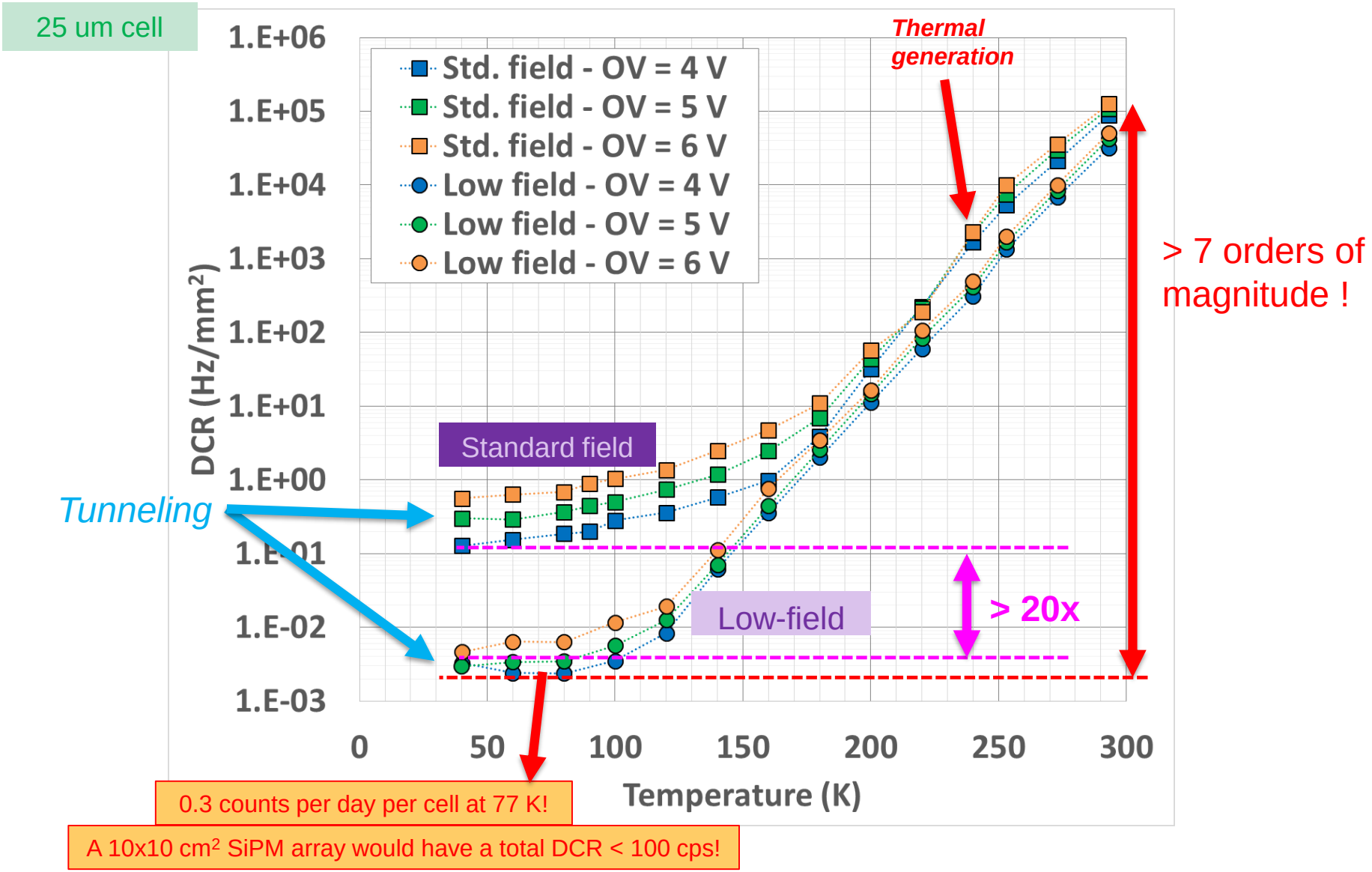


Tunneling



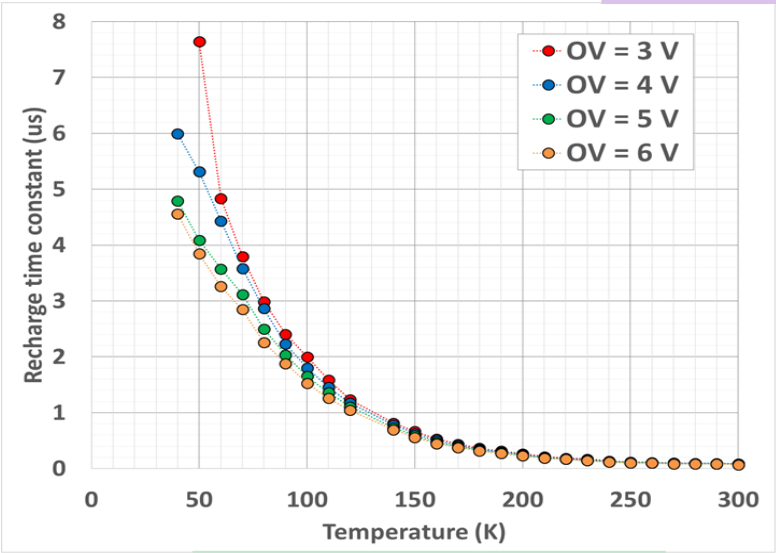


1st optimization: tunneling (DCR) reduction

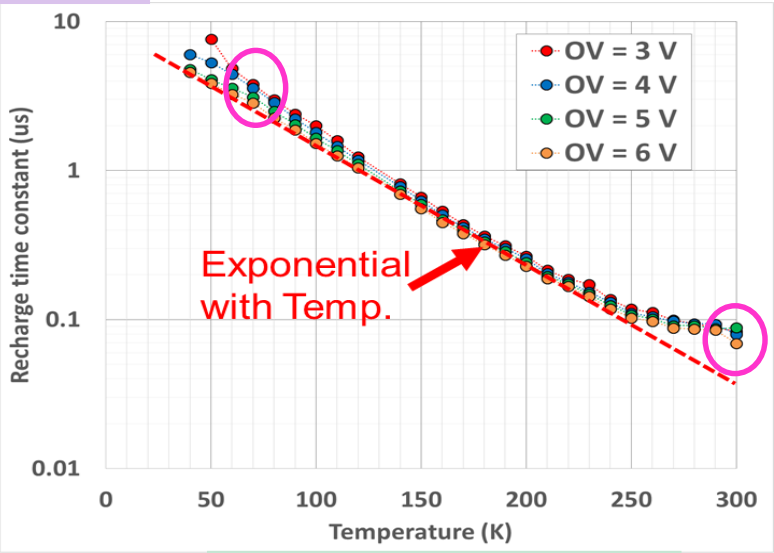


2nd: recharge time const. → reduced temp. dep.

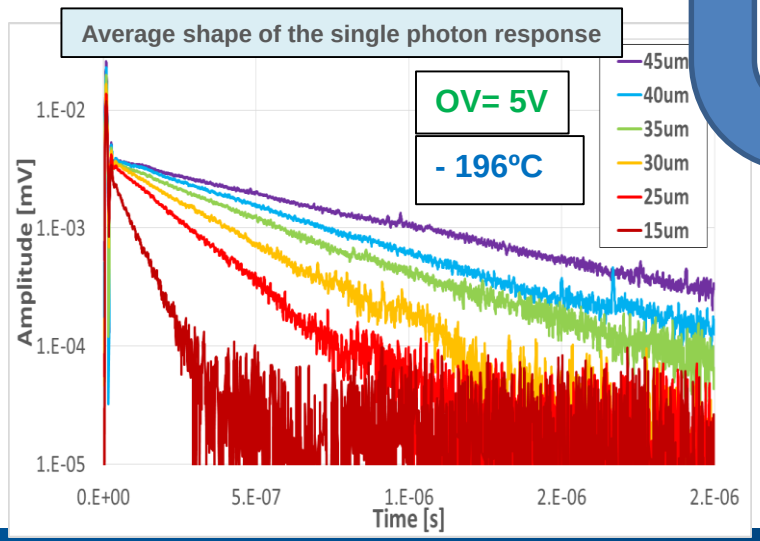
NUV-HD - old batch

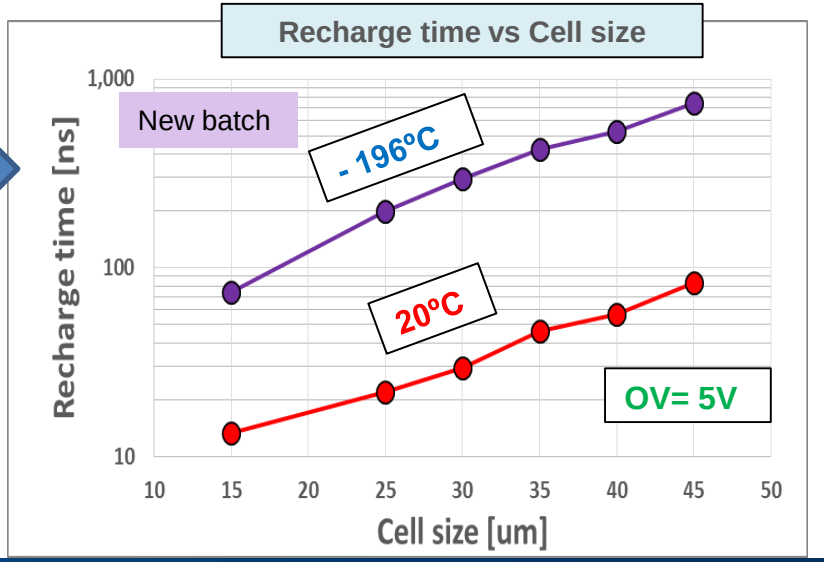


Linear scale



Log scale

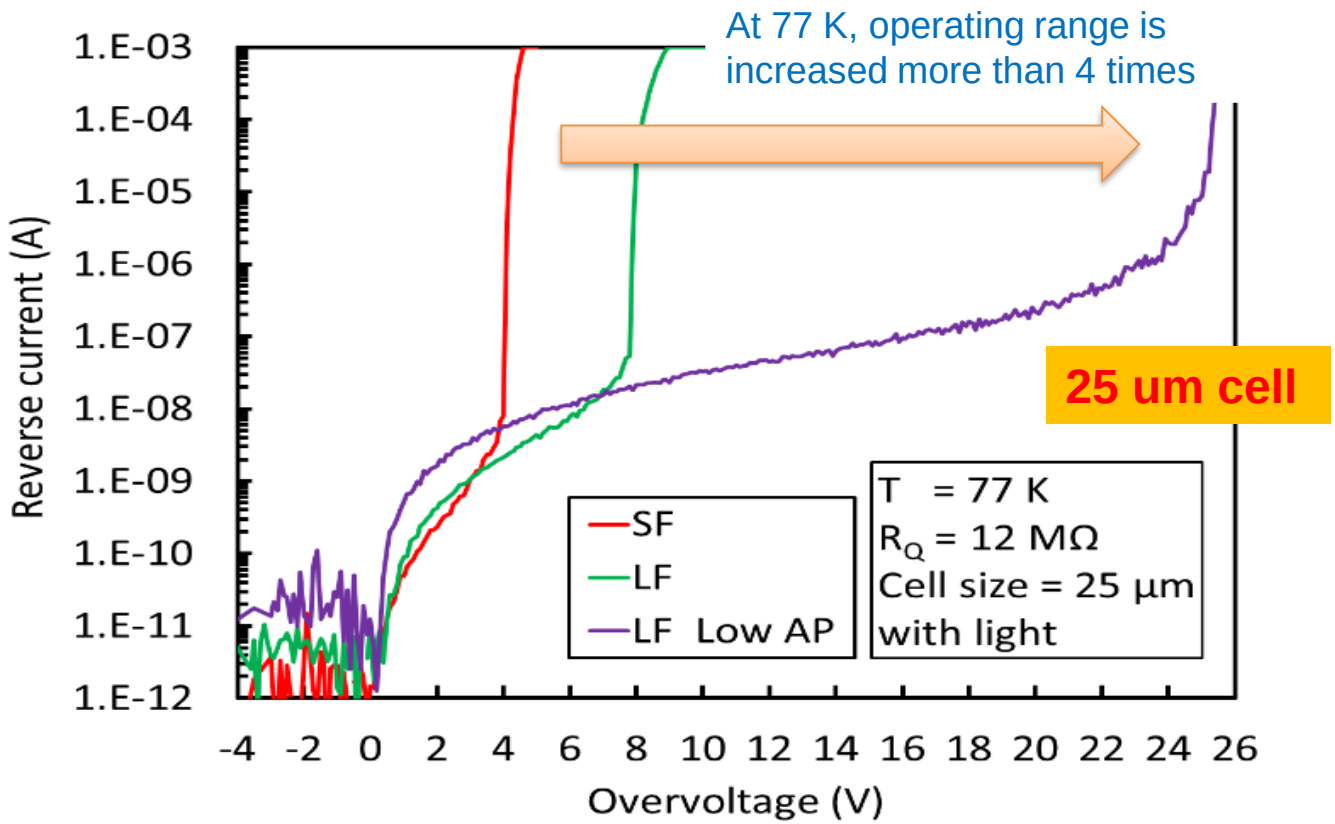




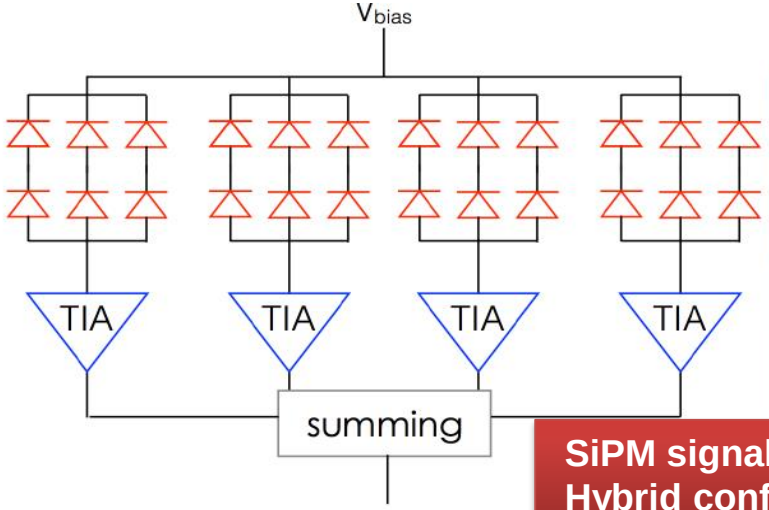
3rd: afterpulsing reduction at low temp.

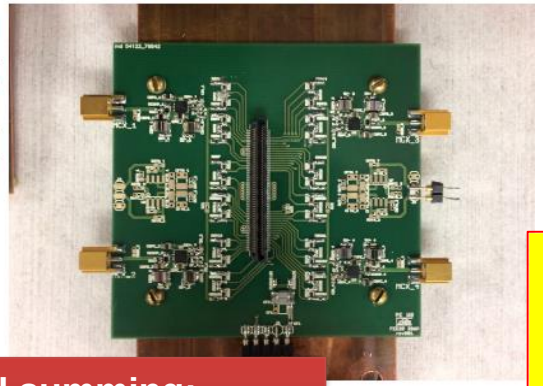
Afterpulsing can significantly increase at low temperatures
because of **increment of deep-levels de-trap time constants**!

Solution: Low-field + modified dopant concentrations in the microcell
→ significantly reduced afterpulsing probability at cryogenic temperatures.



Photon counting at 77 K





SiPM signal summing:
Hybrid configuration 4x2s3p

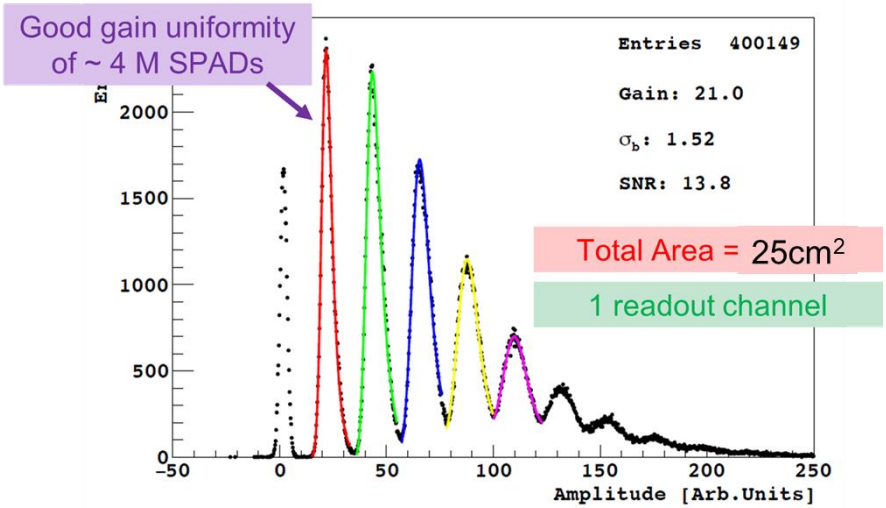
- 4 transimpedance amplifier: each TIA reads 6cm^2
- Hybrid configuration for SiPMs: 4x2s3p
- Further cold amplification before transmission outside

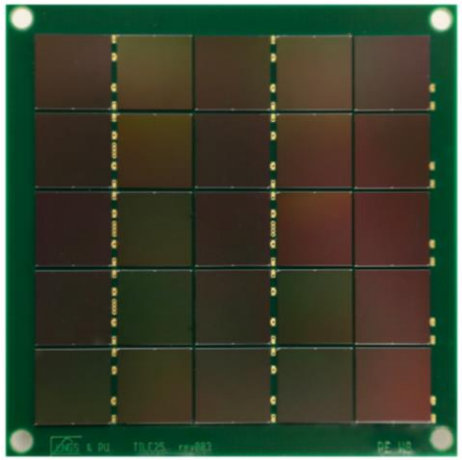
To limit the number of channels the readout of a large area with a single channel is required:

SiPM Capacitance: 50 pF/mm^2

R&D to preserve amplification, signal stability, bandwidth

→ Hybrid configuration

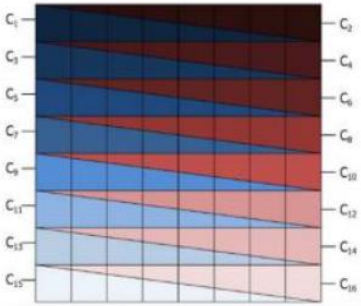




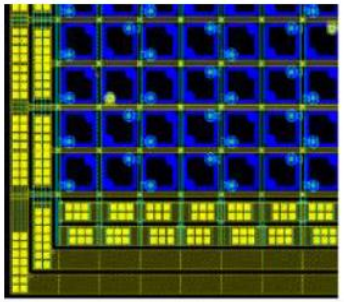
Other interesting development

Position sensitive SiPMs

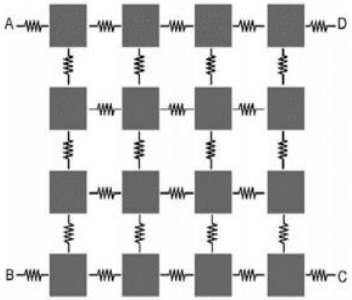
SeSP Uni. of Aachen, Germany [1]



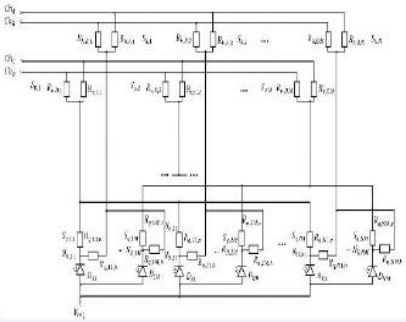
ISiPM Univ. of Heidelberg, Germany[2]



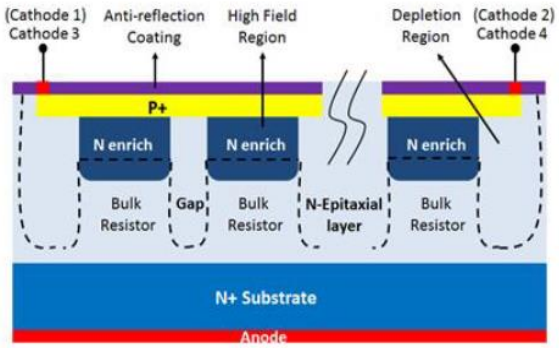
PS-SSPM RMD, USA [3]

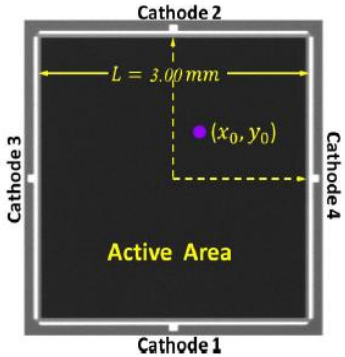


LG-SiPM FBK, Italy [4]



NDL EQR-SiPM → CRL-SiPM [5]





References

[1] Omidvari, N. and V. Schulz, IEEE Transactions on Nuclear Science, 2015. 62(3): p. 679-687.

[2] I., S., et al. IEEE SENSORS. 2013.

[3] J., P.S., et al., IEEE Transactions on Nuclear Science, 2014. 61(3): p. 1074-1083.

[4] Berneking, A., et al., NIM:A, 2018. 888: p. 44-52.

[5] Zhao, T., et al., IEEE Electron Device Letters, 2017. 38(2): p. 228-231.

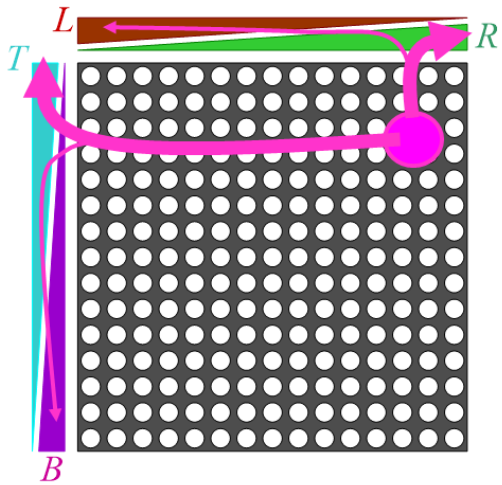
Source:
Y. Peng @ICASiPM 2018, Schwetzingen

Increasing interest for Position-sensitive SiPMs:

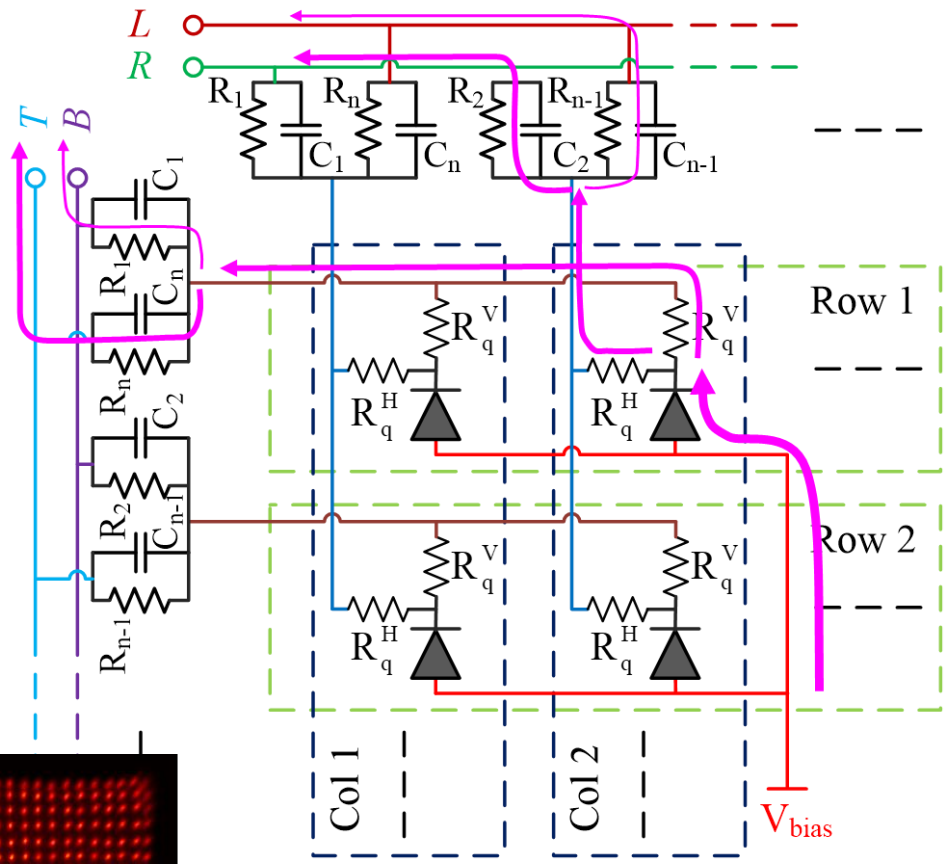
- Useful for small-animal PET
- Interest for imaging secondary scintillation light in TPCs
- Possibly many other applications

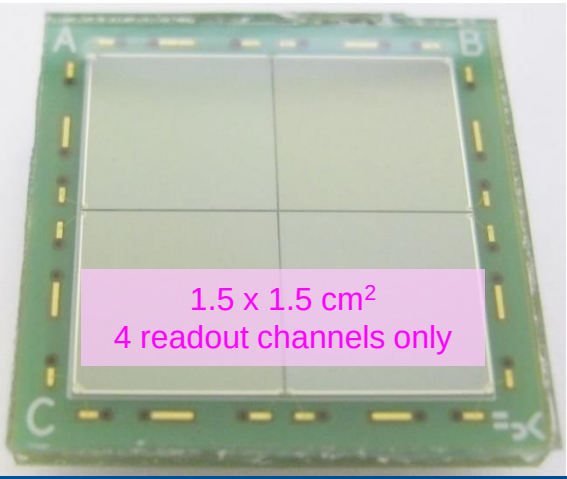
FBK LG-SiPM

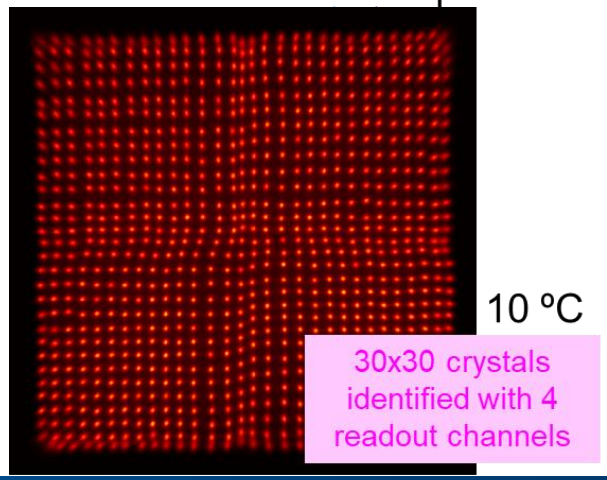
- 4 outputs to encode the interaction position of photons.
- Charge division through 2 different quenching resistors and different dividers.



Schematic of the 2D position encoding method:

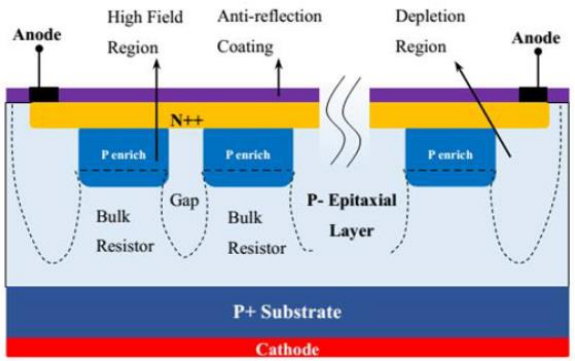




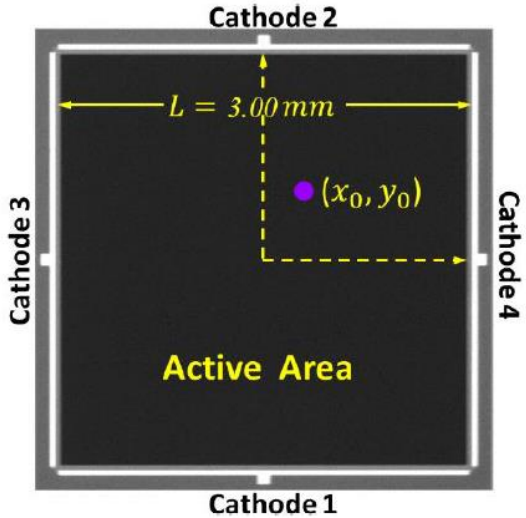


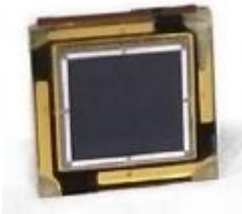
- New: 8x8mm² device produced.
  TILE of total 1.5x1.5 cm² tested with pixelated scintillator.

NDL bulk-resistor Position-Sensitive SiPM



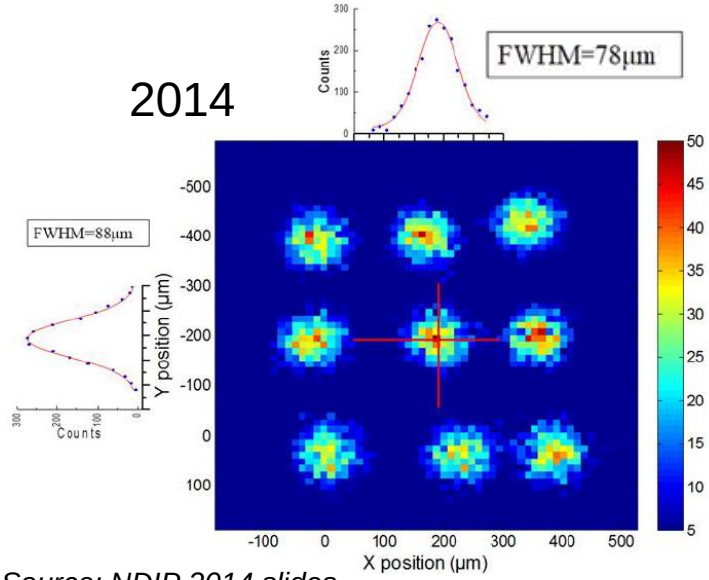
Thanks to the common shallow implant: possible readout from 4 cathodes!



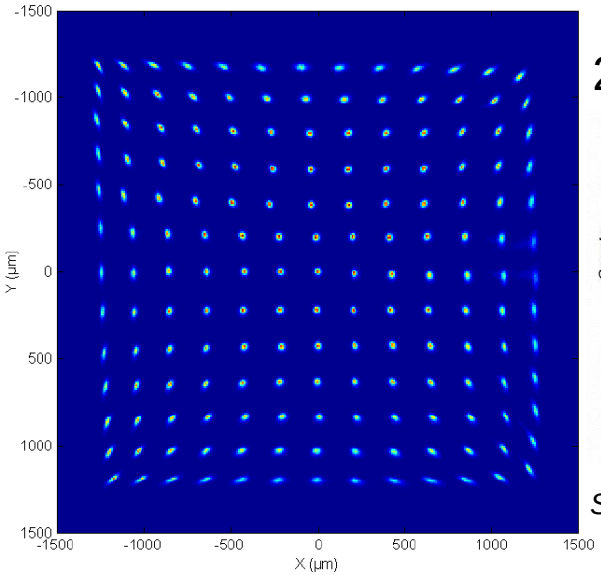


Series	Description	Cell number per pixel	Pixel active area(mm²)
11-1010C	Regular	10000	1.0 × 1.0
11-3030C	Regular	90000	3.0 × 3.0
11-2727PS	Position Sensitive	76730	2.77 × 2.77

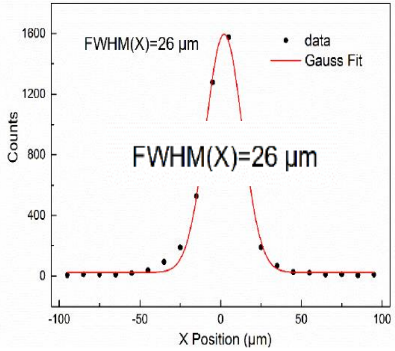
2014



Source: NDIP 2014 slides



2018



Source: ICASIPM 2018 slides

Reconstruction of 13 × 13 incident light spot positions with MPEN ~15 and the diameter of the light spot is ~ 80 μm. $PR_{System\text{-}X}$=34.9±10.3 μm, $PR_{System\text{-}Y}$=40.1±12.7 μm

New topic: setups and methods standardization

New topic: setups and methods standardization

- SiPM performance have been improved a lot recently by most of manufacturer.
- **Need to try to standardize and get common names, techniques and methods** to characterize the performance
- **Also new measurements techniques are emerging…**
  → e.g. driven by too low DCR or big areas SiPMs

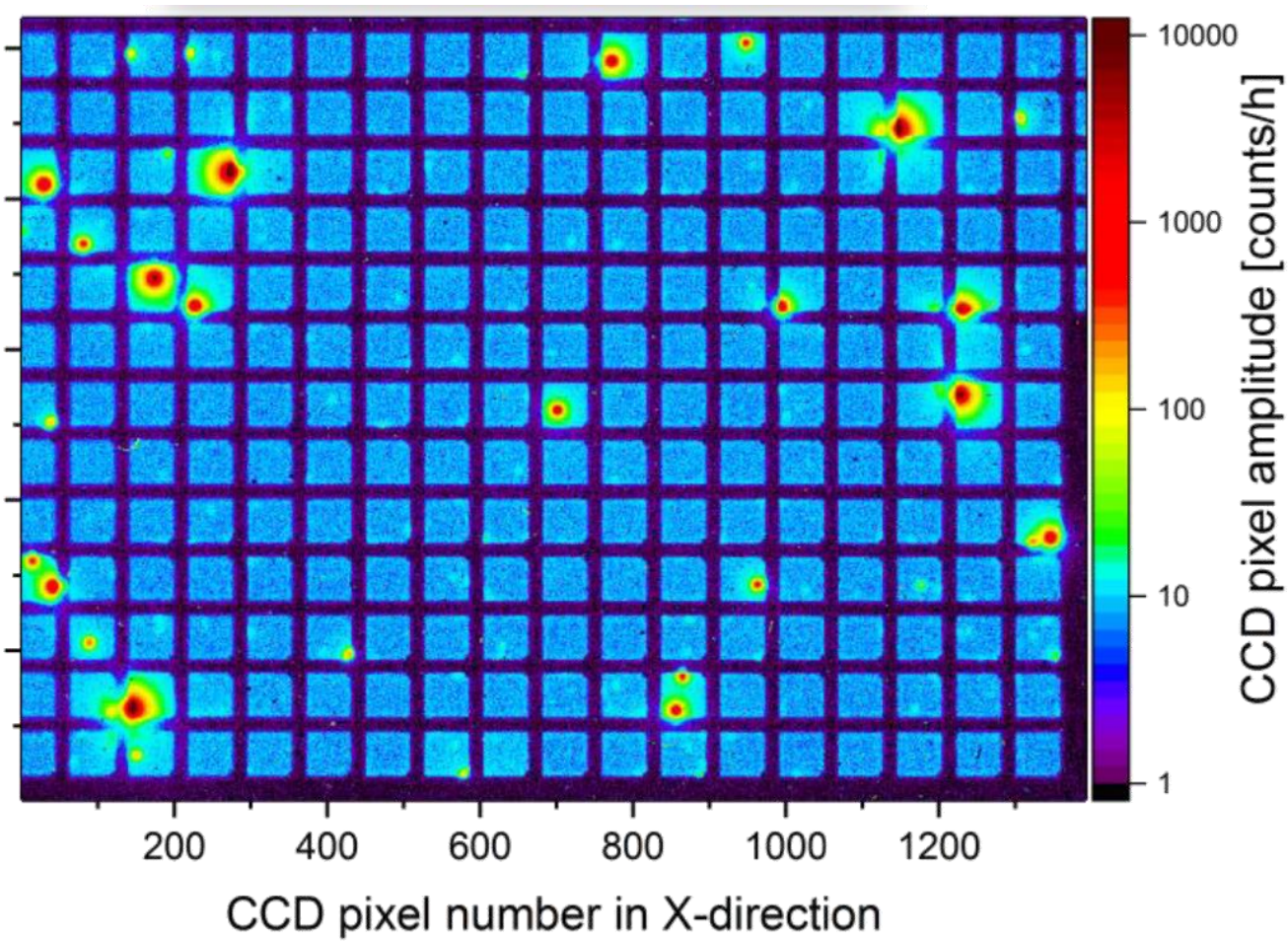
- DCR and correlated noise characterization
  - not only common methods typically based on inter-time measurement, but others ……
  - CT estimation based on optical emission!
- Identification of reference setups and centers for testing
  - for better reproducibility of results

- ICASiPM conference
- SENSE proj.
- Others… efforts to standardize and create references.

Example: primary DCR population with EMMI

Map of the white pixels can be measured experimentally.

Measurement Setup:
- Andor cooled CCD camera
- Operating temperature: -55 °C
- Cost: ~ 20 k€



Source: A. Gola, ICASIPM 2018

Conclusions

- **SiPM performance have been improved significantly over last 6 years**
  - PDE > 60% @ ~400nm, DCR<50 kcps/mm^2, optical CT of few percent, external optical CT reduction, lowering of Vbd, etc.
- **Digital SiPMs improving with the CMOS technology**
  - New interesting developments merging the dSiPM and SPAD imagers
  - 3D integration very important in the future
- **Efforts to create SiPMs with small cell pitch:**
  - ~10µm, 15µm from different manufacturer
  - Useful for highr dynamic range and higher radiation hardness
- **Now what are the main trends?**
  - Product differentiation: applications enlarged and request are different.
  - Efforts to simplify the device fabrication and packaging costs/complexity
  - Efforts to extend the sensitivity in the VUV
  - NEW important applications in the NIR !
    - LIDAR (automotive and industrial) → big efforts and new product developed
- **Other emerging applications, based on:**
  - Very small SiPMs
  - Position sensitive SIPMs
- **Important SiPM development in big scientific experiments, with liquid Noble-gases**
  - VUV technology improved
  - NUV-Cryo-SiPM technology

FONDAZIONE BRUNO KESSLER

FUTURE BUILT ON KNOWLEDGE

5th International Workshop on New Photon-Detectors

PD18

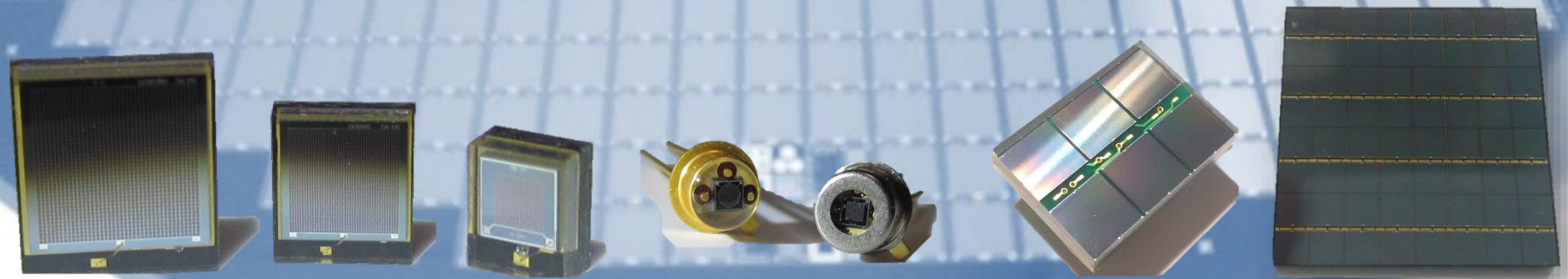
Nov. 27-29, 2018, The University of Tokyo, Tokyo, Japan

Silicon photomultipliers: overview and trends

***Fabio Acerbi*, G. Paternoster, A. Gola**

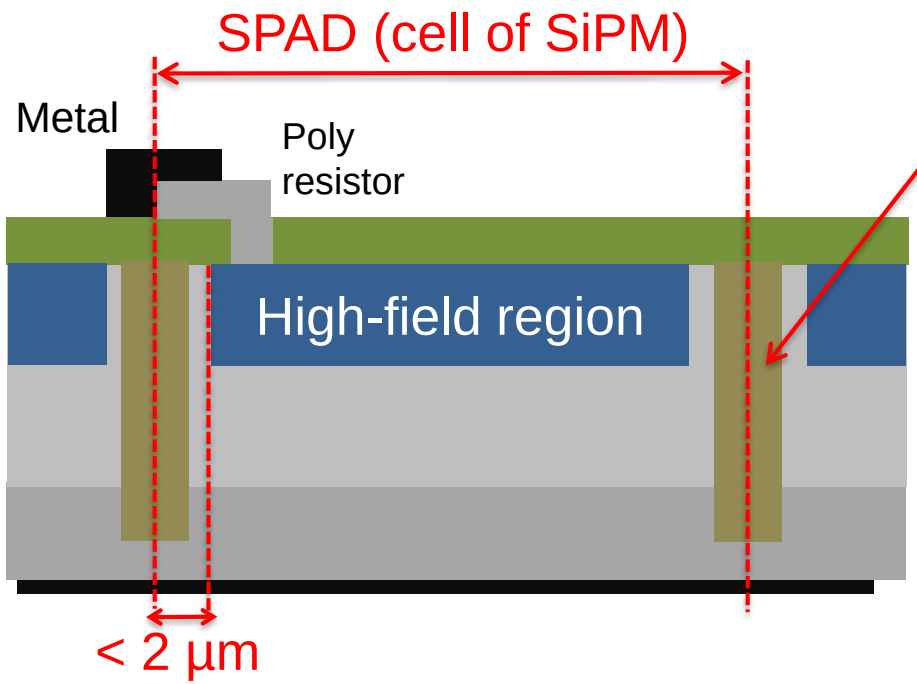
Fondazione Bruno Kessler (FBK), Trento, Italy.

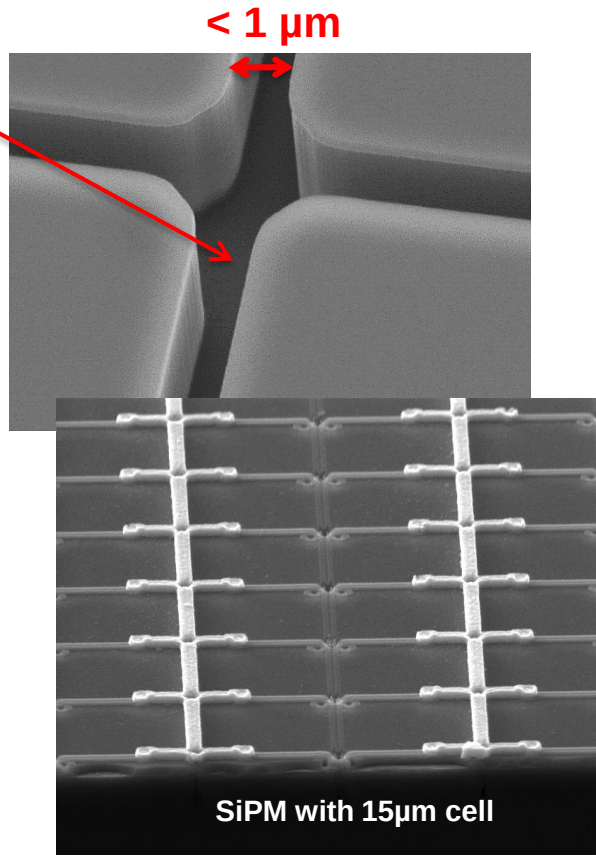
acerbi@fbk.eu



backup

NUV-HD: technology



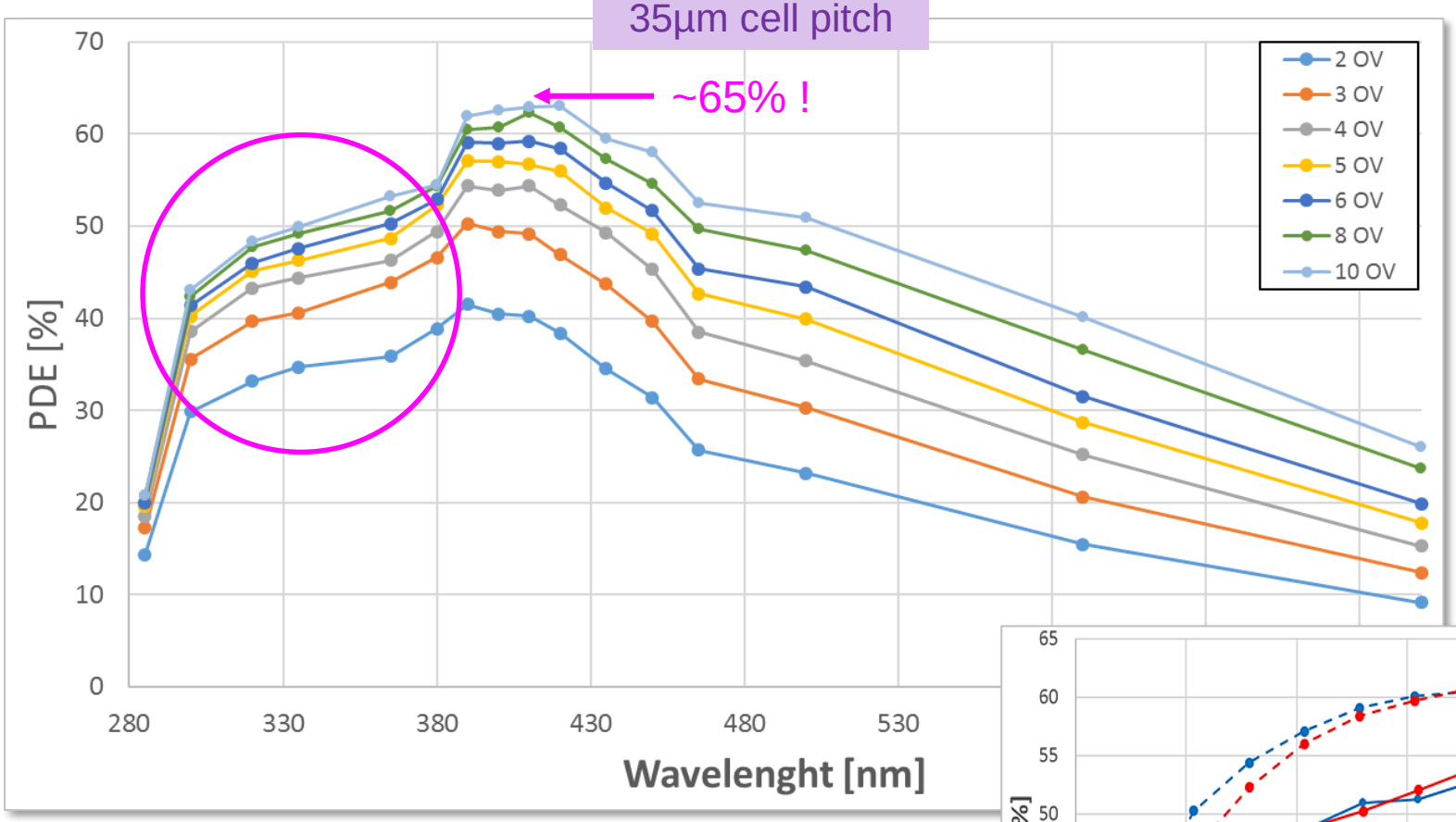


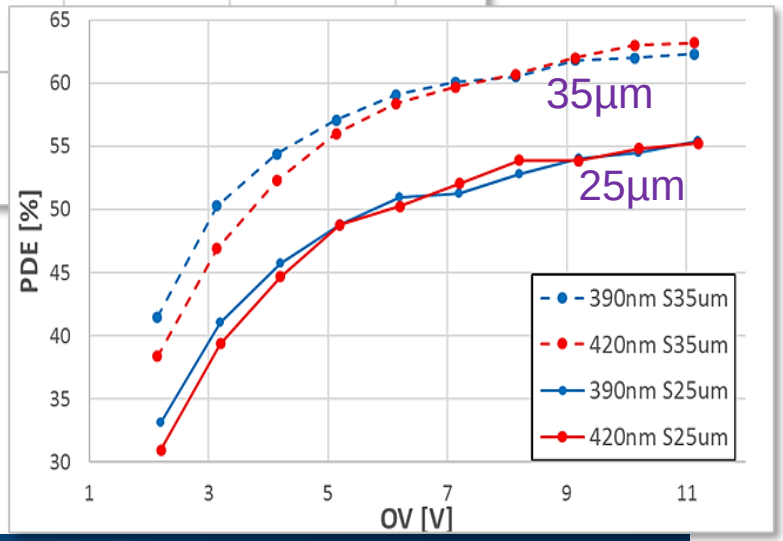
- "NUV": p-on-n junction → **higher Pt for NUV light**
- Narrow dead border region → **Higher Fill Factor**
- Deep trenches between cells → Lower Cross-Talk
- **Medium/Small cells with high FF**
- "Simple" fabrication process: 9 lithographic steps

(C. Piemonte et. al., (2016) IEEE T. Electr. Dev., 10.1109/TED.2016.2516641)

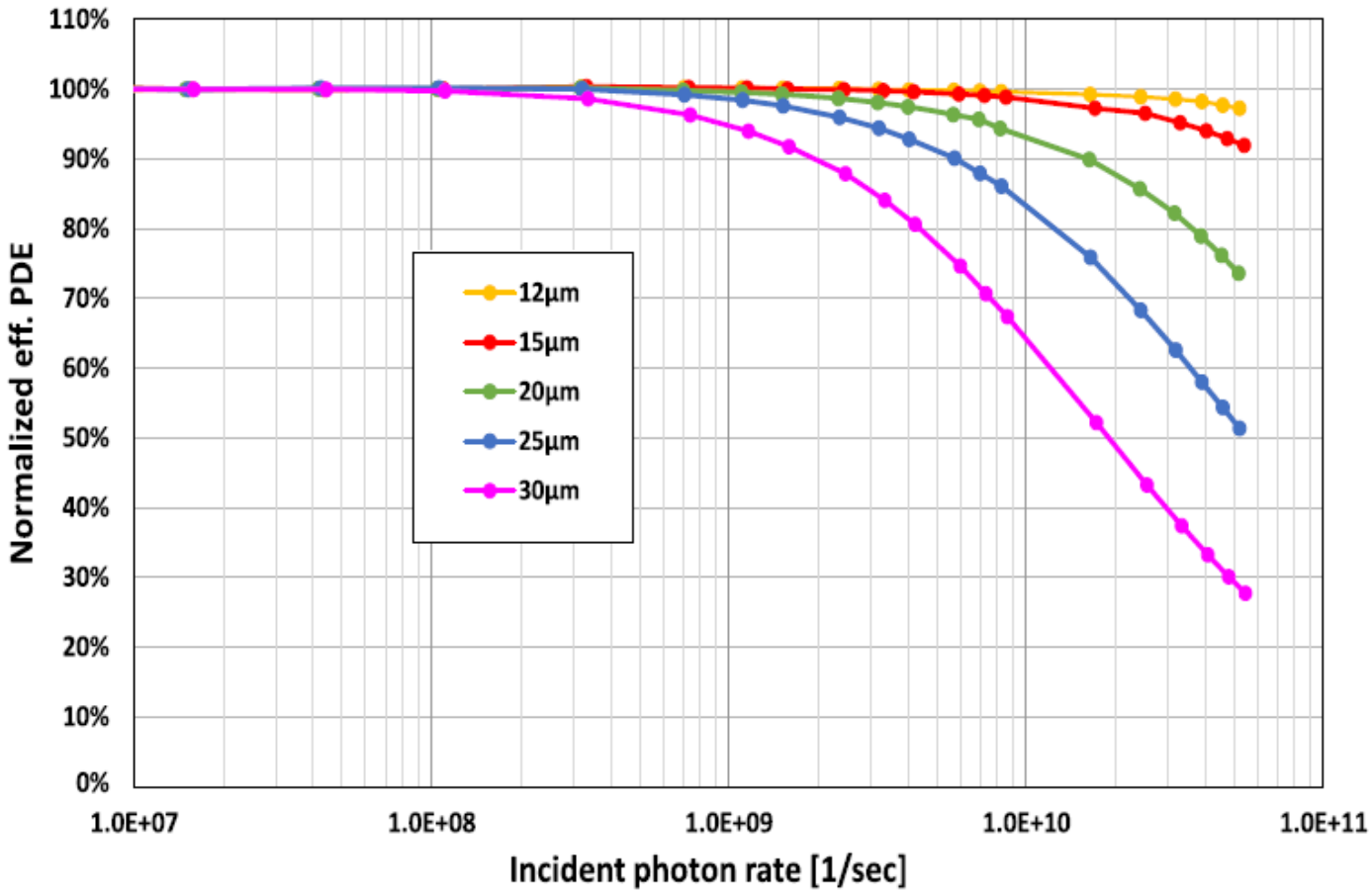
Photon detection efficiency

35µm cell pitch





Linearity test (photocurrent)

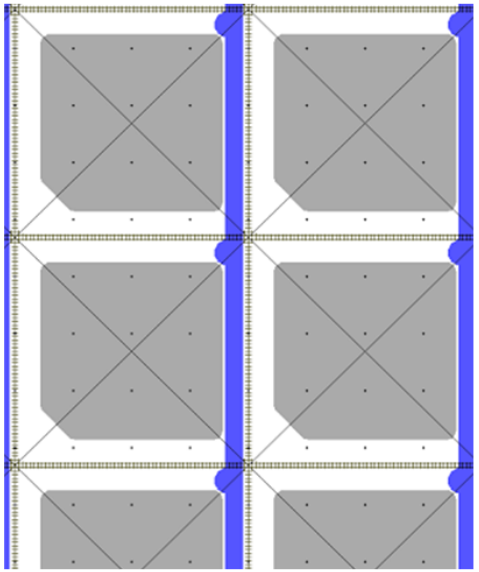


Smaller cells → higher linearity:
higher number of cell per area
& faster recharge of each cell
& lower correlated noise.

*** Measured on RGB-HD technology*
(from I-V curve, vs extracted photon rate from calibrated photodiode)

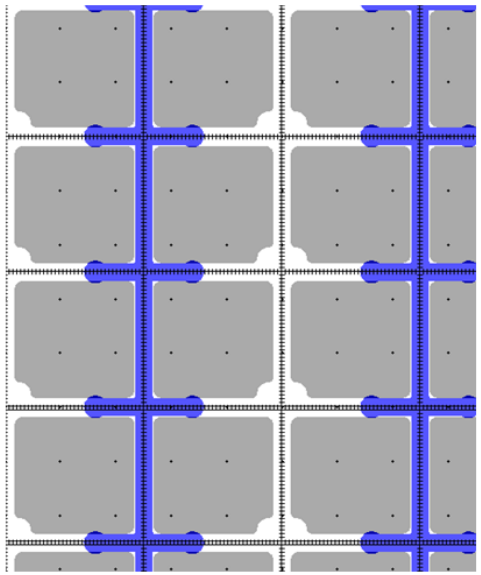
HD and UHD technologies

RGB SiPMs



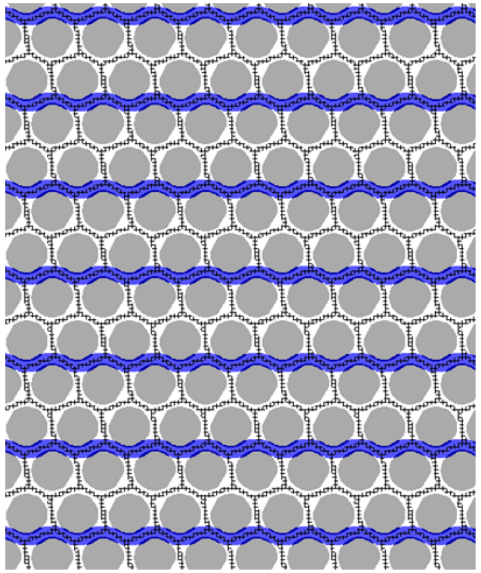
Example with **40 um cell**

RGB-HD SiPMs



Example with **25 um cell**

RGB-UHD SiPMs



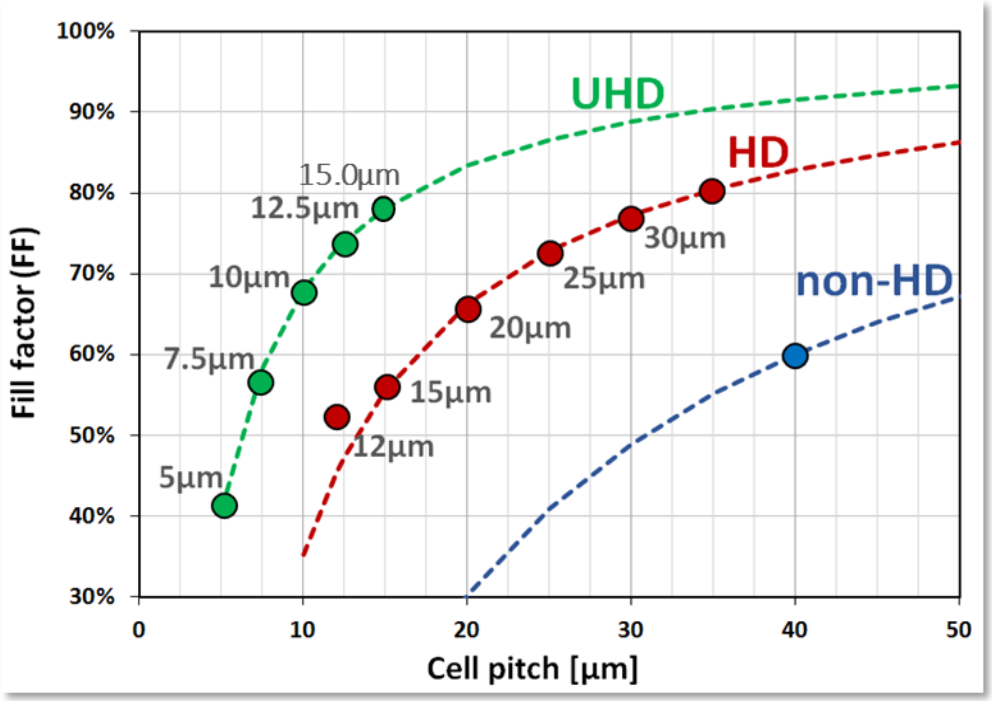
Example with **7.5 um cell**

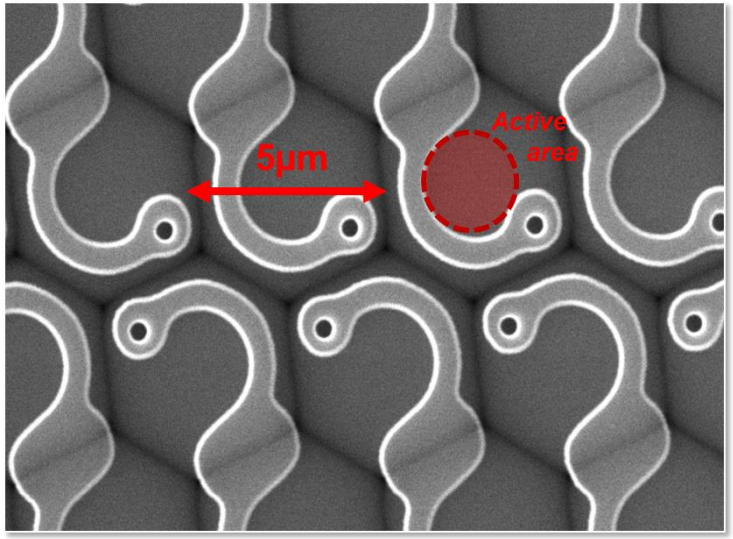
UHD SiPMs → Aggressive layout

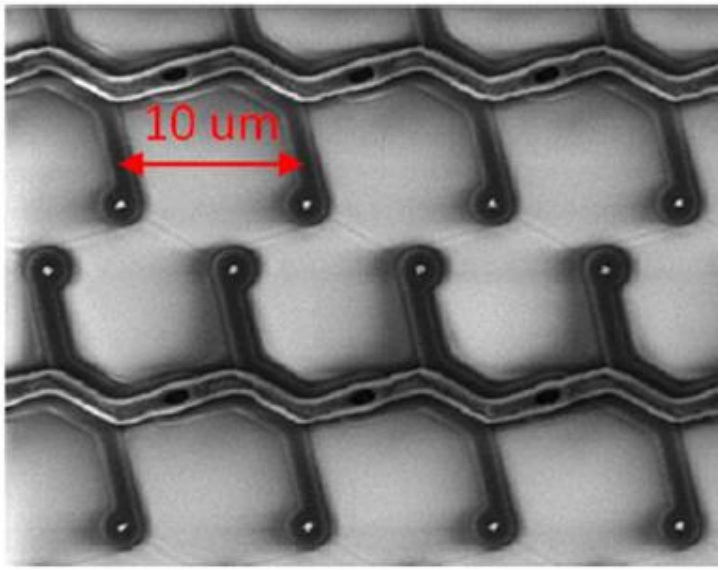
Reduced all the feature size of the process!

Very small cells → 5 µm ÷ 15 µm pitch !

HD and UHD technologies



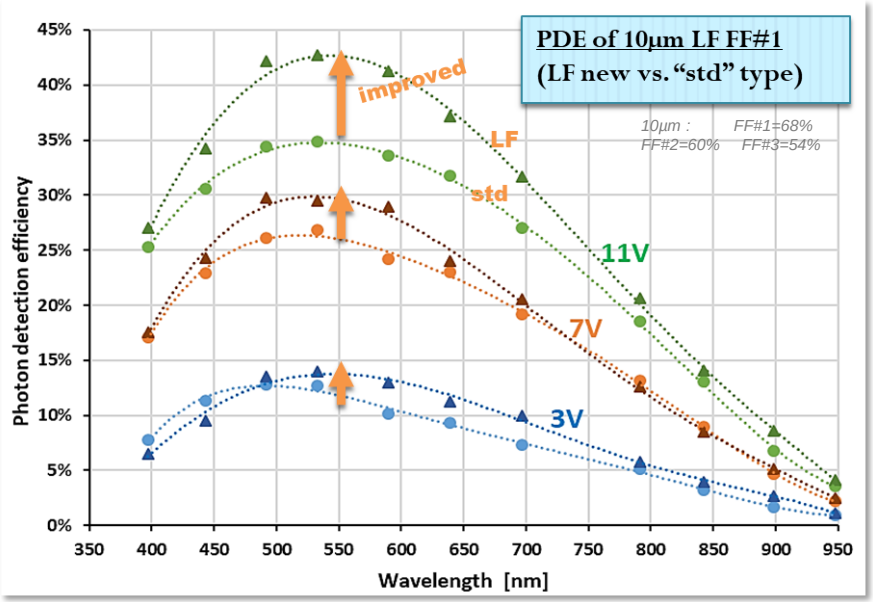


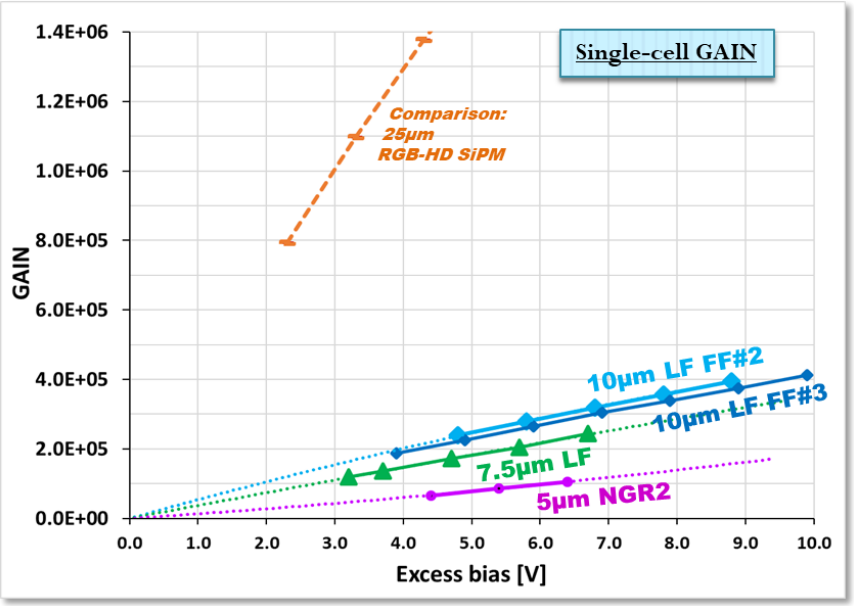


RGB-UHD

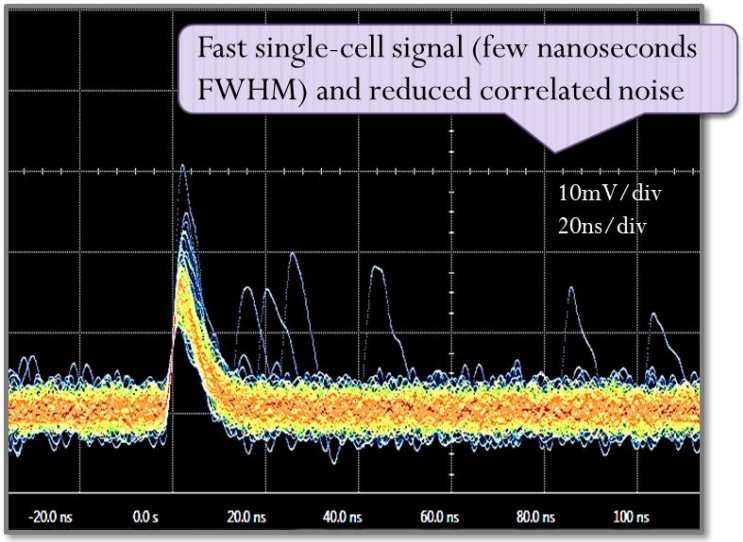
cell size (µm)	cells/mm²
12	7400
10	11550
7.5	20530
5	*46190*

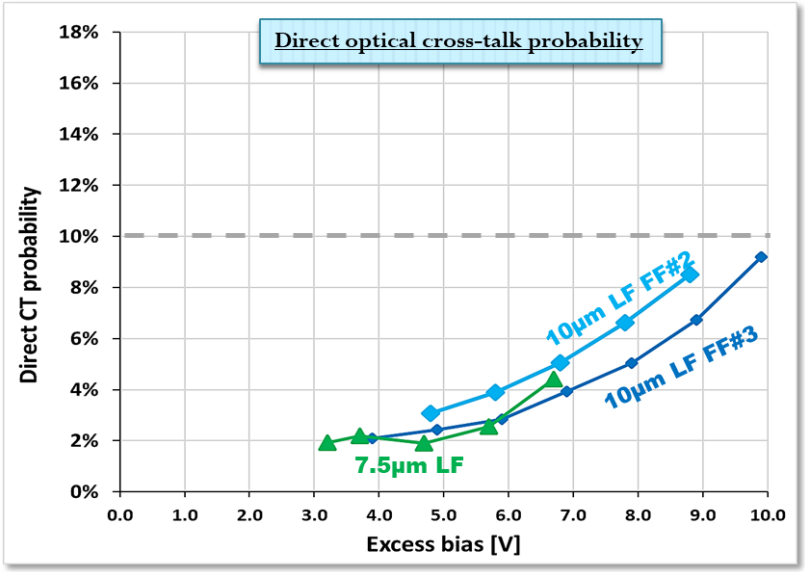
Latest UHD SiPMs: “low-field” and “NGR2”





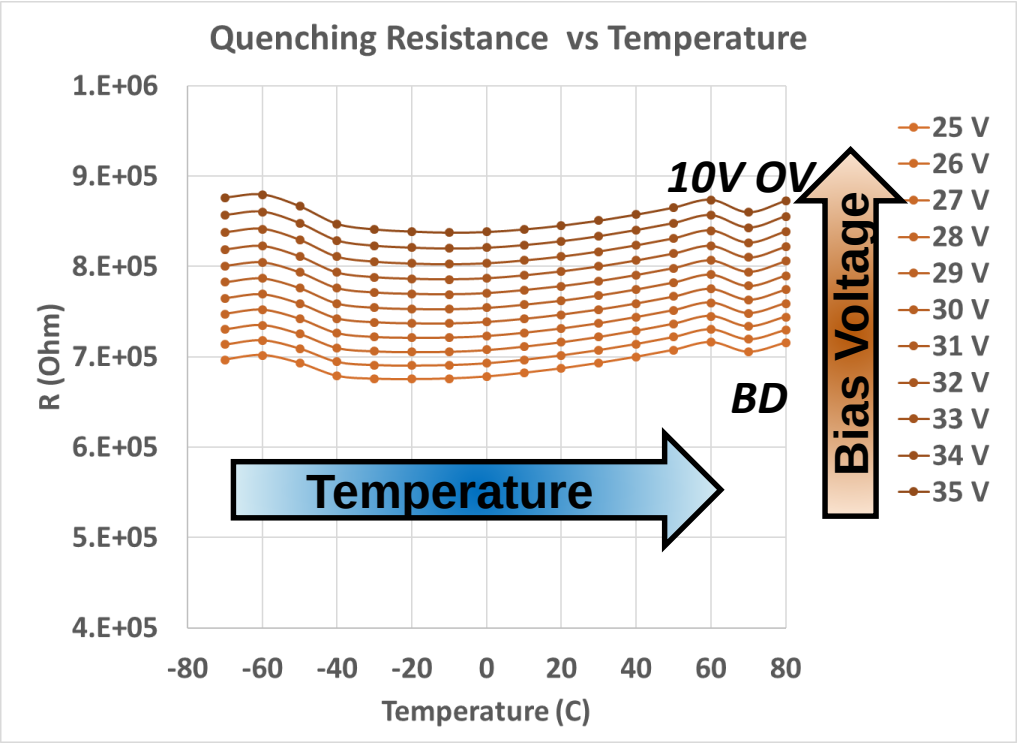
- *DCR ~300÷600 kcps/mm² at 20°C*





SiR - SiPM

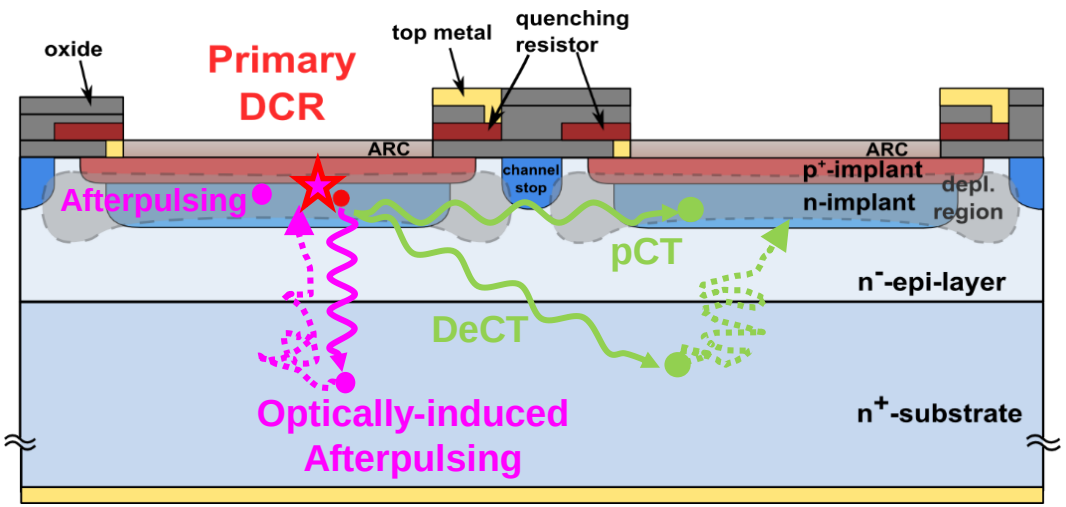
Characterization – Quenching Resistor



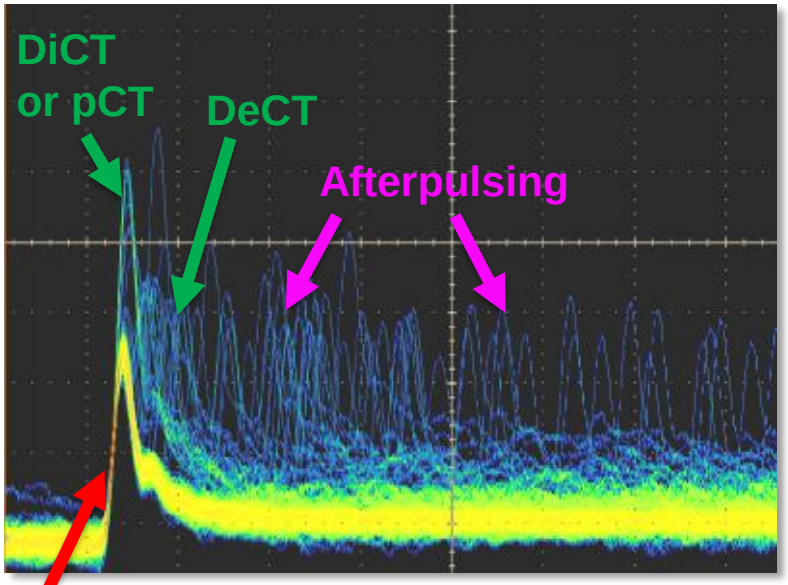
In the operating range the **Rq is almost independent of the temperature** in the range -80C : +80C

Noise in SiPMs

SiPM noise → different components, related to different physical phenomena.



Cross-section of the SiPM microcells.



Primary dark counts

SiPM waveforms acquired with the oscilloscope

DiCT + DeCT + Afterpulsing ➔ correlated noise

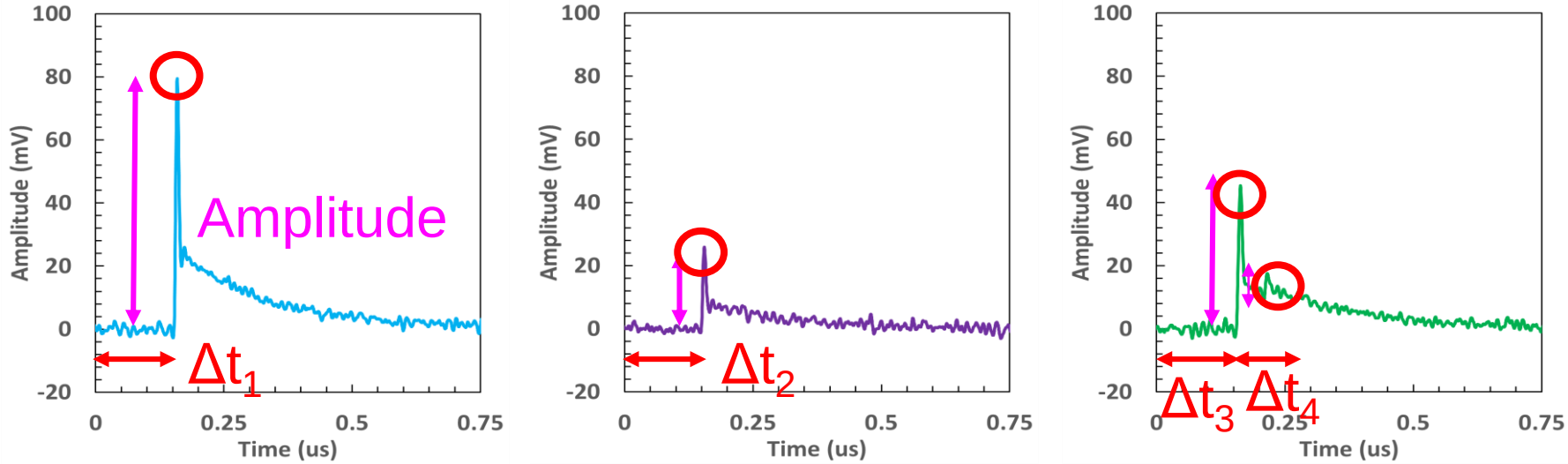
Measurement Technique

- Very low rate of primary events → 1 per second !
- BUT, at the same time → correlated events times: few microseconds
- SOLUTION ➔ oscilloscope acquisition with memory segmentation… to avoid storing unnecessary large amount of "empty" data, when measuring very low DCR.

$$\Delta t_1^{tot} = TS_1 + \Delta t_1$$

$$\Delta t_2^{tot} = TS_2 + \Delta t_2$$

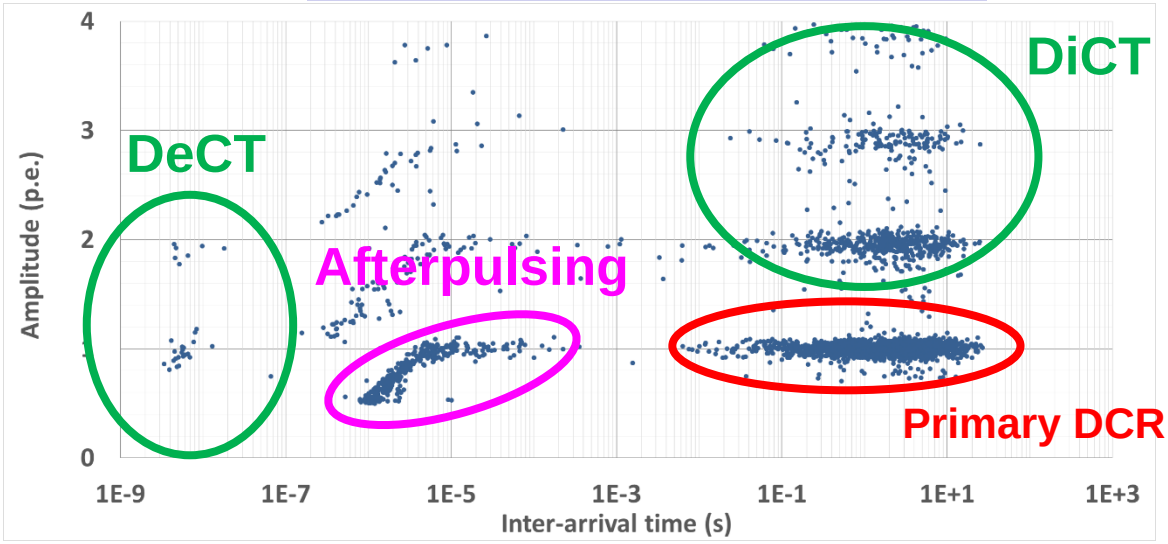
$$\Delta t_3^{tot} = TS_3 + \Delta t_3$$
$$\Delta t_4^{tot} = \Delta t_4$$



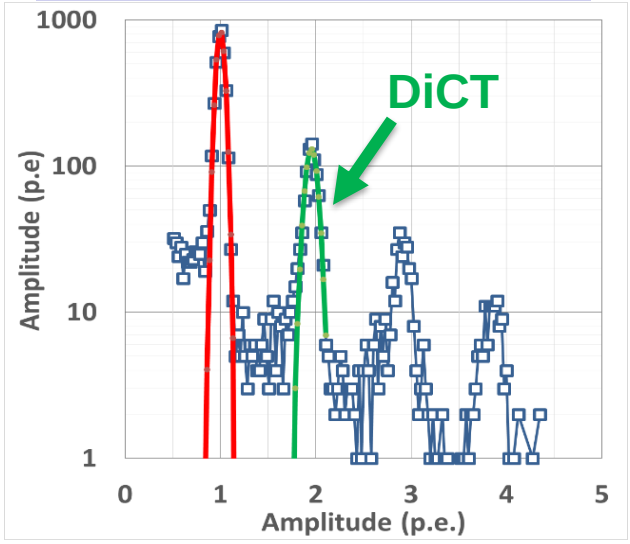
Time-stamp TS_1	Data	Time-stamp TS_2	Data	Time-stamp TS_3	Data

Measurement Technique

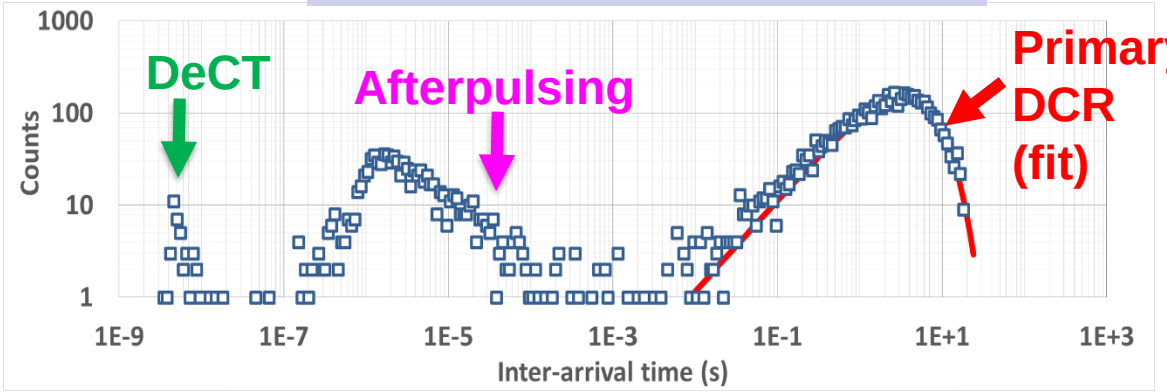
Scatter plot

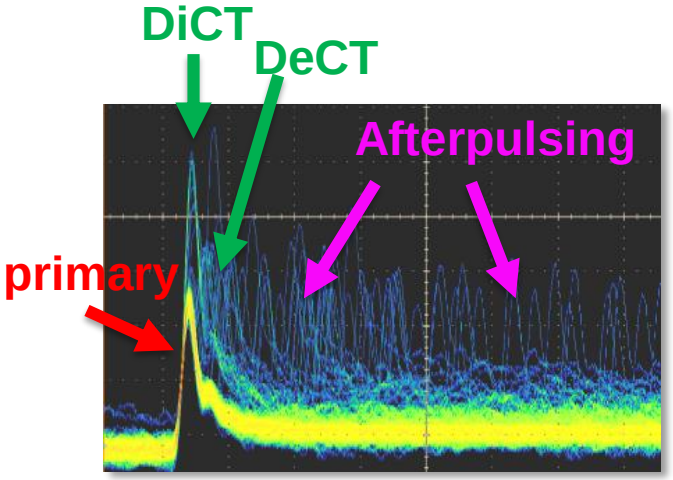


Amplitude histogram



Inter-arrival time histogram





Sensitivity ≥ 12 orders of magnitude!

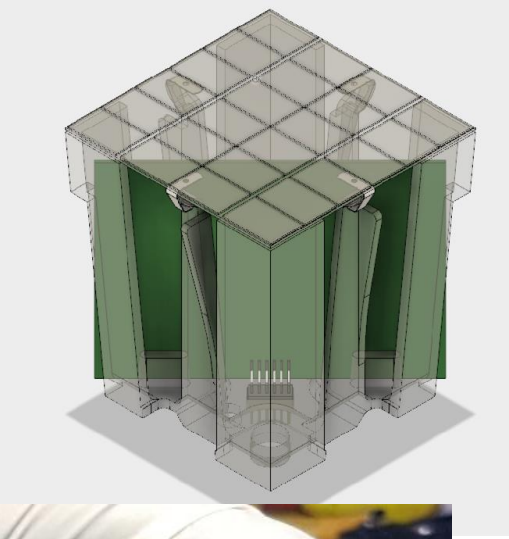
Darkside: New SiPM photo detection module

10000 tiles

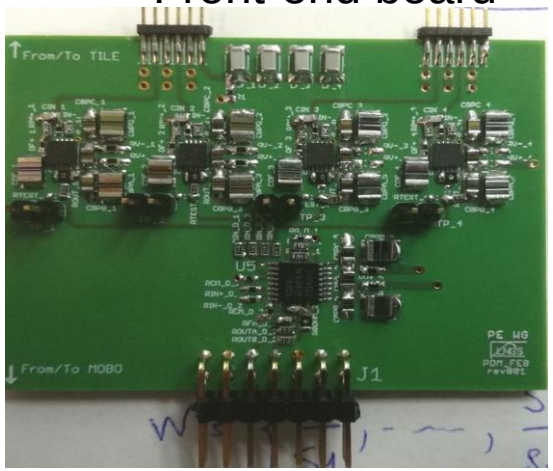
(the final tile will have 24 rectangular SiPMs)

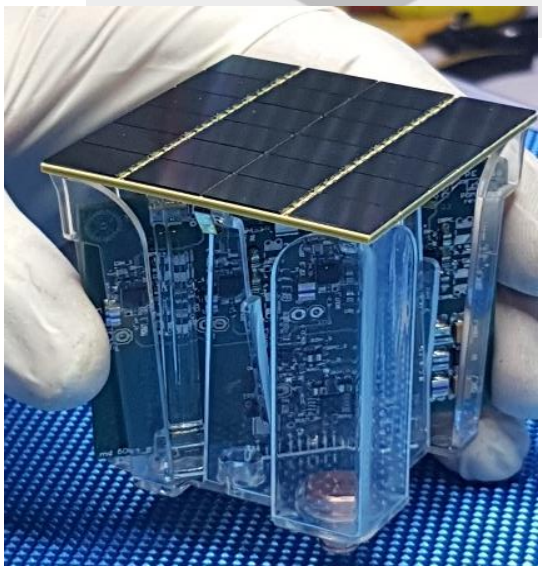
DS – 2k Photo-electronics (PE)

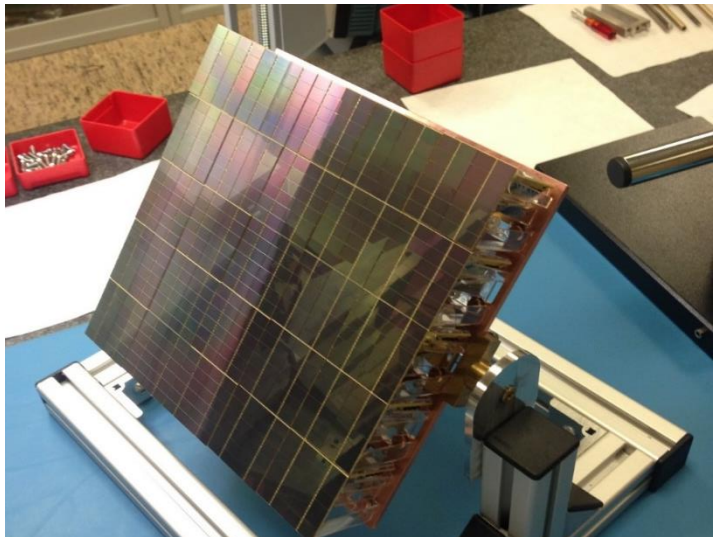
~ 14 m^2 sensitive area



Front-end board







mounted on 220 Motherboards (triangular+ squared (25 PDMs/MB)).