Ultimate Low-Light Level Sensor Development

SiPM mini-school
Ringberg, Tegernsee

SiPM State-of-the-art

Dr. Elena Popova
Moscow Engineering and Physics Institute

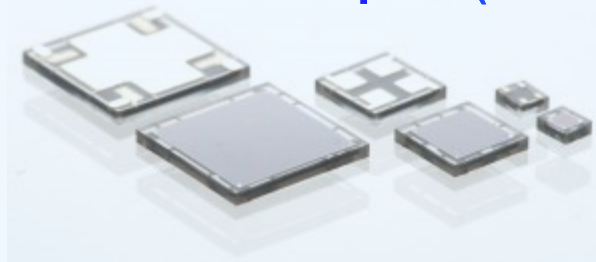
19-21 June 2019

Content

- What is a SiPM?
- Main SiPM parameters
- SiPM Zoo at the time being
- Trends for further SiPM development

Vacuum photomultiplier (PMT)

Silicon Photomultiplier (SiPM)



- **Compactness**
- **Low weight**
- **Low power consumption (~50μW)**
- **Low voltage supply (20-100V)**
- **Fast signal (~1 ns front)**
- **Simple FE electronics**
- **Room temperature operation**
  - **Sensitivity to single photons**
  - **Possibility to measure light intensity**
  - **Excellent amplitude resolution**
  - **Negligible nuclear counting effect**
  - **Immunity to magnetic fields up to 7 T**

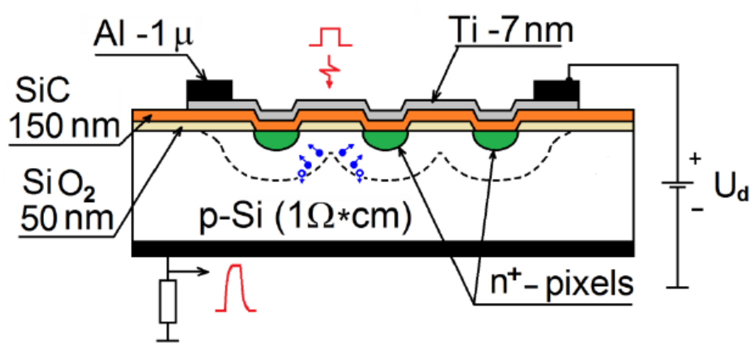
SiPM is a novel type of photon number resolving limited Geiger-mode solid state photodetector

Silicon Photomultiplier (SiPM)

Around 1990 the initial prototypes of SiPM (**MRS** Metal- Resistor Semiconductor APD's) were invented in Russia (*V.Golovin,Z.Sadygov,N.Yusipov (Russian patent#1702831, from10/11/1989)*

This invention was preceded by basic studies of Avalanche with Negative Feedback (ANF) at Lebedev Physical Institute in Moscow) leaded by Dr. V.Shubin concerned to (1970s-1990s)

Avalanche Photodetectors. Vitaly E. Shubin, Dmitry A. Shushakov Encyclopedia of Optical Engineering
DOI: 10.1081/E-EOE 120009727



The first MRS samples had :

- Too difficult and unreproducible technology
- Too low light detection efficiency (of about 1%)
- Unclear operational principle

A.V. Akindinov et al, NIM A 387 (1997) 231

But nevertheless they looked very promising detectors for Experimental Physics due to their ability to detect single photons and moreover to resolve number of photons!

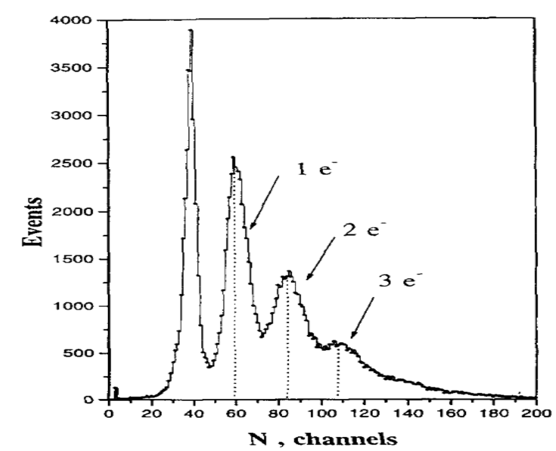


Fig. 3. Pulseheight spectrum from LED at 0°C (epitaxial sample).

Homage of Boris Dolgoshein (1930-2010)

Professor MEPHI

Head of the particle-physics department of MEPHI

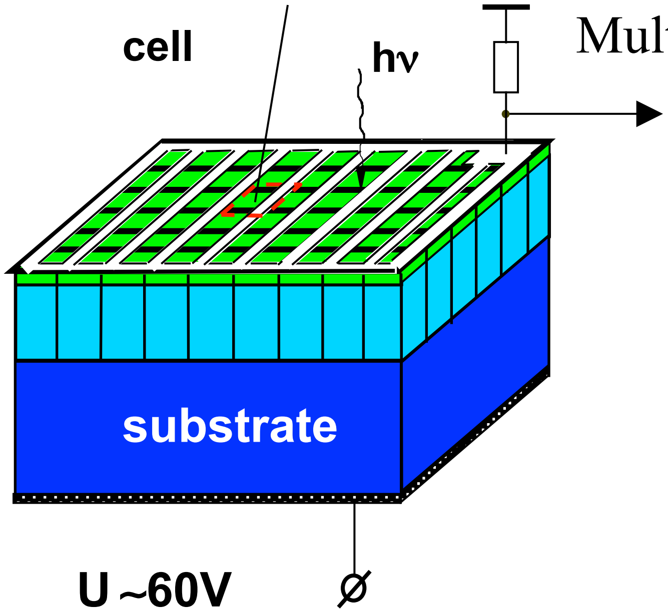
Inventor of streamer chamber (1962)

Developer and pioneer of Transition Radiation Detector (TRD)

prof. Dolgoshein started to develop a novel photodetector which he called Silicon Photomultipliers (SiPM) since 1993

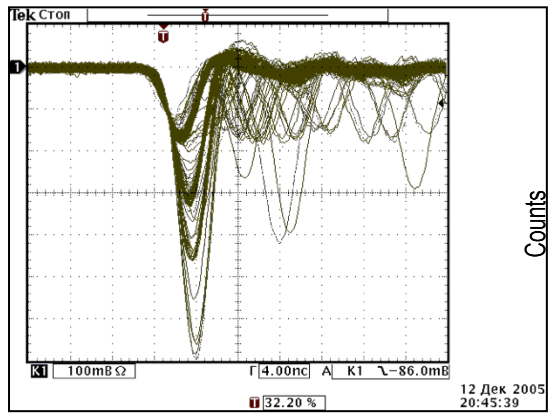
Now we have at MEPHI the well equipped the Silicon Photomultipliers laboratory with ~ 30 employees

Silicon Photomultiplier

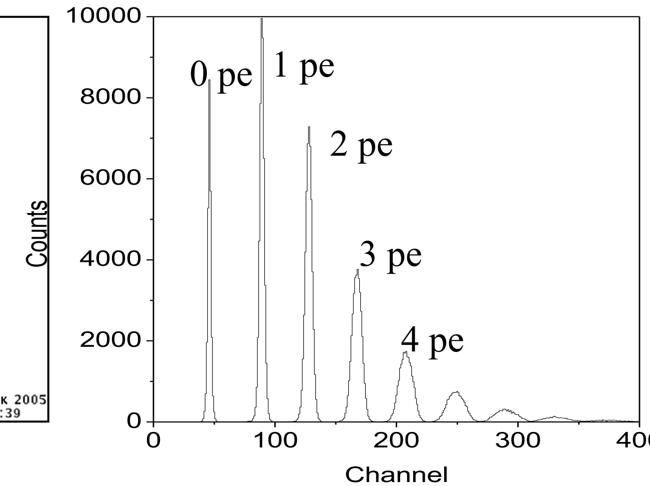


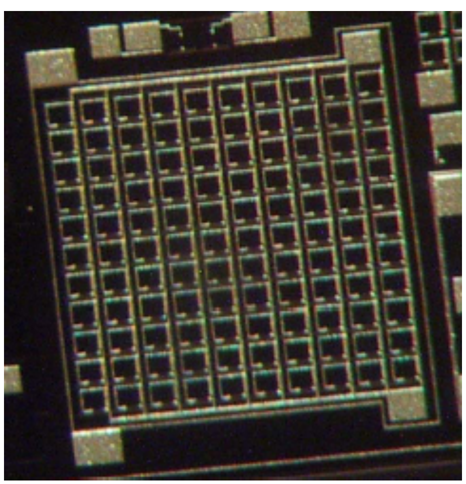
Multicell device with common readout

Scope signal



Amplitude spectrum



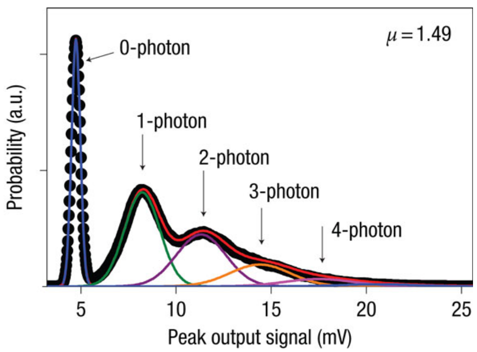


- Each cell – p-n-junction in selfquenching Geiger mode
- cell numbers: ~ 100÷10000/mm^2
- All cells are equal
- Cells are independent from each other
- Signal – is a sum of all fired cells

Cell signal - 0 or 1
But SiPM is analogue device

SiPM: photon number resolution

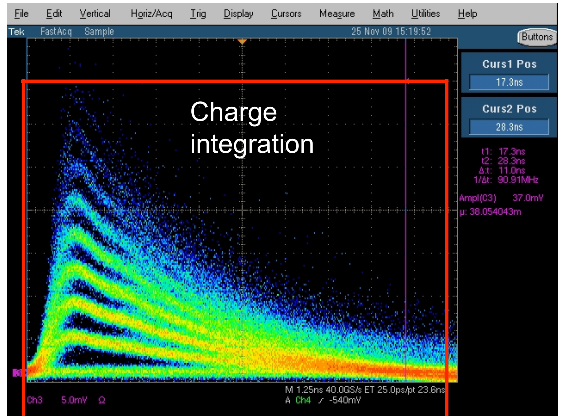
APD (self-differencing mode)



B. Kardinal et al., Nat. Photonics, 2008

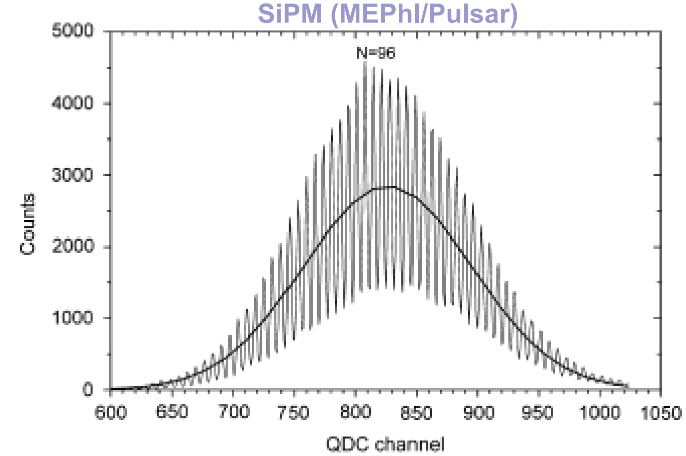
APD QE ~ 80%

SiPM (Hamamatsu MPPC)



SiPM PDE ~ 30%

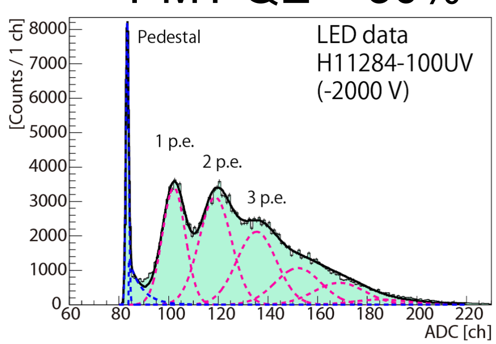
SiPM (MEPhI/Pulsar)



R. Mirzoyan et al., NDIP, 2008

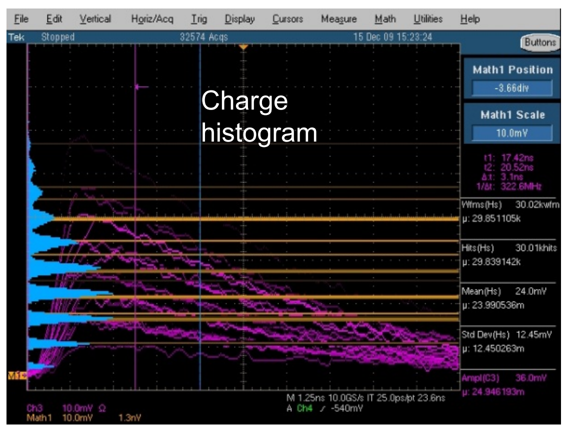
PMT (Hamamatsu H11284-100UV)

PMT QE ~ 30%



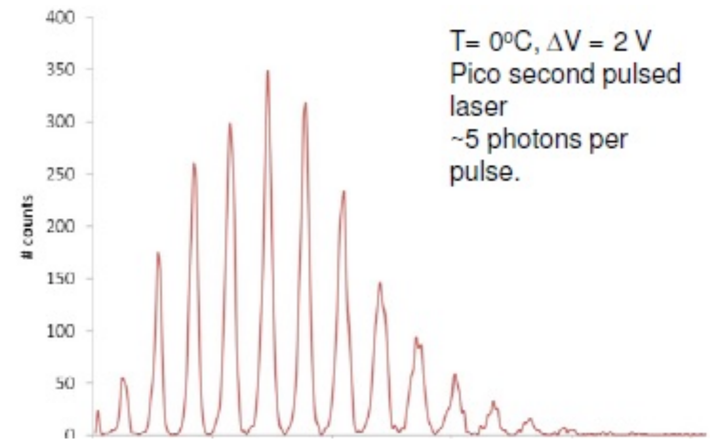
T. Cogami et al, Water Cherenkov detector, NIMA 2016

SiPM (Hamamatsu MPPC)



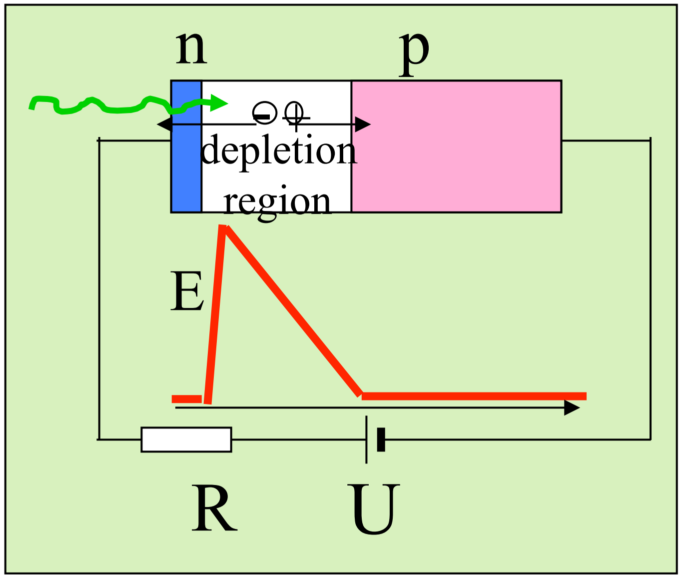
S. Vinogradov, SPIE 2017

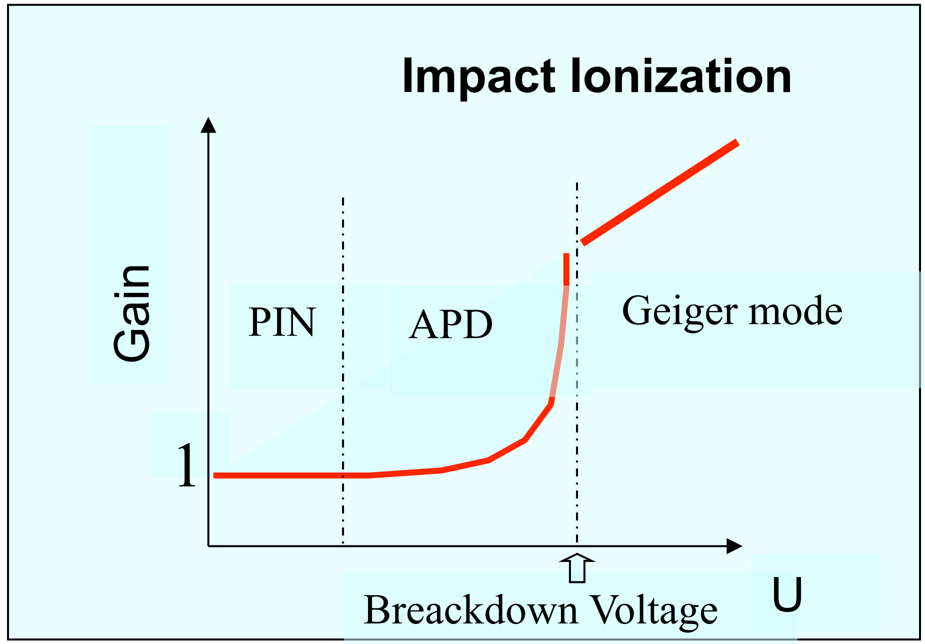
SiPM (Excelitas by MPI/MEPhI license)



A. Barlow and J. Schilz, SiPM matching event, CERN, 2011

p-n-junction based detectors





Geiger discharge

- Output signal doesn't depend from input signal
- Output signal value Q is determined by charge accumulated on a pixel capacitance
- Discharge duration < 1 ns
- self-quenching due to the quenching resistor

$Q = C_{cell} \cdot (V - V_{breakdown})$

$\Delta V = (V - V_{breakdown})$ - overvoltage

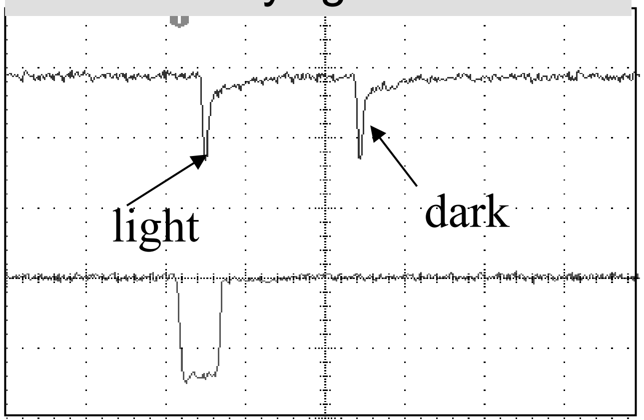
$M = Q/e$ –microcell gain

$M = 10^5 - 10^6$

Silicon Photomultiplier (SiPM)

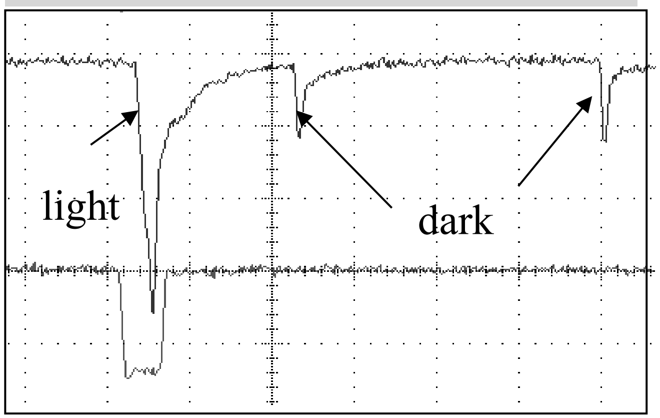
Response function for SiPMs with different microcells numbers

low intensity light

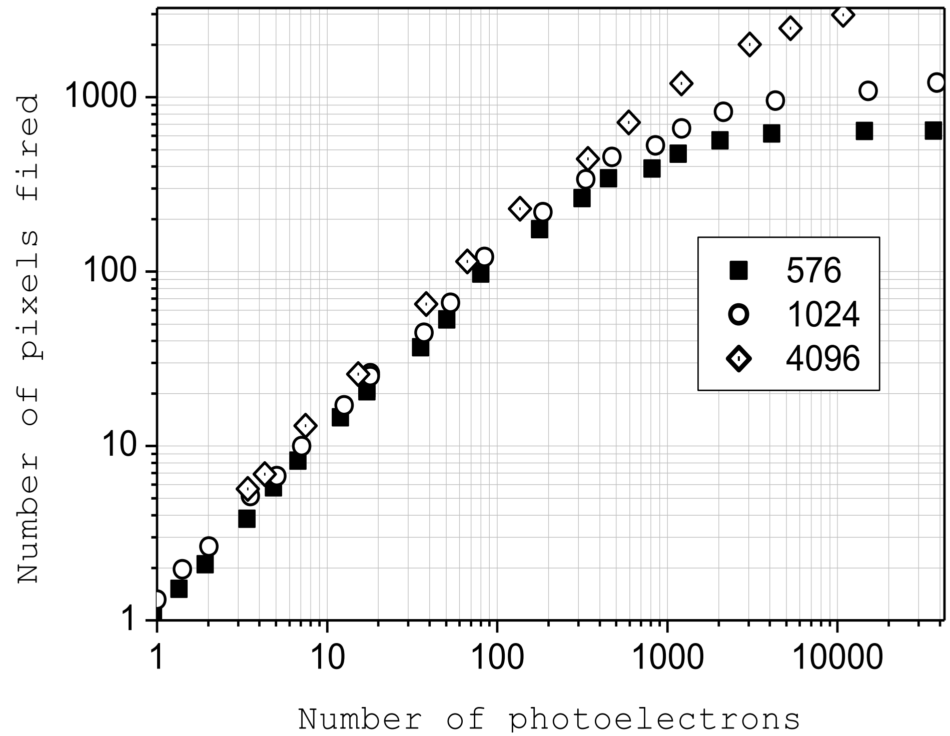


"light" and "dark" signals are identical

more intensive light



V. Andreev et al. / NIM A 540 (2005) 368–380



$$N_{firedcells} = N_{total} \cdot \left[1 - e^{-\frac{N_{photon} \cdot PDE}{N_{total}}} \right]$$

- Response function depends on total number of microcells inside SiPM
- Saturation correction is possible

Main SiPM's parameters

- Photon Detection Efficiency **PDE** ⟹ Primary events

$$PDE = \frac{< N_{fired\_cell} >}{< N_{photons} >} \quad P(n,\lambda) = \frac{\lambda^n e^{-\lambda}}{n!} \quad < N_{cell} > = -\ln P(0, < N_{cell} >)$$

Important – no signal, no crosstalk!!!

- Dark rate **f= <ndark>/T,**

where T – integration time

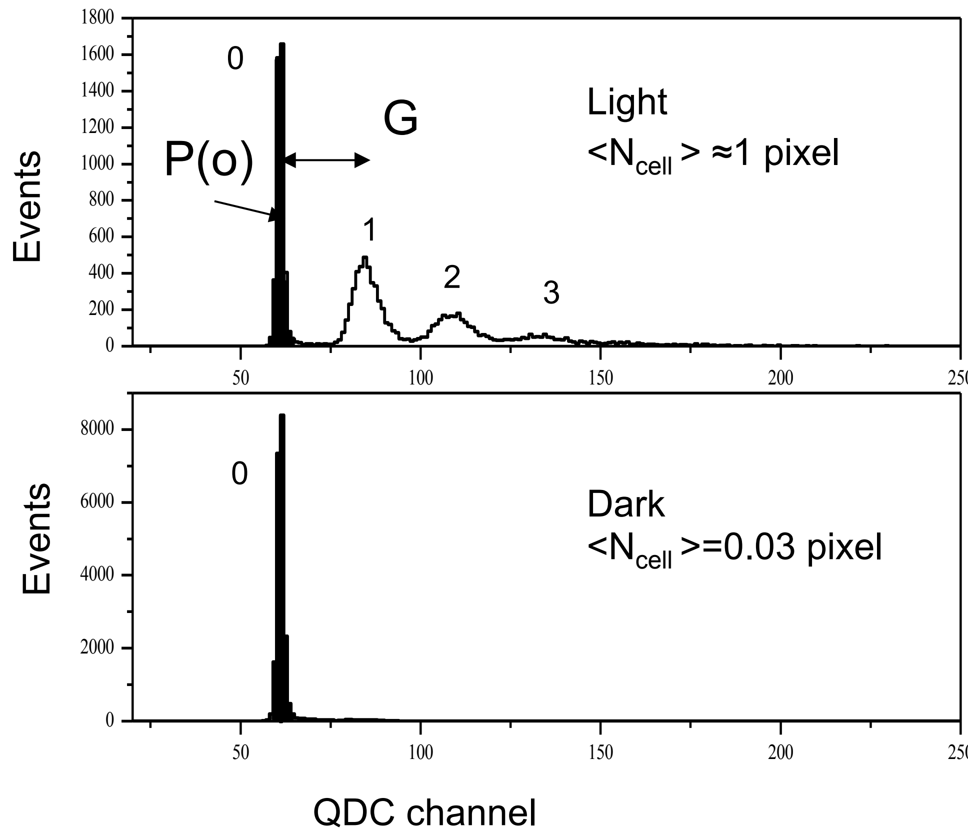
- Gain **G**

- Crosstalk **xt** (afterpulsing **ap**)

⟹ Correlated events

•Intrinsic timing jitter **SPTR**

(single pixel time resolution)



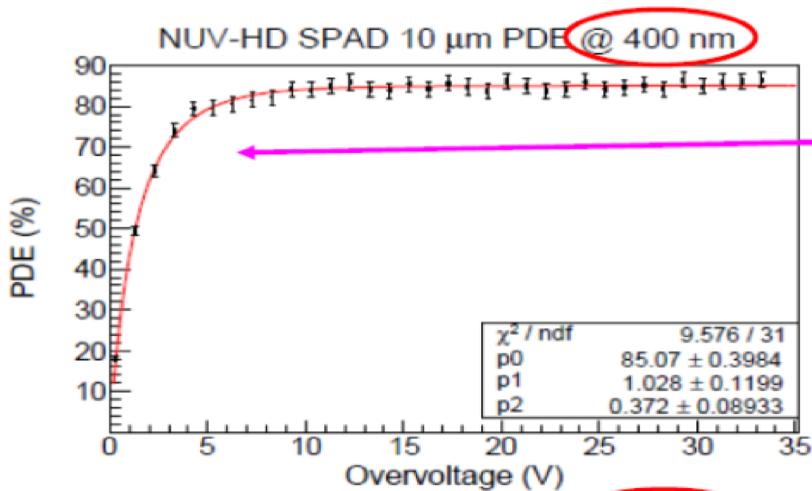
SiPM's single pixel spectra is very useful thing for precise measurements! There are allow us to determine all main SiPM parameters.

Quite important – **PDE**, **gain** and **xt** are measured independently

P.Eckert, et al."Characterisation studies of silicon photomultipliers." Nucl. Instr. Meth. Phys. Res. A620 (2009), 217-226

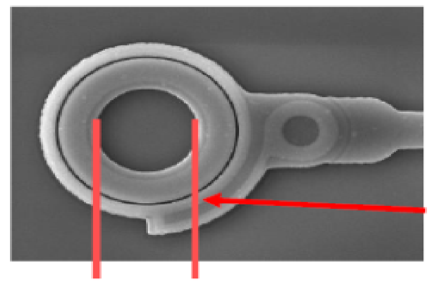
FONDAZIONE BRUNO KESSLER

NUV-HD: QE*Pt

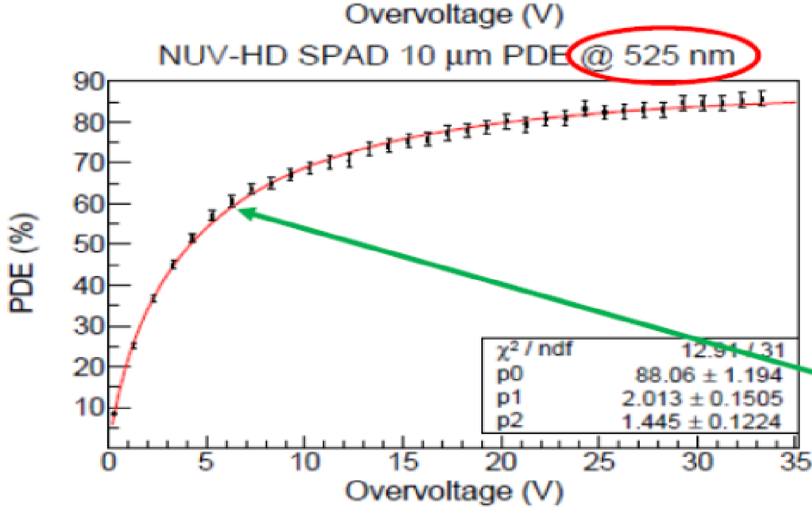


Fast increase with over-voltage:
→ avalanche is initiated by electrons

Measured on a SPAD with 100% FF



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

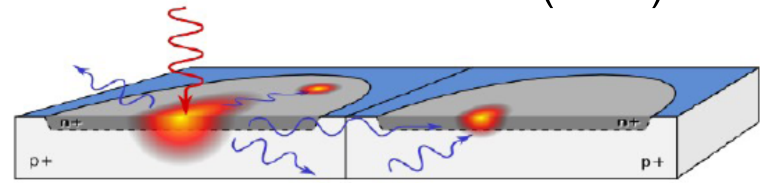


Slower increase with over-voltage:
→ avalanche is initiated by holes (and electrons)

PDE=f(ΔV) we need to apply high overvoltage to reach high value of PDE
Do we have problem here?

Main SiPM's parameters. Crosstalk (XT)

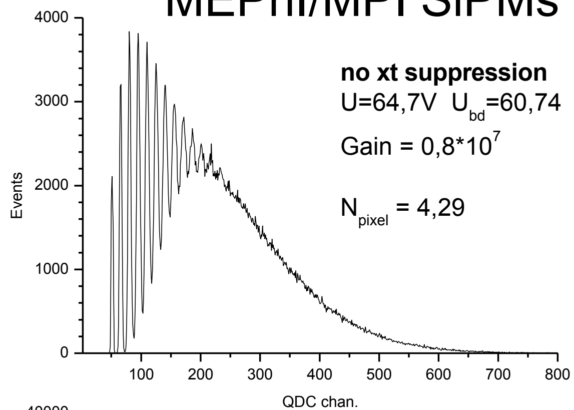
A.Lacaita et al. IEEE TED(1993)

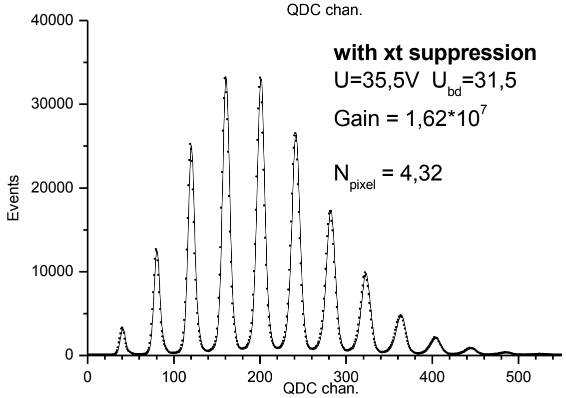


Geiger discharge emits secondary photons

Xt and light signal

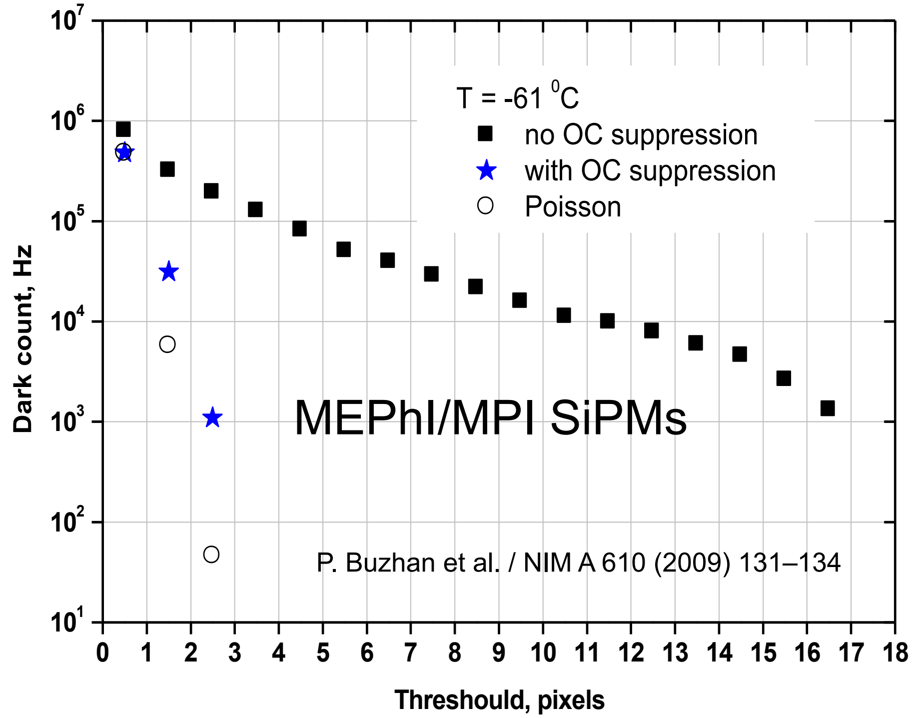
MEPhI/MPI SiPMs





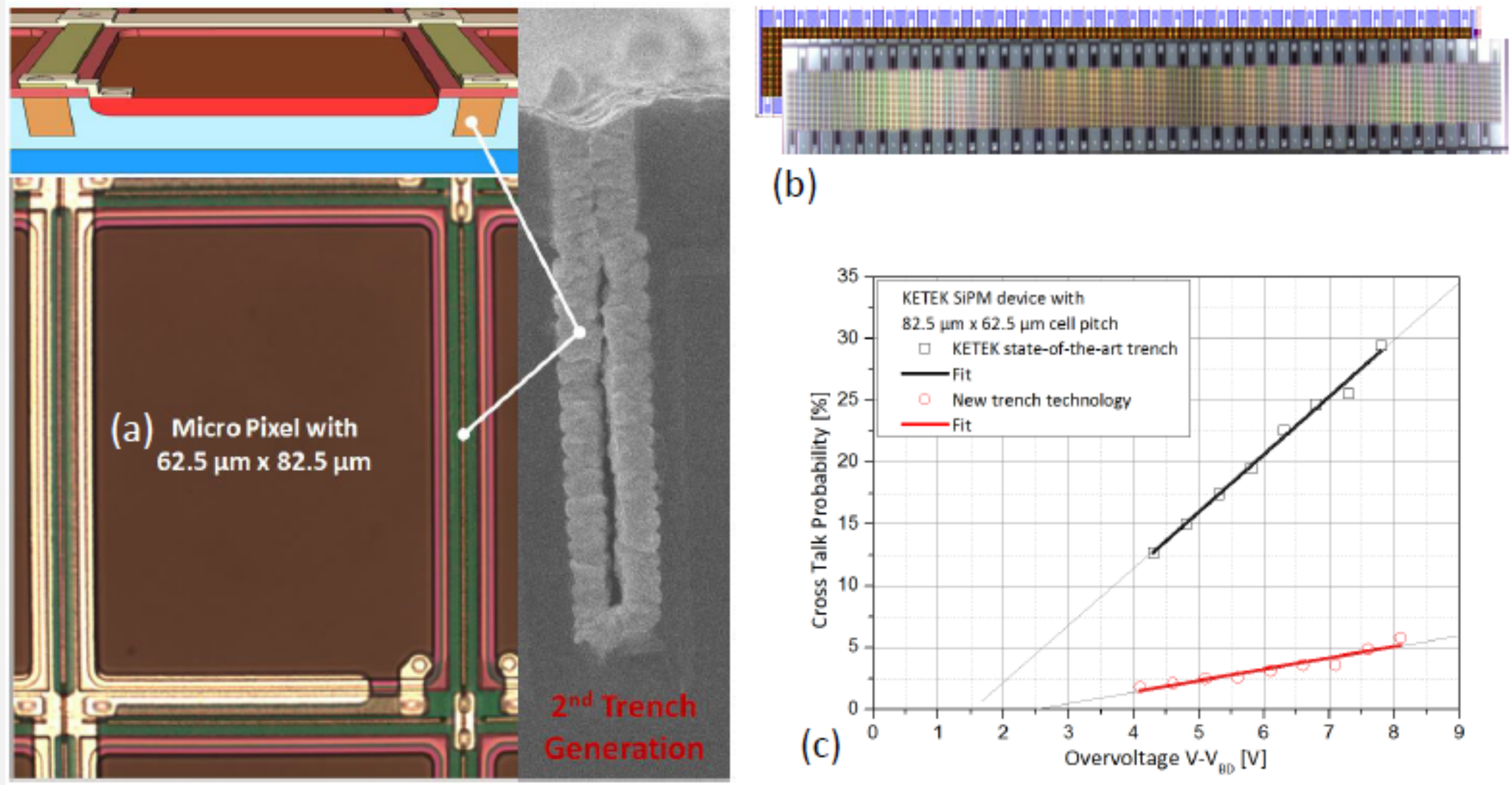
(IMAGING2010 Stockholm, Sweden June 8 – 11, 2010
B.Dolgoshein "Silicon Photomultiplier")

Xt and dark rate



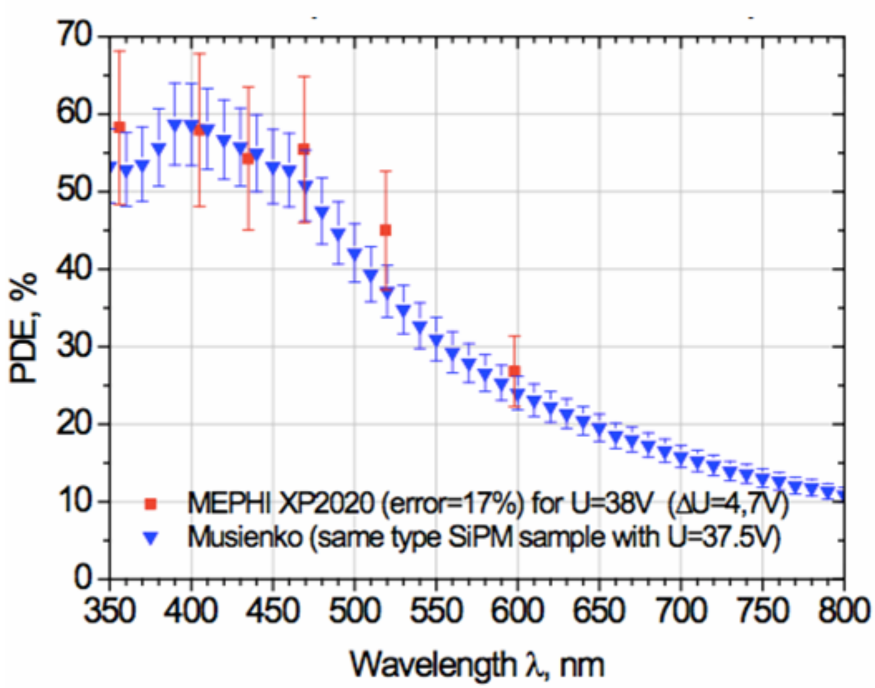
Main protection from crosstalk – optical trenches between the SiPM cells

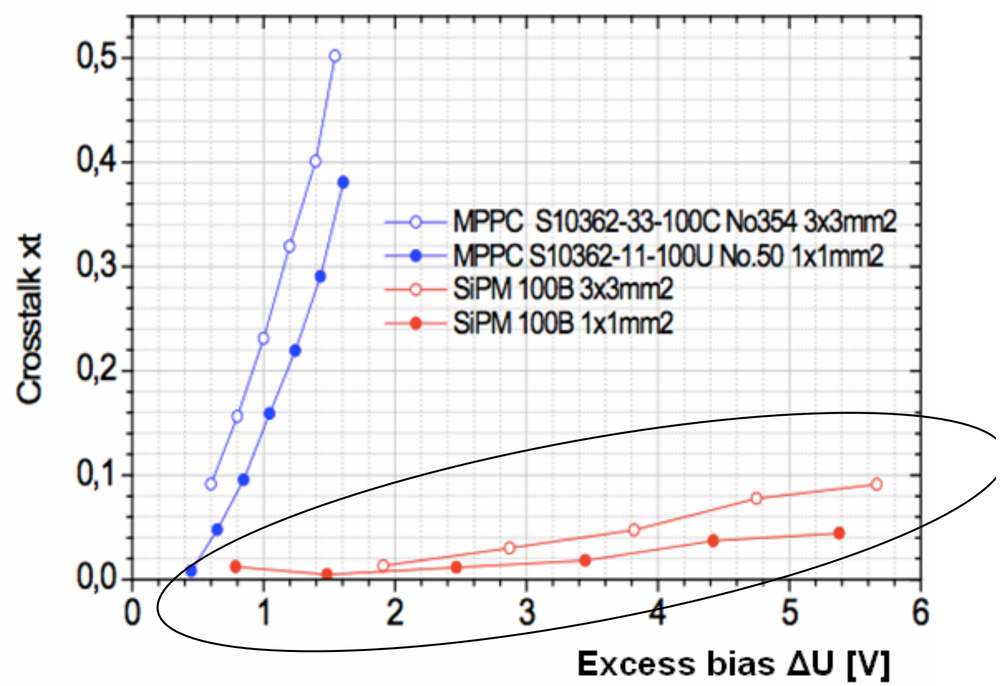
One needs to introduce opaque trenches in-between the SiPM pixels to suppress the optical crosstalk!



F.Wiest NDIP2014

MEPHI-MPI developed SiPMs (2010)
The First demonstration of PDE 60% and crosstalk 3% for 1x1 mm2





Elena Popova, MEPhI (NDIP 2011)

Special SiPM design with 4-fold crosstalk supression

PDE vs. XT

What is better –

- High PDE and high crosstalk?
- Low crosstalk and low PDE?

Of course **High PDE and low crosstalk!**

But you can find quantitative answer in Sergey Vinogradov's SiPM statistical analysis:

S. Vinogradov, Analytical models of probability distribution and excess noise factor of solid state photomultiplier signals with crosstalk, Nucl. Instruments Methods Phys. Res. Sect. A Accel. Spectrometers, Detect. Assoc. Equip. 695 (2012) 247–251. doi:10.1016/j.nima.2011.11.086.
S. Vinogradov et al., Probability distribution and noise factor of solid state photomultiplier signals with cross-talk and afterpulsing, 2009 IEEE Nucl. Sci. Symp. Conf. Rec. (2009) 1496–1500. doi:10.1109/NSSMIC.2009.5402300.
S. Vinogradov et al., Efficiency of Solid State Photomultipliers in Photon Number Resolution, IEEE Trans. Nucl. Sci. 58 (2011) 9–16. doi:10.1109/TNS.2010.2096474.

Excess Noise Factor (ENF) as a measure of noisiness of a process

Input resolution ε_{in} → **Black box** SiPM → output resolution ε_{out}

Input Photons — output pixels

Ex.photon detection

1. **Random input, random output, ε= sigma/Mean**

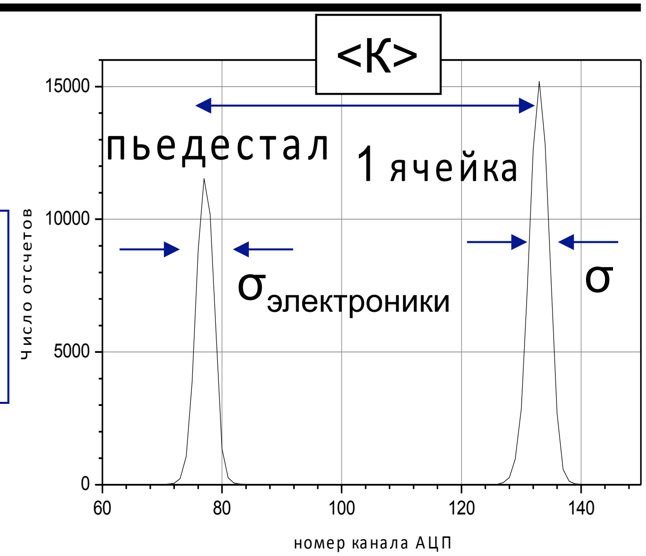
$$\varepsilon_{out} = \sqrt{ENF} * \varepsilon_{in}$$

---

2. Fixed input, random output
Example – single photon response K (gain)

$$ENF_{gain} = \frac{\langle K^2 \rangle}{\langle K \rangle^2} \Rightarrow ENF_{gain} = 1 + \frac{\sigma_1^2}{\langle K \rangle^2}$$

$$\sigma_1 = \sqrt{\sigma^2 - \sigma^2_{electronics}}$$

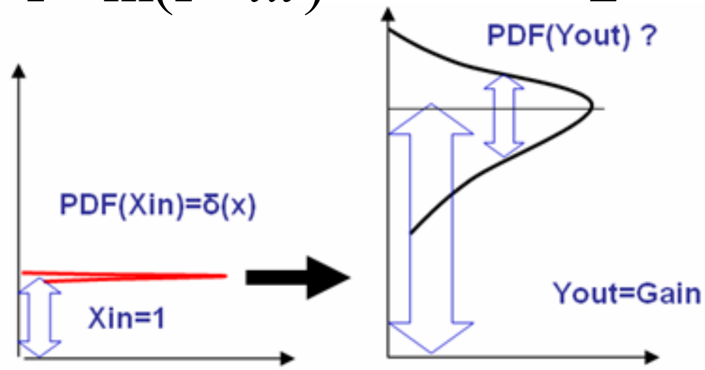


- **Crosstalk**

$$ENF_{xt} = \frac{1}{1 - \ln(1 - xt)} \approx 1 + xt + \frac{3}{2}xt^2 + \ldots$$

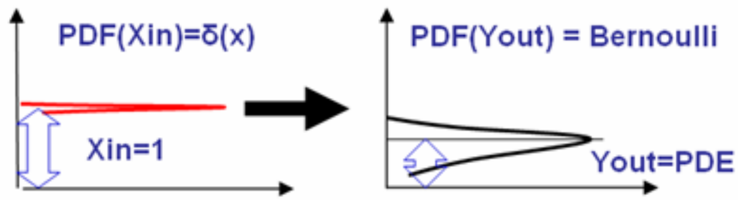
- **Multiplication**

$$ENF_{gain} = 1 + \frac{\sigma^2_{gain}}{\overline{Gain}^2}$$



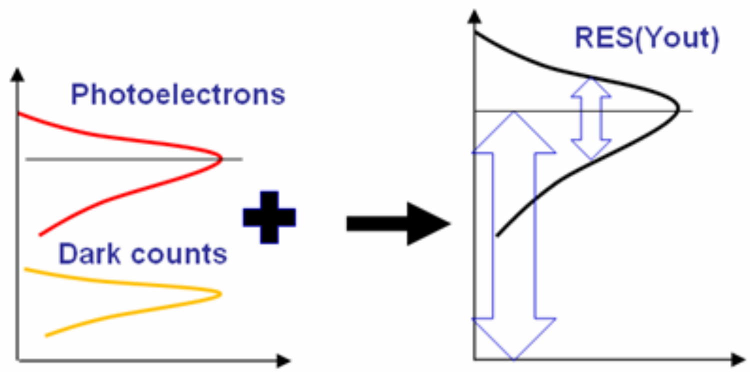
- **Photon detection**

$$ENF_{pde} = 1 + \frac{PDE \cdot (1 - PDE)}{PDE^2} = \frac{1}{PDE}$$



- **Dark counts**

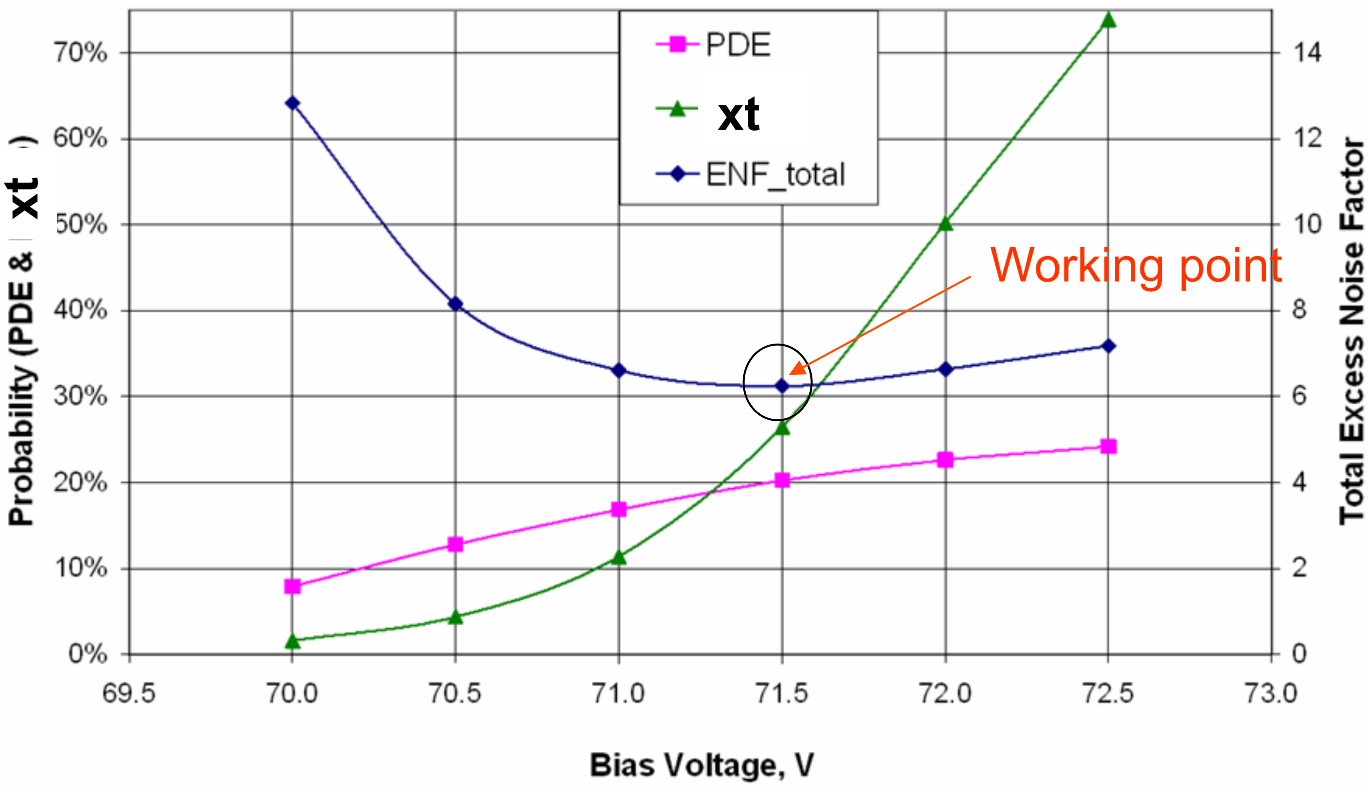
$$ENF_{dcr} = 1 + \frac{DCR \cdot t}{N_{pe}}$$



- **Total ENF for a sequence of specific processes is**

$$RES(Y_{out}) = RES(X_{in}) \cdot \sqrt{ENF_{total}} = RES(X_{in}) \cdot \sqrt{ENF_{process\,1} \cdot ENF_{process\,2} \cdots}$$

PDE &XT overvoltage trade-off



Total ENF based on PDE and P_dup relation (6) in detection of 60 ps 700 photon pulses in 100 ns gate by 1 mm MPPC 1600 pixels (vendor spec. bias 71.2V). S. Vinogradov et al., IEEE NSS/MIC 2009.

Main SiPM producers now

- On Semiconductor (acquires SensL Technologies Ltd.) - worldwide
- Broadcom (license of FBK technology)-worldwide
- Hamamatsu Photonics HPK, Japan
- FBK, Italy
- KETEK GmbH, Germany
- NDL Novel Device Laboratory, China

SiPM Zoo at the time being

The widest range of SiPMs for different applications are offered today by FBK and Hamamatsu

let's consider what types of SiPMs (MPPCs) exist on the example of the Hamamatsu company

2 Ways of development

Industrial

- High volume
- Low cost
- Commercial profit

Scientific

- High performance
- Unique requirements
- Driver for improving of technology

Industrial applications

New MPPC Series

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5

<MPPC Series>	<Application>
S1336x series (UV-VIS : General)	- General use
S1416x series (UV-VIS: Scintillation)	- PET (Positron Emission Tomography) - Radiation monitor
S1442x series (VIS-NIR: Peak shifted)	- Laser microscope - Flow cytometry - Bio-medical
S1372x series (NIR: NIR-enhanced)	- LiDAR (Light Detection and Ranging)

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MPPC Series for Industrial applications

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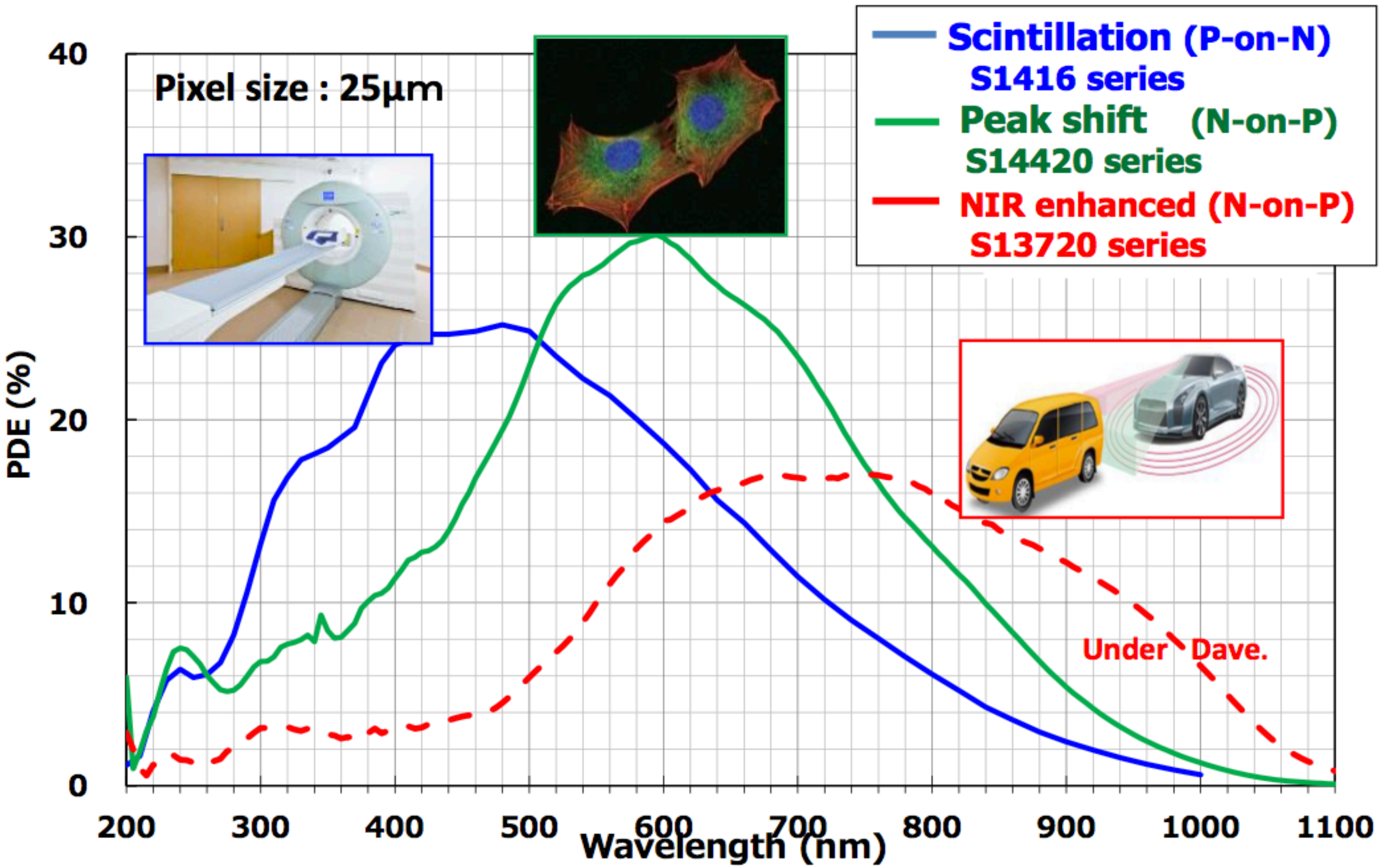

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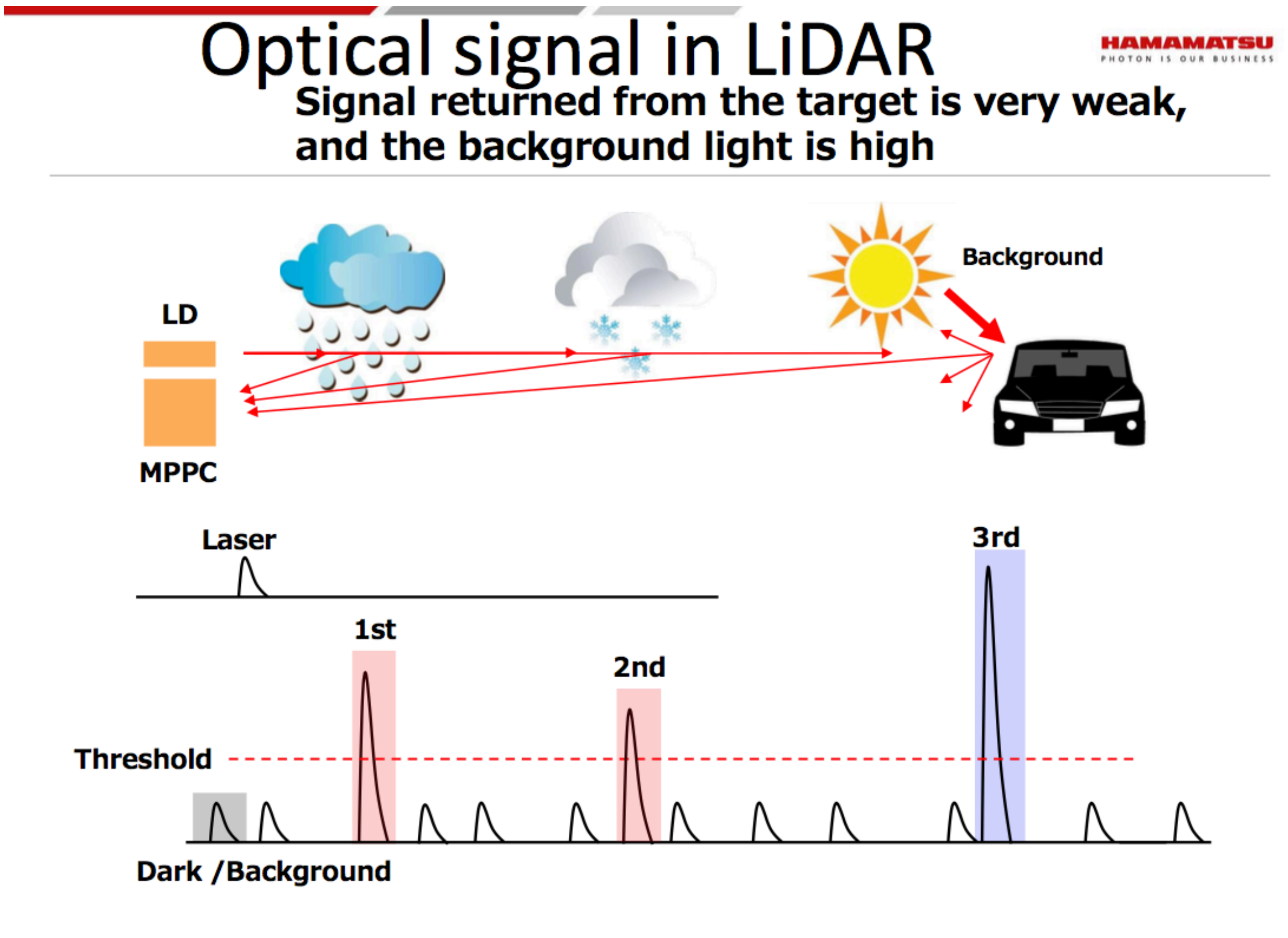
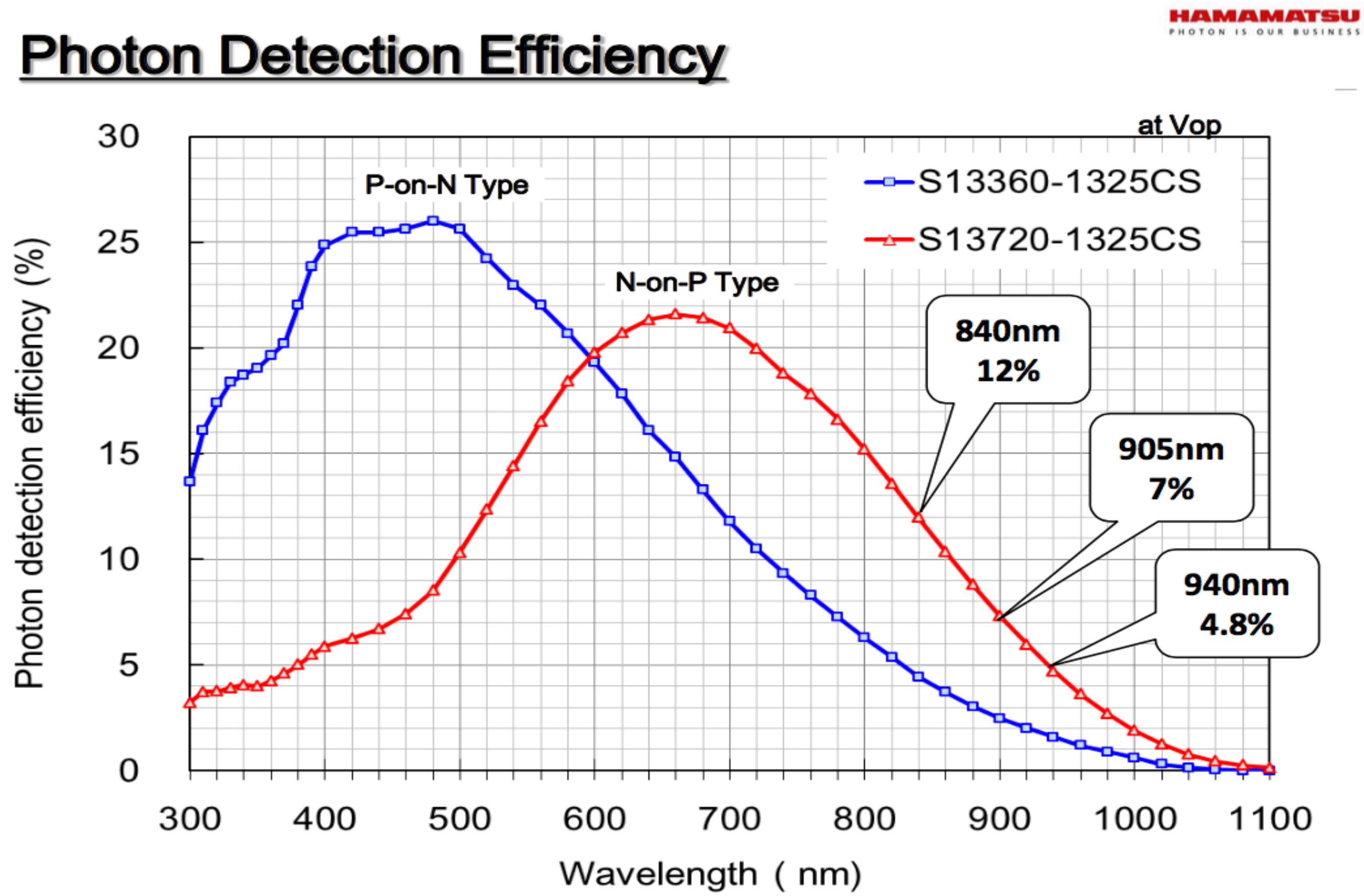
LiDAR : Light Detection and Ranging



Lidar – area of a new SiPM development
Light wavelength 800 nm ~ 1.06 μm – Silicon
Longer wavelength – other non-silicon materials

Photon Detection Efficiency



New development in many companies in order to increase sensitivity to IR light
FBK PDE(905)=12% 35 micron pitch
KETEK PDE(905)=20% 15 micron pitch

To Solid state LiDAR (Flash LiDAR)

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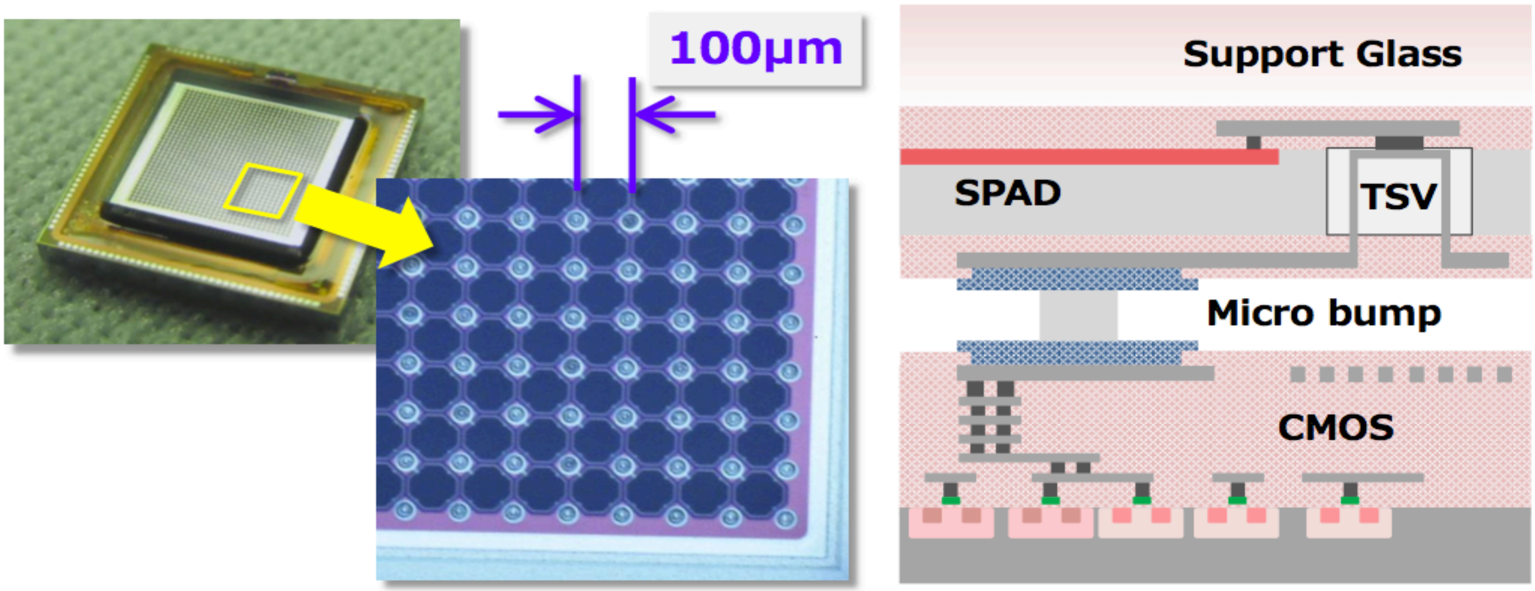
Hybrid photon counting image sensor

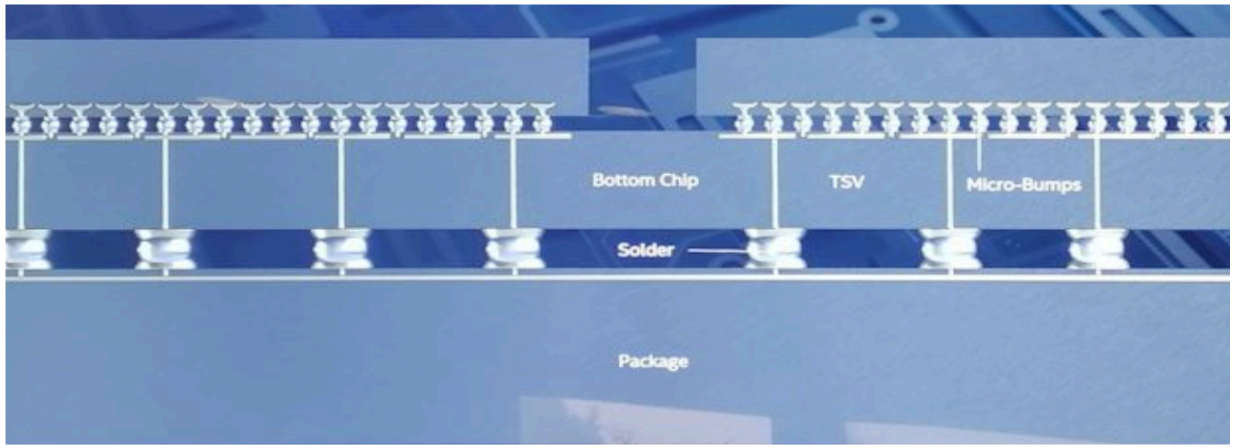


Sectional view

- Sensor and ASIC 2 layer structure
- High aperture ratio >50%
- 100 μm pitch TSV

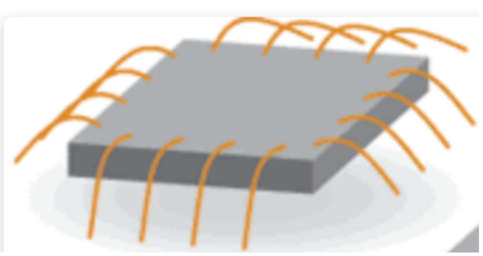
A 3D Flash LIDAR transfers distance and black-and-white video via a single laser pulse with each data frame, where they are captured by a Focal Plane Array of smart pixels.

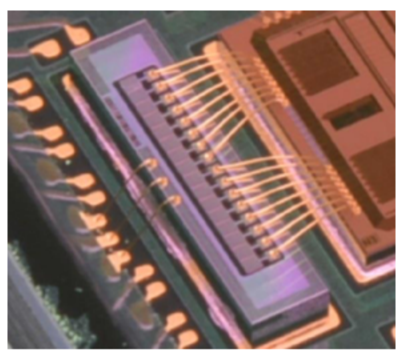
TSV – **through-silicon via** is a vertical electrical connection that passes completely through a silicon wafer or die. TSVs are high performance interconnect techniques used as an alternative to wire-bond and flip chips to create 3D packages and 3D integrated circuits.



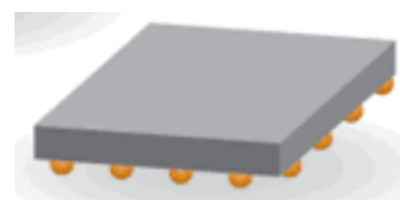
The flip chip ("Reversible assembly") is a method of packaging and interconnection technology for contacting of bare semiconductor chips (Bare die) by means of bump contact - so-called "bumps"

Wire bonding

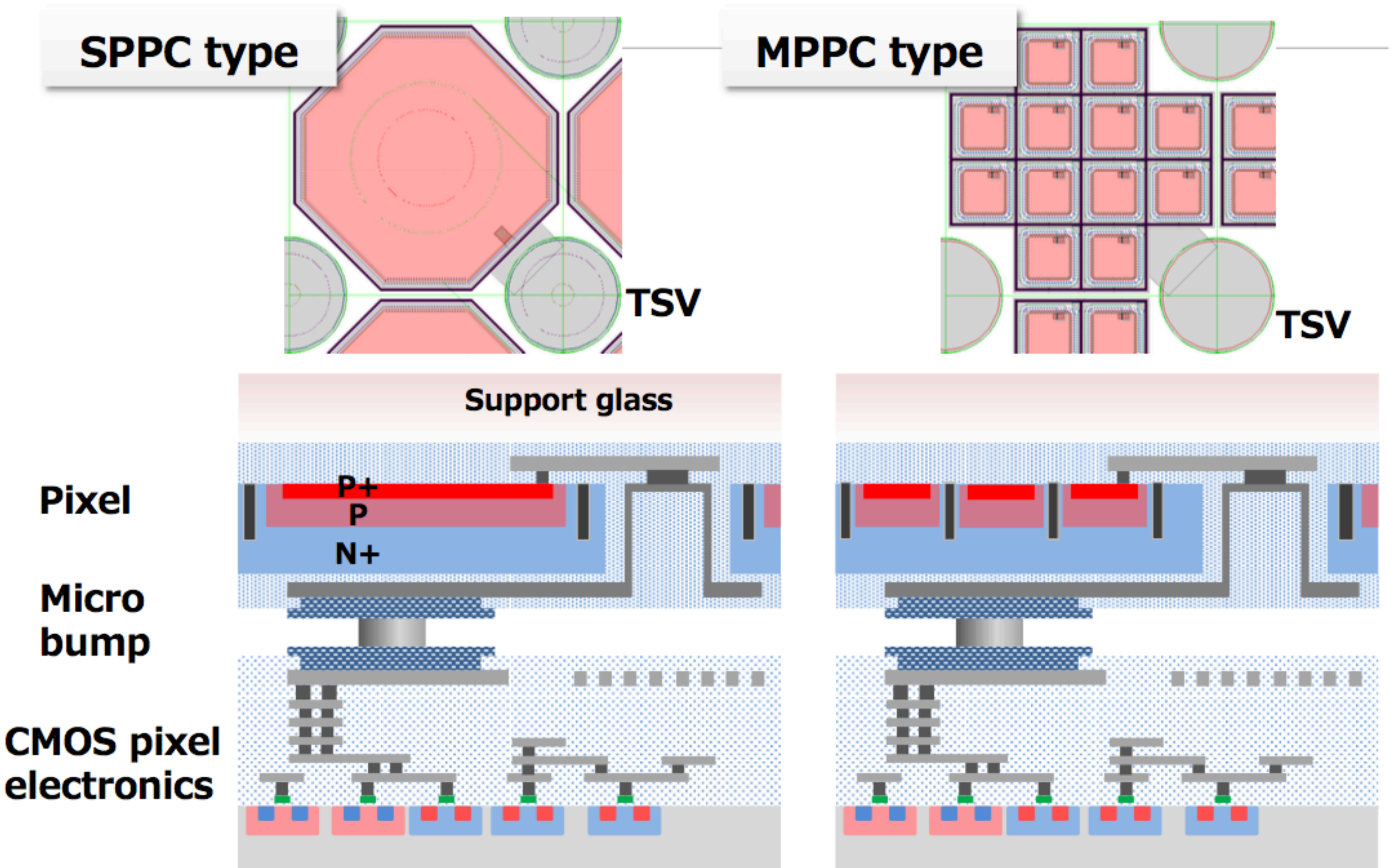




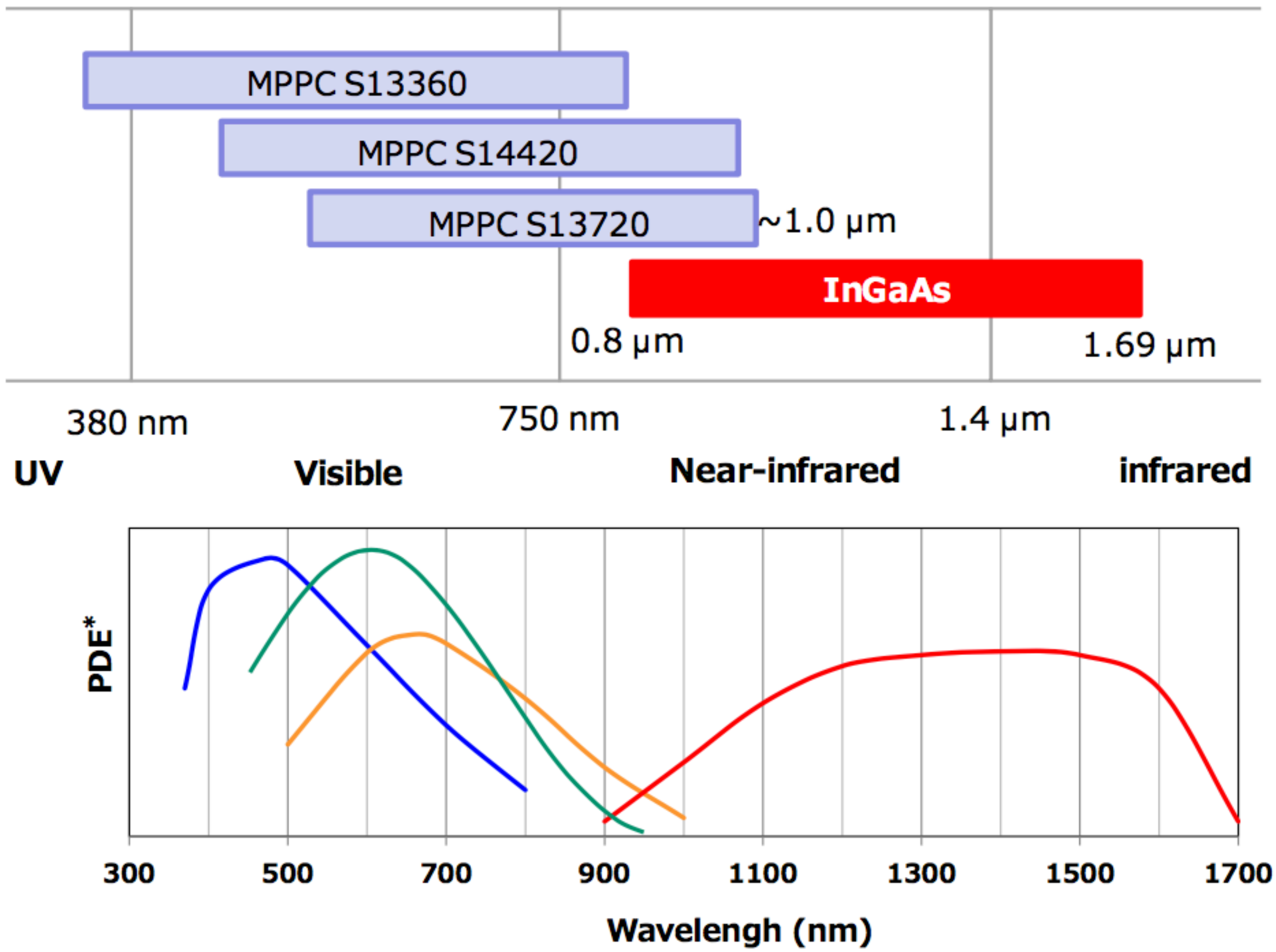
Flip-chip



Si SPAD/Front illuminated MPPC



Si and InGaAs MPPC



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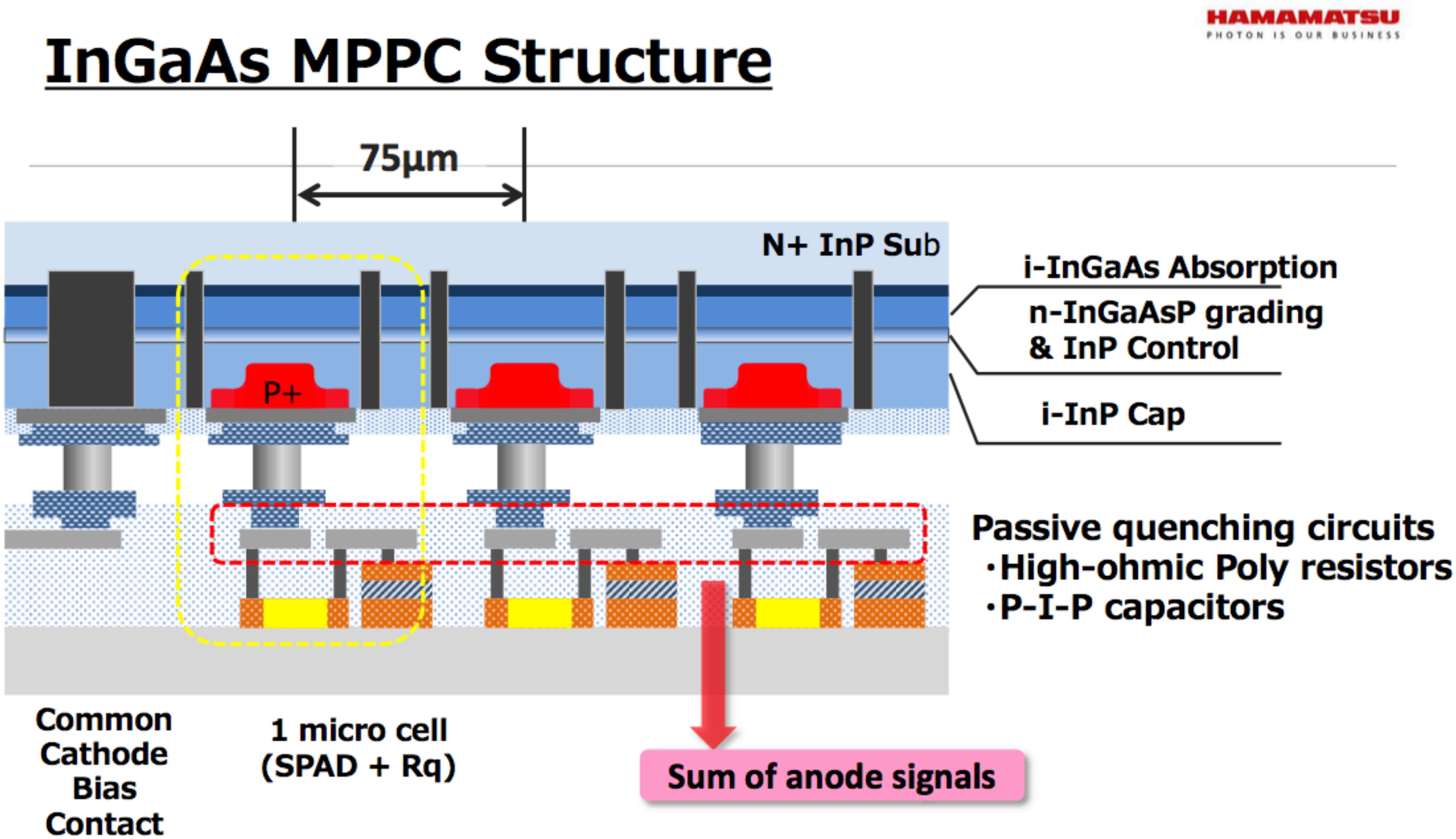
InGaAs MPPC Structure



- This 1st trial design is 3×3 pixel configuration.
- Anode signals from each micro cell are summed and read out as a current signal.

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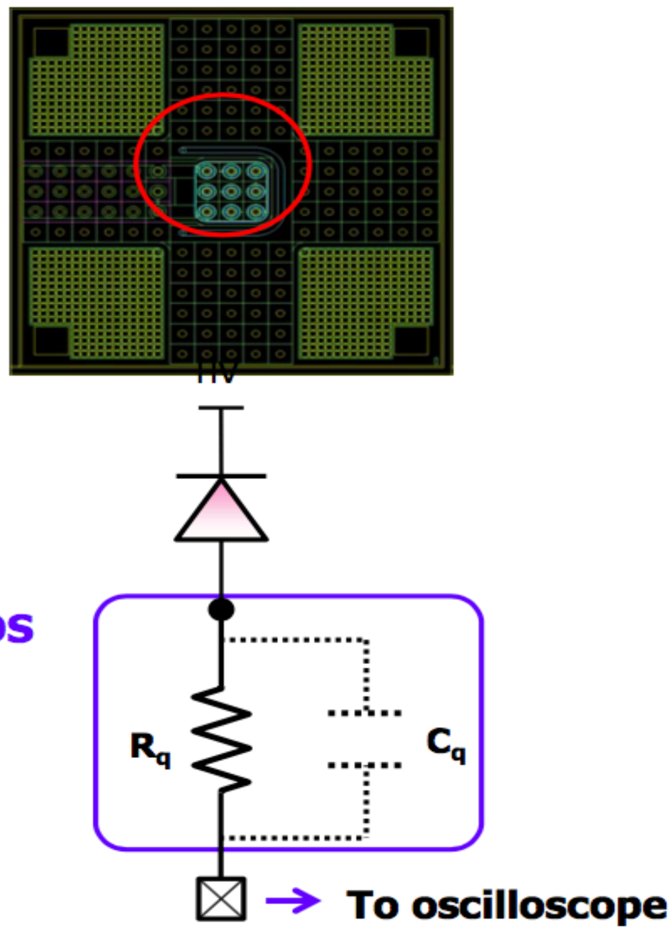
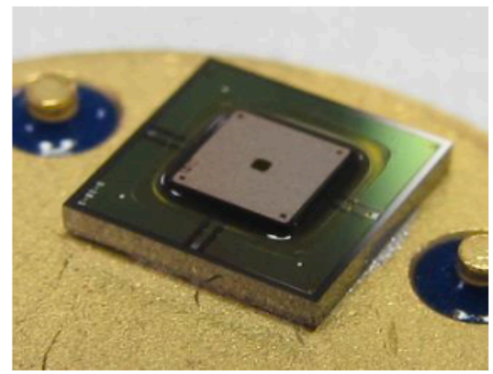
InGaAs-MPPC Development

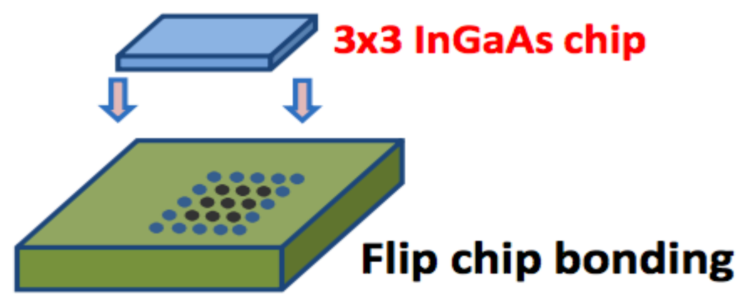
3X3 InGaAs chip



Hybrid Type

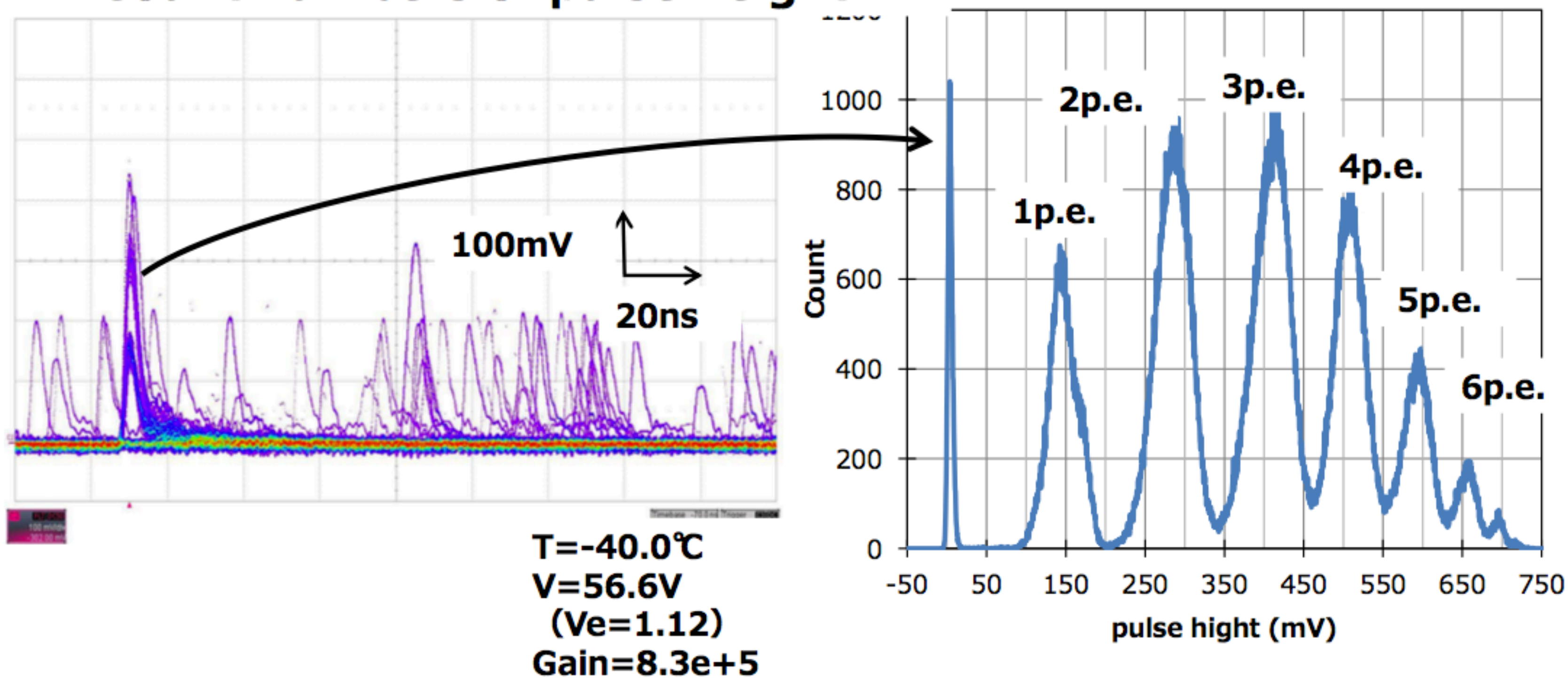
(MPPC chip and ASIC with In bump)





InGaAs-MPPC(Waveform of 3x3 pixel device)

Count numbers of pulse height



We could confirm the basic behavior as MPPC.

New MPPC Series for Scientific Application

<MPPC Series>	<Application>
S1337x series (VUV-MPPC)	- Liq. Xe / Ar scintillation measurement
S1452x series (CTA-MPPC)	- CTA (Cherenkov Telescope Array)
S1416x series (Small microcell: HDR-MPPC)	- Calorie meter - High Dynamic Range measurement

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For Scientific Application

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Dark matter research

VUV MPPC

- High sensitivity for VUV
- Low RI

This presentation is an intermediate, VUV sensitivity increase and new low RI package development are on going

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MPPC : VUV Detection

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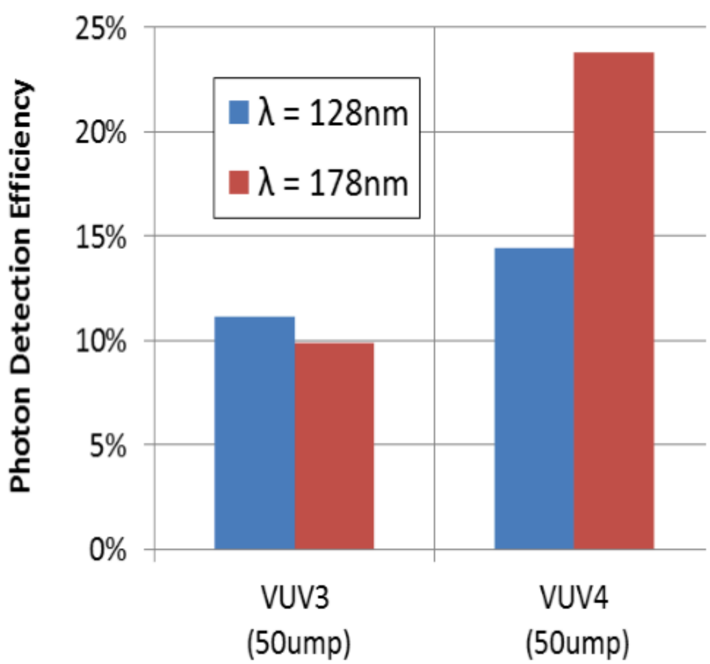
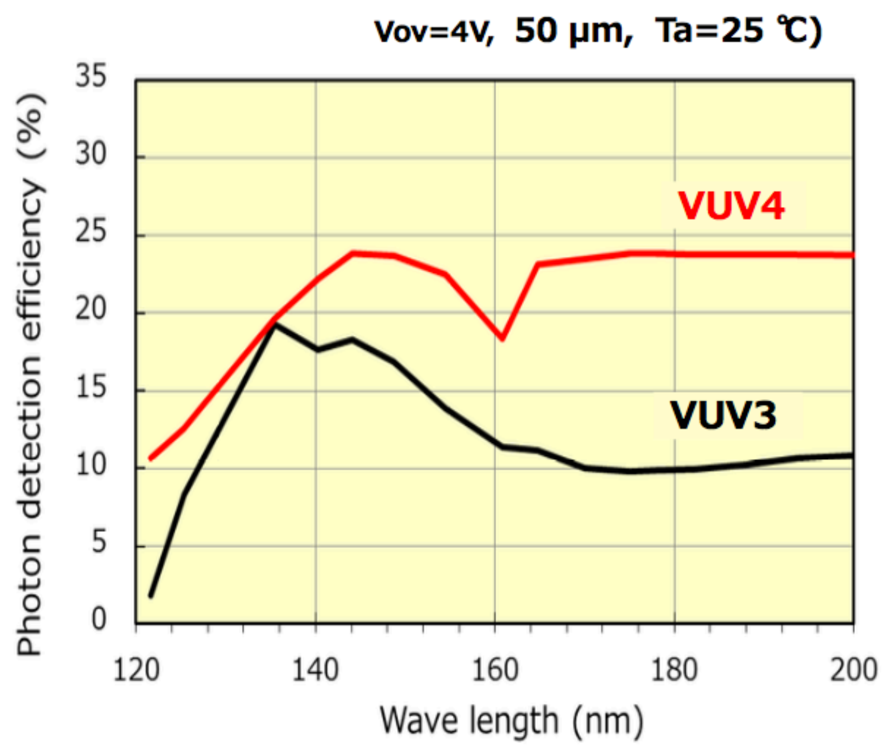
For physics experiments using LXe or LAr scintillator Liquid xenon (LXe) and liquid-argon (LAr) is used as scintillator. Their peak spectra are in VUV region and their temperatures are cryogenic.

- **Improvement for VUV sensitivity (VUV4)**





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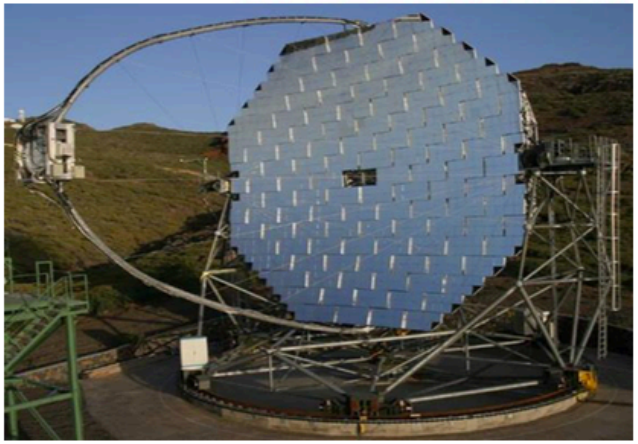
For Scientific Application



MPPC for Cherenkov Telescope

- Higher PDE
- Lower Crosstalk

MPPC for Cherenkov Telescope Array

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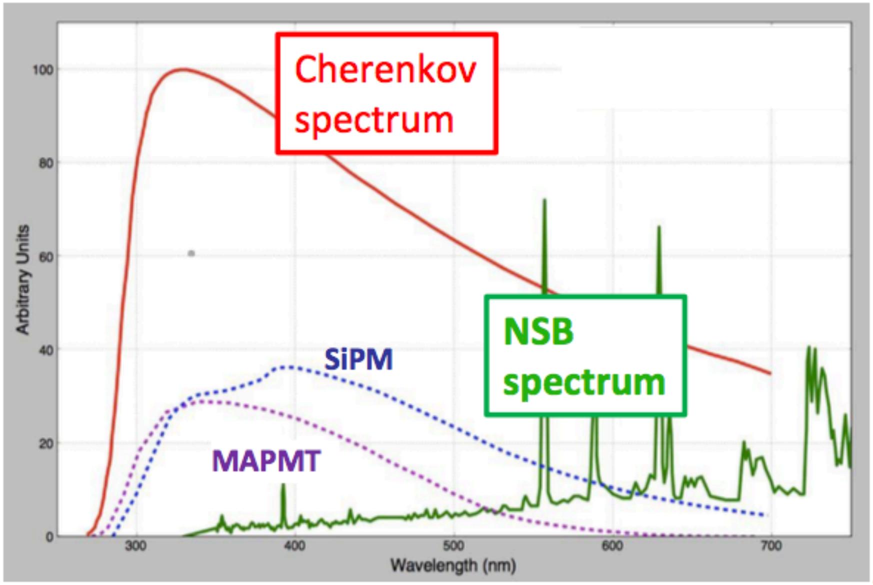
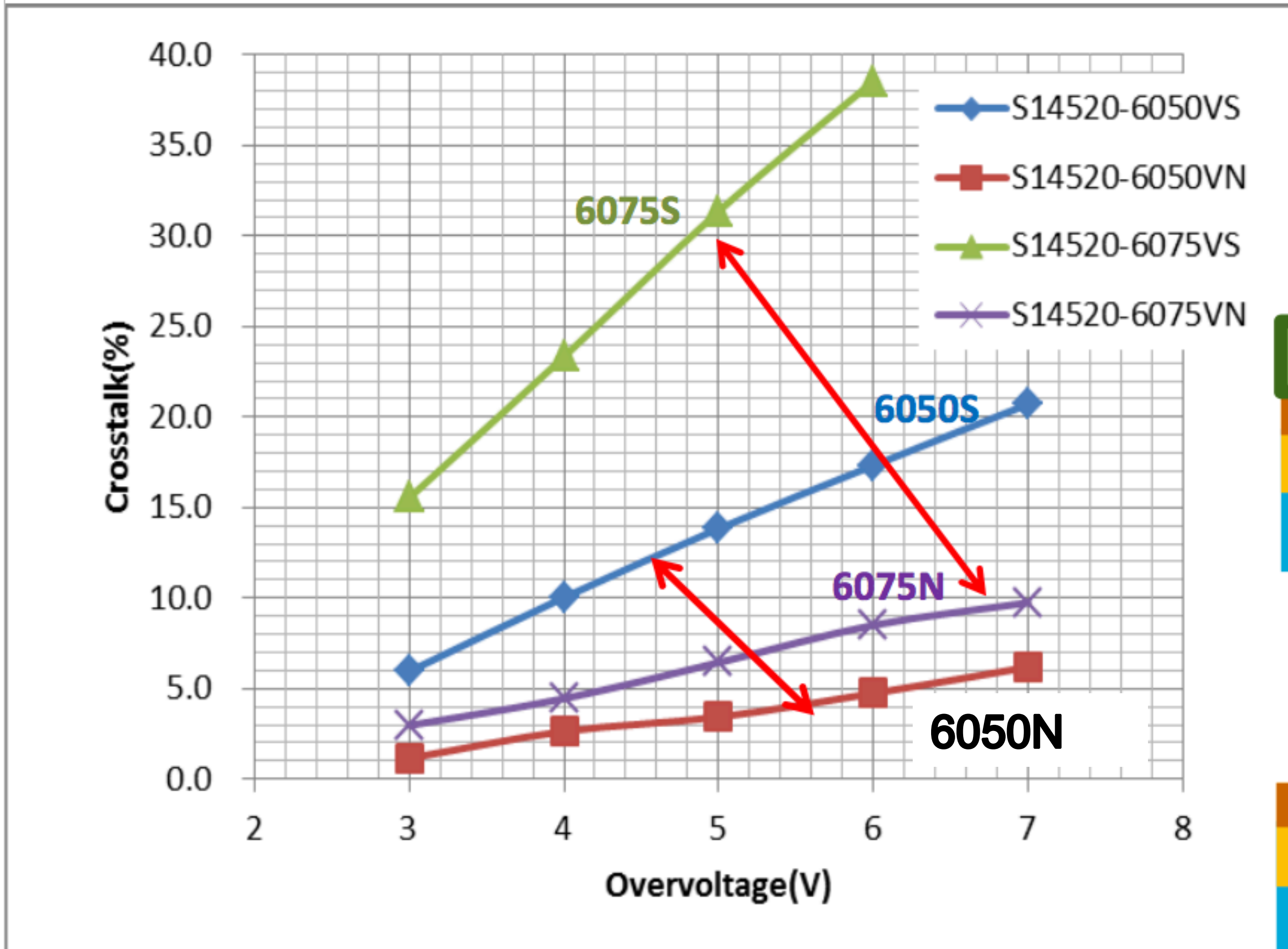
Required Properties

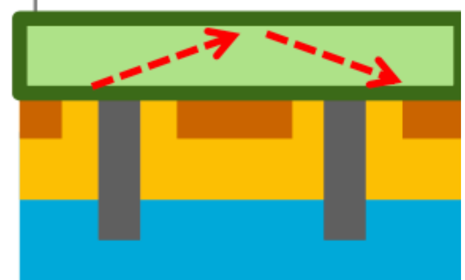
- **High PDE @350nm**····High F.F & large Pixel
- **Large sensitive area**····Bigger than 6mm2 and small dead space
- **Less visible sensitivity**····Not so sensitive to NSB
- **High Gain**
- **Low cross talk**
- **Low dark count**



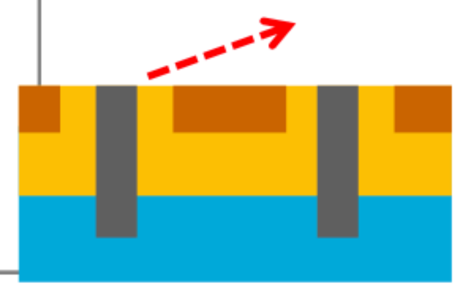
NSB: Night sky background

Crosstalk - Coating vs Without Coating -





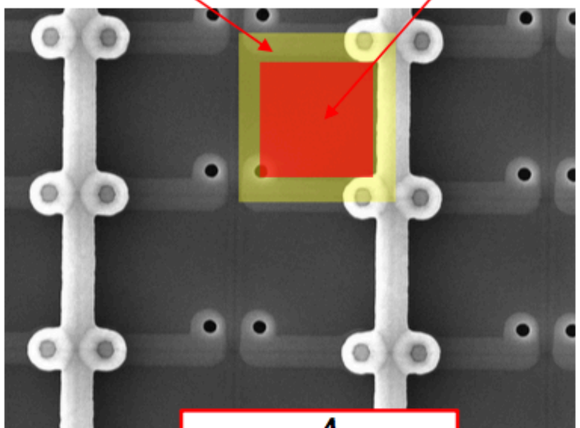
VS (Mold Type)



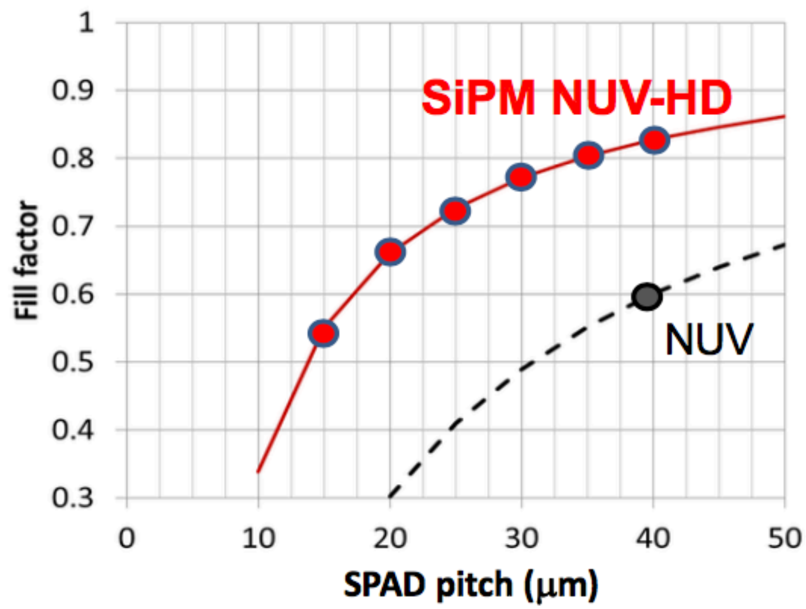
VN (Without Coating)

Crosstalk depends on SiPM area and protective coating!
No coating – less crosstalk

NUV-HD: Fill Factor



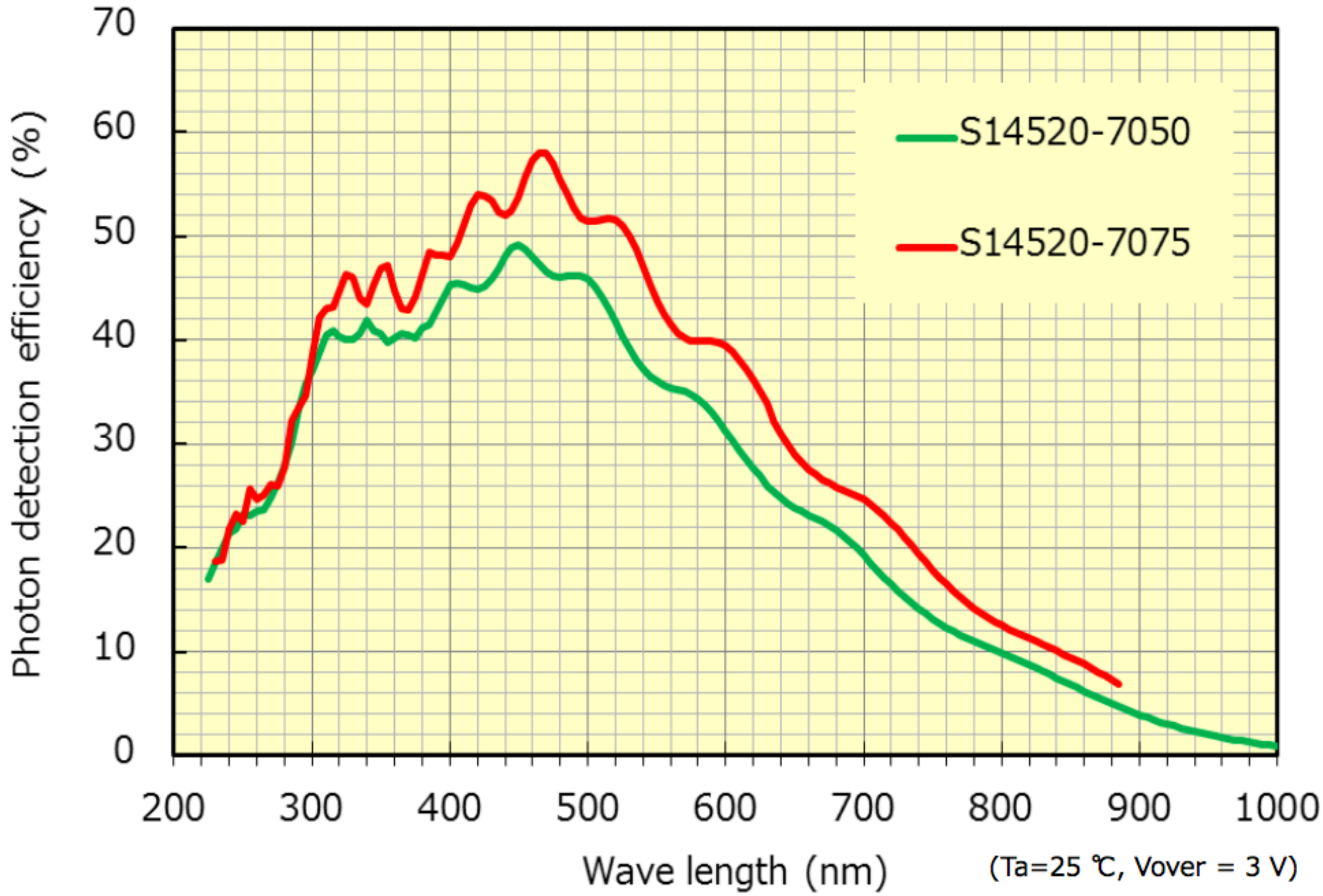
$$FF = \frac{A_{active}}{A_{total}}$$



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

High Dynamic Range (15–20 μm) — **High PDE** (35–40 μm)

PDE



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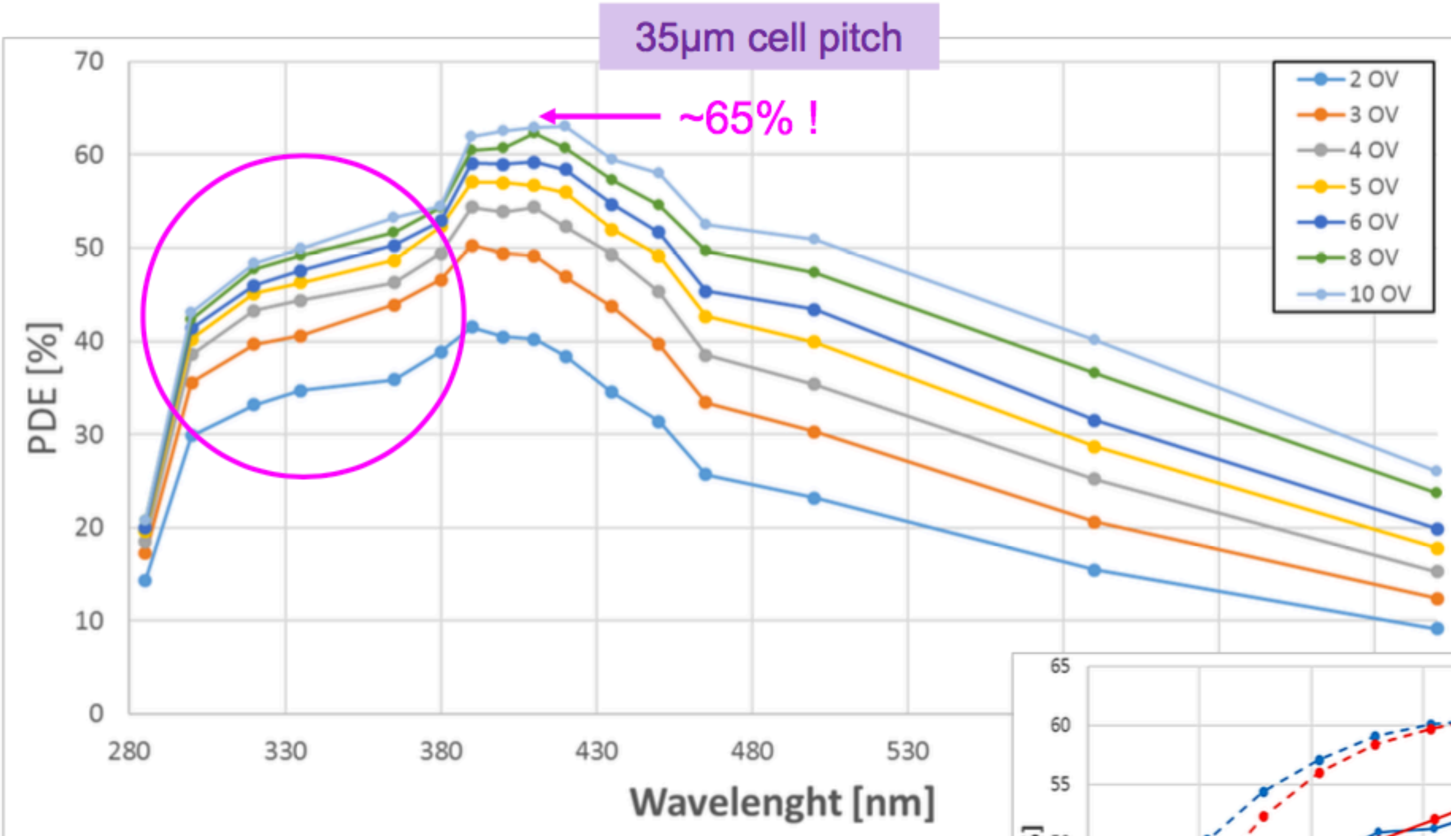
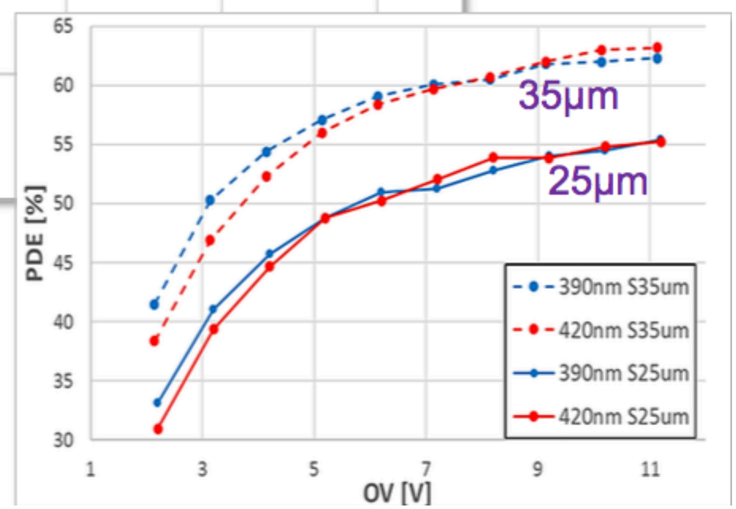
Photon detection efficiency





For Scientific Application

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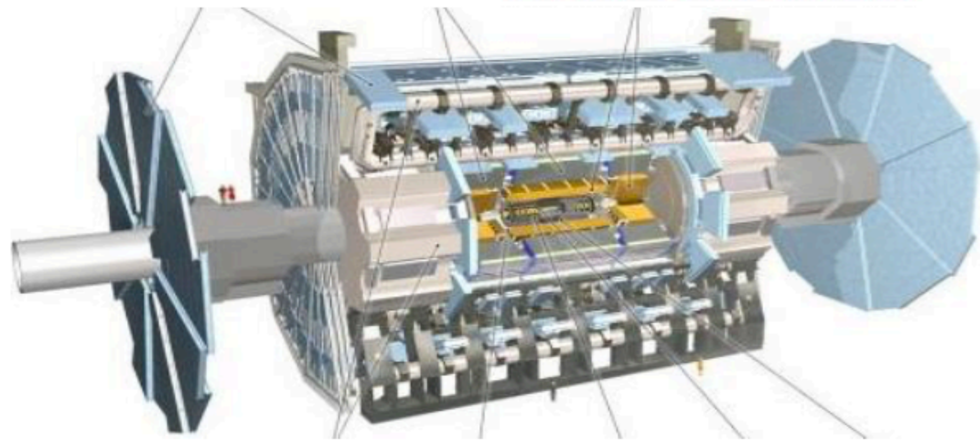


Small Pixel size MPPC

- High dynamic range
- Radiation hardness

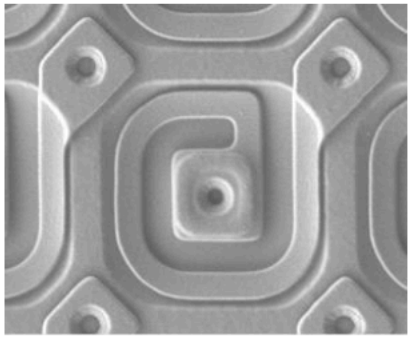
HAMAMATSU PHOTONICS K.K.

Very tiny pixels 10 micron

Old without trenches

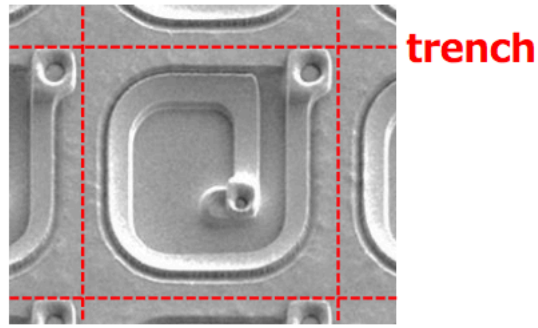
- **Fill factor: 33%**

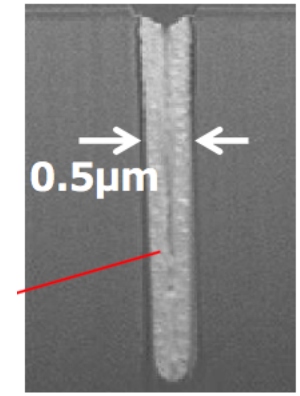
10 μm

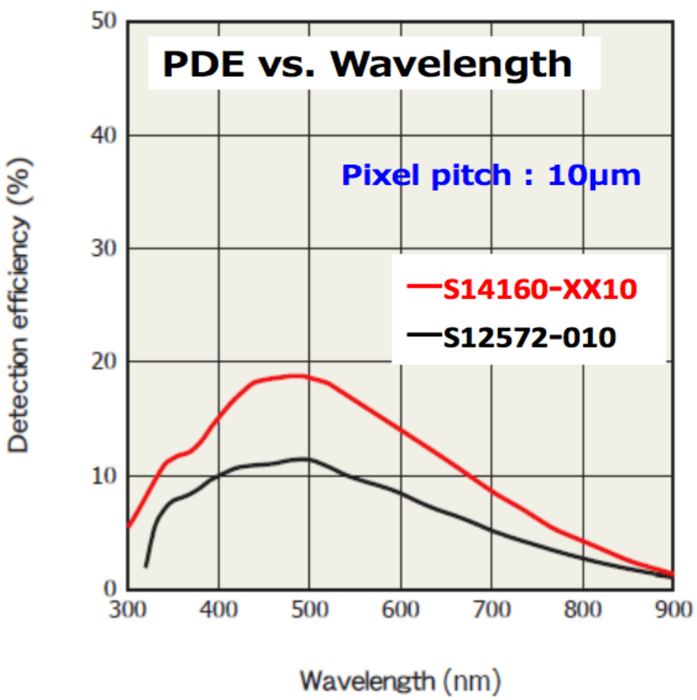


New with trenches

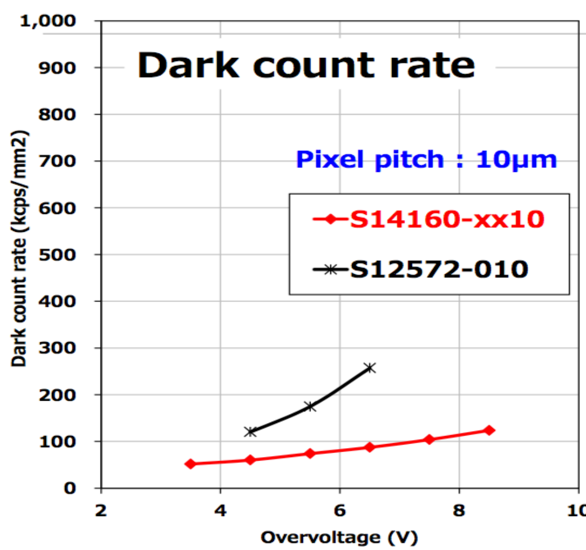
- **Fill factor: 31%**

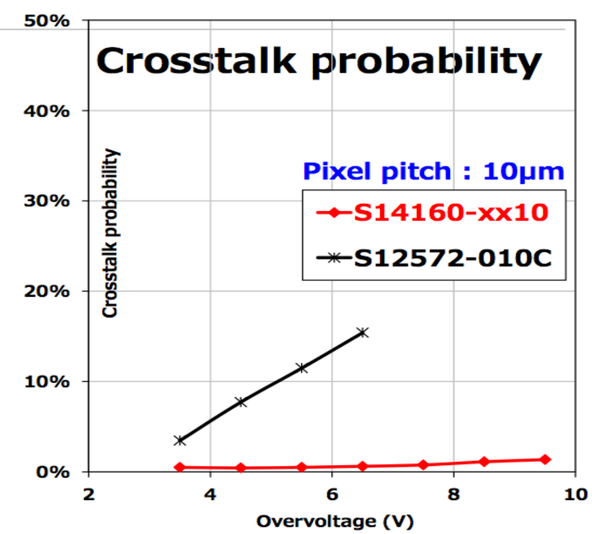




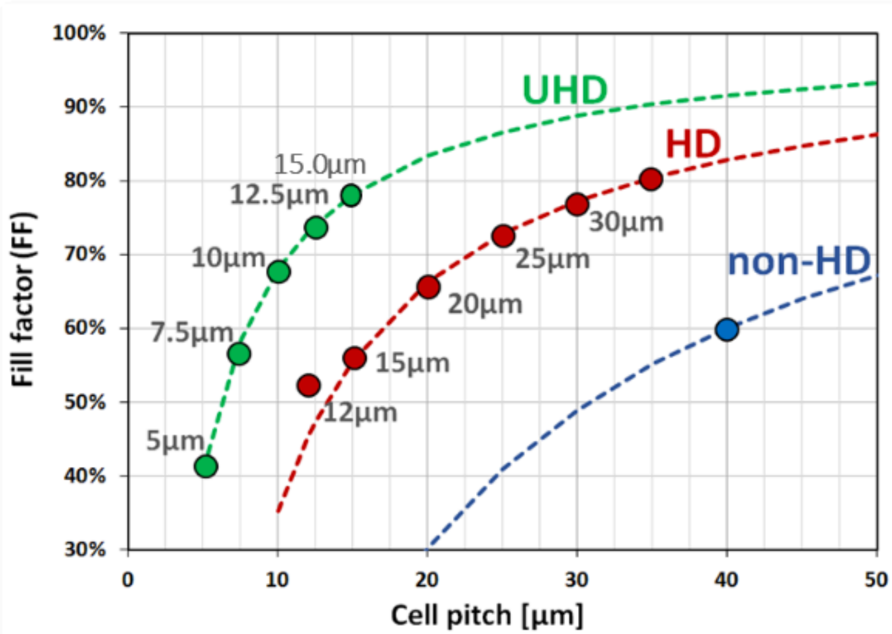


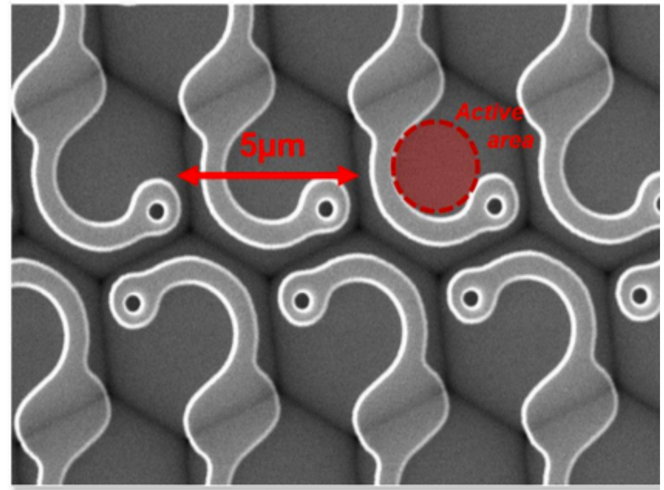
Dark count & Crosstalk





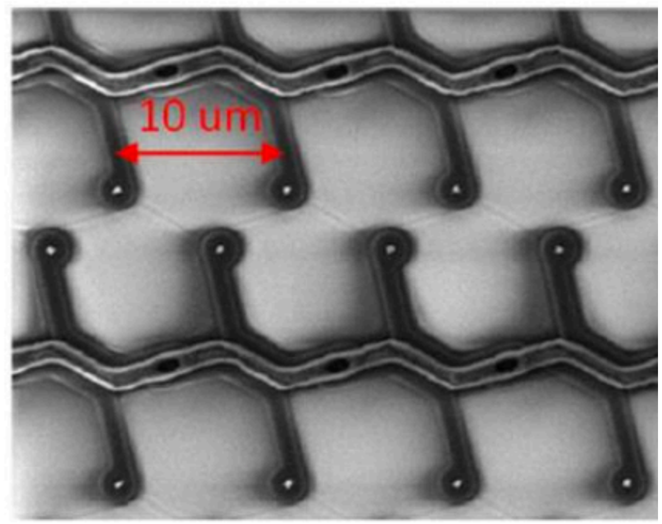
HD and UHD technologies





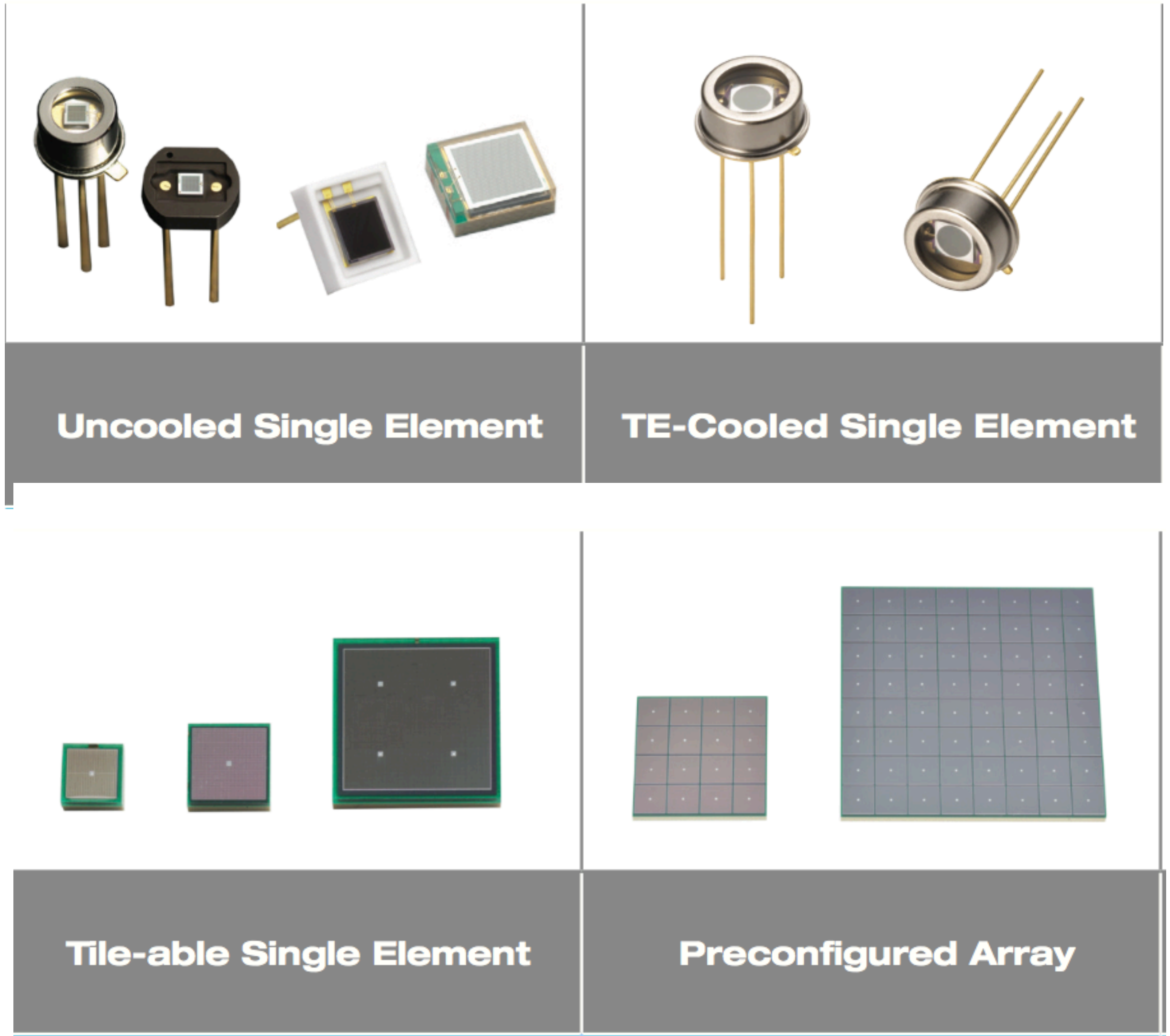
RGB-UHD

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



June 2018 Fabio ACERBI - FBK developments

Packaging

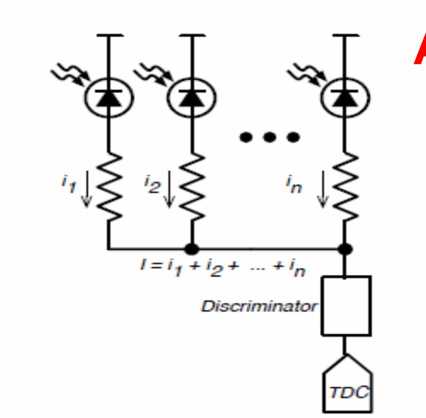


Uncooled Single Element
TE-Cooled Single Element
Tile-able Single Element
Preconfigured Array

Trends for further SiPM development

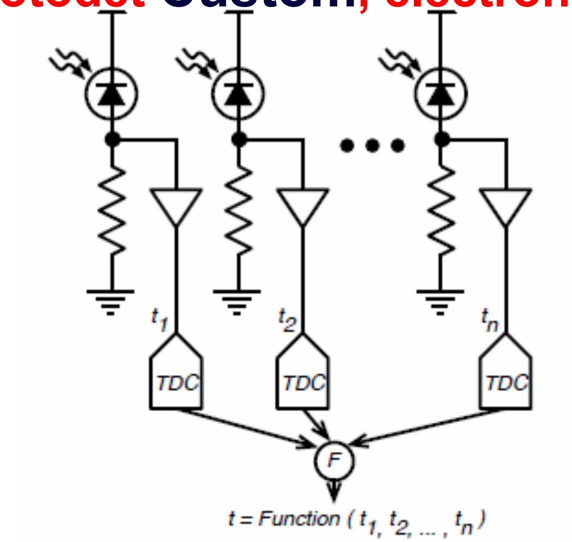
Conventional SiPM, custom technology

Analog SiPM 1D



Ideal multidigital SiPM, 3D integration

Photodet Custom, electronics CMOS

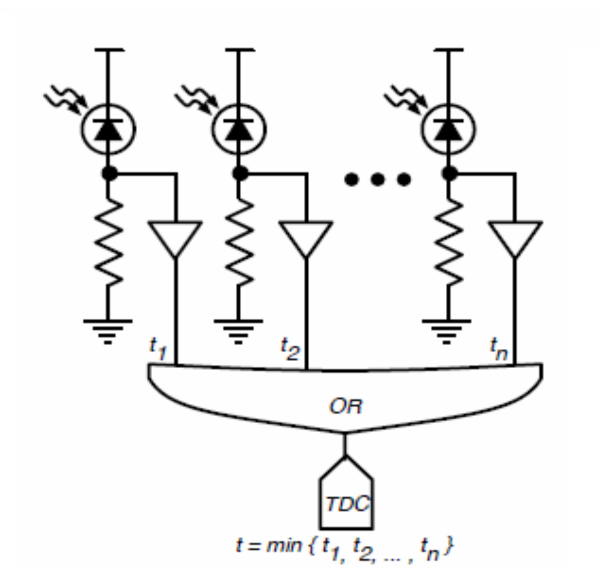


(c)

Digital SiPM (Philips) 2D

CMOS (modified) technology

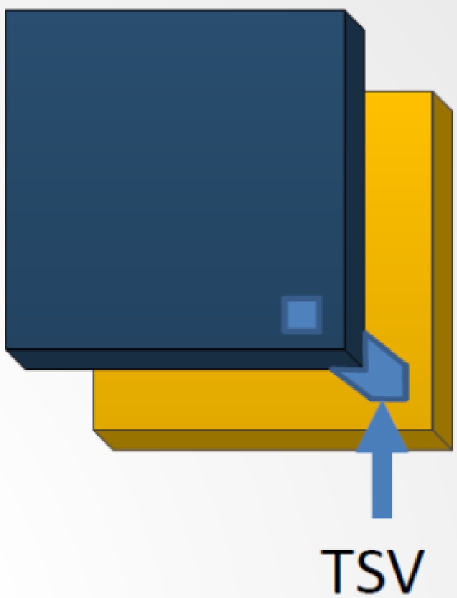
Photodet & electronics



(b)

Digital SiPM: Trade off and Solution

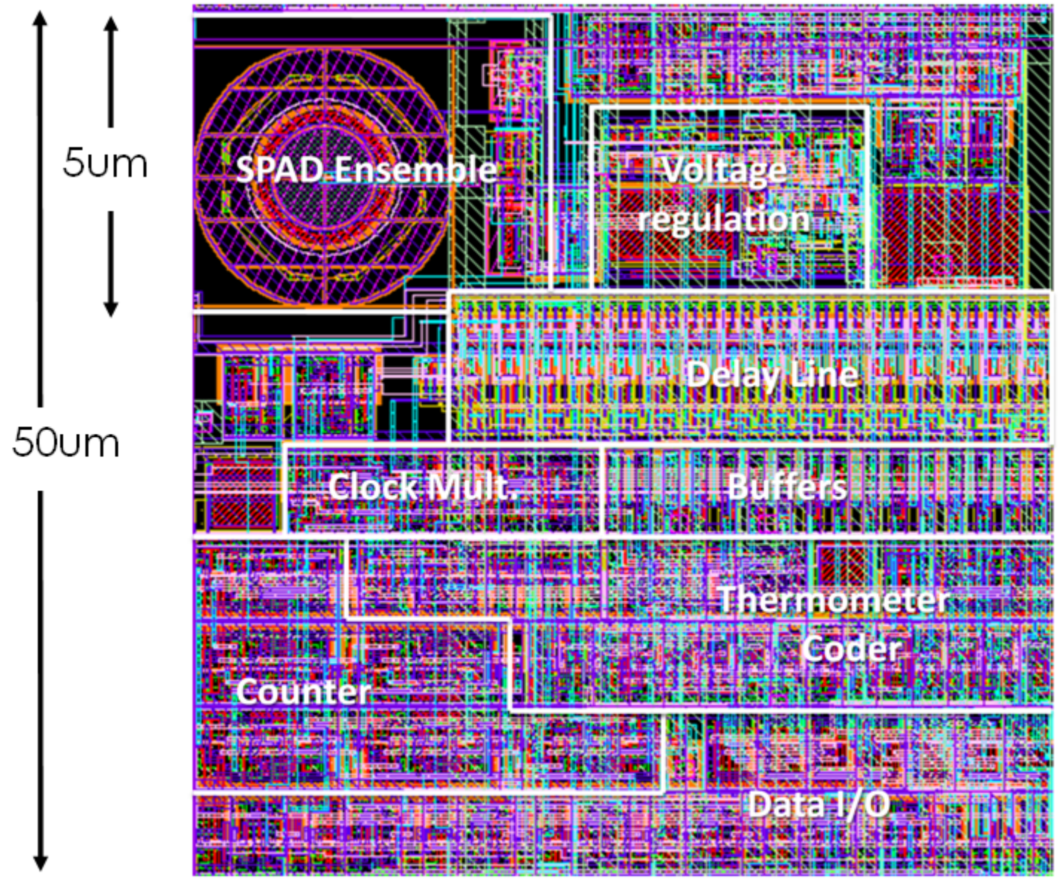
IDEALLY:



- High fill factor - PDE
- The only way to eliminate the SPAD to TDC propagation delay variation in the Single Photon Timing Resolution
- Heterogeneous technologies
- Electronic flexibility

Flexibility in digital SPAD design

- single pixel aspect ratio



Over 500 transistors in 50 x 50 µm^2

can be reduced depending on required functionalities

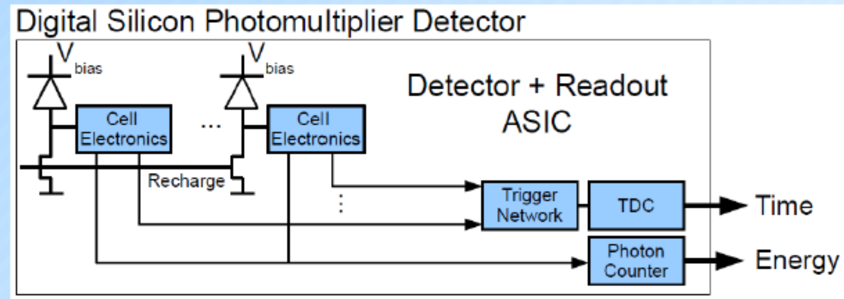
Typically 50/50 sensitive area to electronics

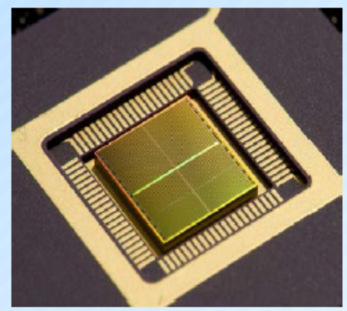
Gersbach, Charbon, et al., *Journal of Solid-State Circuits 2012*

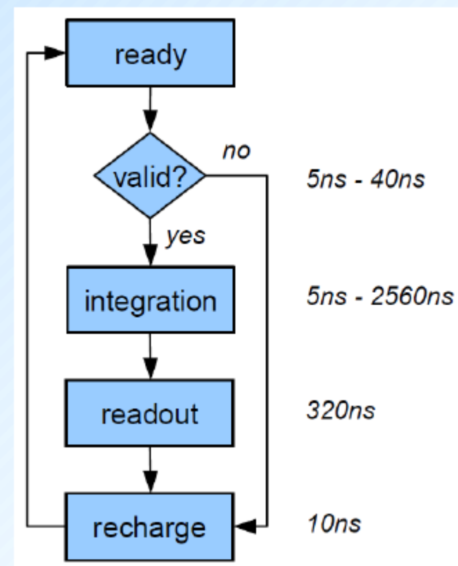
dSiPM-Digital SiPM (Philips)

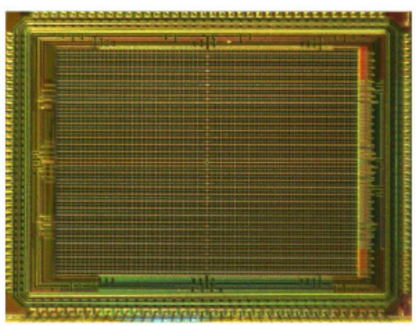
Signal from each pixel is is digitized and the information is processed on chip:

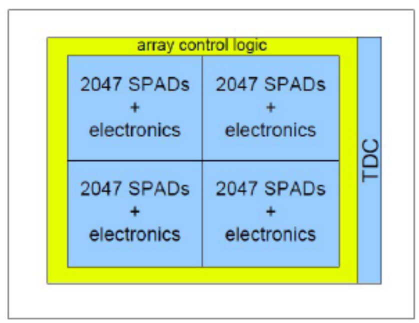
- time of first fired pixel is measured
- number of fired pixels is counted
- active control is used to recharge fired cells
- 4 x 2047 micro cells
- 50% fill factor including electronics
- integrated TDC with 8ps resolution











T. Frach (Philips) @ IEEE2009

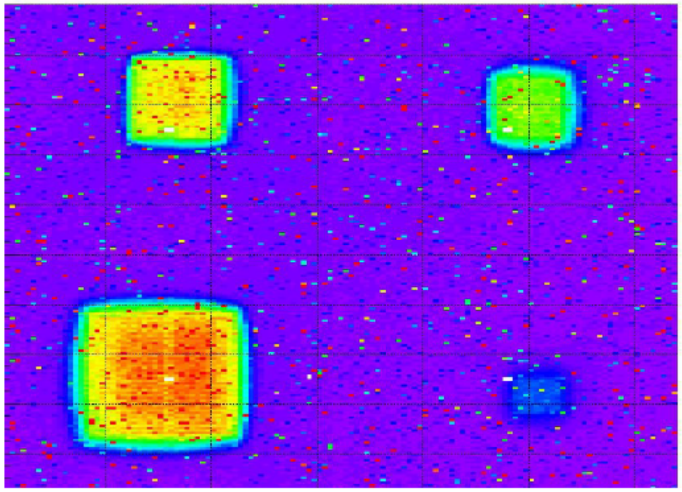
October 6 – 10, 2014
LIGHT14

Fast photon detectors for Cherenkov TOF PET (slide 43)

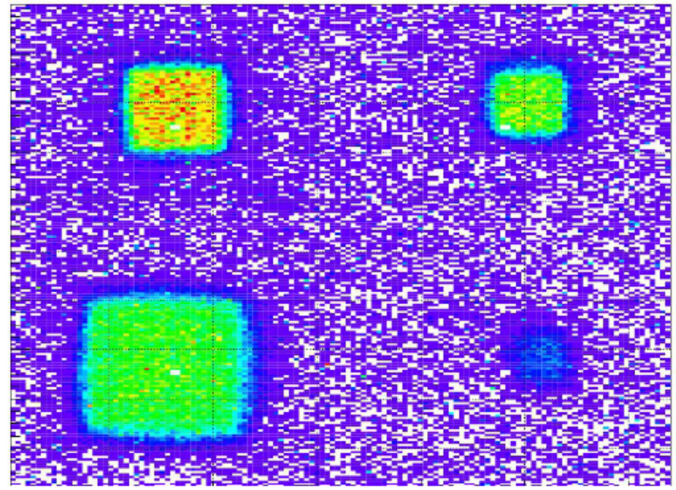
Samo Korpar
Univ. of Maribor and J. Stefan Institute

PHILIPS

Digital SiPM – Slow Scan Imaging Mode

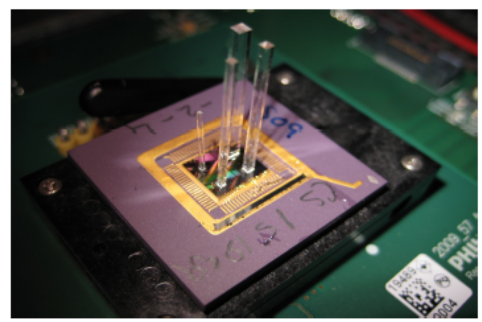


Singles



Coincidences

- *Spatial sampling of the light distribution*
- *Similar to dark count map measurement*
- *Dark count map can be used for correction*
- *Alternatively, use coincidence to reduce noise*
- *Potentially useful for light guide design*



SUMMARY

Actual situation now:

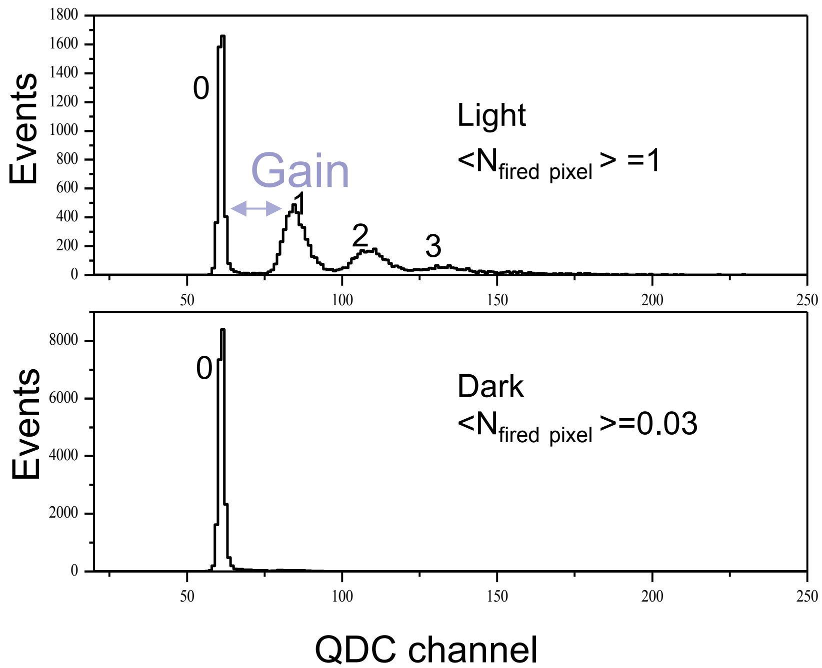
- Conventional 1D (analog) Silicon PM
  - PDE(400nm)≈65%
  - PDE>20% for Lxe and Lar (vacuum UV)
  - PDE(905nm)=10÷20%
  - Pixel pitch 5 micron is the smallest one (46190/mm2), 15 micron (5000/mm2)–is a kind of standard
  - Crosstalk < 10% for 6x6mm^2, 75 micron pitch (PDE = 50%)
  - < 1% for 1.3x1.3mm^2, 10 micron pitch (PDE=20%)

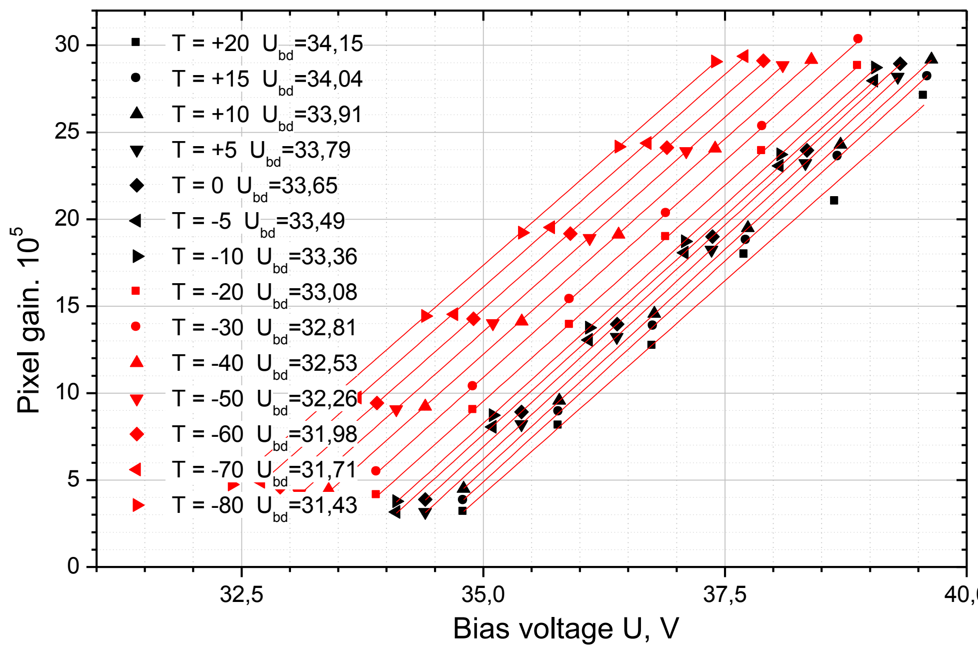
- Trends for future development:

2D (CMOS) and 3D (custom Si or non-Si and CMOS electronics) integration – smart SiPMs with digital information about a number of fired pixels and timestamps

- Industrial SiPM production by Broadcom and OnSemi – new era for the SiPM applications

Main SiPM's parameters. Gain vs Voltage for different T





$$G = \frac{C_{pixel} \cdot (U - U_{breakdown})}{q}$$

$U_{breakdown}$ ⟶ G=0 Overvoltage $\Delta U = U - U_{breakdown}$

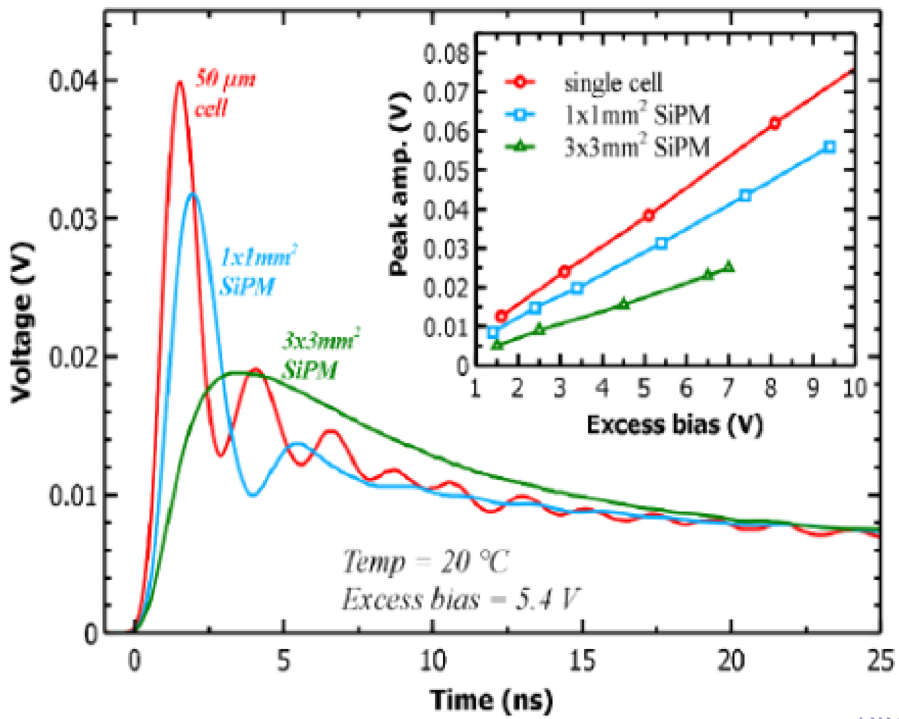
We need to collect SiPM's spectra for different voltages

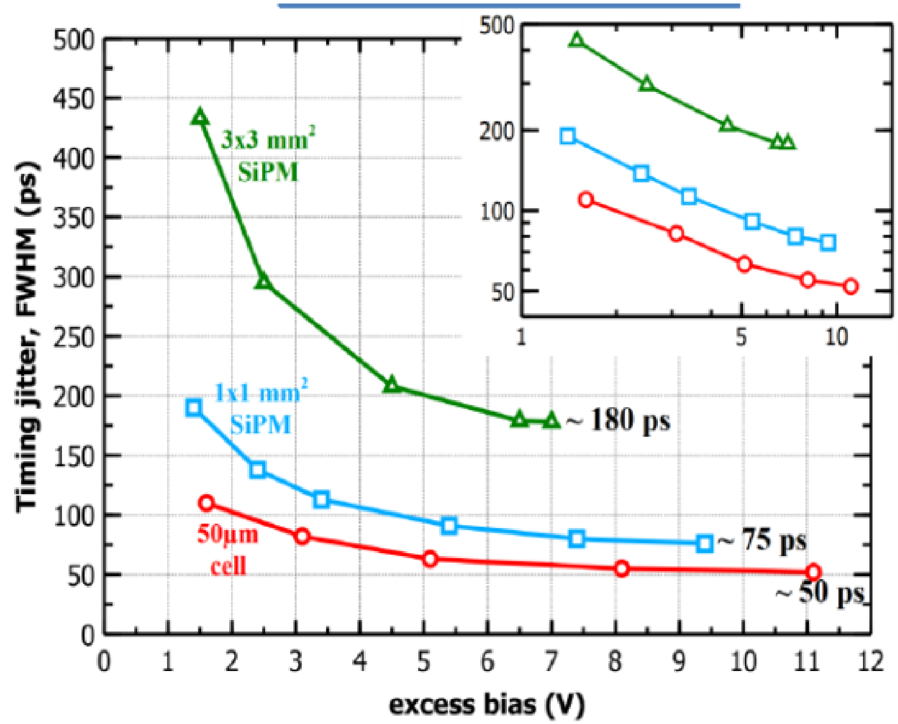
With temperature decreasing $U_{breakdown}$ decreases too – temperature sensitivity

Ubreakdown and ΔU–are needed for different type SiPM comparison

Main trade-off: fast timing vs large area

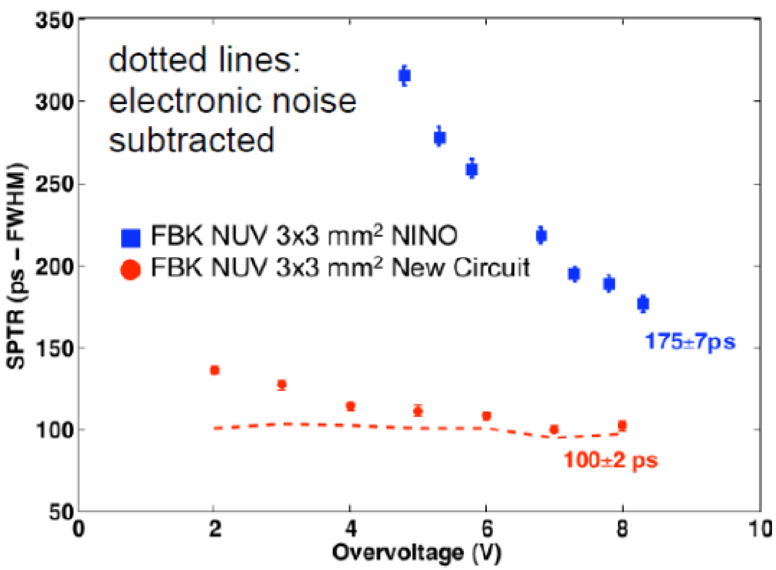
- Larger area => higher noise + slower response => lower TR
  - DCR noise ~ area
  - Electronic noise ~ capacitance ~ area
  - Signal rising slope ~ SER rise time ~ capacitance





F.Acerbi, FAST 2014, NIMA 2015

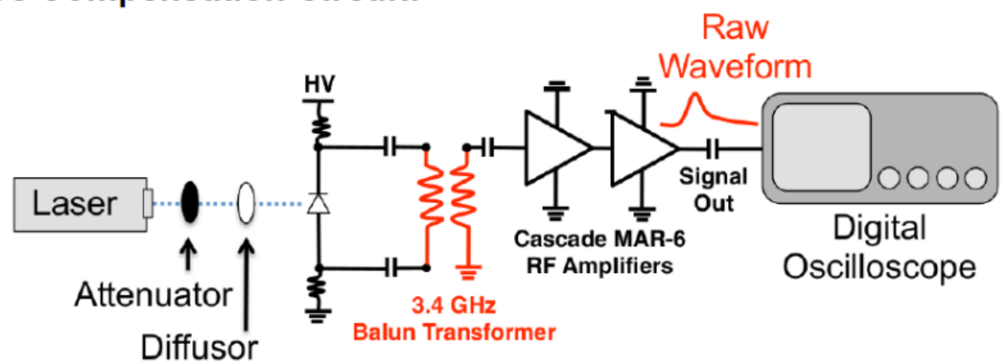
Compensation of large capacitance by transformer

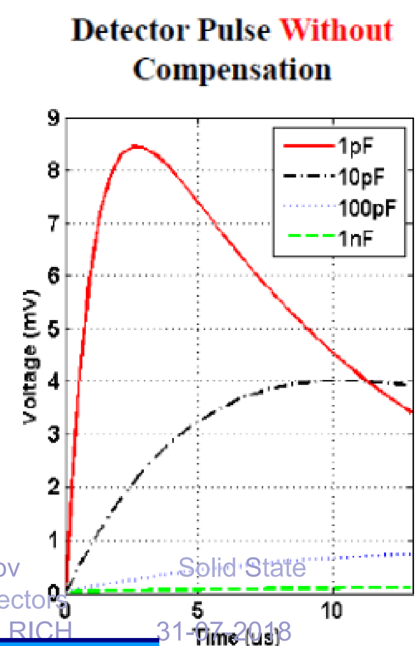


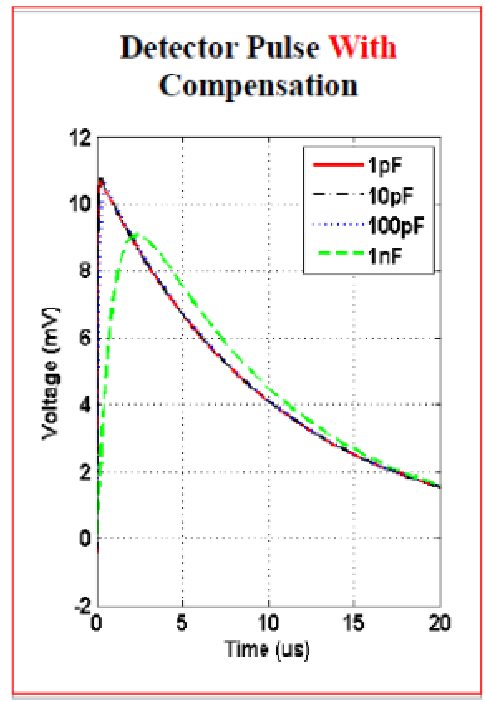
FBK NUV 3x3mm² (40µm):

NINO:	SPTR=175ps FWHM
new Circuit:	SPTR=100ps FWHM

Passive Compensation Circuit:







SPTR of a stand alone SiPM cell

min threshold, focused 2 micron spot, <200fs

scope LeCroy WaveRunner 620Zi 2GHz