Status and perspectives of solid state photon detectors

Yu. Musienko

University of Notre Dame (Notre Dame)

&

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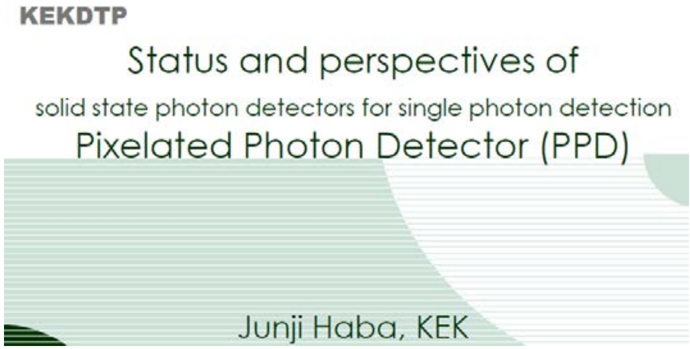
SSPD talks at previous RICH conferences

Excellent reviews on SSPDs were presented at previous RICH conferences. Description of the principles and physics of operation you can find there…



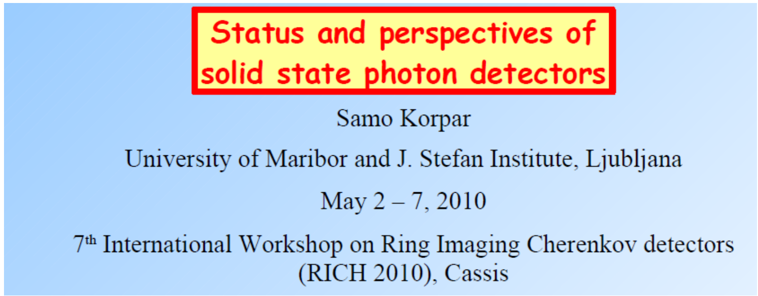
KEKDTP

Status and perspectives of

solid state photon detectors for single photon detection

Pixelated Photon Detector (PPD)

Junji Haba, KEK



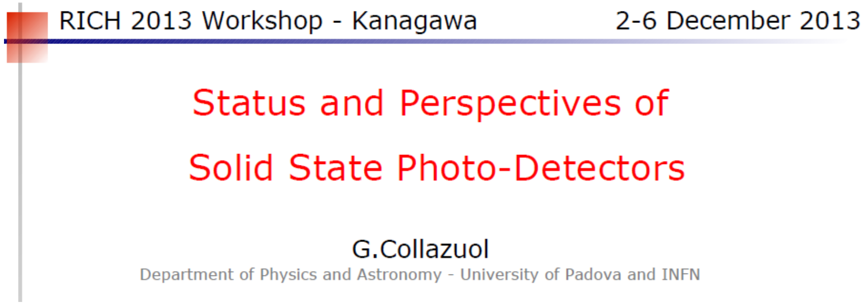
Status and perspectives of solid state photon detectors

Samo Korpar

University of Maribor and J. Stefan Institute, Ljubljana

May 2 – 7, 2010

7th International Workshop on Ring Imaging Cherenkov detectors (RICH 2010), Cassis



RICH 2013 Workshop - Kanagawa 2-6 December 2013

Status and Perspectives of

Solid State Photo-Detectors

G.Collazuol

Department of Physics and Astronomy - University of Padova and INFN

In my presentation I will concentrate on the most recent developments and perspectives in SSPDs (especially in SiPMs).

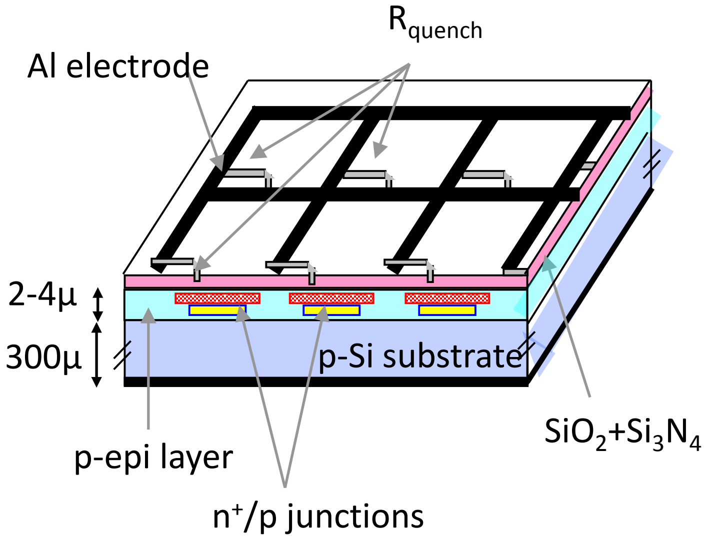
Introduction

At RICH-2013 workshop: excellent review on SiPMs by G. Collazuol: improved understanding of SiPM physics was demonstrated.
As a result (2016)→ significant progress in SiPM development
General trend : **reduce correlated noise (X-talk, afterpulsing)**, improve PDE, reduce dark noise

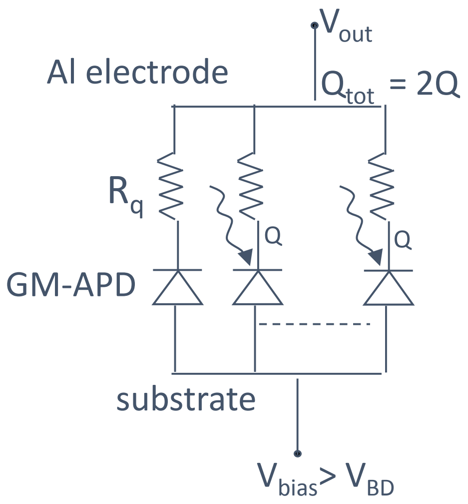
Here I will review current (September 2016) status of SSPM development. Possible perspectives of SSPM development will be also discussed.
I will use some of results presented at NDIP-14, PD-15, VCI-16, Elba-15, 2nd SiPM Advanced workshop-Geneva-2014

Silicon photomultipliers (SiPMs)

Structure and principles of operation (briefly)



(EDIT-2011, CERN)

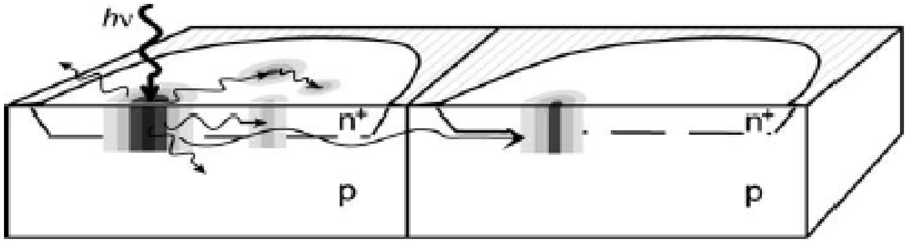


- *SiPM is an array of small cells (SPADs) connected in parallel on a common substrate*
- *Each cell has its own quenching resistor (from 100kΩ to several MΩ)*
- *Common bias is applied to all cells (~10-20% over breakdown voltage)*
- *Cells fire independently*
- *The output signal is a sum of signals produced by individual cells*

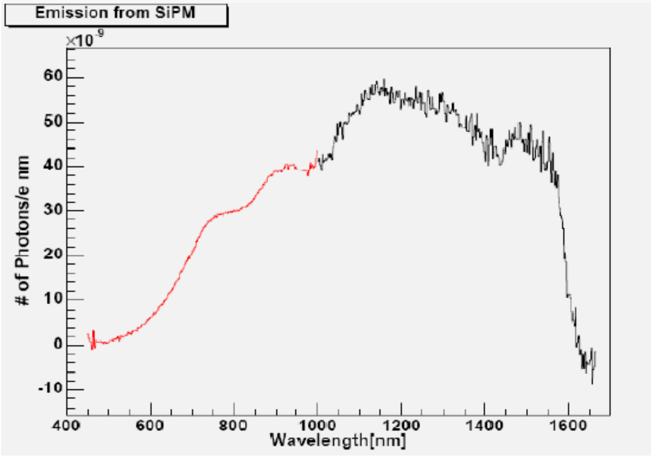
For small light pulses ($N_\gamma << N_{pixels}$) SiPM works as an analog photon detector

The very first metall-resitor-smiconductor APD (MRS APD) proposed in 1989 by A. Gasanov, V. Golovin, Z. Sadygov, N. Yusipov (Russian patent #1702831, from 10/11/1989). APDs up to 5x5 mm2 were produced by MELZ factory (Moscow).

SiPMs: Optical cross-talk between cells (direct cross-talk)



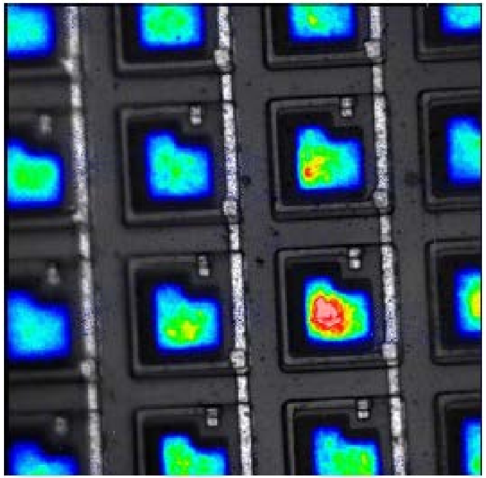
A. Lacaita et al, IEEE TED (1993)



(R. Mirzoyan, NDIP08, Aix-les-Bains)

Hot-carrier luminescence:
10^5 carriers produces ~3 photons with an wavelength less than 1 μm.
Increases with the gain !
Optical cross-talk causes adjacent pixels to be fired → increases gain fluctuations → increases noise and excess noise factor !

Avalanche luminescence

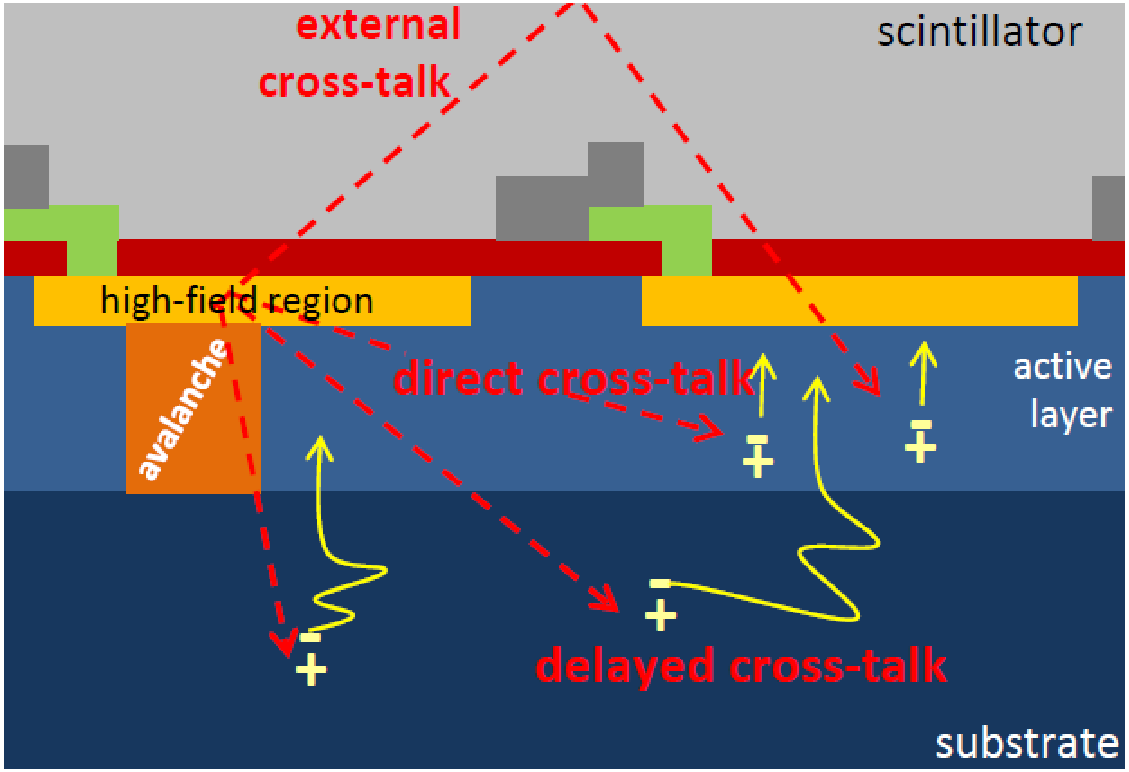


N.Otte, SNIC-2006

SiPMs: Optical cross-talk - II

Other effects of cell luminescence:

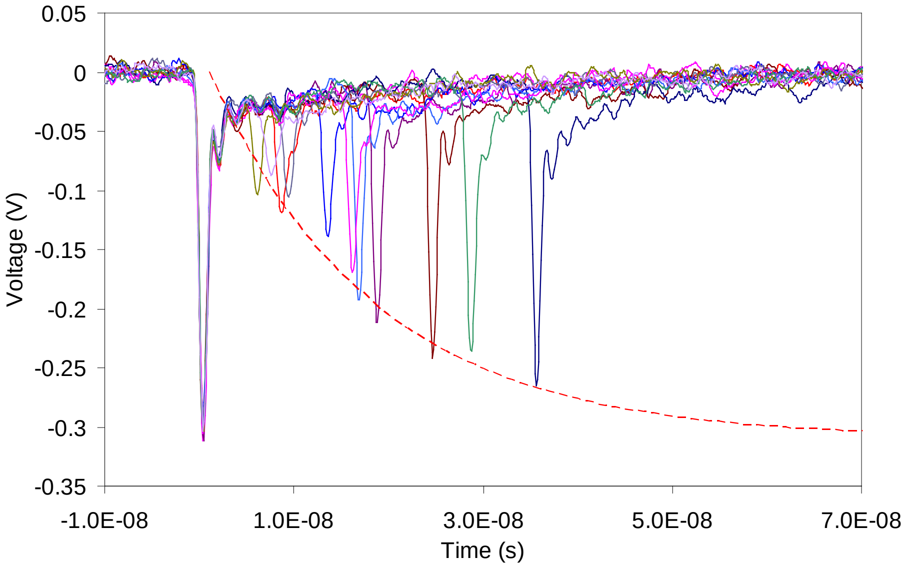
- External cross-talk
- Delayed pulses from light absorbed in non-depleted region (look like after-pulses)

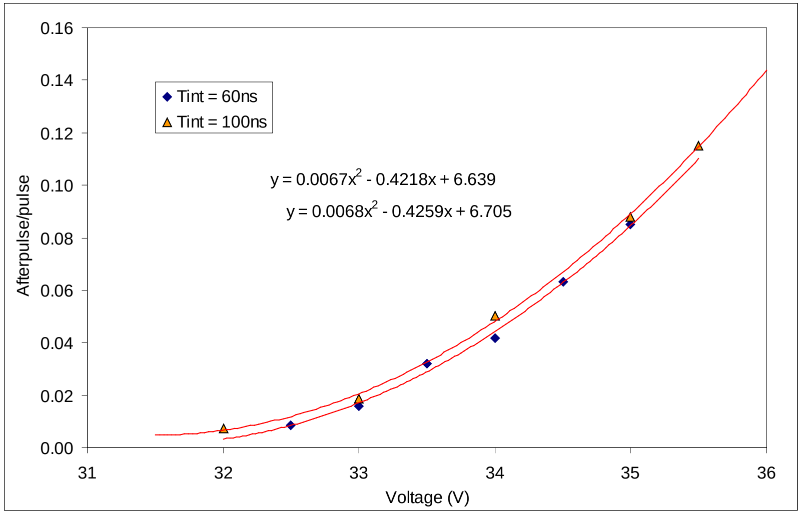


Fabio ACERBI - PhotoDet 2015

SiPMs: After-pulses

Carriers trapped during the avalanche discharging and then released trigger a new avalanche during a period of several 100 ns after the breakdown

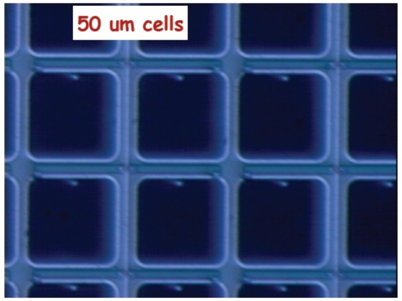


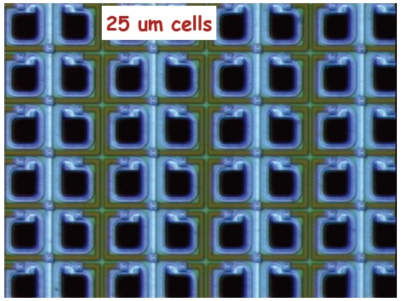


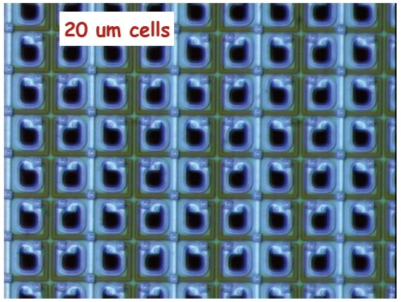
Events with after-pulse measured on a single micropixel.

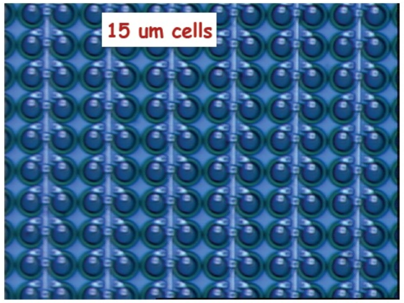
After-pulse probability *vs* bias

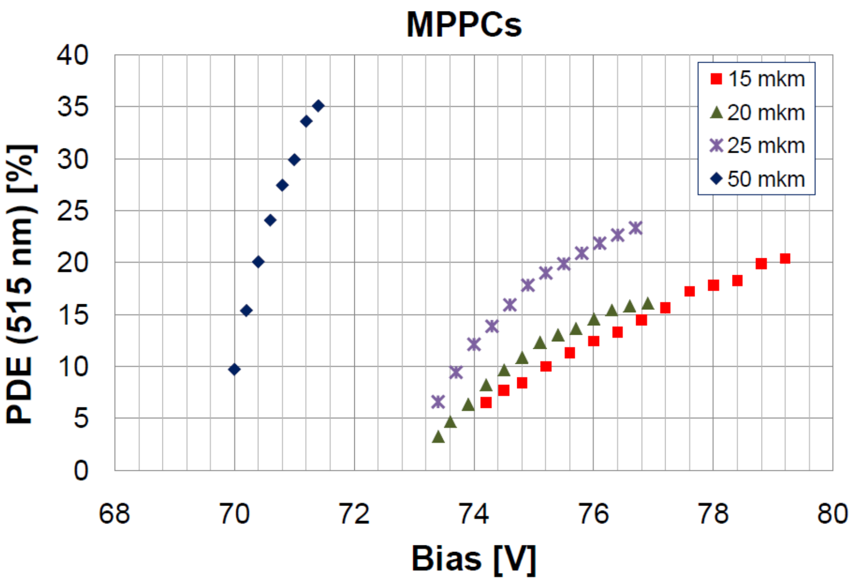
SiPMs: Geometric factor





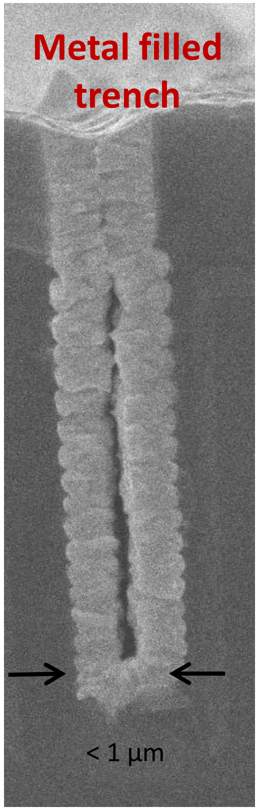




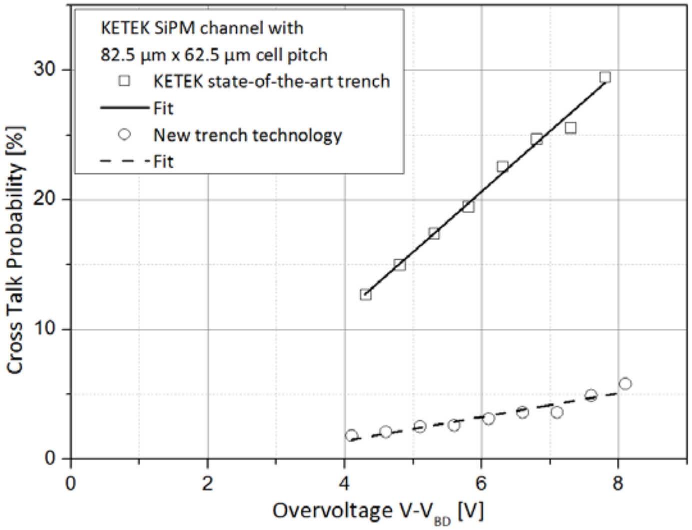


“Dead” space between SiPM cells reduces its PDE. It is especially important for the small cell pitch SiPMs

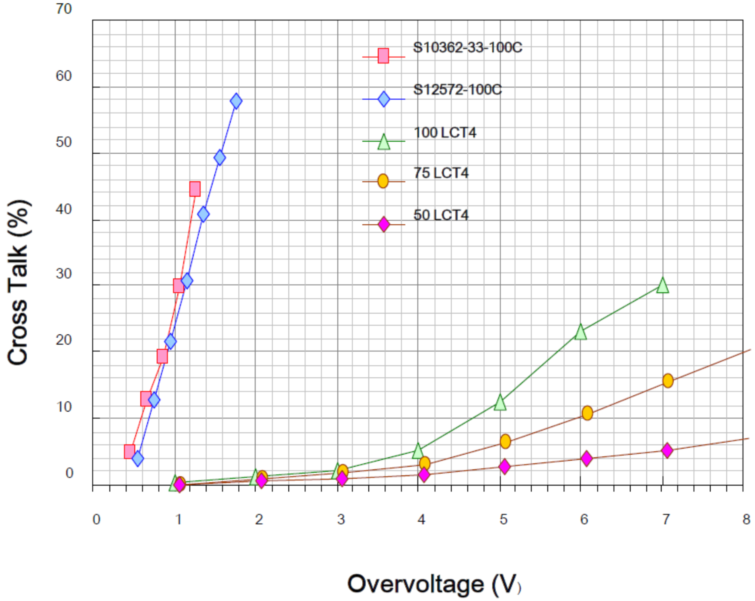
X-talk reduction



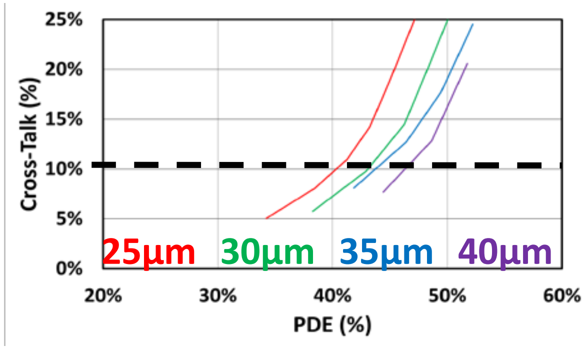
The way to reduce X-talk: trench filled with non-transparent material (tungsten)



(KETEK – Photodet-2015 (Troitsk))



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



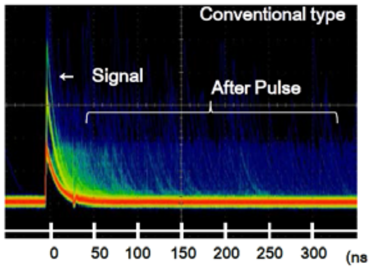
X-talk was reduced from 20÷30% to 3÷5% at dVB=4÷5 V

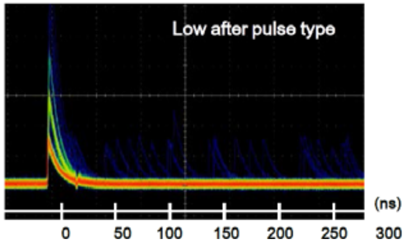
(FBK: G. Zappalà, VCI-2016)

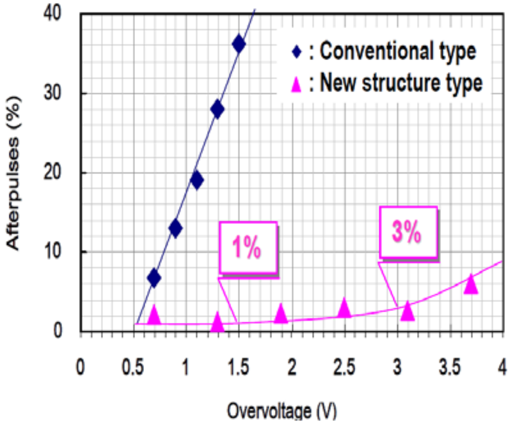
Afterpulsing and delayed X-talk reduction

Low After Pulses

Example of After pulse suppression







After pulse probability has been suppressed by optimization of structure and material.
All new MPPC series have very lower after pulses compared with conventional type.

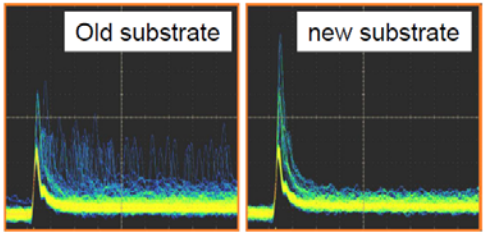
(HPK: Koei Yamamoto, 2nd SiPM Advanced Workshop, March 2014)

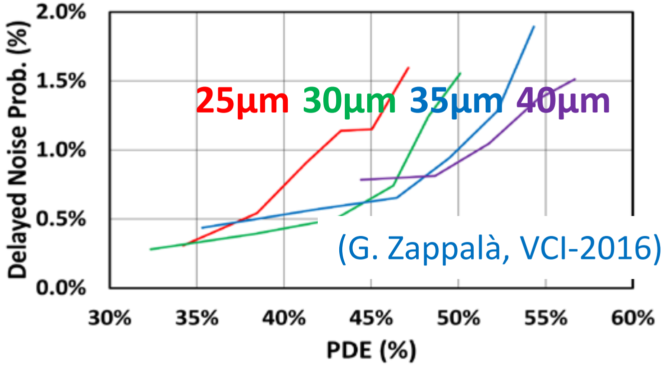
- **Improved substrate**

  Minority carrier lifetime reduced ~ 2 order of magnitude

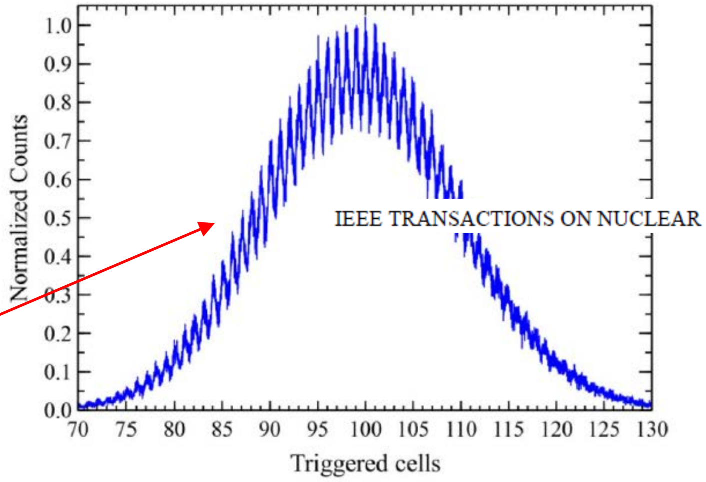
  → lower delayed correlated noise

F. Acerbi et. al., IEEE T. Nucl. Sci., vol. 62, n. 3, 2015





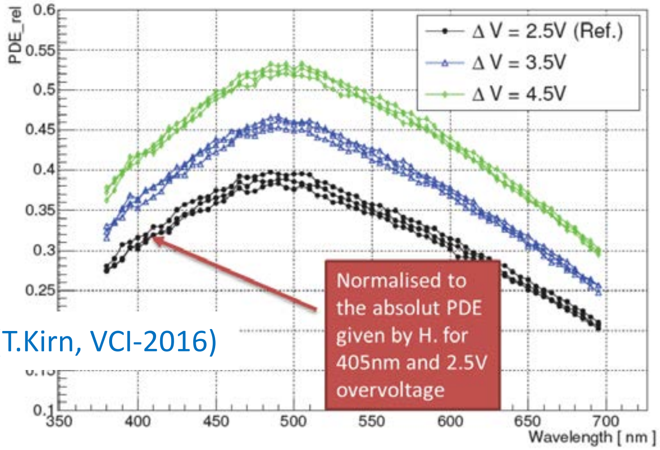
(G. Zappalà, VCI-2016)



IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 62, NO. 3, JUNE 2015

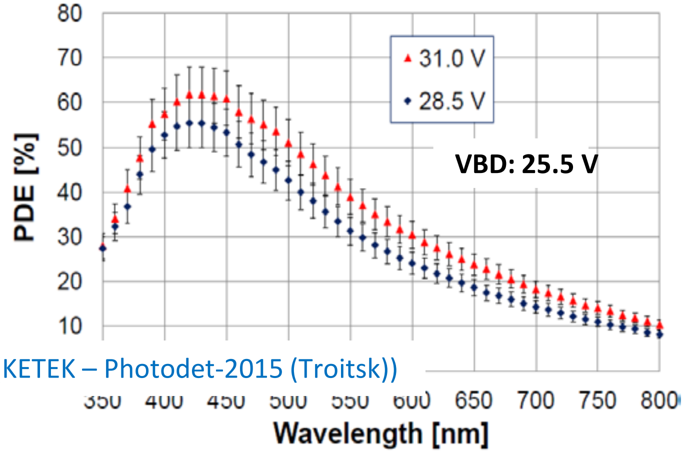
After-pulsing and delayed X-talk were reduced from 30% to <1.5% at high overvoltage

SiPMs: PDE increase



Normalised to the absolut PDE given by H. for 405nm and 2.5V overvoltage

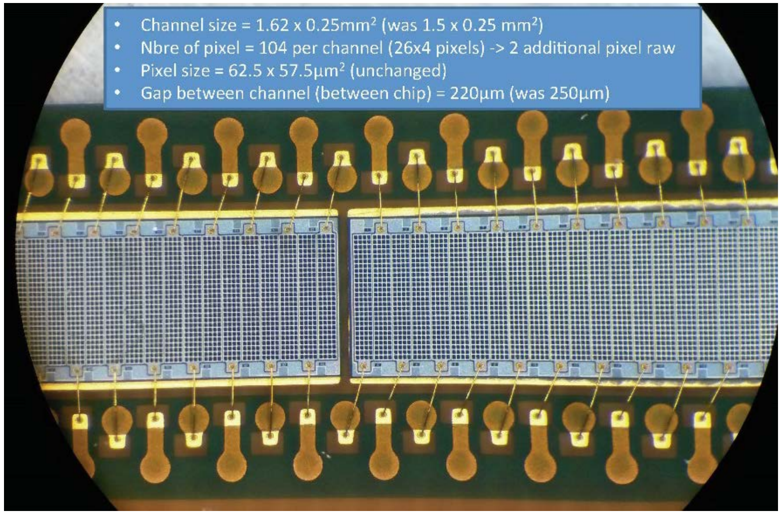
(T.Kirn, VCI-2016)



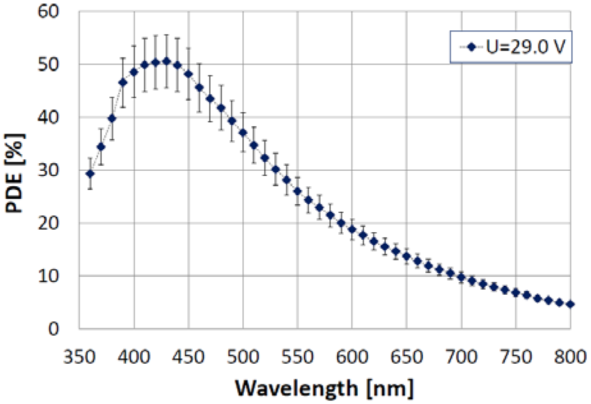
VBD: 25.5 V

(KETEK – Photodet-2015 (Troitsk))

SiPM array for LHCb Scintillating Fibre Tracker



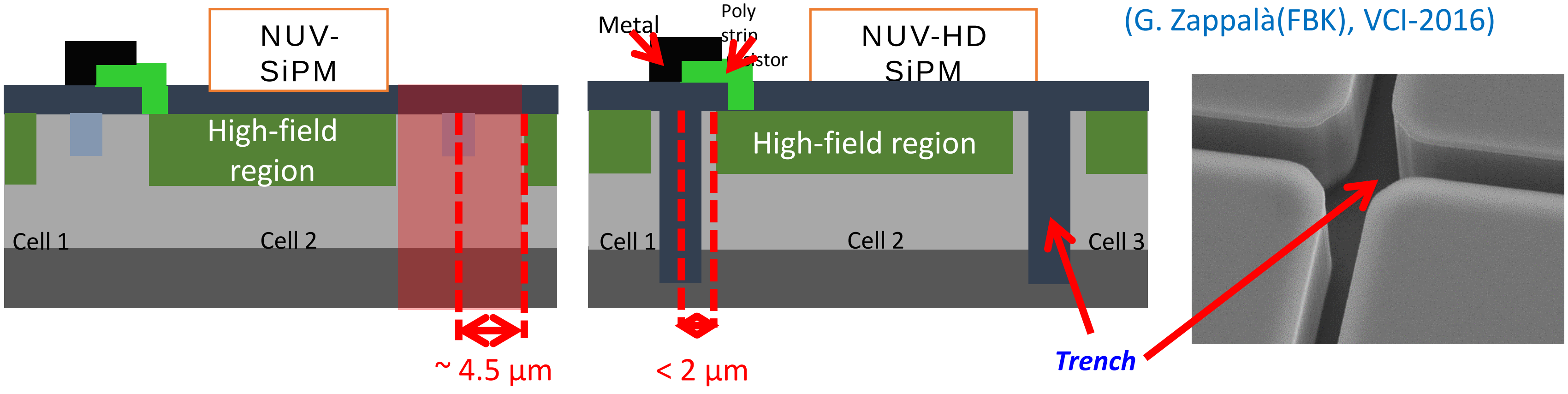
- Channel size = 1.62 x 0.25mm² (was 1.5 x 0.25 mm²)
- Nbre of pixel = 104 per channel (26x4 pixels) -> 2 additional pixel raw
- Pixel size = 62.5 x 57.5µm² (unchanged)
- Gap between channel (between chip) = 220µm (was 250µm)



(SensL MicroFJ-SMA-3035-E46, CERN APD Lab)

Small X-talk and after-pulsing allow SiPM operation at high over-voltages. As a result maximum PDE increased from 20 ÷ 30% to 50 ÷ 60 % (SiPMs with 43÷50 µm cell pitch).

PDE increase: SiPMs with very thin trenches



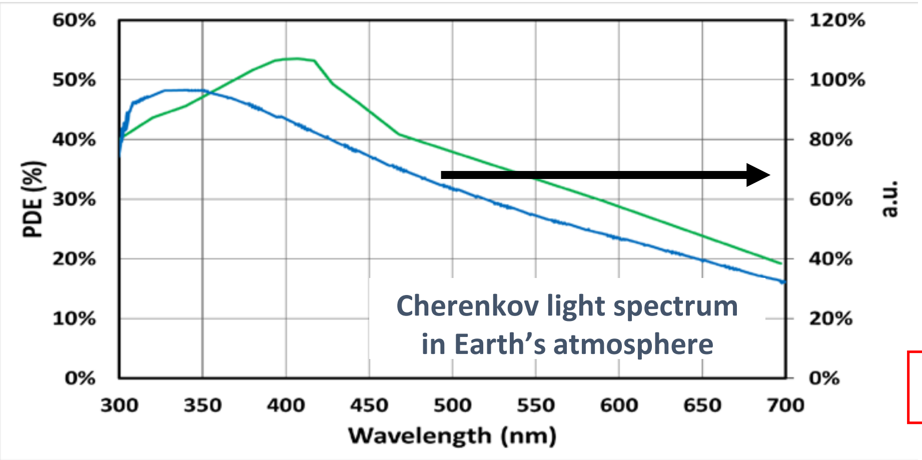
(G. Zappalà(FBK), VCI-2016)

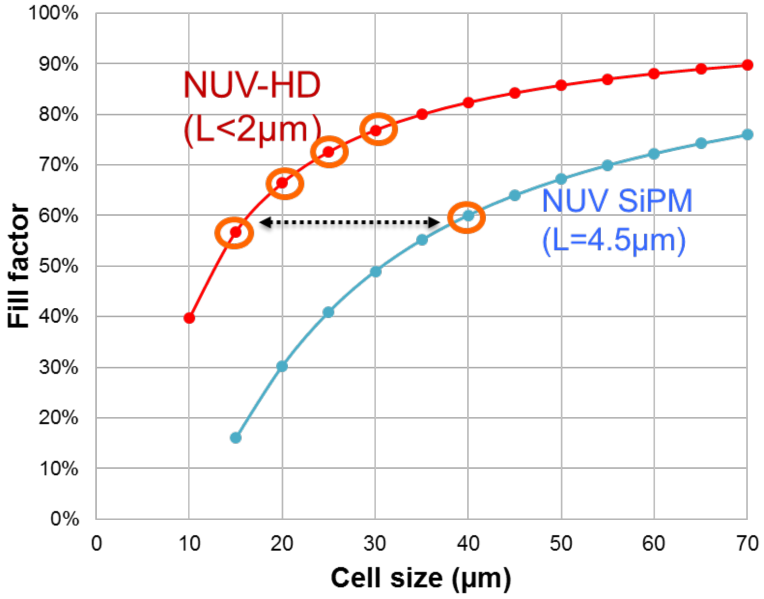
NUV High-Density (HD) technology:

Lower dead border region → Higher Fill Factor

Trenches between cells → Lower Cross-Talk

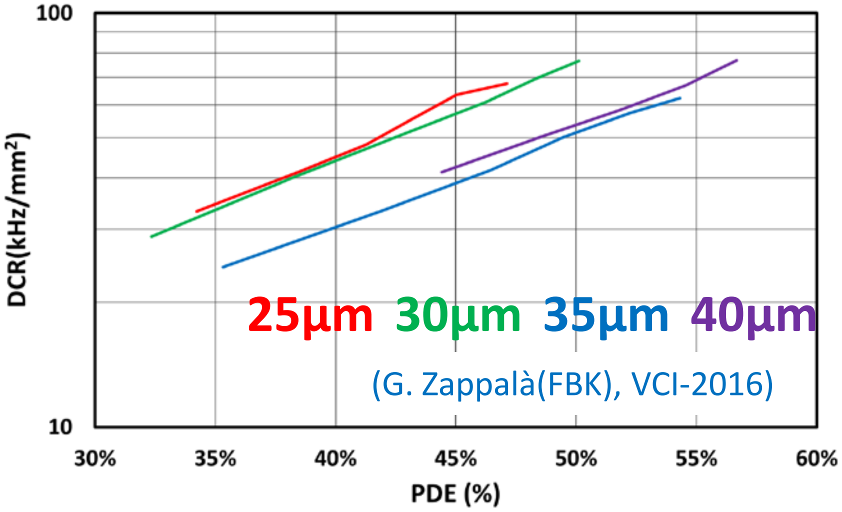
NUV-HD 30µm Cell Pitch PDE, 10V OV



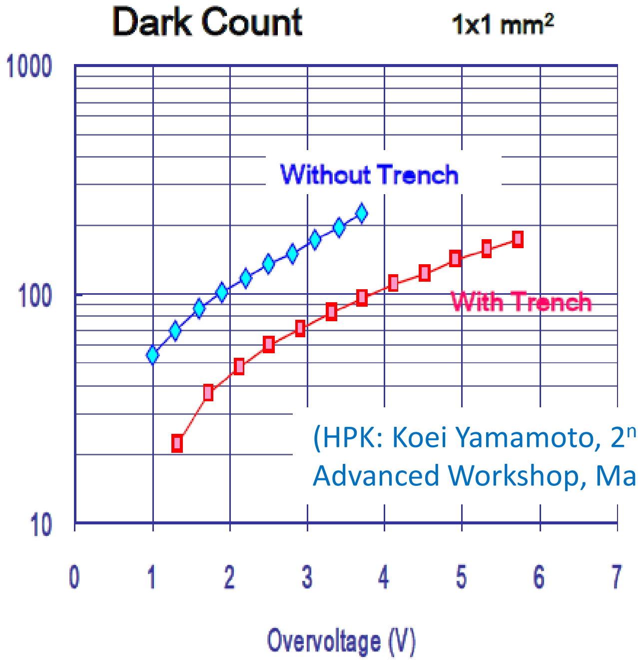


30 µm cell pitch SiPMs: GF=77% → PDE>50 % !!

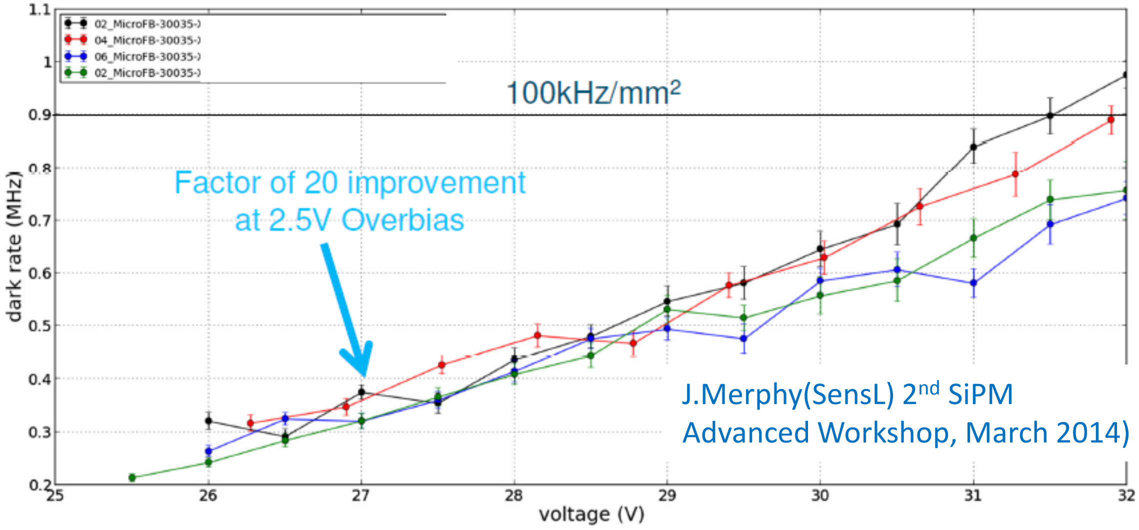
Dark noise reduction



(G. Zappalà(FBK), VCI-2016)



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

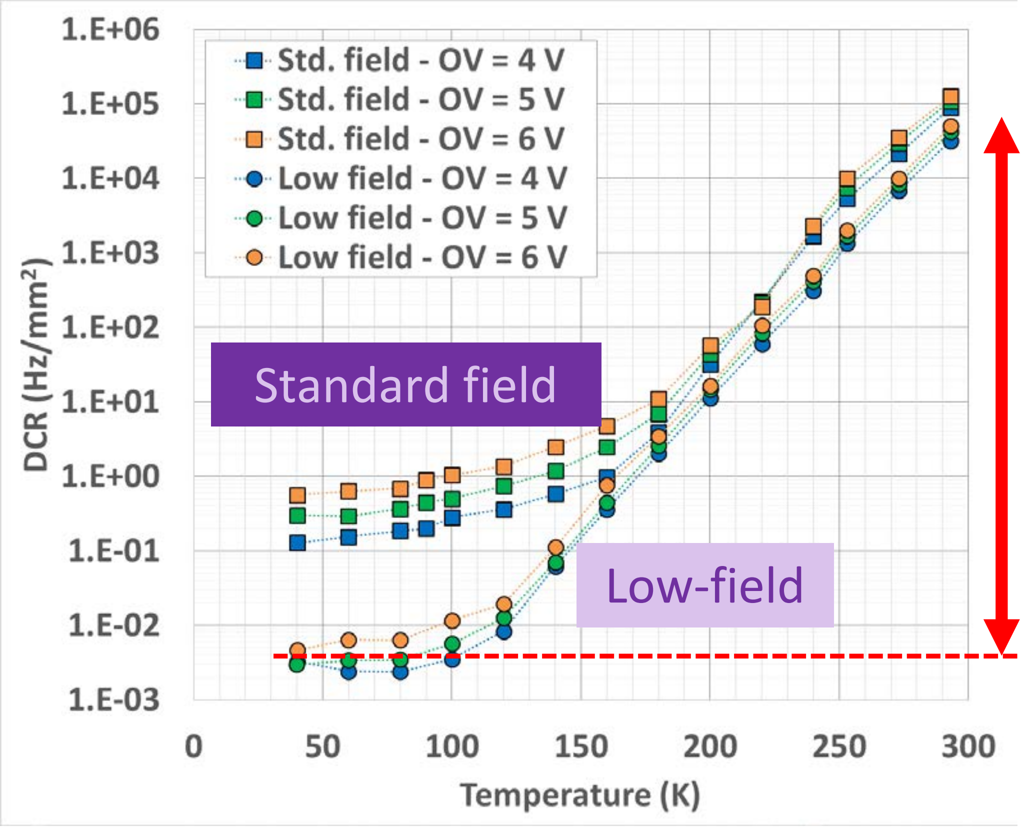


J.Merphy(SensL) 2nd SiPM Advanced Workshop, March 2014)

Dark Count ~30 kHz/mm^2 was measured at dVB=2÷3 V at room temperature with SiPMs from several producers. Now it becomes a standard!!

Dark noise at low temperature

A low-electric field NUV-HD version has been developed by FBK to reduce the tunnelling component of the DCR.



> 7 orders of magnitude !

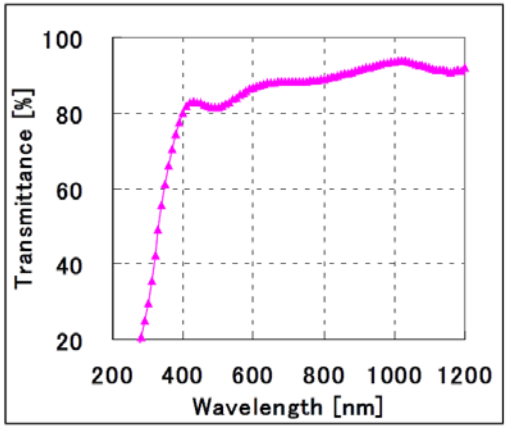
(G. Zappalà(FBK), VCI-2016)

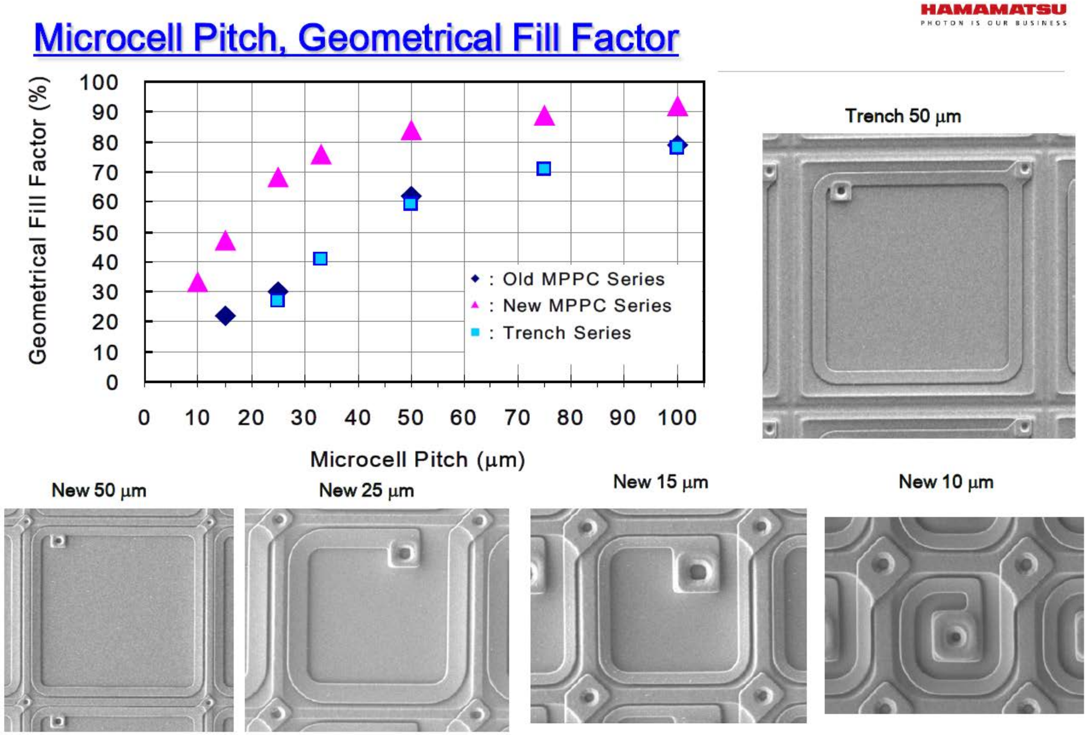
A $10 \times 10\ cm^2$ SiPM array would have a total DCR < 100 Hz!

Further GF increase: Metal Film Quenching Resistor

Quenching resistors occupy some of the cell's sensitive area. They are non-transparent for UV/blue/green light. The loss of sensitivity can be significant (especially for small cells).

Metal Film Transmittance





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

Good Uniformity of resistance
(full 6-inch wafer)

Width	Poly-Si	Metal
2 μm	19%	9%
1 μm	37%	11%

Low Temperature coefficient of resistance

Poly-Si	Metal
-2.37 kΩ	-0.43 kΩ

(/deg C)

Another advantages of MFQ resistors are better uniformity and relatively small temperature coefficient → smaller cell recovery time change with temperature

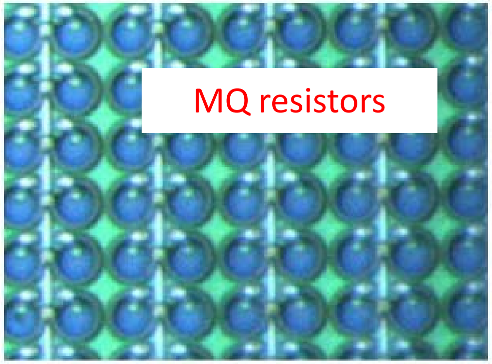
SiPMs with Metal Quenching Resistor: PDE increase

MPPCs developed by HPK for the CMS HCAL Upgrade project

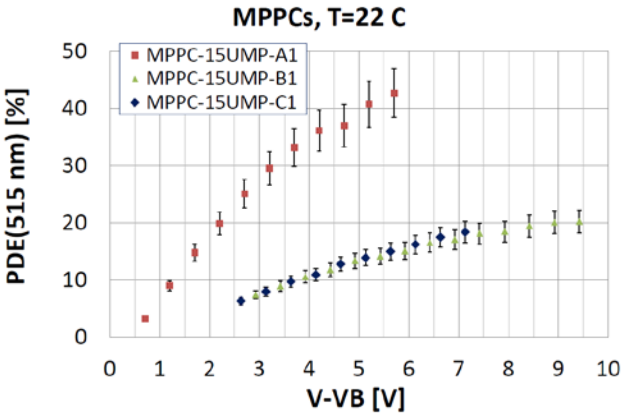
Atype-15 Micron

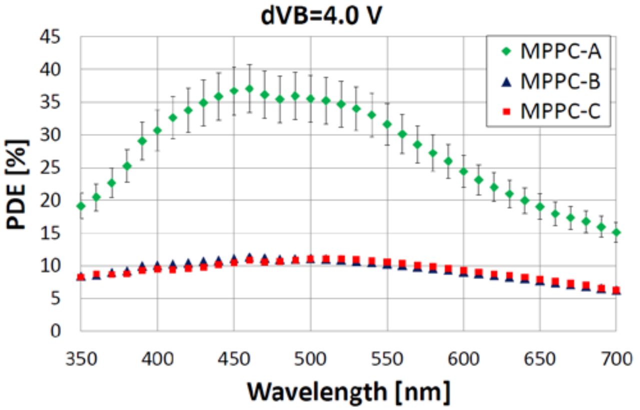
Polysilicon resistors

B/Ctype-15 Micron



MQ resistors



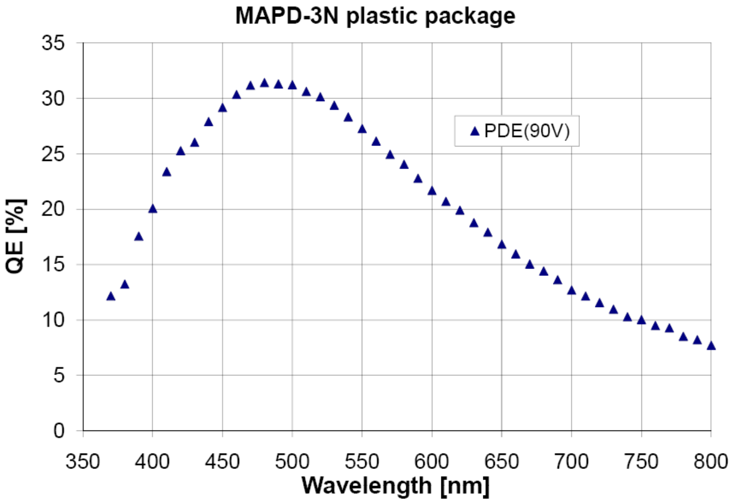


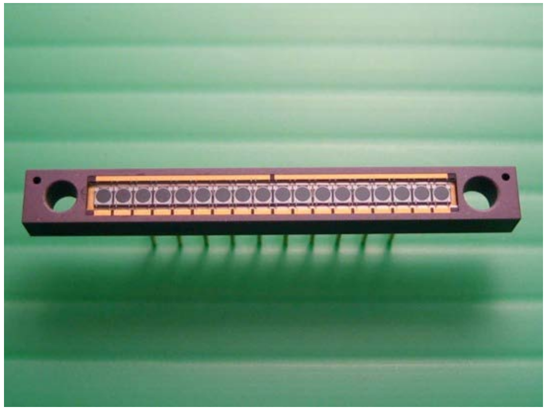
PDE(515 nm)>30% for 15 μm cell pitch MQR MPPCs. It was improved by a factor of >3 in comparison to the 15 μm cell pitch MPPCs with polysilicon quenching resistors.

The future of SiPMs: UHD SiPMs

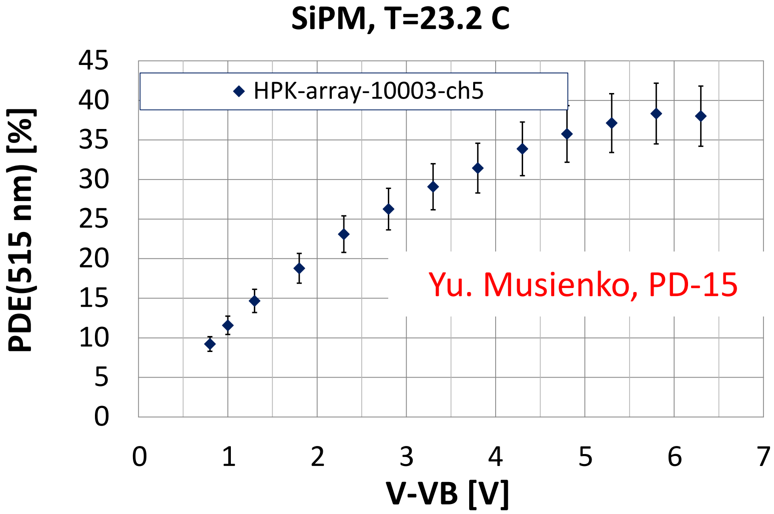
During last 3 years very high geometric factors (up to 80%) were achieved with small cell pitch SiPMs or (Ultra High Density SiPMs). Small cells have many advantages: low gain → smaller X-talk, after-pulsing, recovery time; larger dynamic range, possibility to operate SiPMs at high over-voltages, better resistance to radiation: smaller dark currents of irradiated SiPMs, smaller power dissipation, reduced blocking effects. Small cells potentially should provide better timing resolution (smaller avalanche development time)

Previous development: linear array of MAPDs (18x1 mm^2 , 15 000 cells/mm^2) produced by Zecotek for the CMS HCAL Upgrade project.



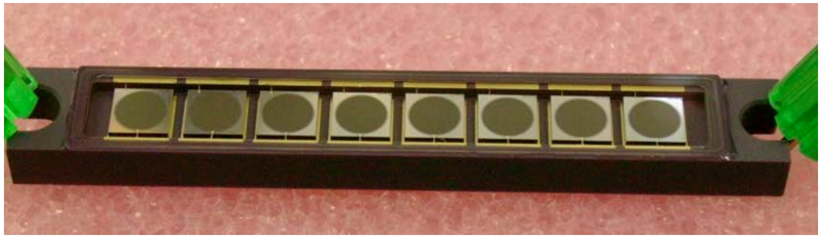


Large dynamic range SiPMs for the CMS HE HCAL Upgrade



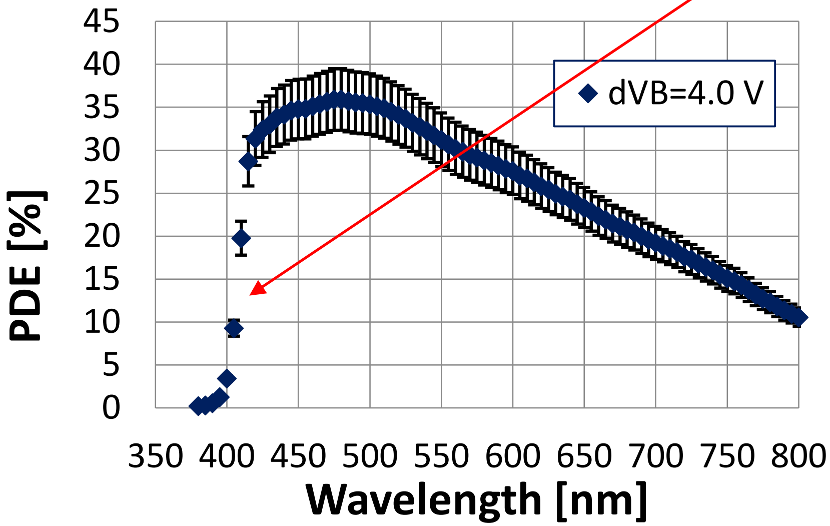
Yu. Musienko, PD-15

8-ch. SiPM array for the CMS HE HCAL Upgrade project: Ø2.8 mm SiPMs, 15 μm cell pitch

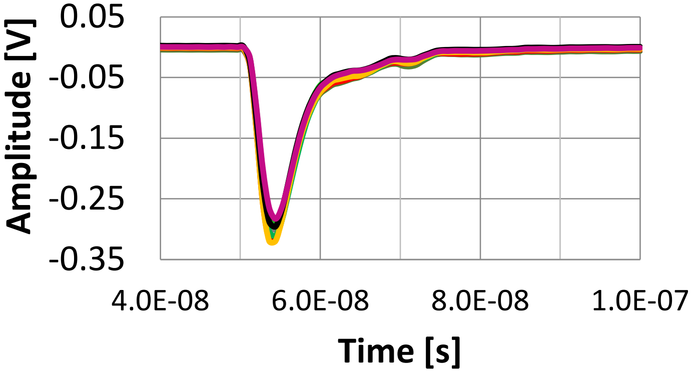


Glass widow with special filter was designed by HPK to cut off UV light which can be produced by muons and hadrons in plastic fibers

1400 SiPM arrays have been delivered to CERN during this year

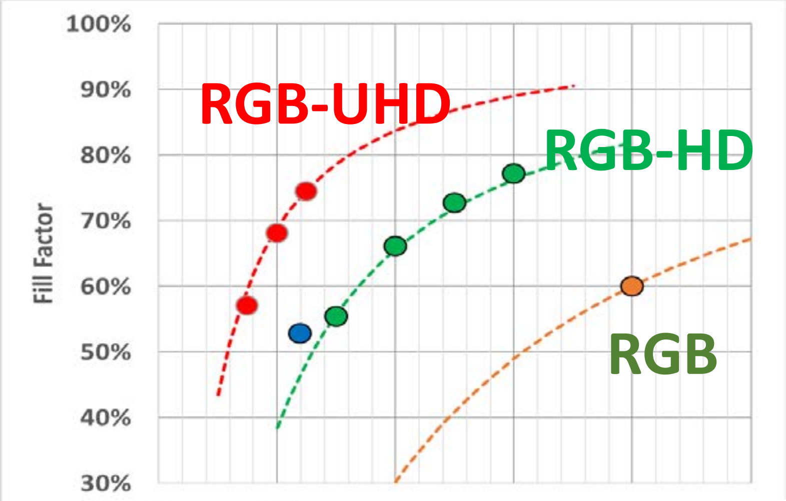


SiPM laser response

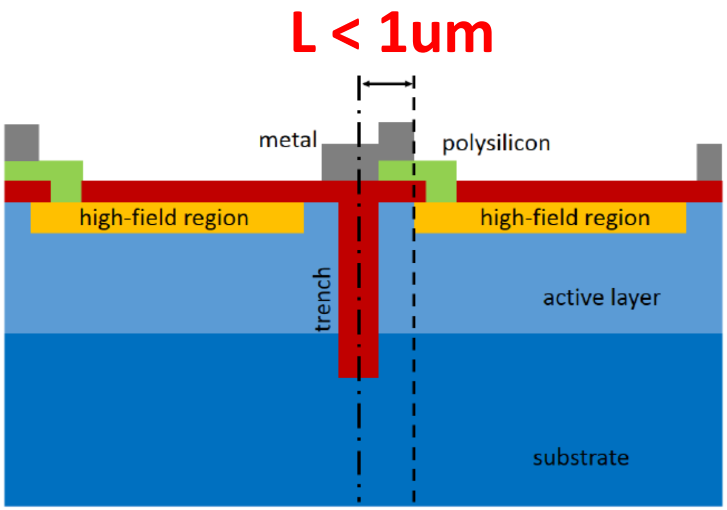


Recovery time 7-8 ns

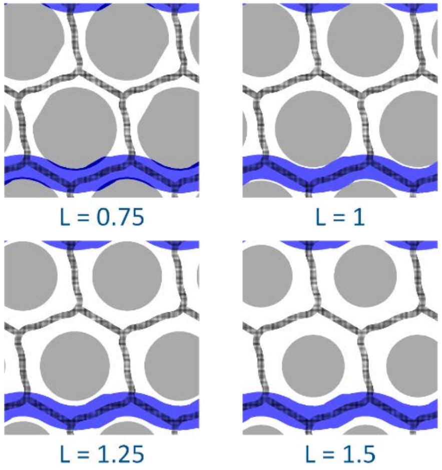
FBK UHD2 SiPMs



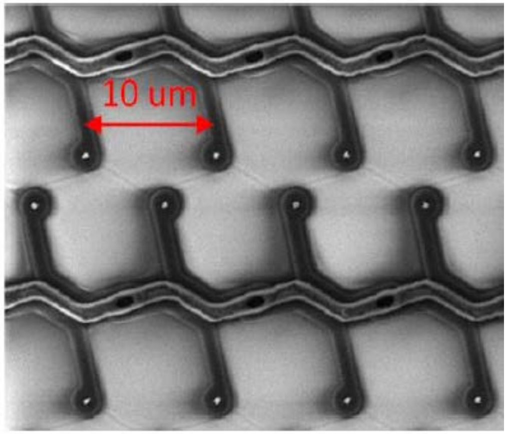
(Alberto Gola – PhotoDet 2015, Troitsk)



Cell sensitive area vs. trench width



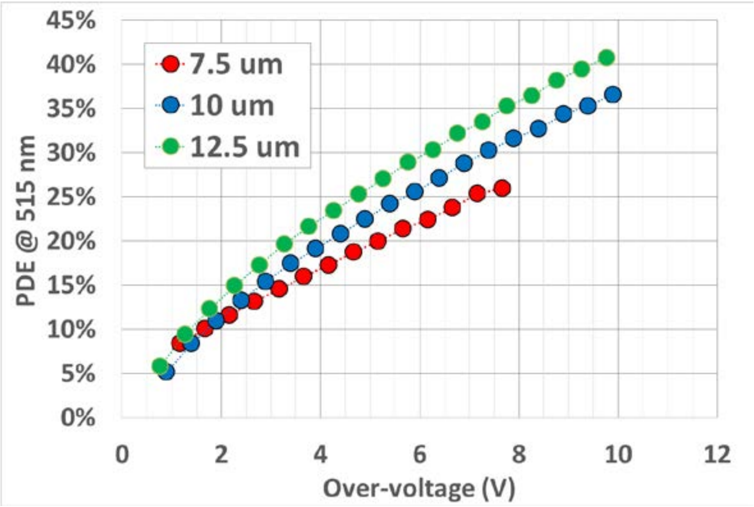
Finished 10 μm cell pitch SiPM

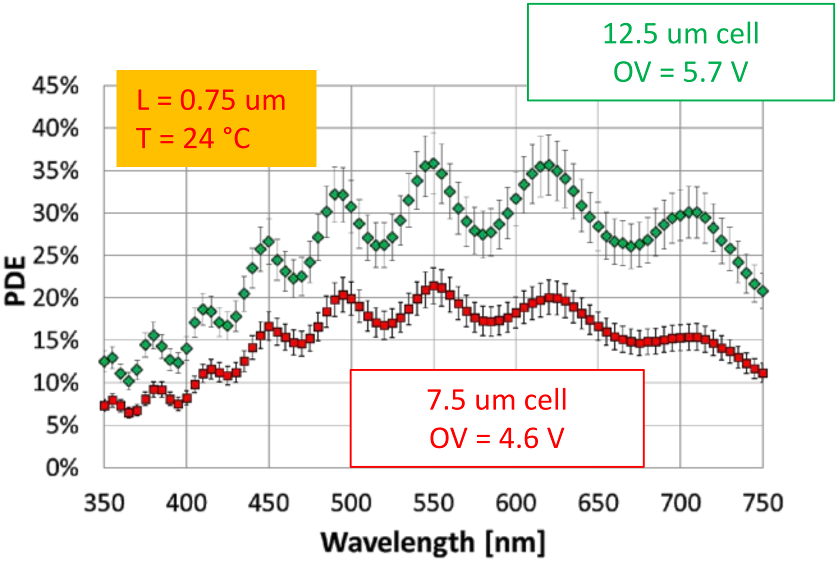


Fill Factor vs. trench width

L (um)	Fill Factor
0.75	57.1%
1	48.8%
1.25	40.3%
1.5	32.6%

UHD2 SiPM parameters



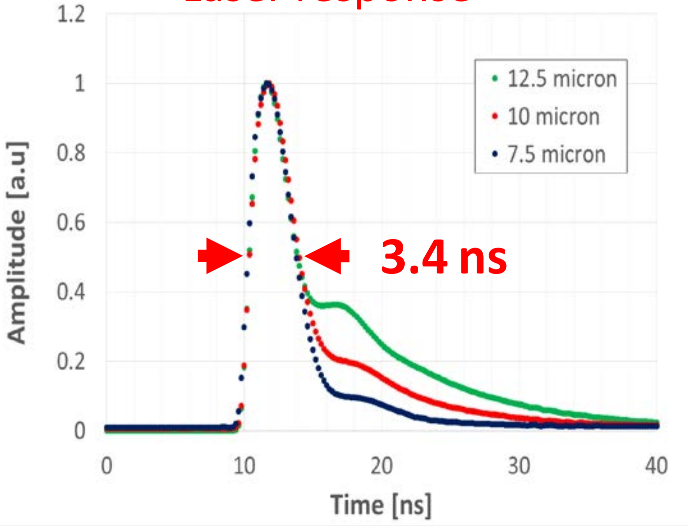

L = 0.75 um
T = 24 °C

12.5 um cell
OV = 5.7 V

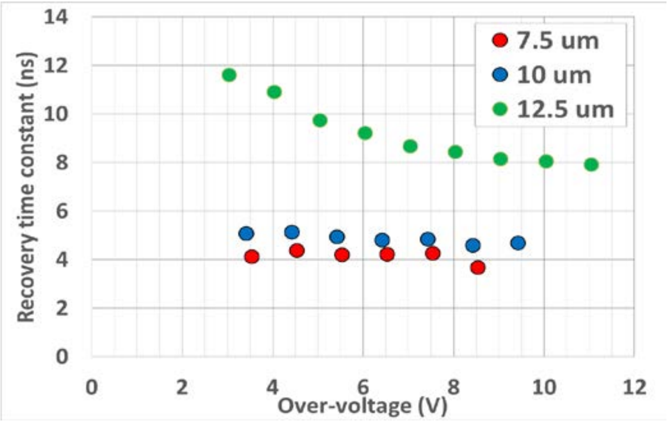
7.5 um cell
OV = 4.6 V

(Alberto Gola – PhotoDet-2015 , Troitsk)

Laser response

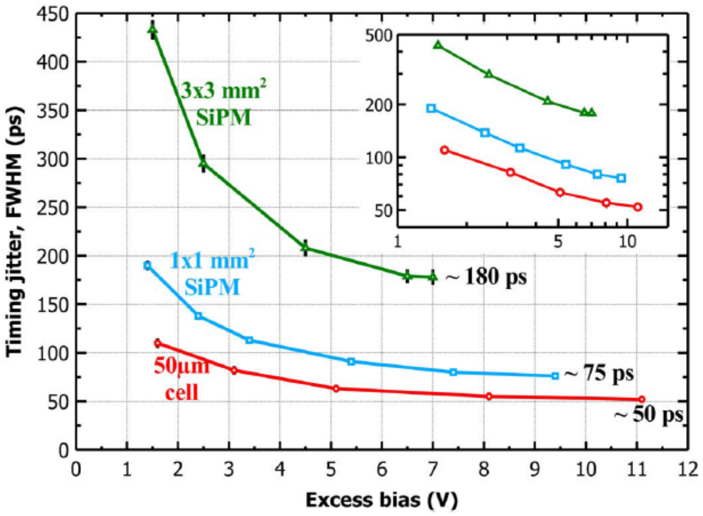

3.4 ns

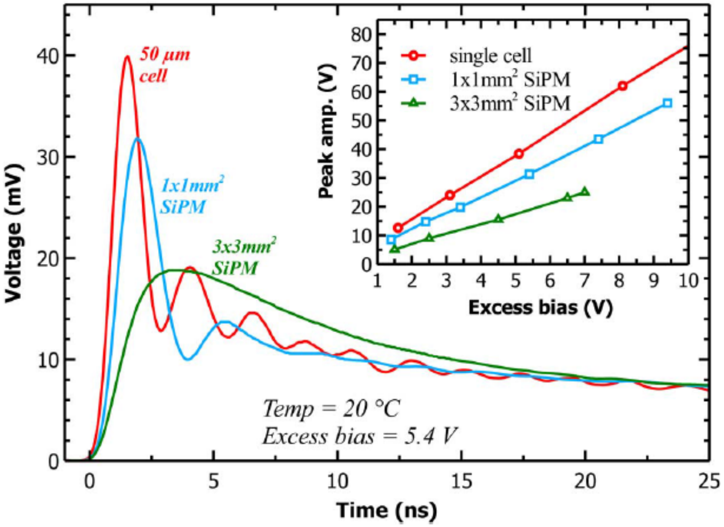
Recovery time

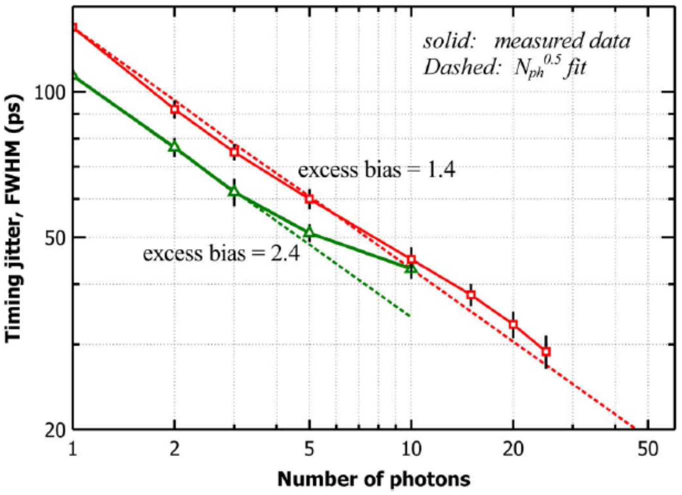


SiPM timing

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 61, NO. 5, OCTOBER 2014



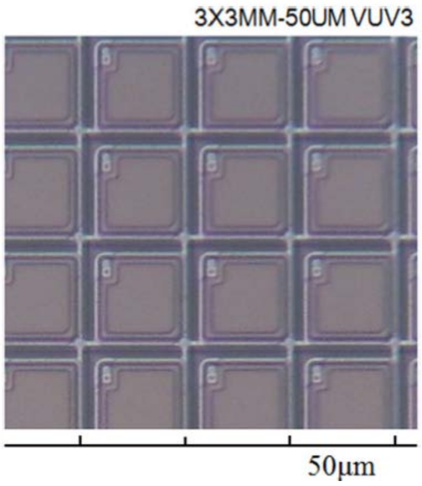


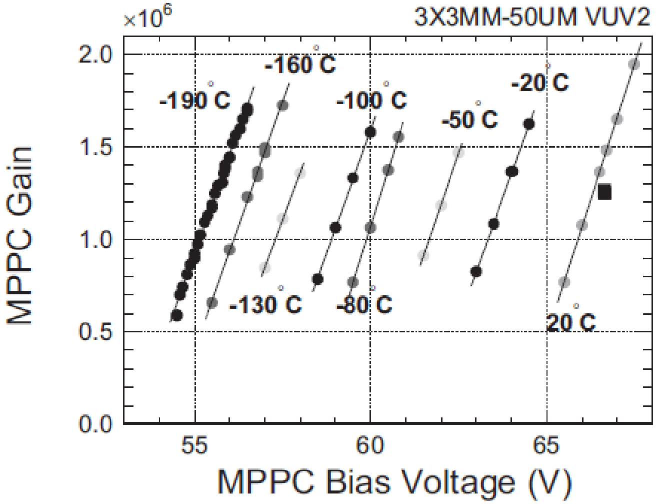


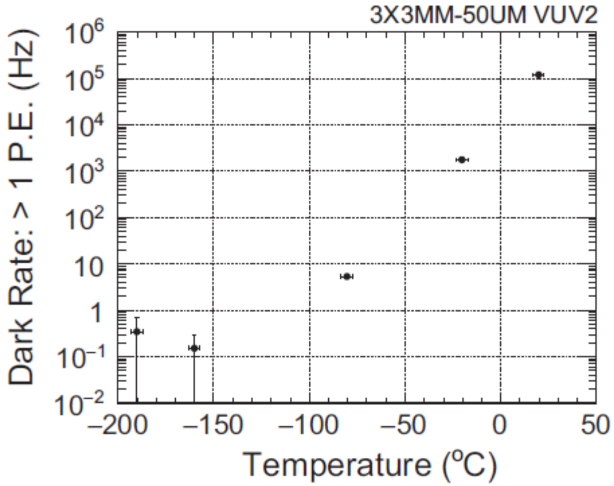
Single-photon time resolution for 3 SiPM area, measured at different biases for 425 nm light. Larger area SiPMs have slower signal rise-time. Factors limiting SPTR are signal rise-time, signal electron resolution and correlated noise (X-talk and delayed pulses). The latest is especially important for multi-photon events. The result which is shown here is among the best measured so far.

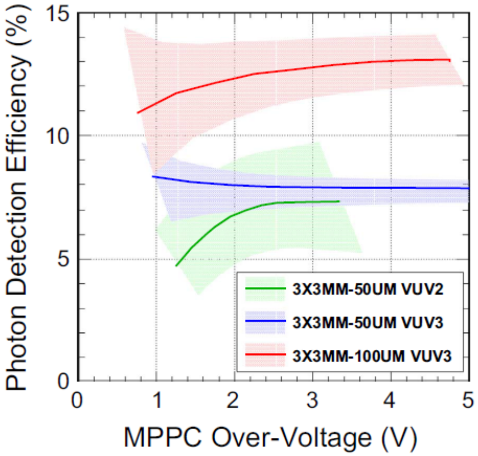
Vacuum ultra violet (VUV) SiPMs

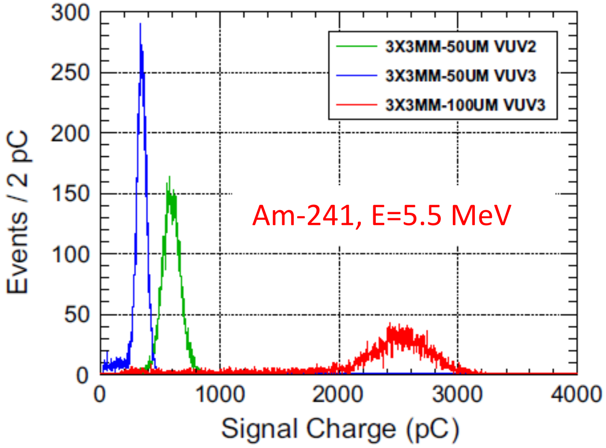
SiPMs sensitive to VUV light (<150 nm) were recently developed by HPK for detection LAr (T=-186 °C) scintillation light (λ = 128 nm).











The PDE(128 nm) was measured ~8% for 50 υm pitch SiPMs and ~13% for 100 µm pitch SiPM at dVB=3 V

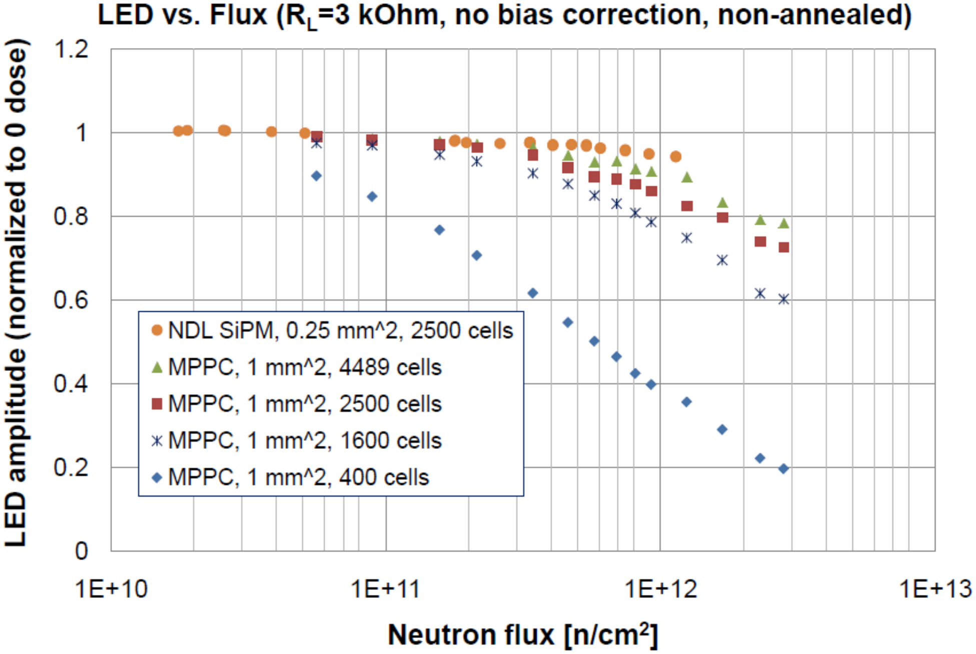
(NIM A833 (2016) 239–244)

SiPM: radiation hardness

Radiation may cause:

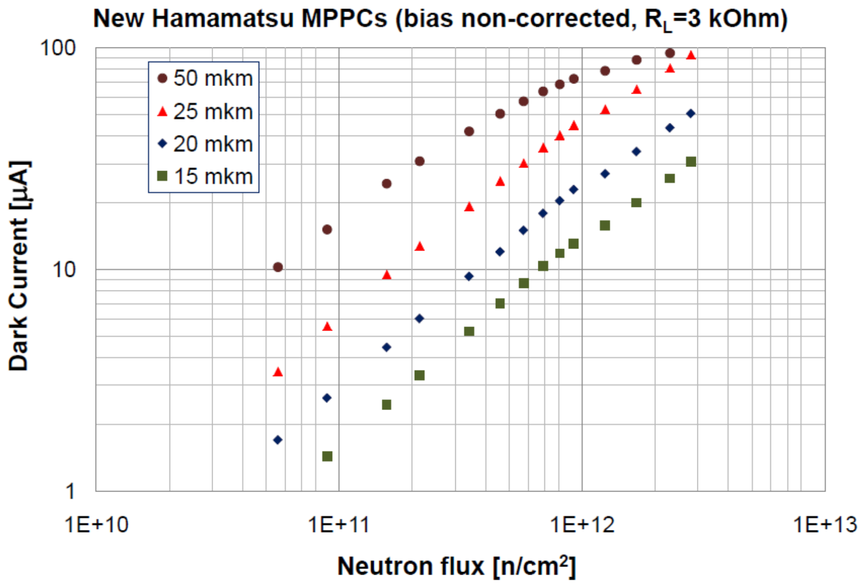
- Fatal SiPMs damage (SiPMs can't be used after certain absorbed dose)
- Dark current and dark count increase (silicon …)
- Change of the gain and PDE vs. voltage dependence (SiPMs blocking effects due to high induced dark carriers generation-recombination rate)
- Breakdown voltage change

Relative response to LED pulse vs. exposure to neutrons (E_{eq}~1 MeV) for different SiPMs



SiPMs with high cell density and fast recovery time can operate up to $3*10^{12}$ neutrons/cm^2 (gain change is< 25%).

Dark current vs. exposure to neutrons (E_{eq}~1 MeV) for different SiPMs



High energy neutrons/protons produce silicon defects which cause an increase in dark count and leakage current in SiPMs:

$$I_d \sim \alpha * \Phi * V * M * k,$$

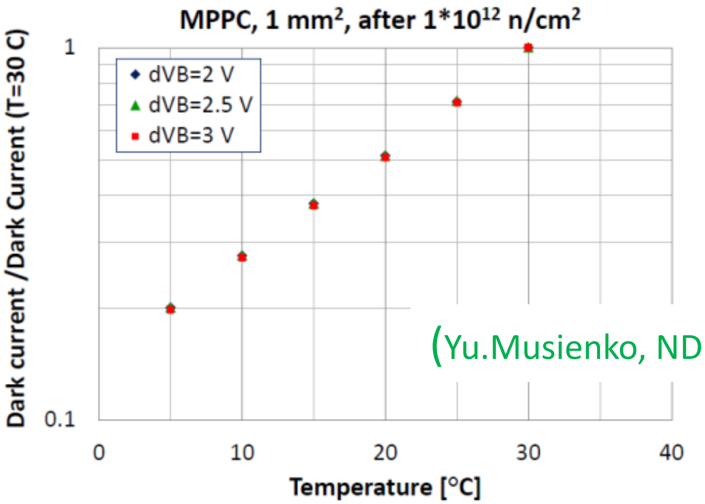
α – dark current damage constant [A/cm];
Φ – particle flux [$1/cm^2$];
V – silicon active volume [cm^3]
M – SiPM gain
k – NIEL coefficient

α_{Si} ~$4*10^{-17}$ A*cm after 80 min annealing at T=60 C (measured at T=20 C)

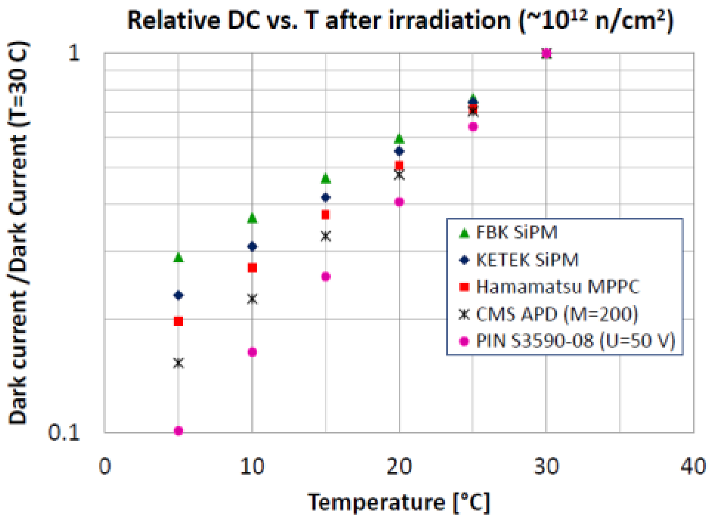
Thickness of the epi-layer for most of SiPMs is in the range of 1-3 µm, however d_{eff} ~ 5 ÷ 50 µm for different SiPMs. High electric field effects (such as tunneling and field enhanced generation) play significant role in the origin of SiPM's dark noise.

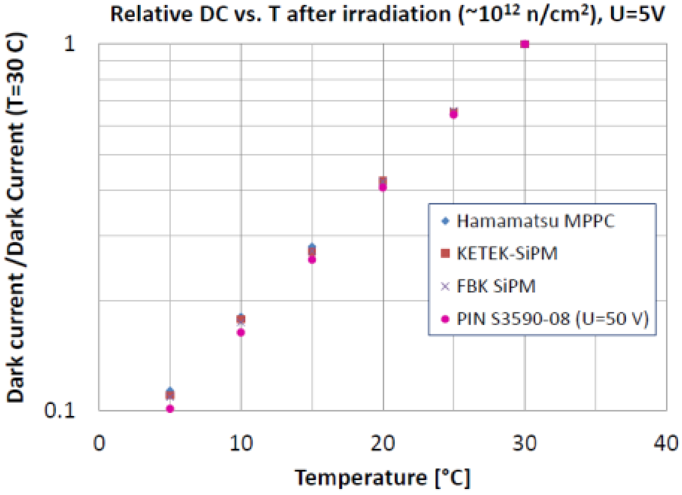
$V \sim S * G_f * d_{eff}$,
S - area
G_f - geometric factor
d_{eff} - effective thickness

Dependence of the SiPM dark current on the temperature (after irradiation)



(Yu.Musienko, NDIP-2014)

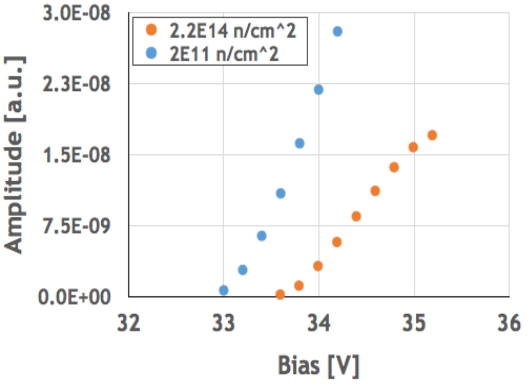


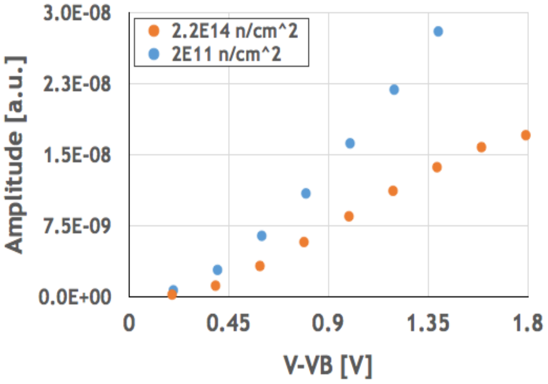


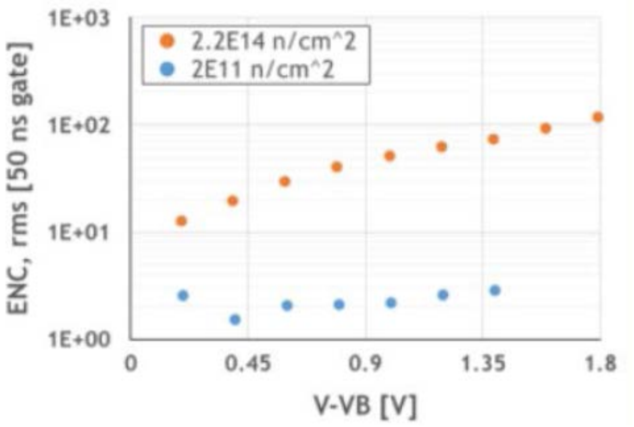
It was observed a rather weak dependence of the SiPM's dark current decrease with temperature on the dVB value. SiPM dark currents at low voltage (5V) behave similar with temperature to that of the PIN diode. However we observed significant difference of this dependence for differenet SiPM types when they operate over breakdown! General trend is that SiPMs with high VB value have faster dark current reduction with the temperature.

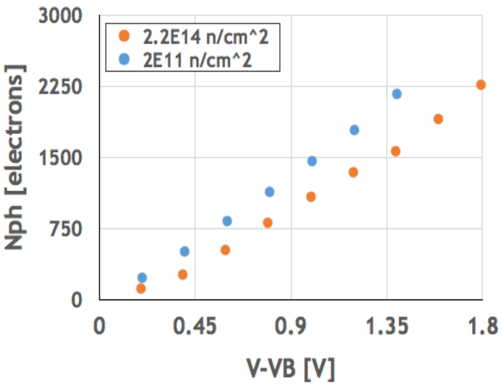
SiPM irradiated up to 2.2*10^{14} n /cm^2

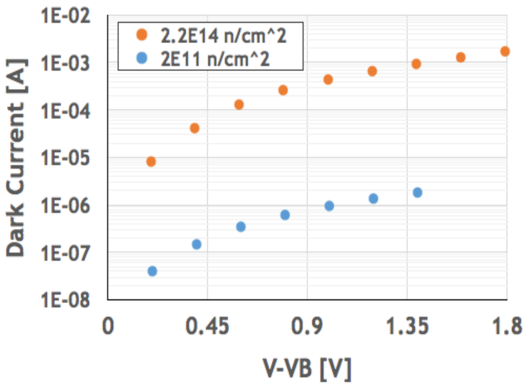
Can SiPM survive very high neutron fluences expected at high luminosity LHC? FBK SiPM (1 mm^2, 12 μm cell pitch was irradiated with 62 MeV protons up to 2.2*10^{14} n /cm^2 (1 MeV equivalent).











We found:

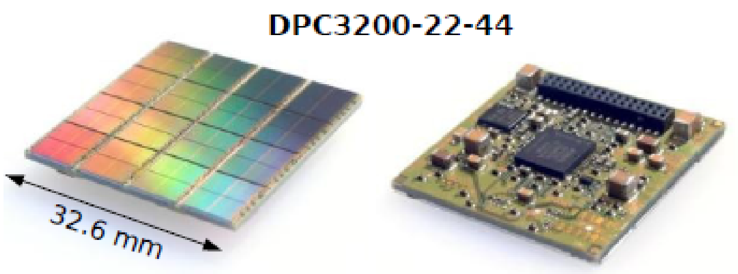
- Increase of VB: ~0.5 V
- Drop of the amplitude (~2 times)
- Reduction of PDE (from 10% to 7.5 %)
- Increase of the current (up to ~1mA at dVB=1.5 V
- ENC(50 ns gate, dVB=1.5V)~80 e, rms

The main result is that SiPM survived this dose of irradiation and can be used as photon detector!

(A.Heering et al., NIM A824 (2016) 111)

Radiation hardness study of the Philips Digital Photon Counter with proton beam

Irradiation by protons with P=800MeV/c (T=295MeV).
Beam size: $\sigma_x \approx \sigma_y \approx 1$ cm.

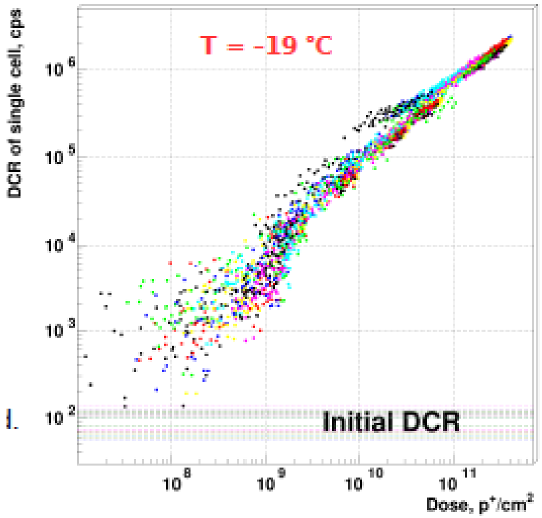


Array of 4x4 die.
Die = 128x100 cells (Geiger-mode APDs) +
+ TDC (LSB=20ps) + 4 photon counters.

Active cell quenching.
Full digital data output.
Noisy cells can be disabled

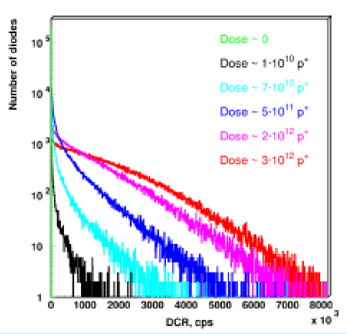
Signal from each pixel is is digitized and the information is processed on chip:

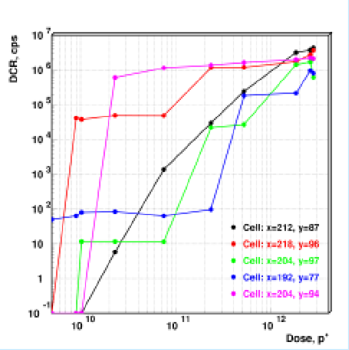
- time of first fired pixel is measured
- number of fired pixels is counted
- active control is used to recharge fired cells
- 4 x 2047 micro cells
- 50% fill factor including electronics
- integrated TDC with 8ps resolution



Dark counting rate vs. total dose

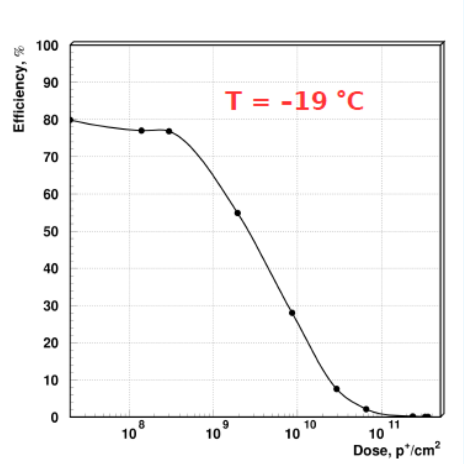
DCR spectra after different total doses accumulation





DCR of single cells from one subpixel as a function of total dose

With the dose accumulation the number of noisy cells increases rather than DCR of each cell. ⇒ Cell damage caused by single interaction of p⁺ with Si lattice.



Optimal efficiency of *single photons* detection as a function of proton fluence.

(M.Barnyakov et al., Elba-2015)

SiC SSPM

Why SiC?

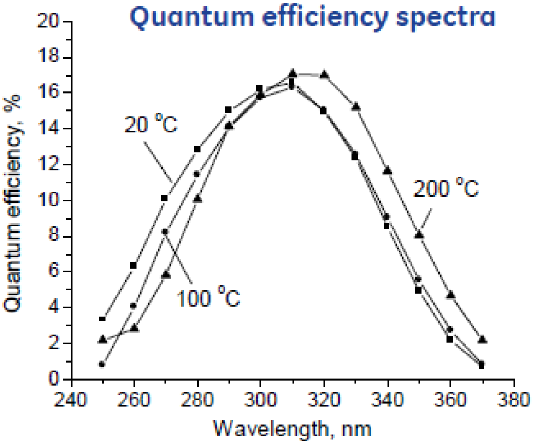
Dark count rate in Si-PM increases rapidly with temperature, resulting in a maximum operating temperature below 50°C

SiC has larger bandgap (3.26 eV)
- Lower leakage current
- Higher operating Temperature
- Higher sensitivity in UV spectra

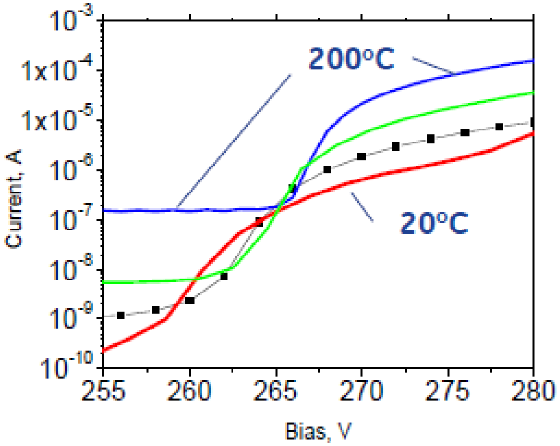
Packaged SiC SSPM

Active area: 4x4 mm²
Pixel size: 60 um
16 sub arrays
Area of sub-array: 1x1 mm²

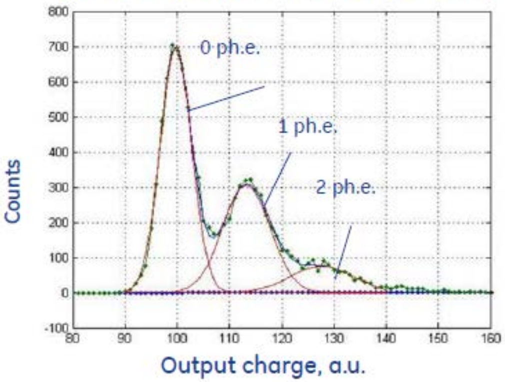
Quantum efficiency spectra



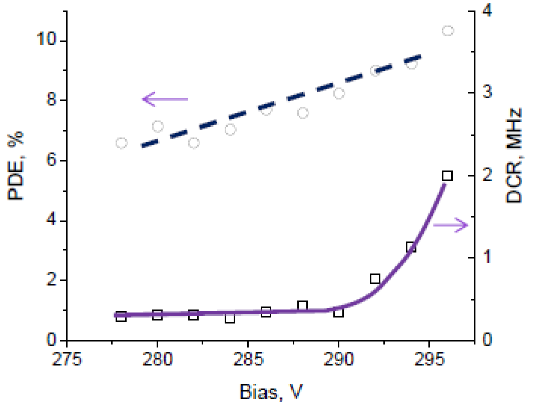
Dark current vs. temperature



Single Photoelectron spectrum recorded for SiC-PM with 256 pixels (1 mm²)



Photodetection efficiency and dark count rate as functions of voltage bias

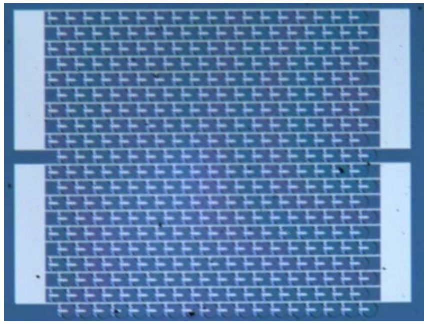


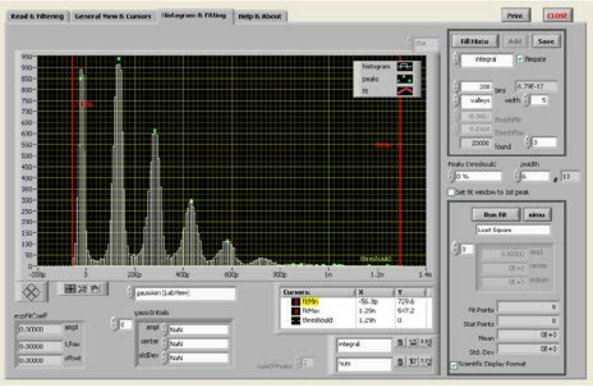
Potentially can be more radiation hard than silicon

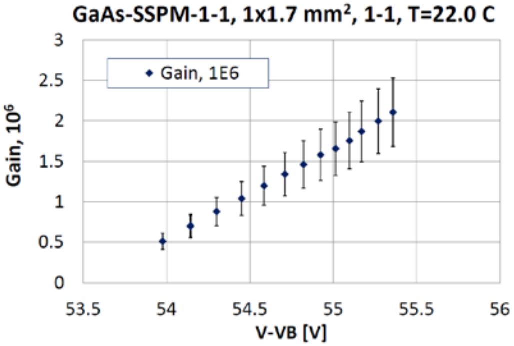
(S.Dolinsky, GE, NDIP-2014)

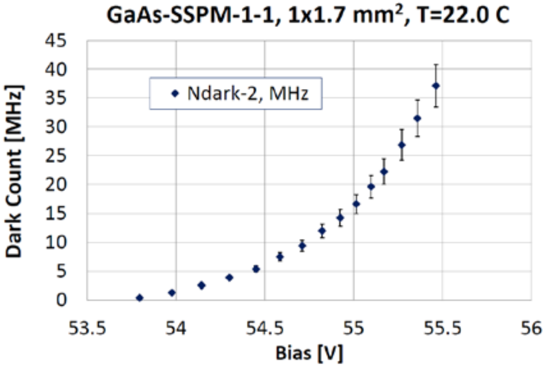
GaAs SSPM

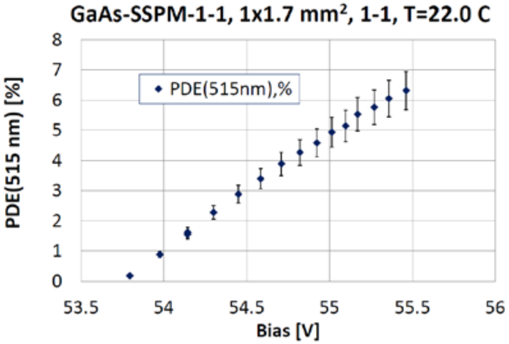
LightSpin Photomultiplier Chip™

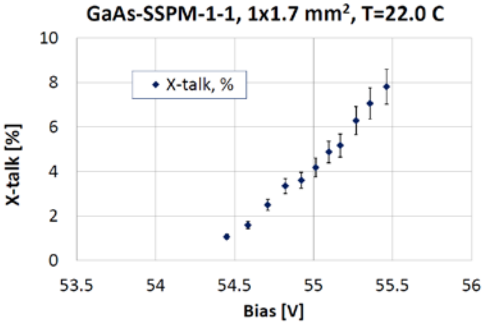


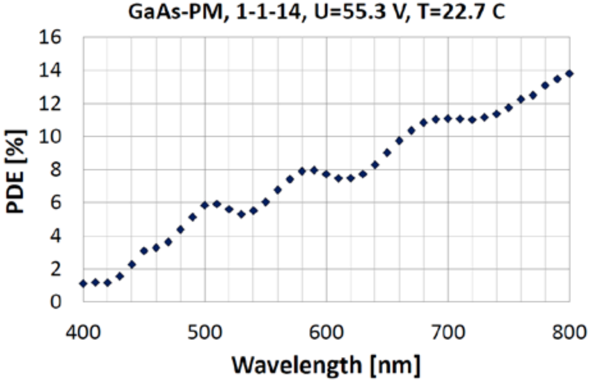



GaAs-SSPM-1-1, 1x1.7 mm², 1-1, T=22.0 C


GaAs-SSPM-1-1, 1x1.7 mm², T=22.0 C


GaAs-SSPM-1-1, 1x1.7 mm², 1-1, T=22.0 C

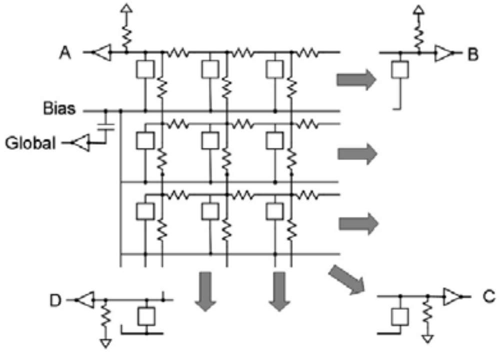

GaAs-SSPM-1-1, 1x1.7 mm², T=22.0 C


GaAs-PM, 1-1-14, U=55.3 V, T=22.7 C

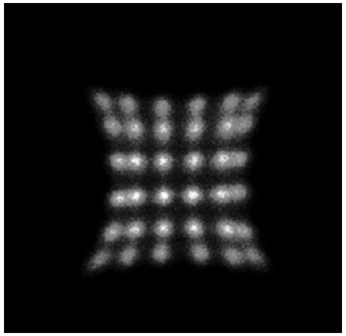
Wide bandgap (1.42 eV): potentially can be more radiation hard than silicon. Timing with GaAs SSPM can be also better (high mobility of electrons and holes, fast avalanche development – direct semiconductor)

Position-Sensitive SiPMs: PS-SiPM RMD

RMD had designed a 5x5 mm^2 position-sensitive solid-state photomultiplier (PS-SSPM) using a CMOS process that provides imaging capability on the micro-pixel level. The PS-SSPM has 11,664 micro-pixels total, with each having a micro-pixel pitch of 44.3 micron.



A basic schematics showing the design layout and pattern for PS-SSPM resistive network. Each square represents a micro-pixel. The network resistors are 246.5 Ohm each.



An image of a 66 LYSO array having 0.5 mm pixels uniformly irradiated with ^{22}Na.

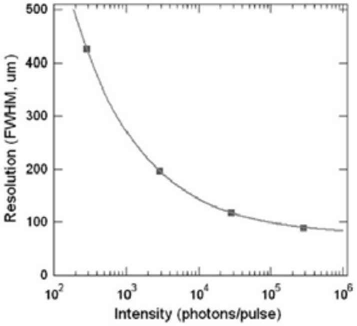
PS-SSPM parameters

Number of micro-pixels	11,664 (108 × 108)
Micro-pixel area	30 × 30 μm^2
Micro-pixel pitch	44.3 × 44.3 μm^2
Geometrical fill factor	46%
Quench resistors	143.8 kΩ
Network resistors	246.5 Ω
Detection efficiency @ 400 nm	~10%
Dark current (μA/mm^2)	10
Dark count rate (kHz/pixel)	~117
Operating bias	~32 V
Operating gain	~10^6
Excess noise factor	~1
Capacitance (fF/pixel)	150

Anger logic:

$$X = \frac{(A+B)-(C+D)}{\Sigma}$$

$$Y = \frac{(A+D)-(B+C)}{\Sigma}$$

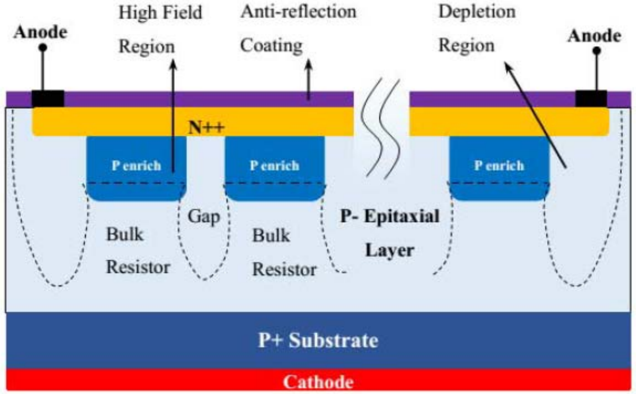


A plot of the X–Y spatial resolution (FWHM) as a function of the incident beam spot light intensity. Spot size was ~30 micron.

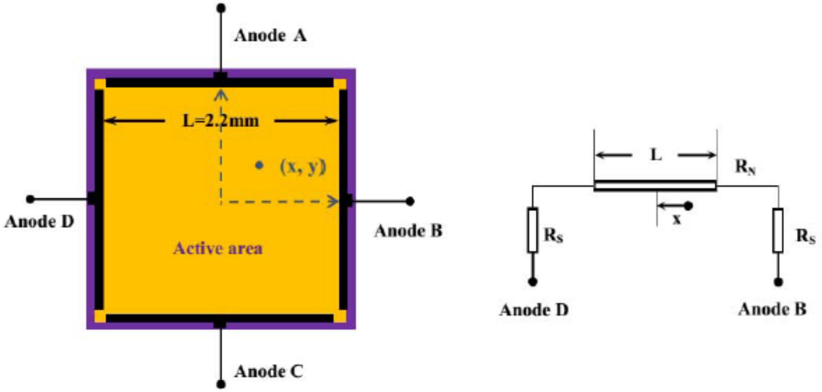
M. McClish et al. / Nuclear Instruments and Methods in Physics Research A 652 (2011) 264–267

PS SiPM - NDL

The device takes advantages of the sheet N+ layer as the intrinsic continuous cap resistor for charge division, the same way adopted in PIN or APD PSD



Schematic cross-section of the PS-SiPM with bulk quenching resistor

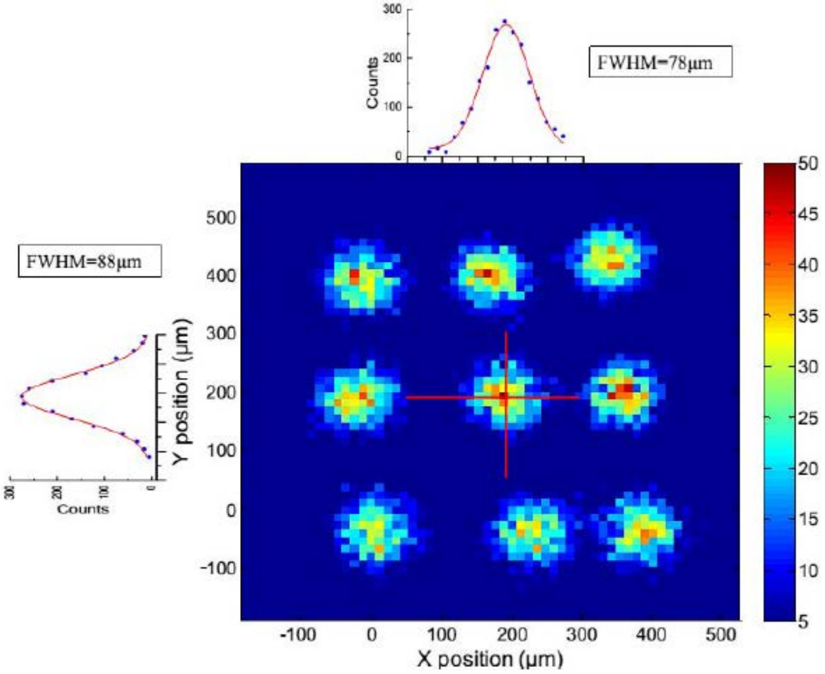


Top view of tetra-lateral type electrodes of the PS-SiPM with 4 anodes

$$x = \frac{P_B - P_D}{P_B + P_D} \cdot \frac{2R_S + R_N}{2R_N} \times L$$

$$y = \frac{P_A - P_C}{P_A + P_C} \cdot \frac{2R_S + R_N}{2R_N} \times L$$

PS-SiPM – NDL (II)

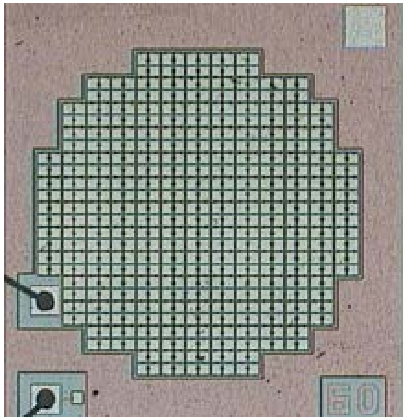


The device, with an active area of 2.2 mm × 2.2 mm, demonstrated spatial resolution of 78–97 μm, gain of 1.4 × 10^5 and 46-ps time jitter of transmission delay for 210–230 photons.

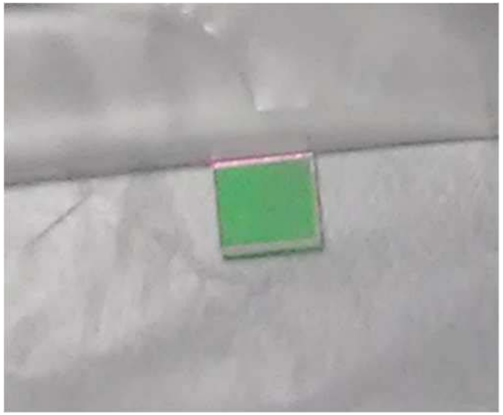
Reconstruction of nine positions of light spots from optical fiber tested in the central part of the device

IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 61, NO. 9, SEPTEMBER 2014

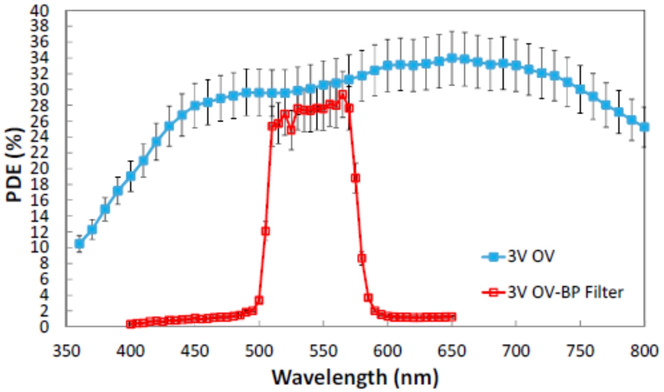
SiPMs with Bandpass Dichroic Filters



Optical microscope picture of the STMicro SiPM (548 cells, 67.4% geometrical factor)

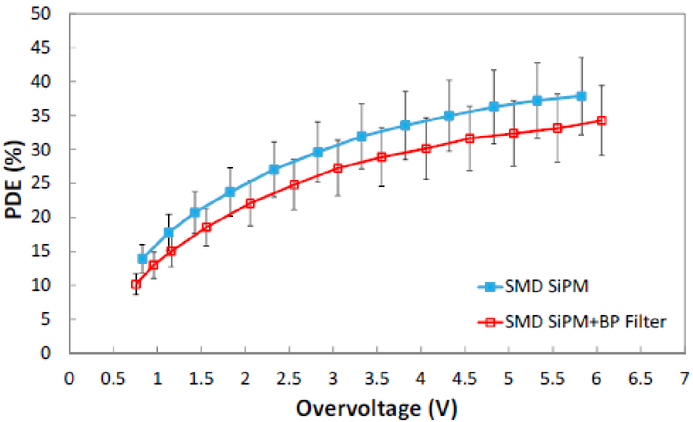


Green bandpath filter with 5x5 mm area and 1.1 mm thickness



PDE spectral shape measured at 24 °C and dVB=3 V on n-on-p SiPM with and without BP filter

Such a photo-sensor can be very used in applications where protection of the detector from unwanted light background (ambient light for example) is required.

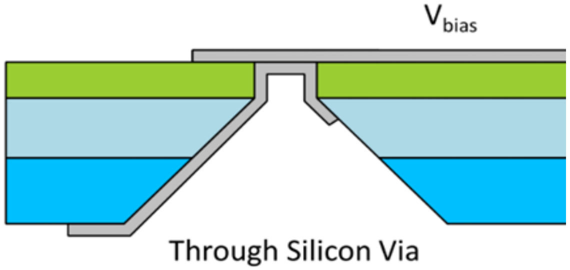


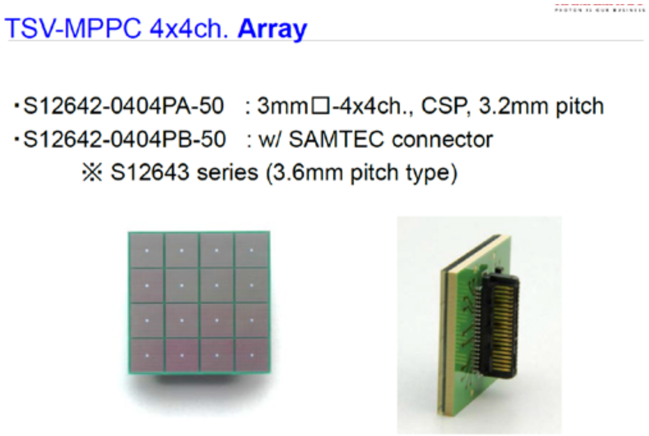
PDE measured at 515 nm vs bias on n-on-p SiPM with and without BP filter

(M.Mazillo et al., to be published in Sensors)

TSV technology (no bonding wire)

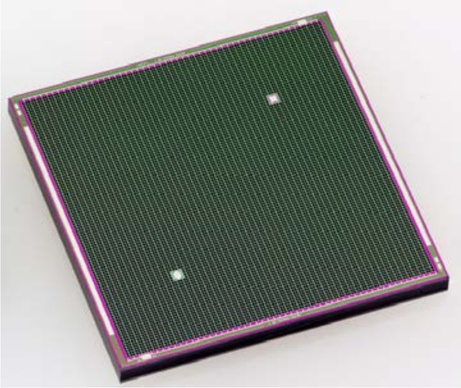
TSV Technology:
Further improved geometrical efficiency for arrays ,

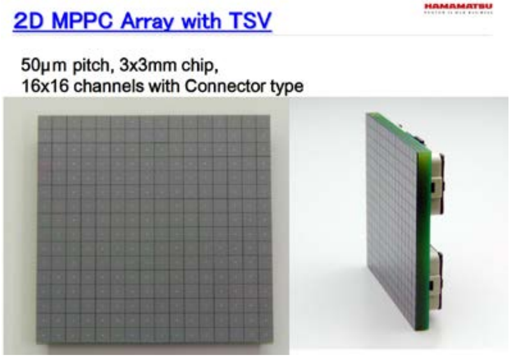



TSV-MPPC 4x4ch. Array

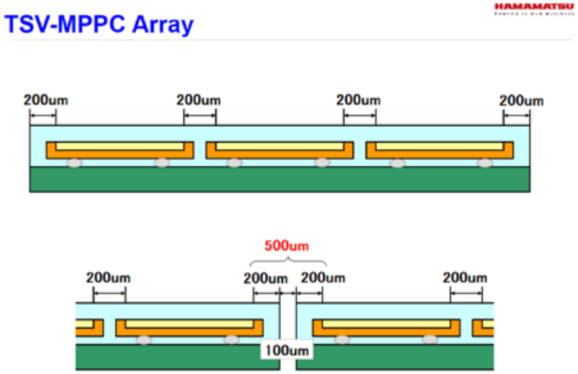
- S12642-0404PA-50 : 3mm□-4x4ch., CSP, 3.2mm pitch
- S12642-0404PB-50 : w/ SAMTEC connector

※ S12643 series (3.6mm pitch type)




2D MPPC Array with TSV

50μm pitch, 3x3mm chip,
16x16 channels with Connector type


TSV-MPPC Array

(KETEK – Photodet-2015 (Troitsk))

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

Summary

Significant progress in development of SSPMs over last 3 years by several developers:

- High PDE: ~50-60% for blue-green light
- SiPMs with good sensitivity (PDE>10%) for VUV light have been developed
- Dark count at room temperature was reduced: ~30 kHz/mm^2
- Low optical cross-talk: <1-5% for high OV
- Fast timing: SPTR~75 ps (FWHM)
- Large dynamic range: >10 000 pixels/mm^2 (with high PDE>30%)
- Very fast cell recovery time: ~4 ns
- Large area: 6x6 mm^2 and more
- TSV technology was introduced to build very compact SiPM arrays
- Position-sensitive SiPMs with good position resolution: <100 μm
- SiPMs demonstrated their rad. tolerance up to 2.2*10^{14} n/cm^2
- SiC, GaAs, InGaP SSPMs were successfully developed
- . . .

SSPM perspectives (3-5 years)

My point of view:

- Further work to reduce correlated noise (this is one of the limiting factors for many applications)
- Small cell pitch (5 μm), large dynamic range SIPMs
- DUV SiPMs with good sensitivity (PDE>30%) for VUV light
- Dark count at room temperature can be reduced: <10 kHz/mm^2
- Development of SiPMs for fast timing: SPTR<50 ps (FWHM)
- Fast cell recovery time: 2-3 ns
- Large area: 10x10 mm^2 and more
- PS SiPMs with position resolution: <50 μm for single photons
- SiPMs with rad. tolerance up to 5*10^{14} n/cm^2
- Further development of SiC, GaAs, InGaP SSPMs.
- Price will go down (for large quantities) <10 CHF/cm^2...

Acknowledgments

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