Advances in Solid State Photon Detectors

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Outline

- Introduction
- SiPM progress
- SiPM radiation damage
- Exotic SSPMs
- Summary and SiPM/SSPM perspectives

Introduction

Progress in understanding of physics of SiPM operation was achieved during last 3-5 years.

As a result → significant progress in SiPM understanding/development. SiPMs with **reduced correlated noise (X-talk, afterpulsing)**, improved PDE, reduced dark noise were developed and produced.

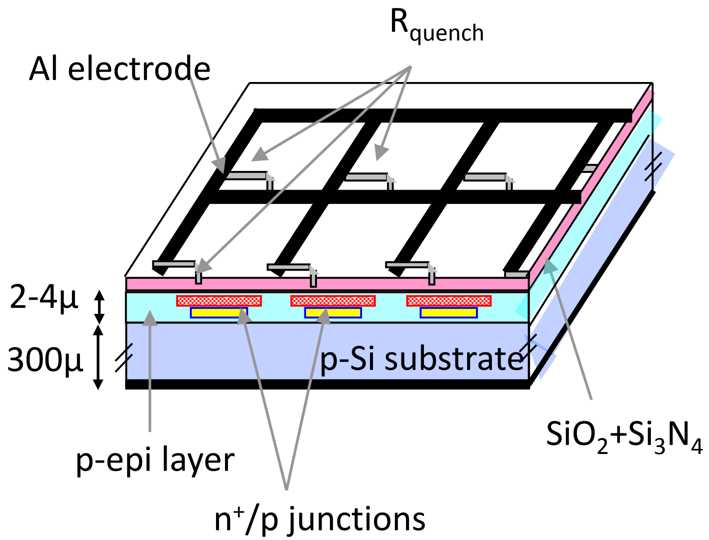
Here I will review current (March 2017) status of SiPM/SSPM development.

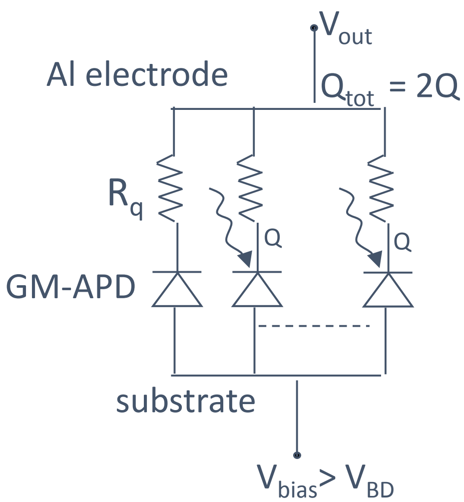
A special attention is paid to new developments in the field of radiation-hard SiPMs. Possible perspectives of SiPM/SSPM development will be also discussed.

I would like to thank all whose slides (shown at PD-2012, NDIP-14, PD-15, VCI-16, Elba-15, 2nd SiPM Advanced workshop-Geneva-2014, CPAD-2016 and RICH-2016, IEEE-NS/MIC-2016 conferences etc.) are used in this presentation.

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 and operated in Geiger mode*
- *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) were 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).

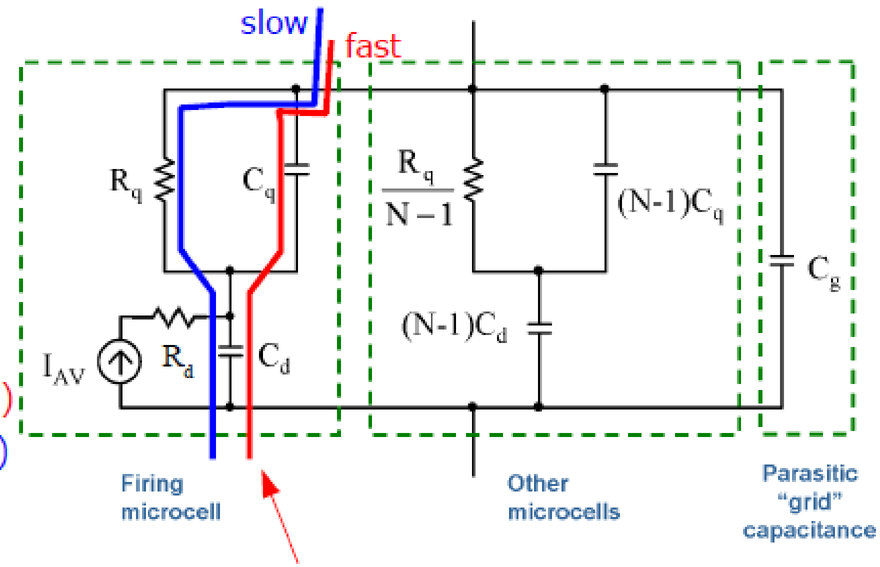
SiPM equivalent circuit (small signal model) and pulse shape

Single cell model → $(R_d||C_d)+(R_q||C_q)$
SiPM + load → $(||Z_{cell})||C_{grid} + Z_{load}$

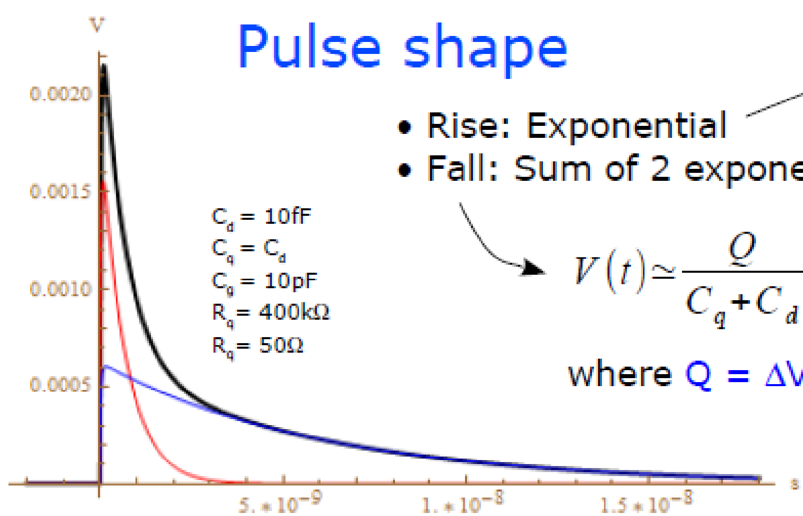
Signal = slow pulse $(\tau_{d\,(rise)}, \tau_{slow\,(fall)})$ +
+ fast pulse $(\tau_{d\,(rise)}, \tau_{fast\,(fall)})$

- $\tau_{d\,(rise)} \sim R_d(C_q+C_d)$
- $\tau_{fast\,(fall)} = R_{load}\ C_{tot}$ (fast; parasitic spike)
- $\tau_{slow\,(fall)} = R_q\,(C_q+C_d)$ (slow; cell recovery)

F.Corsi, et al. NIM A572 (2007) 416
S.Seifert et al. IEEE TNS 56 (2009) 3726



Cq → fast current supply path in the beginning of avalanche



Pulse shape

- Rise: Exponential → Sp.Charge Rd x Cd,q filtered by parasitic inductance, stray C, … (Low Pass)
- Fall: Sum of 2 exponentials

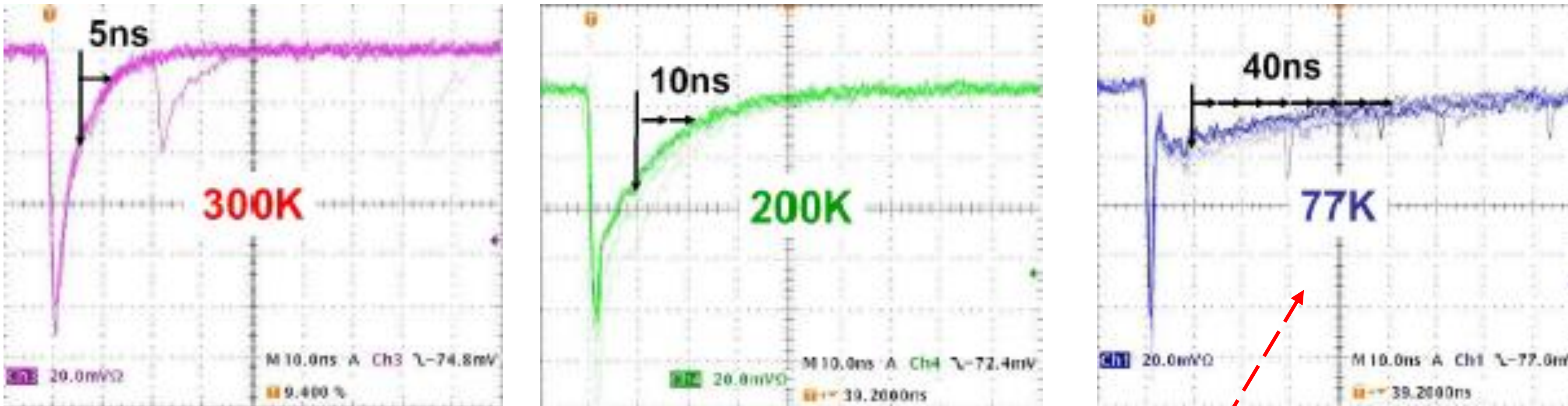
$$V(t) \simeq \frac{Q}{C_q+C_d}\left(\frac{C_q}{C_{tot}} e^{\frac{-t}{\tau_{FAST}}} + \frac{R_{load}}{R_q}\frac{C_d}{C_q+C_d} e^{\frac{-t}{\tau_{SLOW}}}\right) \quad \text{for } R_{load} << Rq$$

where $Q = \Delta V\,(C_q+C_d)$ is the total charge released by the cell

→ 'prompt' charge on C_{tot} is $Q_{fast} = Q\ C_q/(C_q+C_d)$

(slide taken from presentation of G. Collazuol at PD-2012)

Pulse shape vs. T



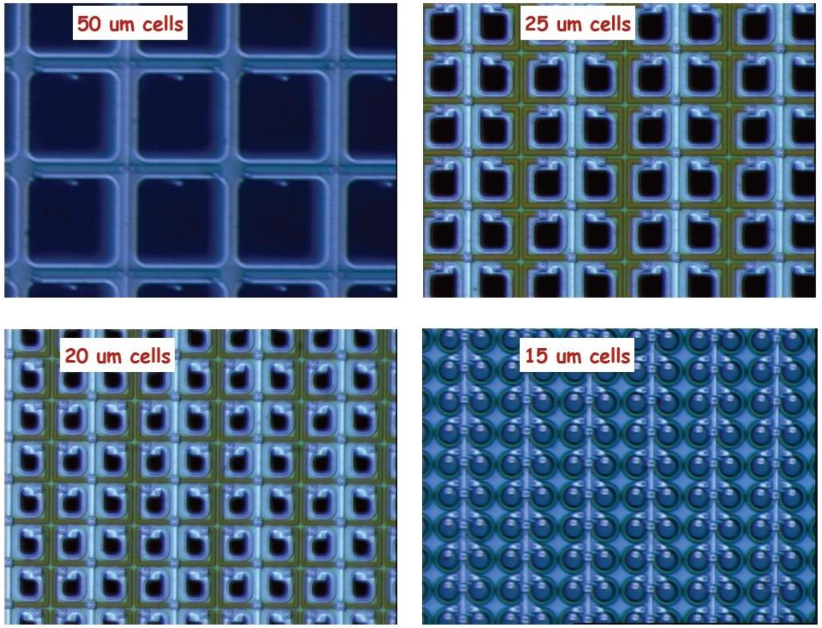
(H. Otono et. al, PD-07)

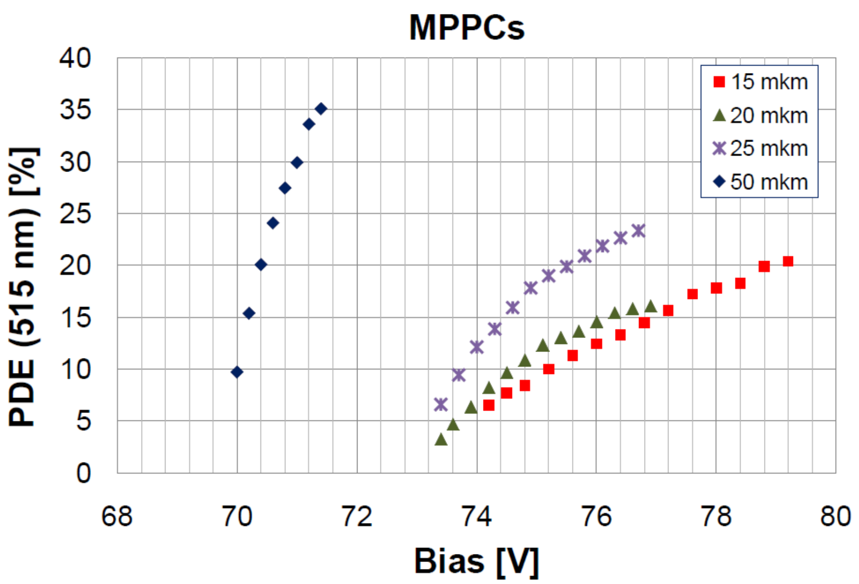
Fast and slow components behave differently with temperature:

- Fast - doesn't depend
- Slow – time constant increases with T due to R_q increase

For HPK SiPM with polysilicon quenching resistor the slow time constant increases ~8 times when temperature drops from 300 K to 77 K

SiPMs: PDE&Geometric factor



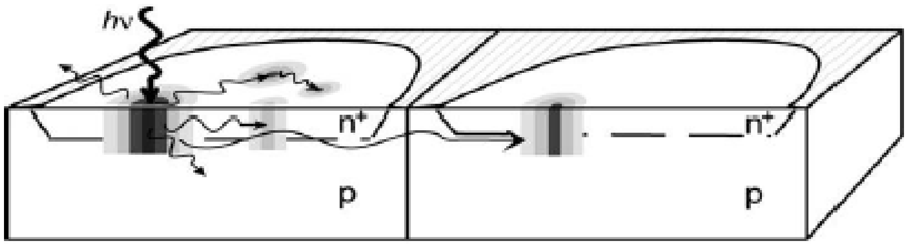


(Yu.Musienko, CTA SiPM Workshop, Geneva, 2014)

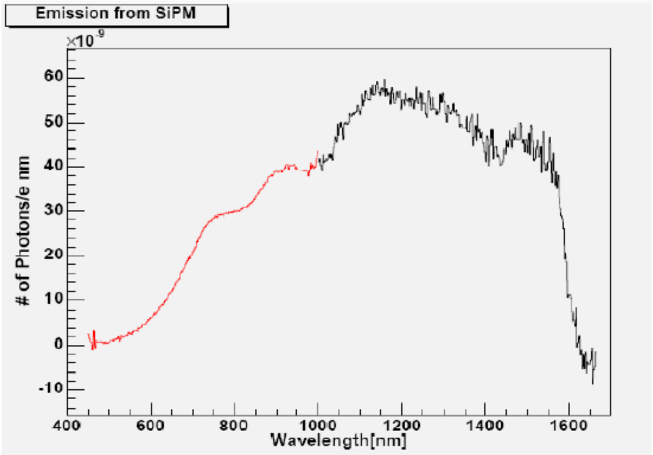
$PDE(\lambda, U,T) = QE(\lambda)*G_f*P_b(\lambda,V,T)$

Cells should be electrically independent → "dead" space between SiPM cells reduces its PDE. It is especially important for the small cell pitch SiPMs

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



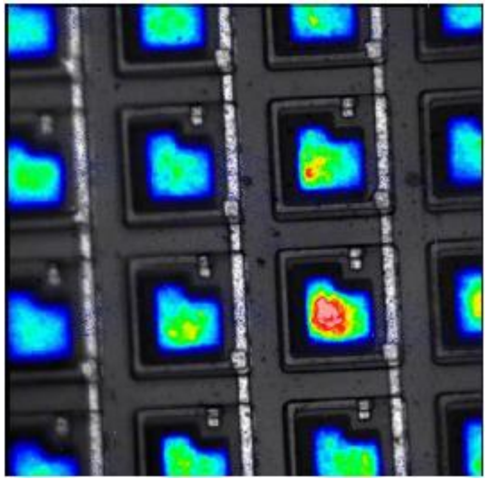
A. Lacaita et al, IEEE TED (1993)



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

Cellls are not optically independent!
Hot-carrier luminescence process:
10^5 carriers produces ~3 photons with an wavelength less than 1 μm.
Optical cross-talk causes adjacent pixels to be fired → increases gain fluctuations → increases noise and excess noise factor !

Avalanche luminescence

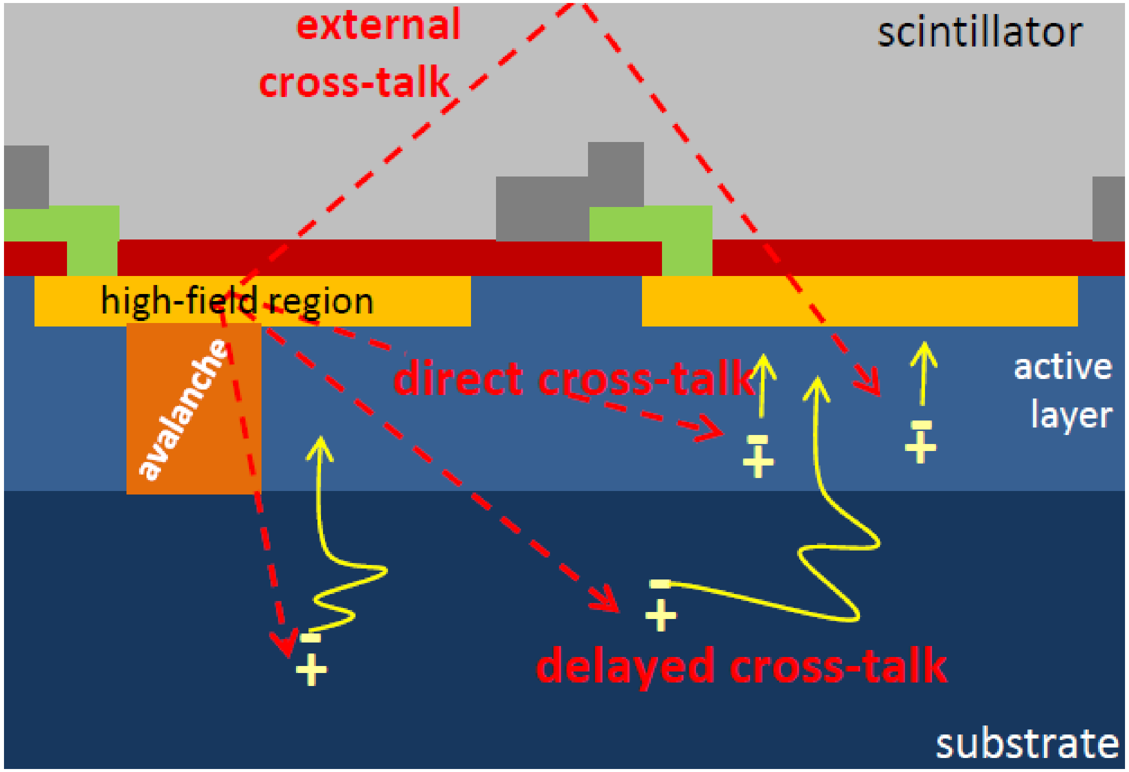


N.Otte, SNIC-2006

SiPMs: Optical cross-talk - II

Other effects of cell luminescence:

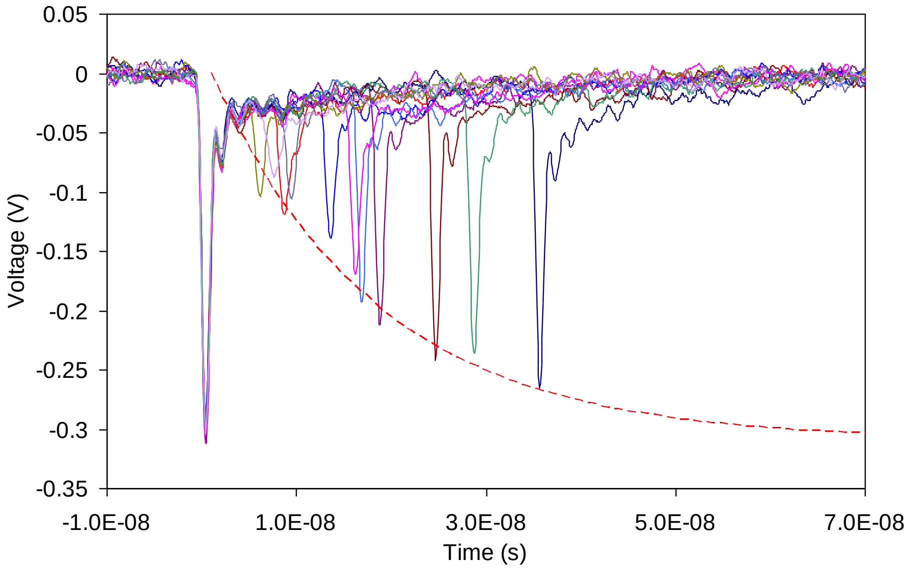
- External cross-talk
- Delayed pulses from light absorbed in non-depleted region (look like after-pulses)

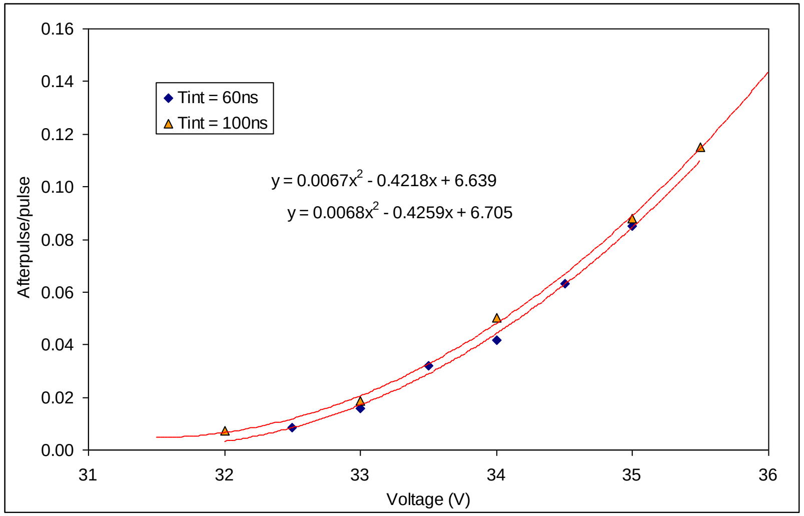


Fabio ACERBI - PhotoDet 2015

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

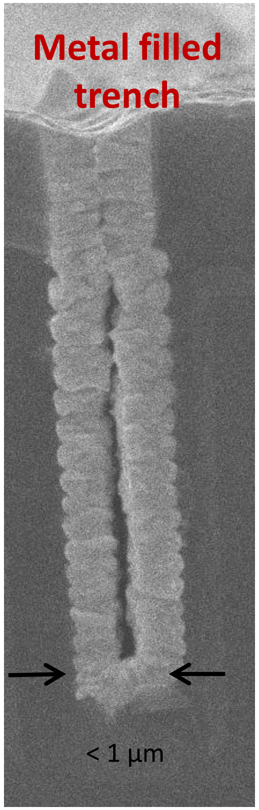




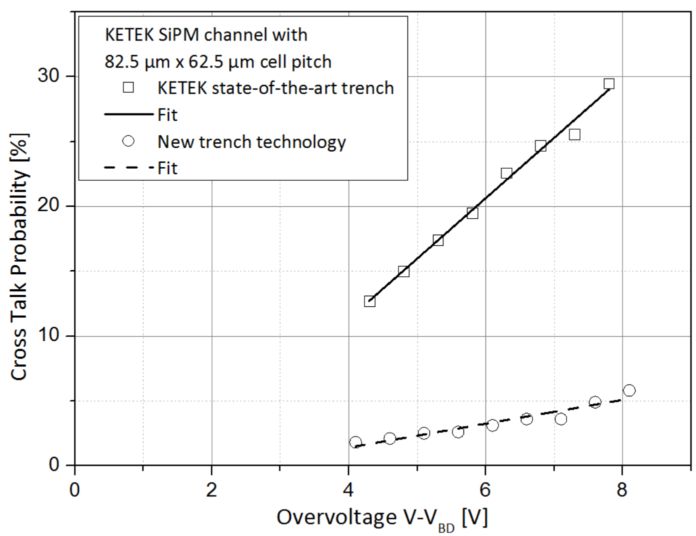
Events with after-pulse measured on a single cell.

After-pulse probability *vs* bias

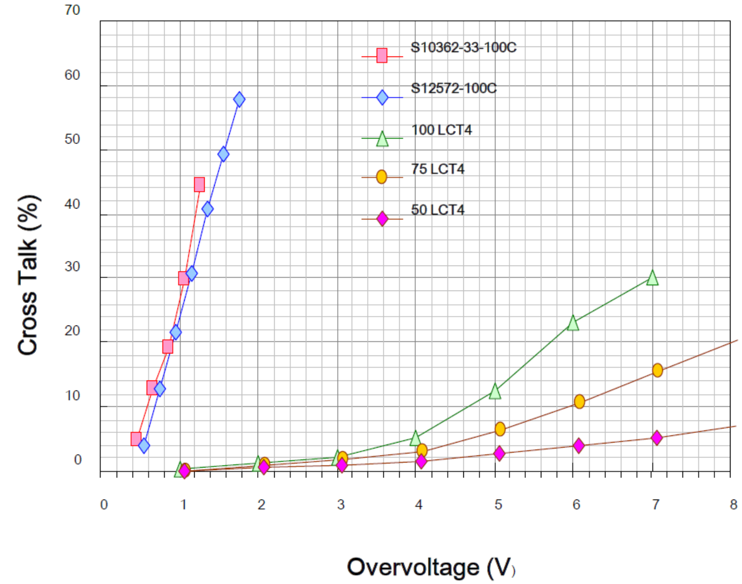
X-talk reduction



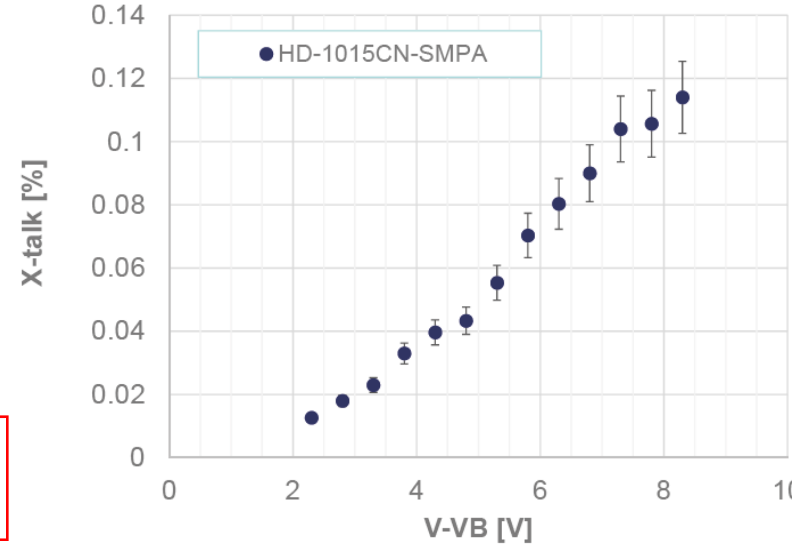
The way to reduce X-talk: trench filled with non-transparent material (tungsten)



(KETEK – Photodet-2015 (Troitsk))



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

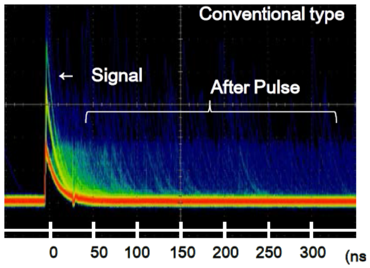


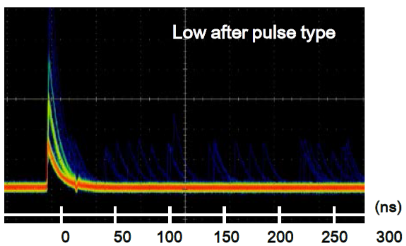
Extremely low X-talk value of 0.05% was measured for Hamamatsu HD-1015CN SiPM (INSTR-17, poster 42)

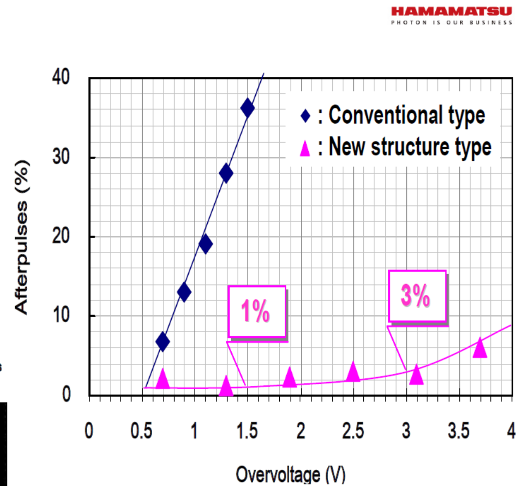
Afterpulsing and delayed X-talk reduction

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.

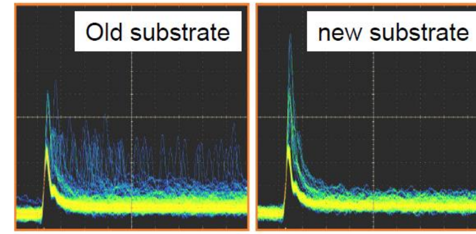
(HPK: Koei Yamamoto, 2nd SiPM Advanced Workshop, March 2014)

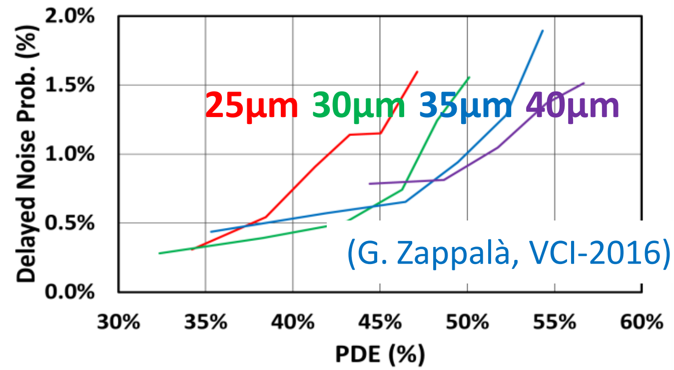
- Improved substrate

Minority carrier lifetime reduced ~ 2 order of magnitude

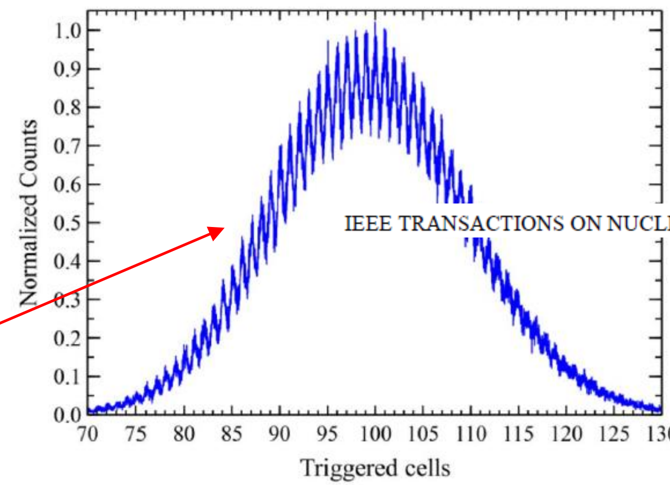
→ lower delayed correlated noise

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





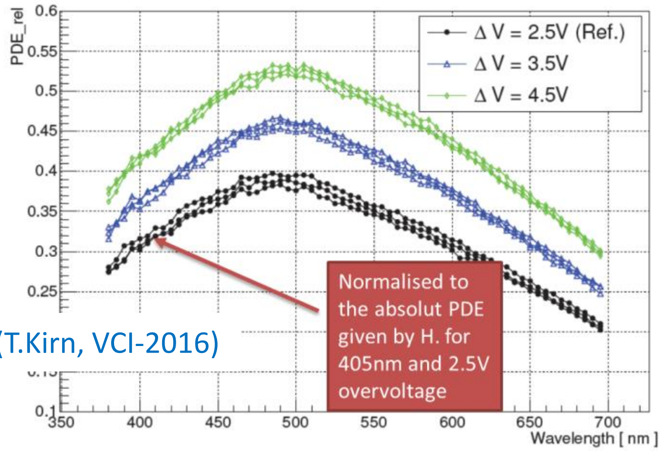
(G. Zappalà, VCI-2016)



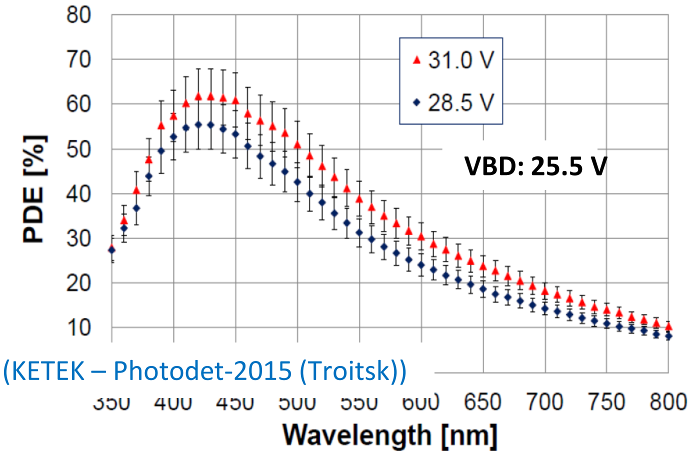
IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 62, NO. 3, JUNE 2015

After-pulsing and delayed X-talk were reduced from 30% to <1.5% at high overvoltage (FBK NUV SiPM)

SiPMs: PDE increase

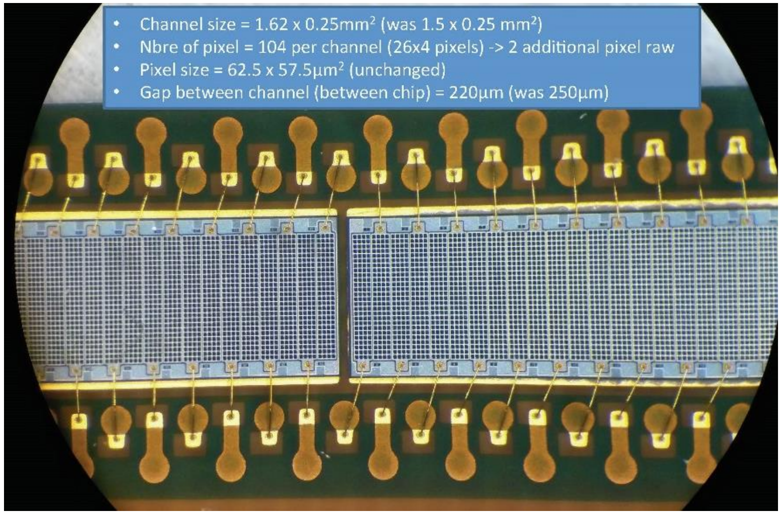


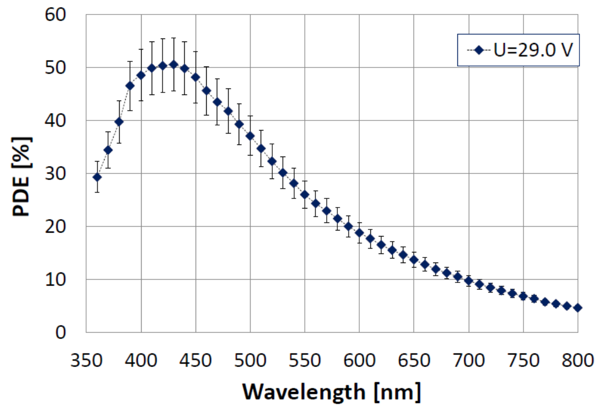
(T.Kirn, VCI-2016)



(KETEK – Photodet-2015 (Troitsk))

SiPM array for LHCb Scintillating Fibre Tracker



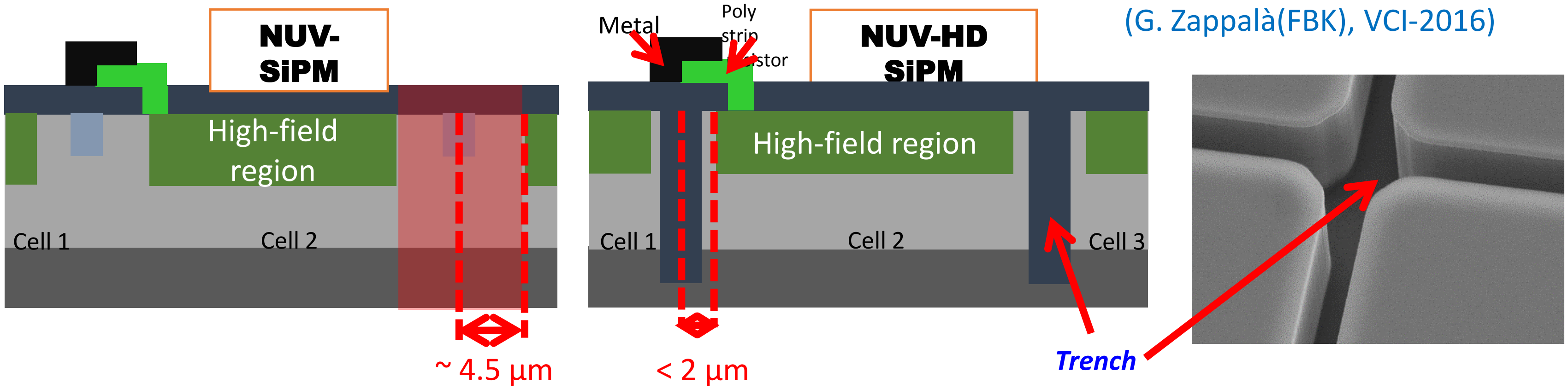


(SensL MicroFJ-SMA-3035-E46, CERN APD Lab)

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)

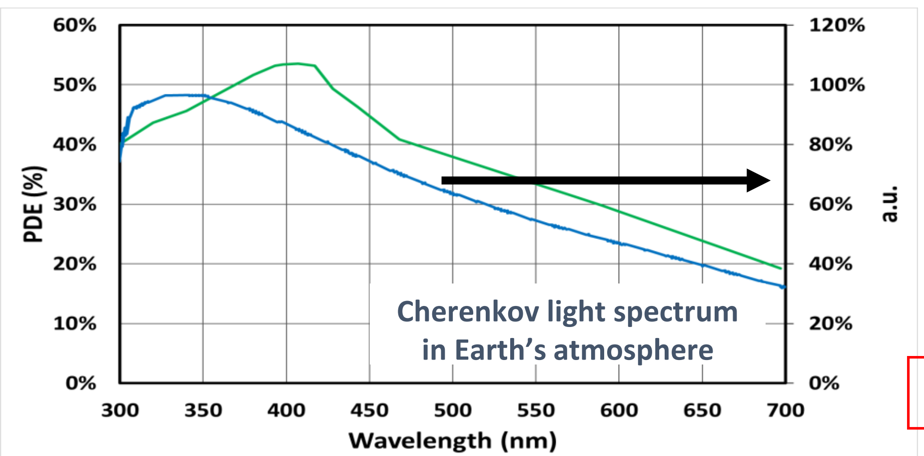


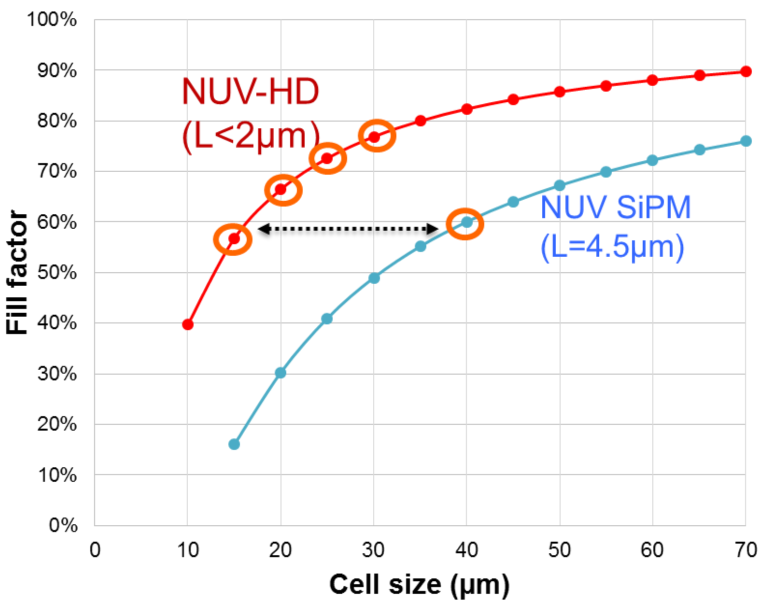
NUV High-Density (HD) technology:

Lower dead border region → Higher Fill Factor

Trenches between cells → Lower Cross-Talk

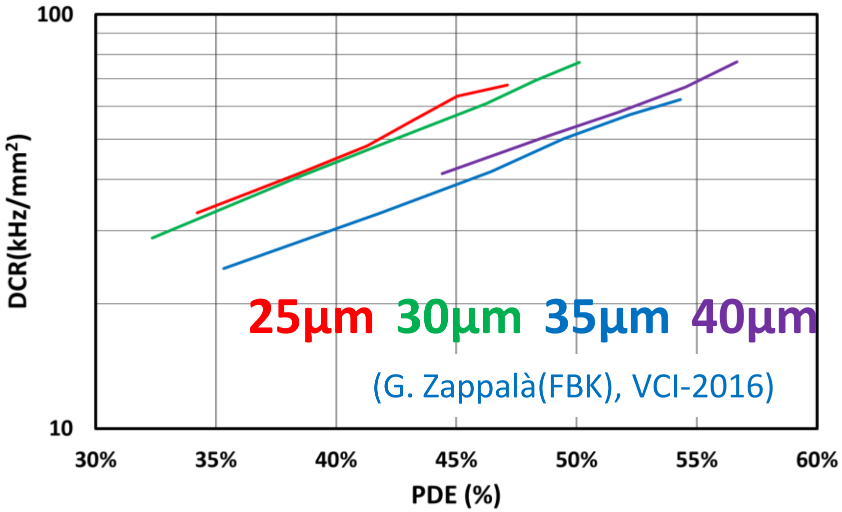
NUV-HD 30µm Cell Pitch PDE, 10V OV

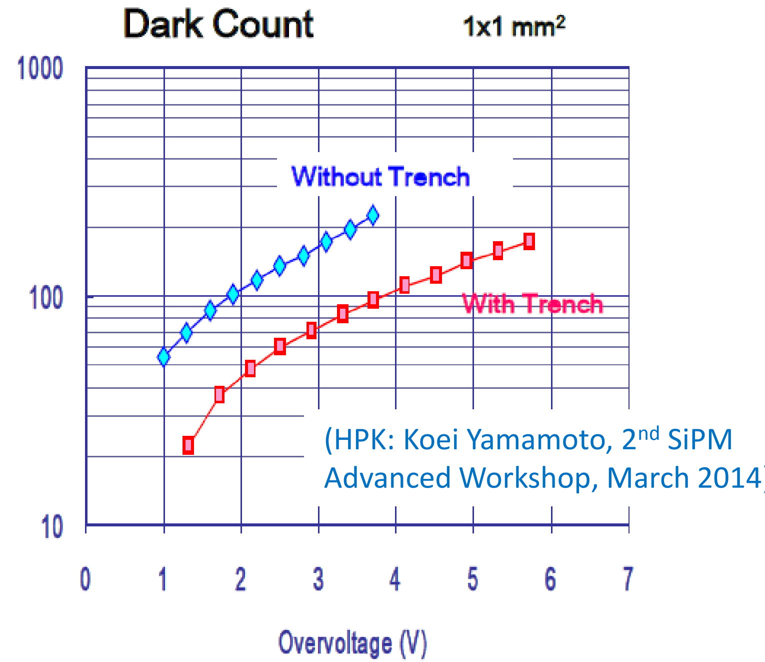


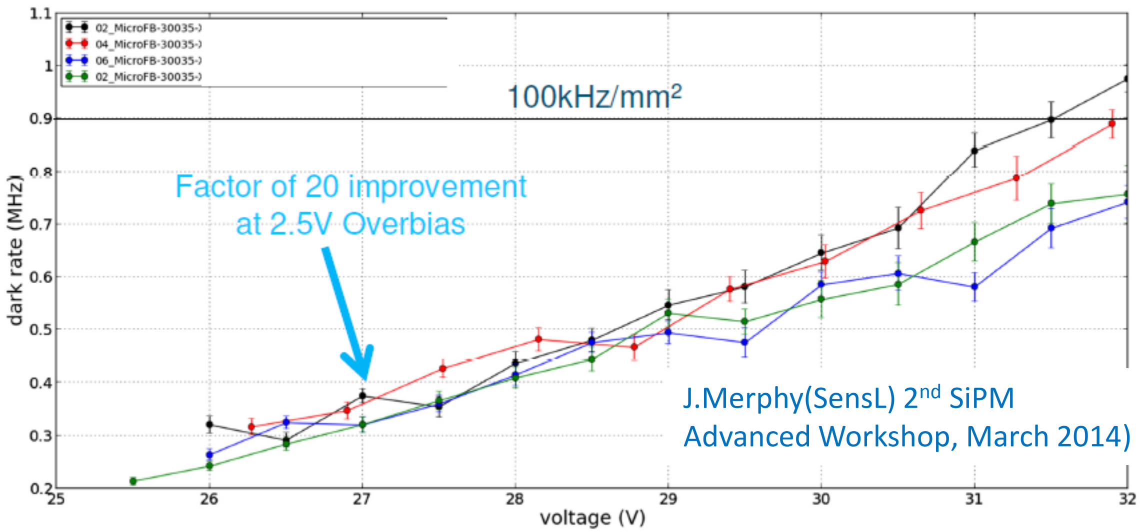


30 µm cell pitch SiPMs: GF=77% → PDE>50 % !!

Dark noise reduction



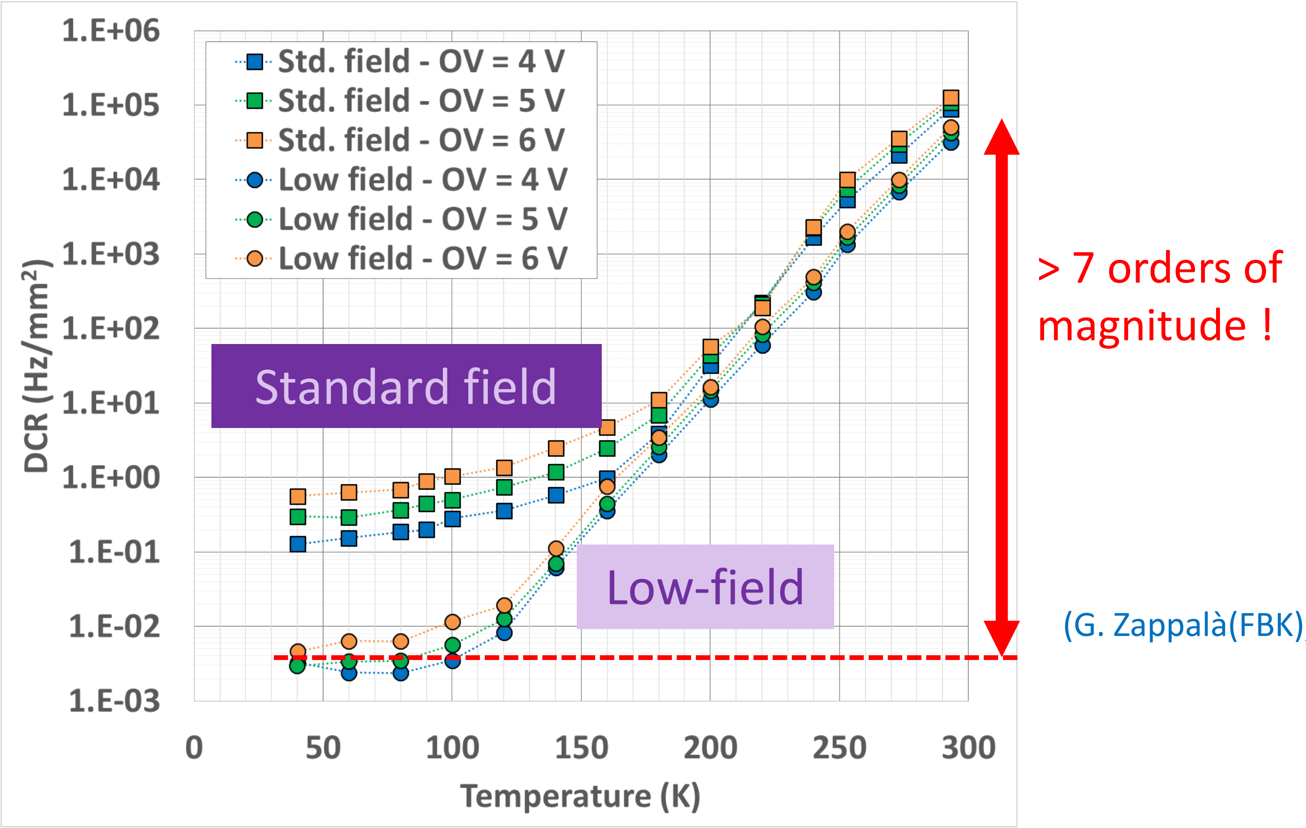




Dark Count ~30 kHz/mm^2 was measured at dVB=2÷3 V at room temperature with SiPMs from several producers. Now it becomes a standard!!

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.



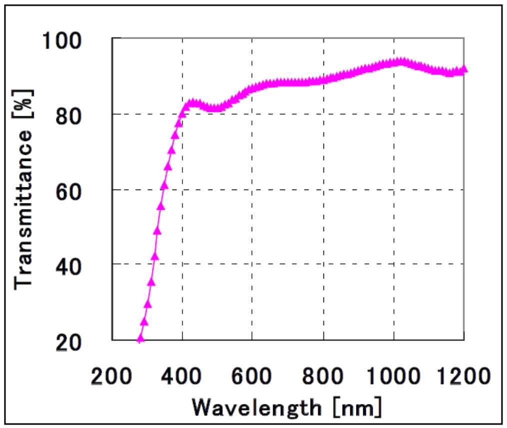
(G. Zappalà(FBK), VCI-2016)

A 10x10 cm^2 SiPM array would have a total DCR < 100 Hz!

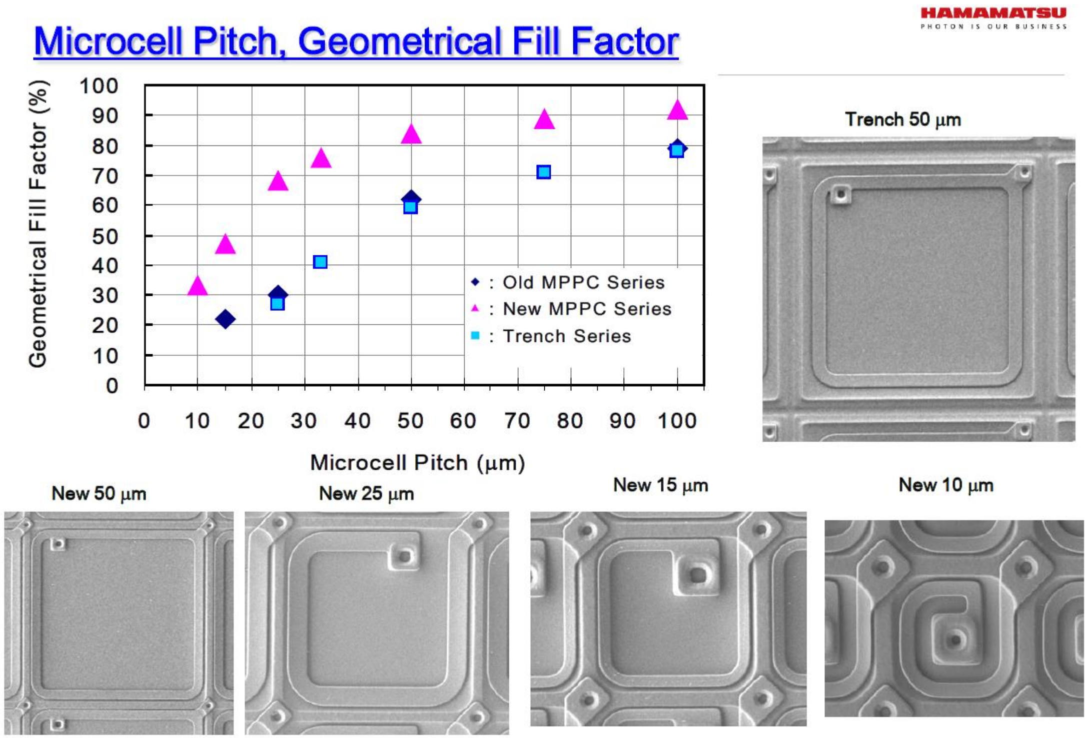
Further GF increase: Metal Film Quenching Resistor

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)

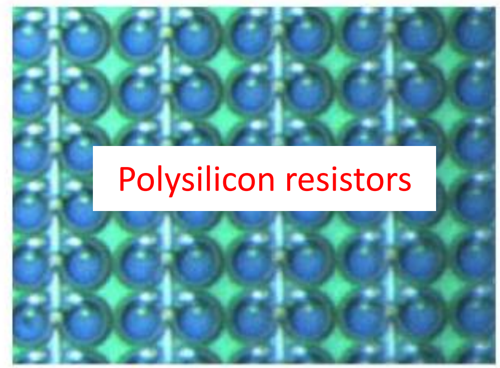
Another advantages of MFQ resistors are better uniformity and relatively small temperature coefficient → smaller cell recovery time change with temperature

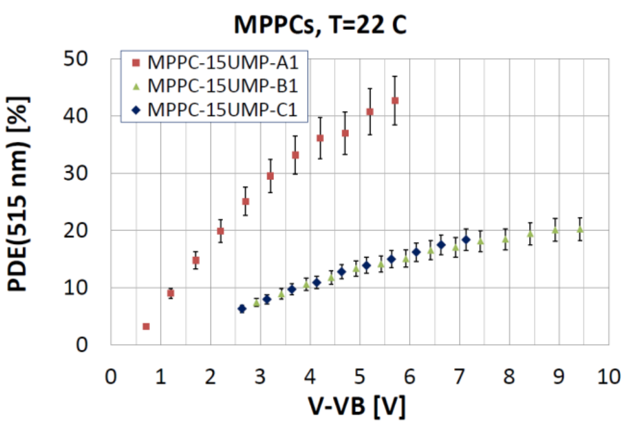
SiPMs with Metal Quenching Resistor: PDE increase

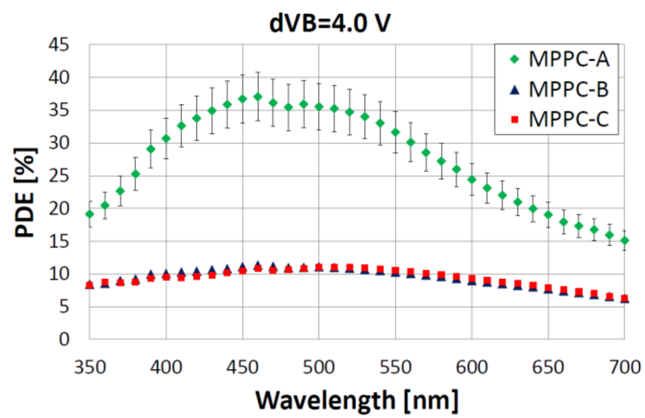
MPPCs developed by HPK for the CMS HCAL Upgrade project

Atype-15 Micron

B/Ctype-15 Micron





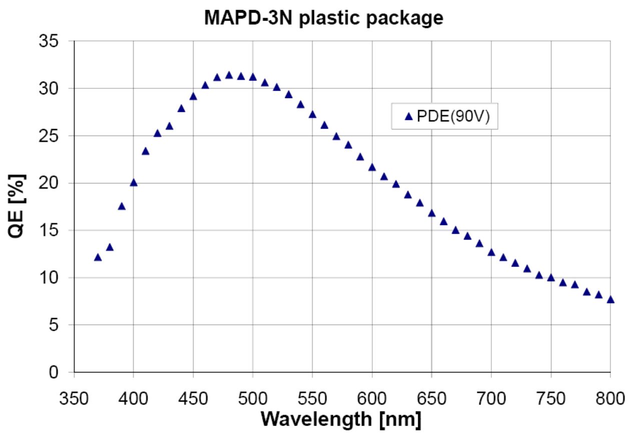


PDE(515 nm)>30% for 15 μm cell pitch MQR MPPCs. It was improved by a factor of >3 in comparison to the 15 μm cell pitch MPPCs with polysilicon quenching resistors.

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)

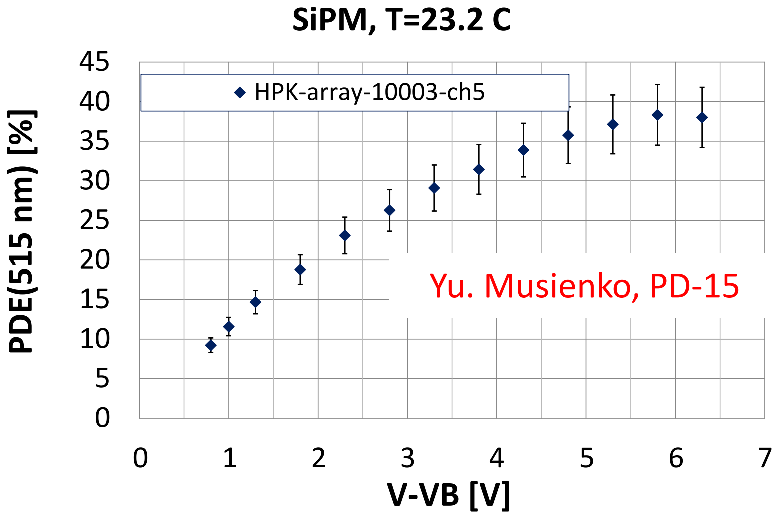
Previous development: linear array of MAPDs (18x1 mm^2 , 15 000 cells/mm^2) produced by Zecotek for the CMS HCAL Upgrade project.



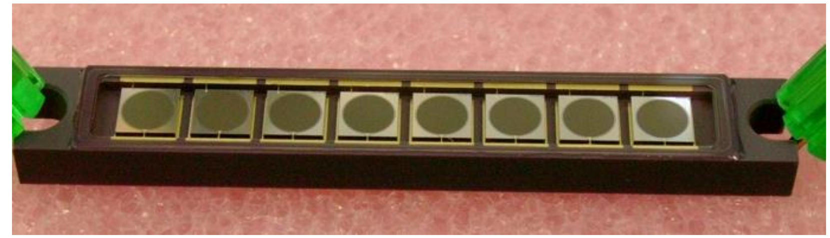
Linearity of SiPM is determined by its total number of cells. In case of uniform illumination response of "ideal" SiPM (no X-talk, no-afterpulsing) to very fast light pulse:

$$N_{firedcells} = N_{total} \cdot (1 - e^{-\frac{N_{photon} \cdot PDE}{N_{total}}})$$

Large dynamic range SiPMs for the CMS HE HCAL Upgrade

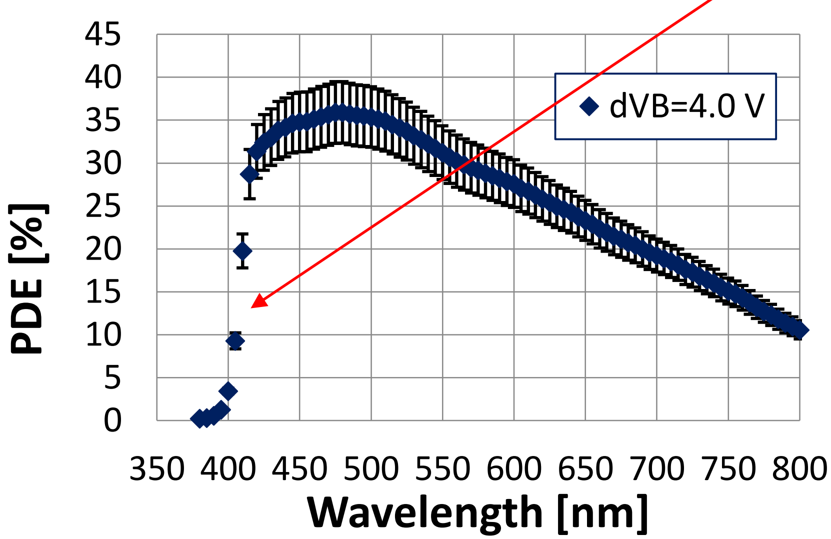


8-ch. SiPM array for the CMS HE HCAL Upgrade project: Ø2.8 mm SiPMs, 15 μm cell pitch

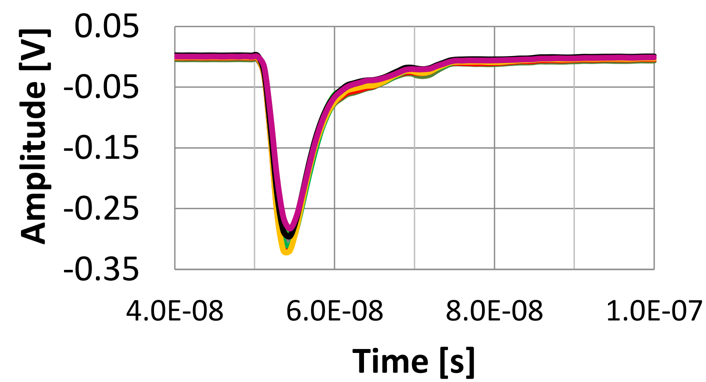


Glass widow with special filter was designed by HPK to cut off UV light which can be produced by muons and hadrons in plastic fibers

1400 SiPM arrays have been delivered to CERN during this year

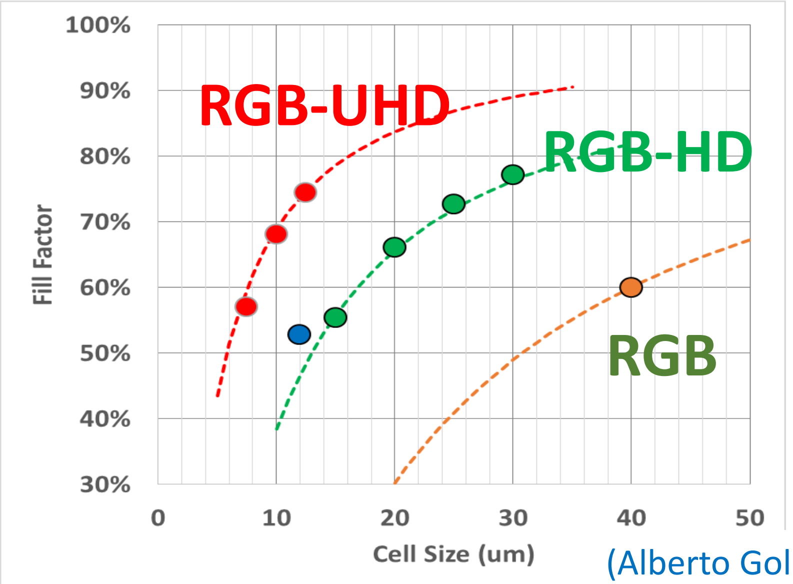


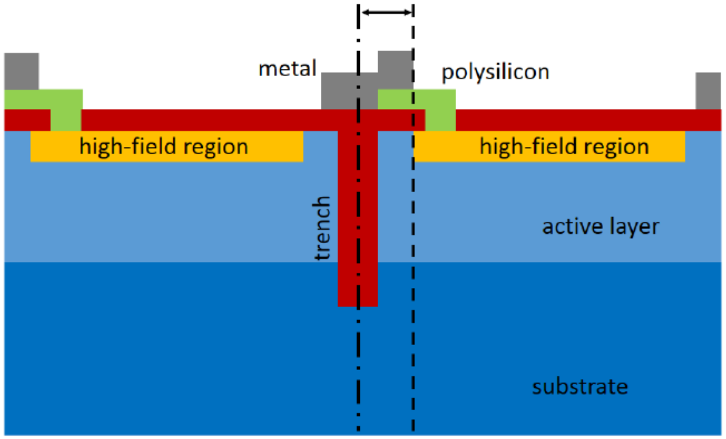
SiPM laser response



Recovery time 7-8 ns

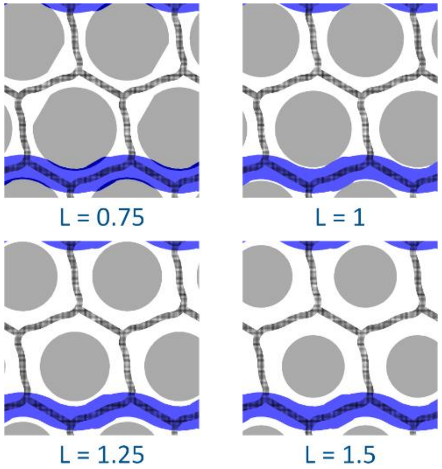
FBK UHD2 SiPMs



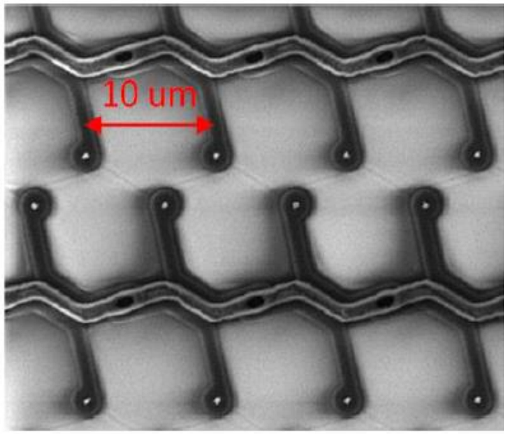


(Alberto Gola – PhotoDet 2015, Troitsk)

Cell sensitive area vs. trench width



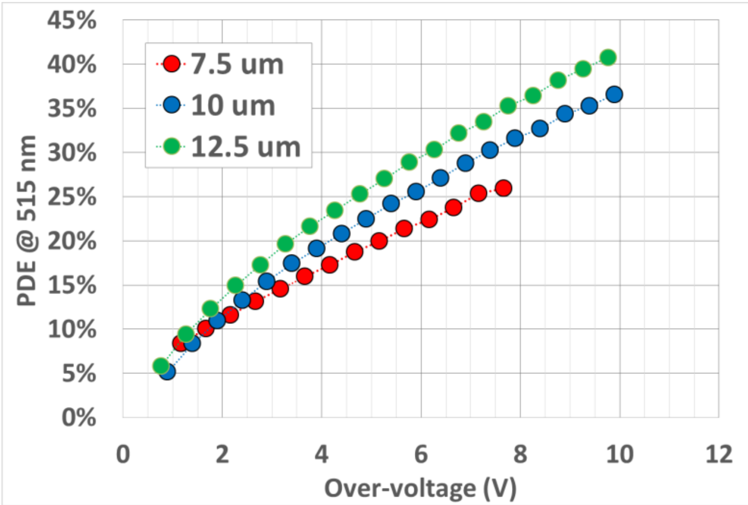
Finished 10 μm cell pitch SiPM

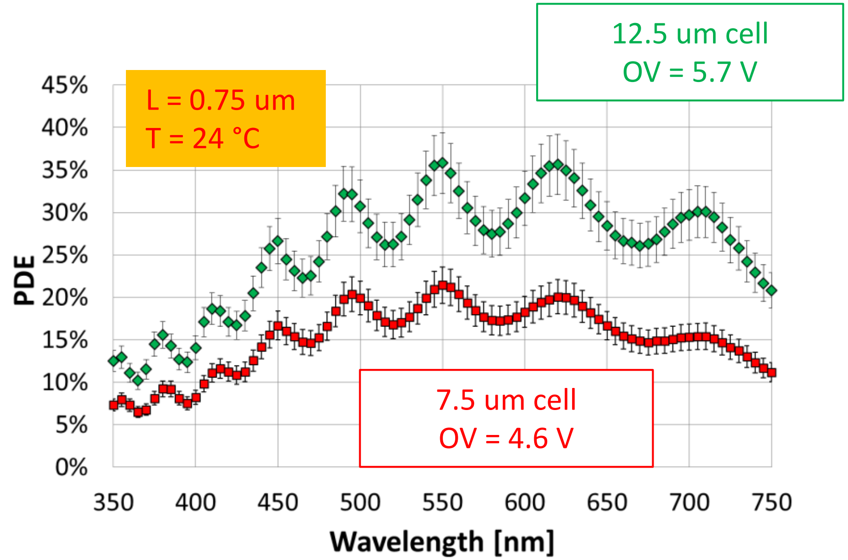


Fill Factor vs. trench width

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

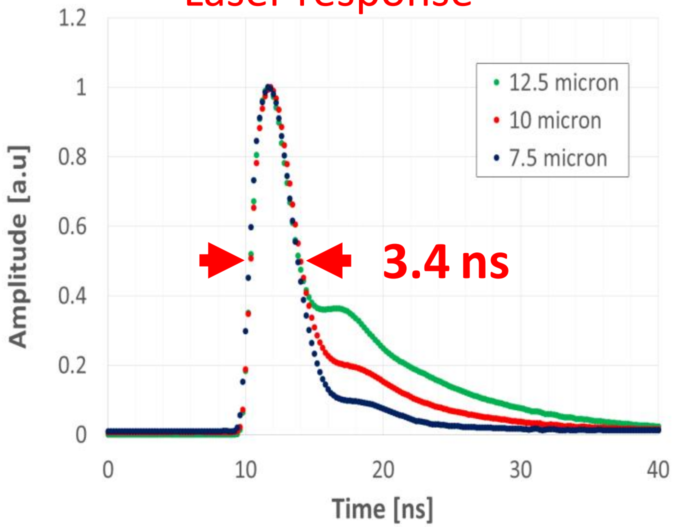
UHD2 SiPM parameters



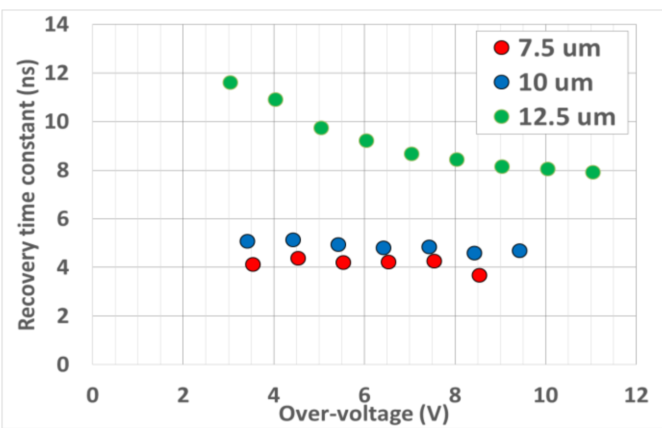


(Alberto Gola – PhotoDet-2015 , Troitsk)

Laser response

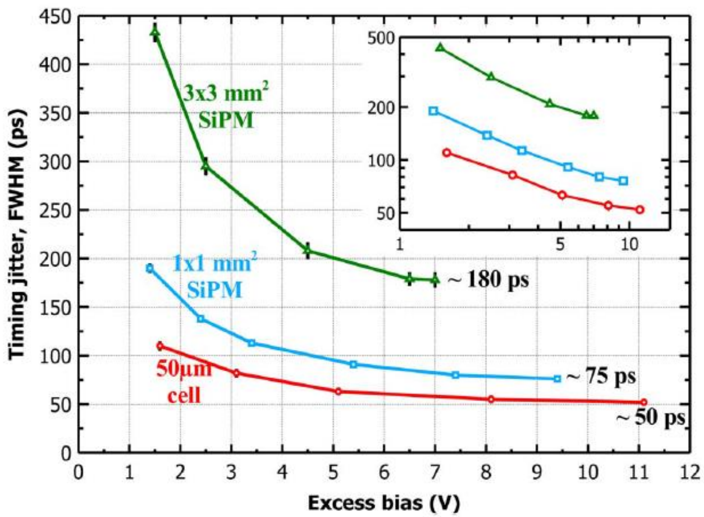


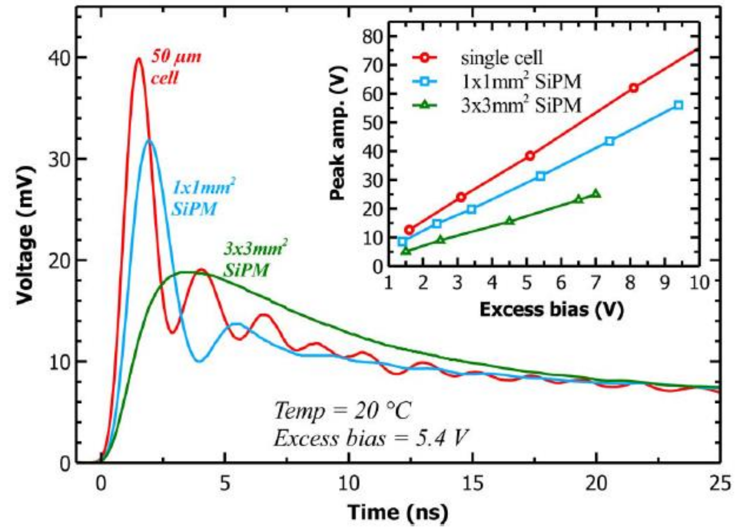
Recovery time

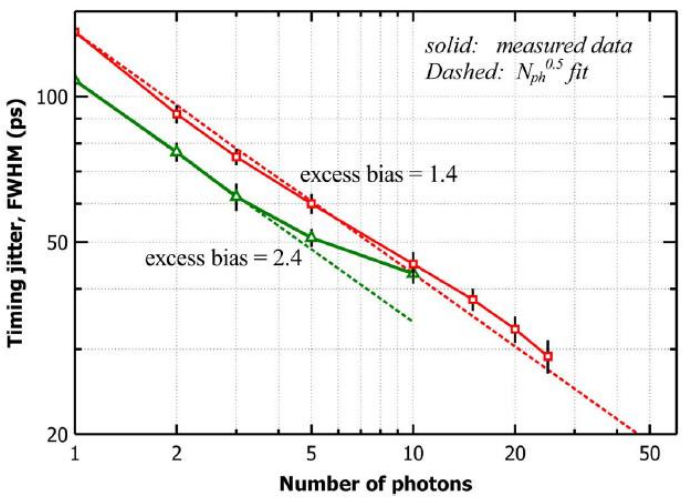


SiPM timing

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



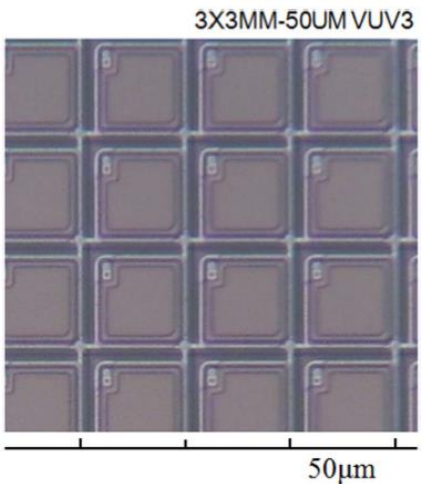


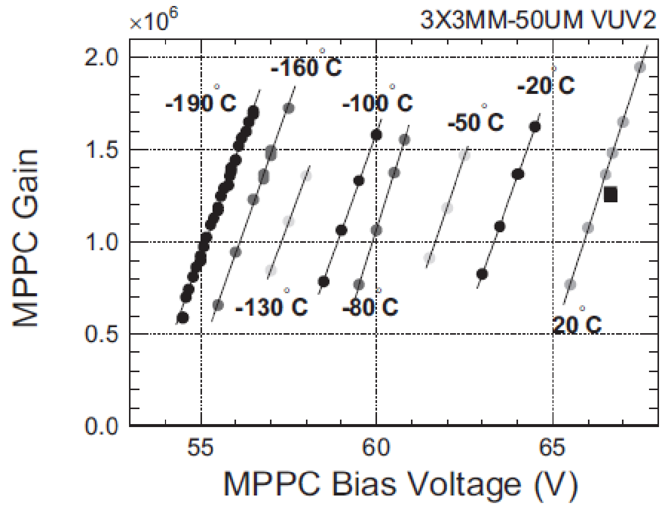


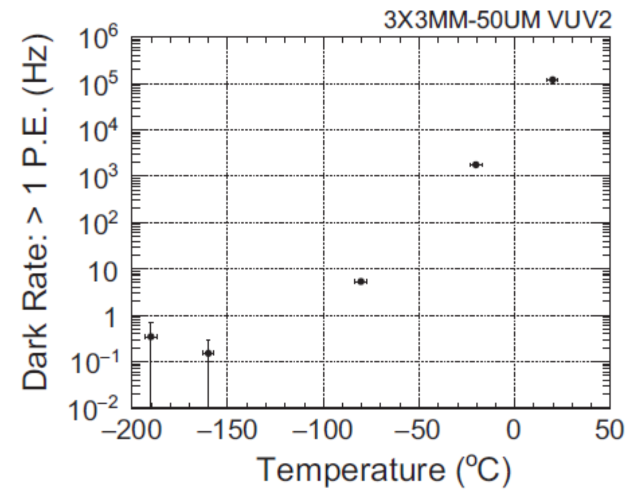
Single-photon time resolution for 3 SiPM area, measured at different biases for 425 nm light. Larger area SiPMs have slower signal rise-time. Factors limiting SPTR are signal rise-time, signal electron resolution and correlated noise (X-talk and delayed pulses). The latest is especially important for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

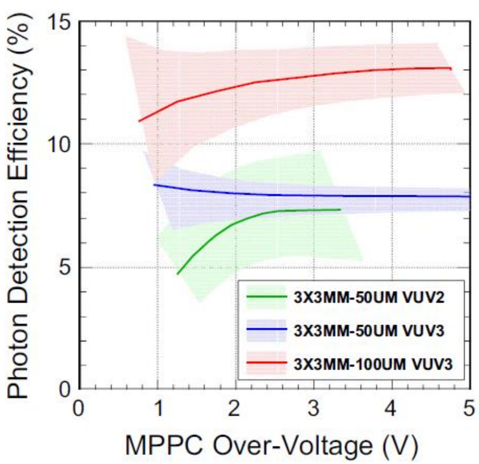
Vacuum ultra violet (VUV) SiPMs

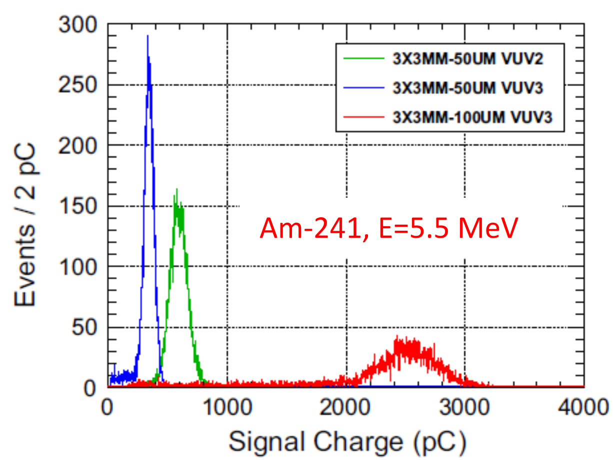
SiPMs sensitive to VUV light (<150 nm) were recently developed by HPK for detection LAr (T=-186 °C) scintillation light (λ = 128 nm).







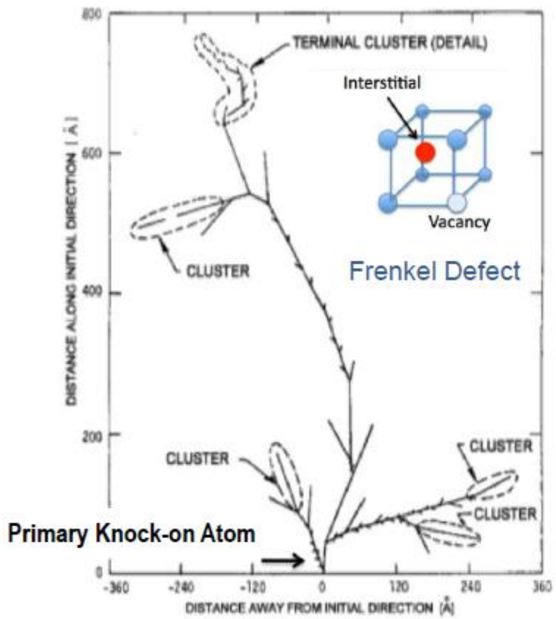




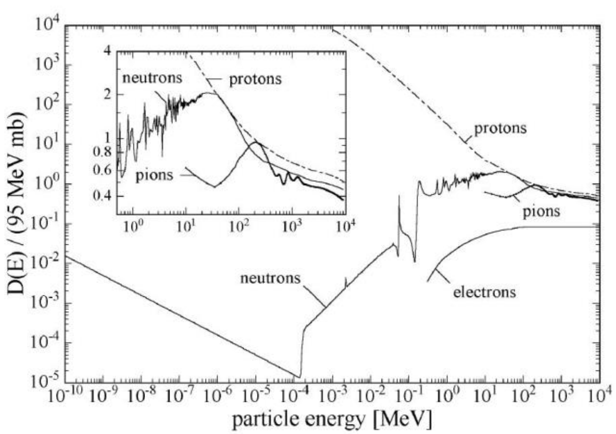
The PDE(128 nm) was measured ~8% for 50 µm pitch SiPMs and ~13% for 100 µm pitch SiPM at dVB=3 V

(NIM A833 (2016) 239–244)

Radiation induced damage in Silicon



G. Cibinetto, ANIMMA 2013
IEEE Conference Proceedings



Bulk damage:

- Incoming particle transfers a certain amount of energy to atom
- If the energy transferred to the atom is large than the binding energy of a silicon atom (~190 eV) then the atom can be displaced, moving it to an interstitial site and leaving a vacancy → single point or cluster defects
- Number of defects is proportional to the Non Ionizing Energy Loss (NIEL)

Surface damage:

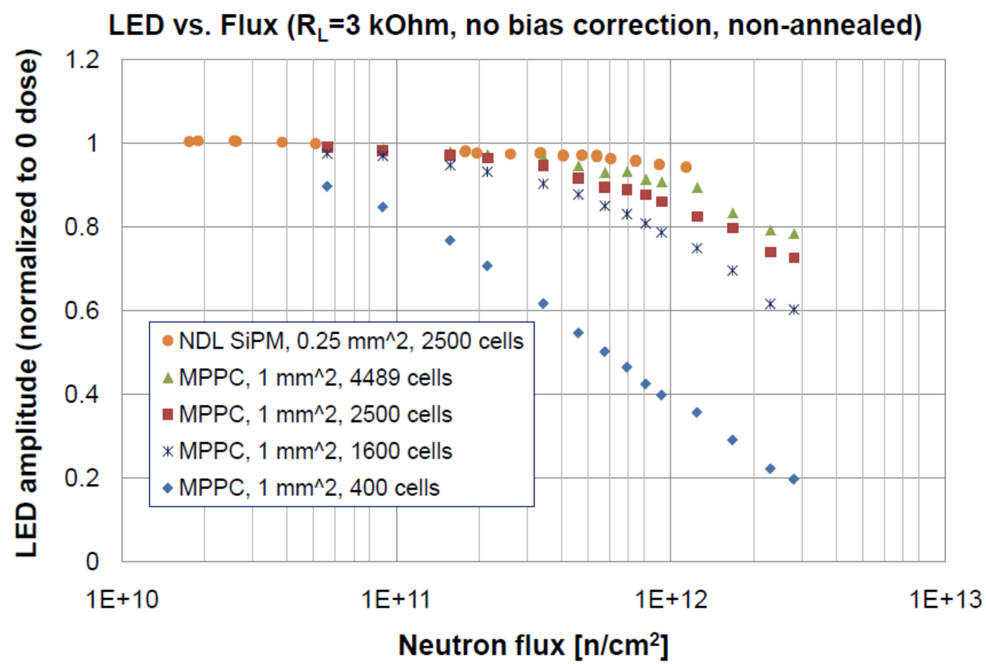
- Low energy X-rays can produce surface damage affecting the SiO_2/Si_3N_4 layer
- Ionizing particles can produce charging up effects affecting the internal fields inside the device

SiPM: radiation hardness

Radiation may cause:

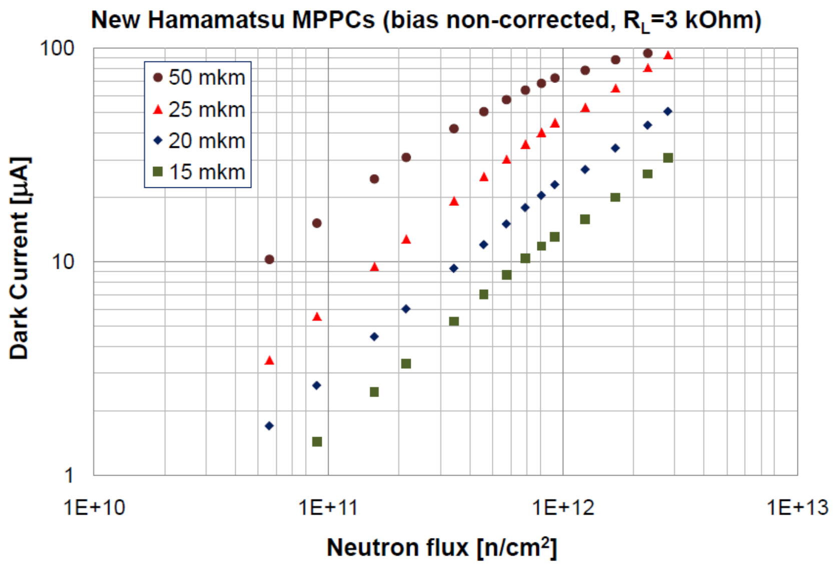
- Fatal SiPMs damage (SiPMs can't be used after certain absorbed dose)
- Dark current and dark count increase (silicon …)
- Change of the gain and PDE vs. voltage dependence (SiPM cell "blocking" effects due to high induced dark carriers generation-recombination rate)
- Breakdown voltage, PDE, Gain change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

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

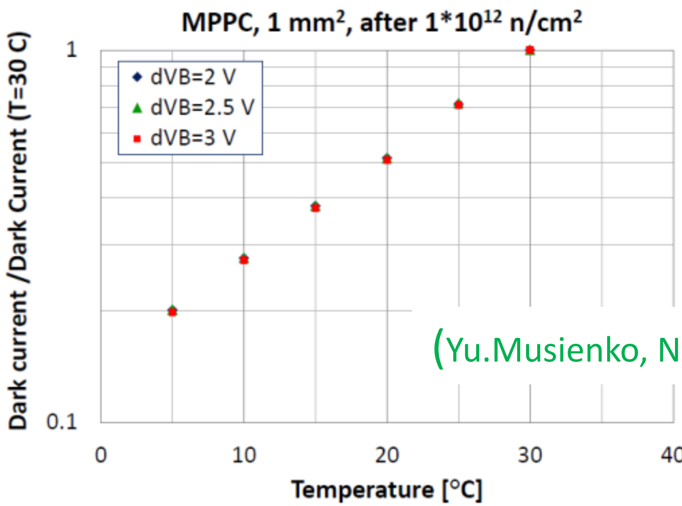
α – dark current damage constant [A/cm];
Φ – particle flux [1/cm^2];
V – silicon active volume [cm^3]
M – SiPM gain
k – NIEL coefficient

α_{Si} ~$4*10^{-17}$ A*cm after 80 min annealing at T=60 °C (measured at T=20 °C)
Damage produced by 40 neutrons (1 MeV) in 1 µm thick Si → 1 dark count/sec at 20 °C

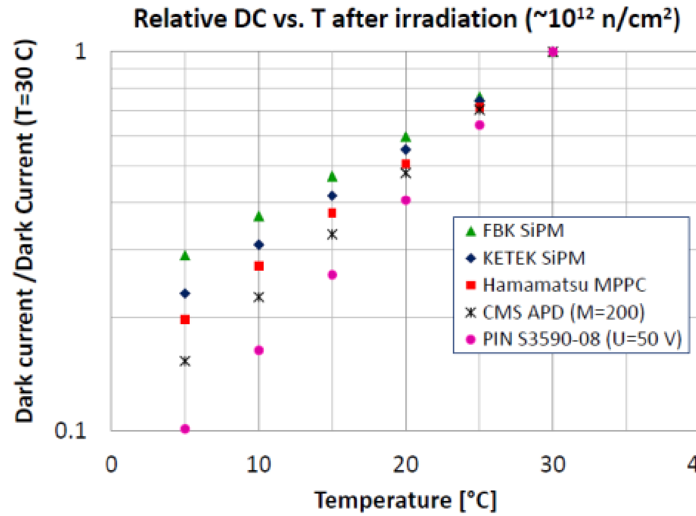
Thickness of the epi-layer for most of SiPMs is in the range of 1-2 µm, however d_{eff} ~ 4 ÷ 50 µm for different SiPMs. High electric field effects (such as phonon assisted tunneling and field enhanced generation (Pool-Frenkel effect) play significant role in the origin of SiPM's dark noise.

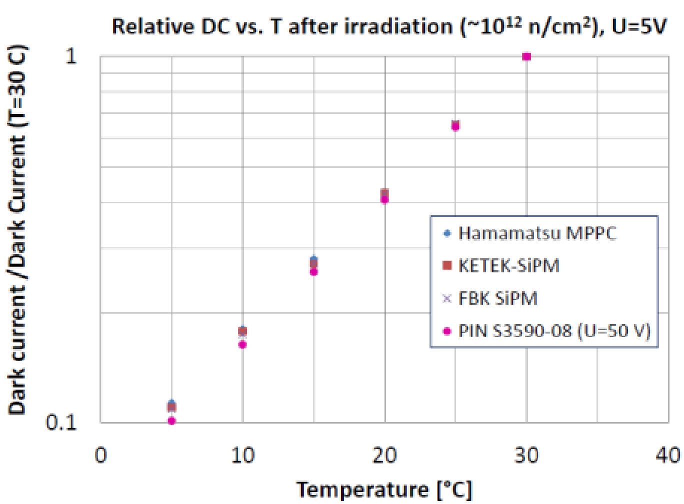
$V \sim S*G_f*d_{eff}$,
S - area
G_f - geometric factor
d_{eff} - effective thickness

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



(Yu.Musienko, NDIP-2014)

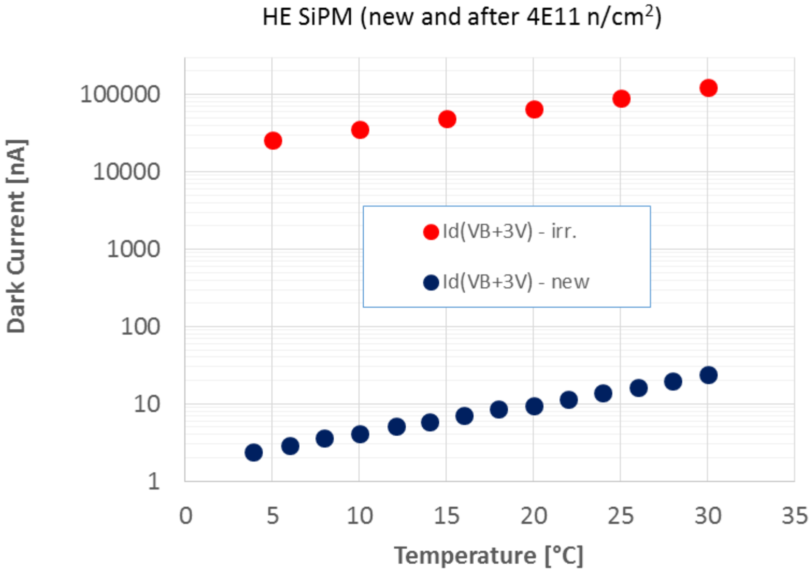




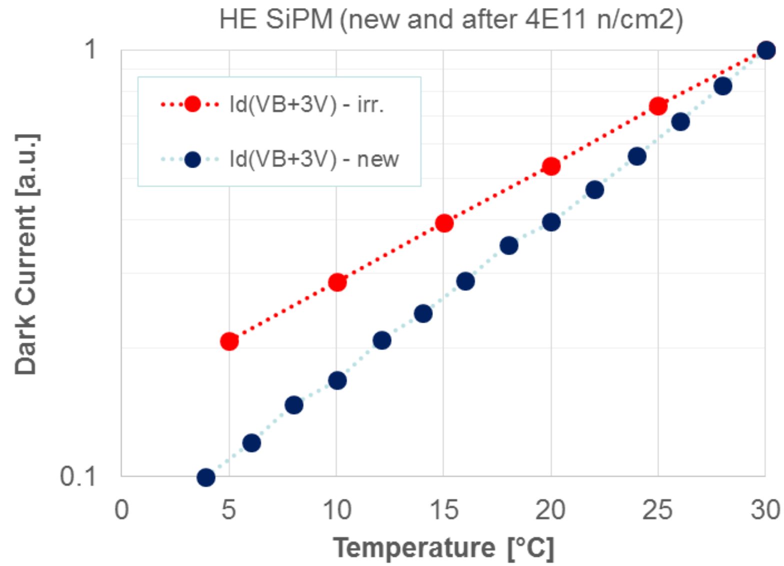
It was observed a rather weak dependence of the SiPM's dark current decrease with temperature on the dVB value. SiPM dark currents at low voltage (5V) behave similar with temperature to that of the PIN diode. However we observed significant difference of this dependence for differenet SiPM types when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

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

Dark current at V-VB=3 V vs. temperature (SiPM was irradiated with 4E11 n/cm^2)



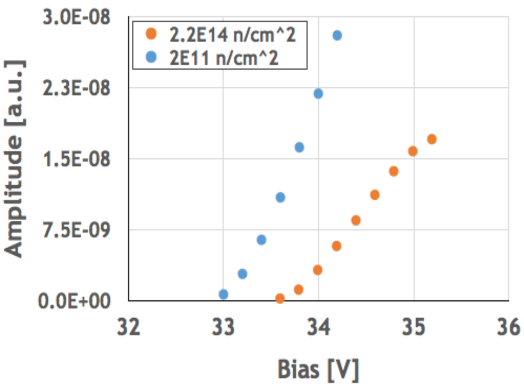
Normalized dark current at V-VB=3 V vs. temperature (for new and irradiated SiPM)

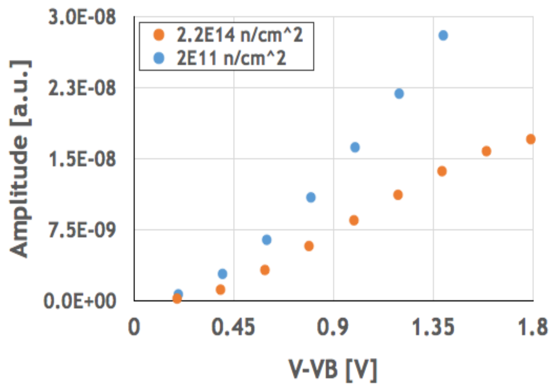


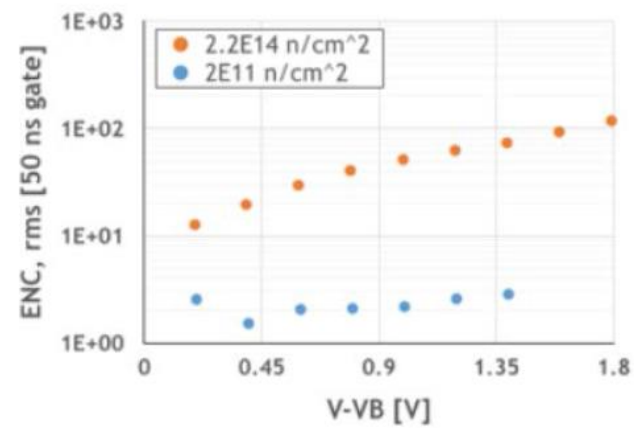
Irradiated HE MPPC, Id reduction: ~1.88 times/10 °C
Non-irradiated HE MPPC, Id reduction: ~2.4 times/10 °C (like it should be for silicon diodes!)

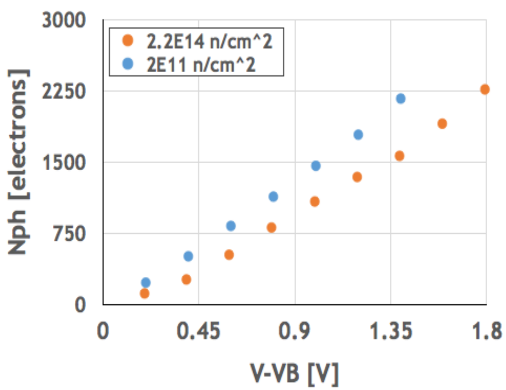
SiPM irradiated up to $2.2*10^{14}$ n /cm^2

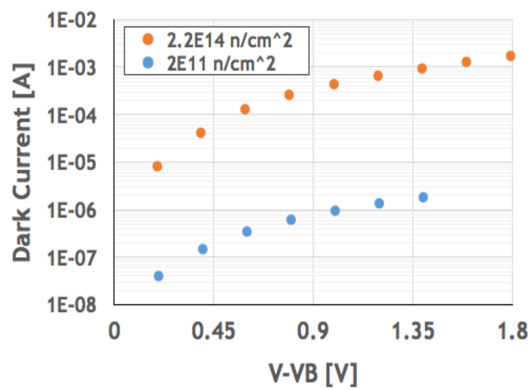
Can SiPM survive very high neutron fluences expected at high luminosity LHC? FBK SiPM (1 mm^2, 12 μm cell pitch was irradiated with 62 MeV protons up to $2.2*10^{14}$ n /cm^2 (1 MeV equivalent).











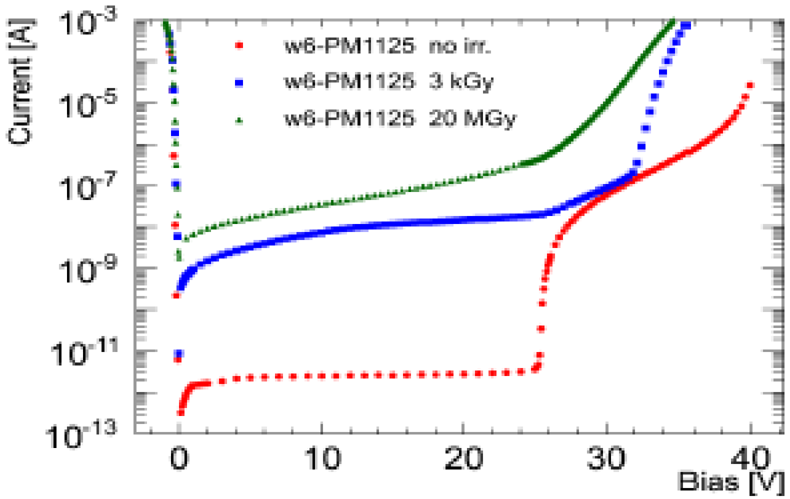
We found:

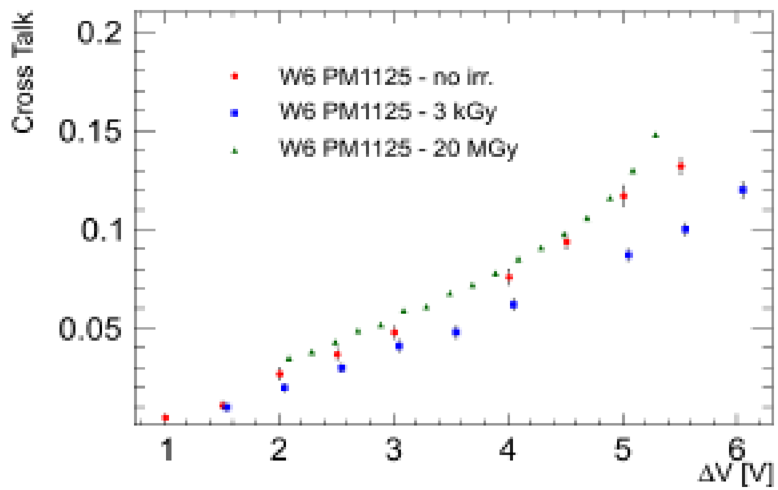
- Increase of VB: ~0.5 V
- Drop of the amplitude (~2 times)
- Reduction of PDE (from 10% to 7.5 %)
- Increase of the current (up to ~1mA at dVB=1.5 V
- ENC(50 ns gate, dVB=1.5V)~80 e, rms

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)

X-ray damage





KETEK PM1125 (1.2 x 1.2 mm, 25 μm pixels)

Left: KETEK PM1125 I-V curves before irradiation (in red), compared with 3 kGy irradiation (blue) and 20MGy irradiation (green); measurements have been performed at 20 ◦C. Right: inter-pixel cross-talk measurements for the sensors before irradiation (in red), compared with 3 kGy irradiation (blue) and 20 MGy irradiation (green); no relevant changes in cross talk probability are measured.

- No significant change in breakdown voltage
- Increased dark current below as well as above breakdown voltage
- Slight decrease in gain

(E.Garutti et.al., 2014 JINST 9 C03021)

SiC SSPM

Why SiC?

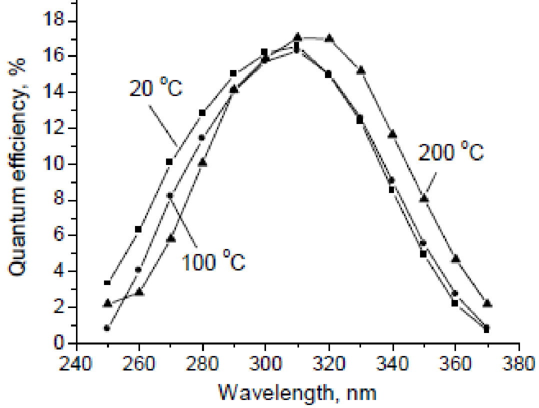
Dark count rate in Si-PM increases rapidly with temperature, resulting in a maximum operating temperature below 50°C

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

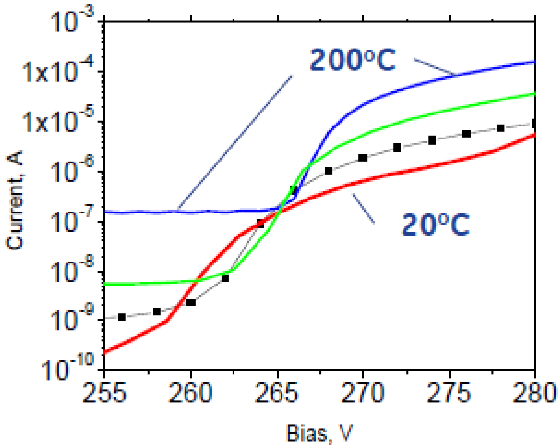
Packaged SiC SSPM

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

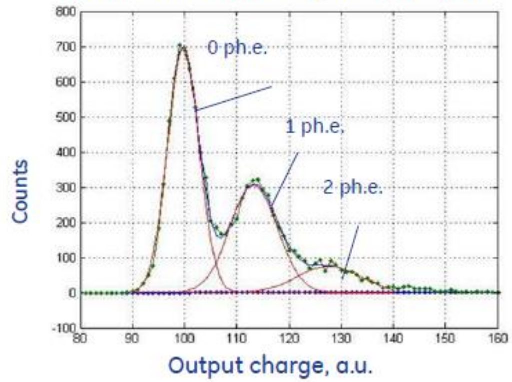
Quantum efficiency spectra



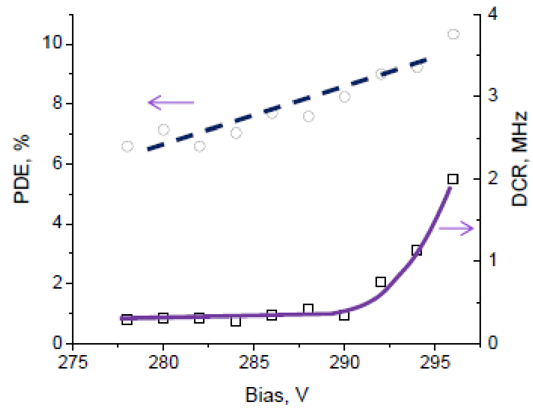
Dark current vs. temperature



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



Photodetection efficiency and dark count rate as functions of voltage bias

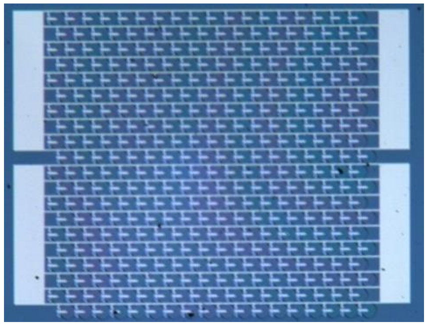


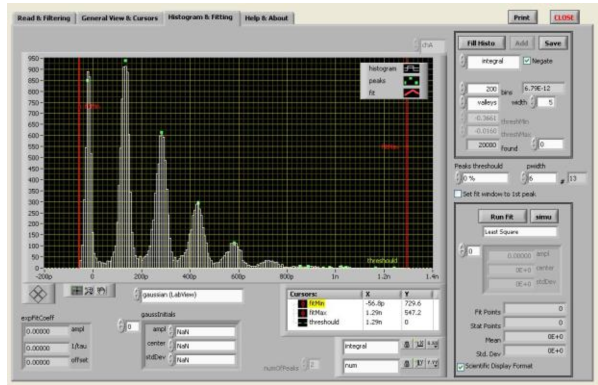
Potentially can be more radiation hard than silicon

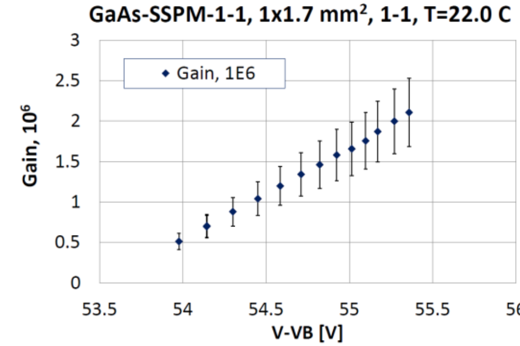
(S.Dolinsky, GE, NDIP-2014)

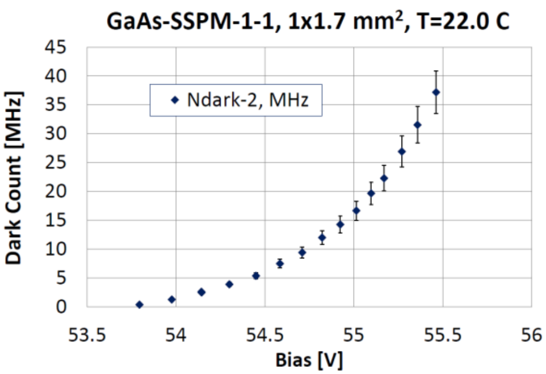
GaAs SSPM

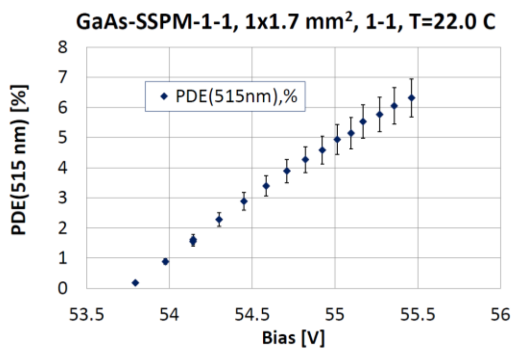
LightSpin Photomultiplier Chip™

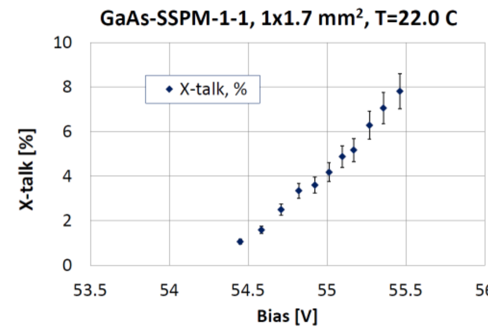


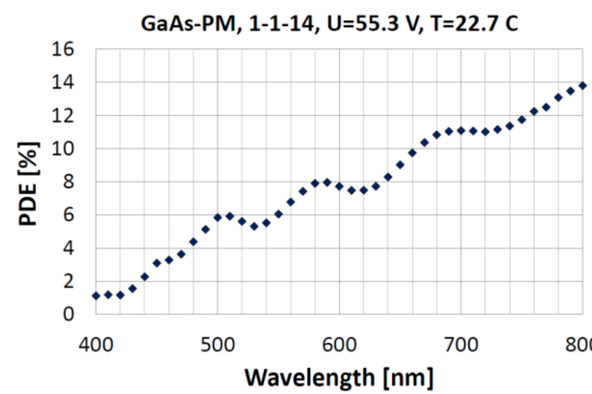












Wide bandgap (1.42 eV): potentially can be more radiation hard than silicon. Timing with GaAs SSPM can be also better (high mobility of electrons and holes, fast avalanche development – direct semiconductor)

Summary

Significant progress in development of SiPMs/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
- . . .

SiPM/SSPM perspectives (3-5 years)

My point of view:

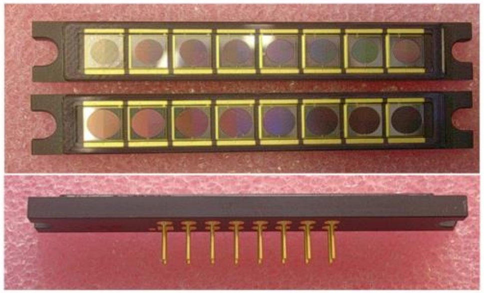
- Further work to reduce correlated noise (this is one of the limiting factors for many applications)
- Small cell pitch (5 μm), large dynamic range SIPMs
- DUV SiPMs with good sensitivity (PDE>30%) for VUV light
- Dark count at room temperature can be reduced: <10 kHz/mm^2
- Development of SiPMs for 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...

Thank you for your attention!

Back-up

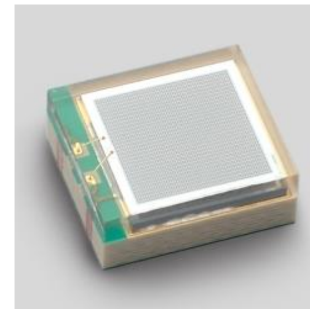
Studies of SiPMs irradiated with 2E13 n/cm²

HE MPPC arrays (Ø2.8(3.3) mm SiPMs) and 3x3 mm² MPPCs (SMD package)



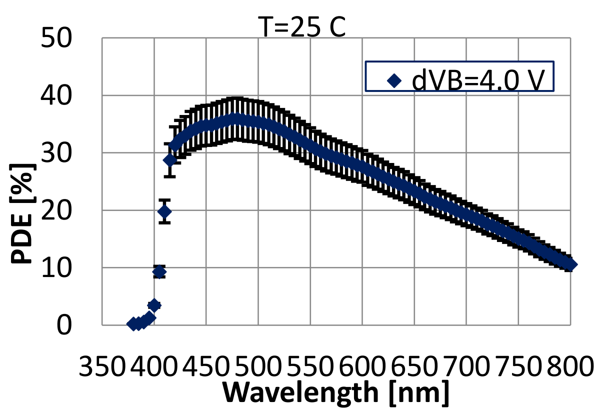
S10943-4732 and S10943-4733 MPPCs
(developed by Hamamatsu and CMS SiPM group for the CMS HE HCAL):

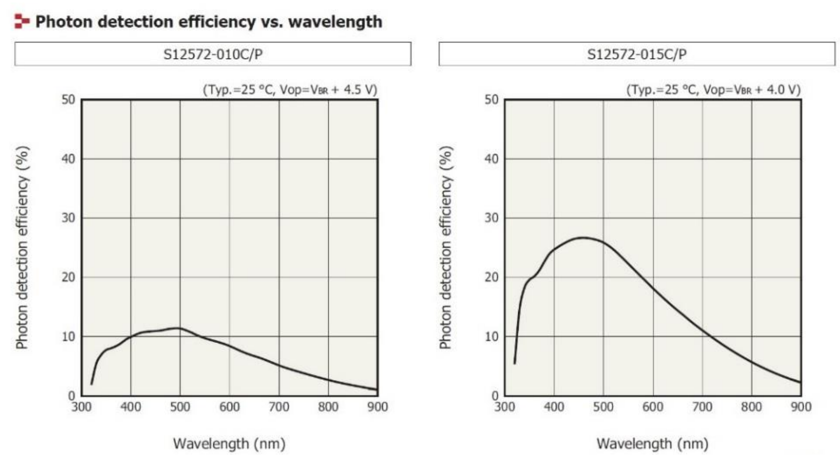
- Area: 6.15(8.55) mm²
- Cell pitch: 15 μm
- V_{op}: ~69 V
- Gain (V_{op}): ~300*10³
- PDE(515nm): 30%



S10943-4732
S10943-4733

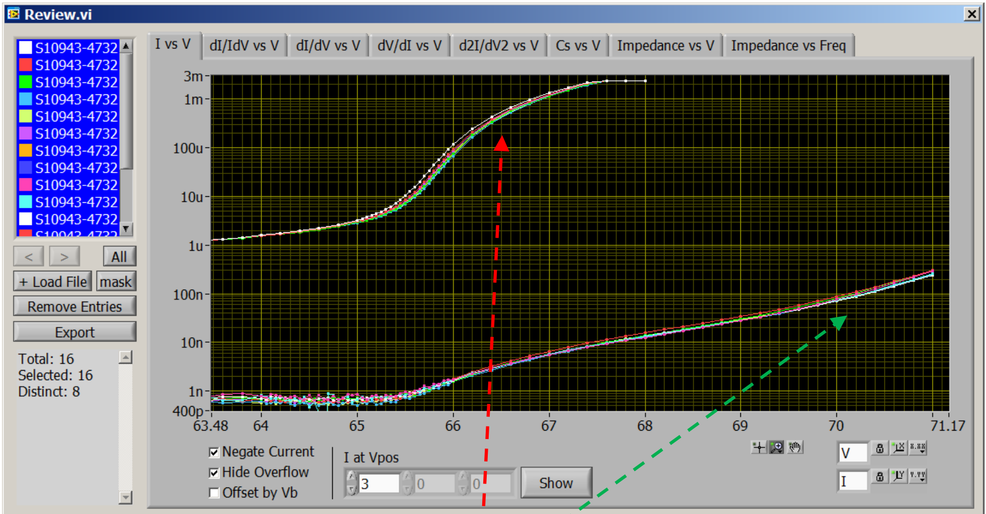
S12572-010P
S12572-015P





Irradiation performed at Ljubljana reactor

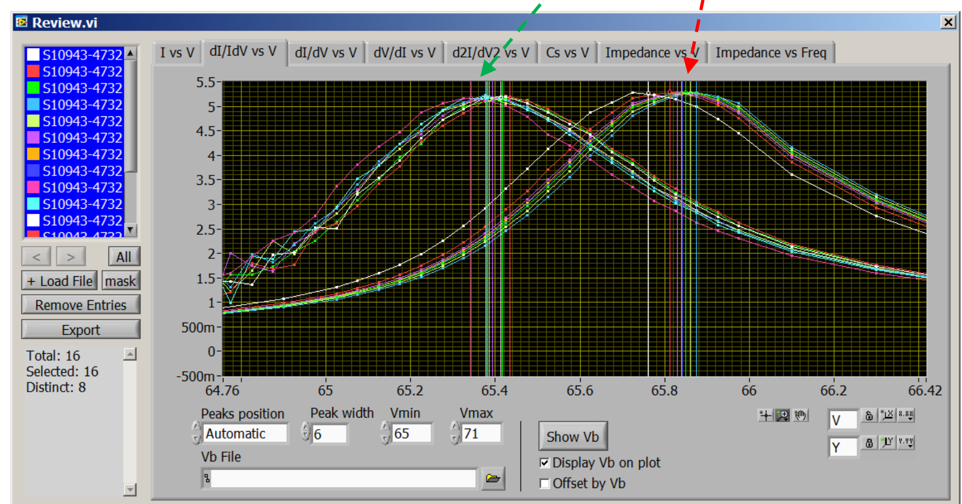
VB determination before after 2E13 n/cm²



SiPMs VB measured using 1/I*dI/dV max. technique.

VB before/after irr.

Dark current vs. bias before/after irr.

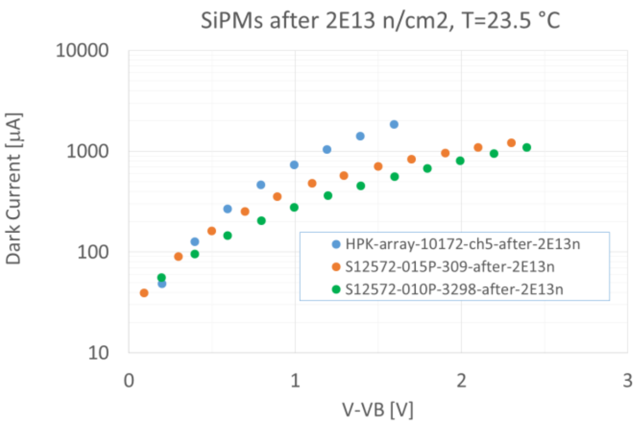


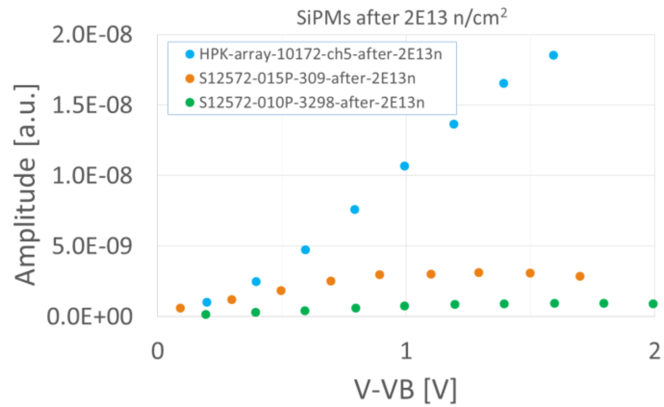
VB is increased by 0.43 V

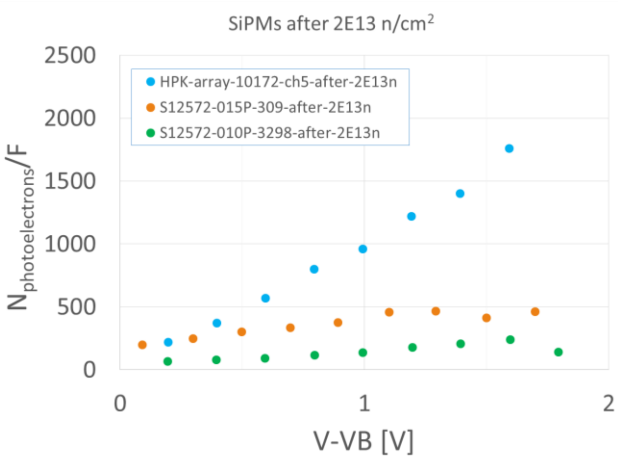
(A. Heering et.al, IEEE-NSS/MIC 2016, N27-19)

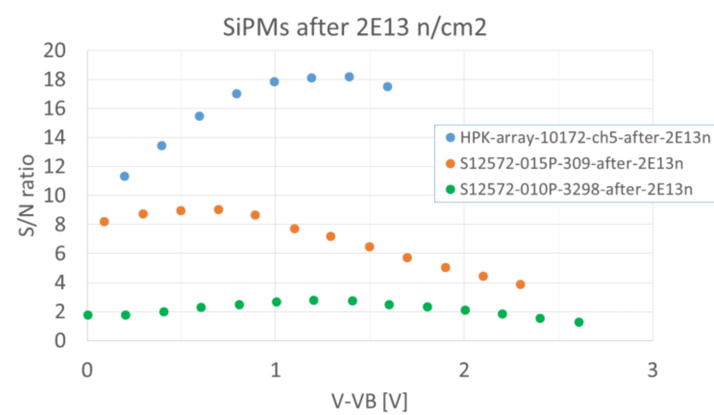
HPK SiPM after 2E13 n/cm^2

LED (515 nm, 15 ns) pulse amplitude ~ 12 000 photons/pulse high enough to see signals from all SiPMs





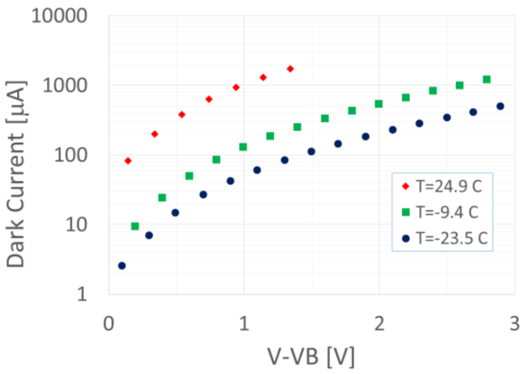


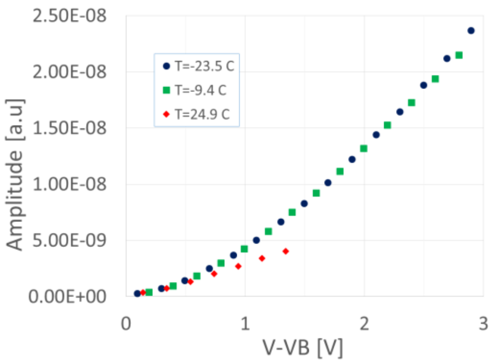


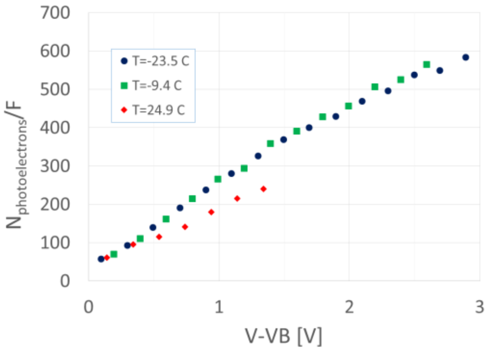
Self-heating effects? SMD package!

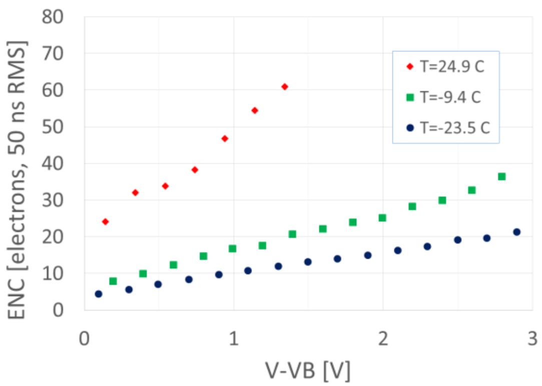
HPK S10943-4732 2.8 mm SiPM after 2E13 n/cm² at reduced temperature

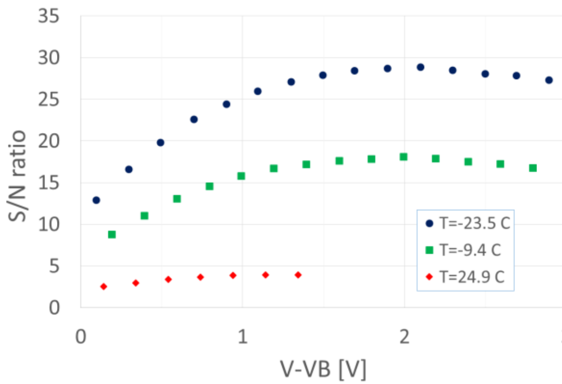
Average LED pulse amplitude ~2400 photons/pulse











- At T=-9.4 °C SiPM LED pulse response recovers to that of non-irradiated SiPM
- From 24.9 °C to -23.5 °C: ~21 times Id reduction (~1.88 times/10 °C)
- Maximum S/N improves >7 times due to dVB increase

(IEEE-NSS/MIC 2016, N27-19)

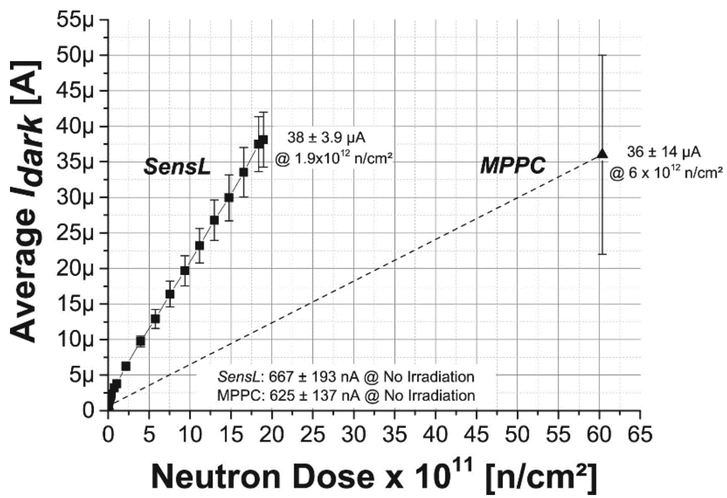
Irradiation with cold neutrons

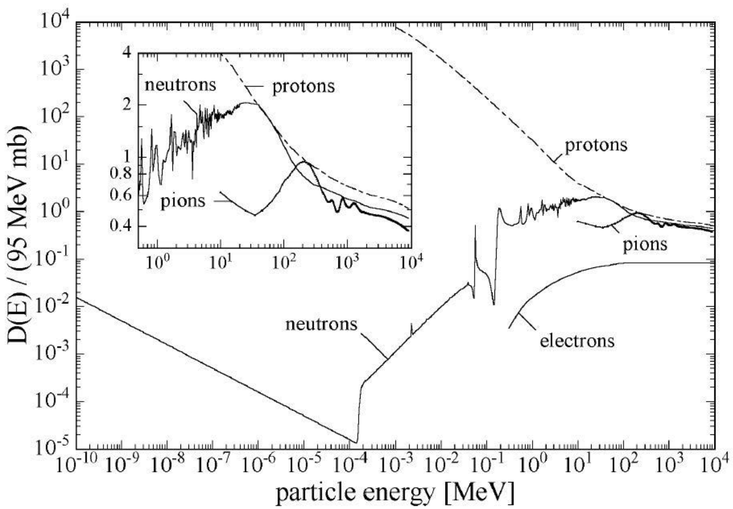
Thermal neutron study (T=23 °C) at FMR II reactor at Julich (E_n = 3.27 meV, up to 6E12 n/cm^2)

Thermal neutron capture can cause nuclear transmutations

$^{30}Si + n \rightarrow {}^{31}Si \rightarrow {}^{31}P + \beta^-$

Produces isolated defects with ~ 2-5 defects per absorbed neutron





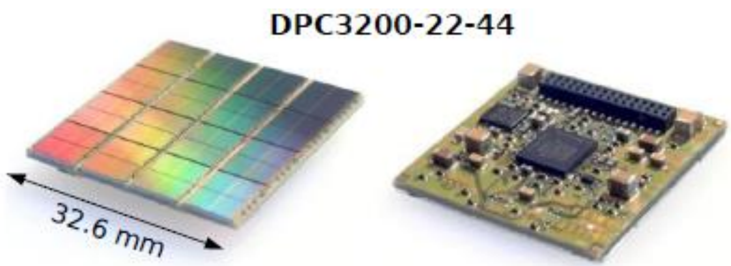
Neutron dose dependent average dark currents measured respectively on 10 SiPM detectors from the SensL 12x12 SiPM Series-C detector board, and on 12 MPPC detectors from the Hamamatsu 8x8 MPPC array S12642–0808PB-50 detector board.

SensL: 12x12 detector array ArrayC-30035-144P-PCB, 3x3 mm^2, 35 μm cell pitch, VB+2.5 V
Hamamatsu: 8x8 MPPC array 12642–0808PB-50, 3x3 mm^2, 50 μm cell pitch, VB+2.4 V

(D.Durini et. all, NIM A835 (2016) 99-109)

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

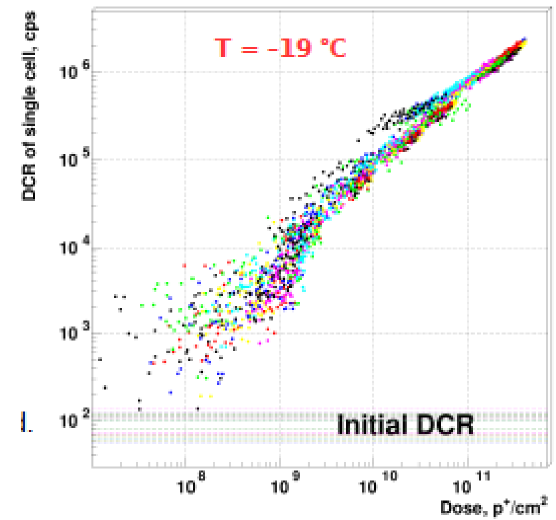
Irradiation by protons with P=800MeV/c (T=295MeV).
Beam size: $\sigma_x \approx \sigma_y \approx 1$ cm.



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

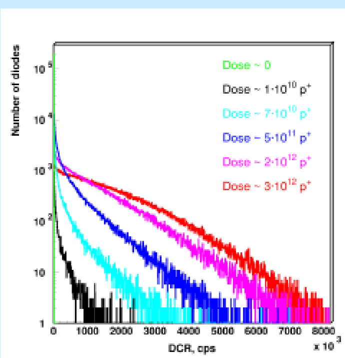
Active cell quenching.
Full digital data output.
Noisy cells can be disabled

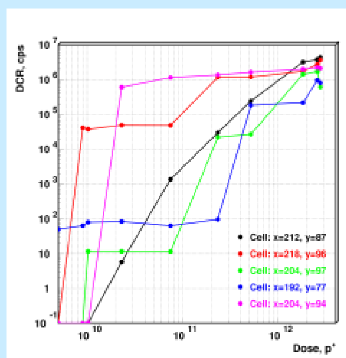
Signal from each pixel is is digitized and the information is processed on chip:
- time of first fired pixel is measured
- number of fired pixels is counted
- active control is used to recharge fired cells
- 4 x 2047 micro cells
- 50% fill factor including electronics
- integrated TDC with 8ps resolution



Dark counting rate vs. total dose

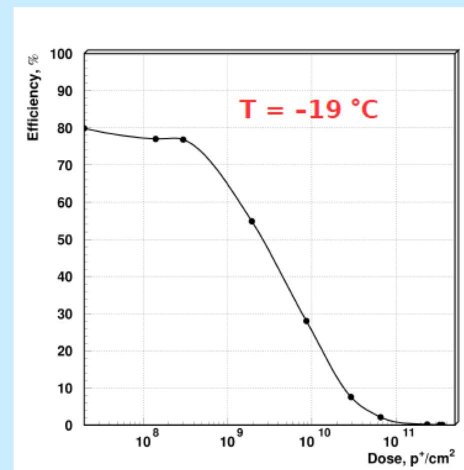
DCR spectra after different total doses accumu-lation





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. $\Rightarrow$ Cell damage caused by single interaction of p^+ with Si lattice.

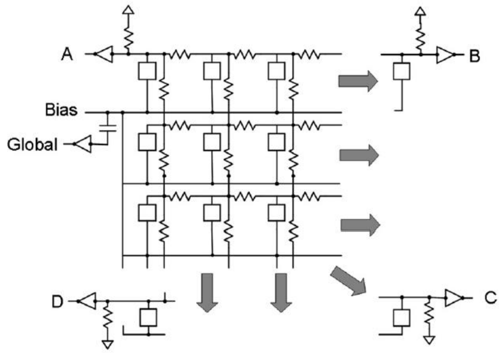


Optimal efficiency of *single photons* detection as a function of proton fluence.

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

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.

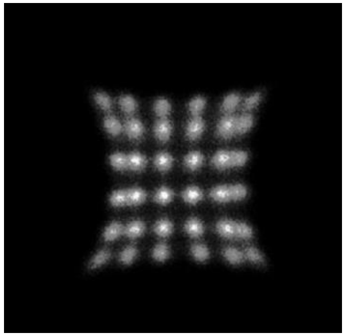
PS-SSPM parameters

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

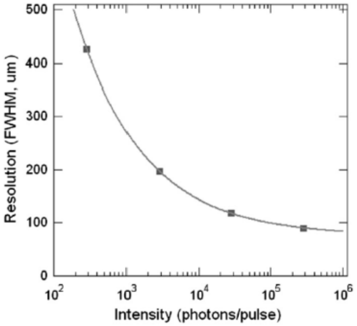
Anger logic:

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

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



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

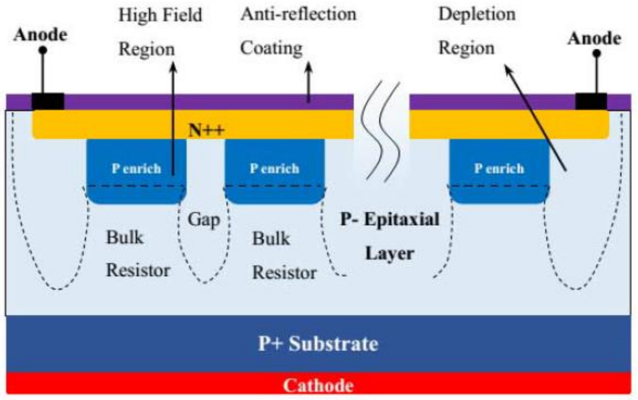


A plot of the X–Y spatial resolution (FWHM) as a function of the incident beam spot light intensity. Spot size was ~30 micron.

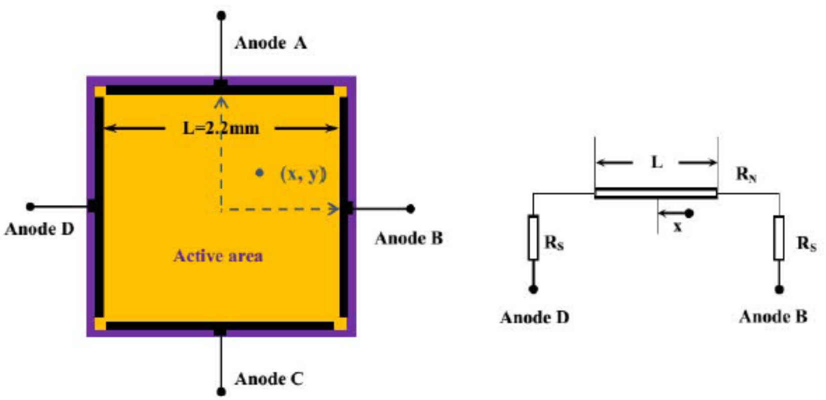
M. McClish et al. / Nuclear Instruments and Methods in Physics Research A 652 (2011) 264–267

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

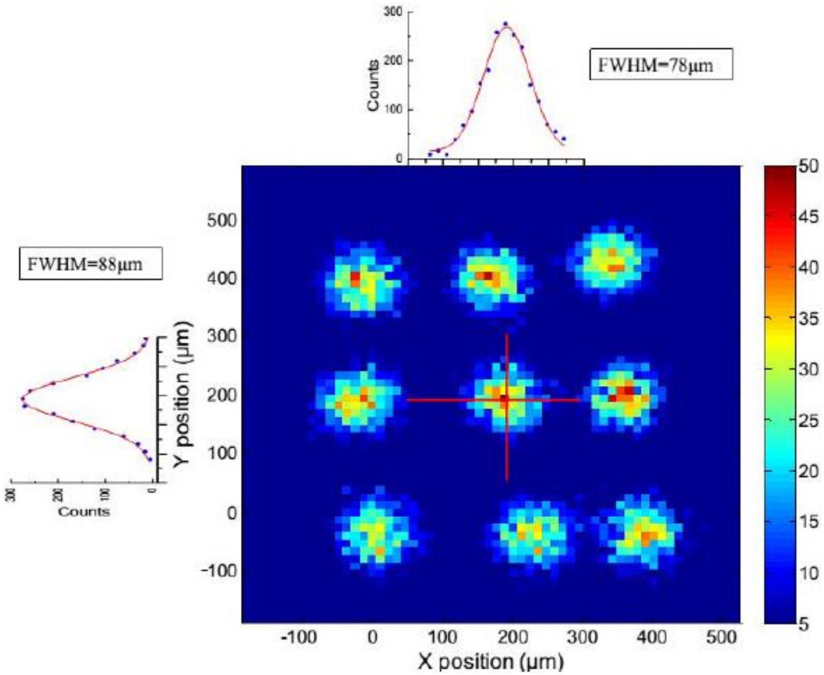


Top view of tetra-lateral type electrodes of the PS-SiPM with 4 anodes

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

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

PS-SiPM – NDL (II)

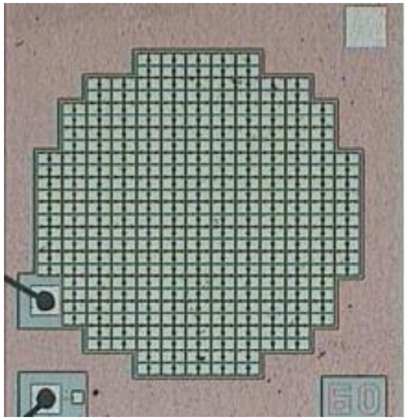


Reconstruction of nine positions of light spots from optical fiber tested in the central part of the device

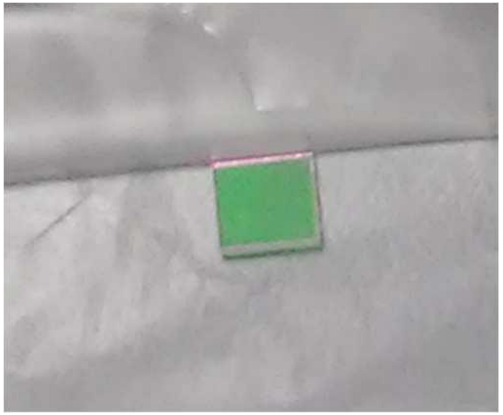
The device, with an active area of 2.2 mm × 2.2 mm, demonstrated spatial resolution of 78–97 μm, gain of 1.4 × 10^5 and 46-ps time jitter of transmission delay for 210–230 photons.

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

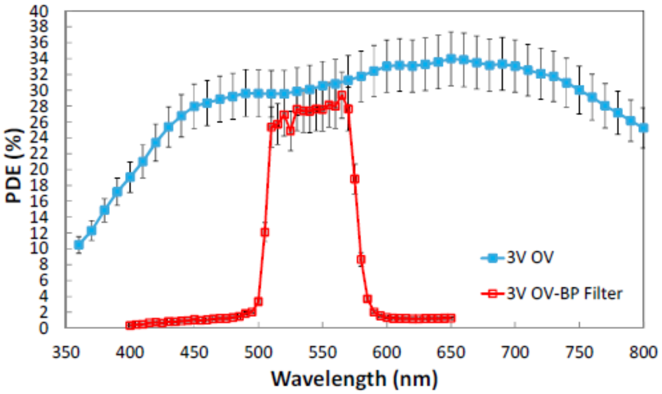
SiPMs with Bandpass Dichroic Filters



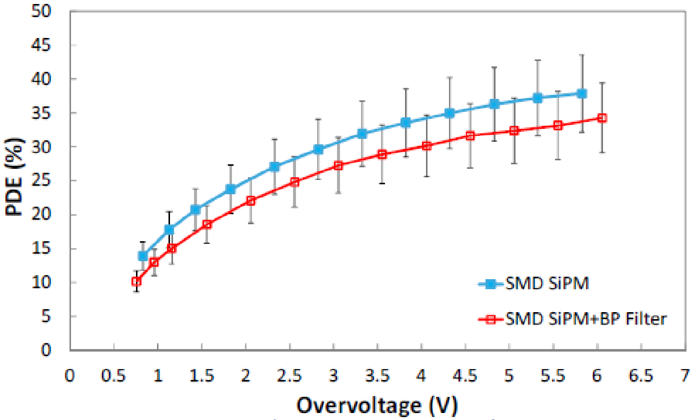
Optical microscope picture of the STMicro SiPM (548 cells, 67.4% geometrical factor)



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



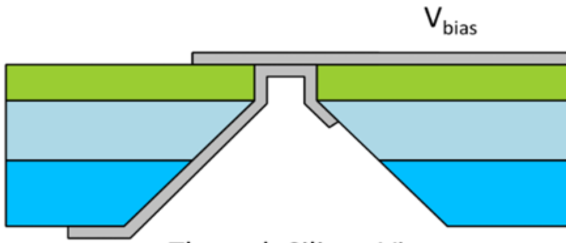
PDE measured at 515 nm vs bias on n-on-p SiPM with and without BP filter

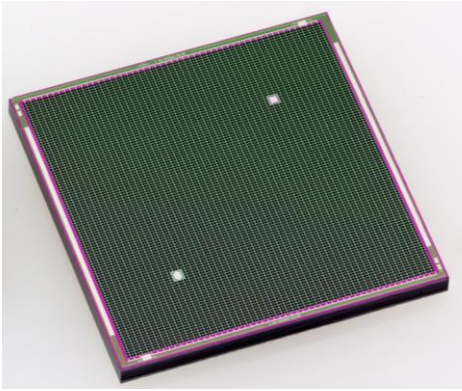
Such a photo-sensor can be very used in applications where protection of the detector from unwanted light background (ambient light for example) is required.

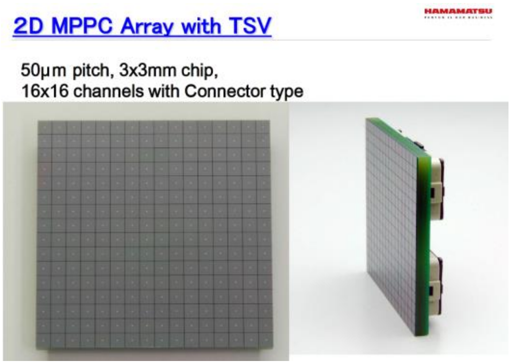
(M.Mazillo et al., to be published in Sensors)

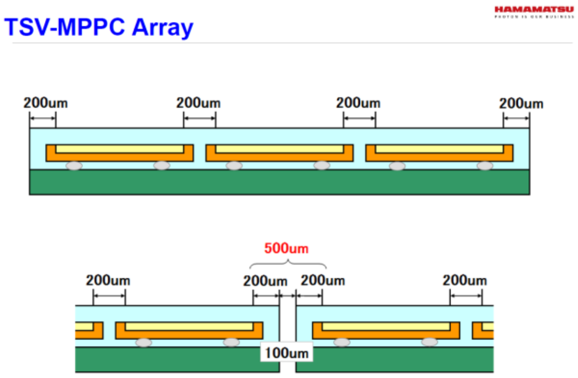
TSV technology (no bonding wire)

TSV Technology:
Further improved geometrical efficiency for arrays ,





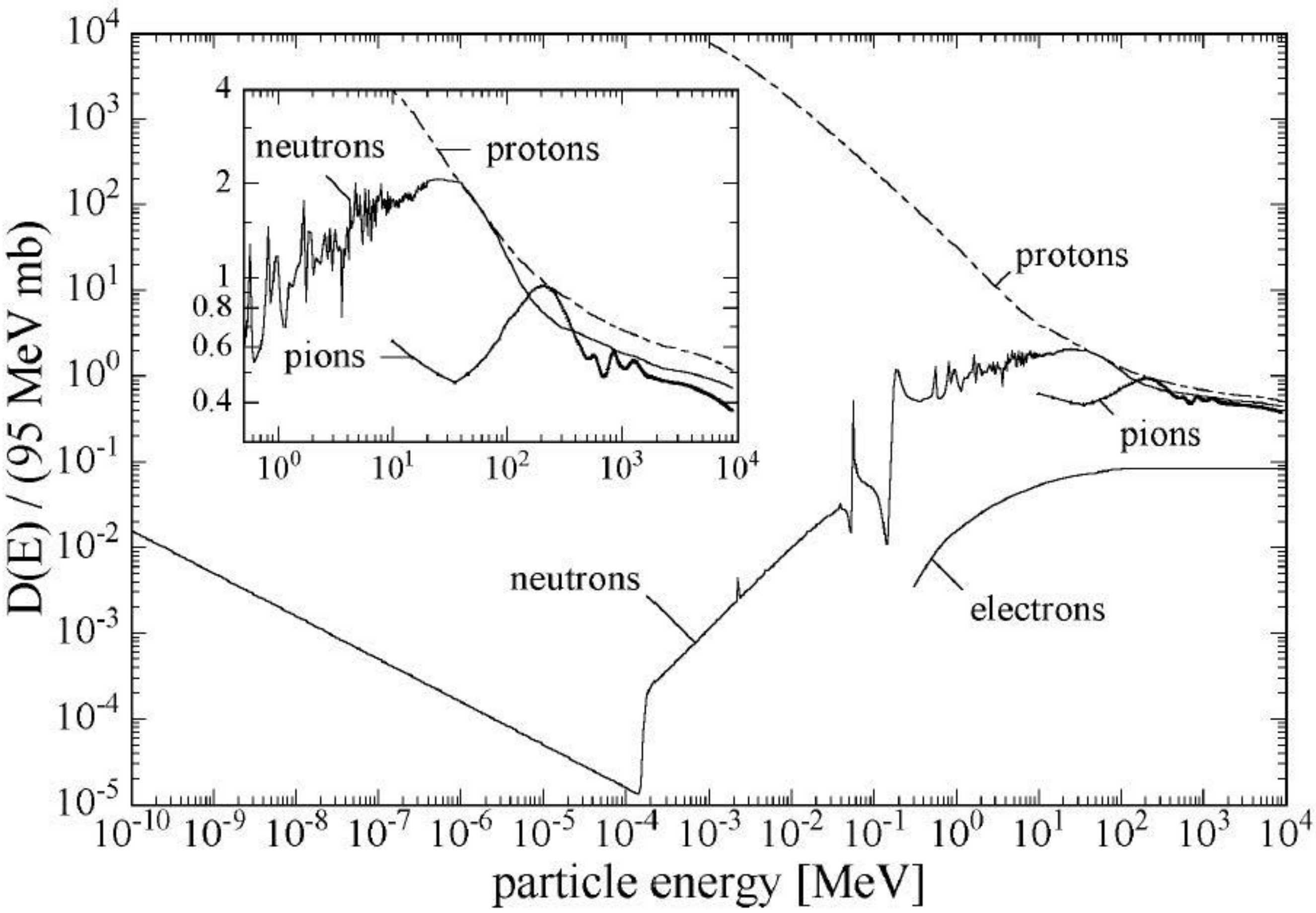




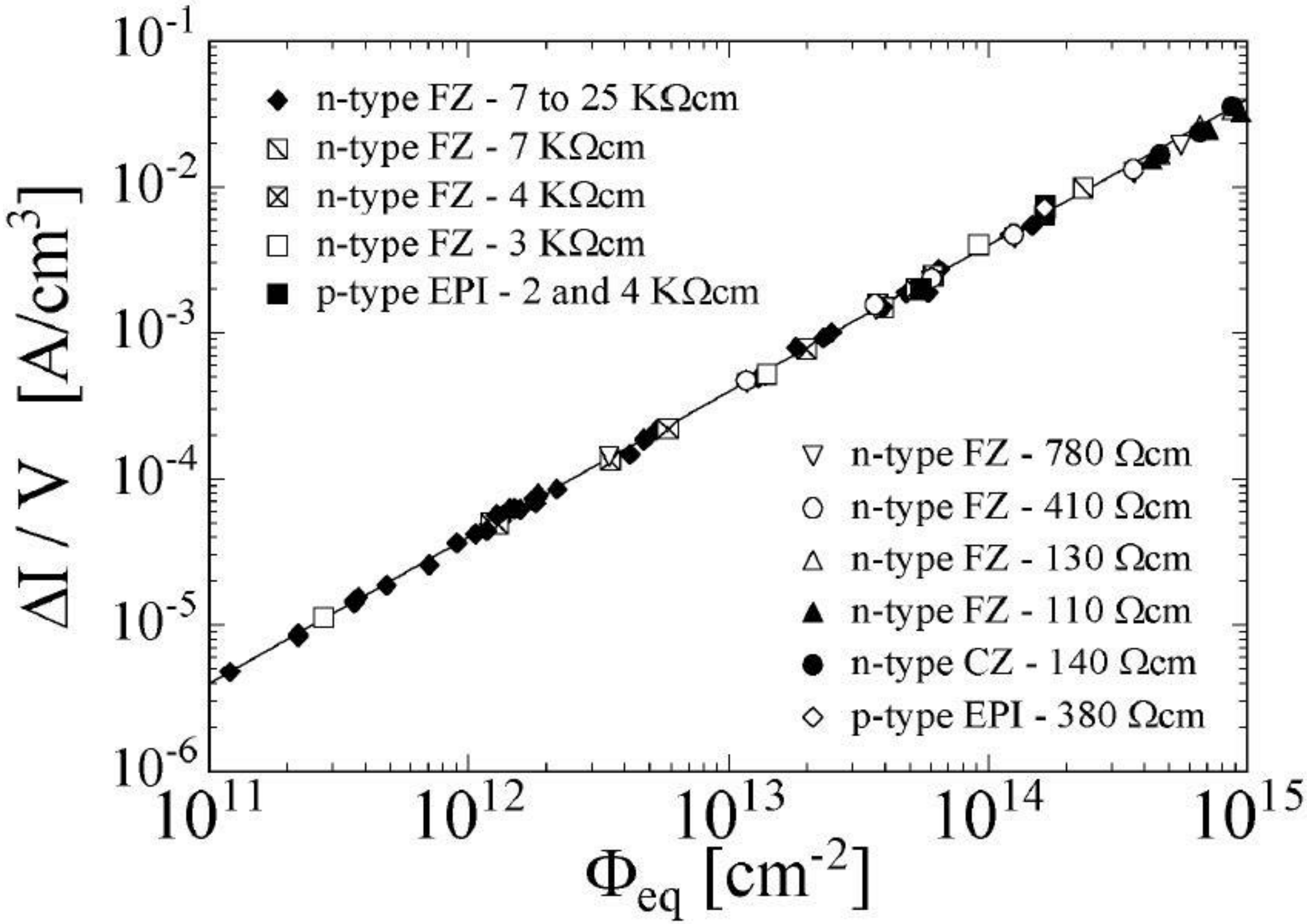
(KETEK – Photodet-2015 (Troitsk))

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

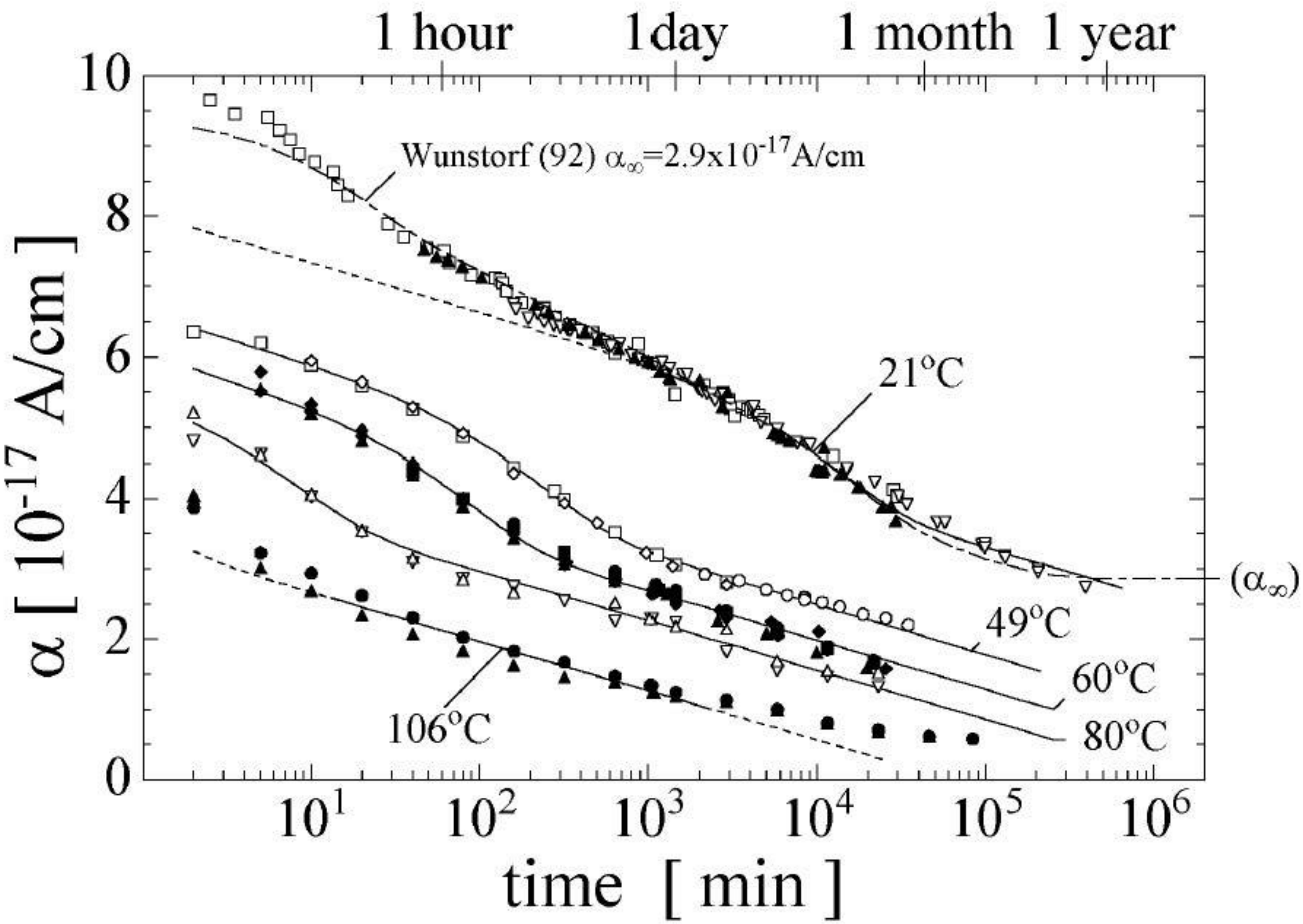
Displacement damage function (NIEL) for protons, neutrons, pions and electrons vs. their energy



Fluence dependence of leakage current for silicon detectors



Current related damage rate α as function of cumulated annealing time



(M.Moll, PhD thesis)