# New developments in solid state photomultipliers

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*&*

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# Outline

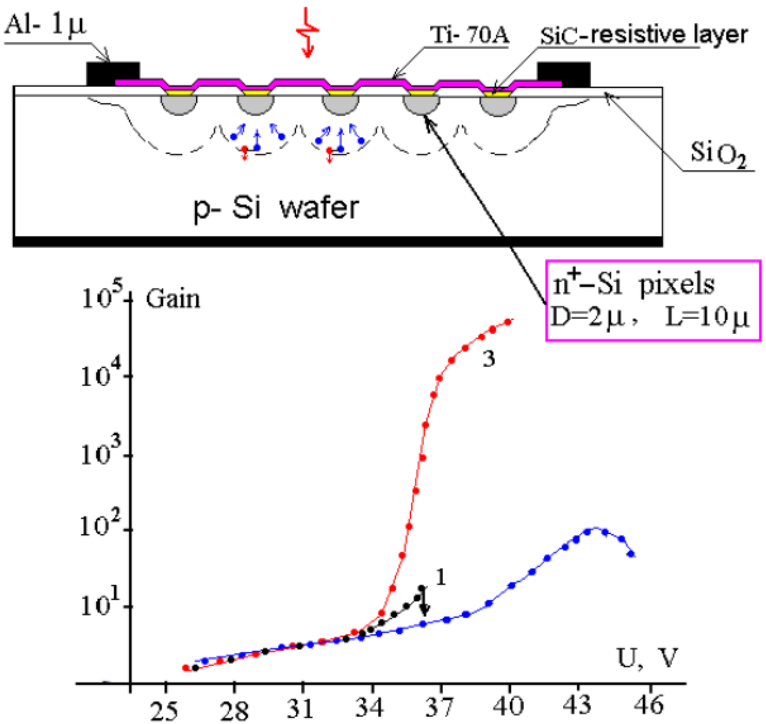
- New developments in SiPMs:
  - high PDE
  - low noise
  - low X-talk
  - low after-pulsing
  - fast timing
  - large dynamic range, fast recovery time
  - radiation hard
- New developments in HAPDs
- Exotics
- SSPMs prospects

# SiPMs

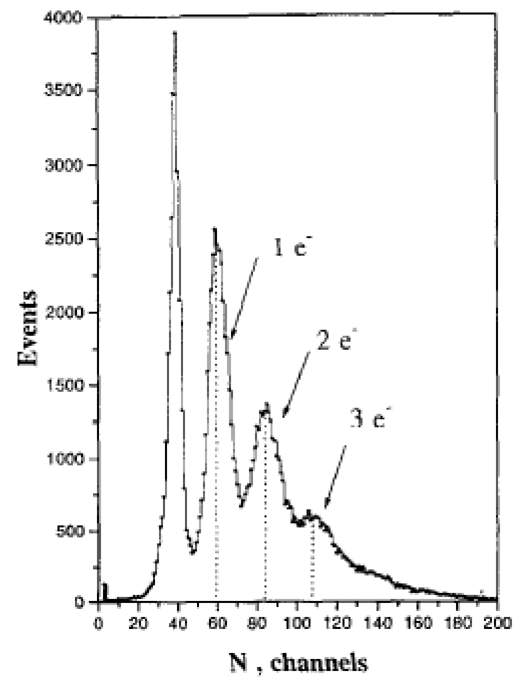
# First design (MRS APD, 1989)

*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).*

*Geometric factor was low. Only few % photon detection efficiency for red light was measured with 0.5x0.5 mm² APD. MRS APD had very good pixel-to-pixel uniformity.*




1- Si p-n-junction; 2- Si-SiC–planar structure
3- Si-SiC–micro-pixsel (micro-channel)



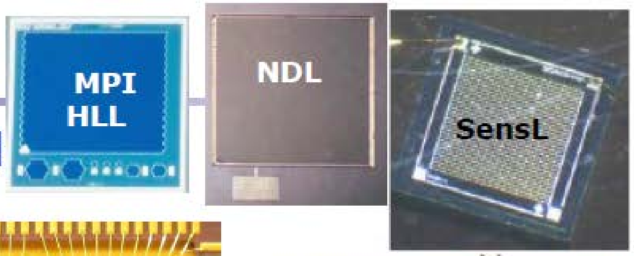

*LED pulse spectrum*
*(A. Akindinov et al., NIM387 (1997) 231)*

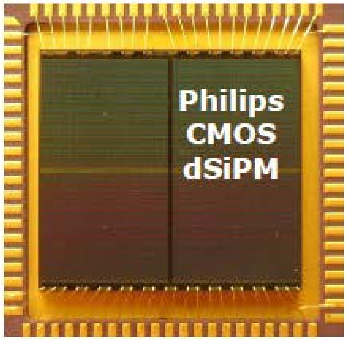
# Developers and producers

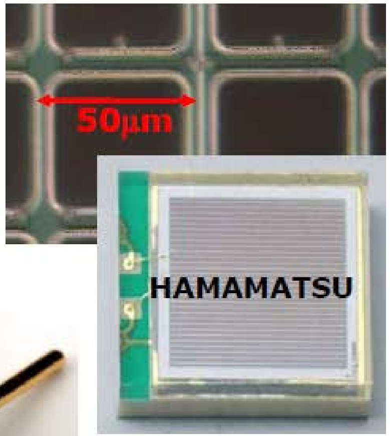
## Today

Many institutes/companies are involved in SiPM development/production:

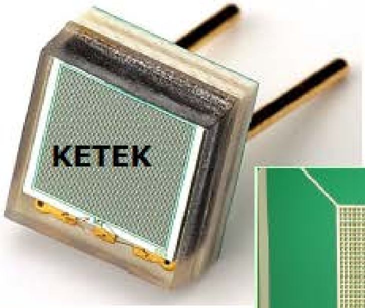
- **CPTA**, Moscow, Russia
- **MePhi/Pulsar** Enterprise, Moscow, Russia
- **Zecotek,** Vancouver, Canada
- **Hamamatsu HPK**, Hamamatsu, Japan
- **FBK-AdvanSiD**, Trento, Italy
- **ST Microelectronics**, Catania, Italy
- **Amplification Technologies** Orlando, USA
- **SensL**, Cork, Ireland
- **MPI-HLL**, Munich, Germany
- **RMD**, Boston, USA
- **Philips**, Aachen, Germany
- **Excelitas** tech. (formerly Perkin-Elmer)
- **KETEK**, Munich, Germany
- **National Nano Fab Center**, Korea
- **Novel Device Laboratory** (**NDL**), Bejing, China
- **E2V**
- **CSEM**

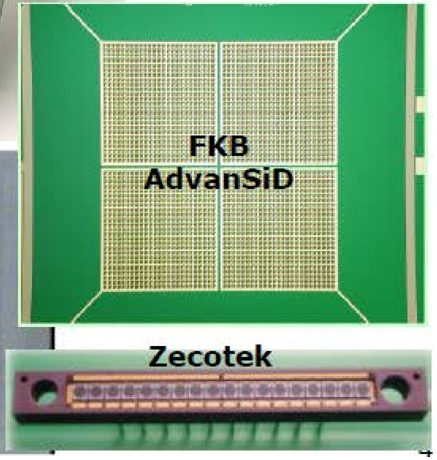


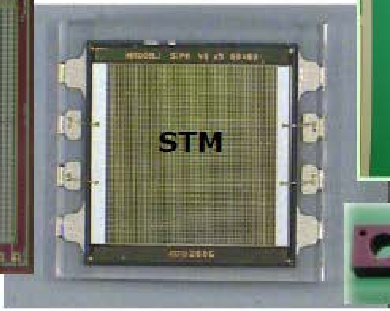



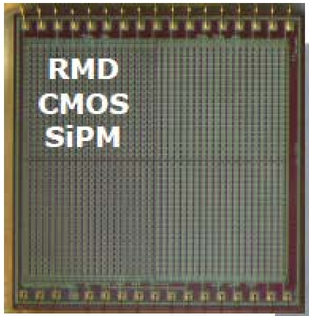





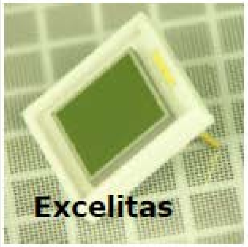



Amplification Technologies (DAPD)



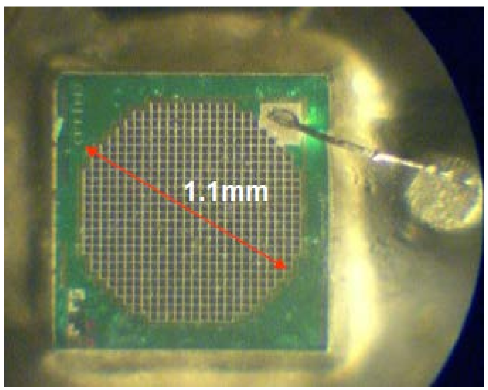

G.Collazuol - PhotoDet 2012

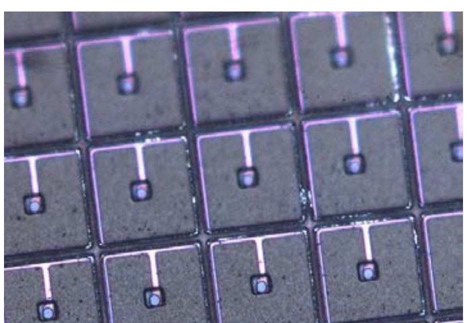
# Photon Detection Efficiency

Photon detection efficiency (PDE) is the probability to detect single photon when threshold is <1 pixel charge. It depends on the pixel active area quantum efficiency (QE), geometric factor ($G_f$) and probability of primary photoelectron to trigger the pixel breakdown $P_b$ (depends on the $V-V_b$ , $V_b$ – is a breakdown voltage)

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

## CPTA SSPM

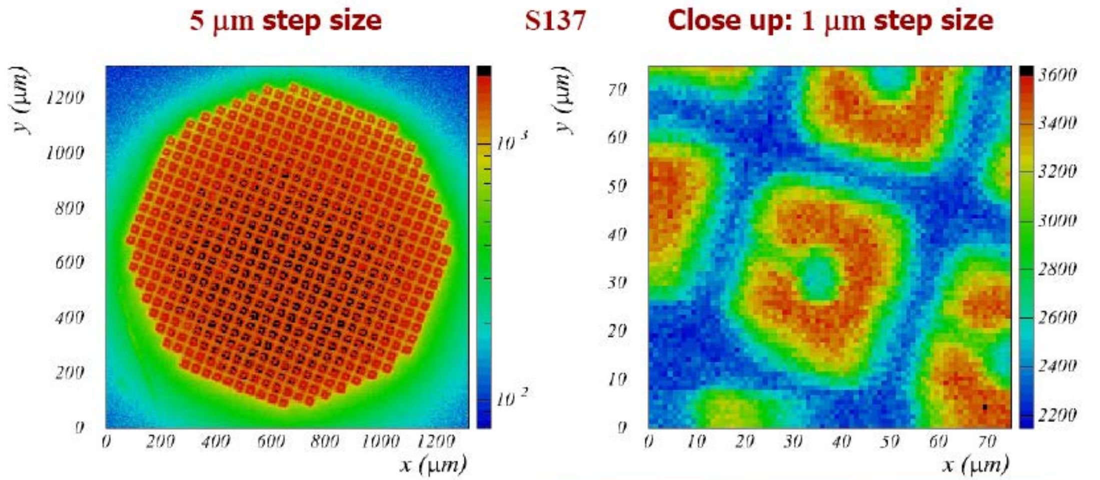


## SSPM 2d scan with focused laser beam

### Surface sensitivity for single photons

- 2d scan in the focal plane of the laser beam ($\sigma \approx 5$ μm)
- intensity: on average << 1 photon
- Selection: single pixel pulse height, in TDC 10 ns window

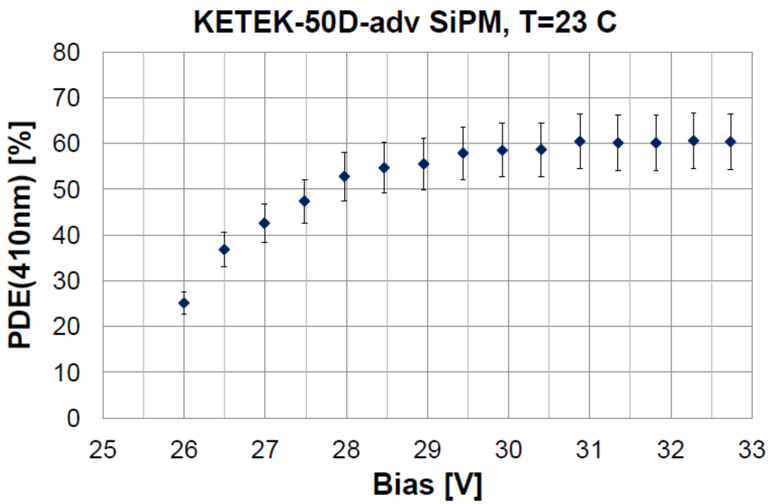


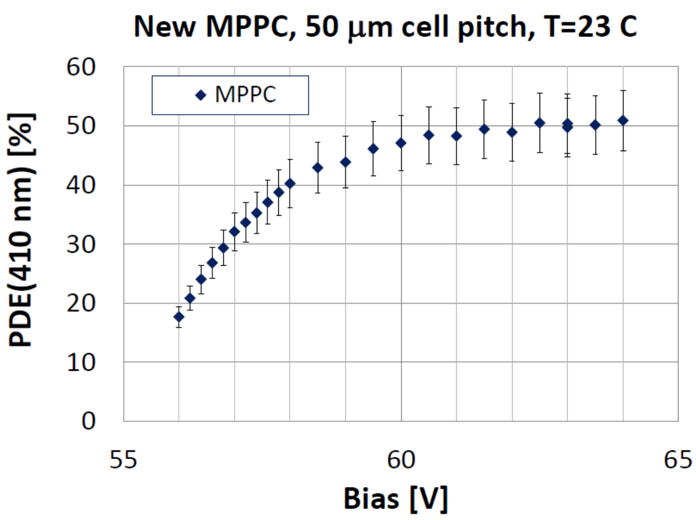

September 26, 2007 Light07, Ringberg castle Peter Križan, Ljubljana

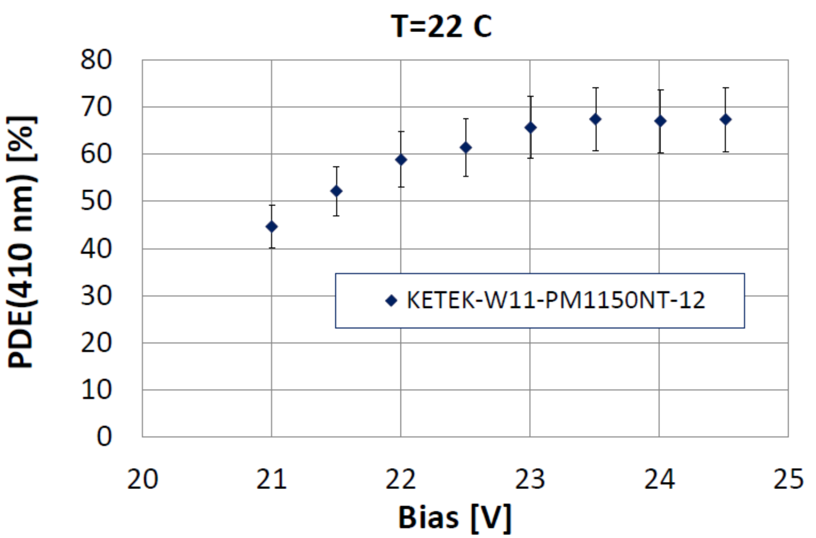
Non-sensitive zones between cells reduce PDE

# New High PDE SiPMs

Recently KETEK and Hamamatsu developed 50 μm cell pitch SiPMs with high $G_f$>80% and PDE=50-65% for blue/UV light !!

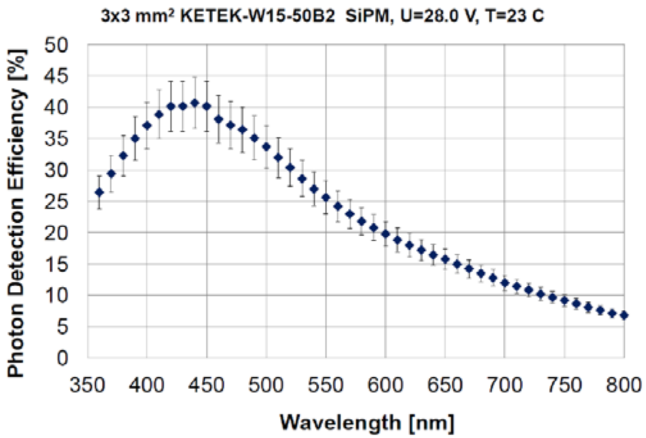


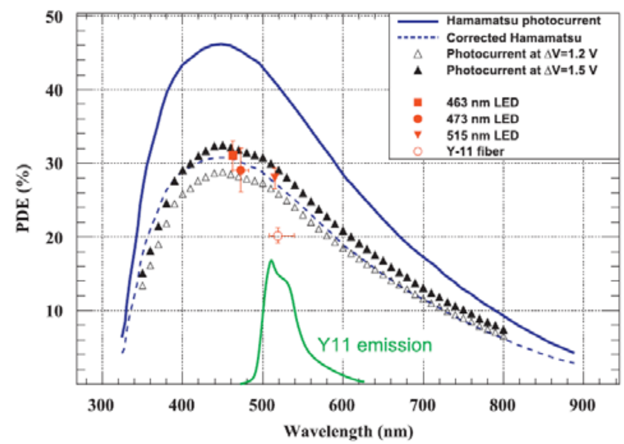



# SiPM spectral response

KETEK 2011 SiPM (50 μm cell pitch)

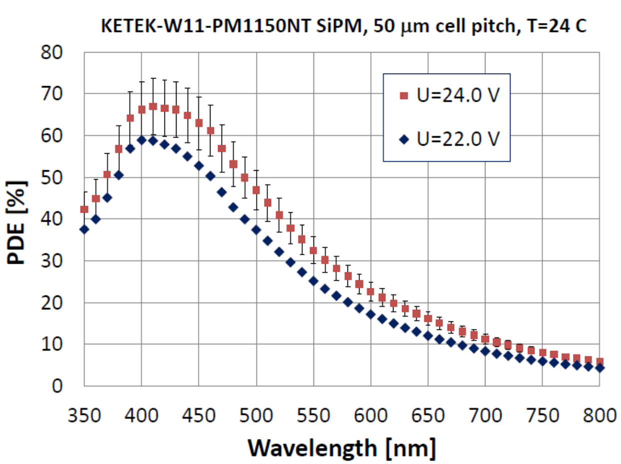



Hamamatsu-2010 MPPC (50 μm cell pitch)

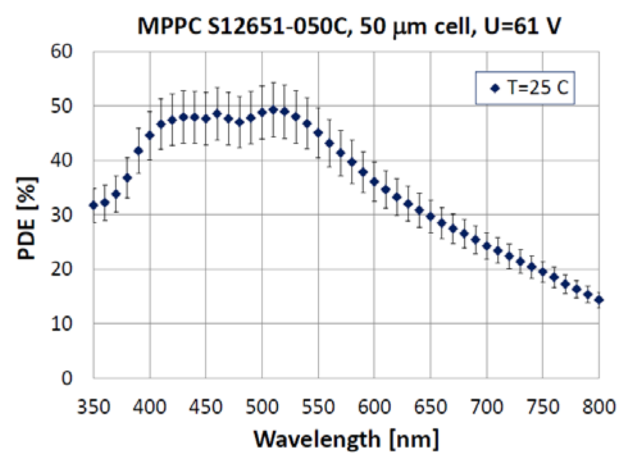



*A. Vacheret et al. / Nuclear Instruments and Methods in Physics Research A 656 (2011) 69–83*

KETEK 2013 SiPM (50 μm cell pitch)

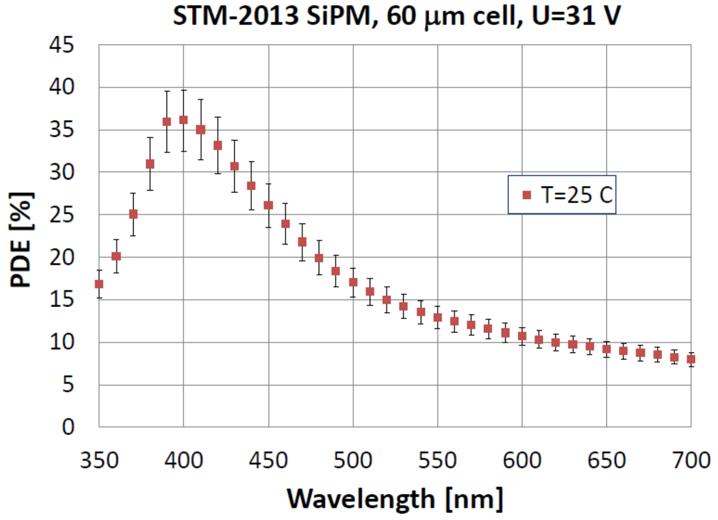



Hamamatsu-2013 MPPC (50 μm cell pitch)

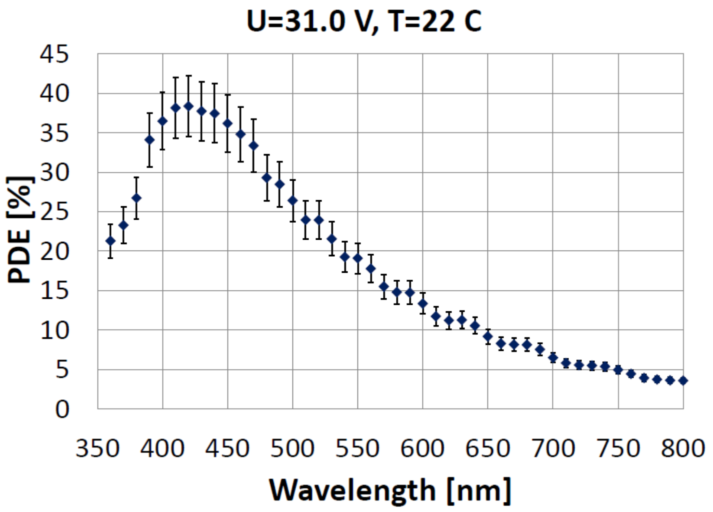


# Blue/UV light sensitive SiPMs (P on N)

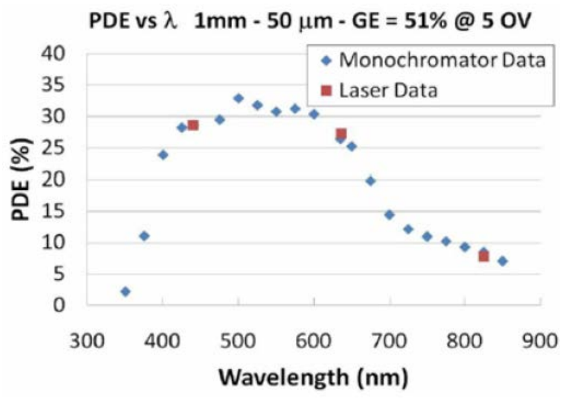
ST Misro-2013 SiPM (60 μm cell pitch)




SensL Micro-FB-10035-X18 SiPM (45 μm cell pitch)

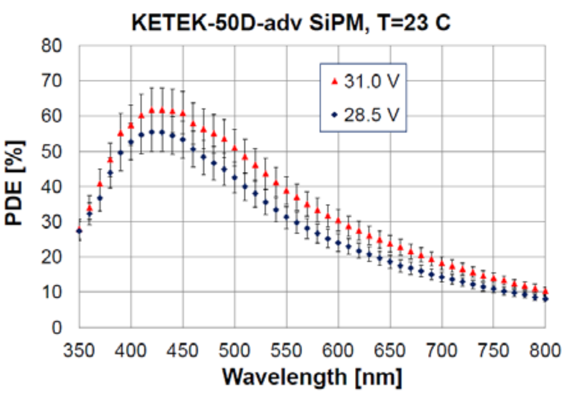



Excelitas SiPM (50 μm cell pitch) – NDIP-11



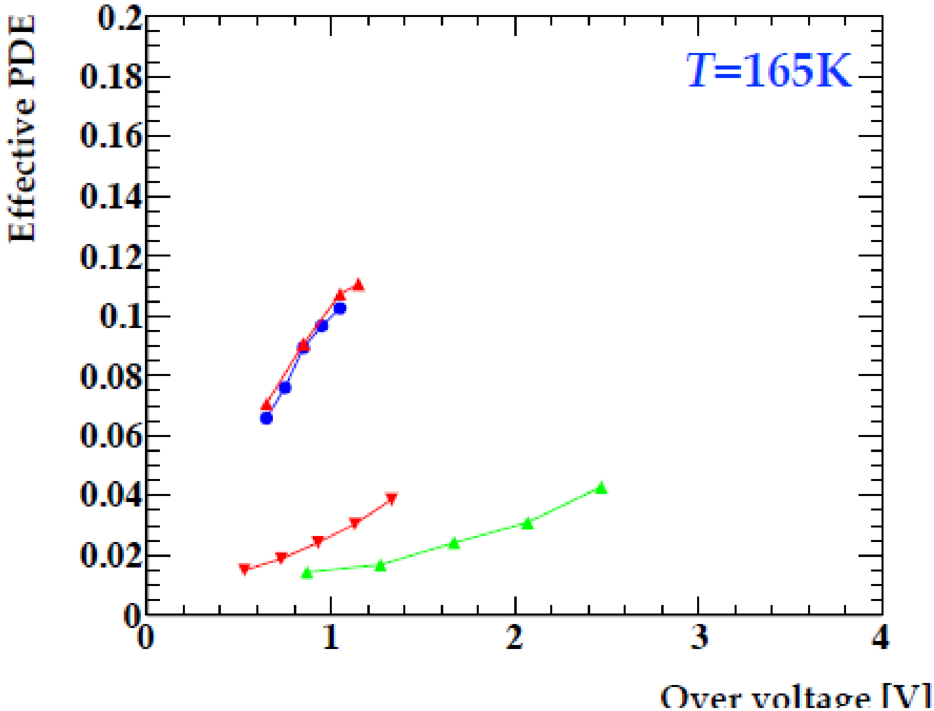

**Ubreakdown 90-140V**

KETEK 2012 SiPM



# UV-enhanced SiPMs (for MEG LXe Sci. Detector)

UV-enhanced MPPC is under development by Hamamatsu in collaboration with KEK




- Remove protection coating
- Optimize MPPC parameters
  - Thinner p$^+$ contact layer
  - Anti-reflection coating
  - Refractive index of surface material
  - Quench resistor
  - Pixel size

PDE~10 % achieved for 175 nm light (best samples)

# SiPM Noise Sources

## Noise sources:

**Dark counts** – pulses triggered by non-photo-generated carriers (thermal / tunneling generation in the bulk or in the surface depleted region around the junction)

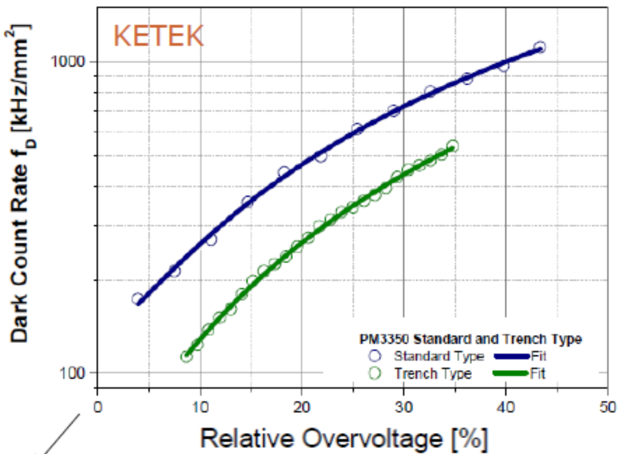
**After-pulsing** – carriers can be trapped during an avalanche and then released triggering another avalanche

**Cross-Talk** "optical" – photo-generation during the avalanche discharge. Some of the photons can be absorbed in the adjacent cell possibly triggering new discharges

G.Collazuol PhotoDet 2012

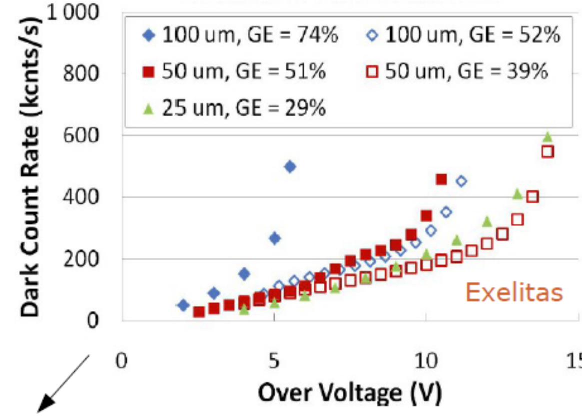
# Dark Count Rate

KETEK PM 3350 ($p^+$-on-n, shallow junction)
3x3mm[2] active area pixel size 50x50 μm[2]

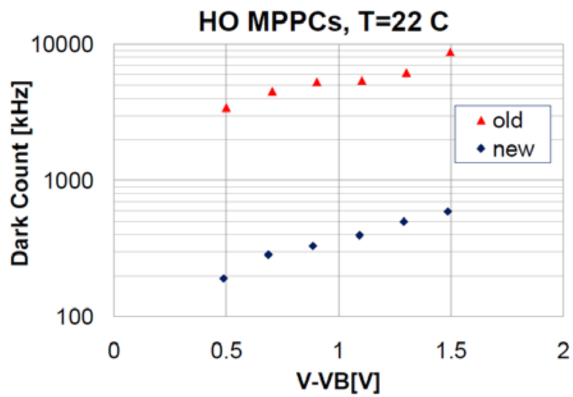


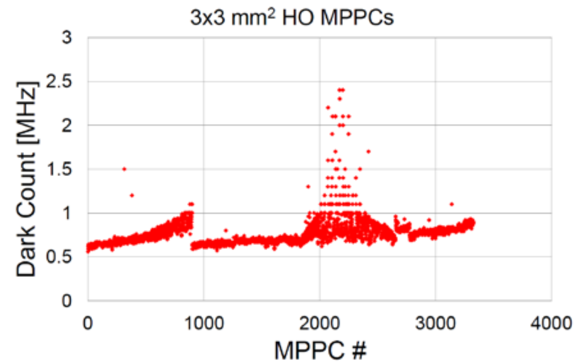

$V_{bd}$ ~ 25V *F.Wiest – AIDA 2012 at DESY*

Exelitas 1[st] generation SiPM 2011
($p^+$-on-n) 1x1mm[2]




$V_{bd}$ ~ 140V *P.Berard – NDIP 2011*

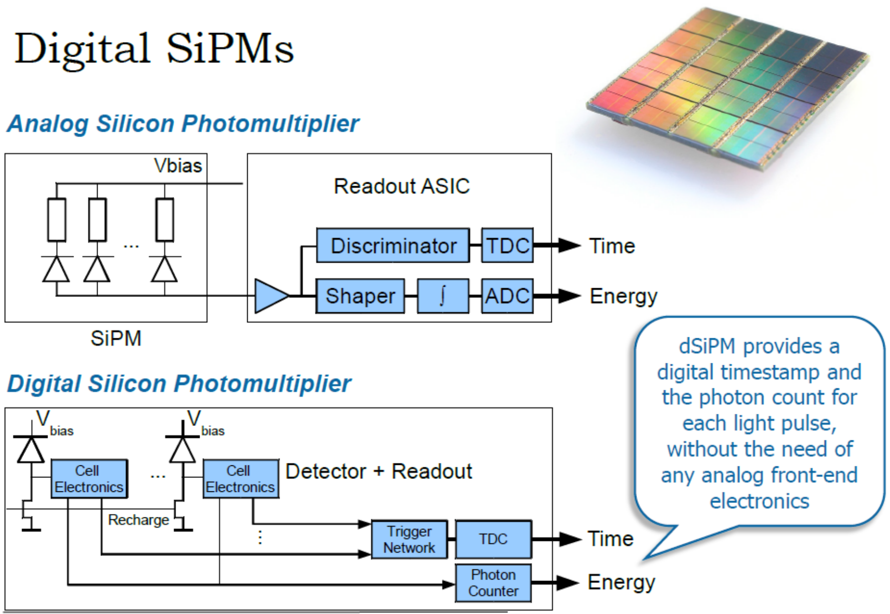


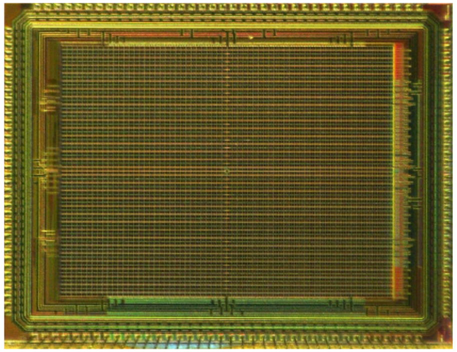

Latest MPPCs reached DCR<100 kHz/mm[2] at RT and dVB=1.1 V (PDE(450nm)~30%)

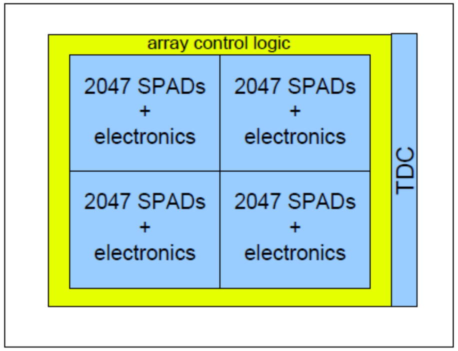
# Low Dark Count Rate dSiPM (Philips)

dSiPM - array of SPADs integrated in a standard CMOS process. Photons are detected and counted as digital signals using a dedicated cell electronics block next to each diode. This block also contains active quenching and recharge circuits, one bit memory for the selective inhibit of detector cells. A trigger network is used to propagate the trigger signal from all cells to the TDC.




## Digital SiPM – Test Chip Architecture

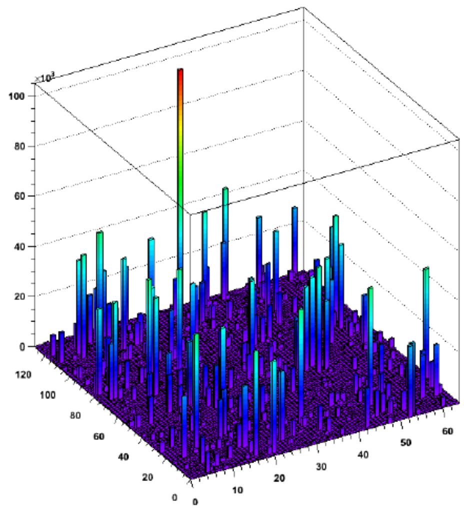


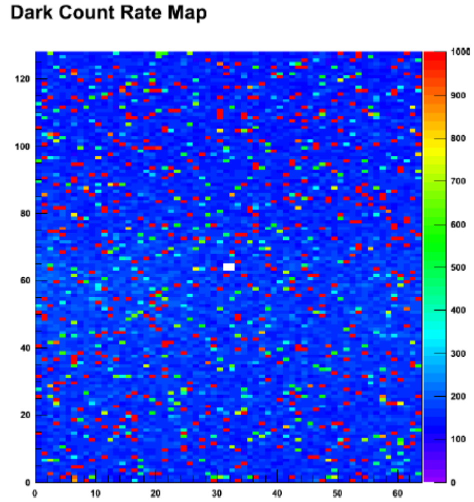


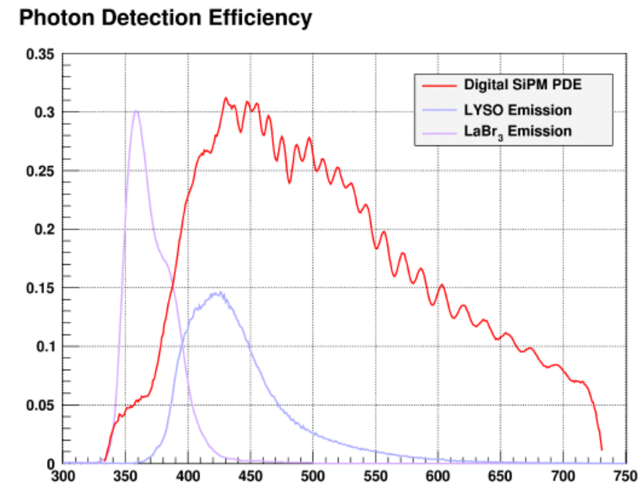

- Pixel composed of 4 identical sub-pixels with 2047 microcells each
- Microcell size 30μmx52μm, 50% fill factor including electronics
- A 1 bit inhibit memory in each microcell to enable/disable faulty diodes
- Active quench & recharge, on-chip memory and array controllers
- Integrated time-to-digital converter with σ = 8ps time resolution
- Variable trigger (1-4 photons) and energy (1-64 photons) thresholds
- Acquisition controller implemented in FPGA for flexibility and testing

(T. Frach, IEEE-NSS/MIC, Orlando, Oct. 2009)

# dSiPM – dark count rate, PDE





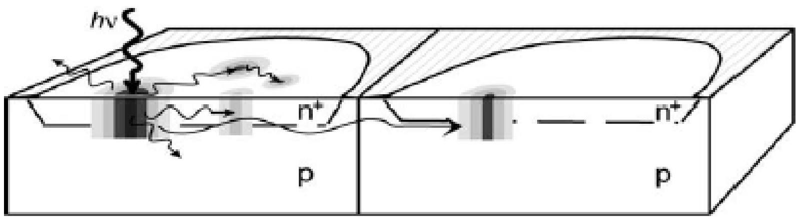




*Only 5 to 10% of the diodes show abnormally high dark count rates due to defects. These diodes can be switched off. The average dark count rate of a good diode at 20 °C is approximately 150 cps (or ~100 kHz/mm$^2$).*
*Digital signal – only PDE varies with the temperature → low temperature sensitivity ~0.33%/C*

(T. Frach, IEEE-NSS/MIC, Orlando, Oct. 2009)

# Optical cross-talk

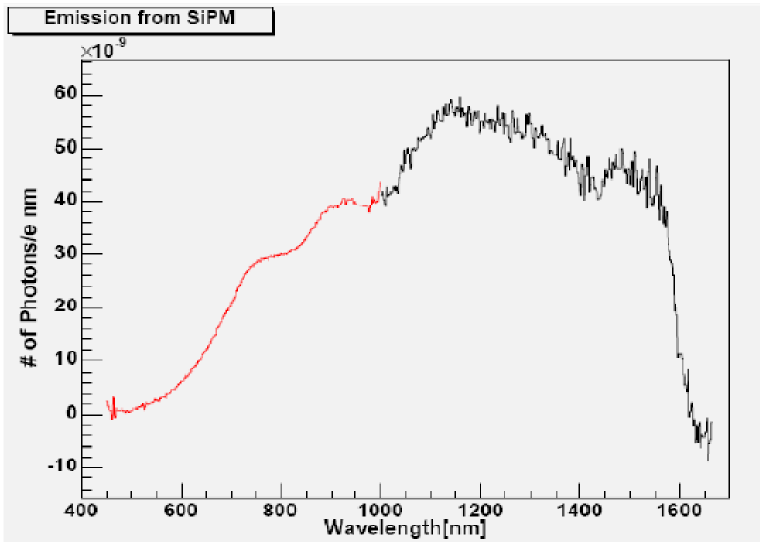
SiPM is not an ideal multiplier!




A. Lacaita et al, IEEE TED (1993)

Light is produced during cell discharge. Effect is known as a hot-carrier luminescence:
$10^5$ carriers produce ~3 photons with an wavelength less than 1 μm

Light emission spectrum from SiPM

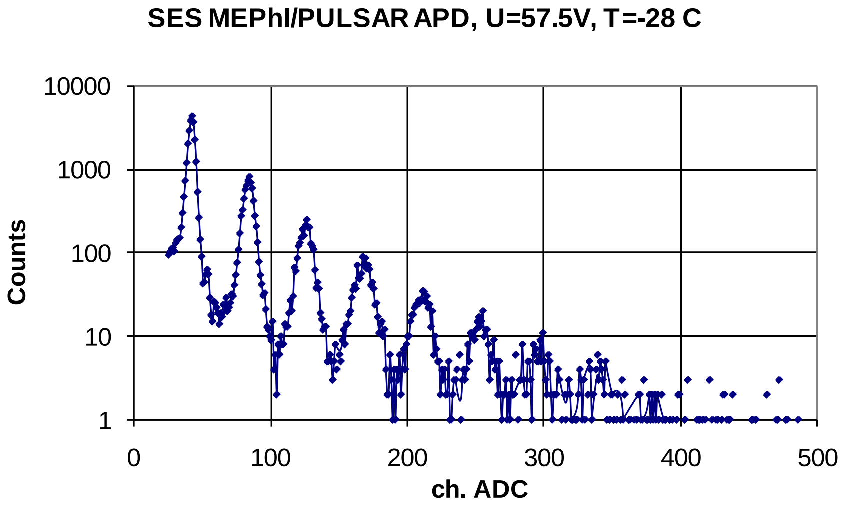


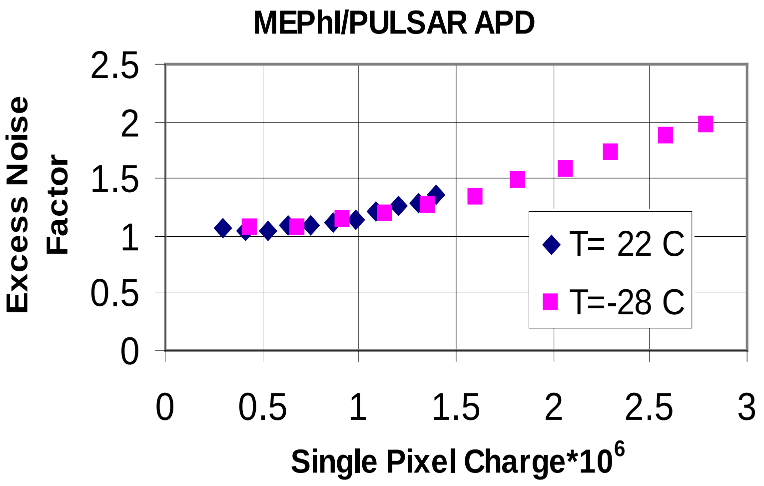

*(R. Mirzoyan, NDIP08, Aix-les-Bains)*

Light emitted in one cell can be absorbed by another cell. Optical cross-talk between cells causes adjacent pixels to be fired → increases gain fluctuations → increases noise and excess noise factor !

# Single electron spectrum and ENF

When V-$V_b$>>1 V typical single pixel signal resolution is better than 10% (FWHM)). However an optical cross-talk results in more than one pixel fired by a single photoelectron. Single electron spectrum can be significantly deteriorated and the excess noise factor can be >>1

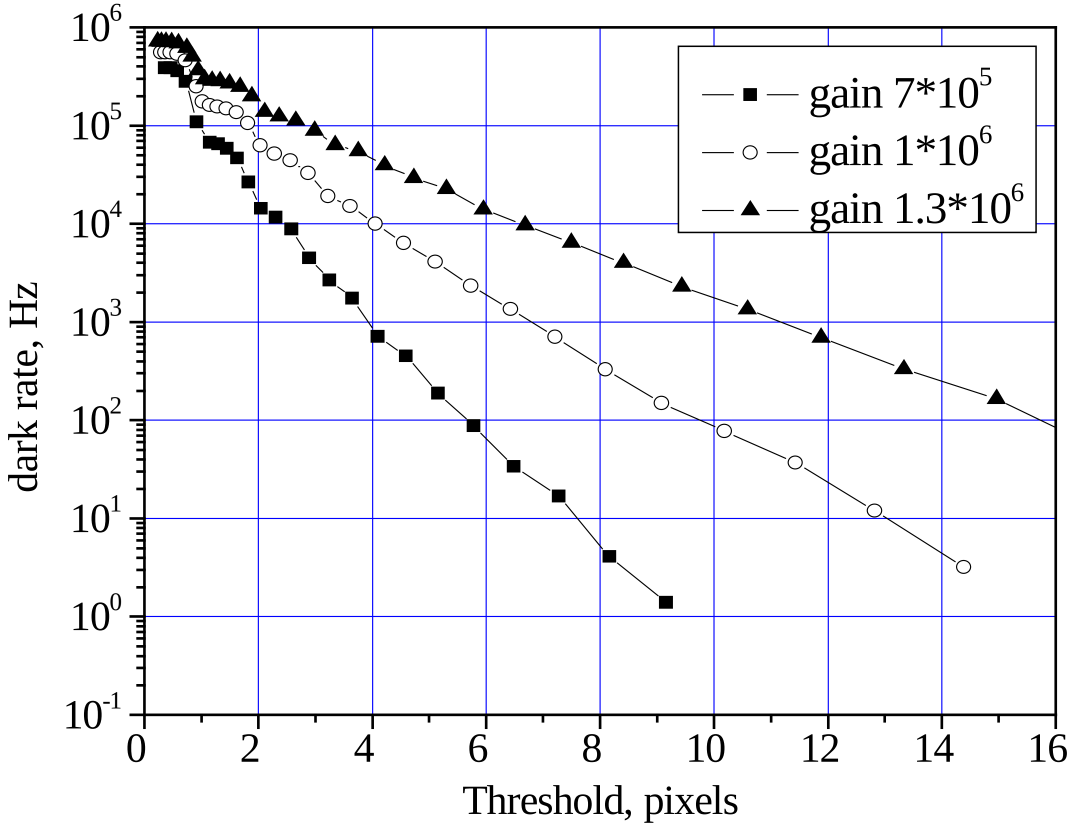



(Y. Musienko, NDIP-05, Beaune)

$$F = 1 + \frac{\sigma_M^2}{M^2}$$

# Dark count rate vs. electronics threshold




Optical cross-talk also increases the dark count at high electronics thresholds

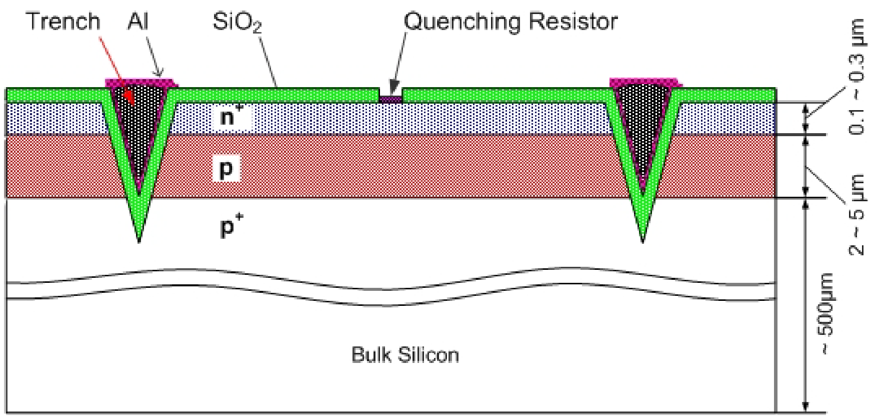
(E.Popova, CALICE meeting)

This effect is more pronounced at high SiPM gain!

# Optical cross-talk reduction

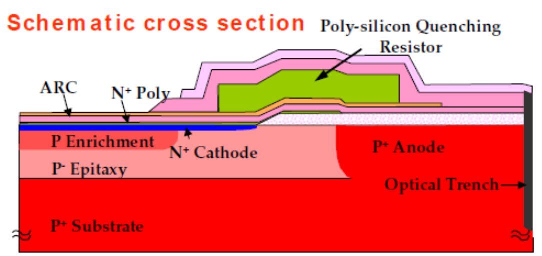
*Solution: optically separate cells trenches filled with optically non-transparent material*

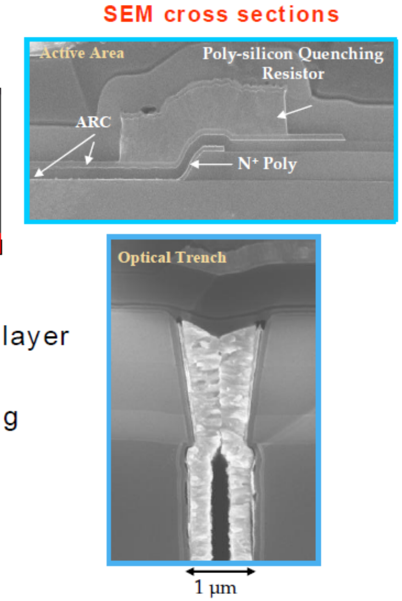
## CPTA structure




*(D. McNally, G-APD workshop, GSI, Feb. 2009)*

## STM structure



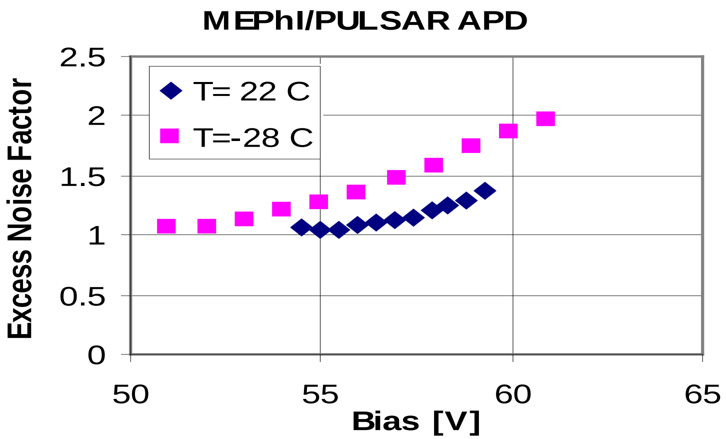

- Shallow junction
- In-situ doped poly-silicon cathode layer
- Integrated poly-silicon resistors
- Thin optical trench with metal filling
- Tunable Anti-reflection coating
- Dedicated gettering techniques
- Double layer passivation

STMicroelectronics CERN, Geneva, February 17th, 2011

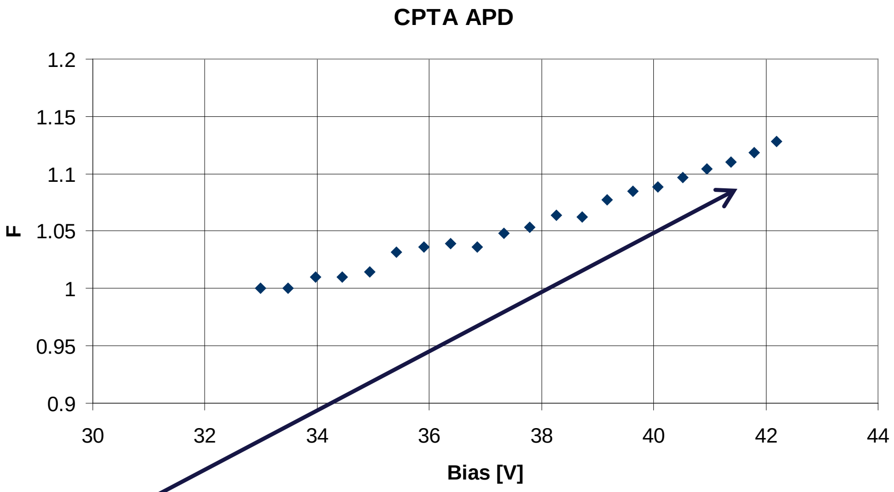
# SiPMs with reduced optical cross-talk

*Trenches really help …*

*MEPhI/Pulsar SiPM without trenches*




*CPTA/Photonique SSPM with trenches*

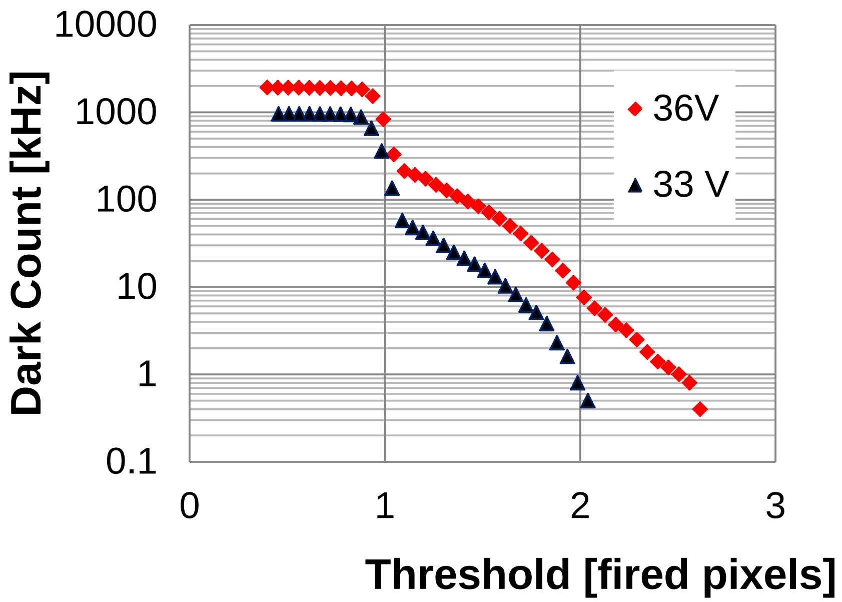



*The excess noise factor is small even at V-VB~10 V !*

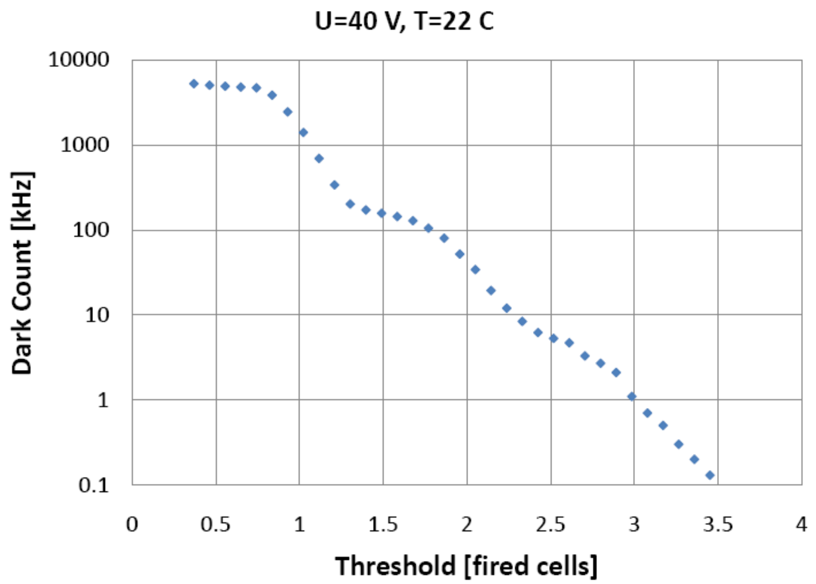
# Dark count rate of the SiPMs with trenches vs. electronics threshold

*… and dark count at a few photoelectrons threshold level is significantly reduced*

CPTA/Photonique SSPM with trenches




ST-Micro SiPM with trenches




*SiPMs with trenches can have an optical cross-talk <2%*

# Very low X-talk SiPMs (MEPhI)

SiPM: 1x1 $mm^2$, 100x100 $\mu m^2$, Geometrical Efficiency ~80%, T=+25°C, $\lambda$ = 435 nm

Same light impinging on both sensors

## 3+ -fold X-talk suppression

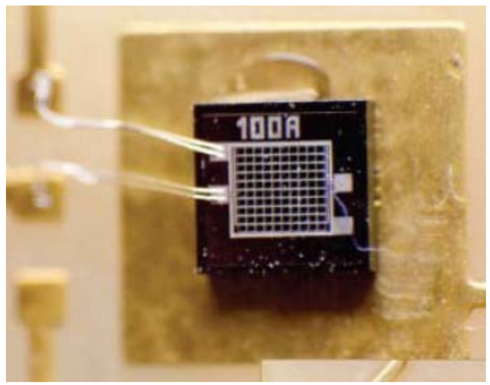
A known way to suppress X-talk:

1. Isolating trenches

**New ways:**

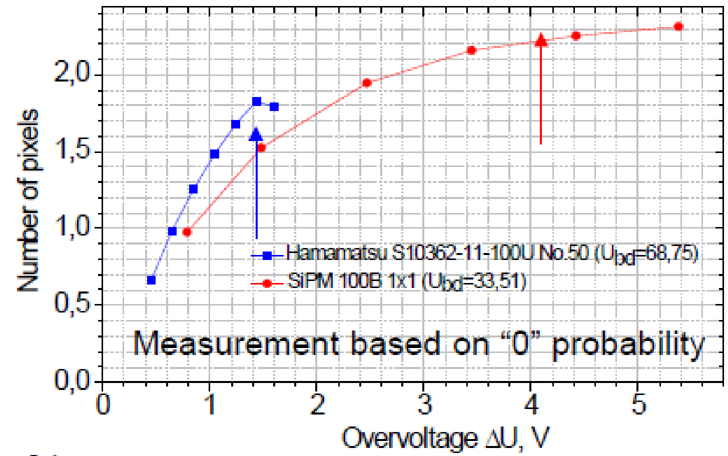
2. $2^{nd}$ p-n junction for isolating the bulk from the active region (patented)

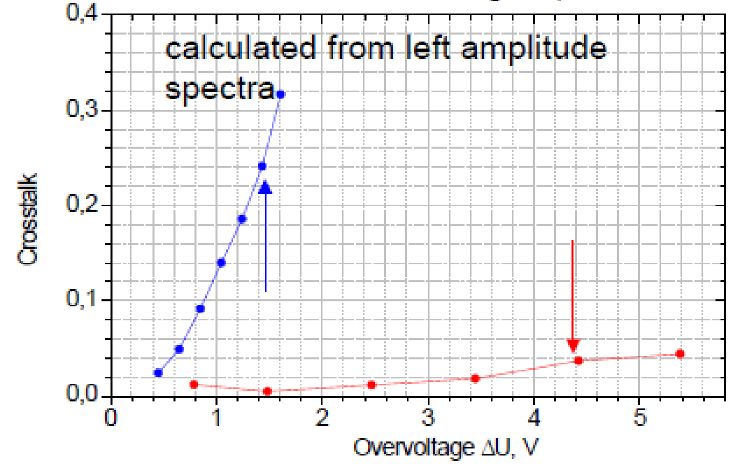
3. OC suppression by ion implantation (patent pending)




E.Popova: Large area SiPM with very high PDE and very low X-talk

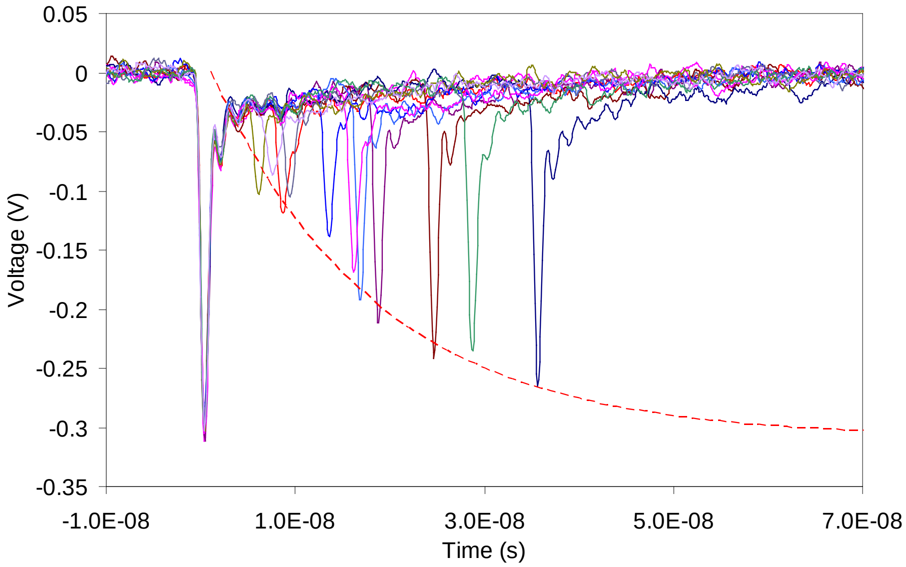
4th July 2011, NDIP-11, Lyon, France

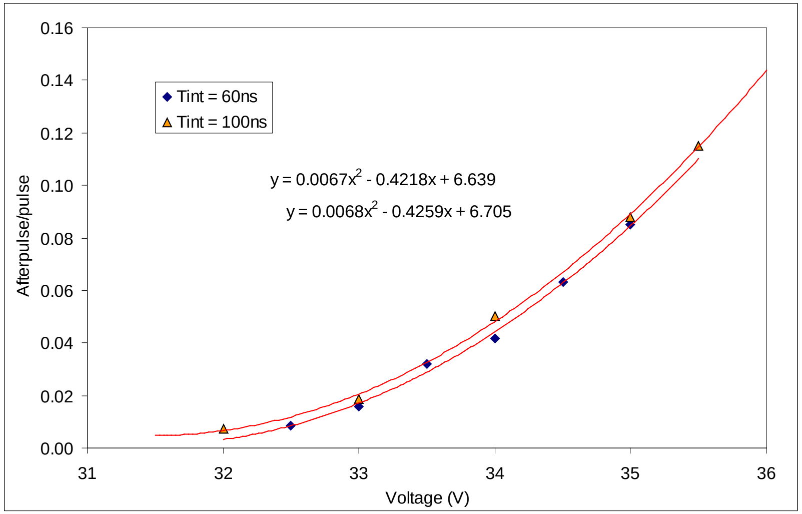


# After-pulsing

Another problem: carriers trapped during the avalanche discharge 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.*

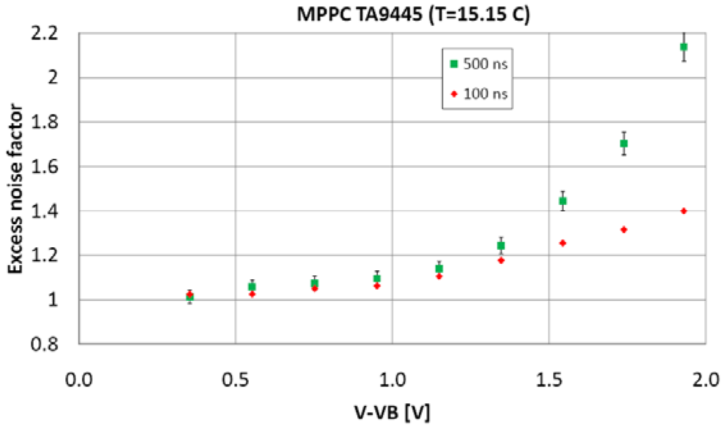
*After-pulse probability increases with the bias*

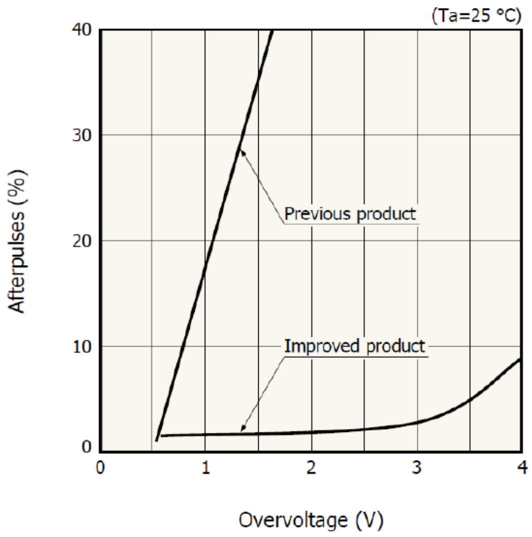
*(C. Piemonte: June 13th, 2007, Perugia)*

Solutions: "cleaner" technology, longer pixel recovery time and smaller gain

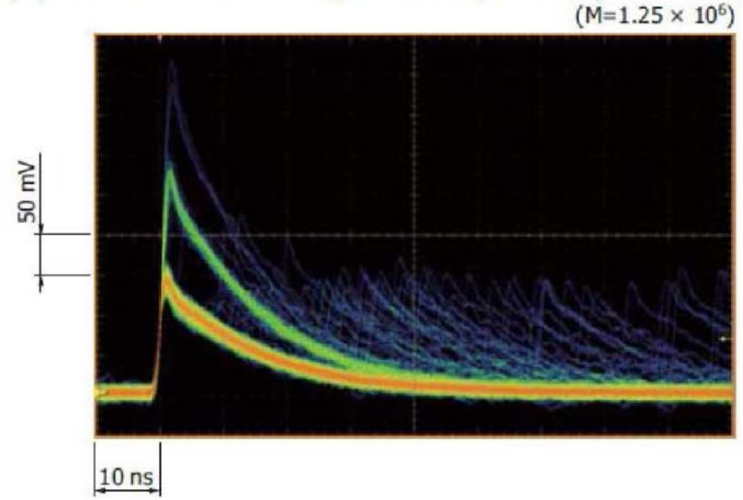
# After-pulses in MPPCs (old and new)

***After-pulses cause an increase of the SiPM dark count rate. They also increase the excess noise factor if the signal integration time is long***

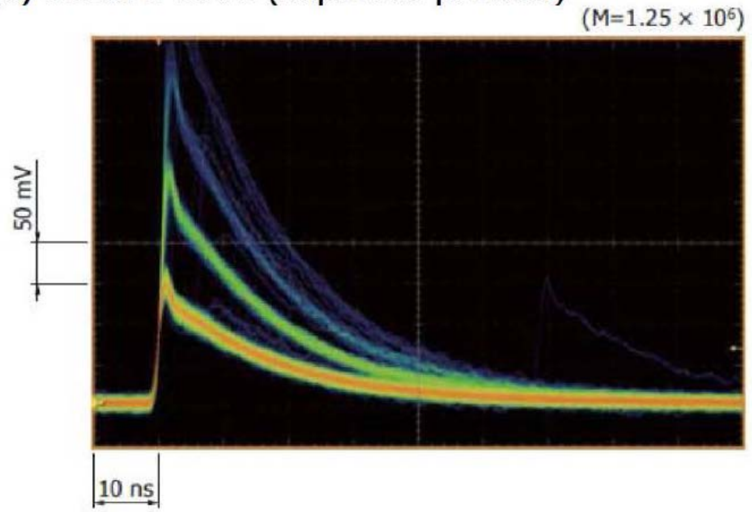



(a) S10362-11-050C (previous product)

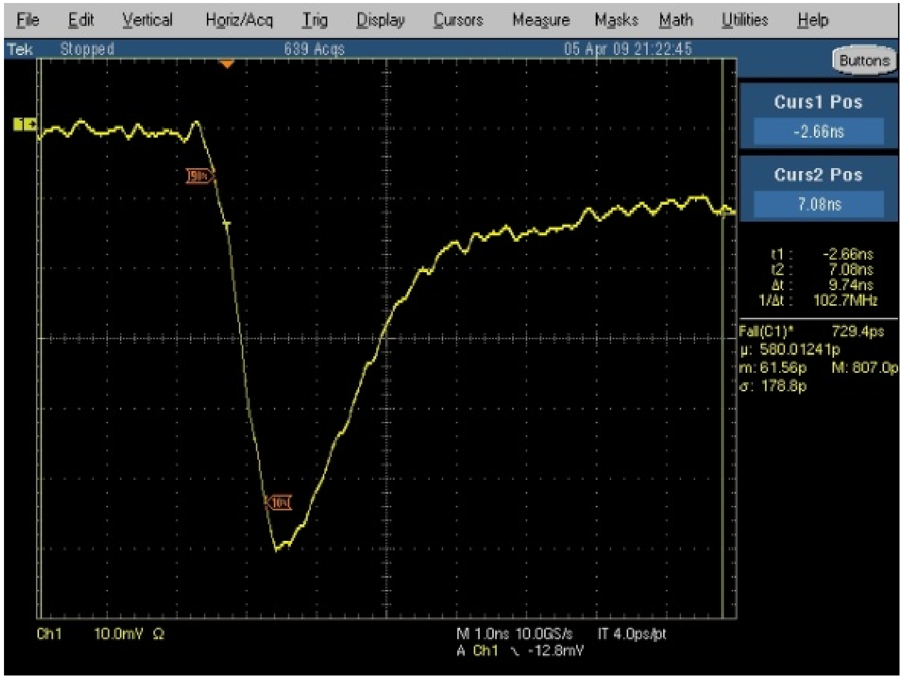



(b) S12571-050C (improved product)

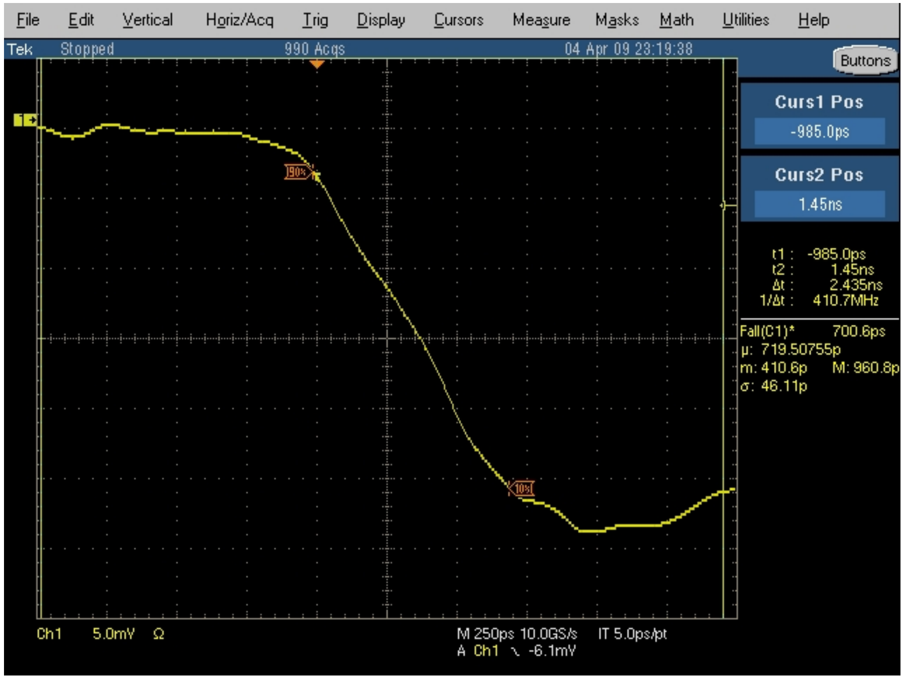


# Signal rise time

CPTA/Photonique 1 mm$^2$ SSPM response to a 35 psec FWHM laser pulse ($\lambda$=635 nm)



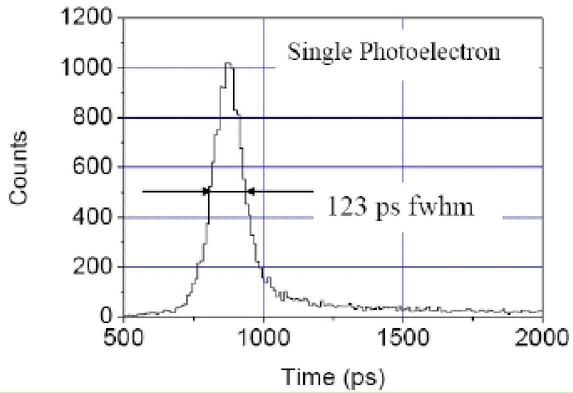

Zecotek 3x3 mm$^2$ MAPD response to a 35 psec FWHM laser pulse ($\lambda$=635 nm)

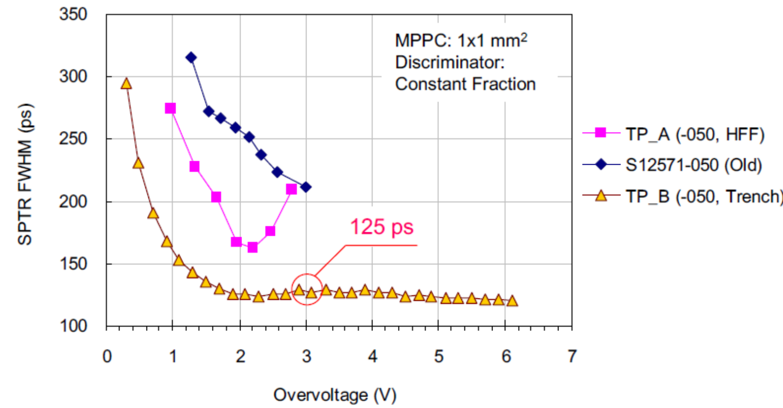



~700 psec rise time was measured (limited by circuitry)

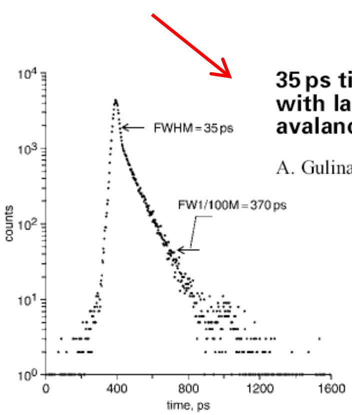
# Single photon time resolution

SiPMs have excellent timing properties



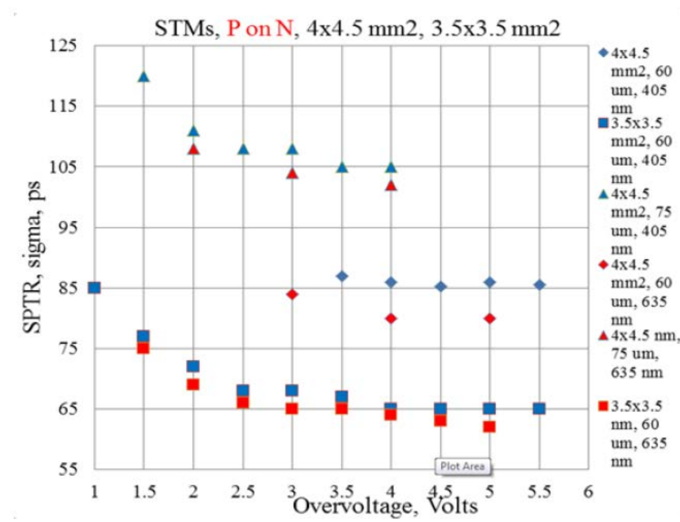

123 psec FWHM time resolution was measured with MEPhI/Pulsar SiPM using single photons (B. Dolgoshein, Beaune-02 and T.Nagano et. al, IEEE NSS-MIC 2013 ). And this can be improved …




**35 ps time resolution at room temperature with large area single photon avalanche diodes**

A. Gulinatti, P. Maccagnani, I. Rech, M. Ghioni and S. Cova

35 ps FWHM timing resolution was measured with 100 µm SPAD using single photons




(A.Ronzhin et. al, IEEE NSS-MIC 2013)

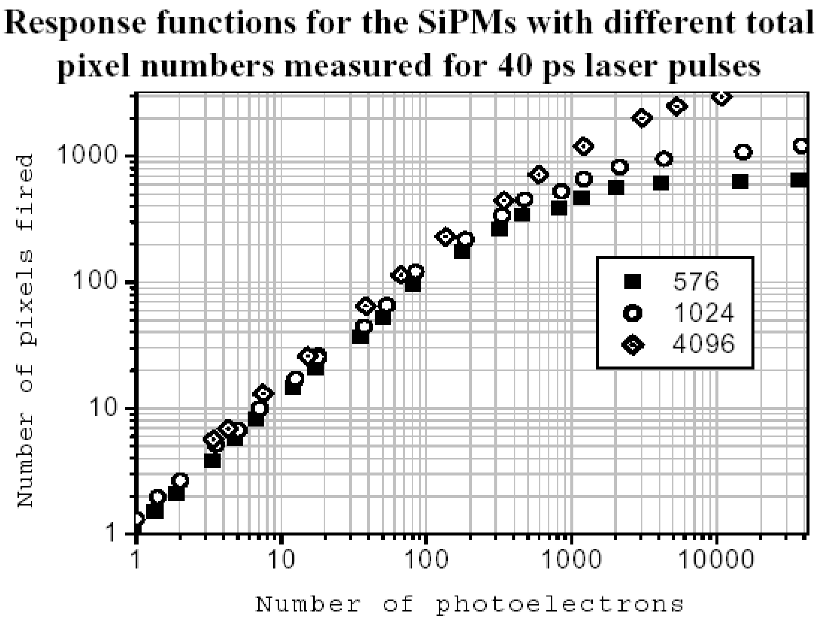
# Linearity and dynamic range

SiPM linearity is determined by its total number of cells

In the case of uniform illumination:

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

This equation is correct for light pulses which are shorter than pixel recovery time, and for an “ideal” SiPM (no cross-talk and no after-pulsing)



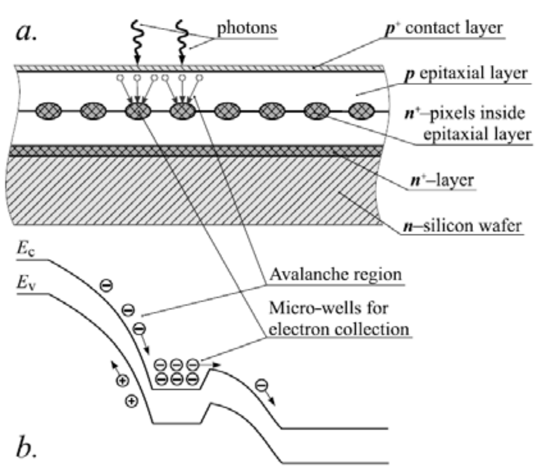

*(B. Dolgoshein, TRD05, Bari)*

*More cells/area needed for large dynamic range*

# Large dynamic range Micro-pixel APDs from Zecotek

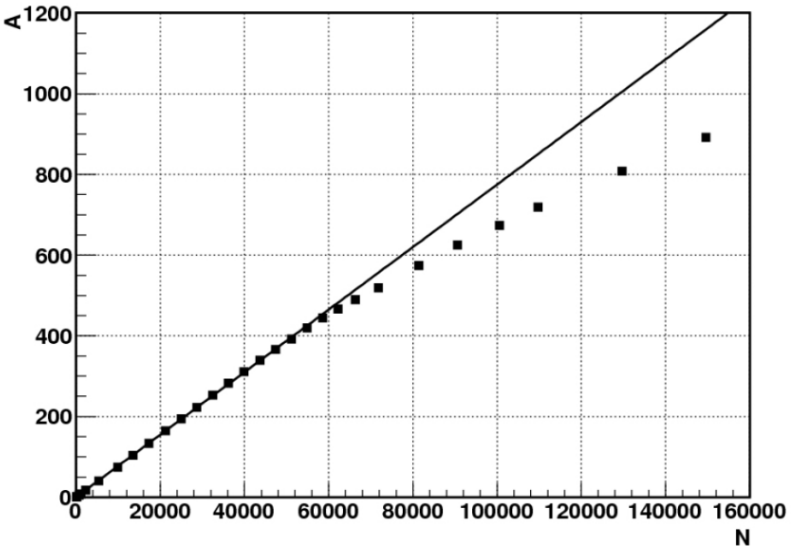
Micro-well structure with multiplication regions located in front of the wells at 2-3 µm depth was developed by Z. Sadygov. MAPDs with 10 000 – 40 000 cells/mm$^2$ and up to 3x3 mm$^2$ in area were produced by Zecotek (Singapore).

Schematic structure (a) and zone diagram (b) of Micro-pixel APD (MAPD)




This structure doesn't contain quenching resistors. Specially designed potential barriers are used to quench the avalanches.

Dependence of the MAPD (135 000 cells, 3x3 mm$^2$ area) signal amplitude A (in relative units) on a number of incident photons N




***(Z. Sadygov et al, arXiv;1001.3050)***

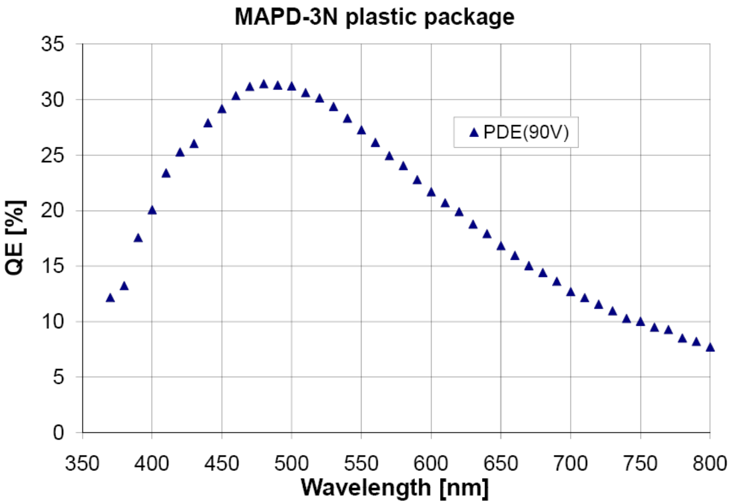
# Micro-pixel APDs for the CMS HCAL Upgrade

MAPD (3N type) with 15 000 cells/mm$^2$ and 3x3 mm$^2$ in area produced by Zecotek for the CMS HCAL Upgrade project.

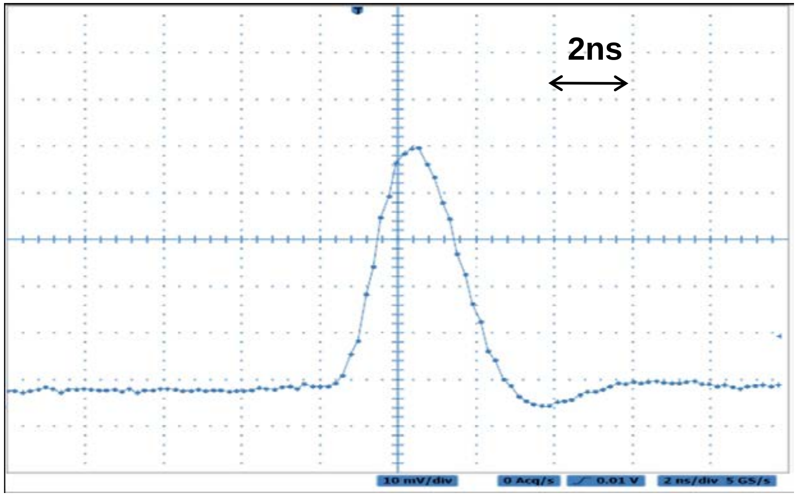
Linear array of MAPDs (18x1 mm$^2$ , 15 000 cells/mm$^2$ ) produced by Zecotek for the CMS HCAL Upgrade project.

Dark count rate is ~300-500 kHz/mm$^2$ at T=22 C

PDE vs. wavelength



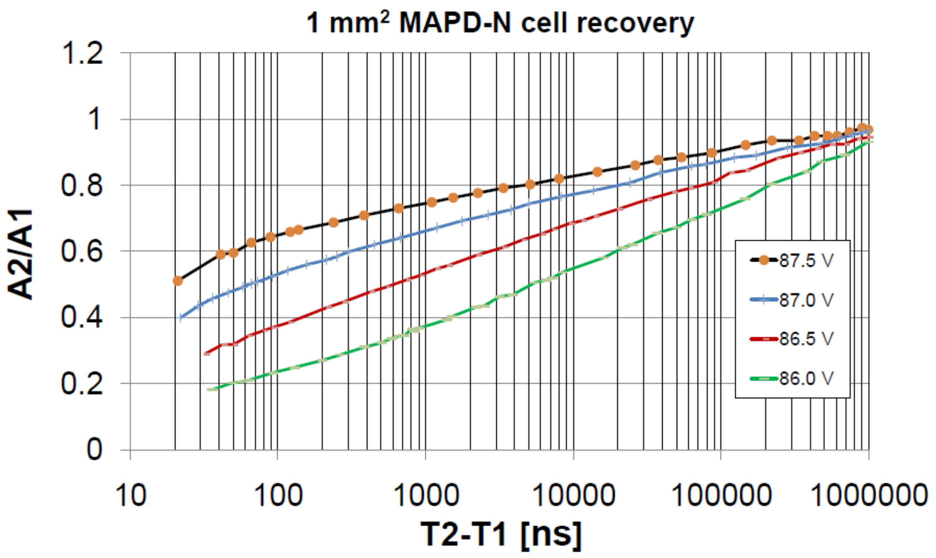

1 mm$^2$ MAPD response to a 35 psec (FWHM) laser pulse



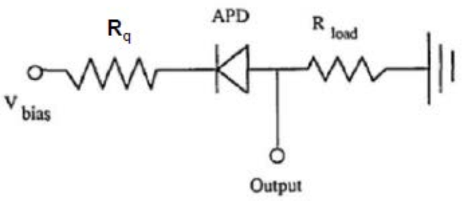
# MAPD cell recovery

MAPD cell recovery is not exponential

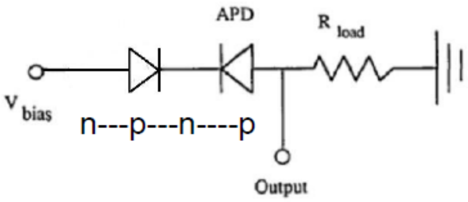
MAPD (3N type) cell recovery (measured using 2 LED technique)



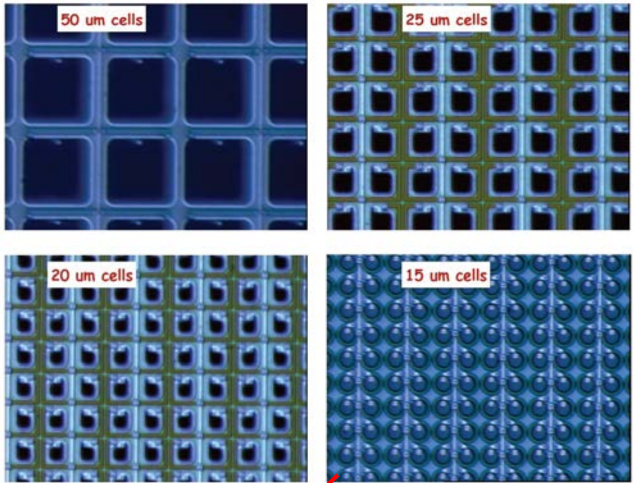

SiPM cell equivalent circuit

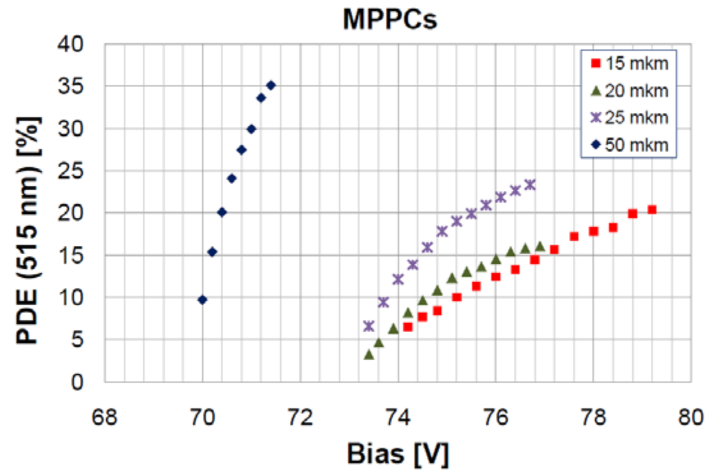



MAPD cell equivalent circuit

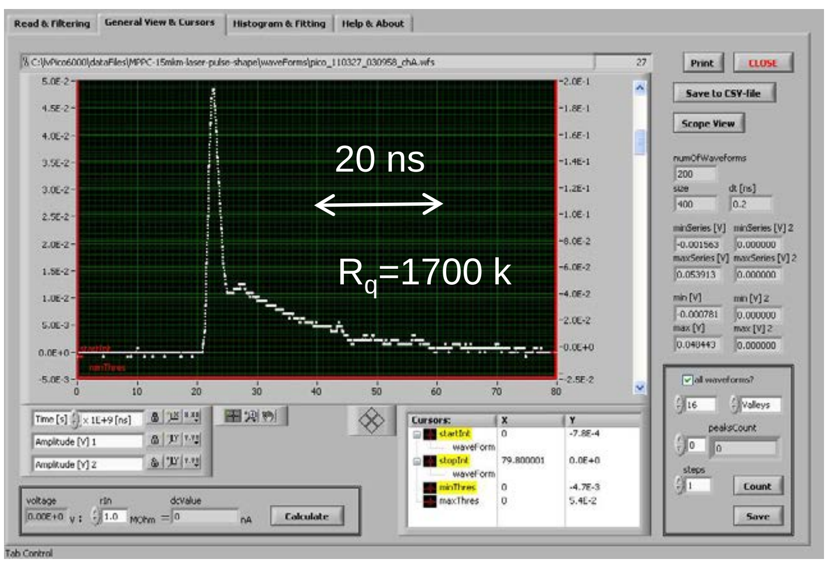


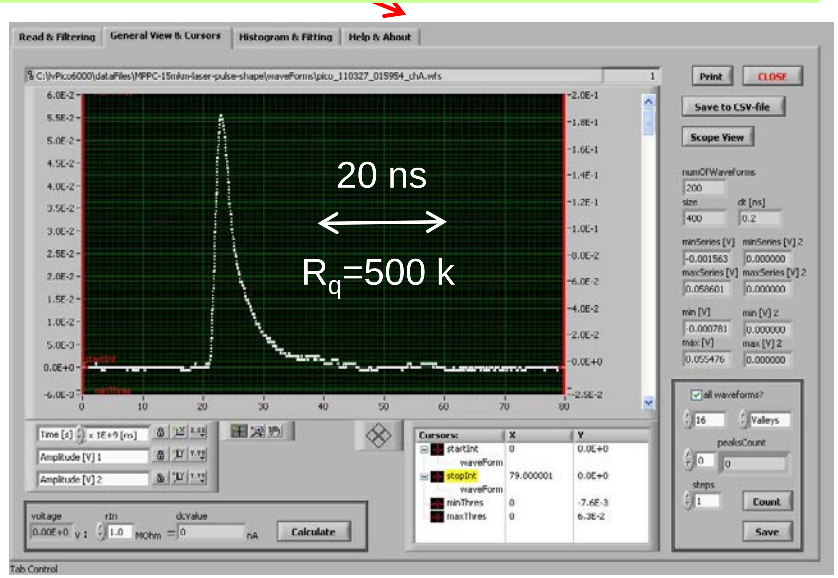
# Large dynamic range MPPCs (Hamamatsu)




**MPPC (15 μm cell pitch) responses to a fast (35 psec FWHM) laser pulse**



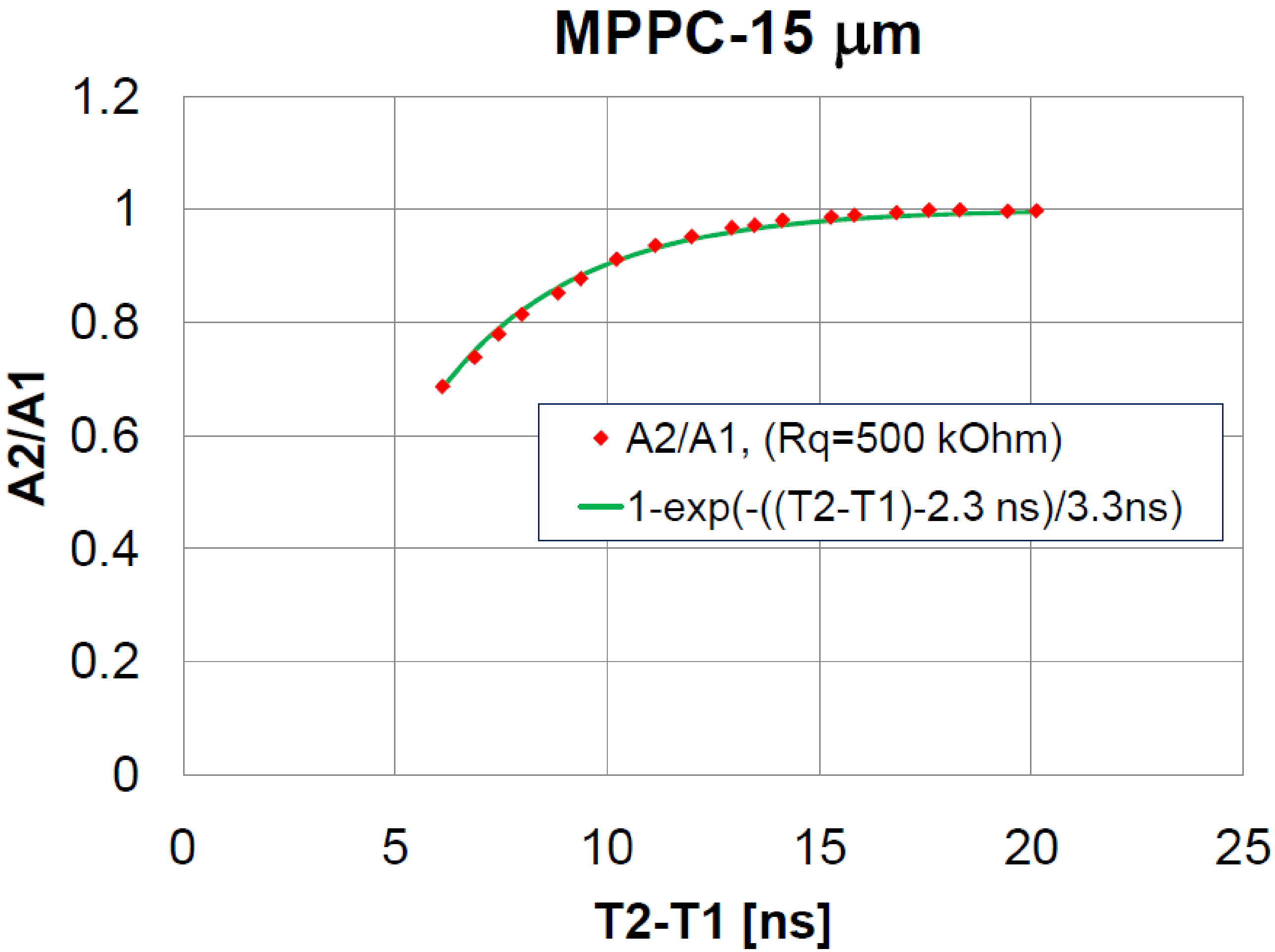



# New MPPC parameters

| MPPC type | # cells $1/mm^2$ | C, pF | $R_{cell}$, kOhm | $C_{cell}$, fF | $\tau=R_c x C_c$, ns | VB, V T=23 C | $V_{op}$, V T=23 C | Gain(at $V_{op}$), $X10^5$ |
|---|---|---|---|---|---|---|---|---|
| 15 μm pitch | 4489 | 30 | 1700 | 7 | 11.9 | 72.75 | 76.4 | 2.0 |
| 15 μm pitch | 4489 | 30 | 500 | 7 | 3.5 | 73.05 | 76.7 | 2.0 |
| 25 μm pitch | 1600 | 32 | 301 | 20 | 6.0 | 72.95 | 74.75 | 2.75 |
| 50 μm pitch | 400 | 36 | 141 | 90 | 12.7 | 69.6 | 70.75 | 7.5 |

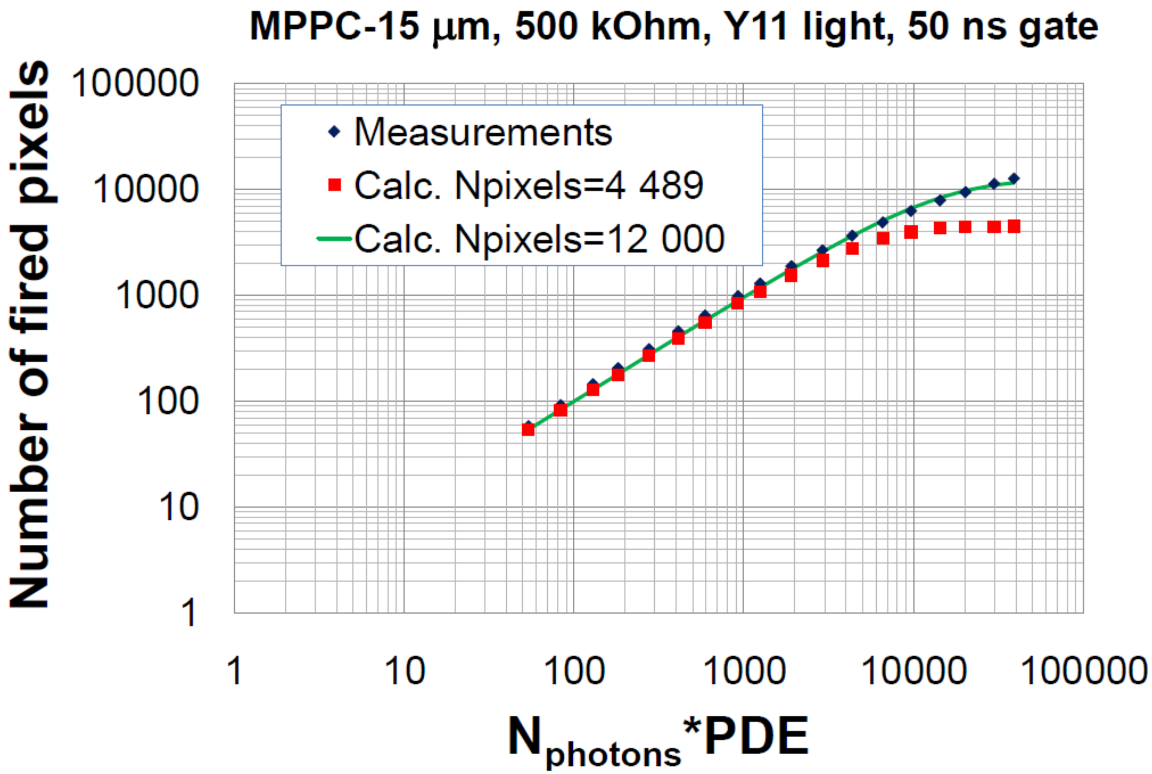
Fast cell recovery time improves SiPM's dynamic range in case of slow signals

# $R_q$=500 kOhm cell recovery




99% cell recovery after ~15 ns

# SiPM linearity measurements (MPPC with 4 500 cells)

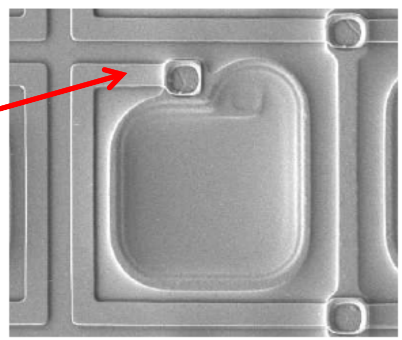



For Y11 light (emission time ~10 ns) MPPC works as a SiPM with 12 000 cells. Pixel recovery time constant: $\tau$~3.3 ns.

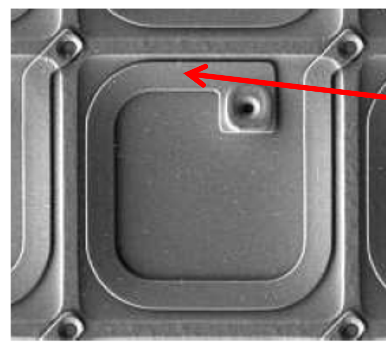
# MPPCs with Metal Quenching Resistors

In the newly developed line of MPPCs, MQRs are used instead of poly-Si for quenching. MQR has a high transmittance which allows for it to be put directly on the photosensitive surface to achieve a higher fill factor without reducing the sensitivity of the MPPC

SEM images of a MPPC which has 25 μm micro-cell pitches.



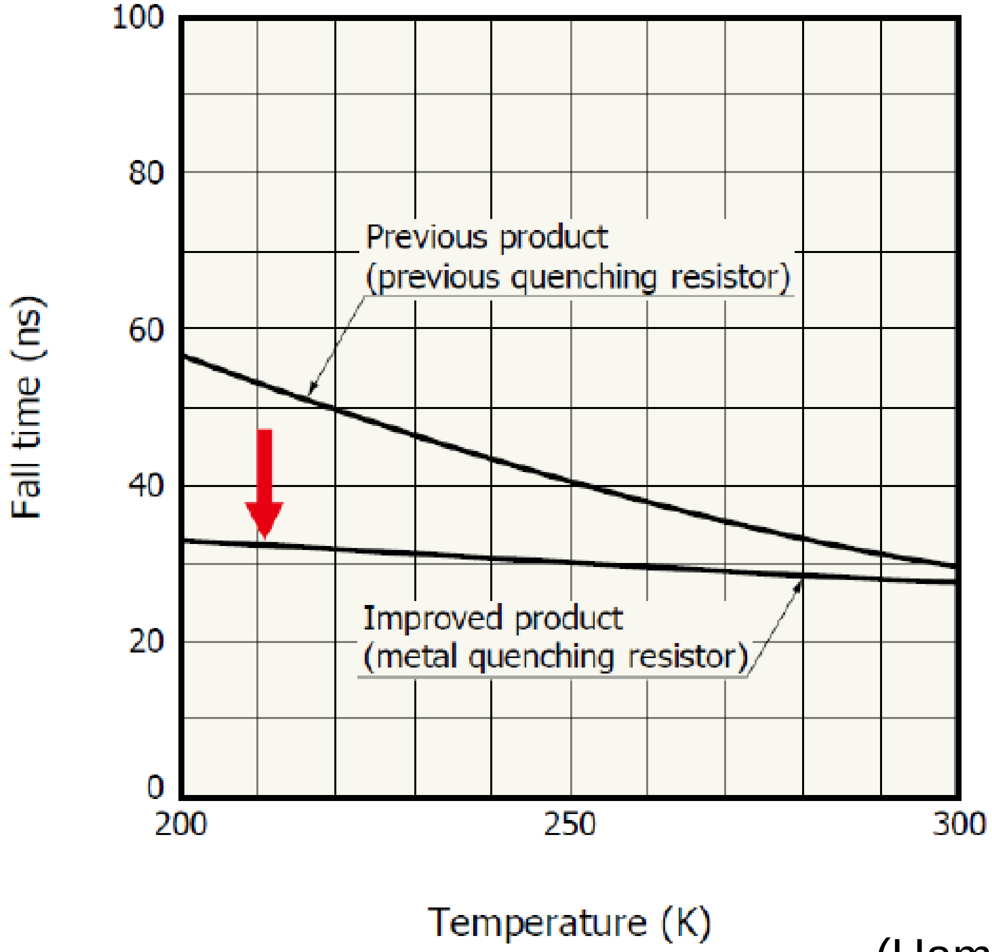
Poly-Si resistors



Metal resistors

(K.Sato et. al, IEEE NSS-MIC 2013 Conf. record)

# Recovery time vs. temperature dependence




(Hamamatsu Technical info.)

Metal resistor has small temperature dependence → weak recovery time vs. temperature dependence

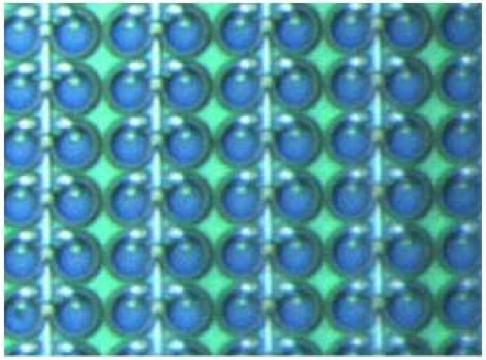
# Hamamastu SiPM development in 2012

• New 15 μm cell pitch MPPCs with MQR were developed for the CMS HCAL Upgrade project. Types B/C have standard structure (similar to 2011). Types A has a modified structure (MQRs).

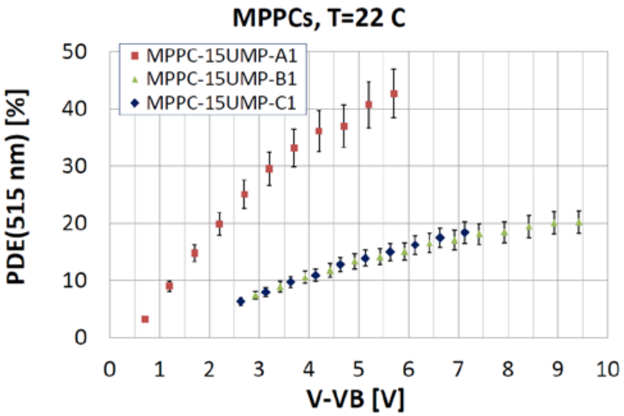
Atype-15 Micron

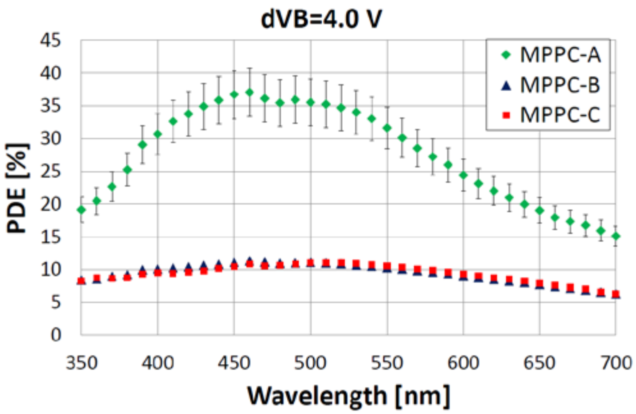
Metal resistors

B/Ctype-15 Micron



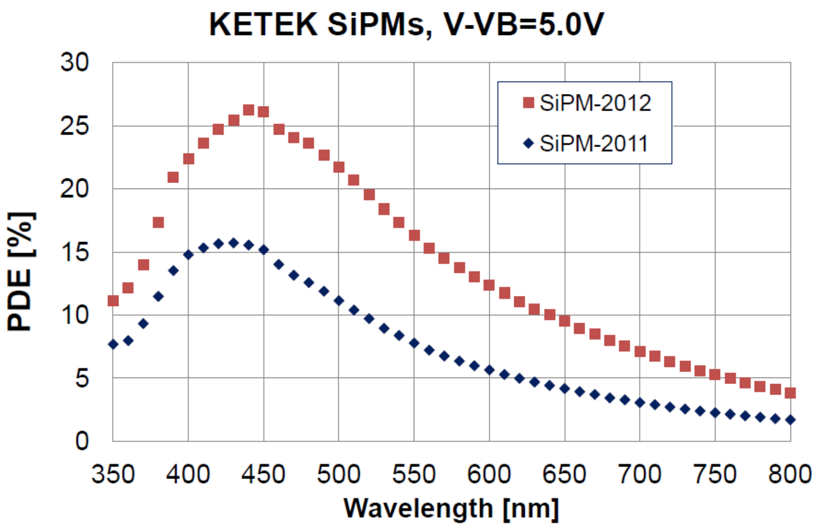
Poly-Si resistors

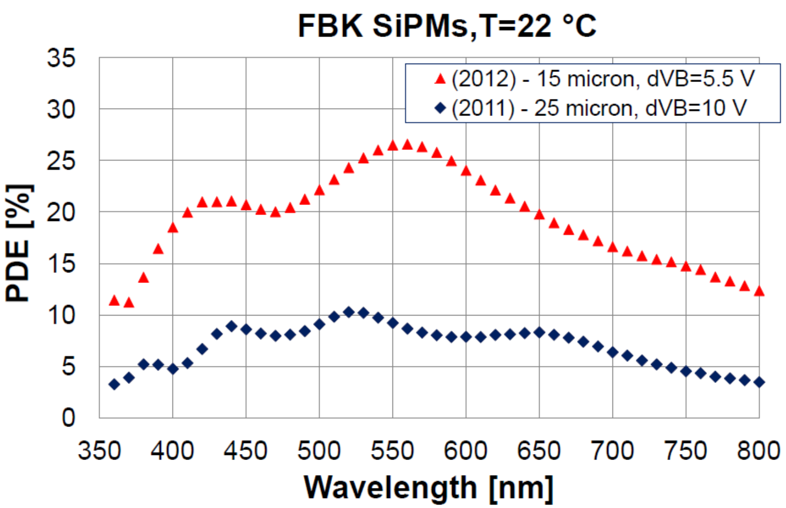



PDE(515 nm)>30% for 2012 15 μm cell pitch MPPCs (with MQRs). It was improved by a factor of >3 in comparison to the 2011 15 μm cell pitch MPPCs.

# KETEK and FBK large dynamic range SiPM development for the CMS HCAL Upgrade




PDE(515 nm) for 15 cell pitch SiPMs was improved by a factor of 2 (SiPM with additional 0.8 μm epi-layer and deep p-n junction)

PDE(515 nm)>20% for 2012 15 μm cell pitch SiPMs. It was improved by a factor of >2 in comparison to the 2011 25 μm cell pitch SiPM.

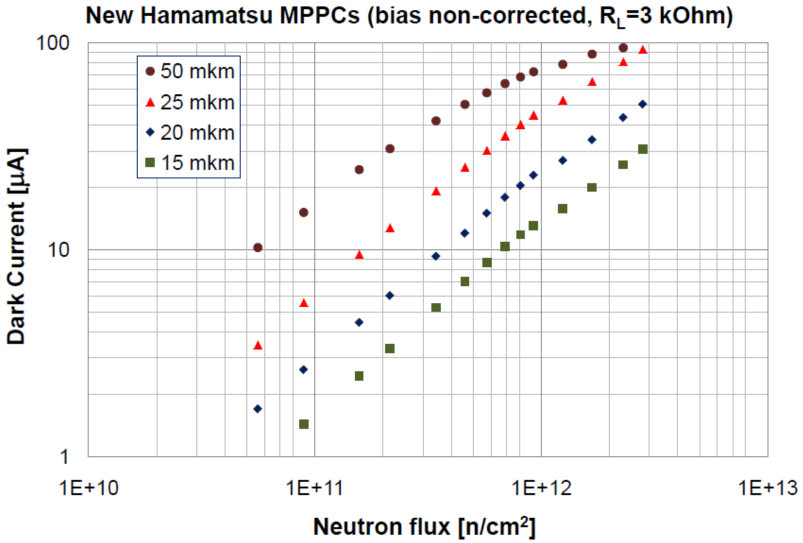
# Radiation hardness studies

Motivation:  SiPMs will be used in HEP experiments

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

# 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:

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

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

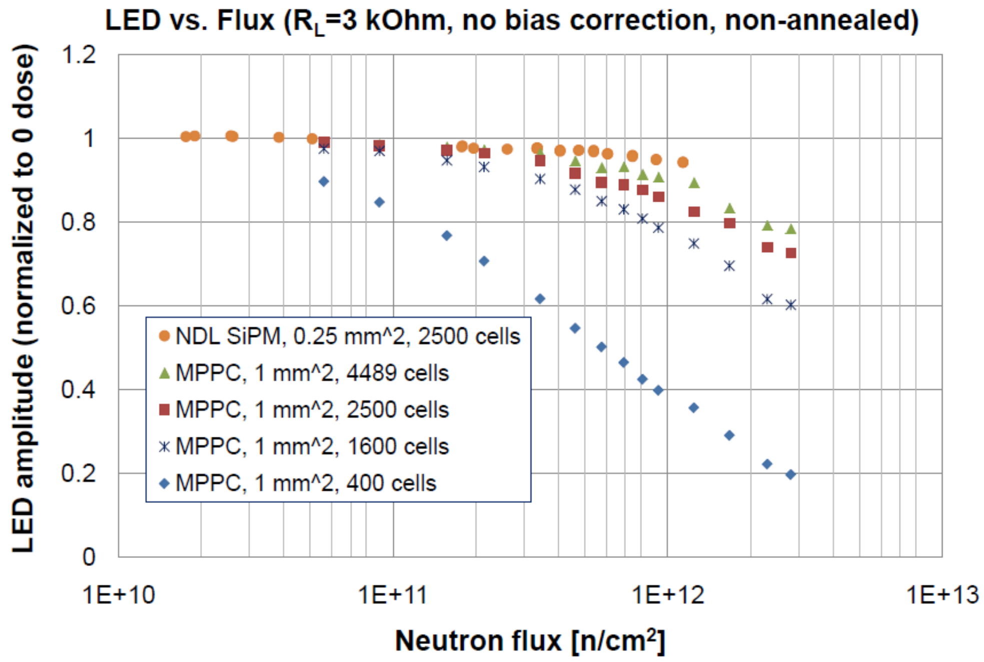
$\alpha_{Si}$ ~4*10$^{-17}$ A*cm after 80 min annealing at T=60 C (measured at T=20 C)

- No change of VB (within 50 mV accuracy)
- No change of $R_{cell}$ (within 5% accuracy)
- Dark current and dark count significantly increased for all the devices

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

For Hamamatsu MPPCs : $d_{eff}$ ~ 4 - 8 μm

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

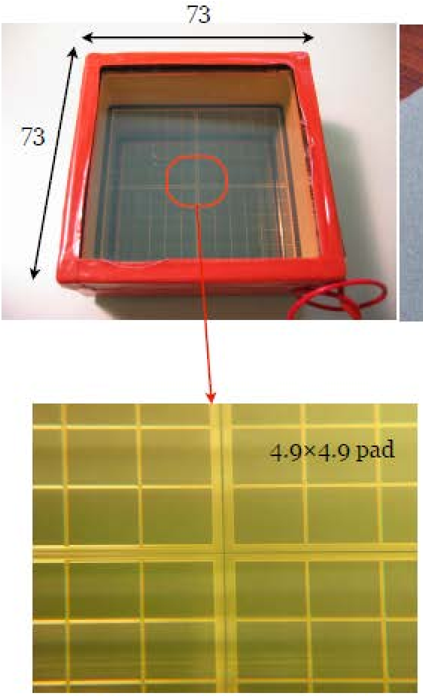



SiPMs with high cell density and fast recovery time can operate up to $3*10^{12}$ neutrons/cm$^2$ (gain change is< 25%).

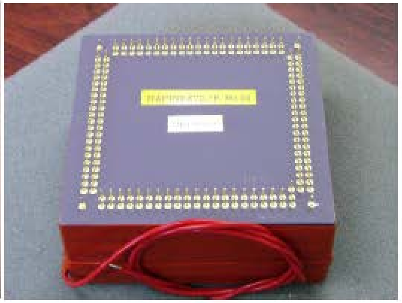
# HPDs/HAPDs

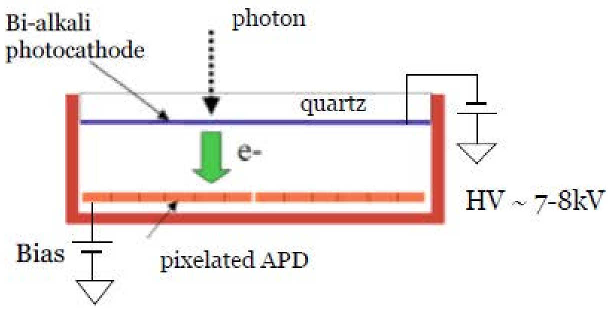
# Hybrid Avalanche Photo-detector (HAPD)

144 ch. HAPD developed by Hamamatsu for Belle II proximity focusing RICH counter with silica aerogel radiator




4 pixelated APDs are housed



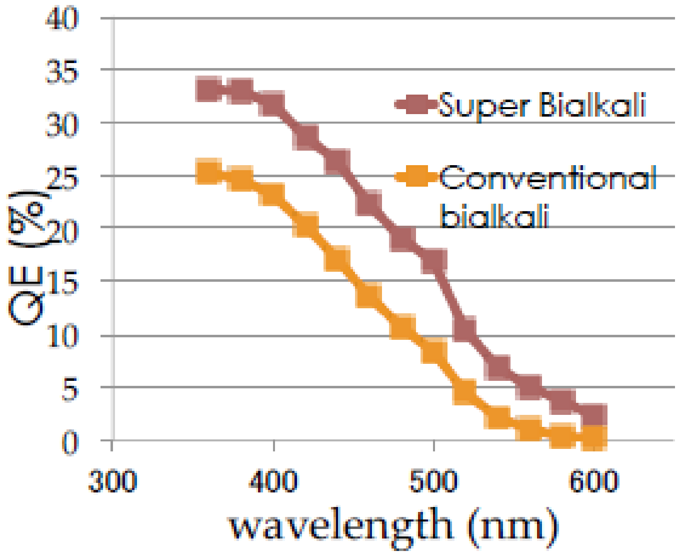


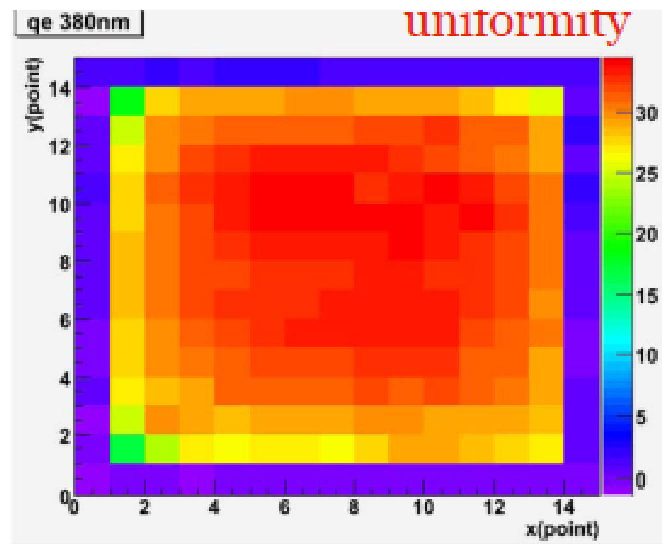

Specifications

| | |
|---|---|
| package | 73×73mm² |
| sensitive area | 64% |
| # of pixels | 144(36×4chips) |
| capacitance | 80pF |
| weight | 220g |
| peak QE | 27~31% |
| bombardment gain | 1300~1500 |
| avalanche gain | ~50 |
| total gain | ~$10^5$ |

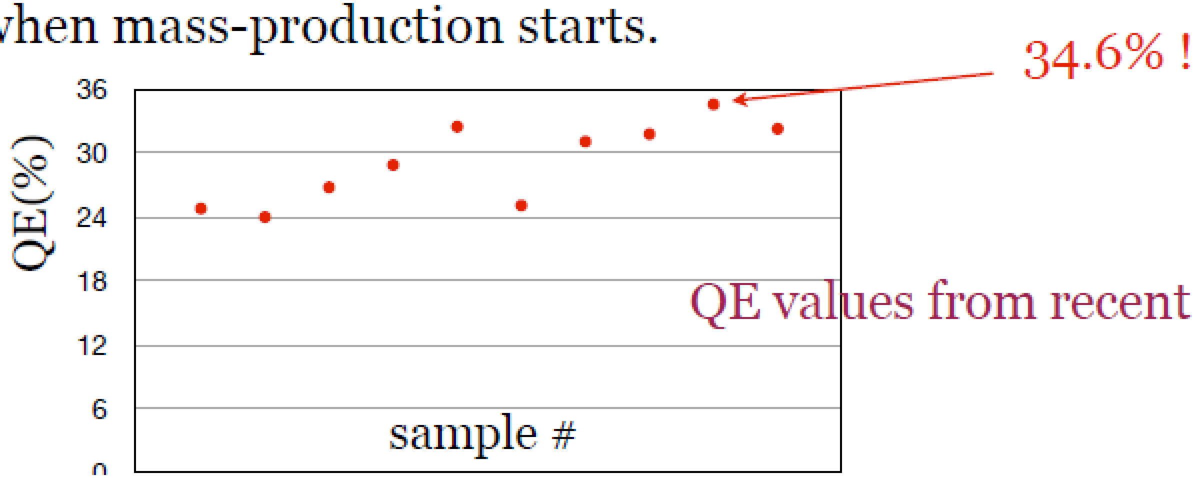
(I.Adachi, PhotoDet 2012)

# HAPD Quantum Efficiency




HAPD samples show ~35 % at the best. Expect more stable and high values when mass-production starts.

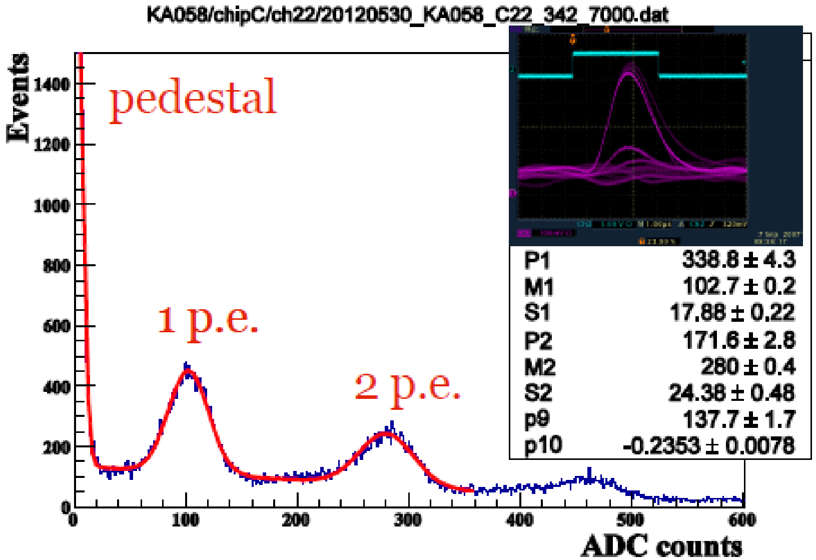



QE values from recent HAPDs

(I.Adachi, PhotoDet 2012)

# HAPD Single Photon Response

pulse heigh distribution




$\sigma_{pedestal} = 2.9\times10^3$ electrons

Gain $= 8.2\times10^4$

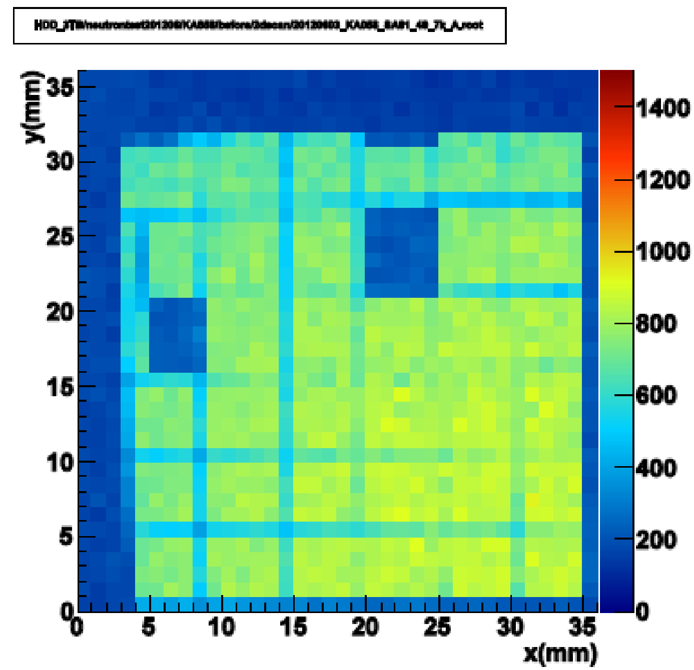
from 1 and 2 p.e. peaks

$S/N = G/\sigma_{pedestal} \sim 28$

blue LED illuminated

HV: -7kV bias: 342V

1 APD uniformity scan

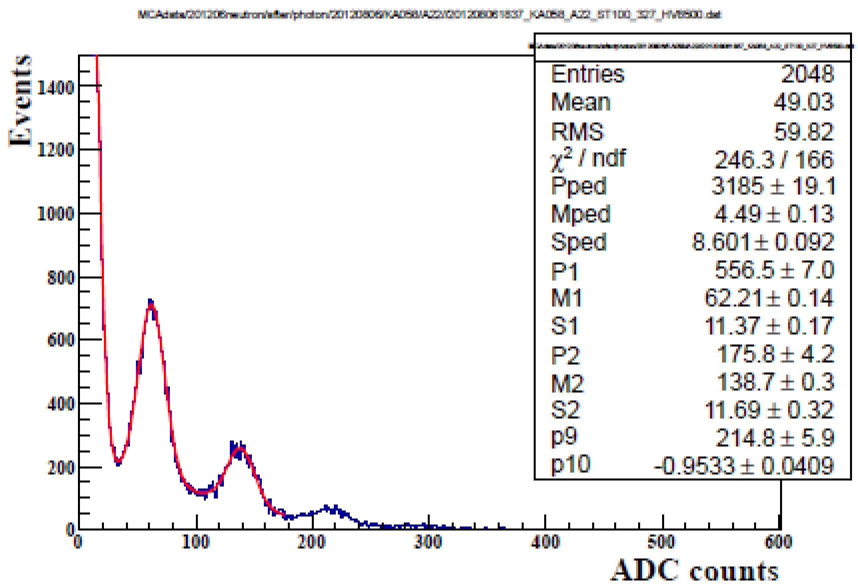



Clear single photon signal observed !

(I.Adachi, PhotoDet 2012)

# Neutron radiation damage

HAPD samples were irradiated up to $10^{12}$ n/cm$^2$ at the JPARC MLF BL10 beam facility




(I.Adachi, PhotoDet 2012)

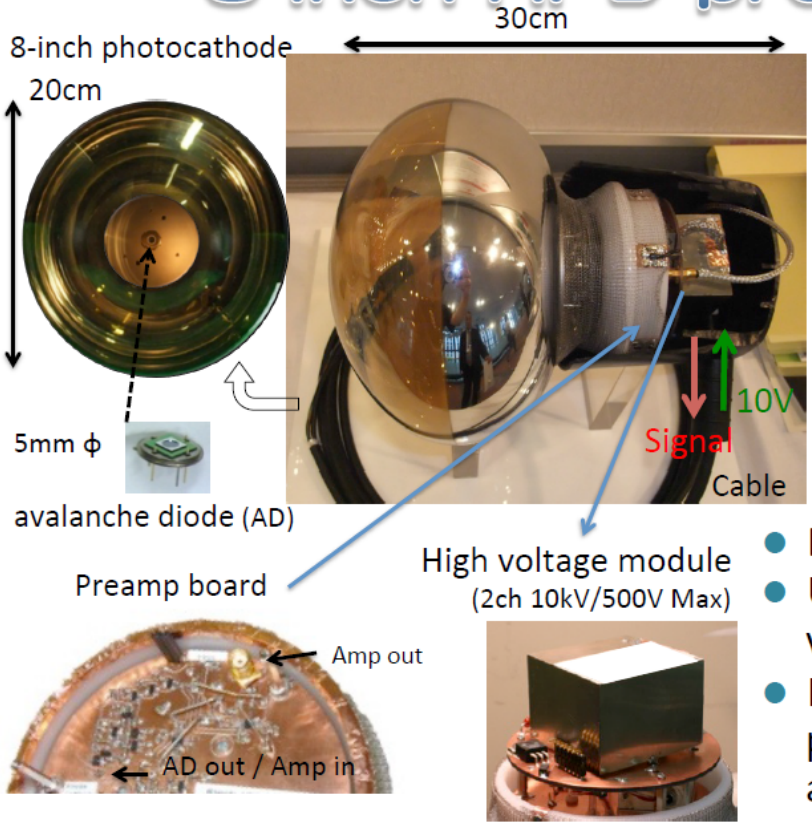
Single-photon signal 30 days after neutron irradiation test.

Sufficient single-photon sensitivity is still retained after $10^{12}$ n/cm$^2$

# Large-Aperture HAPD for Hyper-Kamiokande

Hyper-Kamiokande ~1 Mton water Cherenkov detector needs low cost, high performance large aperture photodetector

## 8-inch HPD prototype




### Specification

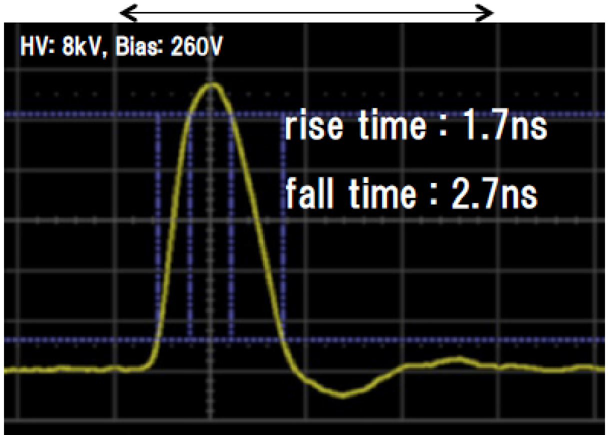
| | | |
|---|---|---|
| Spectral response | | 300 - 650 (420 max.) nm |
| Photocathode | | Bialkali |
| Window material | | Borosilicate glass |
| Gain | | 4 - 9 x$10^4$ |
| Time | Rise | 1.7 ns |
| | Fall | 2.7 ns |
| | T.T.S. | 0.62 ns (σ) |
| Dynamic range | | 100 pC (1.5x$10^4$ p.e.) |

- By Hamamatsu Photonics
- Use in water without high voltage line.
- HV module and preamplifier are packed and waterproofed.

(Y. Nishimura, IEEE NSS-MIC 2013)

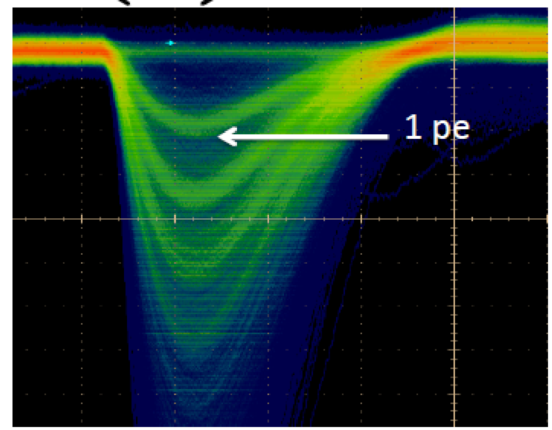
# Single Photon Response

Output of HPD 20 ns




Timing resolution 0.62 ns σ

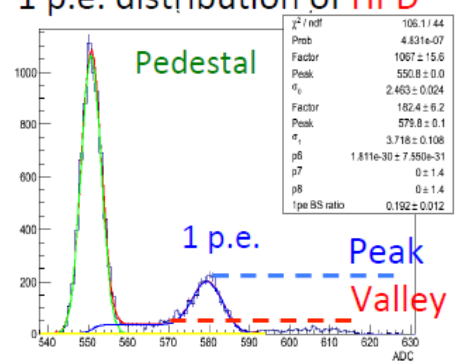
20 ns Output of amplifier



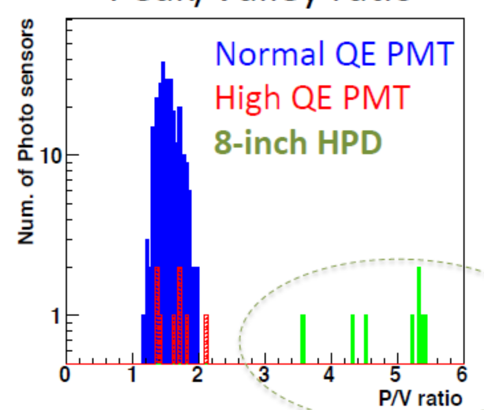

1.2 ns σ

(Y. Nishimura, IEEE NSS-MIC 2013)

1 p.e. distribution of HPD




Peak/Valley ratio

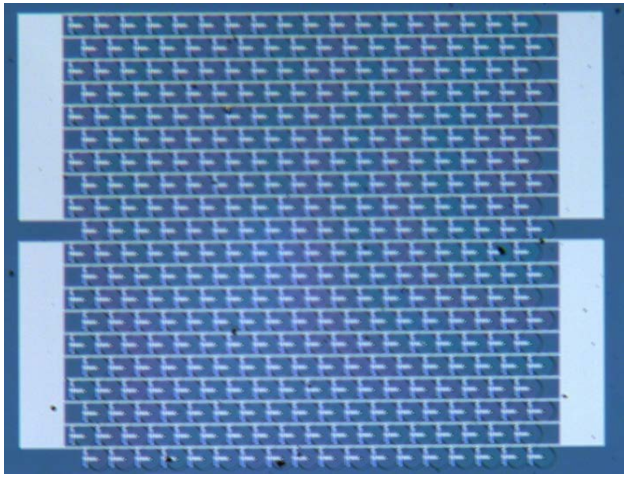



Results are very encouraging. 20 inch HAPD is under development!

# GaAs SSPMs

# GaAs SSPM

LightSpin's GaAs Photomultiplier Chip™

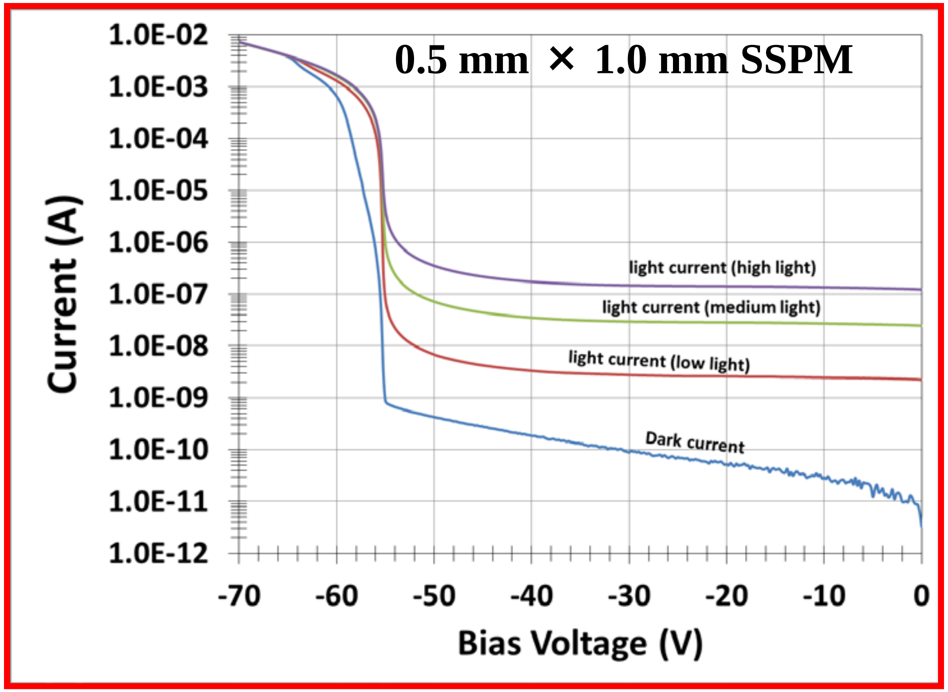


Array of single-photon avalanche devices (SPADs): 2x0.5mmx1 mm, 360 SPADs/mm$^2$

Developed for the CMS HCAL Upgrade Phase II Project:

University of Virginia

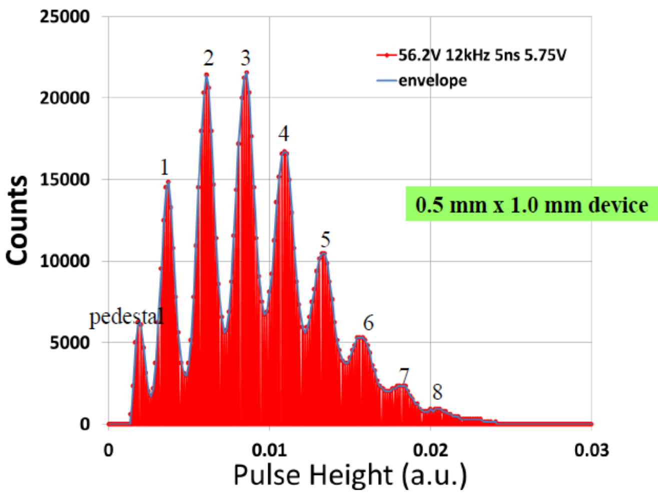
LightSpin Technologies, Inc.



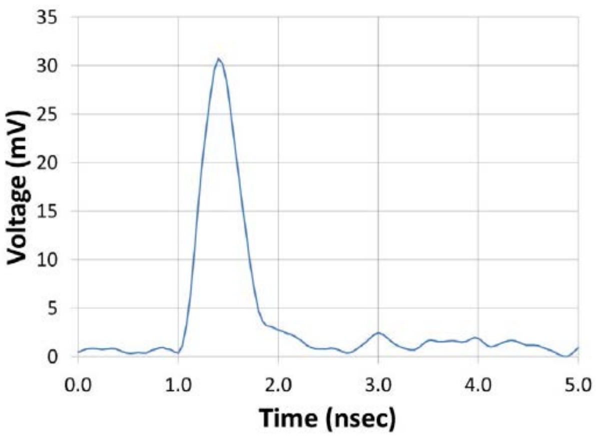

$E_g$(GaAs)~1.4 eV ($E_g$(Si)~1.1 eV) → potentially smaller DC after irradiation? Very high electron mobility → fast timing?

# GaAs SSPM parameters - I

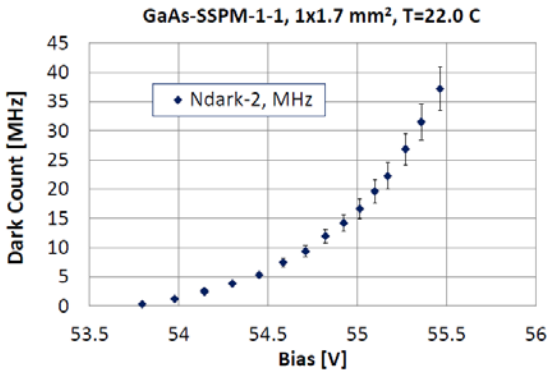
B. Cox
May 24, 2012



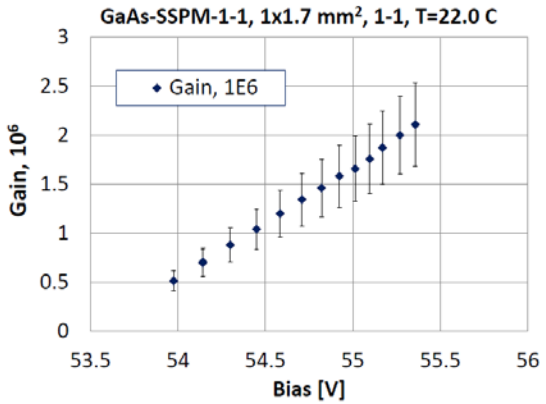

Pulse Height Spectrum




Single Photon pulse from GaAs SPAD

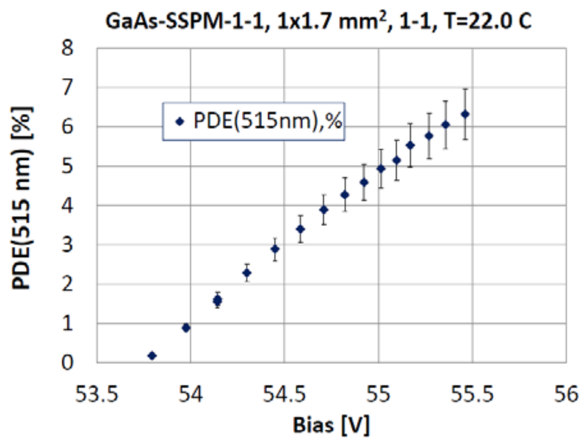



Dark Count vs. Bias

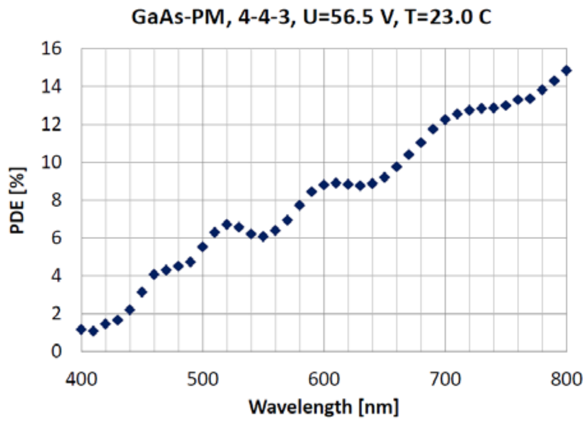



Gain vs. Bias

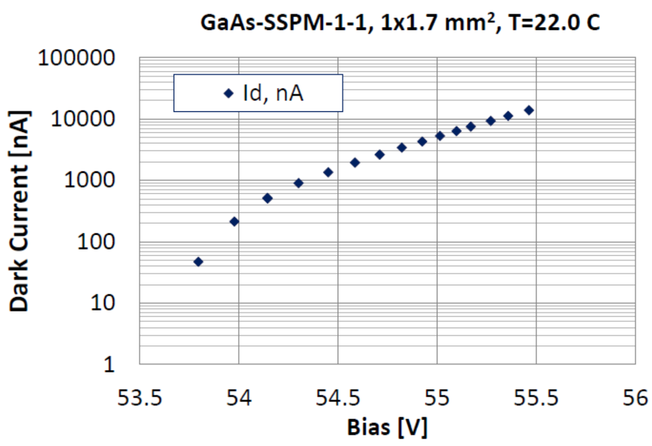
# GaAs SSPM 1x1.7 mm$^2$



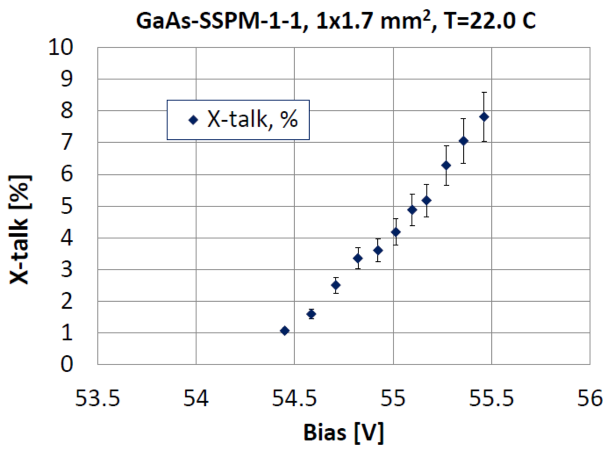

**PDE vs. Bias**




**PDE vs. wavelength (U=56.5 V)**




**Dark Current vs. Bias**




**X-talk vs. Bias**

# Summary

***Significant progress in development of SSPMs over last 2-3 years:***

- High PDE~50-65% for blue-green light (KETEK and Hamamatsu)
- Reduction of dark count at room temperature ~50-100 kHz/mm$^2$, (Hamamastu, KETEK, Philips, Exelitas)
- Low cross-talk (<1-3%, CPTA/Photonique, STMicroelectronics, KETEK, Hamamatsu)
- Low temperature coefficient (~0.3-0.5%/C – CPTA, Philips, KETEK)
- Fast timing (~50 ps (RMS) for single photons)
- Large dynamic range (>4 000 pixels/mm$^2$, Zecotek, NDL, KETEK, Hamamatsu)
- Large area (≥6x6 mm$^2$ - Hamamatsu, FBK, SensL, STMicroelectronics KETEK, Philips …)
- SiPM arrays: 8x8, 0.25x128 …
- GaAs SSPMs were developed. InGaP SSPMs will be produced soon

***All this (together with good understanding of radiation hardness issues) makes these devices excellent candidates for applications in HEP experiments, astroparticle physics and in medicine (PET, MRI/PET, CT …)***

# Future of SiPM development

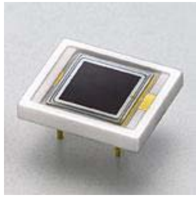
The development of SiPMs is accelerating. What can we expect in 2-4 years from now?

- PDE > 70% for 350-650 nm light
- dark count rate <30 kHz/mm$^2$ at room temperature
- single photon timing < 50 psec (FWHM)
- active area >100 mm$^2$
- high DUV light sensitivity (PDE(128 nm~20-40%)
- radiation hard SiPMs - up to $10^{14}$ n/cm$^2$
- production cost <1 $/мм$^2$
- ….

## Thank you for your attention!

# Back-up

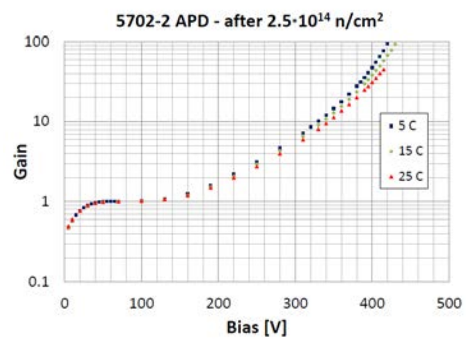
# APDs



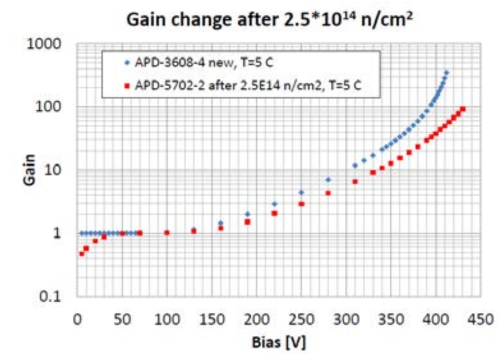
The CMS APD (produced by Hamamatsu ) was irradiated up to 2.5×10$^{14}$ n/cm² (1 MeV equivalent ).

**S8148 APD**

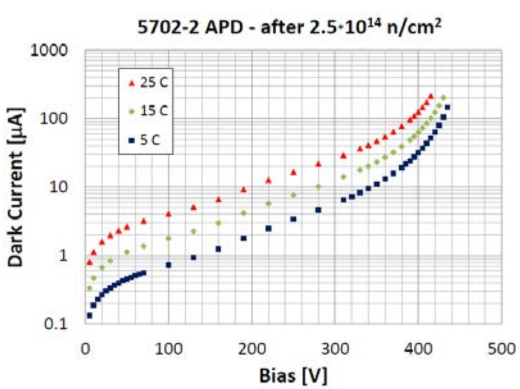
- Area: 5x5 mm$^2$
- $V_{op}$: 350-400 V
- Gain ($V_{op}$): 50
- QE(420nm): 75%
- Capacitance: 80 pF
- ENF(M=50): 2.2



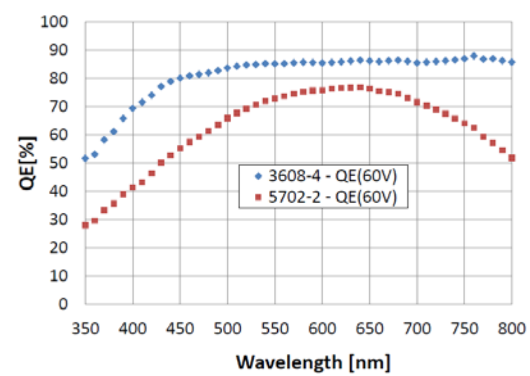

Gain vs. bias at T=25, 15 and 5 C




Gain vs. bias (new and irradiated)




Dark current vs. bias at T=25, 15 and 5 C

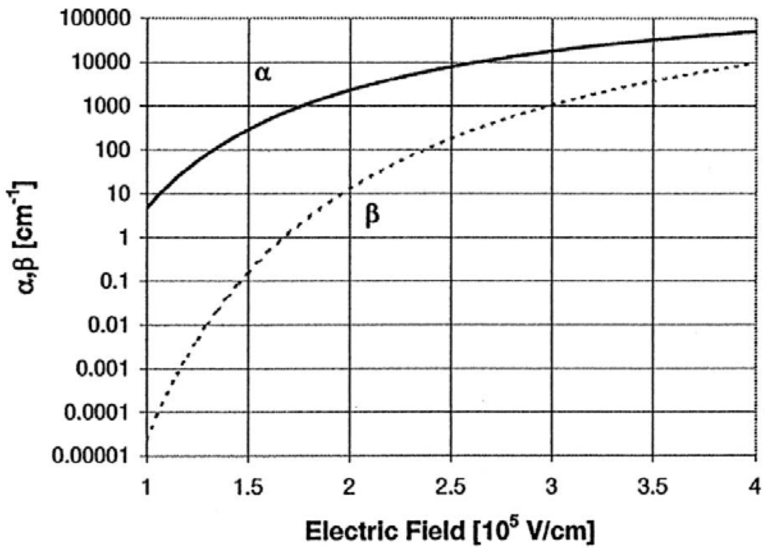


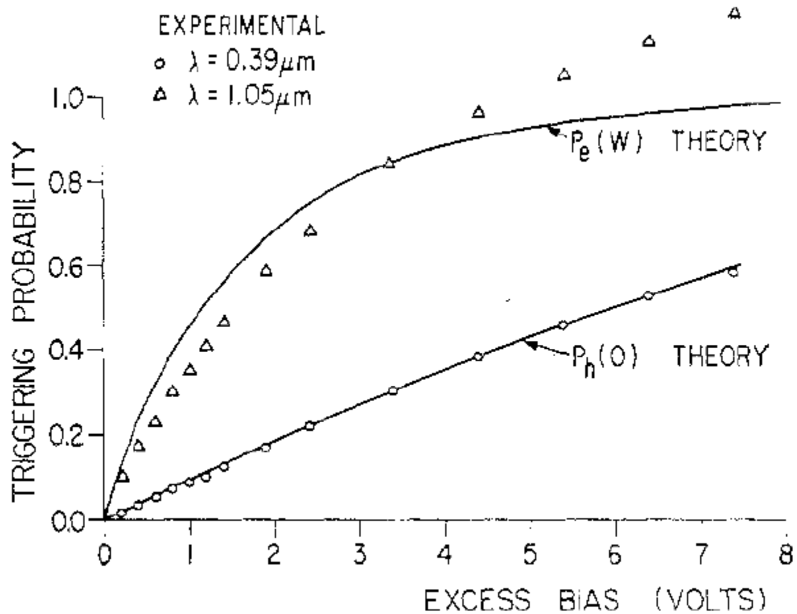

Quantum efficiency (new and after 2.5E14 n/cm$^2$, Gain=1)

APD irradiated with 2.5*10$^{14}$ n/cm$^2$ is still operational as a light detector with gain>50 at T<15 C

# Breakdown initiation probability

Ionization coefficients for electrons and holes in silicon




IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. ED-19, NO. 9, SEPTEMBER 1972

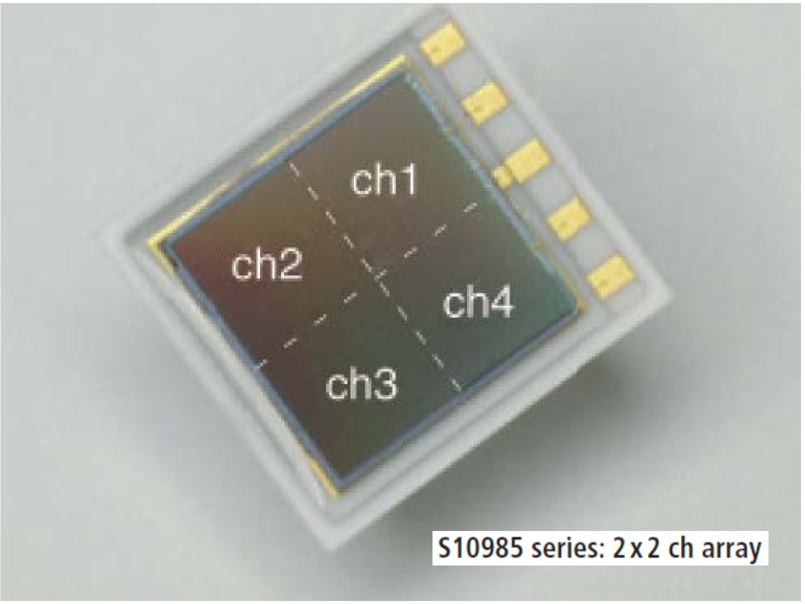
**Triggering Phenomena in Avalanche Diodes**

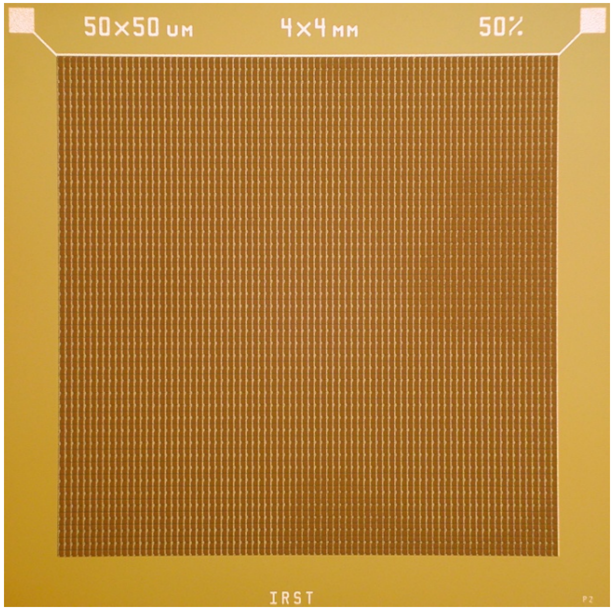
WILLIAM G. OLDHAM, MEMBER, IEEE, REID R. SAMUELSON, MEMBER, IEEE, AND PAOLO ANTOGNETTI, MEMBER, IEEE

Because of the higher ionization coefficient, the electron triggering probability is always higher than that for holes

# Large area SiPMs

SiPMs with ≥ 3x3 mm$^2$ sensitive area produced by many companies: Hamamatsu, CPTA, Pulsar, Zecotek, SensL, FBK, STMicro …




Hamamatsu MPPC, 6x6 mm$^2$, 14 400 cells

FBK SiPM, 4x4 mm$^2$, 6400 cells

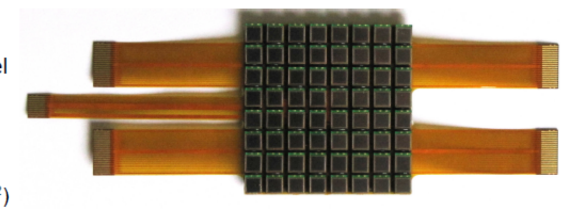
# SiPM arrays

SensL array for PET/MRI (16x9 мм$^2$)

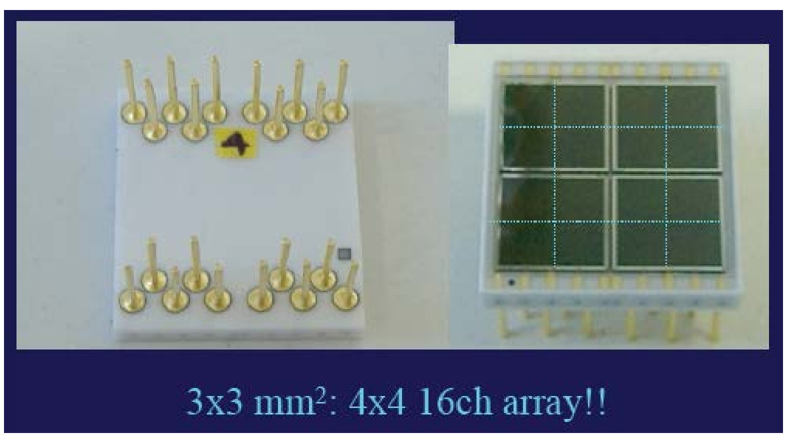
64 ch. MPPC array for RICH

**Array of SiPMs: Hamamatsu MPPC S11834-3388DF**

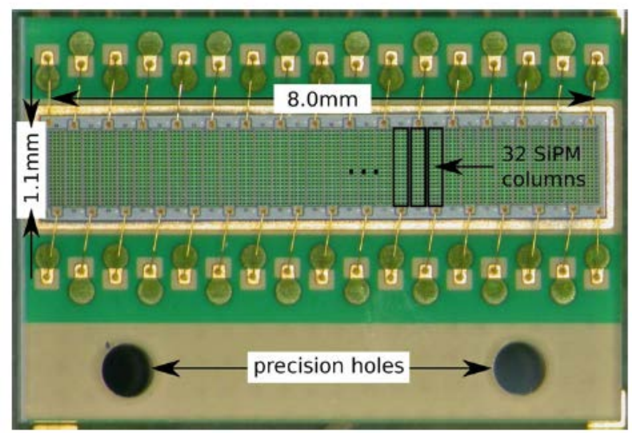
- Multi-pixel Photon Counter (MPPC) is a novel 8x8 SiPM array, each SiPM representing one 5x5 mm$^2$ channel
- Active area is large (3x3 mm$^2$)
- Pixel size: 50 µm
- Dark count rate is rather low (~$10^5$ Hz/mm$^2$)
- Operating voltage: (70 ± 10) V



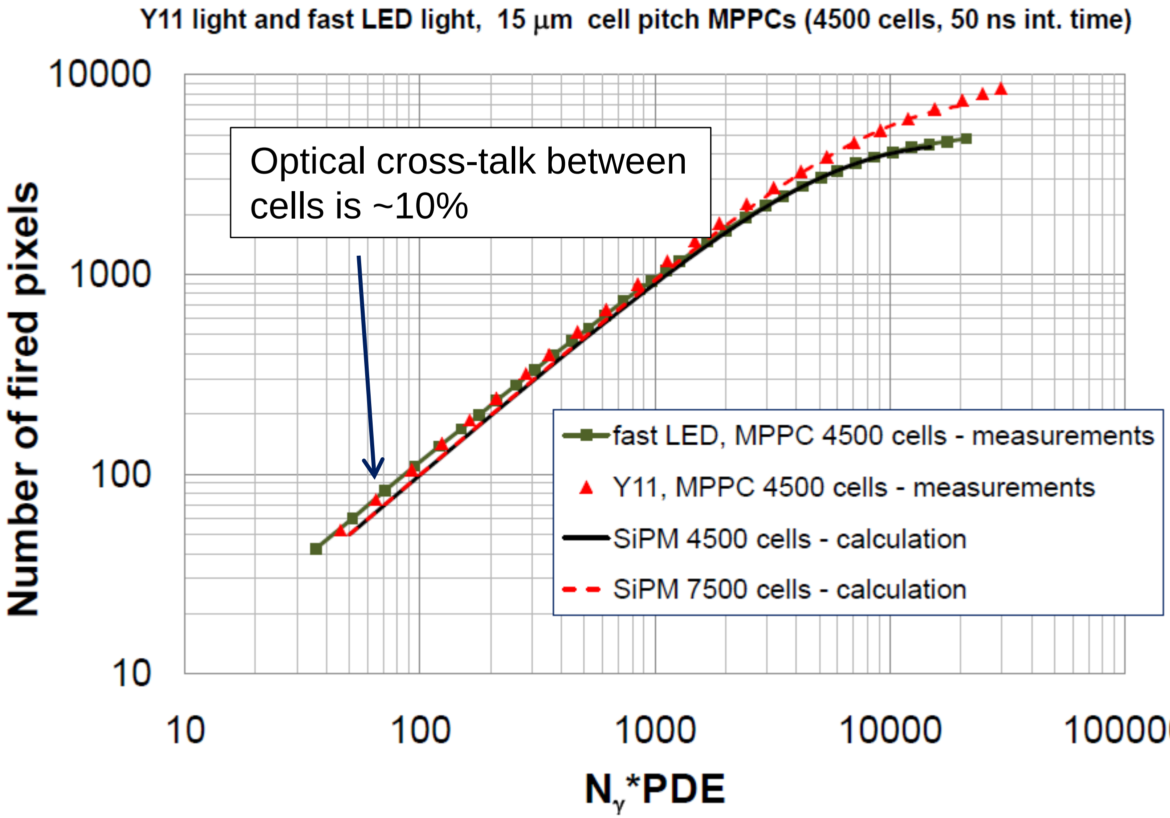
MPPC array for MAGIC telescope




MPPC array for PEBS scintillating fiber (250 µm Ø) сцинт. tracker
NIM A 622 (2010) 542)



# SiPM linearity measurements (MPPC with 4 500 cells)

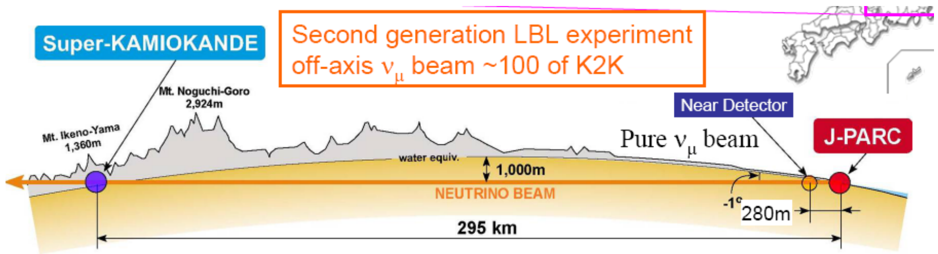


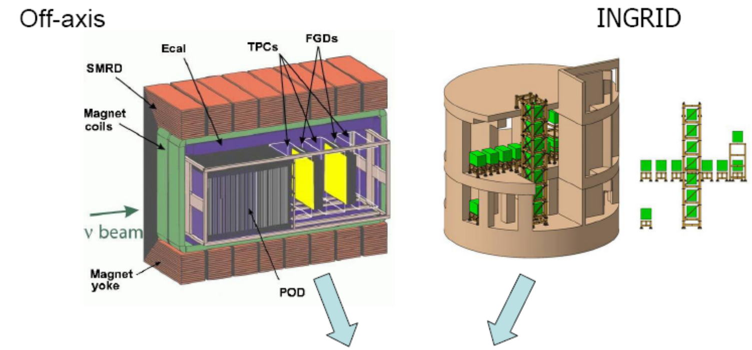

Fast LED light: the MPPC with 4 500 cells is equivalent to a SiPM with 4 500 cells.
Y11 light (emission time ~10 ns): the same MPPC works as a SiPM with 7 500 cells. Pixel recovery time constant: $\tau$~12 ns.

# SiPMs for HEP experiments

(SiPMs are used in large quantities now!)

# T2K neutrino experiment

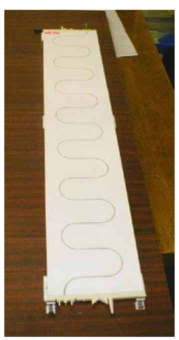



**Scintillator detectors with WLS fibers**
- **Individual fiber readout**
  **FGD, POD, Ecal, SMRD, INGRID: ~ 60000 readout channels**
- **Limited space for photosensors**
- **Magnetic field**

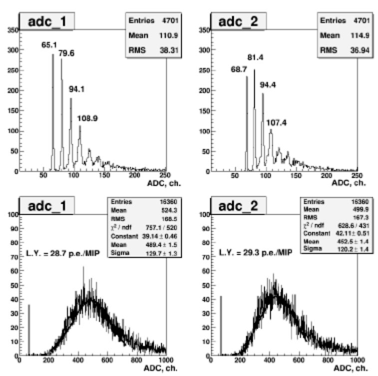
## SMRD detectors

Extruded plastics ~7x170x870 mm$^3$
Y11 fibers embedded in S-grooves



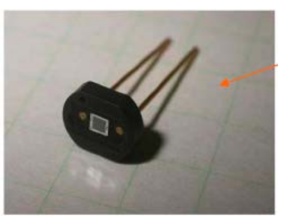
| | |
|---|---|
| **MIP detection efficiency** | **> 99.9%** |
| **$\sigma_t$ (MIP)** | **~ 0.7 ns** |
| **Spatial resolution** | **~ 7 cm** |

## Light yield




l.y. (sum of 2 ends) = 58 p.e./MIP

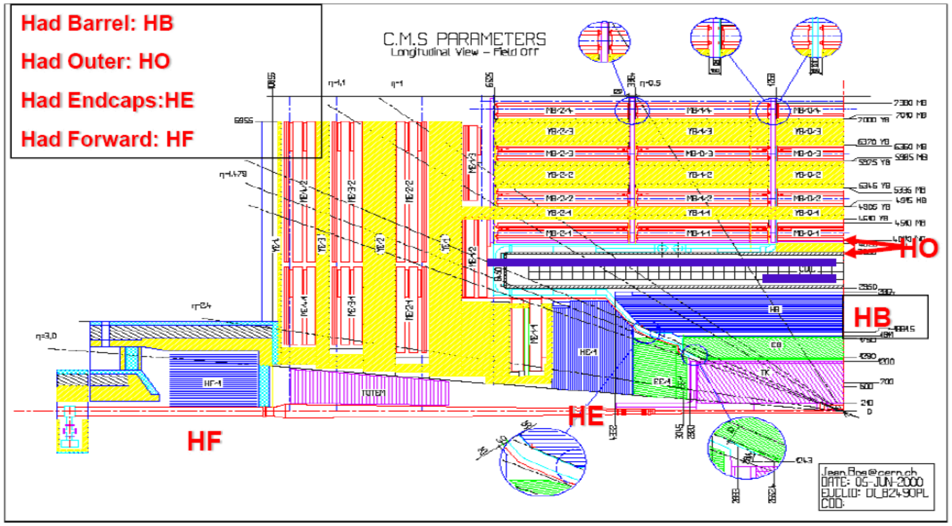
Hamamatsu MPPC: active area 1.3×1.3 mm$^2$



| | |
|---|---|
| Number of pixels | 667 |
| Pixel size | 50×50 μm |
| Gain | ~$0.7\times10^6$ |
| PDE at 525 nm | 25-30% |
| Dark rate, th = 0.5 p.e.,22C | ≤1000 kHz |
| Pulse width | <100 ns |
| Cross-talk | 10-15% |
| After pulses | 10-15% |

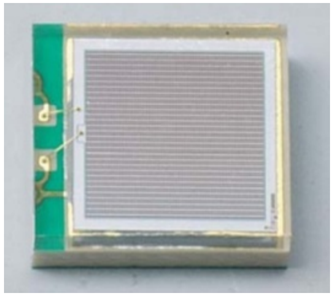
*(Yu. Kudenko, G-APD workshop, GSI, Feb. 2009)*

# MPPCs for the CMS HO HCAL




HO HPDs will be replaced with the MPPCs (3x3 mm$^2$, ~3 000 channels)

Hamamatsu 3x3 mm$^2$ MPPC



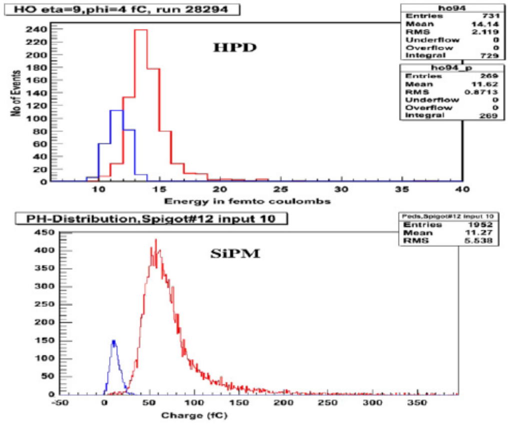
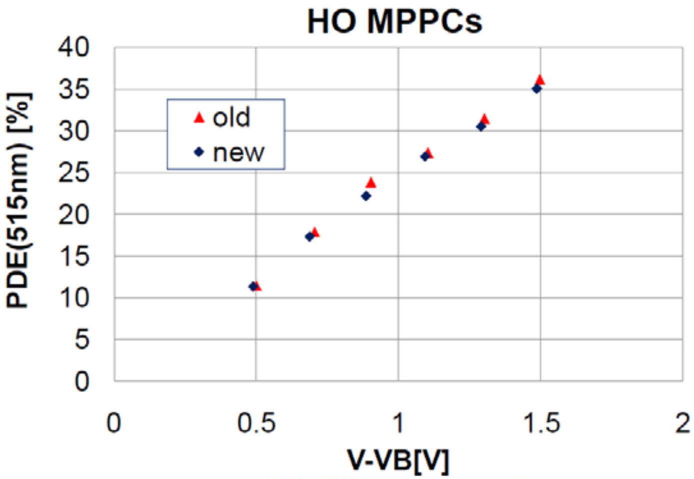


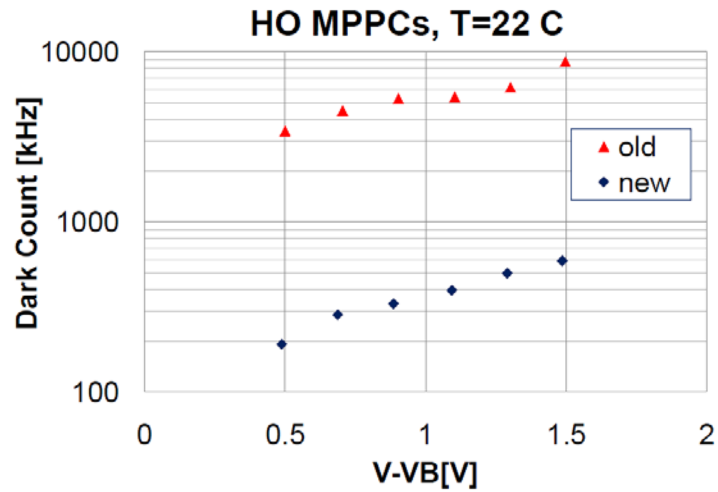

Fig. 3. Pedestal and muon signal distributions for HPD and SiPM [3].

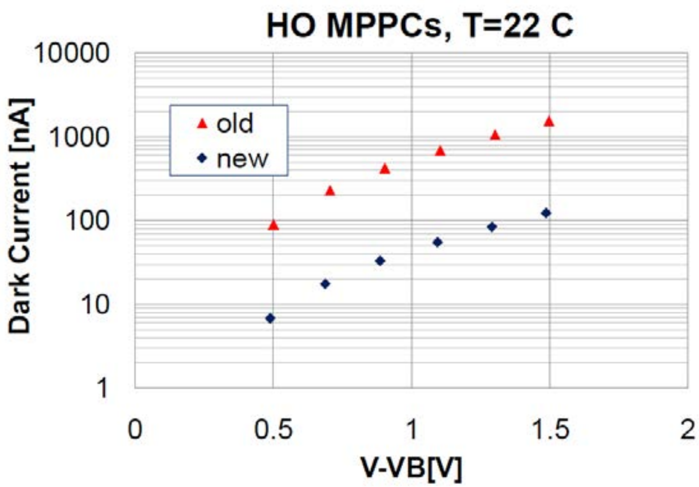
HO SiPM readout module – 18 channels

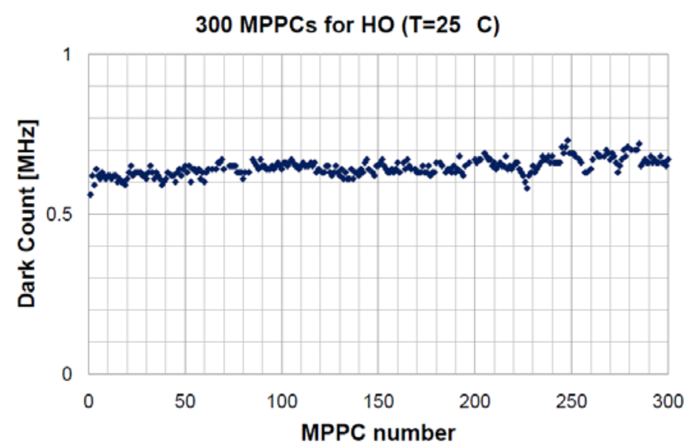

*Y. Musienko (Iouri.Musienko@cern.ch)*

# Some properties of the CMS HO MPPC's



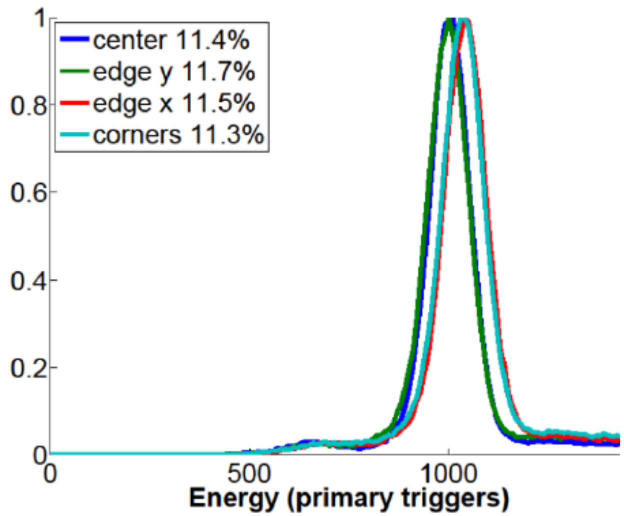




Dark count of new 3x3 $mm^2$ MPPCs is ~ 600 kHz (or ~70 $kHz/mm^2$) at T=25 C !

# dSiPM for PET application

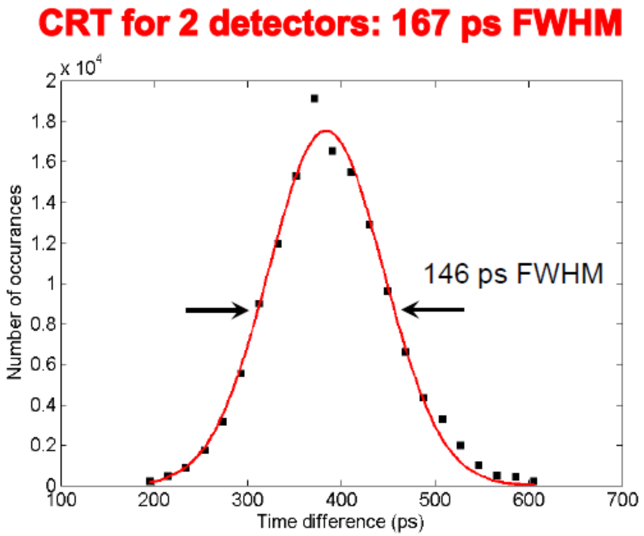
## Energy resolution

- 24 mm x 24 mm x 10 mm Ca-codoped LSO:Ce
- PDPC DPC-6400-44-22 dSiPM array
- Average energy resolution: ~11.5% FWHM
- Negligible saturation




Measured using $^{22}$Na $\gamma$-source

## Coincidence resolving time




Timing measurement against 85 ps FWHM reference detector

G.J. van der Lei et al, NSS-MIC 2011, MIC15.S-83

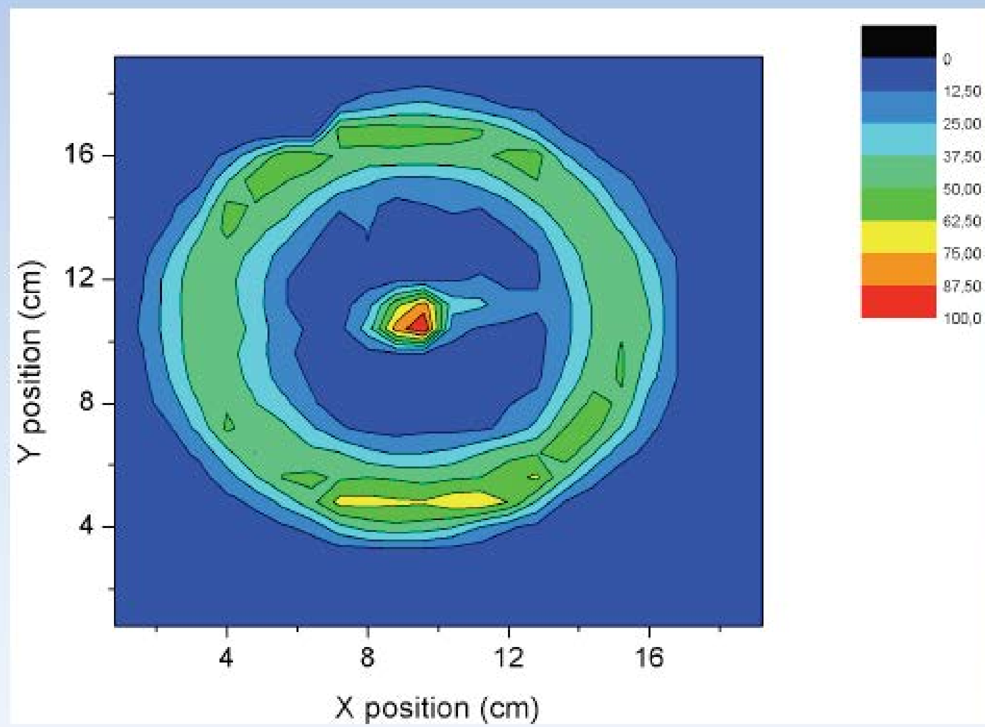
# Use of dSiPM with aerogel RICH detector

- Philips dSiPM looks very promising for large scale applications
- FARICH prototype with ~ 20x20 cm array of Philips dSiPM is being tested now in CERN at T10 test beam from PS:

**Test beam experiment with FARICH prototype**

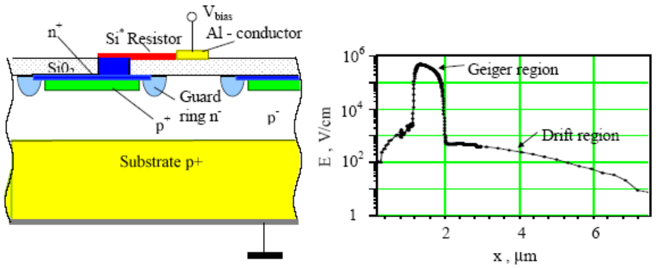
A.Yu.Barnyakov, M.Yu.Barnyakov, I.Yu.Basok
V.E.Blinov, V.S.Bobrovnikov, A.A.Borodenko,
A.R.Buzykaev, A.F.Danilyuk, V.V.Gulevich,
S.A.Kononov, E.A.Kravchenko, I.A.Kuyanov,
A.P.Onuchin, I.V.Ovtin, A.A.Talyshev

*Budker Institute of Nuclear Physics, Novosibirsk*
*Boreskov Institute of Catalysis, Novosibirsk*

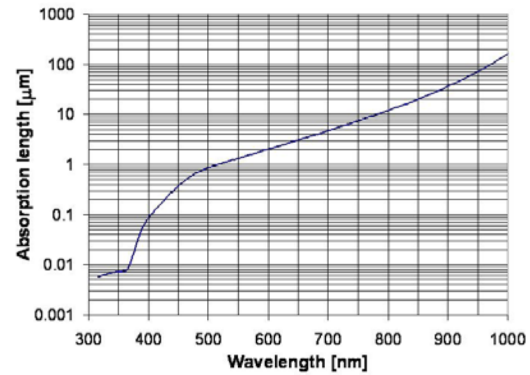


# Structure for green/red light (n on p)

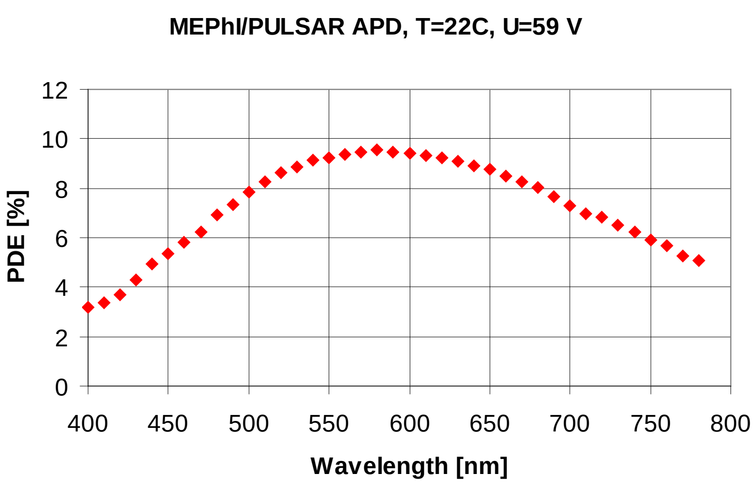
Sensitivity for blue light is low. Blue light is absorbed close to the SiPM surface – holes initiate an avalanche

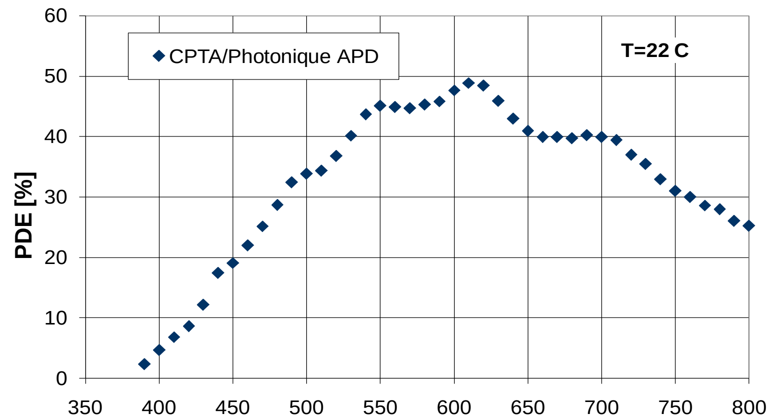



Absorption length for light in silicon




B. Dolgoshein et. al., "An advanced study of silicon photomultiplier", ICFA-2001



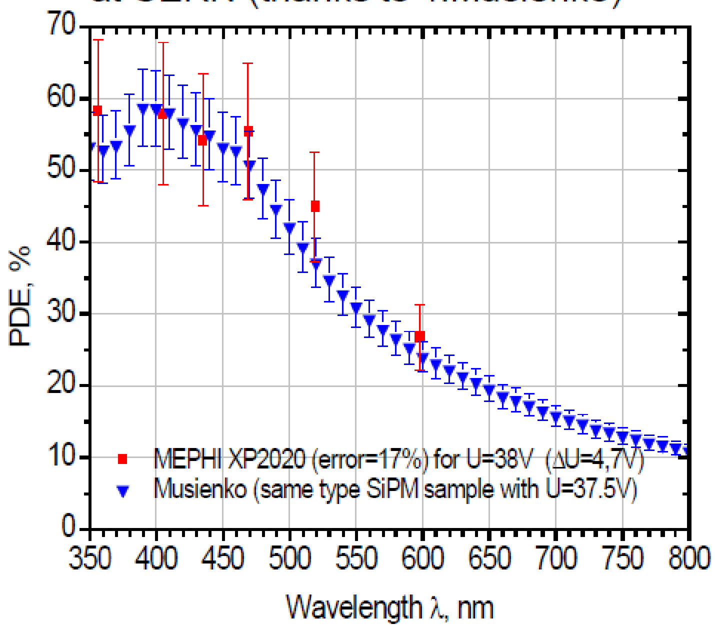

SiPMs with ~60-70% GF (for 50µm cell pitch) were produced: PDE=40-50% (red light)

(Y. Musienko, PD-07, Kobe)

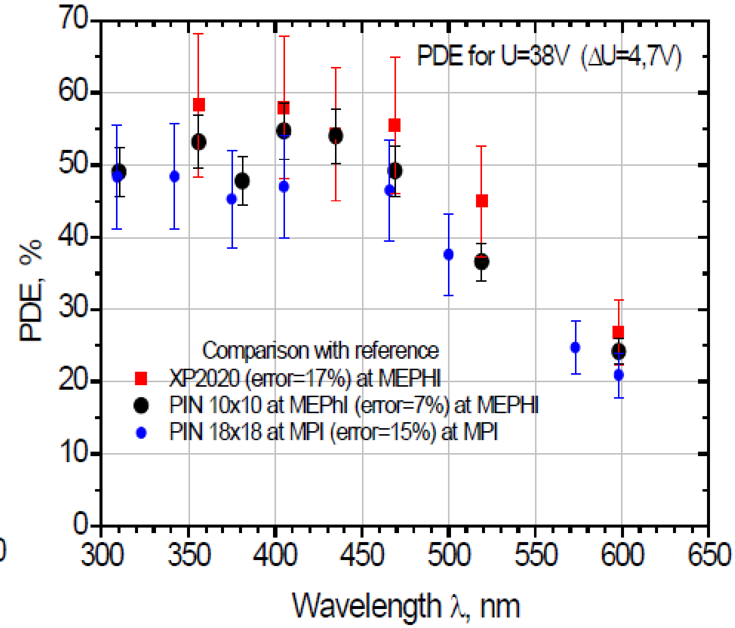
# UV-enhanced SiPMs

MEPhI SiPM (100 μm cell pitch)

Measurements at MEPHI and at CERN (thanks to Y.Musienko)




Measurements at MEPHI and at MPI

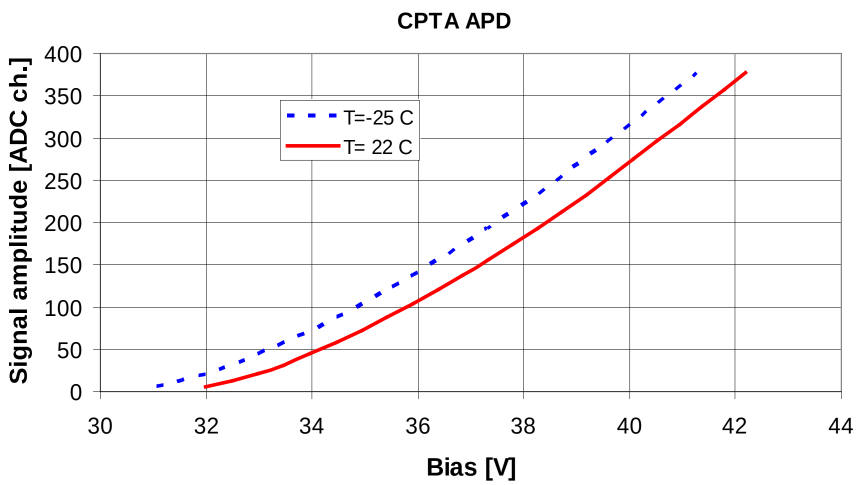


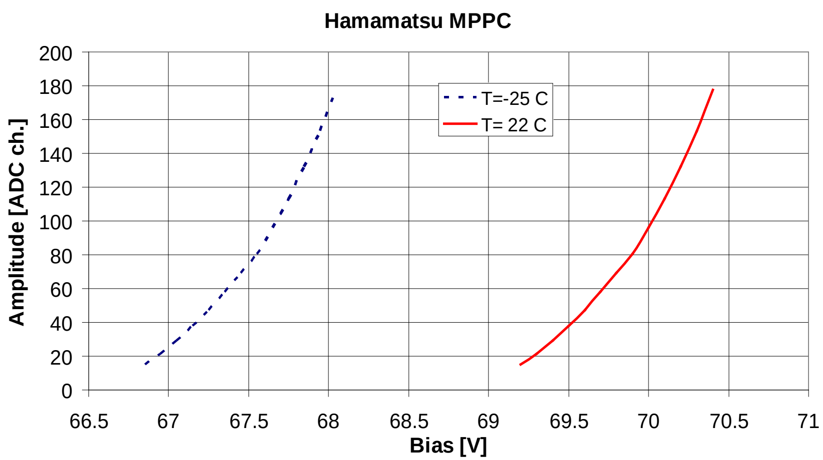

4th July 2011, NDIP-11, Lyon, France

E.Popova: Large area SiPM with very high PDE and very low X-talk

# SiPM response vs. temperature

SiPM gain and PDE depend on the temperature



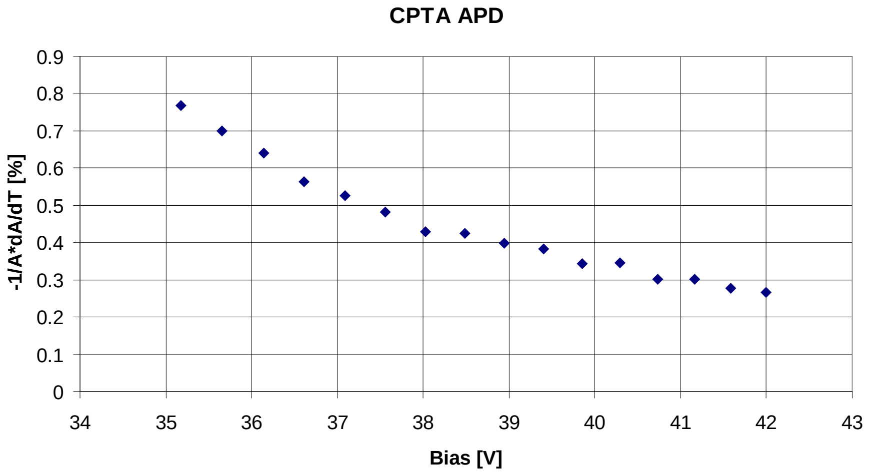



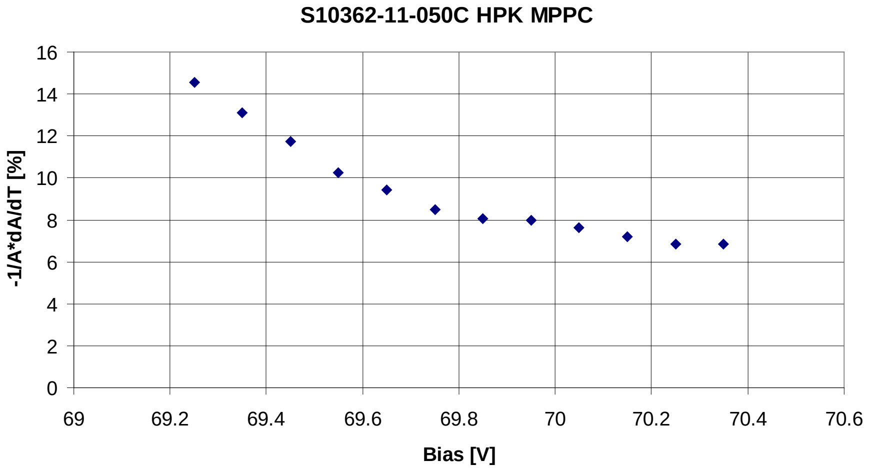

LED signal was measured in dependence on bias at 2 temperatures for SiPMs from 2 producers

***CPTA/Photonique SSPM:***
dVB/dT=-20 mV/C
***Hamamatsu MPPC:***
dVB/dT=-55 mV/C

(Y. Musienko, PD-07, Kobe)

# Temperature coefficient



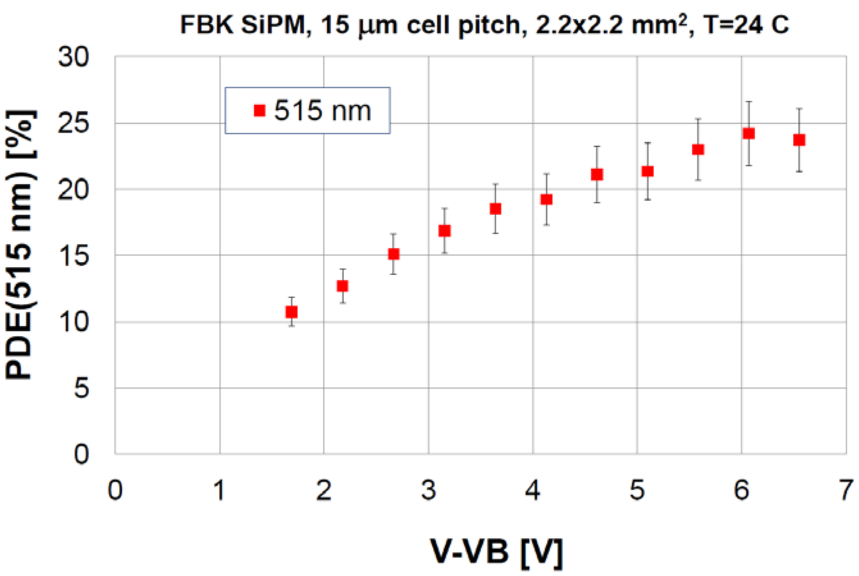

$k_T$=dA/dT*1/A, [%/°C]

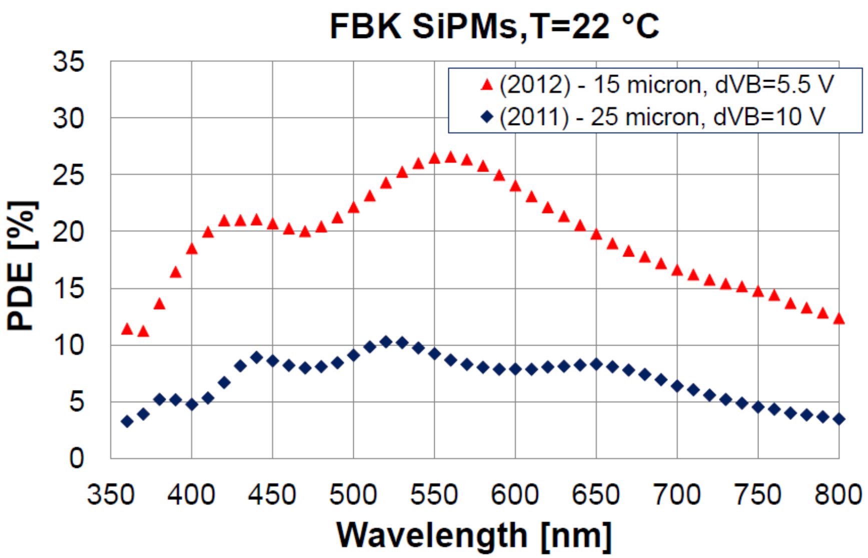
SiPMs operated at high V-VB have $k_T$~0.3%/C

(Y. Musienko, PD-07, Kobe)

# FBK SiPM development in 2012

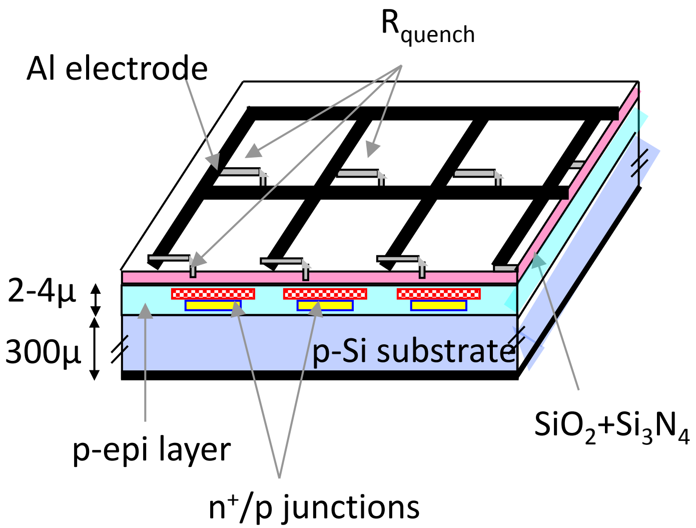
In 2012 FBK developed large dynamic range N-on-P SiPMs for the CMS HCAL project.
The main goals of the R&D were:
- Reduce cell pitch from 25 to 15 micron
- Produce 2.5 mm dia. SiPM with 15 micron cell pitch
- Improve the PDE of the FBK SiPMs for green light (515 nm)
- Improve radiation hardness of the KETEK SiPMs

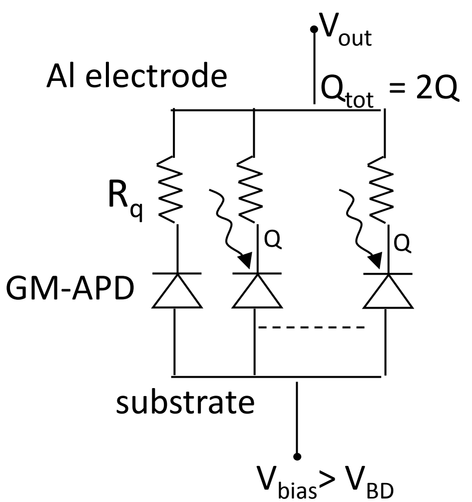



PDE(515 nm)>20% for 2012 15 μm cell pitch SiPMs. It was improved by a factor of >2 in comparison to the 2011 25 μm cell pitch SiPM.

# SiPM structure and principles of operation



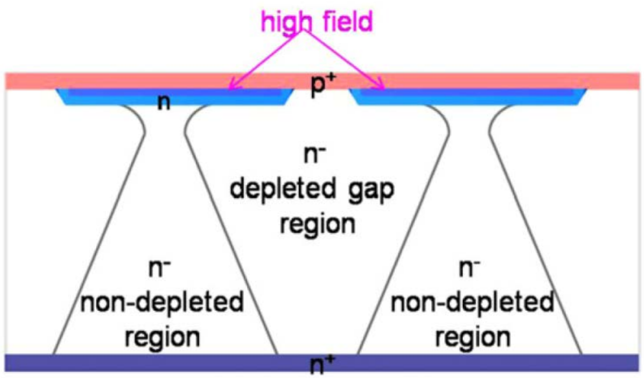

*(EDIT-2011, CERN)*

- *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*

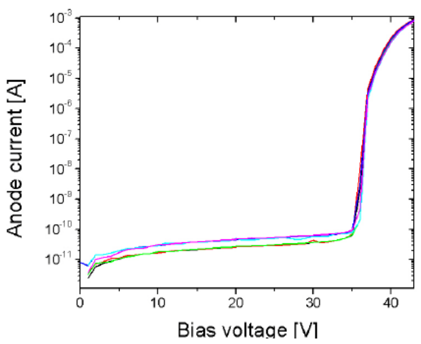
*For small light pulses ($N_{\gamma}$<<$N_{pixels}$) SiPM works as an analog photon detector*

# SiPMs with bulk integrated quenching resistors from MPI (SiMPl concept)

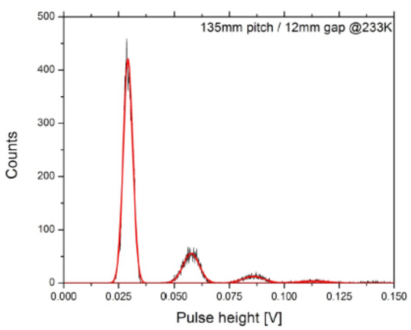
Schematic cross-section of two neighboring cells




Static measurements




Dynamic measurements




*(J. Ninkovic et al., NIM A628 (2011))*

**Advantages:**

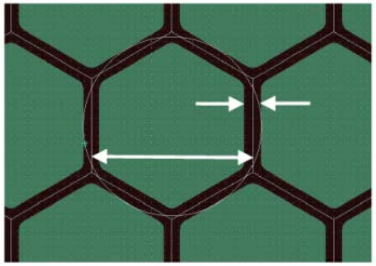
- ➔ **no need of polysilicon**
- ➔ **free entrance window for light, no metal necessary within the array**
- ➔ **simple technology**

**Drawbacks:**

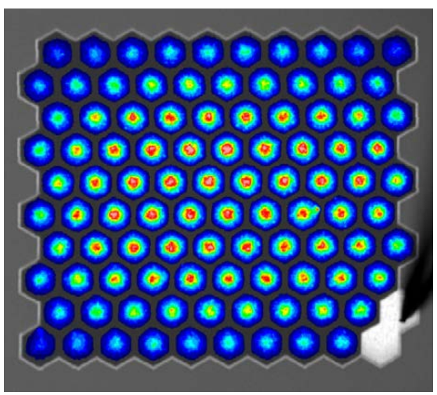
- ➔ **required depth for vertical resistors does not match wafer thickness**
- ➔ **wafer bonding is necessary for big pixel sizes**
- ➔ **significant changes of subpixel size requires change of material**
- ➔ **worse radiation hardness ??**

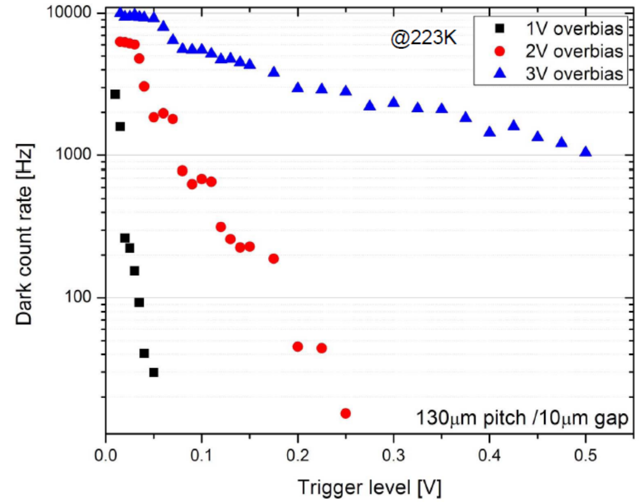
# SiMPl results

*Prototype structure was recently produced*



Photoemission micrograph for the 100 cell array (135 µm pitch and a 17 µm gap size) operated at 5V overbias.






| Pitch / Gap | Fill factor | Cross talk |
|---|---|---|
| 130µm / 10µm | 85.2% | 29% |
| 130µm / 11µm | 83.8% | 27% |
| 130µm / 12µm | 82.4% | 25% |
| 130µm / 20µm | 71.6% | 15% |

PDE estimate:

- Optical entrance window: 90% @400nm
- Geiger efficiency : 50% @ 2V overbias 80% @5V overbias

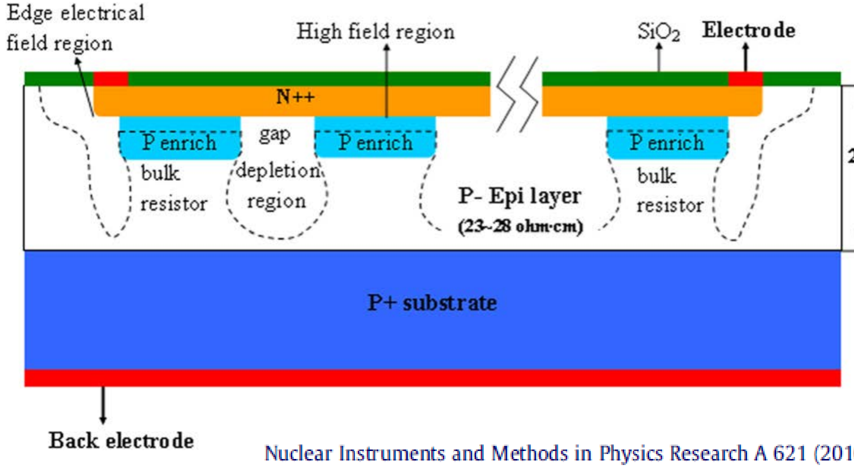
| Pitch / Gap | Fill factor | PDE | |
|---|---|---|---|
| 130µm / 10µm | 85.2% | 39% | 61% |
| 130µm / 11µm | 83.8% | 38% | 60% |
| 130µm / 12µm | 82.4% | 37% | 59% |
| 130µm / 20µm | 71.6% | 32% | 52% |

***(J. Ninkovic et al., NIM A628 (2011))***

***(J. Ninkovic, IEEE NSS/MIC conf., 2010)***

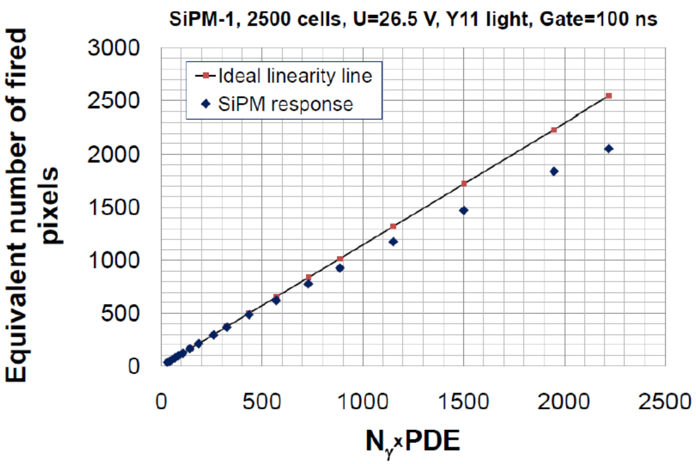
# Large dynamic range SiPMs with bulk integrated quenching resistors from NDL(Beijing)

Schematic structure of the SiPM with bulk integrated resistors (S=0.5x0.5 mm$^2$, 10 000 cells/mm$^2$)



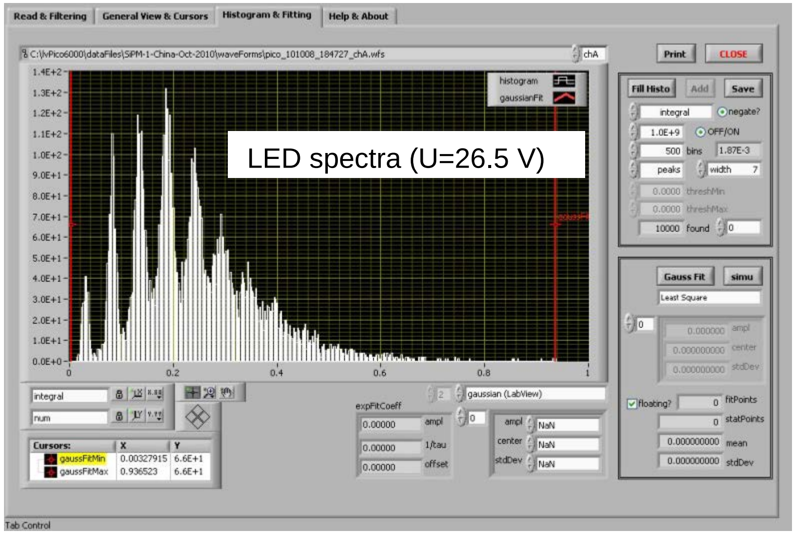

Nuclear Instruments and Methods in Physics Research A 621 (2010) 116–120

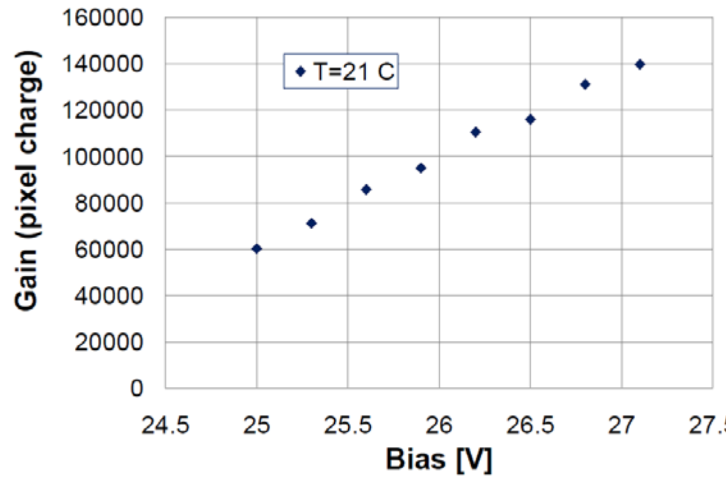
SiPM non-linearity

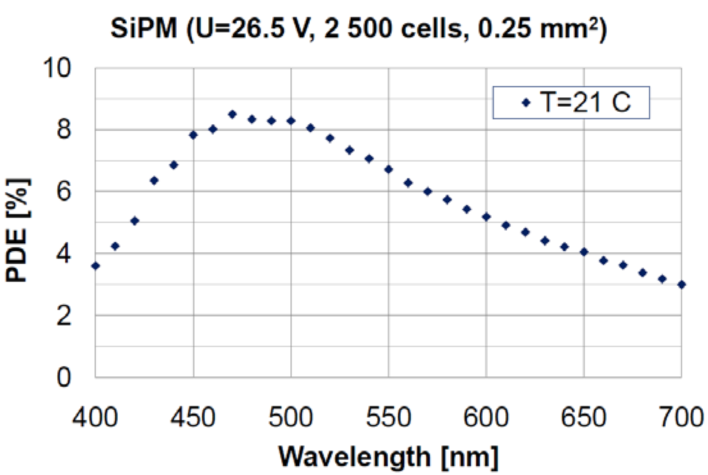


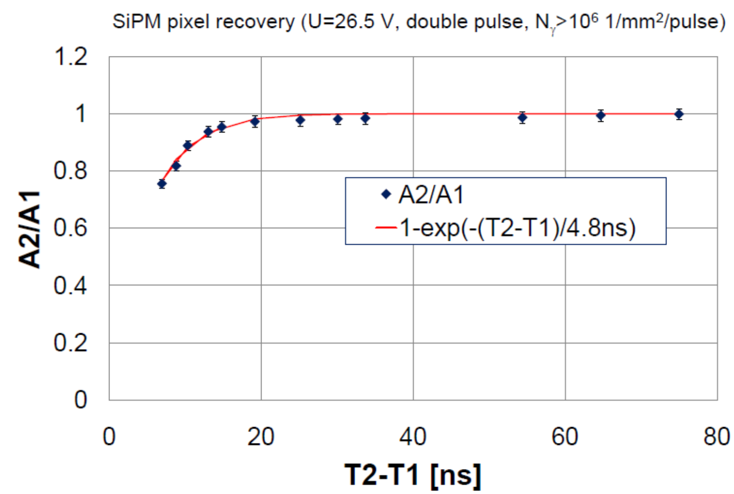

- n on p (structure for green light)
- sensitive area - 0.25 мм$^2$
- number of cells - 2 500
- operating voltage- 26.5 V
- quenching resistor value - 200-300 кОм

# NDL SiPM results



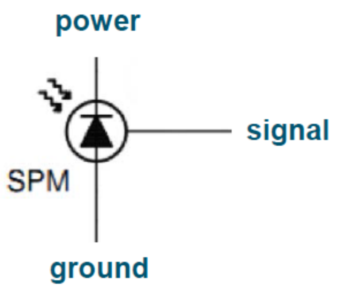



# SiPM with Fast Timing Output (SensL)

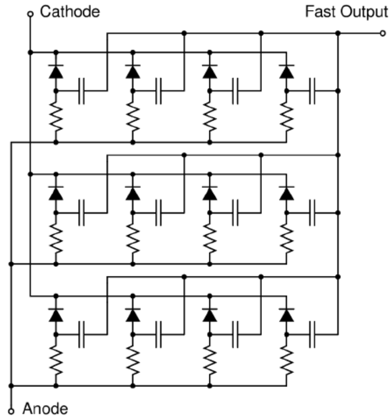
SensL has developed a fast mode output in addition to the standard output

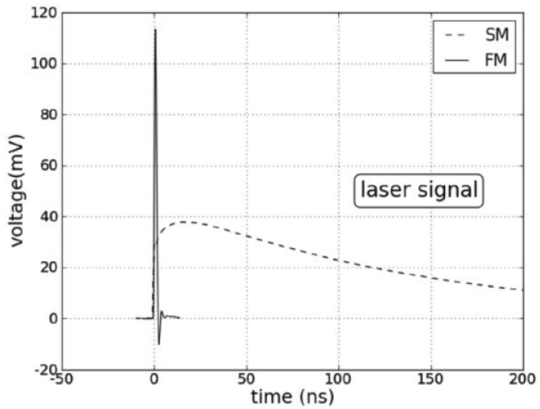
SensL Micro-FB-10035-X18 SiPM (45 μm cell pitch)




N. Pavlov, "Silicon Photomultiplier and Readout Method", *USPTO Patent Application Publication*, No. US2013/0099100 A1, 2013.

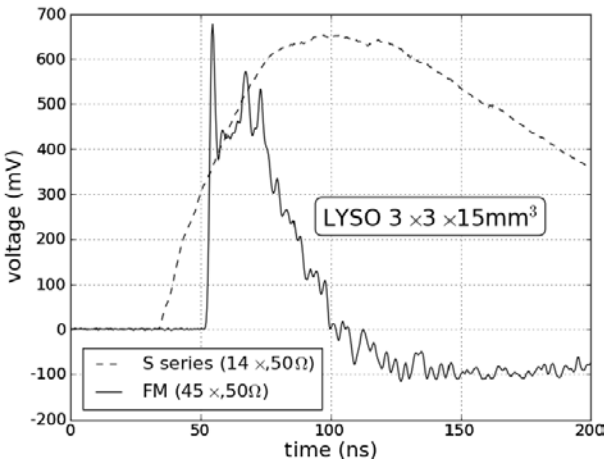
Concept schematic of the SensL fast output SiPM



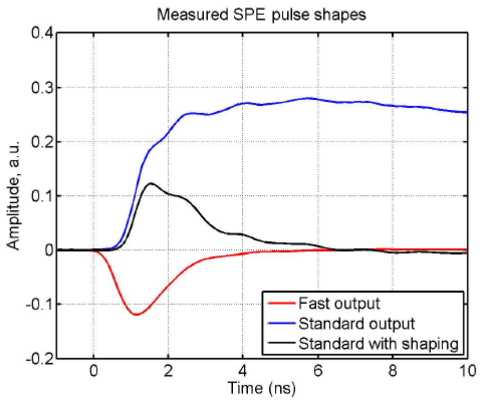




*Comparison of typical MicroFM output with that from other conventional SensL SPMs (such as the MicroSM) when illuminated with a fast laser.*

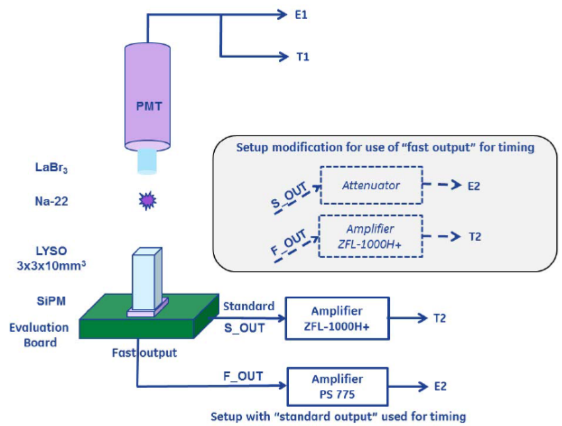
FM Signal with L(Y)SO Output

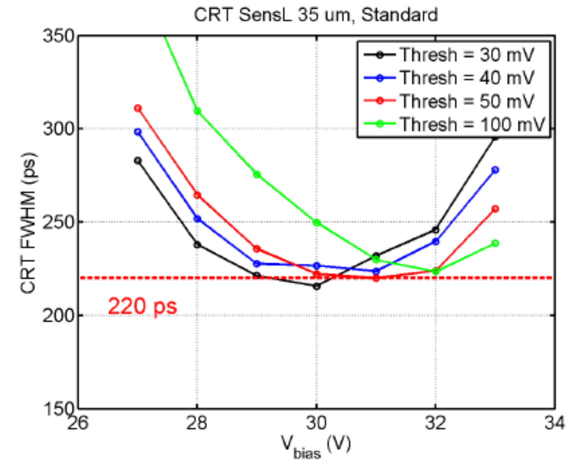


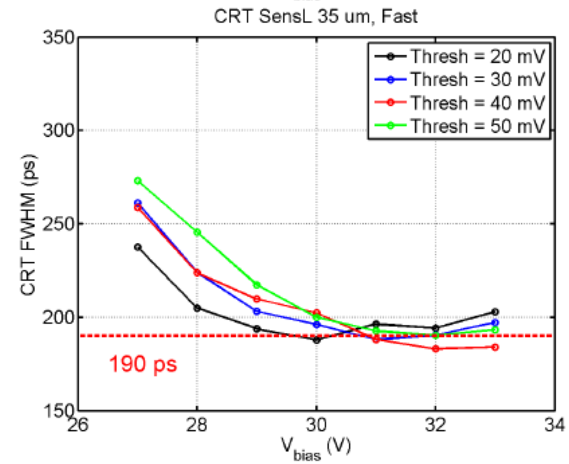
# CRT measurements using MicroFB SensL SiPM



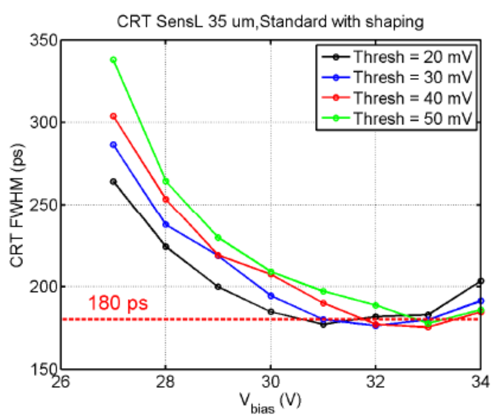

Measured SPE signals from SensL MicroFB-30035 SiPM




CRT measurement set-up



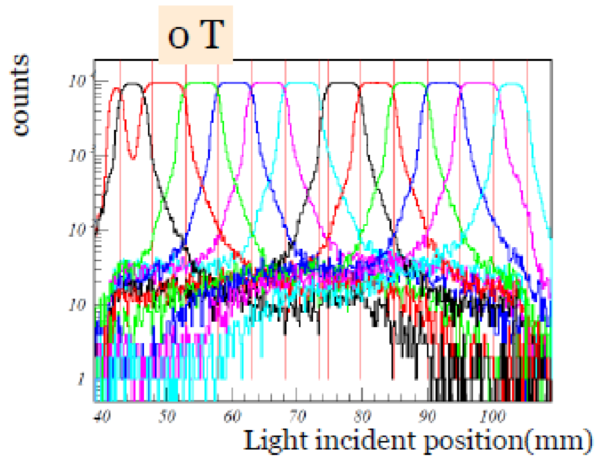

S.Dolinsky et al., 2013
IEEE NSS-MIC Conference Record

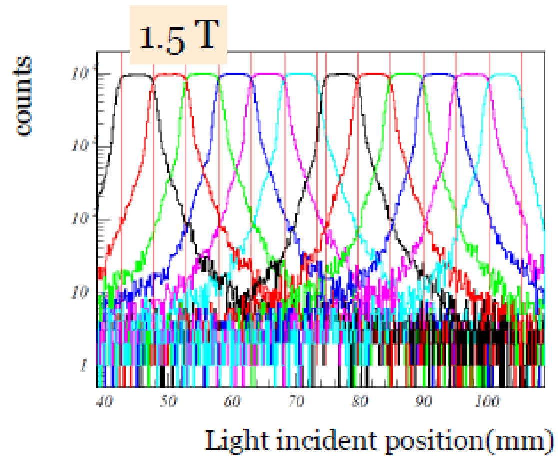
Measured CRT vs. SiPM bias from SensL MicroFB-30035 SiPM with external C-R shaping (t=2 ns) applied to standard output.

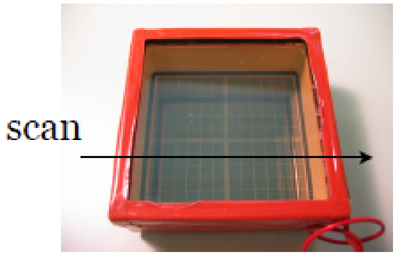
Measured CRT vs. SiPM bias for a fixed timing comparator threshold for SensL MicroFB-30035 SiPM. Top: standard output used for timing. Bottom: fast output used fro timing

# HAPD response in magnetic field

- Response scan for entire HAPD channels were done under an axial magnetic field of 1.5 Tesla.



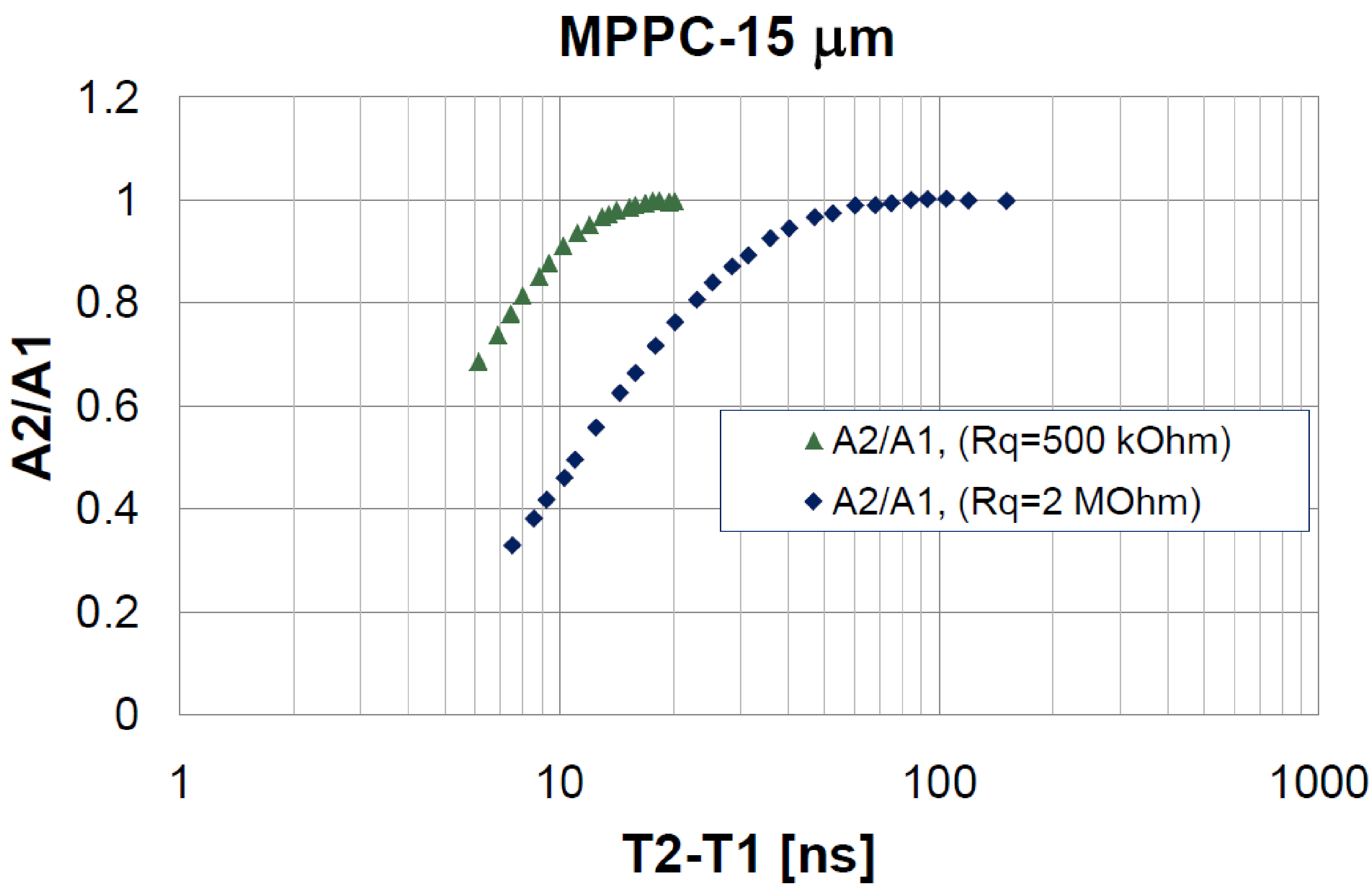




The excellent response for single photon and background becomes better

Performance is improved in the presence of a magnetic field !

(I.Adachi, PhotoDet 2012)

# Cell recovery studies with fast UV LED




Measured using double LED pulse method

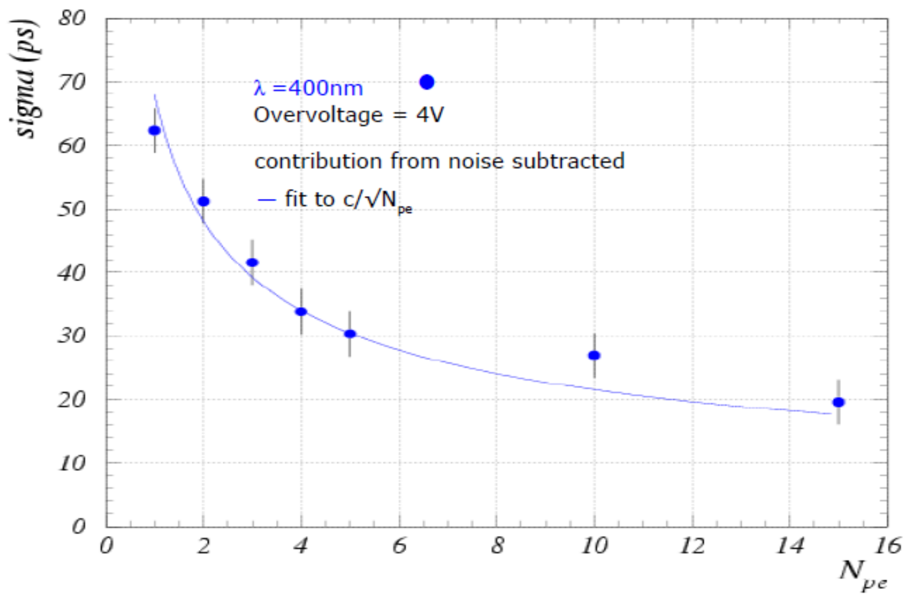
# Time resolution

SiPMs have excellent timing properties

Dependence of SiPM timing on the number of simultaneous photons

FBK SiPM

Poisson statistics: $\sigma_t \propto 1/\sqrt{N_{pe}}$




N of simultaneous photo-electrons

G. Collazuol et al. / Nuclear Instruments and Methods in Physics Research A 581 (2007) 461–464