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Progress in the development of SiPMs

D. Renker

Ljubljana, 9.7.2015

Outline

For the demonstration of the progress I will mostly show results from my recent measurments with the very new device 3x3-50UM LCT5 from Hamamatsu

Principle

Dynamic Range

Dark Counts

Photon Detection Efficiency (PDE)

Temperature Dependence

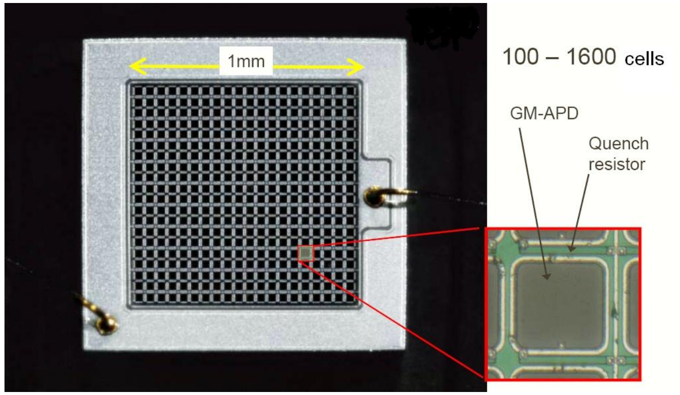
Crosstalk

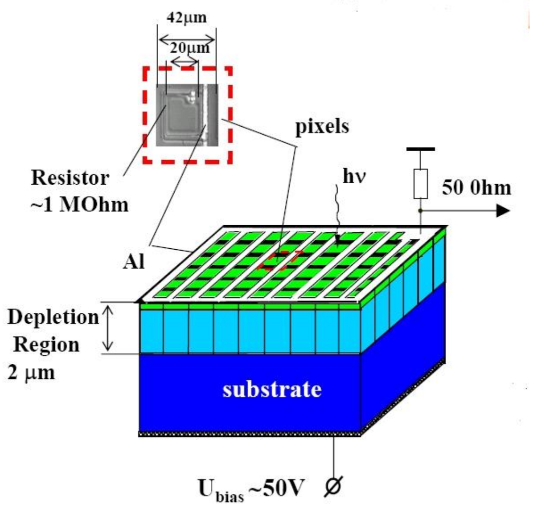
Afterpulses

Timing

Radiation Hardness

Geiger-mode APD (SiPM): principle of operation





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Key personalities in this development:
V. Golovin, Z. Sadygov

- Each cell is reverse biased above breakdown
- Selfquenching of the Geiger breakdown by individual serial resistors
- Sensitive to single photons
- High gain up to 10^7
- Number of cells 100 to 40,000 / mm^2
- Recovery of cells after breakdown 5 to 1000 ns

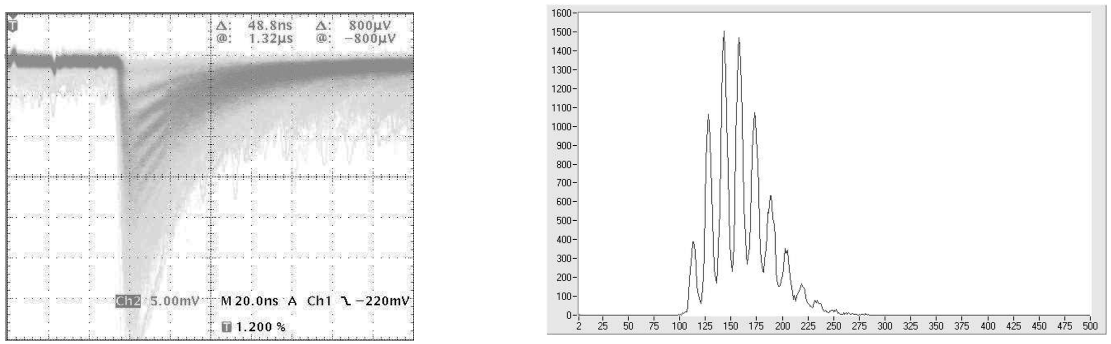
High gain

G-APDs produce a standard signal when any of the cells goes to breakdown. The amplitude A_i is proportional to the capacitance of the cell divided by the electron charge times the overvoltage.

$A_i \sim C/q \bullet (V - V_b)$ $(V - V_b)$ we call "overvoltage"

V is the operating bias voltage and V_b is the breakdown voltage.
When many cells are fired at the same time, the output is the sum of the standard pulses.

$A = \sum A_i$ The summing makes the device analog again.



Oscilloscope picture of the signal from a G-APD (Hamamatsu 1-53-1A-1) recorded without amplifier (a) and the corresponding pulse height spectrum (b).

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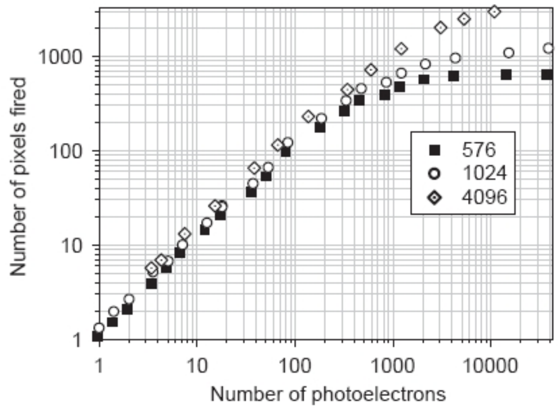
Saturation

The output signal is proportional to the number of fired cells as long as the number of photons in a pulse (N_{photon}) times the photo detection efficiency PDE is significantly smaller than the number of cells N_{total}.

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

2 or more photons in 1 cell look exactly like 1 single photon.

When 50% of the cells fire the deviation from linearity is 20%.



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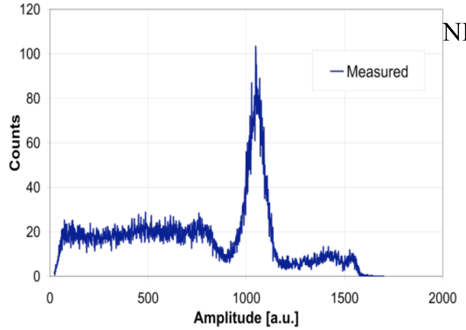
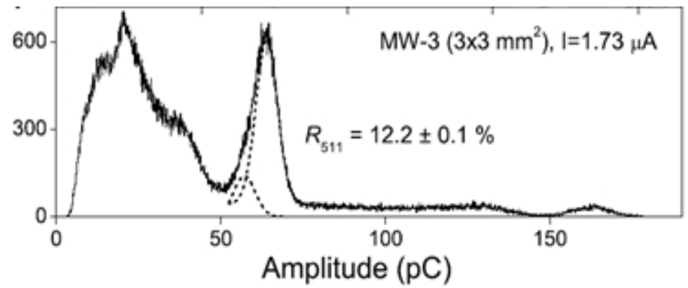
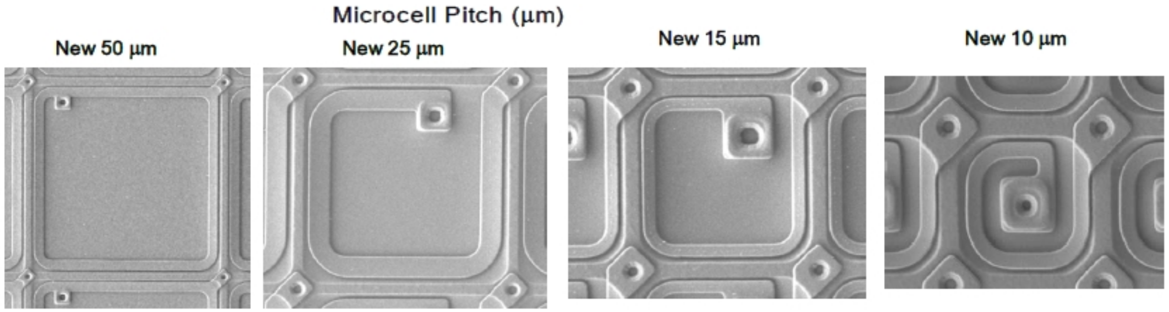




G-APD from CPTA/Photonique with ~400 cells/mm^2 and from Zecotek with 15'000 cells/mm^2.

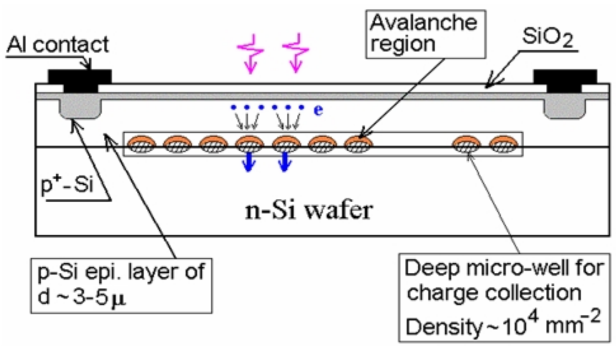
Saturation: solutions

G-APDs from Hamamatsu have up to 10,000 cells/mm²



Zecotek (Singapure) produces devices with 15,000 and 40,000 cells/mm².

The structure is different:



Similiar are devices based on the principle of avalanches with negative feeback from Amplification Technologies. They call them Discrete amplification Photo Diode (DAPD).

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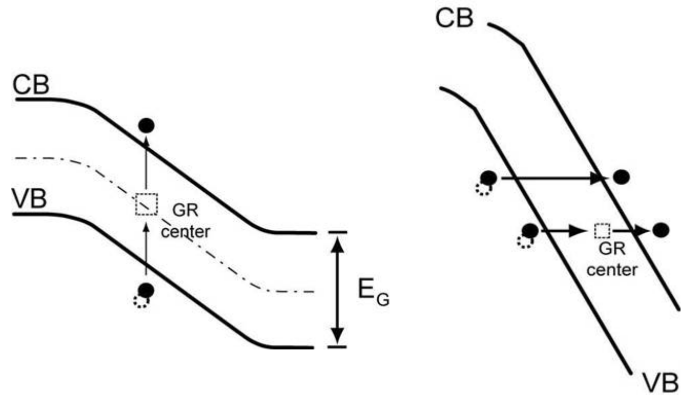
Dark count rate

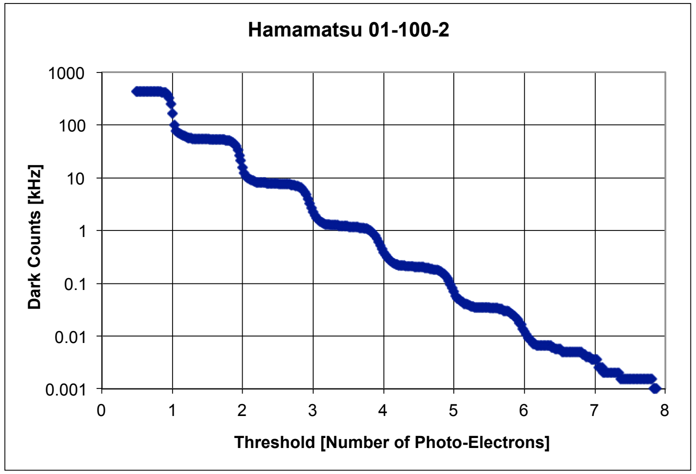
A breakdown can be triggered by an incoming photon or by any generation of free carriers. The latter produces dark counts with a rate of 100 kHz to several MHz per mm^2 at 25°C when the threshold is set to half of the one photon amplitude.

Breakdown events initiated by thermally generated free carriers can be reduced by cooling (factor 2 reduction of the dark counts every 8°C) and by a smaller electric field (lower gain).

Field-assisted generation (tunneling) is a relative small effect. It can only be reduced by a smaller electric field (lower gain).

The dark count rate falls rapidly with increasing threshold with steps that depend on the crosstalk probability (~12% for the G-APD shown)





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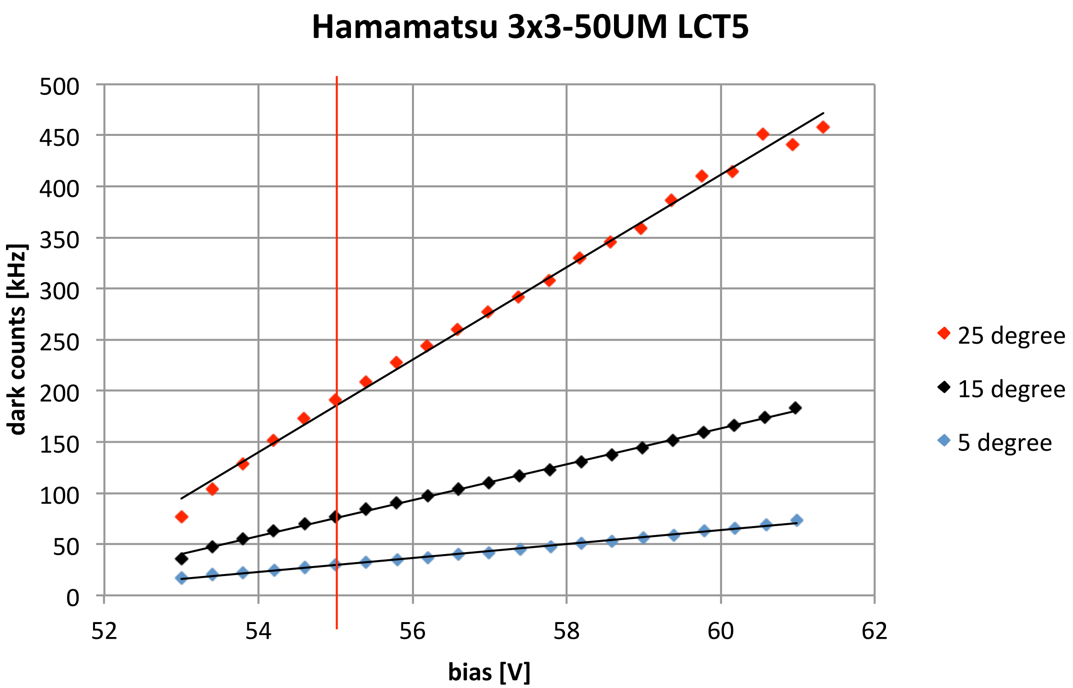
Dark Counts today

A carefull design and the use of high purity silicon reduced the dark count rate significantly to 25 kHz/mm^2 at the nominal operating voltage.



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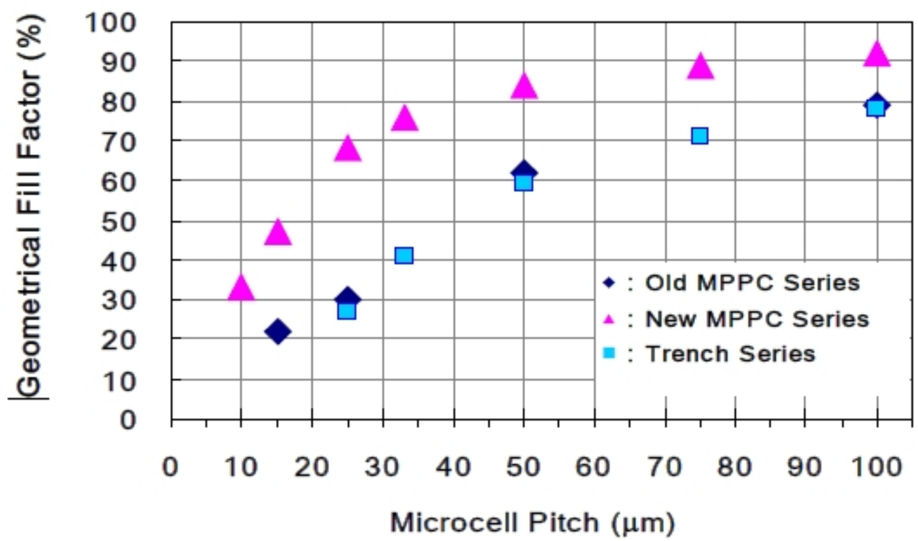
Photon Detection Efficiency (PDE)

The photon detection efficiency (PDE) is the product of quantum efficiency of the active area (QE), a geometric factor (ε, ratio of sensitiv to total area) and the probability that an incoming photon triggers a breakdown ($P_{trigger}$)

$$PDE = QE \cdot \varepsilon \cdot P_{trigger}$$

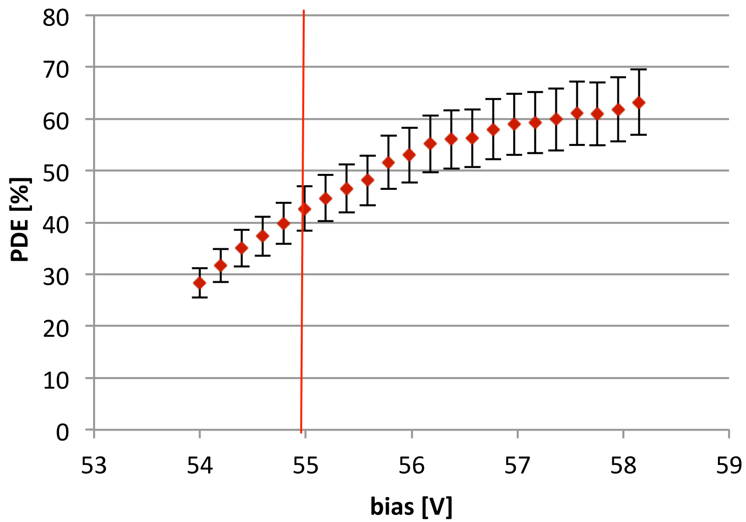
The QE is maximal 80 to 90% depending on the wavelength.

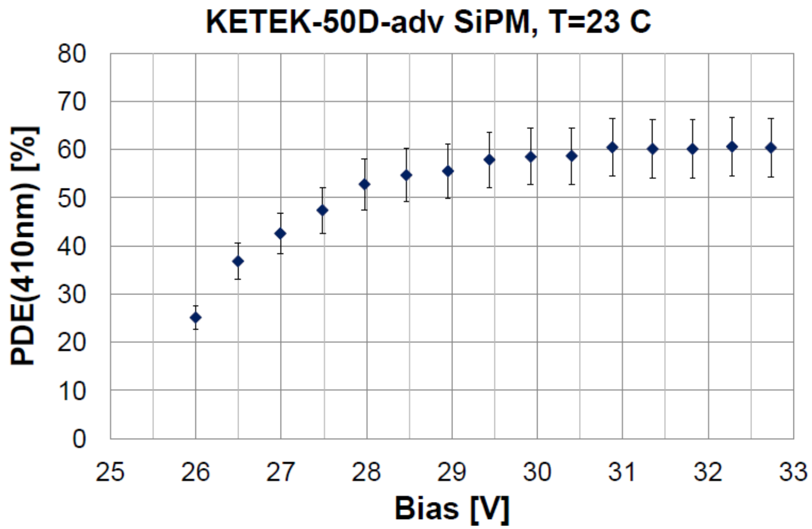
ε, the geometric factor has been optimized by all producers.
The plot is from Hamamatsu



Photon detection efficiency

Hamamatsu 3x3-50UM LCT5 (50 micron pitch):





from

I. Musienko

The PDE at the nominal voltage of 55 V (Hamamatsu recommendation) is 25% below the maximal value. When we want a high PDE we need to go to higher bias voltages with all the consequences on dark counts, crosstalk etc.

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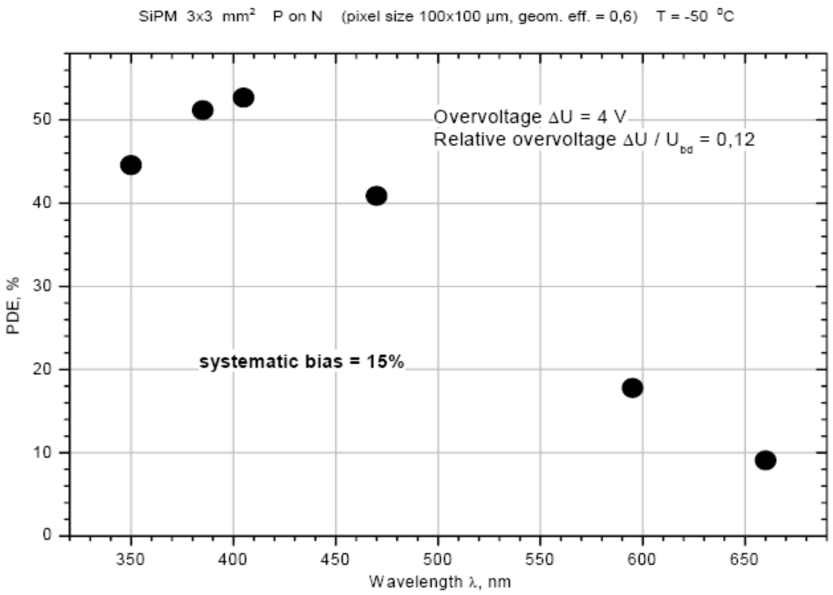
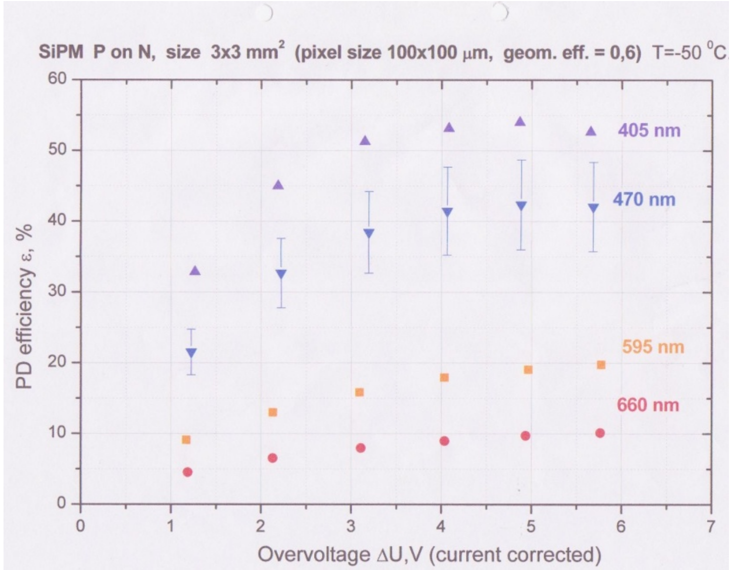
Photon detection efficiency

PDE ,SiPM p on n,3x3 mm^2,
OV/V=12% +OC suppression





Test-product of Excelitas

R. Mirzoyan, SiPM for CTA SST

PDE = QE(~85%) · **ε(60%)** · $P_{trigger}$

$\Rightarrow P_{trigger} = 1$

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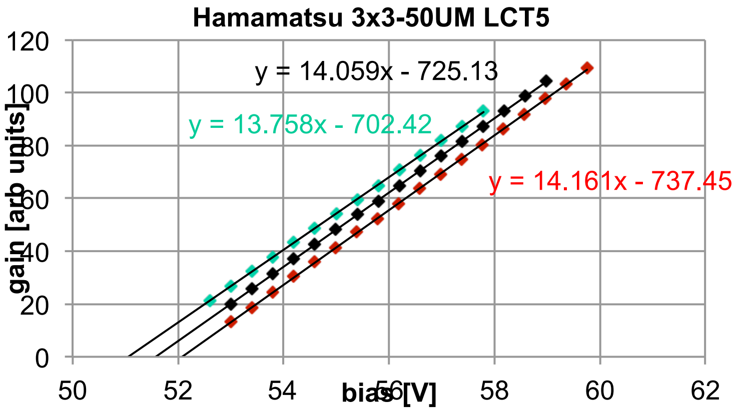
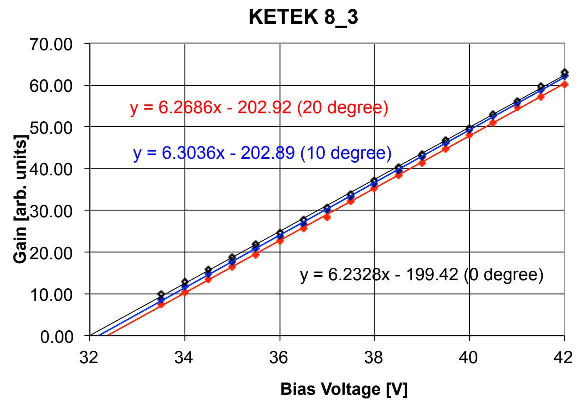
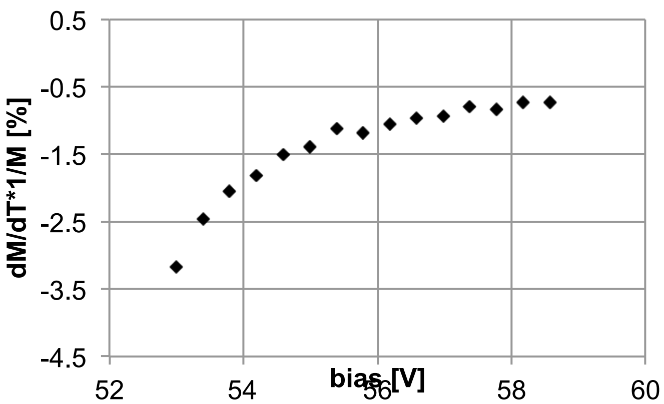
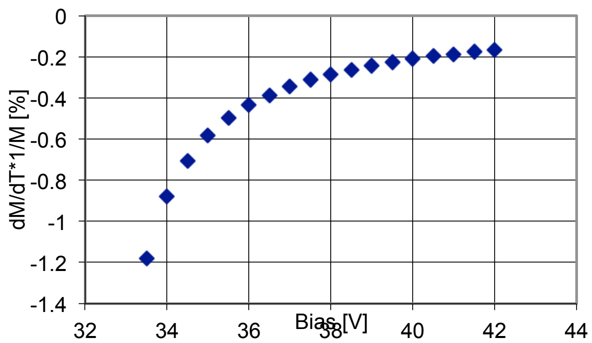
Stability

The breakdown voltage and by this the gain varies with the temperature (phonon interactions). Hamamatsu MPPCs have a rather wide high field region and therefore the temperature coefficient is higher compared to SiPMs from other producers.









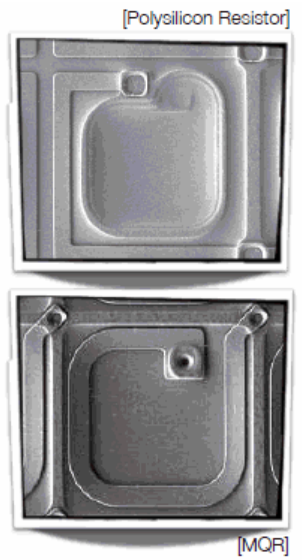
Stability

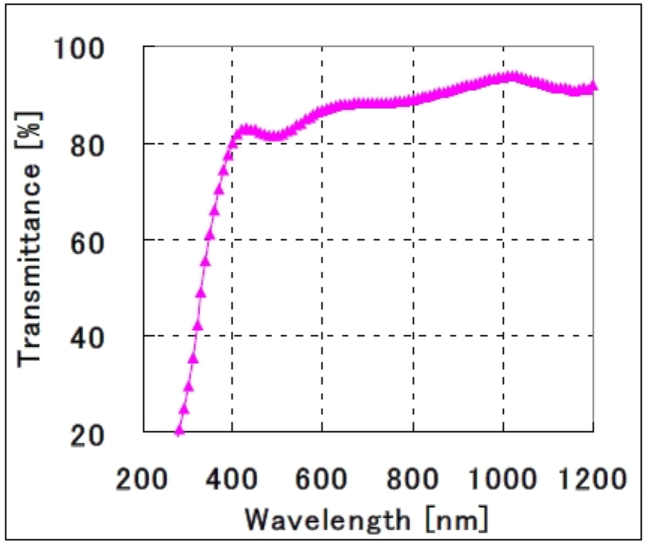
Hamamatsu replaced the polysilicon quenching resistor by a thin metal layer.

Low Temperature coefficient of resistance

Poly-Si	Metal
-2.37 kΩ	-0.43 kΩ

(/deg C)





The Metal Quenching Resistor (MQR) is transparent and allows a better fill factor: 74% for the 3x3-50UM LCT5 type.

Maybe the radiation hardness is improved.

Optical crosstalk

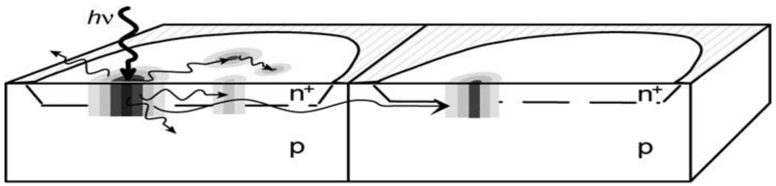
Hot-Carrier Luminescence:

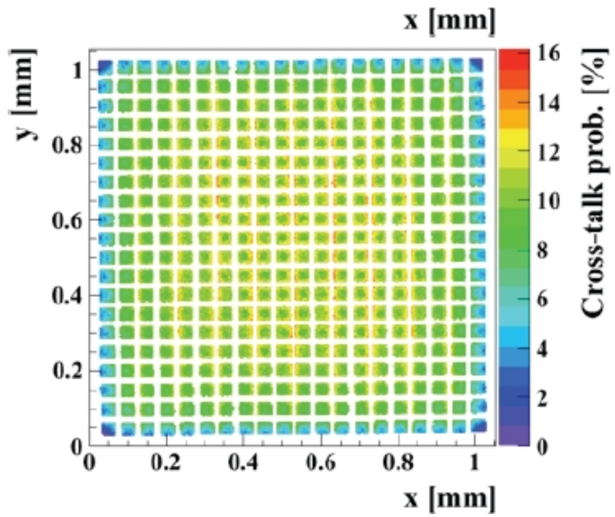
10^5 carriers in an avalanche breakdown emit in average 3 photons with an energy higher than 1.14 eV. (A. Lacaita et al, IEEE TED (1993))

When these photons travel to a neighboring cell they can trigger a breakdown there.

Optical crosstalk acts like avalanche fluctuations in a normal APD. It is a stochastic process. We get an excess noise factor (F = 1 + crosstalk probability)

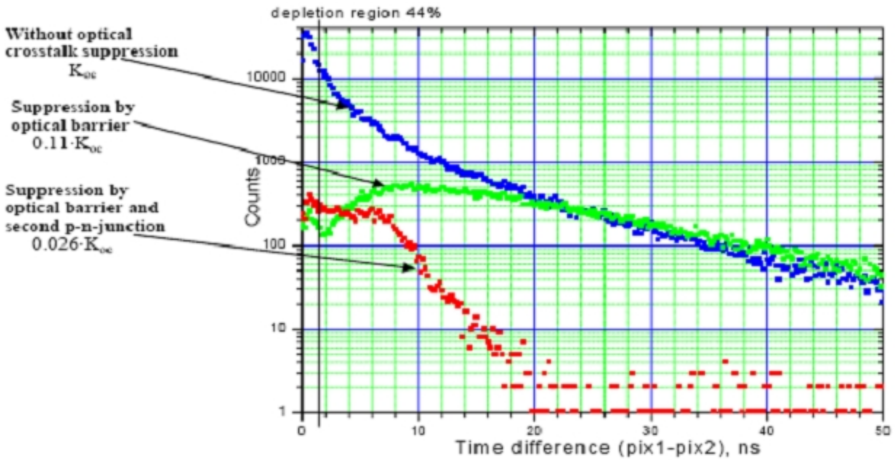
$$F = 1 + \frac{\sigma_M^2}{M^2}$$

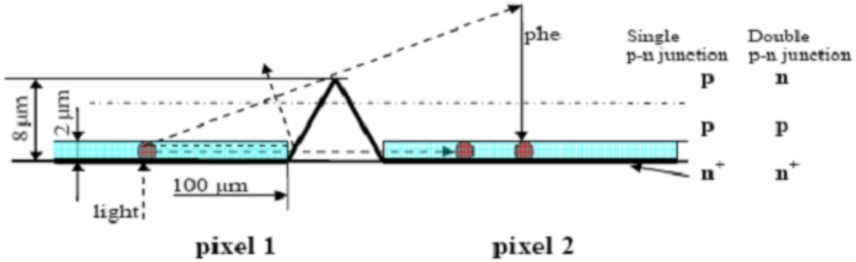




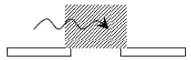
A. Tadday, 22.02.2010, SiPM Workshop DESY Hamburg

Crosstalk: solutions

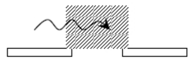




Optical crosstalk between two separate pixels

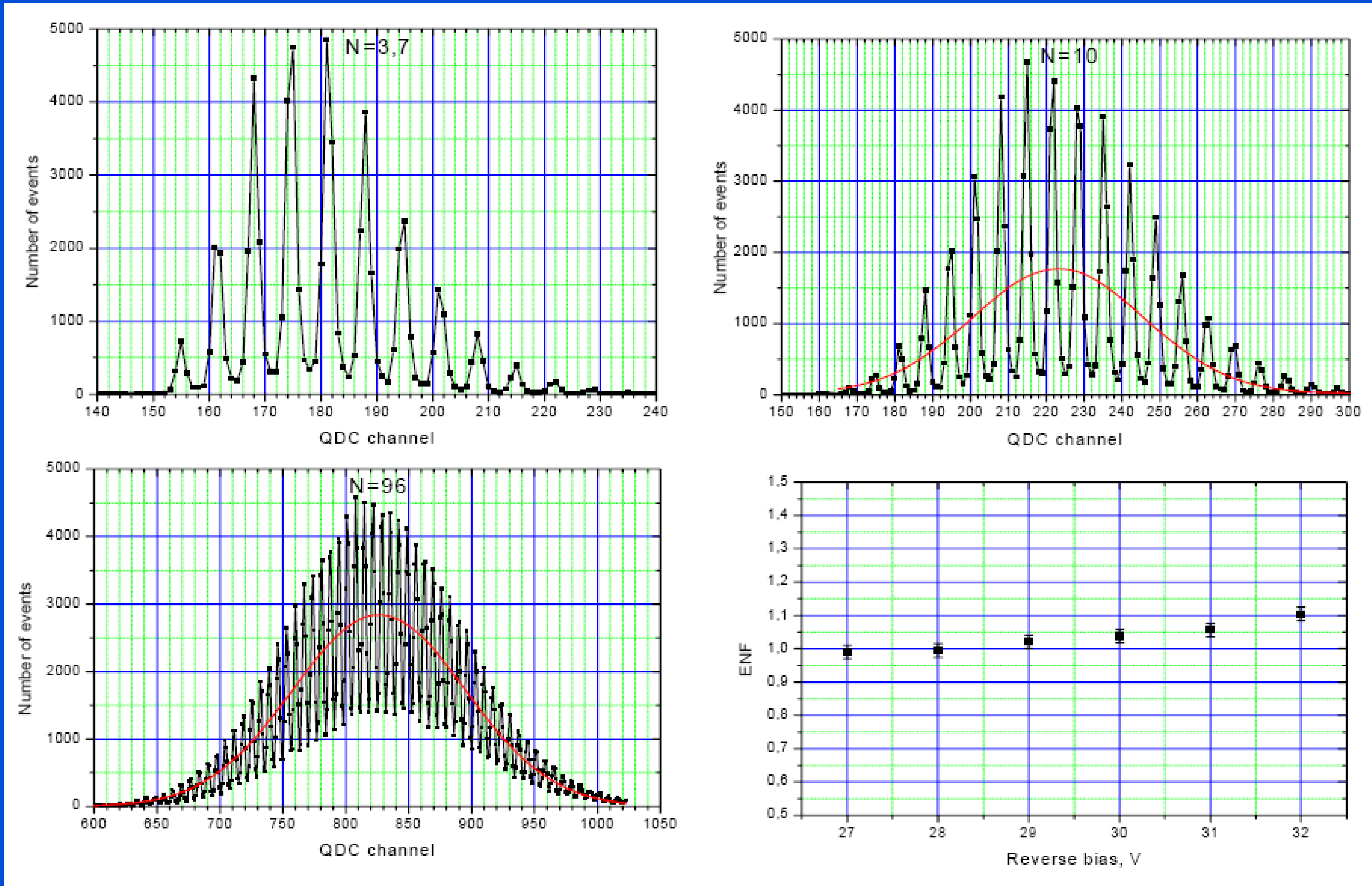


High doping concentration ~10^19 in between pixels - free carrier absorption of OC light (~1000 nm)
(I.Resh et al. Optic Express 16(12)2008)



Absorption of OC light(~1000 nm) in Si damaged by ion implantation (*Patent pending*)

SiPM with cross-talk suppression: World record of ultra-fast light sensors in amplitude resolution



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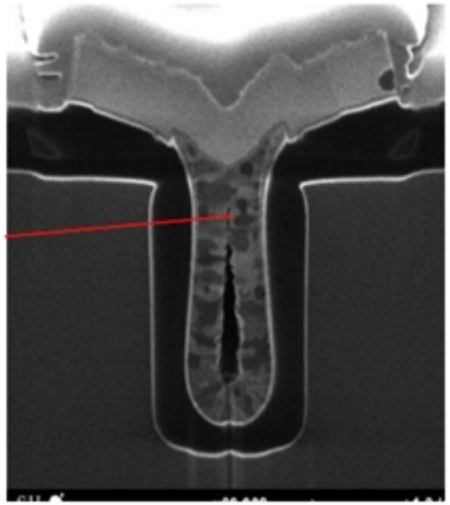
Ljubljana, 9.7.2015

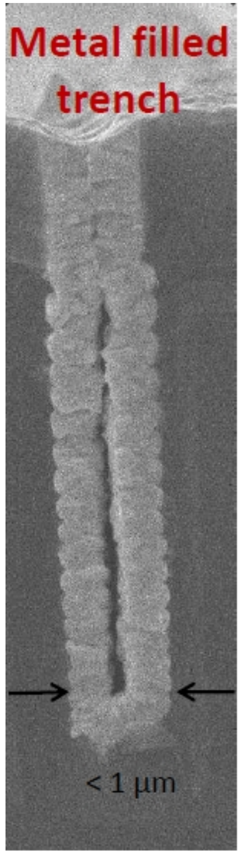
Crosstalk: solutions

Almost all SiPM from the different producers have now trenches between the cells.

Hamamatsu:



Ketek:



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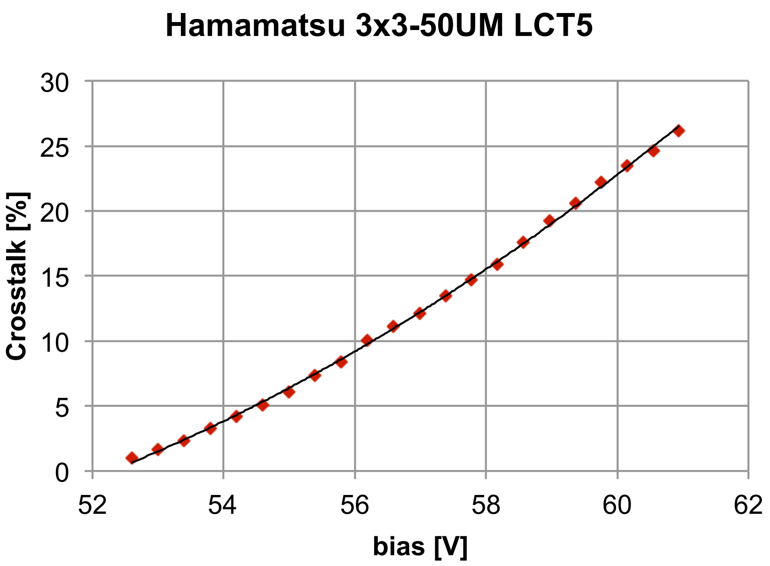
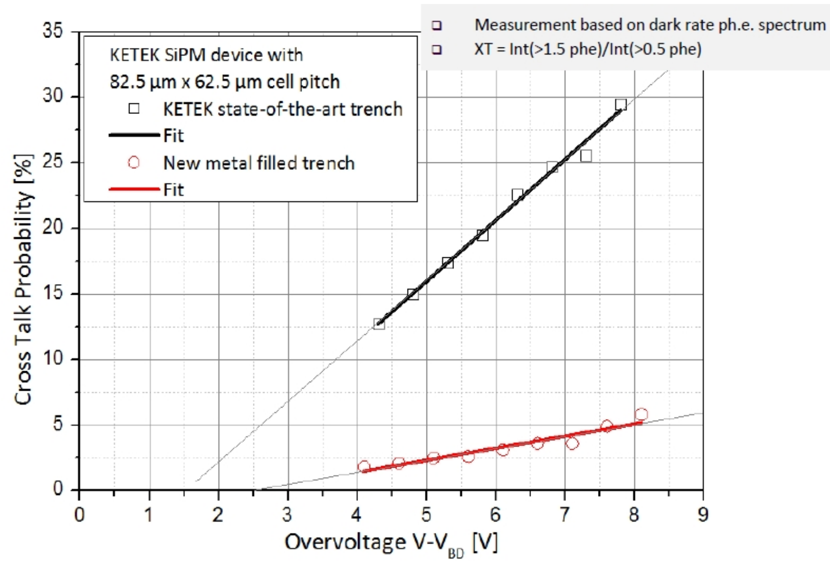
Crosstalk





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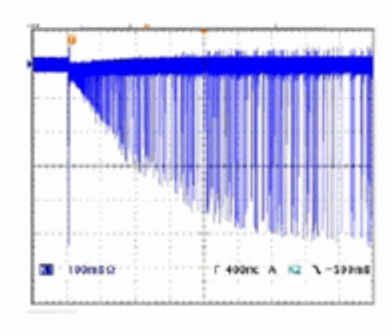
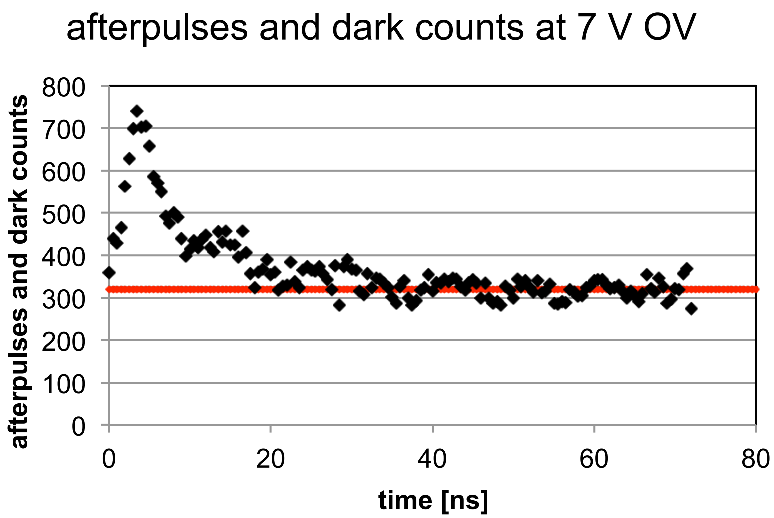
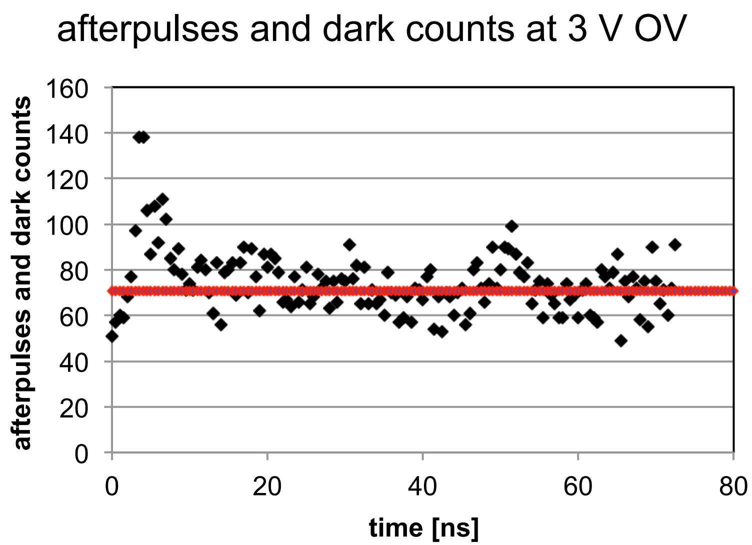
Afterpulses



In the silicon volume, where a breakdown happened, a plasma with high temperatures (few thousand degree C) is formed and deep lying traps in the silicon are filled. Carrier trapping and delayed release causes afterpulses during a period of several 100 nanoseconds after a breakdown.

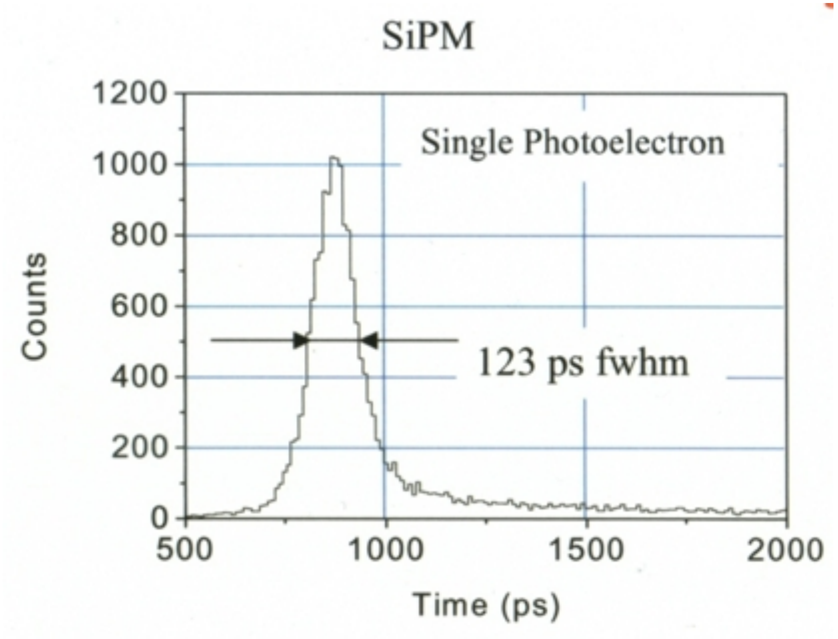
Hamamatsu 3x3-50UM LCT5:





Time resolution

Excellent time resolution can be achieved when the G-APDs are operated at high overvoltage.



Includes the contribution of the laser (40 ps) and the electronics (60 ps) ⇒ 100 ps FWHM for the SiPM from MEPhI/Pulsar

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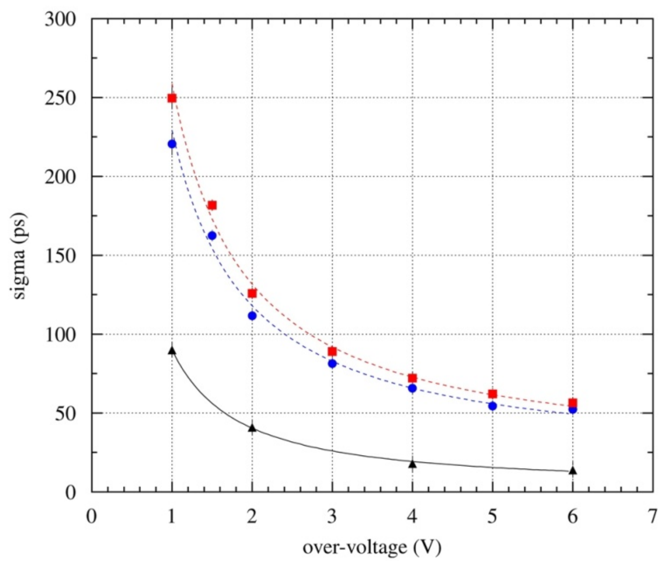

Time resolution for single photons with λ= 400 nm ● and λ=800 nm ● as a function of overvoltage. G-APD from FBK-irst

▲ show the contribution of electronic noise

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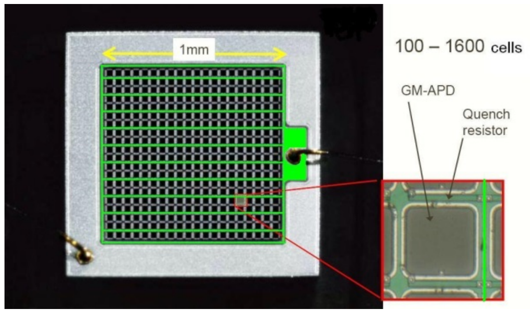
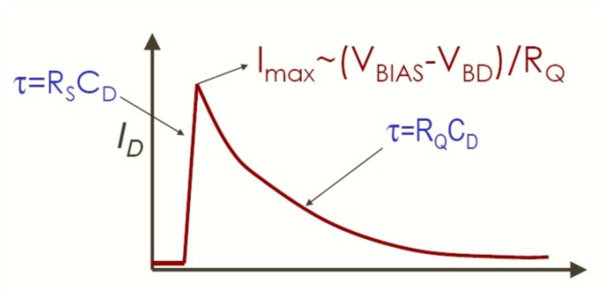
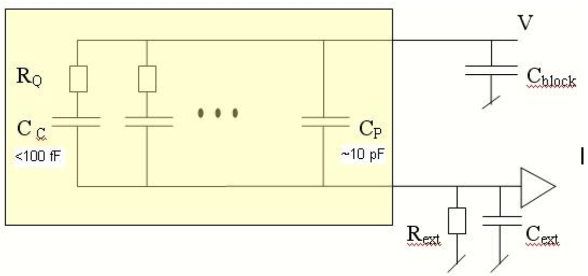
Timing: pulse shape

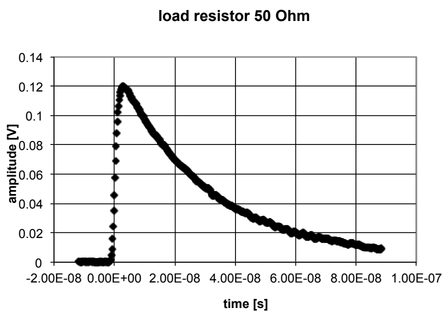


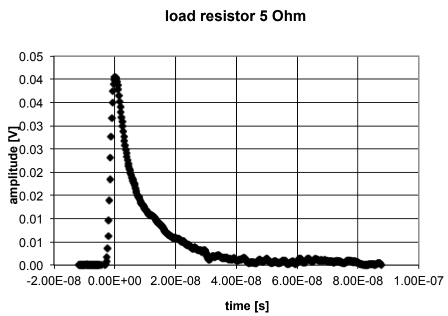
The usual interpretation
of the pulse shape:



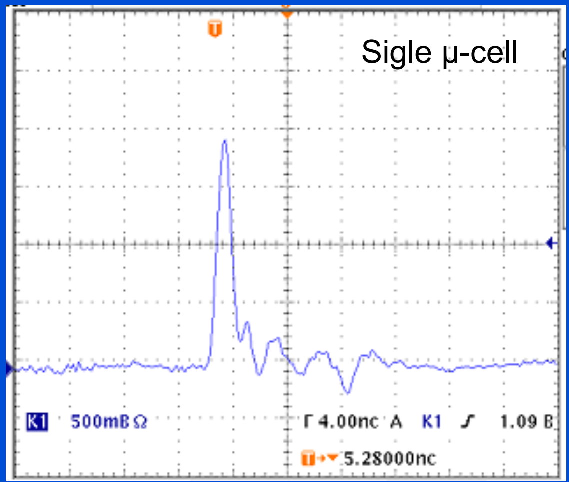
Simple equivalent circuit:

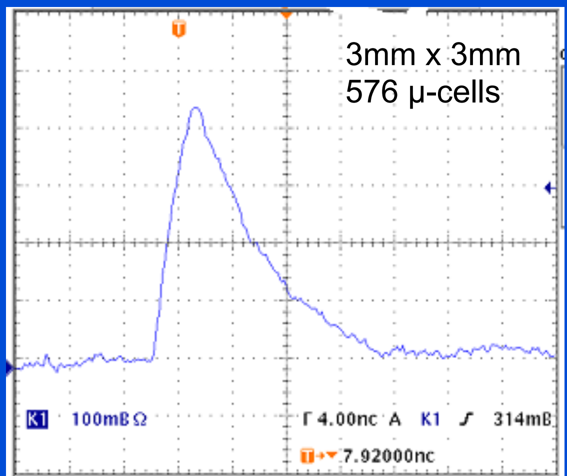






Pulse width depends on the SiPM chip size

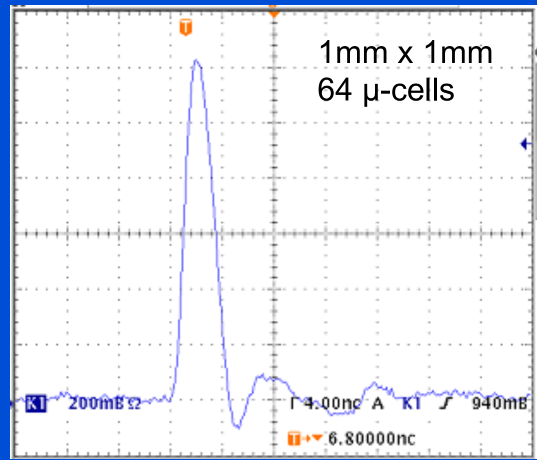


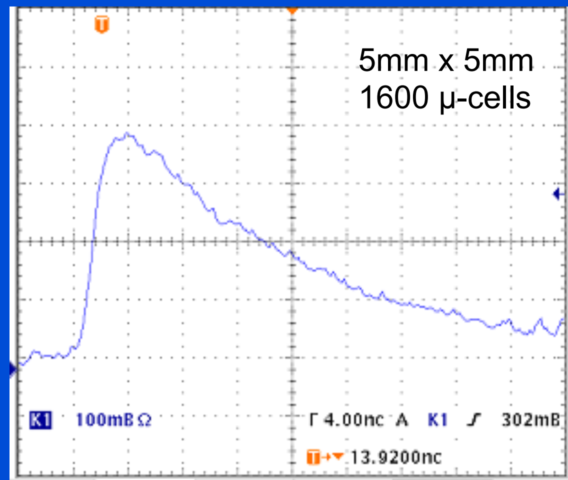


A single ph.e. pulse shape for different SiPMs

All tested devices had µ-cell size of 100µm x 100µm

Operated under gain: 10^7





Timing chip level

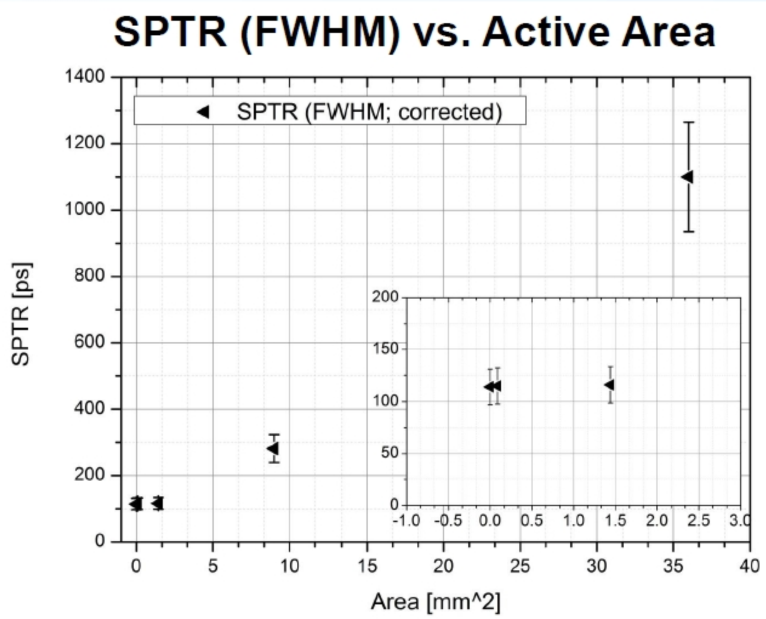
Universität der Bundeswehr München

SPTR-Comparison of SiPMs with Different Active Area

- All devices had 50 µm microcells
- Single-microcell: 114ps
- Array of 6 x 6 microcells: 115ps
- 1.2 x 1.2 mm² SiPM: 116ps
- 3.0 x 3.0 mm² SiPM: 270ps
- 6.0 x 6.0 mm² SiPM: 1.1ns

- Significant degradation of time resolution for large area device

- What is the reason? Transit Times?



Timing chip level

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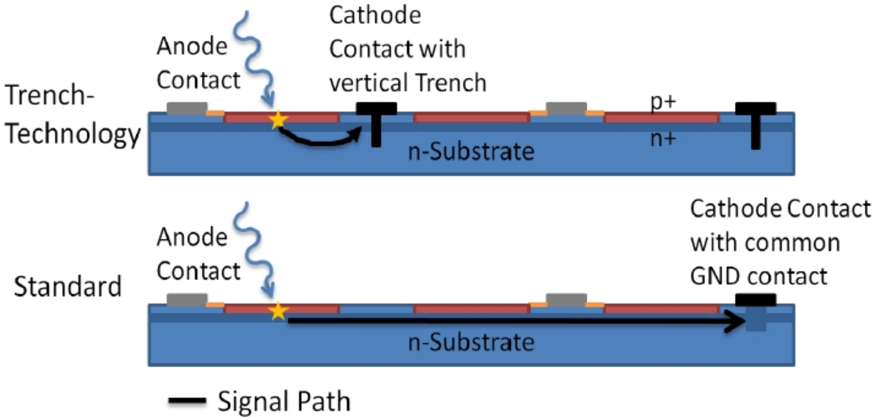
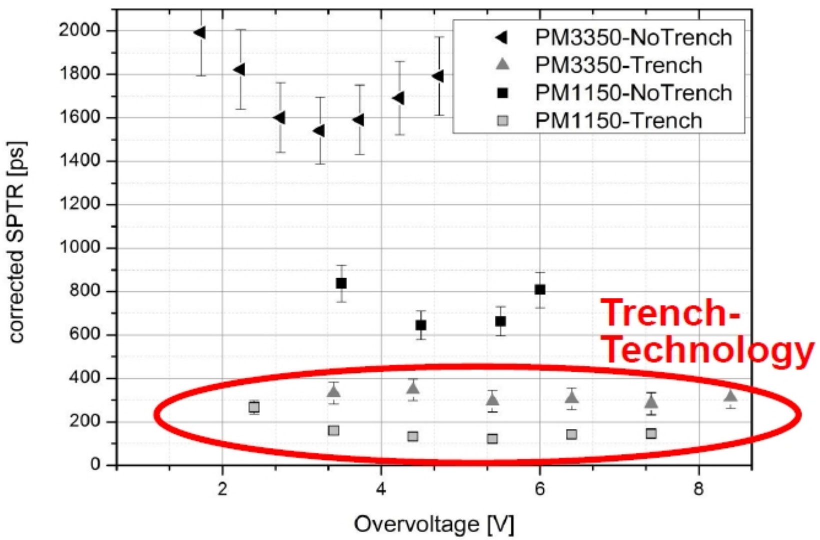
Comparison of Different Read-Out Methods

- Short and low resistive connection between microcell and aluminum grid improves pulse shape and time resolution
- Long path in burried n-doped layer decreases pulse shape homogenity





Trench-Technology achieves promising SPTR results.

Timing chip level

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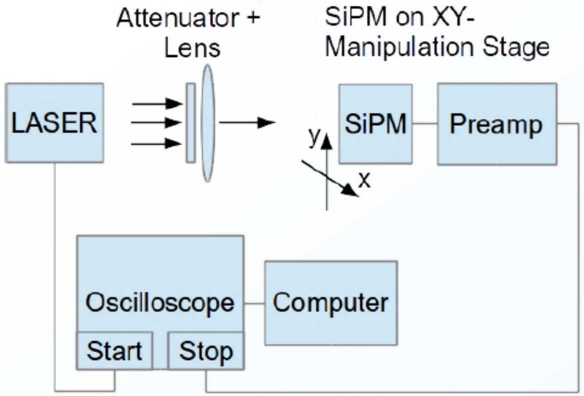
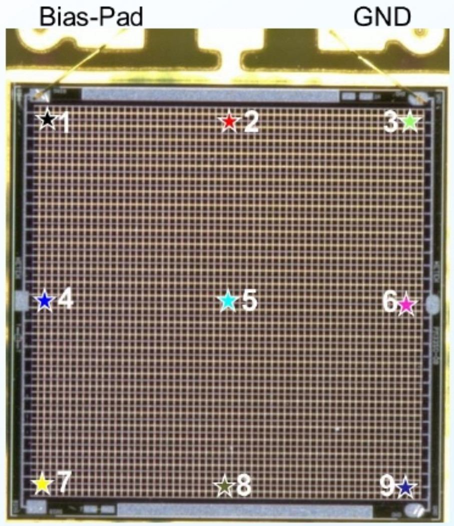
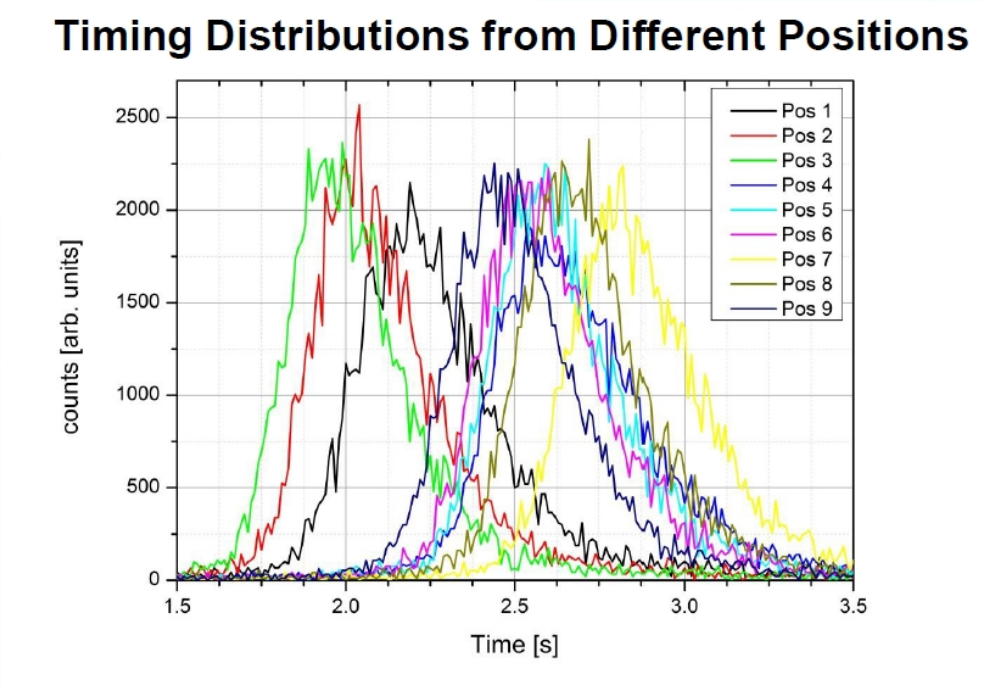
Transit time measurement with modified setup







- Transit times difference (TTD) significantly increases time jitter of the device
- For this reason a simulation model was developed

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Timing chip level

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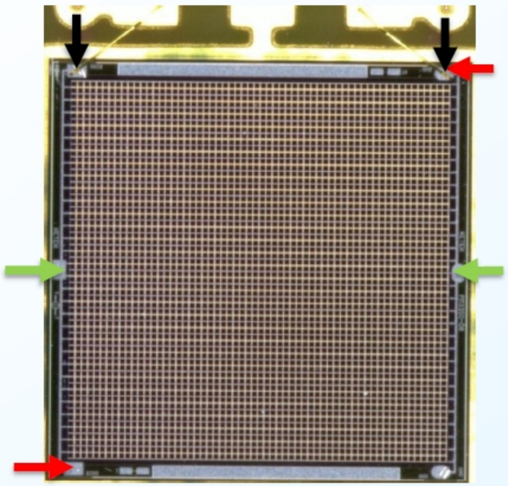
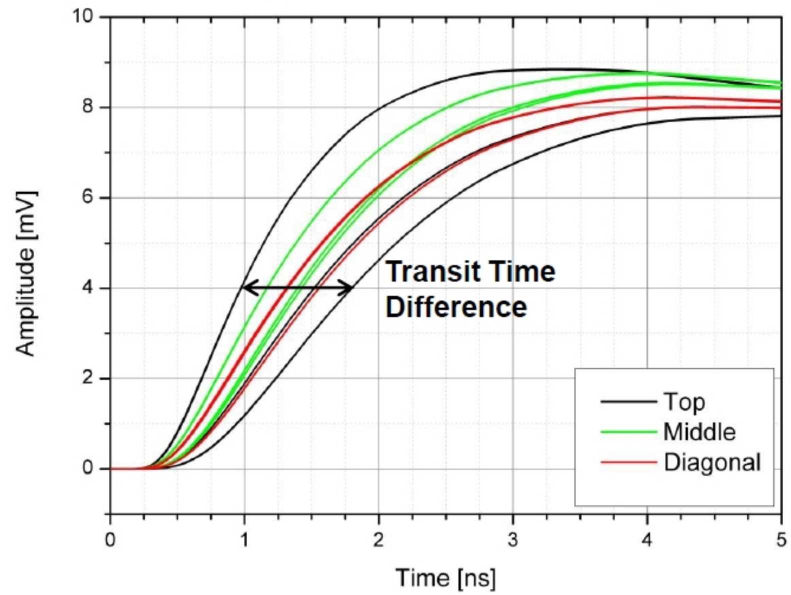
Variation of Signal and Bias Bond-Wire Connection

- Time difference between first and last occurring signal is used to calculate TTD
- Three different contact configurations were simulated and measured



Simulation of signals from different positions



Position of bond-wires has significant influence on the transit time difference between occurring signals

Timing chip level

Comparison of Simulation and Measurement

- Measurement of TTD between 9 different positions
- Arrows show the contact positions

Contact Configuration	Simulated max. Transit Time [ps]	Measured max. Transit Time [ps]
Standard (black)	860	900
Diagonal (red)	250	260
Middle (green)	270	240

Measurement of TTD with different contact configurations

0.13	0.17	0.19
0.03	0.03	0.00
0.24	0.23	0.21

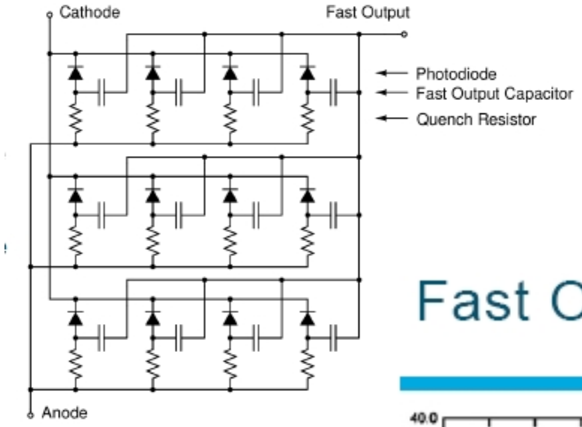
0.00	0.02	0.00
0.26	0.26	0.22
0.08	0.07	0.05

0.09	0.08	0.00
0.43	0.45	0.43
0.90	0.87	0.69

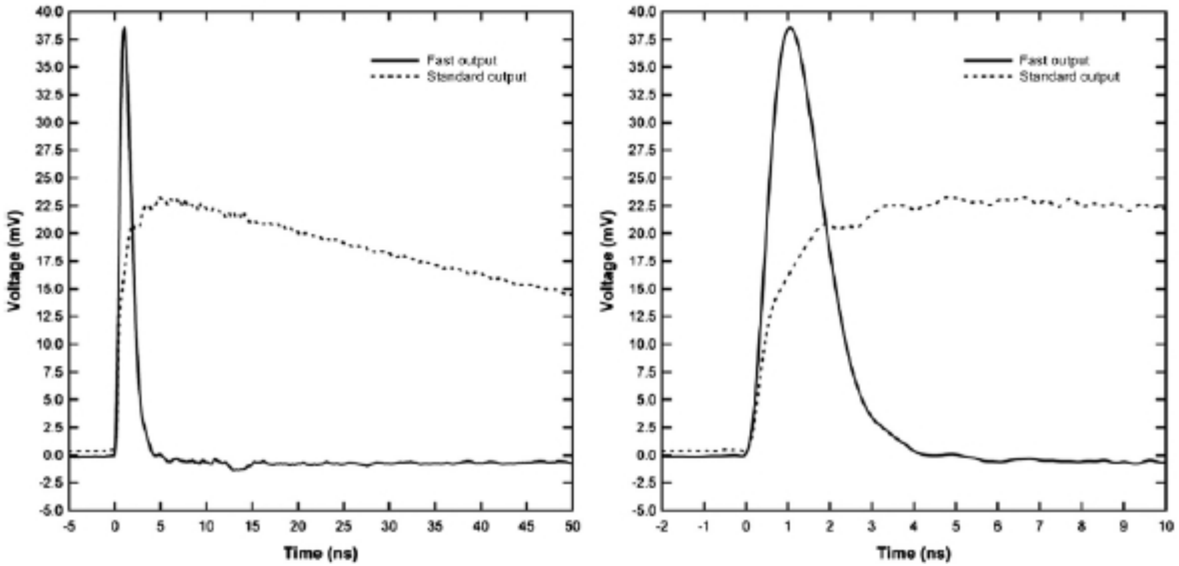
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00

Values in [ns] with ± 50ps tolerance

SensL approach



Fast Output Advantages



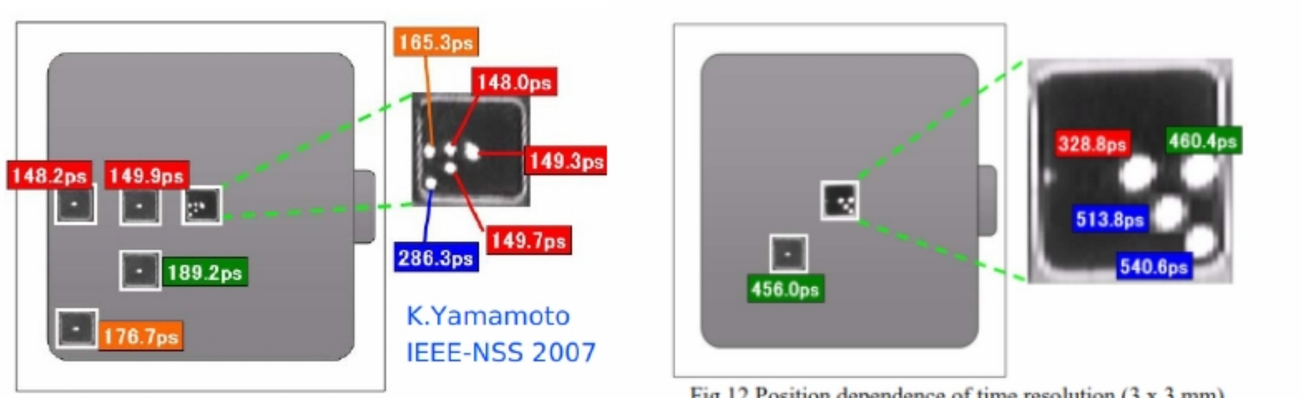
Plots show pulsed outputs for a 30035 sensor in response to a pulsed source

Timing at cell level (Elena Popova, Light 14)

SPTR for SiPM single cell

$\sigma_T = \sigma_V / dV(t)dt|_{t=T}$

1x1 mm2 –> 3x3mm2



Data include the system jitter
(common offset, not subtracted)

Fig.12 Position dependence of time resolution (3 x 3 mm)

- Another position of threshold (50% signal level)
- smaller amplitude (higher noise contribution)

+ TTS

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Timing at cell level (Elena Popova, Light 14)

Stand alone SiPM cell (p-n junction with limiting Si* resistor)

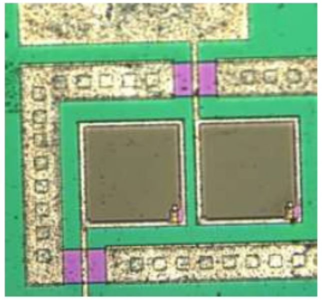
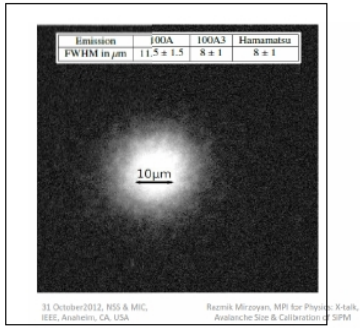


Photo of Geiger discharge in 100x100µm2 SiPM cell



100 µm

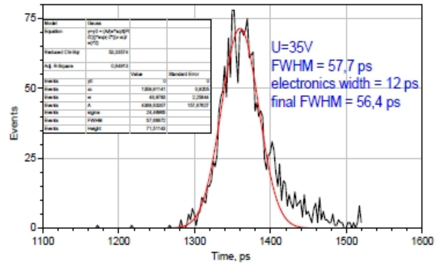
10µ dia independent of OV !

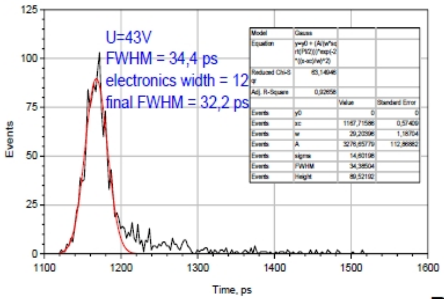
motivation

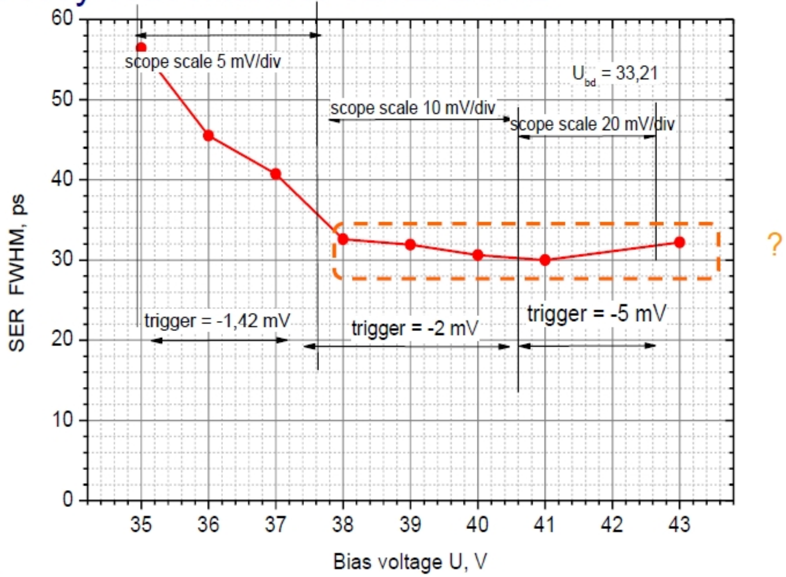
SPTR of a stand alone SiPM cell

min threshold, focused 2 micron spot, <200fs

scope LeCroy WaveRunner 620Zi 2GHz







Do we have ability to improve SPTR further?

06-10 of October 2014

E.Popova Light2014

Timing at cell level (Elena Popova, Light 14)

Geiger discharge

Starting point

SPAD Geiger discharge development

A.Lacaita, et al."Observation of avalanche propagation by multiplication assisted diffusion in p-n junction" Appl.Phys.Lett. 57, 489-491 (1990)
A.Lacaita, S.Cova et al."Photon-assisted avalanche spreading in reach-through photodiodes" Appl. Phys. Lett., 62, 606-608 (1993)
A.Lacaita, et al.:"Avalanche transients in shallow p-n junctions biased above breakdown", Appl. Phys. Lett. 67, 2627-2629 (1995)
A. Spinelli, A. Lacaita"Physics and Numerical Simulation of Single Photon Avalanche Diodes"IEEE Trans. Electron Devices, 44, 1931-1943 (1997)

SPAD (external or active quenching)

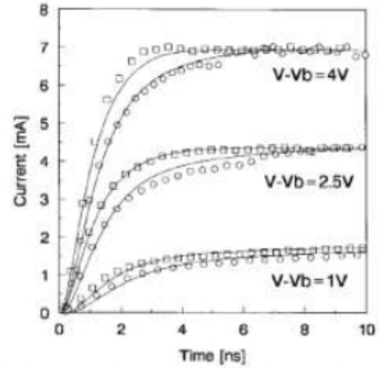
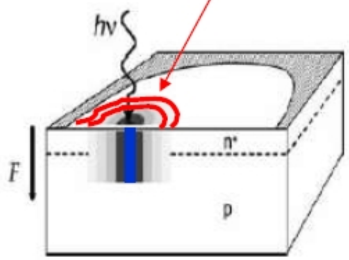


Fig. 18. Experimental data for avalanche triggered in the center of the active area (squares) and at one edge (circles). The solid lines are the corresponding simulation results. The active area of the SPAD is 140 × 14 μm.

Photon absorption

longitudinal (vertical) build-up of avalanche process

Transversal (lateral) spreading of avalanche

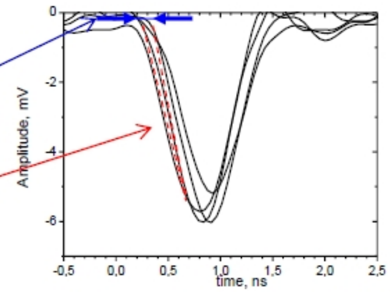


Multiplication assisted diffusion

Vertical build-up - latent jitter

Pulse waveform – lateral discharge spreading

SiPM cell (selfquenching)



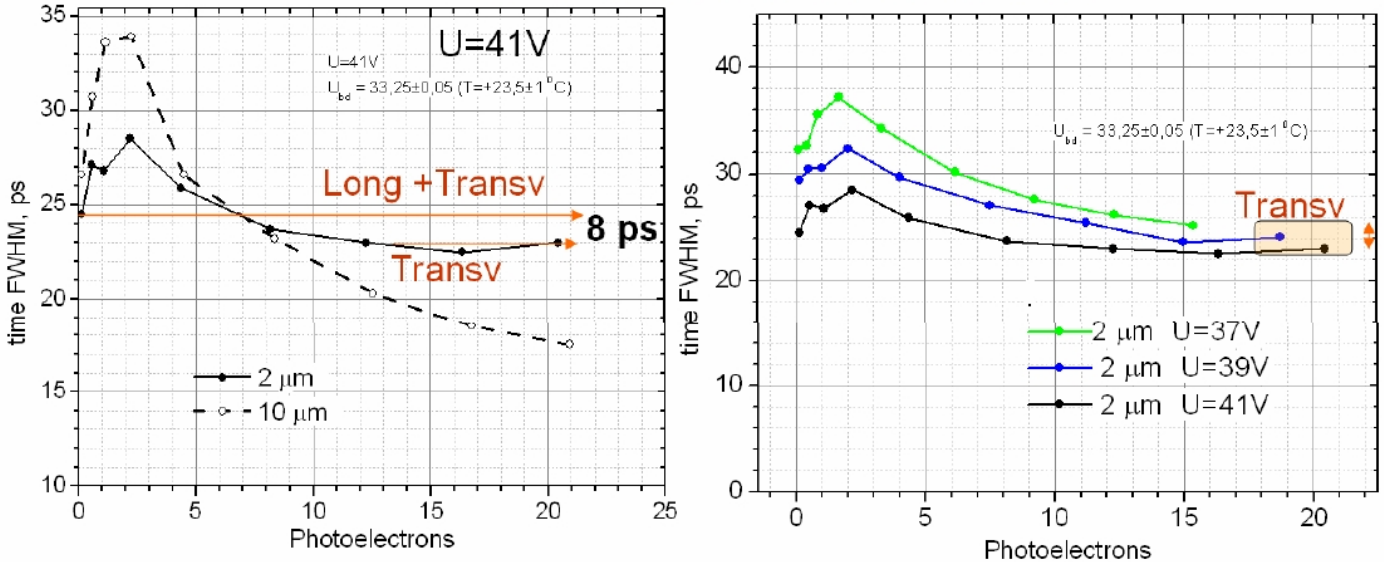
Similar approach approach can be applied to SiPM cell

06-10 of October 2014

E.Popova Light2014

Timing at cell level (Elena Popova, Prague 2015)

Timing for focused and unfocused light of different intensity
min threshold, FEMTO-T <200fs
scope LeCroy WaveRunner 620Zi 2GHz



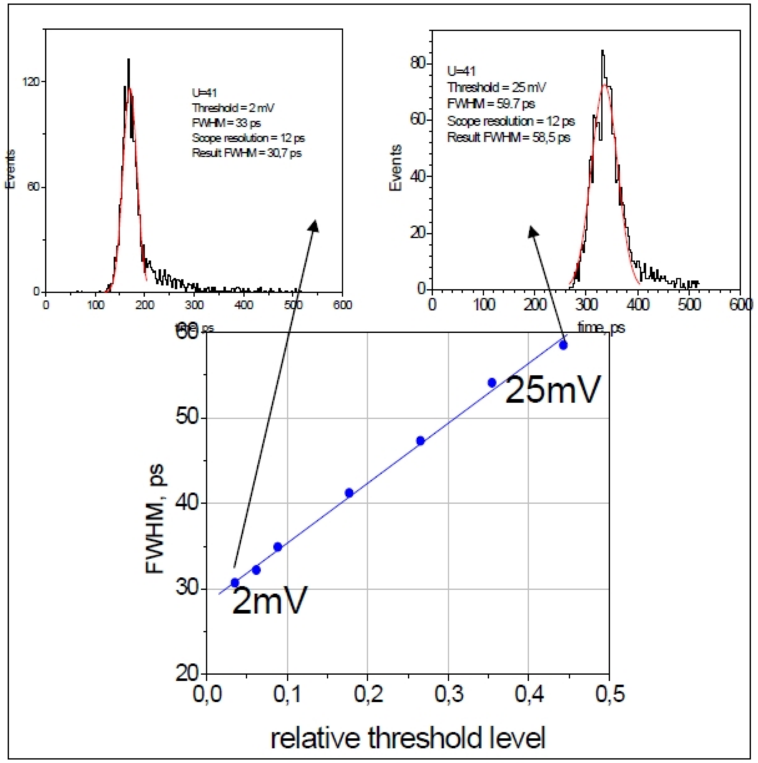
- We see difference between focused and unfocused light (number of avalanches), but 2 micron focusing is not small enough
- For 41V longitudinal component is 8ps (transversal is 19.6, scope - 12 ps)
- Transversal spreading has small dependence from overvoltage)
- With lower threshold timing may improve further

E.Popova MEPhI FAST 15th April 2015

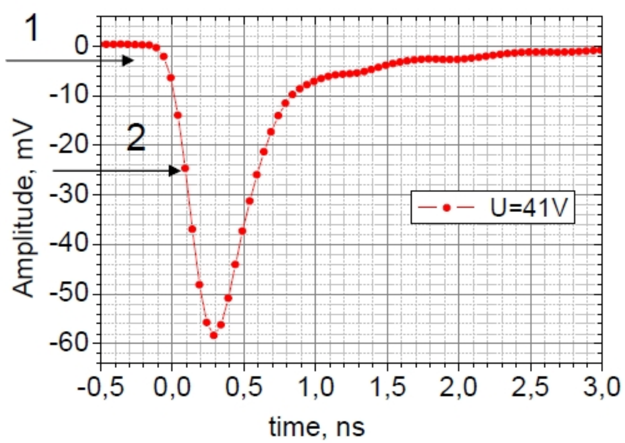
Timing at cell level (Elena Popova, Prague 2015)

MEPHI tests

Single Photon Time Resolution of SiPM cell 100x100μm2
FEMTO-T Laser+microscope system t_{pulse}<200 fs, λ=876 нм.



U=41V (23%OV) no preamp



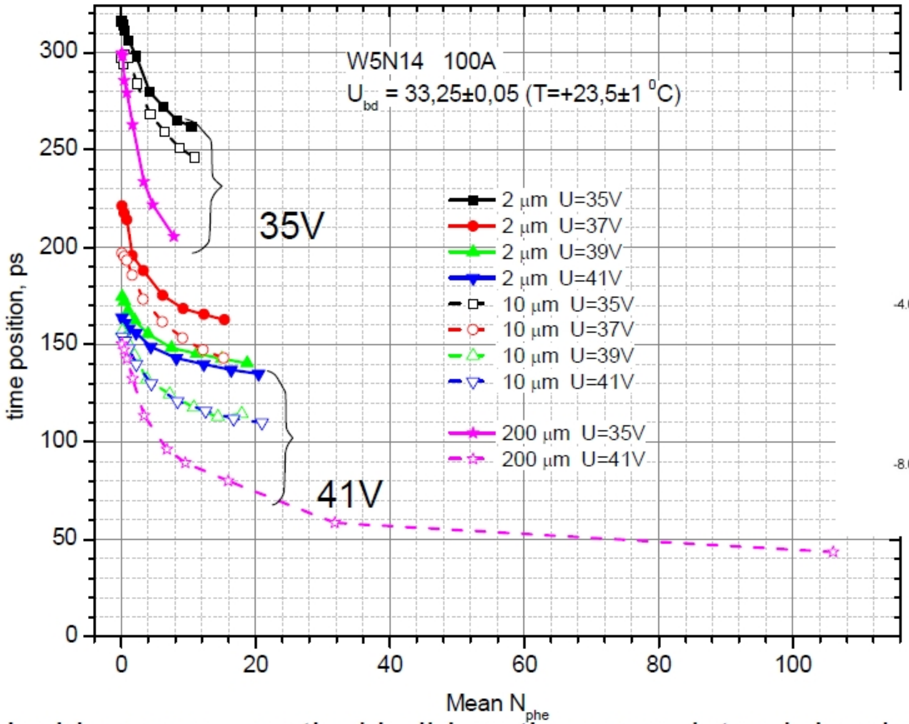
Digital scope LeCroy
WaveRunner 620Zi 2GHz

E.Popova MEPhI

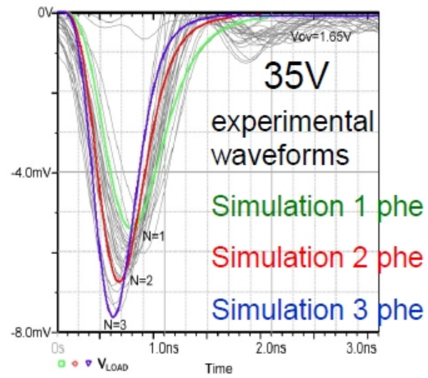
FAST 15th April 2015

Timing at cell level (Elena Popova, Prague 2015)

Average response delay



SPICE model for lateral discharge development



Inside group – vertical build-up the same, lateral development - different

Focused light (2 µm)– 35 and 37V – different curves, 39 and 41 almost equal.

Concernig with vertical build-up

Timing

What can we do?

- Operate at high overvoltage with the consequence of high dark count rates, crosstalk, afterpulses.
- Set the threshold as low as possible. Needs a low noise amplifier.
- Sacrifice PDE:

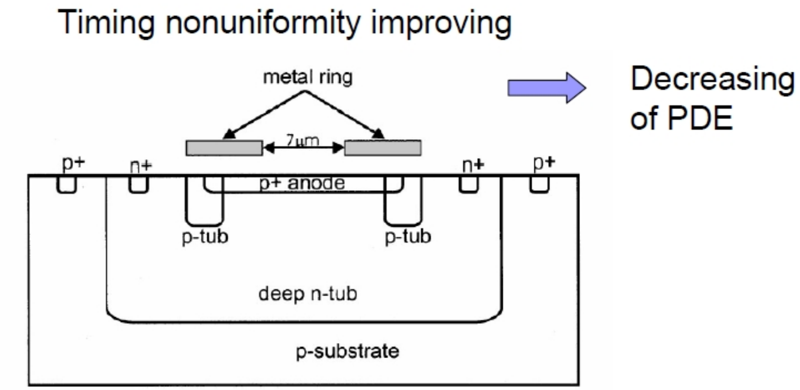
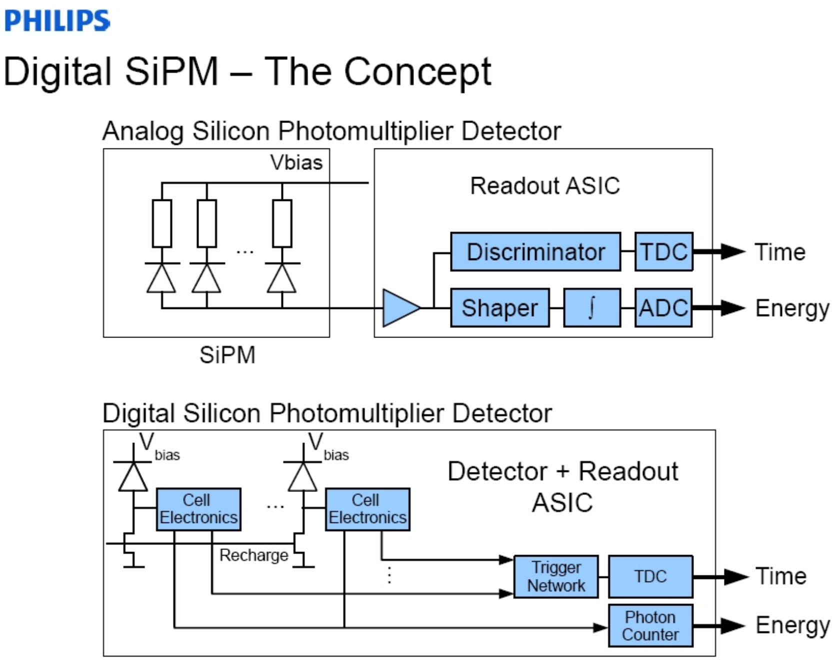
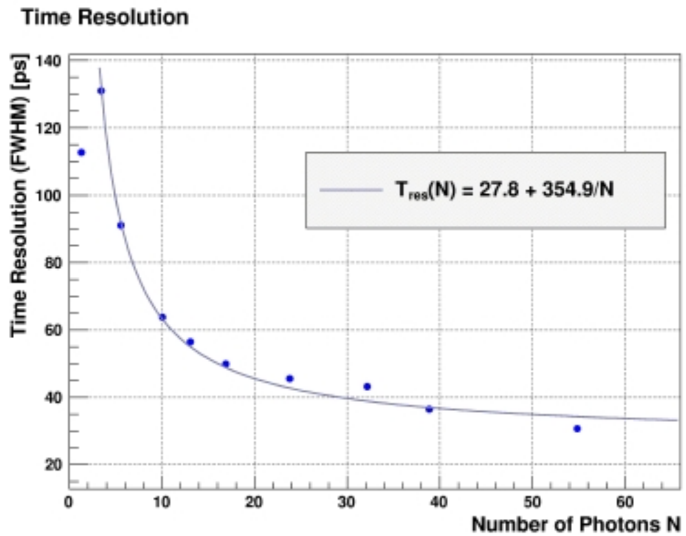


FIG. 1. Schematic of the APD cross section. The p-tub implantation acts as a guard ring, preventing premature edge breakdown.

Rochas et al.
Rev. Sci. Instrum., Vol. 74, No. 7, July 2003

Timing: PHILIPS SiPM





- Sensor triggered by attenuated laser pulses at first photon level
- Laser pulse width: 36ps FWHM, λ = 410nm
- Contribution to time resolution (FWHM):

  SPAD: 54ps, trigger network: 110ps, TDC: 20ps

- Trigger network skew currently limits the timing resolution
- Manual fine-tuning of the trigger network will reduce the skew

3D-SiPM (Sherbrooke)

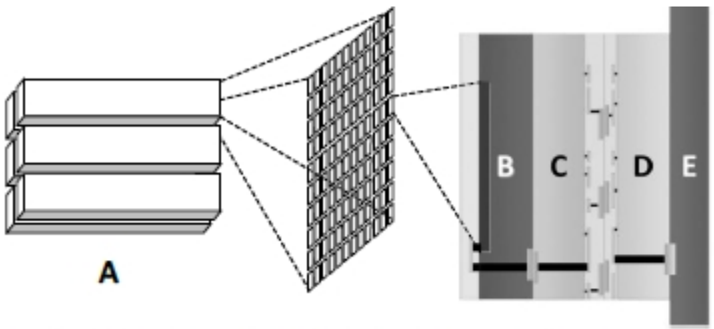


Fig. 1. Detector module break down. A) Scintillation crystal array. B) 22 x 22 SPAD array implemented in Dalsa 0.8 µm HV CMOS. C) Quenching circuit layer, Global Foundries 130 nm CMOS. D) DAQ, Global Foundries 130 nm CMOS. E) PCB.

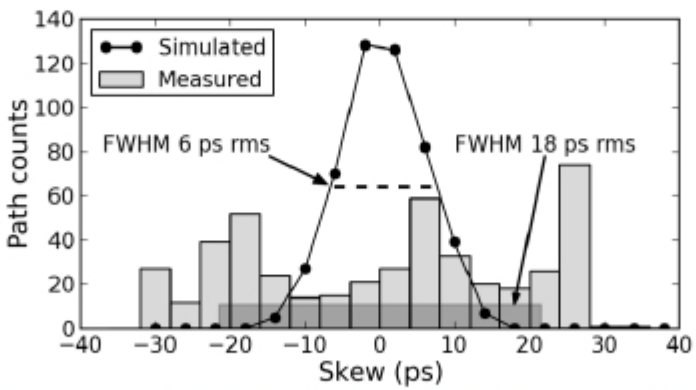


Fig. 11. Trigger tree skew histogram for the 484 possible paths between a SPAD input pulse and the TDC. Dotted line shows simulated FWHM, transparent grey box shows measured FWHM.

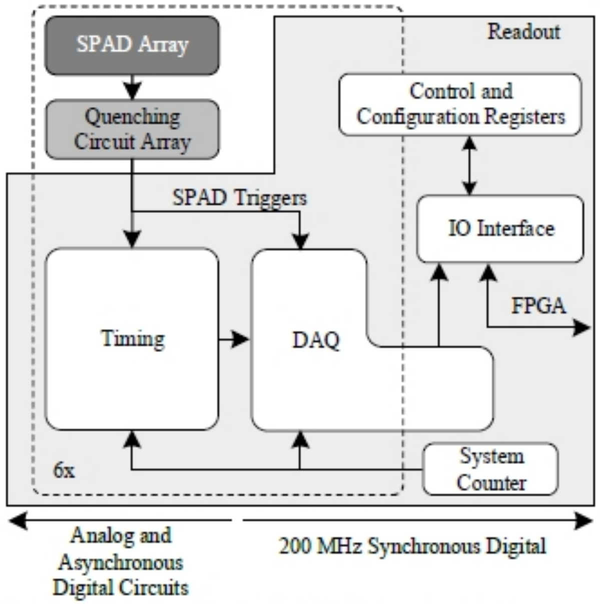


Fig. 2. Architecture dataflow. The SPAD array, quenching circuit array and readout sections are layers C, D and E in figure 1, respectively. Dotted line represents channel physical separation.

M.-A. Tetrault et al., arXiv: 1406.3858

Timing (S. Gundacker et al., NIMA 787(2015)6–11)

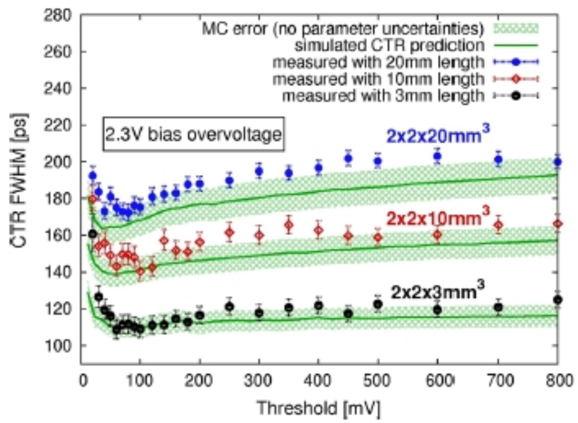


Fig. 5. Comparison of CTR simulations with measurements as a function of the NINO threshold voltage for crystals with dimensions of $2 \times 2 \times 3\ mm^3$, $2 \times 2 \times 10\ mm^3$ and $2 \times 2 \times 20\ mm^3$ [8].

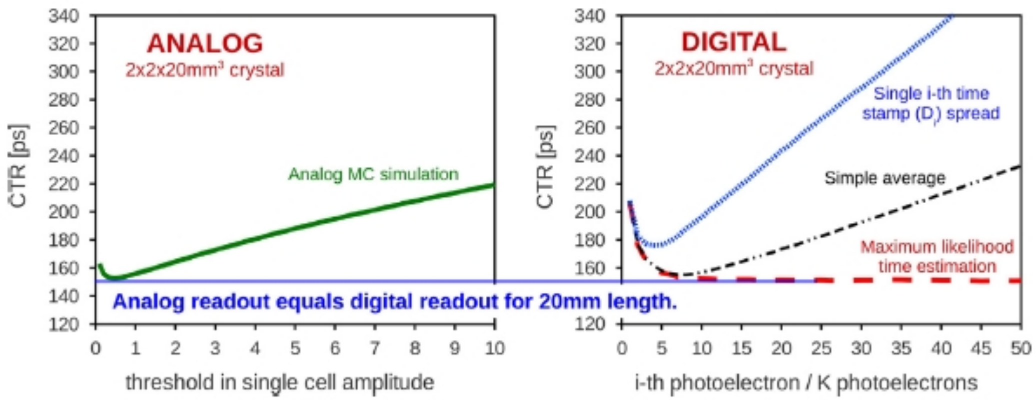
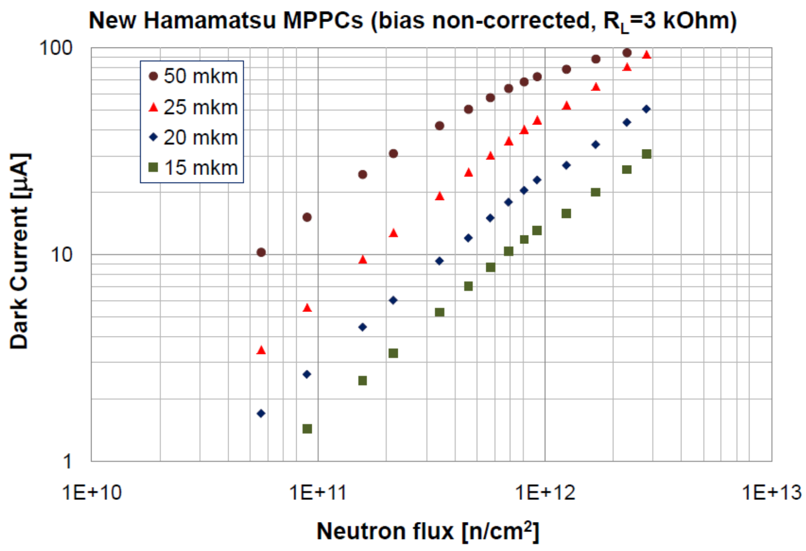
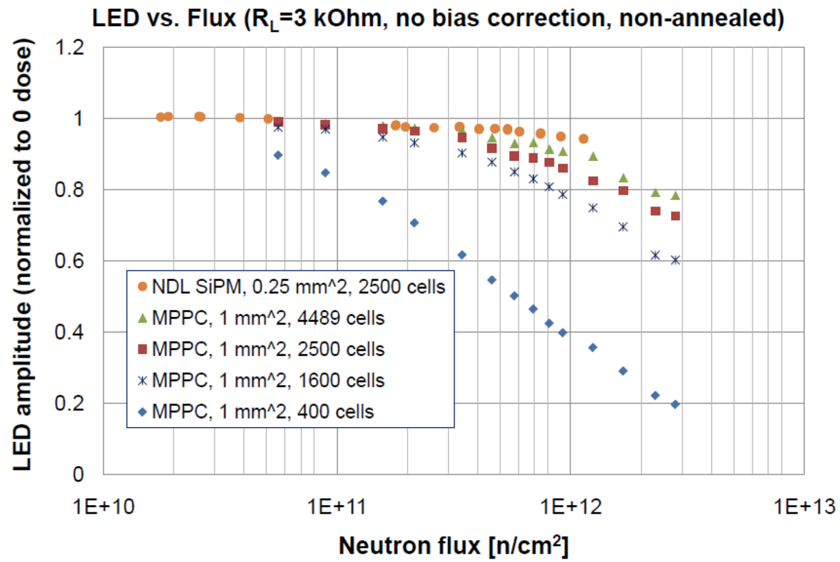


Fig. 7. Analog and MD-SiPM simulations for a crystal with dimensions of $2 \times 2 \times 20\ mm^3$. In the simulations we set to zero the dark count rate and the crosstalk of the SiPM as well as the electronic noise. The simulation error is in the range of 5%, not including parameter uncertainties.

Radiation hardness





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

2nd CHIPP Workshop on Detector R&D, 12 September 2013

Radiation hardness

^{60}Co irradiation:

R. Pagano et al. / Nuclear Instruments and Methods in Physics Research A 767 (2014) 347–352

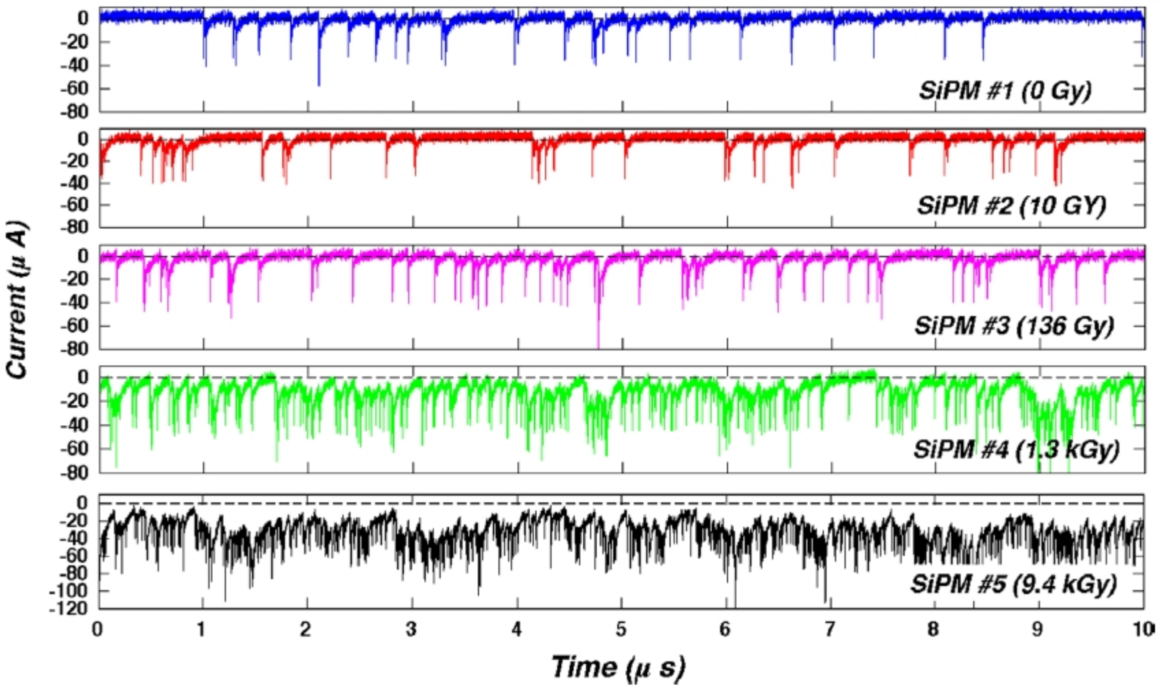


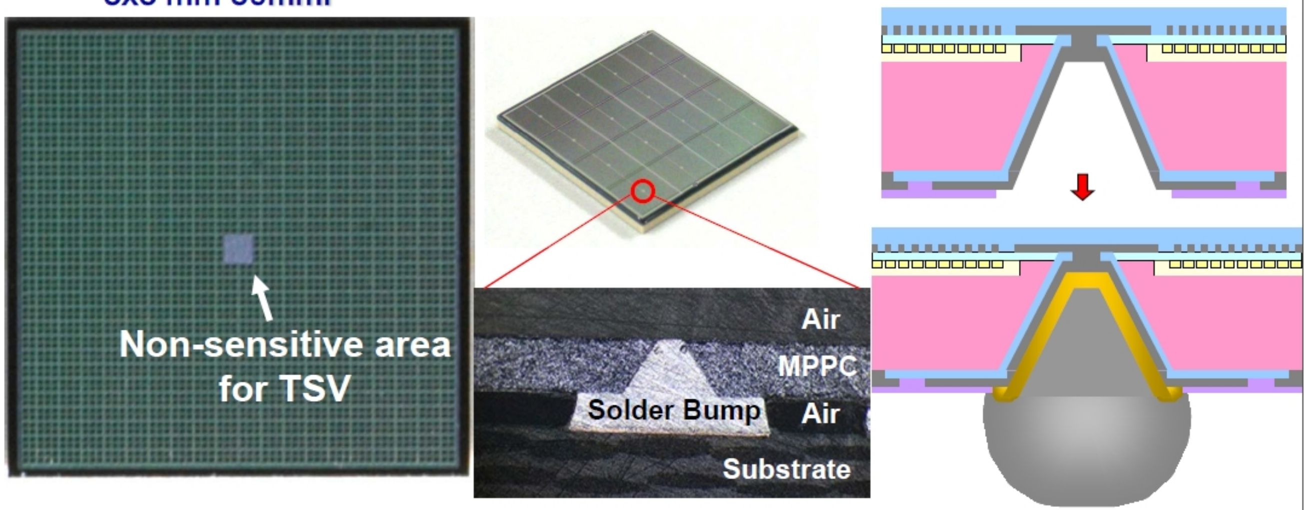
Fig. 2. Dark current traces at RT (21° ± 3 °C) for a ΔV=3 V for the SiPM before and after irradiation at different doses.

Large area - arrays

HAMAMATSU
PHOTON IS OUR BUSINESS

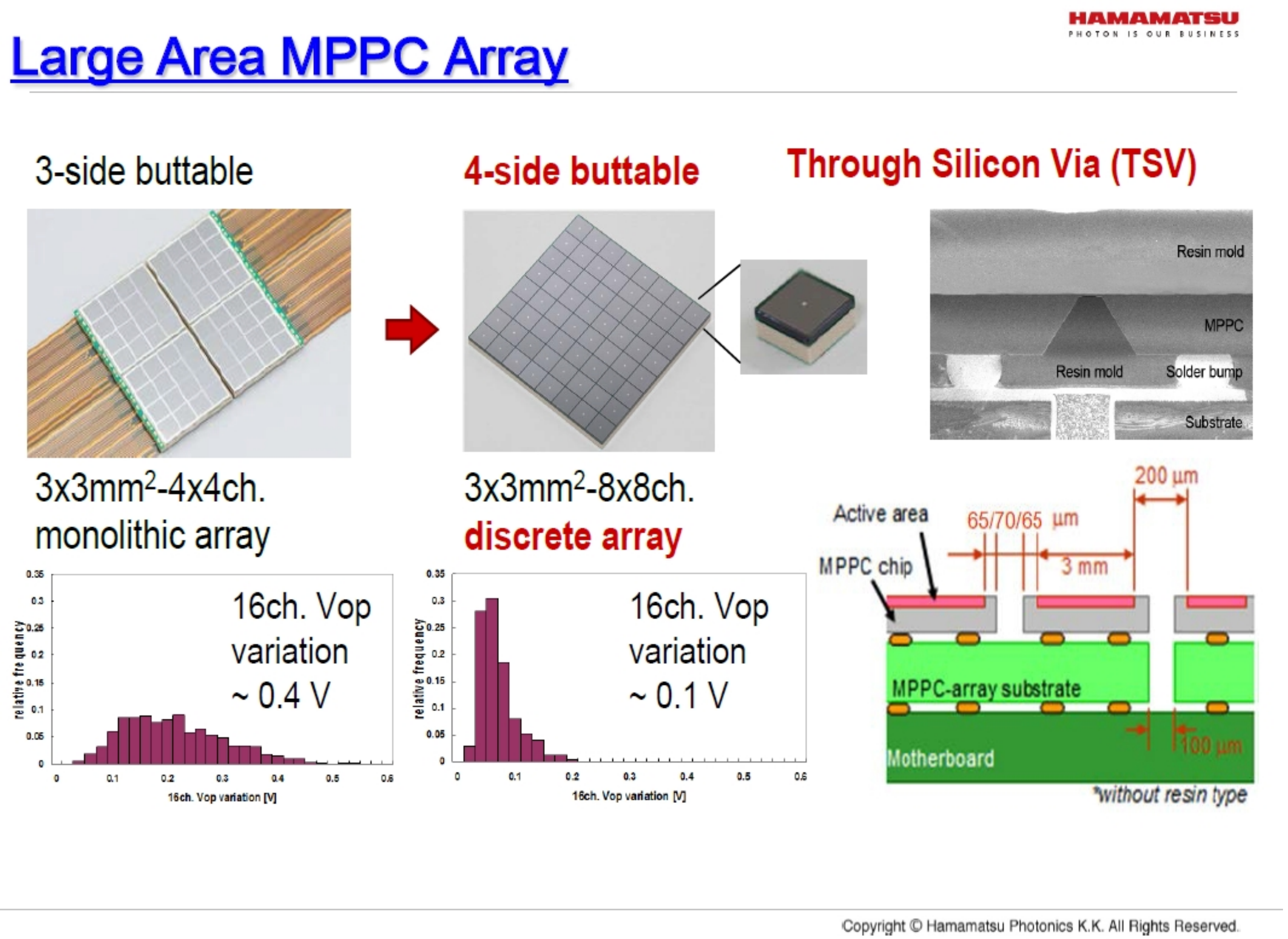
Through Silicon Via (TSV) Technology

3x3 mm 50mmP



- The TSV process requires small non-sensitive area (200 μm sq.).
- This area is corresponding to 0.44% of total active area, and it is hardly affected to the PDE (photon detection efficiency).

Large area - arrays



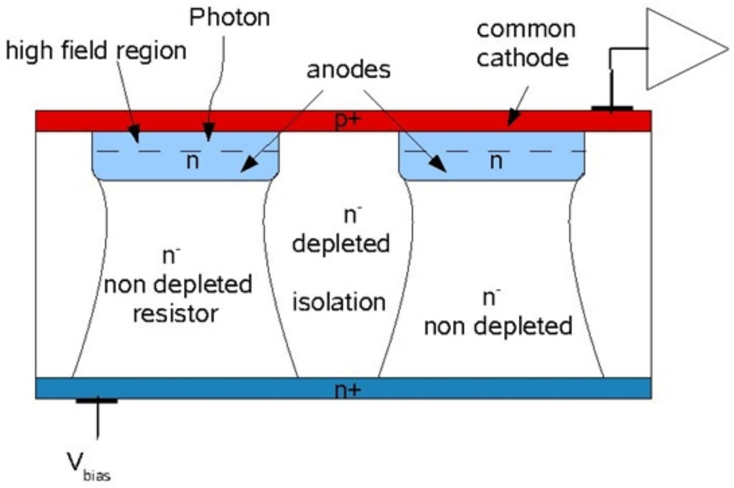
SiMPI: G-APD with bulk integrated quench resistors from MPI-HLL

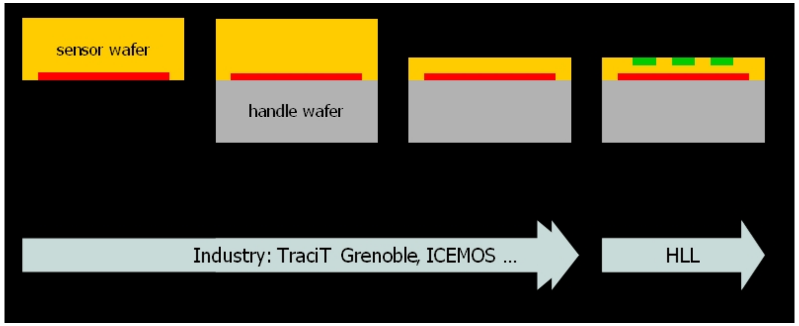
geometric factor ~75 % - no resistor on the surface → PDE ~ 60 %

free entrance window for light, no metal necessary within the array

allows engineering of the entrance window

improved radiation hardness – no lateral high field regions on the surface





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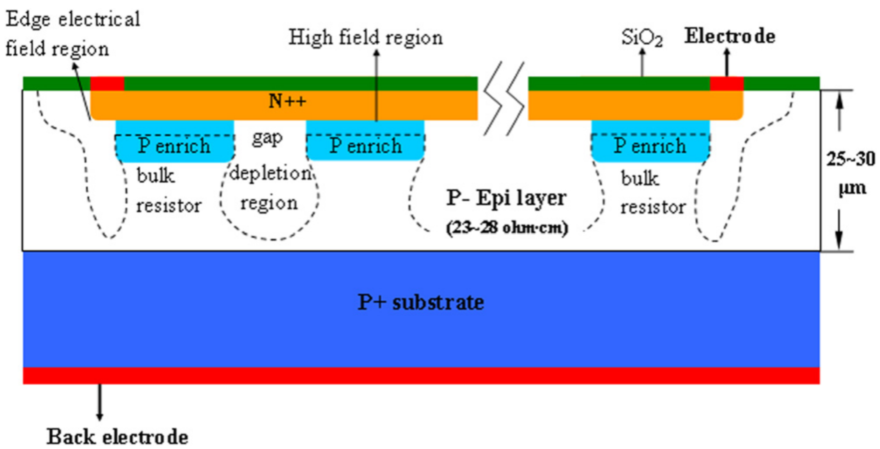
SiPMs with bulk integrated quenching resistors from NDL(Beijing)



Structure of the SiPM with bulk integrated resistors (Area: 0.5x0.5 mm^2, 10 000 $cells/mm^2$)

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

Conclusion

SiPMs have been rapidly improved in the 15 years after their invention. There is still room for further improvements but I assume the development speed will slow down.

Hamamatsu considers their LCT5 type as sort of ‚final product‘.

What we can expect is the implementation of technological progress like through silicon vias.

Very important seems to me that we gain a better understanding of the devices which will allow us a better design of detectors employing SiPMs and of the readout electronics.

List of producers (incomplete)

Since 1989 many G-APD structures were developed by different developers:

- CPTA (Moscow)
- Zecotek (Singapore)
- MEPhI/Pulsar (Moscow)
- Excelitas (Montreal, Canada)
- Amplification Technologies (Orlando, USA)
- Hamamatsu Photonics (Hamamatsu, Japan)
- SensL (Cork, Ireland)
- RMD (Boston, USA)
- MPI Semiconductor Laboratory (Munich, Germany)
- KETEK (Munich, Germany)
- FBK-irst (Trento, Italy)
- STMicroelectronics (Italy)
- ……

Every producer uses its own name for this type of device: MRS APD, MAPD, SiPM, SSPM, SPM, DAPD, PPD, G-APD