October 27, 2013

SiPM's Timing Properties

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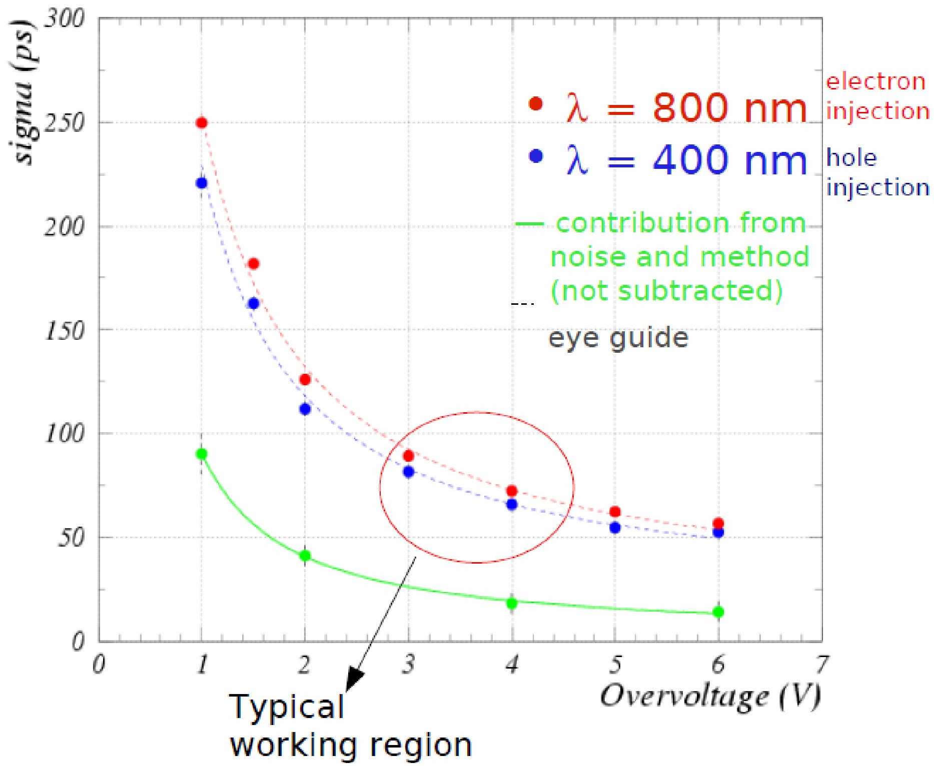
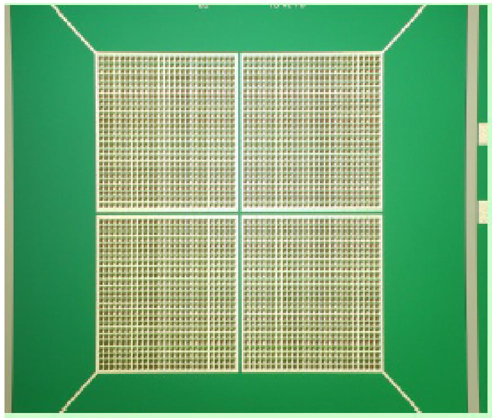
Moscow Engineering and Physics Institute

Seoul meeting on fast timing

Single Photon Time Resolution (SPTR) of SiPM



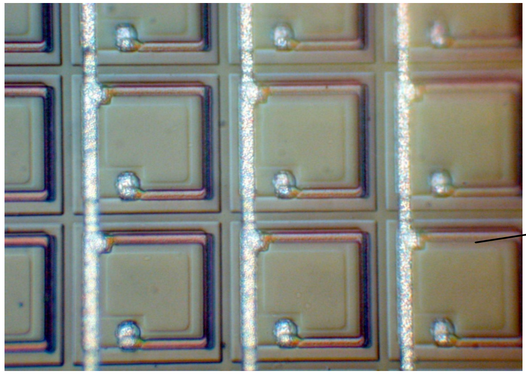


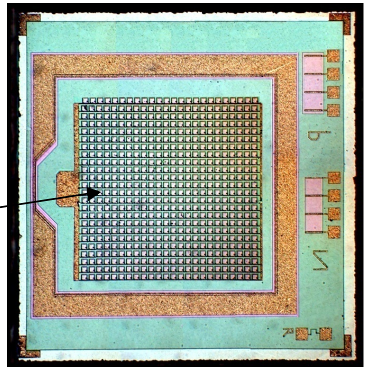
G.Collazuol et al NIMA 581 (2007) 461

- •Which processes contribute
- •to SPTR?
- •SPTR of different area SiPMs
- •SiPM + Scintillating (Cherenkov) crystals

SiPM signal

SiPM is a system of connected together cells with one common readout pad





Metal buses
–
delay lines

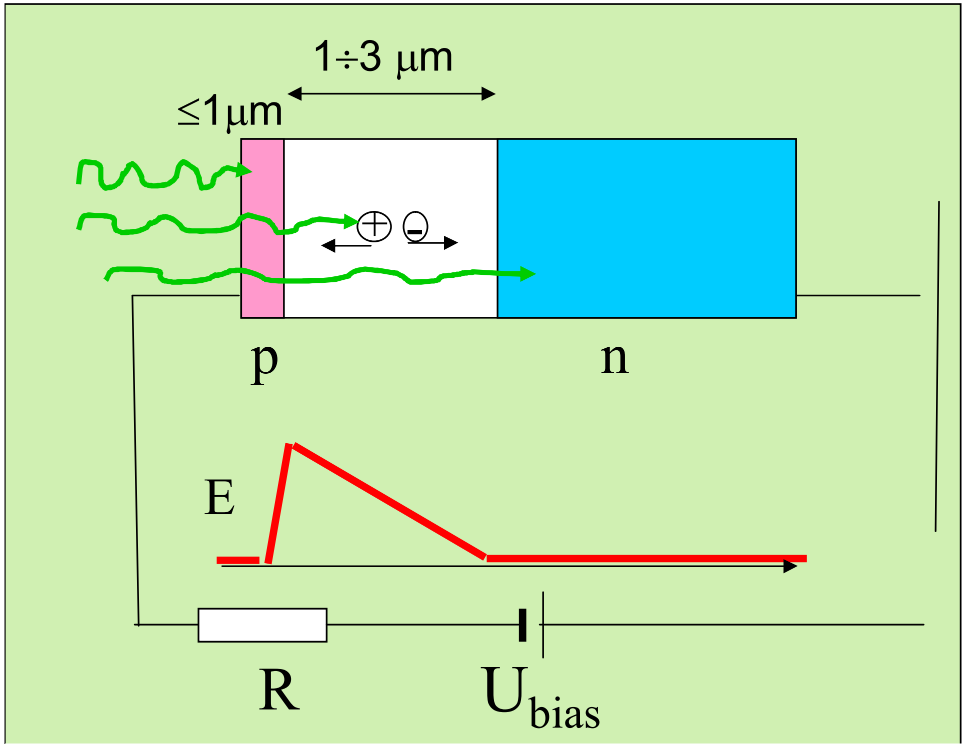
Geiger discharge generation

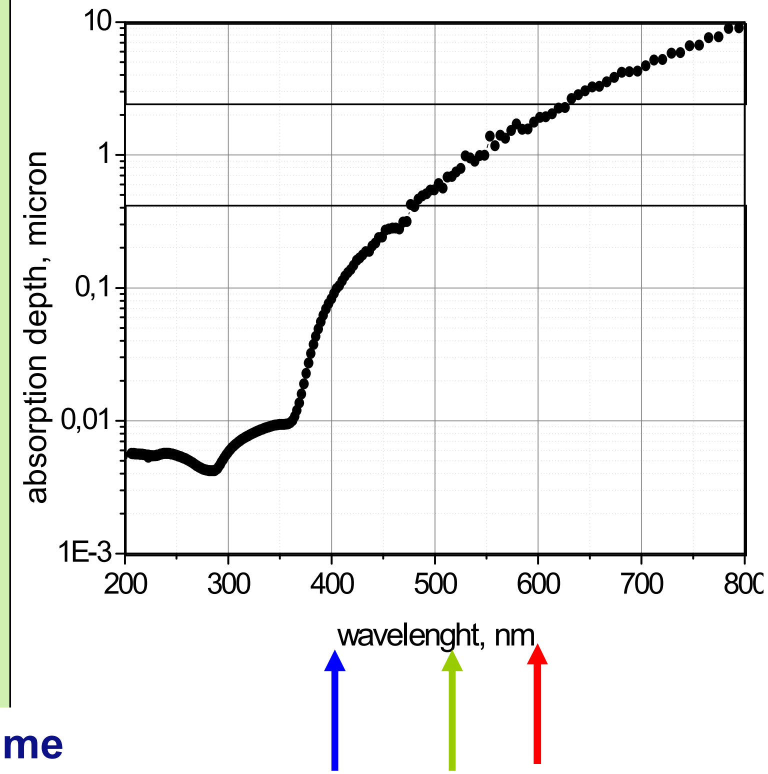
- Photoeffect (0 time delta-function)
- Diffusion in undepleted regions
- Drift in depleted region
- Vertical Avalanche build-up
- Transversal Geiger discharge expansion

Electrical signal propagation

•Pixel position
•Total number of pixels in SiPM
•Signal readout

SiPM cell





1.Photoeffect (light absorption) - **0 time**

2. Diffusion inside undepleted regions (~0 fields) - $\tau=L^2/D$ D=38cm^2/c L=0.3-1μm

τ≈25-250ps

3. Drift in depleted region (low fields) 10^7 cm/c – saturated e^- velocity x=1-3μm

τ≈10-30ps

Avalanche build up 1D

Impact ionization in high electric fields

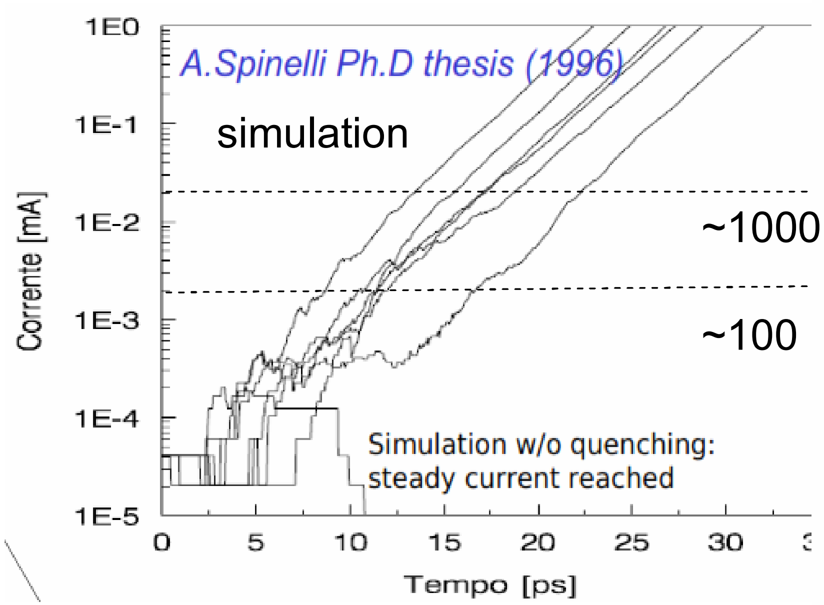
α electron
β hole

Ionization coefficients

Average number of ionization along carrier trajectory on unit length

$I = qNv/W$ Ramo's theorem

q- charge,
N- number of charged carriers,
V – velosity of carriers,
W- depletion region width



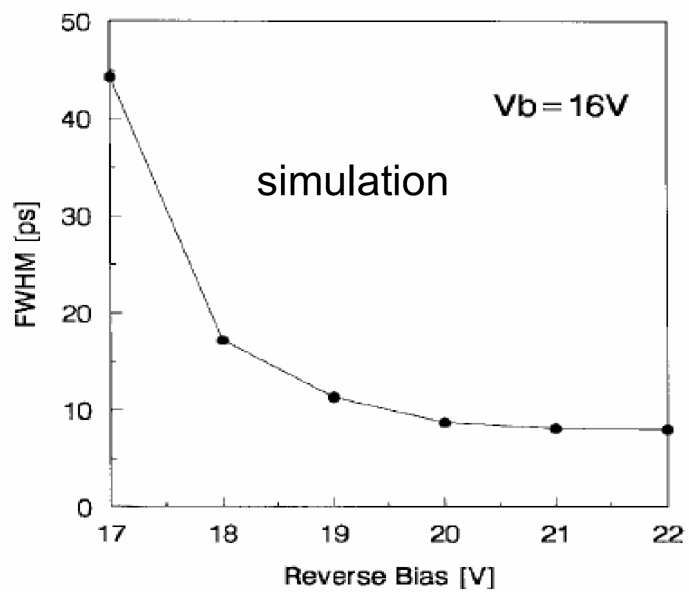


Fig. 6. Time jitter due the avalanche buildup statistics in a shallow junction SPAD as a function of the reverse bias voltage.

Speed of avalanche build up depends from applied voltages and depletion region depth

Geiger discharge

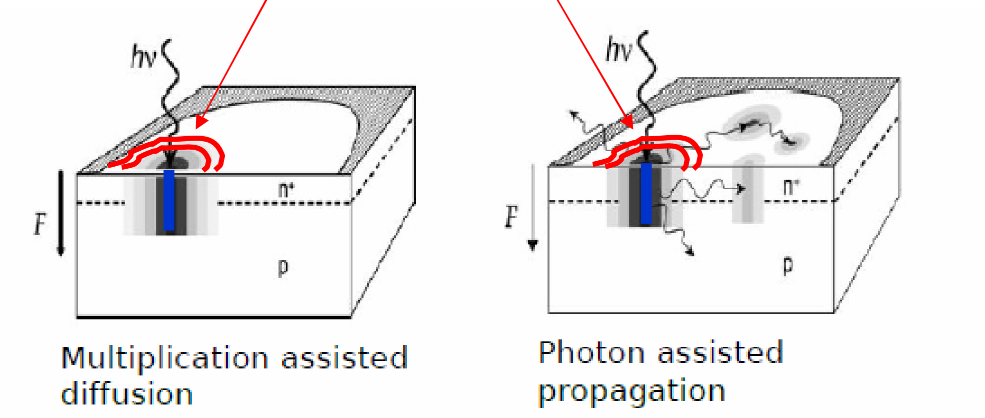
SPAD Geiger discharge development

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)

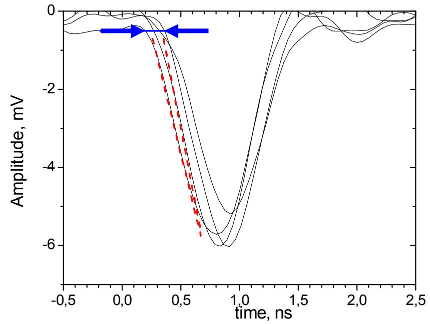
Photon absorption

longitudinal build-up of avalanche process

transversal spreading of avalanche



SiPM cell



Similar approach approach can be applied to SiPM cell

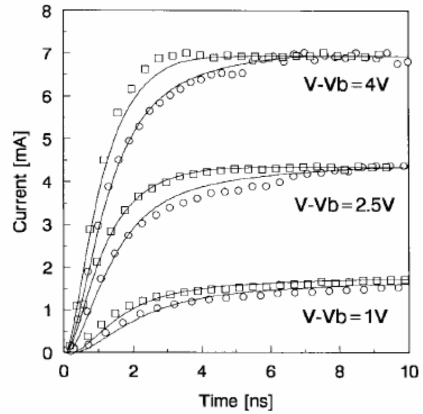
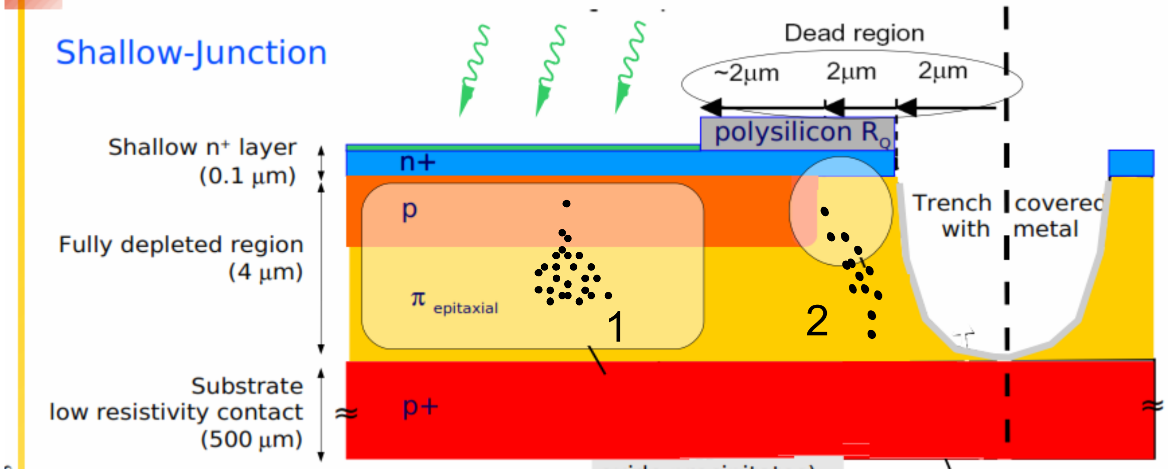


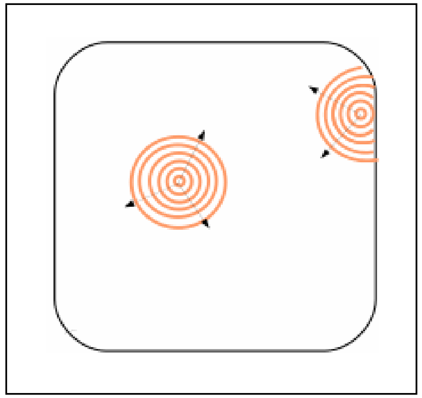
Fig. 18. Experimental data for avalanche triggered in the center of the active area (squares) and at one edge (circles). The solid lines are the corresponding simulation results. The active area of the SPAD is $140 \times 14\ \mu m$.

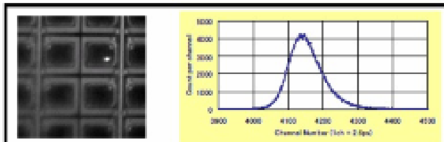
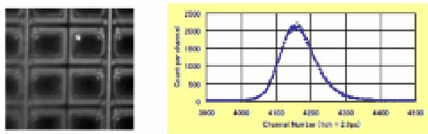
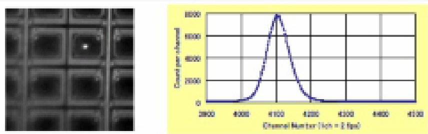
Single SiPM cell

Close up of a cell (IRST technology)



areas in a cell:
1.Active central part of the cell
2.Cell's perifery
3.Intercells area



	FWHM = 263 ps
	FWHM = 294 ps
	FWHM = 192 ps

K.Yamamoto PD07

Lower jitter if photoproduction at the center of the cell

SPAD SPTR. Threshold level

Statistical fluctuations in the avalanche:

- Longitudinal build-up (minor contribution)
- Transversal propagation (main contribution):

For minimization of jitter a discriminator threshold has to be as low as possible. Noise is a problem

Electronics letters 3rd March 2005 Vol.41 №5, I. Rech et al.

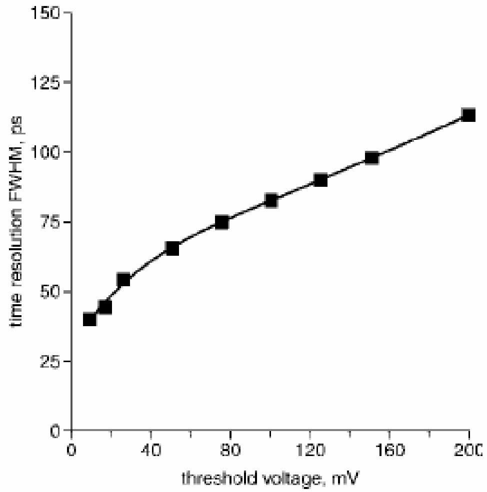
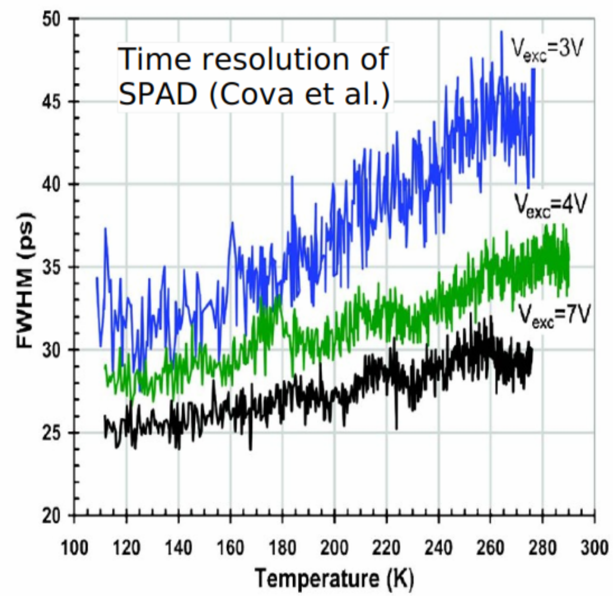


Fig. 2 FWHM time resolution of SPAD having active area diameter of 50 µm against threshold voltage of timing discriminator

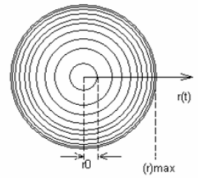


I.Rech el al, Rev.Sci.Instr. 78 (2007)

For very low threshold (before transversal propagation)jitter doesn't depend from SPAD (SiPM) cell size. But for SiPM cell we can see only small part of Geiger discharge current - equivalent SiPM curcuit

$I_{load}=[Cfast/(Cfast+Cpixel)]*I_{inside}$

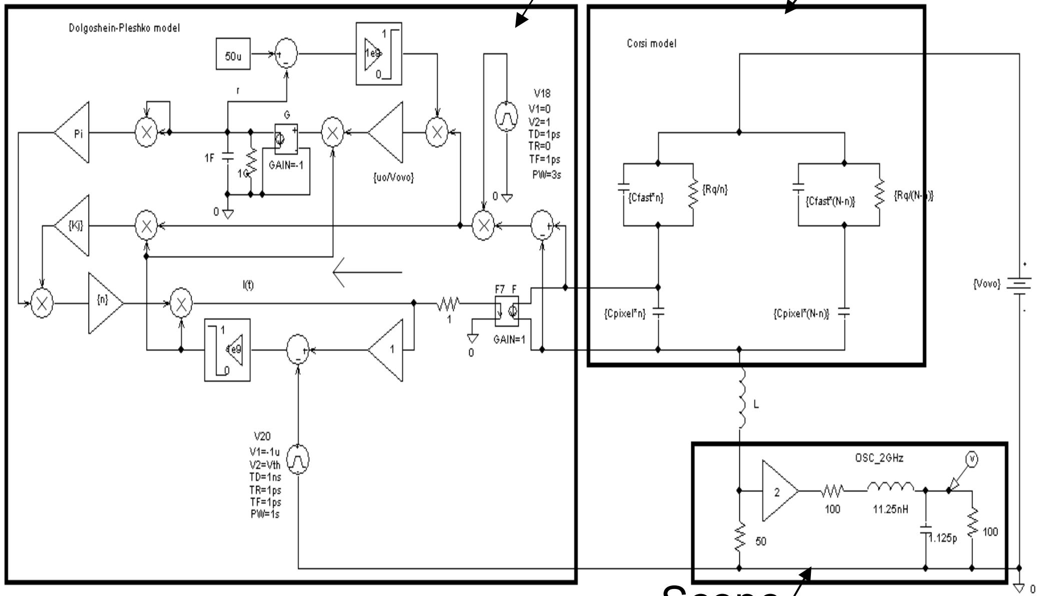
Spice model of avalanche development in a SiPM cell (transversal propagation)



Transversal avalanche propagation & Avalanche current selfquenching

Corsi model

Dolgoshein-Pleshko model



Scope

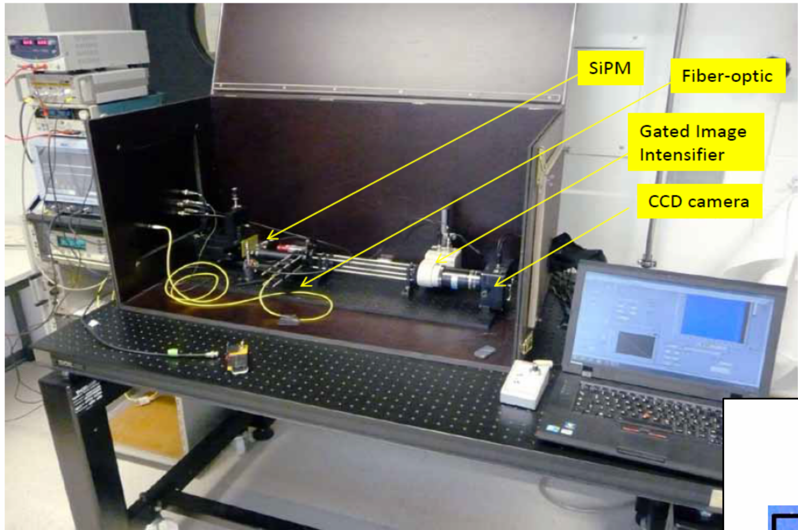
- Geiger discharge starts in a tiny spot inside a cell (1st disk)
- Current $J(t)=K_J*Vov(t)$, where Kj- is disk specific conductivity
- Discharge spreads from spot to 1st elementary ring, 2nd,..., with velocity u(t) = $u_0 \times V_{OV}(t)/V_{OV0}$,
- The capacitor of the cell discharges through the Geiger-avalanche current, after a while overvoltage drops down to 0

V_{OV0}-initial overvoltage, $V_{OV}(t)$ – momentary overvoltage

***K_j, u_0** - are experimental parameters*

$$I(t) = J(t)S(t) = J(t)\times \pi r^2(t) = \pi k_J V_{ov}(t)\left[\int_0^t u_0 \frac{V_{ov}(t')}{V_{ov\,0}}\right]^2 dt'$$

Light-Emission Microscopy (LEM) applied to SiPM

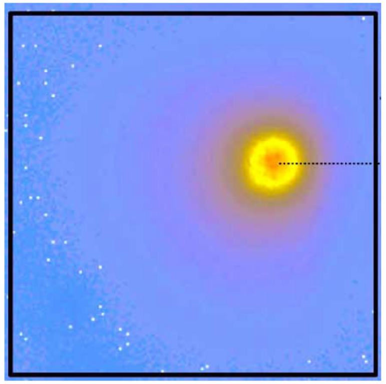


Double Peltier element cooled low-noise CCD camera "CLARA" from ANDOR

Integration time ~600 s

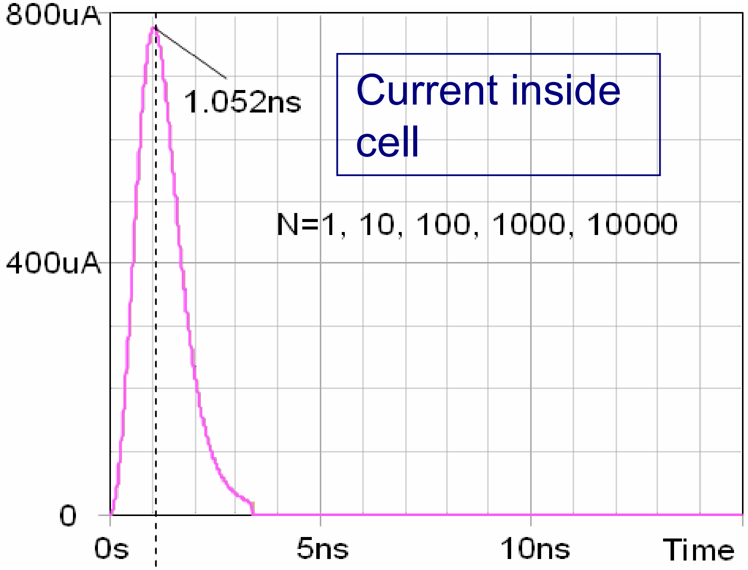
laser 70 ps 405nm

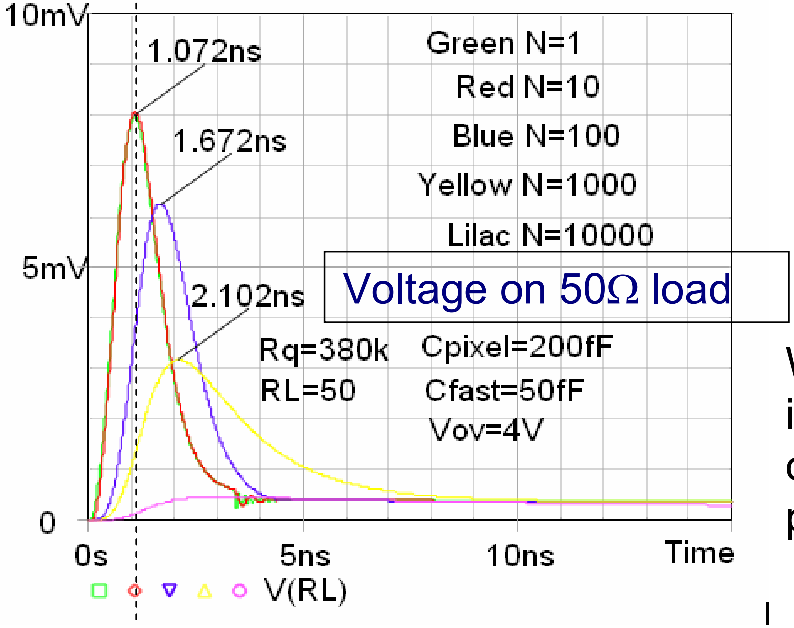
LEM Applied to Single SiPM Cell



- Shooting with laser to a cell of 100x100μm² size
- The laser light is focused to a spot size of ~2μm
- Observing that the avalanche occupies only a small part of the cell

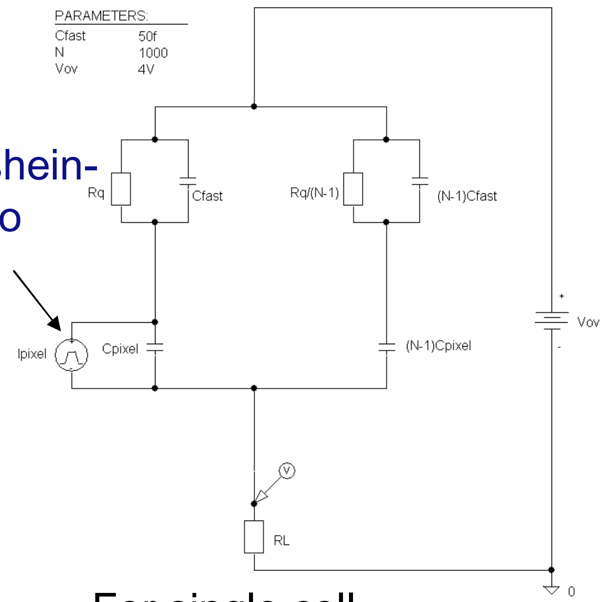
Different number of cells N inside SiPM





SiPM SPICE model with
Transversal current expansion

Dolgoshein-Pleshko model



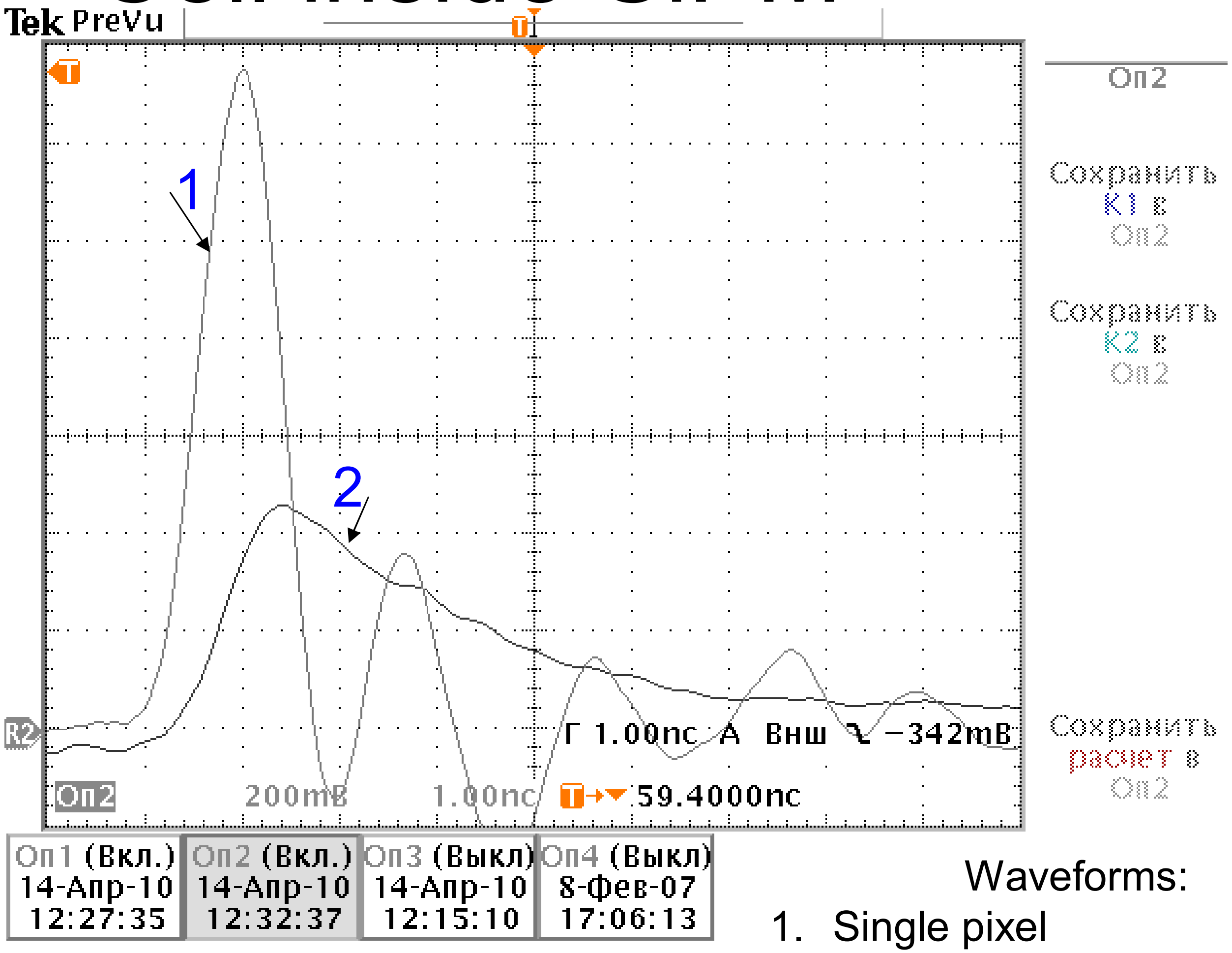
For single cell

$$I_{load}=[C_{fast}/(C_{fast}+C_{pixel})]*I_{inside}$$

$$I_{load} = 8mV/50\Omega=160\mu A$$

With increasing total number of cells inside SiPM we decrease amplitude of single cell signal and obtain more slower pulse front

Cell inside SiPM

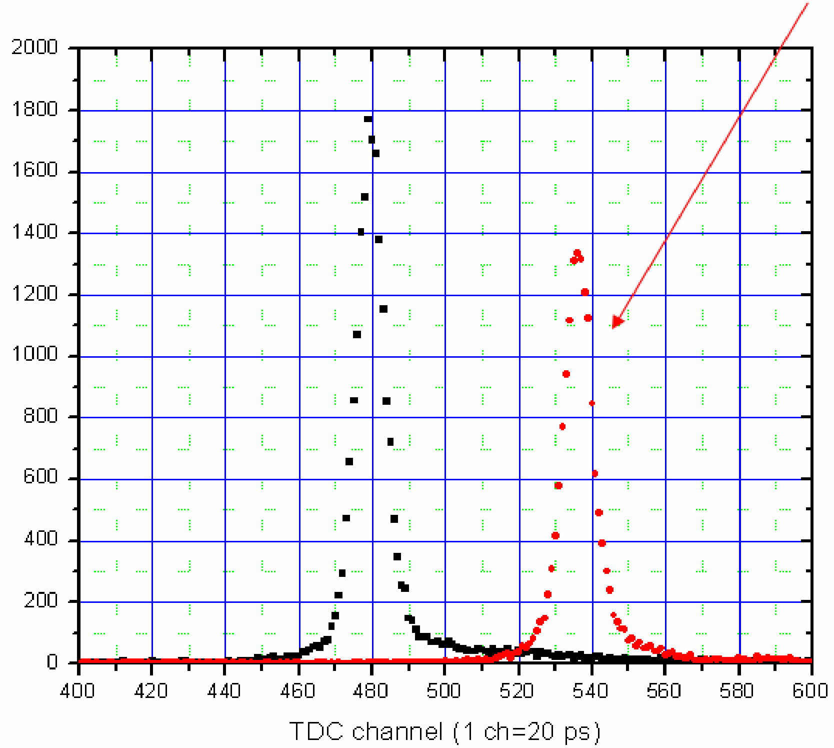


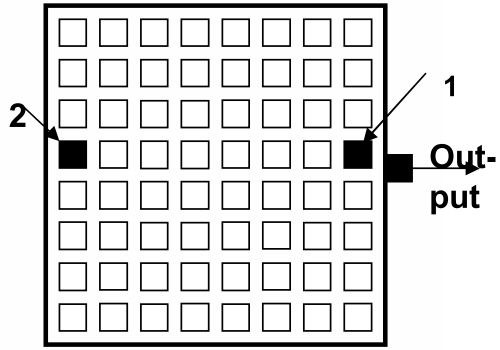
Waveforms:

1. Single pixel
2. One pixel from 1x1mm2 SiPM the same topology

SiPM Transit time spread

Single µ-cell time resolution when illuminated near the output and 5mm away

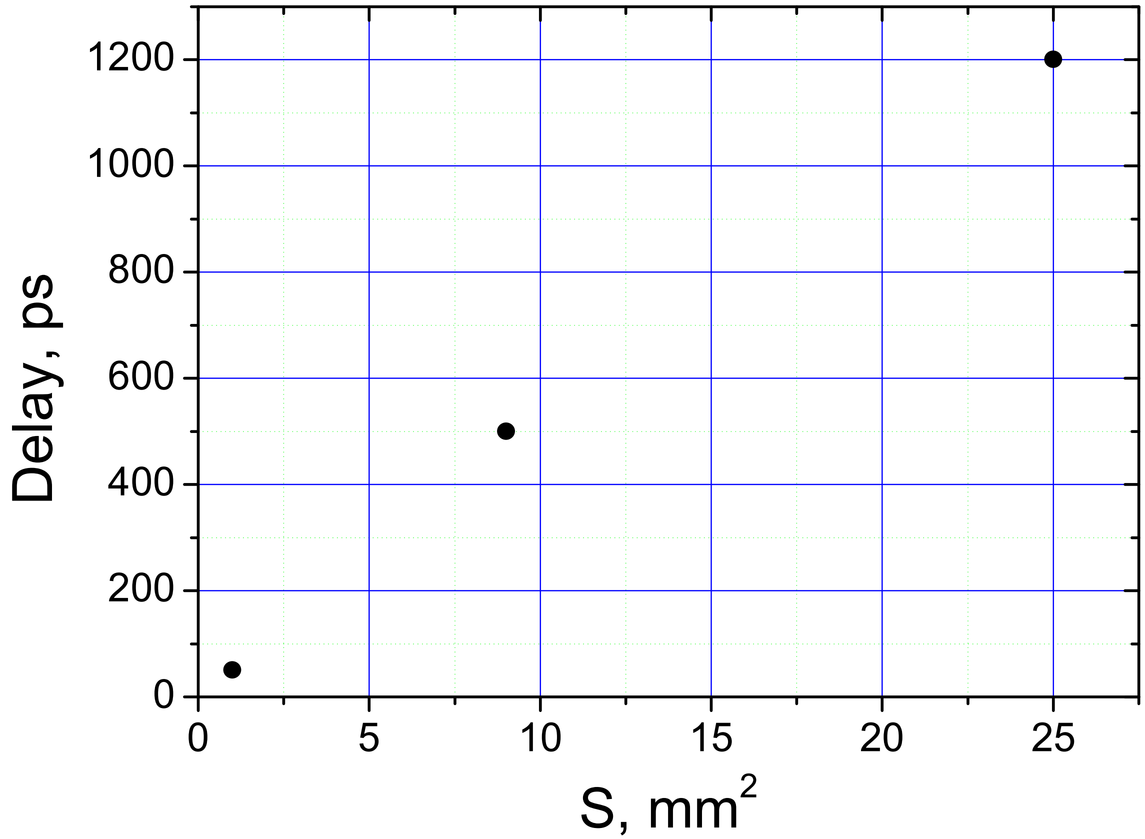




Wednesday June 24th 2009, Shinshu Univ.

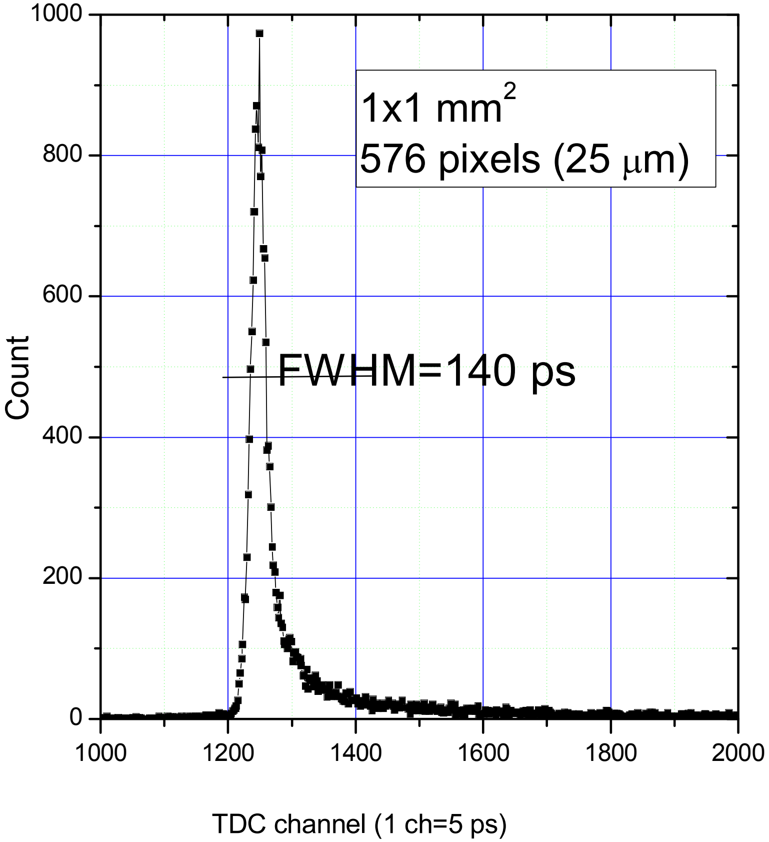
R. Mirzoyan et al.: SiPM + Scintillator, Timing, PD09

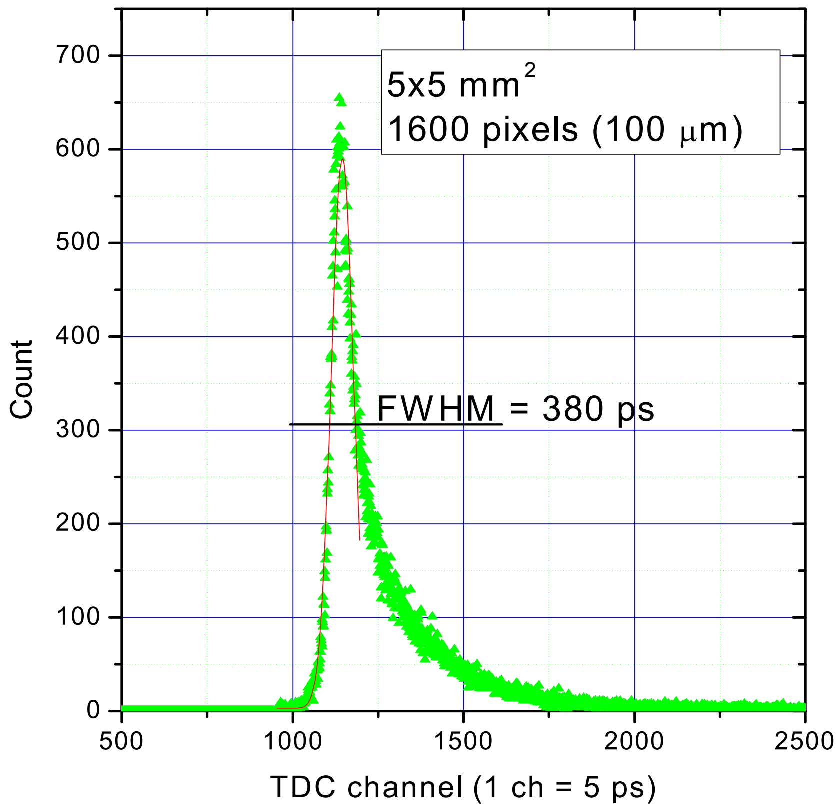
SiPM signal delay dependence on the SiPM chip area



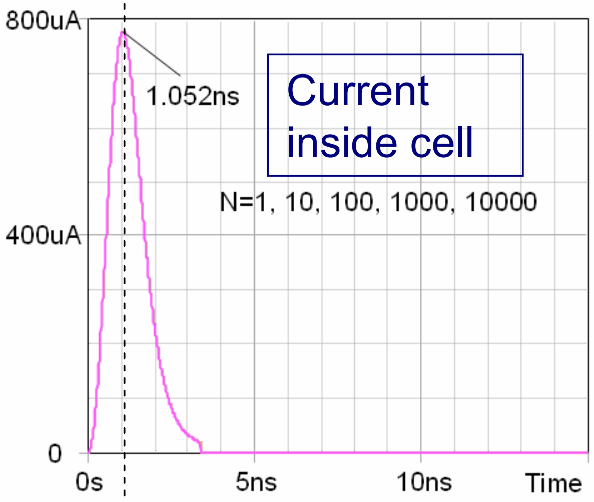
Timing by 5x5mm2 SiPM: a single phe resolution

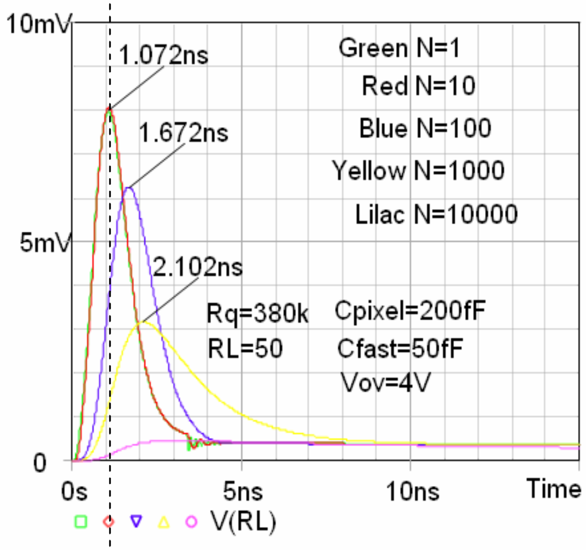
Fig.'s below show the impact of SiPM size(size of one pixel and SiPM itself)on single phe resolution FWHM for SiPMs 1x1mm2(pixel size 25mkm) and 5x5mm2(pixel size 100mkm)

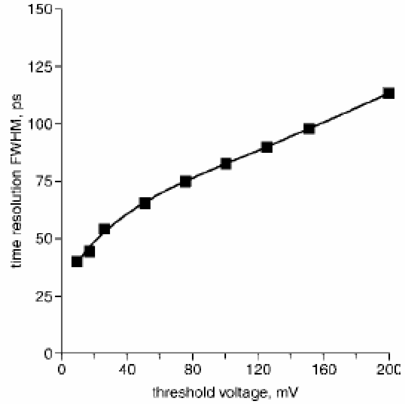




SPTR for stand alone cell and cell inside SiPM



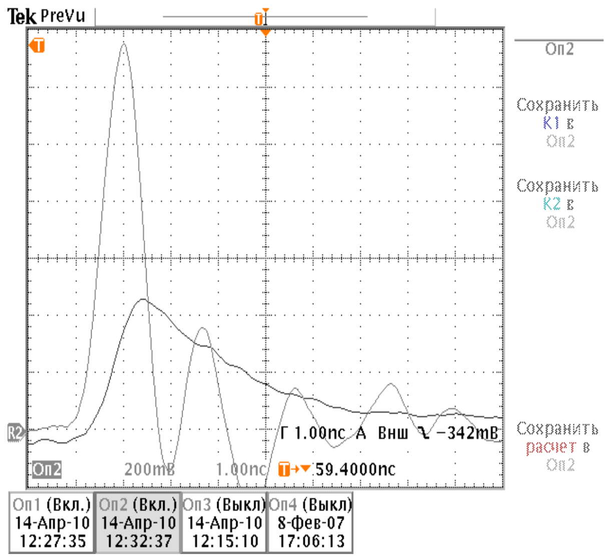




FWHM time resolution of SPAD having active area diameter of against threshold voltage of timing discriminator

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

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

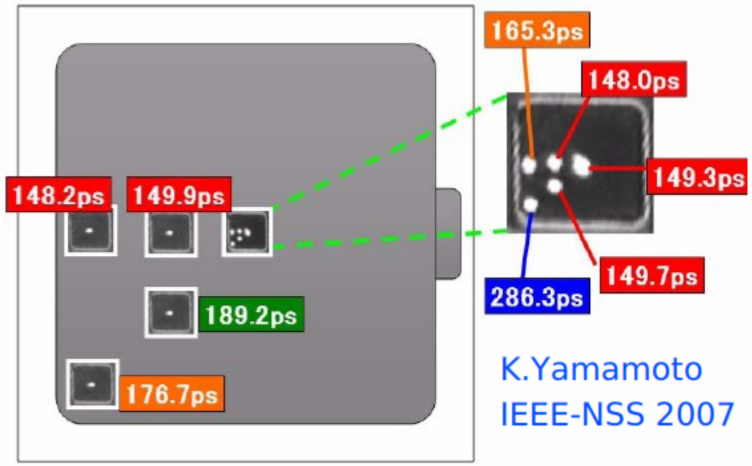


+TTS

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)

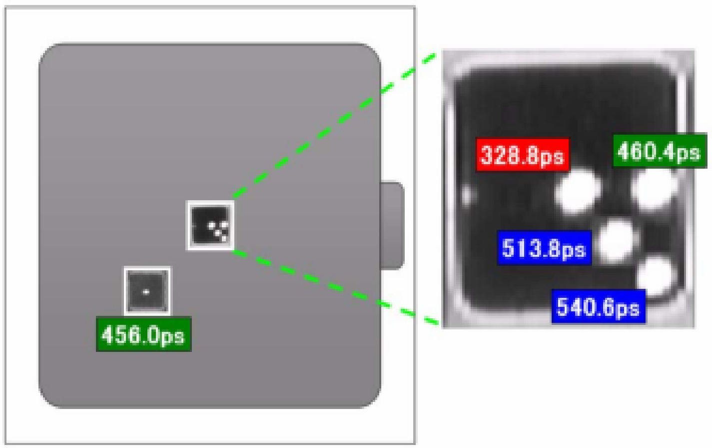


Fig.12 Position dependence of time resolution (3 x 3 mm)

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

+ TTS

ENF, photon number resolution & time resolution

P.N.Lebedev Physical Institute of the Russian Academy of Science

$$ENF = \begin{cases} 1+\dfrac{\sigma^2_{out}}{\mu^2_{out}} & Input \equiv non-random \quad (1,0) \\ \dfrac{\dfrac{\sigma^2_{out}}{\mu^2_{out}}}{\dfrac{\sigma^2_{in}}{\mu^2_{in}}} & Input \equiv random \quad (\mu_{in}, \sigma_{in}) \end{cases}$$

Burgess variance theorem

$$\frac{\sigma_{out}}{\mu_{out}} = \frac{\sigma(N_{ser})}{\mu(N_{ser})} = \frac{\sigma(N_{ph})}{\mu(N_{ph})} \cdot \sqrt{ENF_{total}} = \frac{\sigma_{in}}{\mu_{in}} \cdot \sqrt{ENF_{total}}$$

S. Vinogradov et al., IEEE NSS/MIC 2009

$$\sigma_t(Amplitude) = \left. \frac{\sqrt{\sigma_\Sigma\left(Amplitude(t)\right)^2}}{\dfrac{d\,\mu\left(Amplitude(t)\right)}{dt}} \right|_{t_{thr}\{Amplitude(t) = Discrim\}}$$

N_{ser}-number of fired pixels

Light statistics

Scint, First fired cell

$$\sigma_t(N_{ser}) = \left. \frac{\sigma_{out}}{\dfrac{d\,\mu_{out}}{dt}} = \frac{\sigma_{in}}{\dfrac{d\,\mu_{in}}{dt}} \cdot \sqrt{ENF_{total}(N_{ser})} \right|_{N_{ser}(t) = Discrim} = \frac{\sqrt{N_{ph}(t)}}{I_{ph}(t)} \cdot \sqrt{ENF_{total}(N_{ser})} \sim \tau_{1-ph}^{*} \cdot \sqrt{ENF_{total}}$$

Light Intensity

Total ENF / DQE expressions

P.N.Lebedev Physical Institute of the Russian Academy of Science

$$ENF_{total} = ENF_{pde} \cdot ENF_{m} \cdot ENF_{dup} \cdot ENF_{n-l} \cdot F_{dcr} = \frac{1}{DQE}$$

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

Burgess variance theorem

$$ENF_{m} = 1 + \frac{\sigma^2(gain)}{\mu^2(gain)}$$

$$ENF_{dup} = \begin{cases} 1 + P_{dup}, & Geometric\ chain\ (AP) \\ \dfrac{1}{1 + \ln(1 - P_{dup})}, & Branching\ Poisson\ (CT) \\ \dfrac{1 + P_{ap}}{1 + \ln(1 - P_{ct})}, & Both\ effects\ (AP + CT) \end{cases}$$

$$ENF_{n-l} = \begin{cases} \dfrac{\exp\left(N_{ph} \cdot PDE / N_{pix}\right) - 1}{N_{ph} \cdot PDE / N_{pix}}, & t << \tau_{dead} \\ 1 + \dfrac{N_{ph} \cdot PDE}{N_{pix}} \cdot \dfrac{\tau_{rec}}{t}, & t >> \tau_{dead} \end{cases}$$

Cherenkov

Scintill

$$F_{dcr} = 1 + \frac{DCR \cdot t}{N_{ph} \cdot PDE}, \quad excess\ primaries\ \ factor$$

Information losses

- ***ENFpde*** **- Losses of single photon hits in active pixel**
- ***ENFm*** **- Fluctuation of gain in multiplied signal**
- ***ENFdup*** **- Noise of CT&AP duplication events**

SiPM Saturation curve

- ***ENFn-l*** **- Losses of hits in already fired or dead pixels**
- ***Fdcr*** **- Dark noise contribution**

LSO time resolution

S.Vinogradov

Scintillation:

Total Nph = 10K;

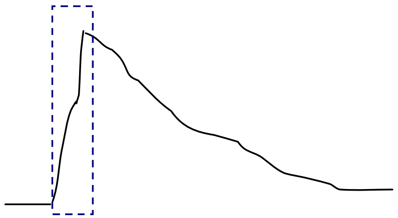
T rise = 1 ns; T decay = 40 ns

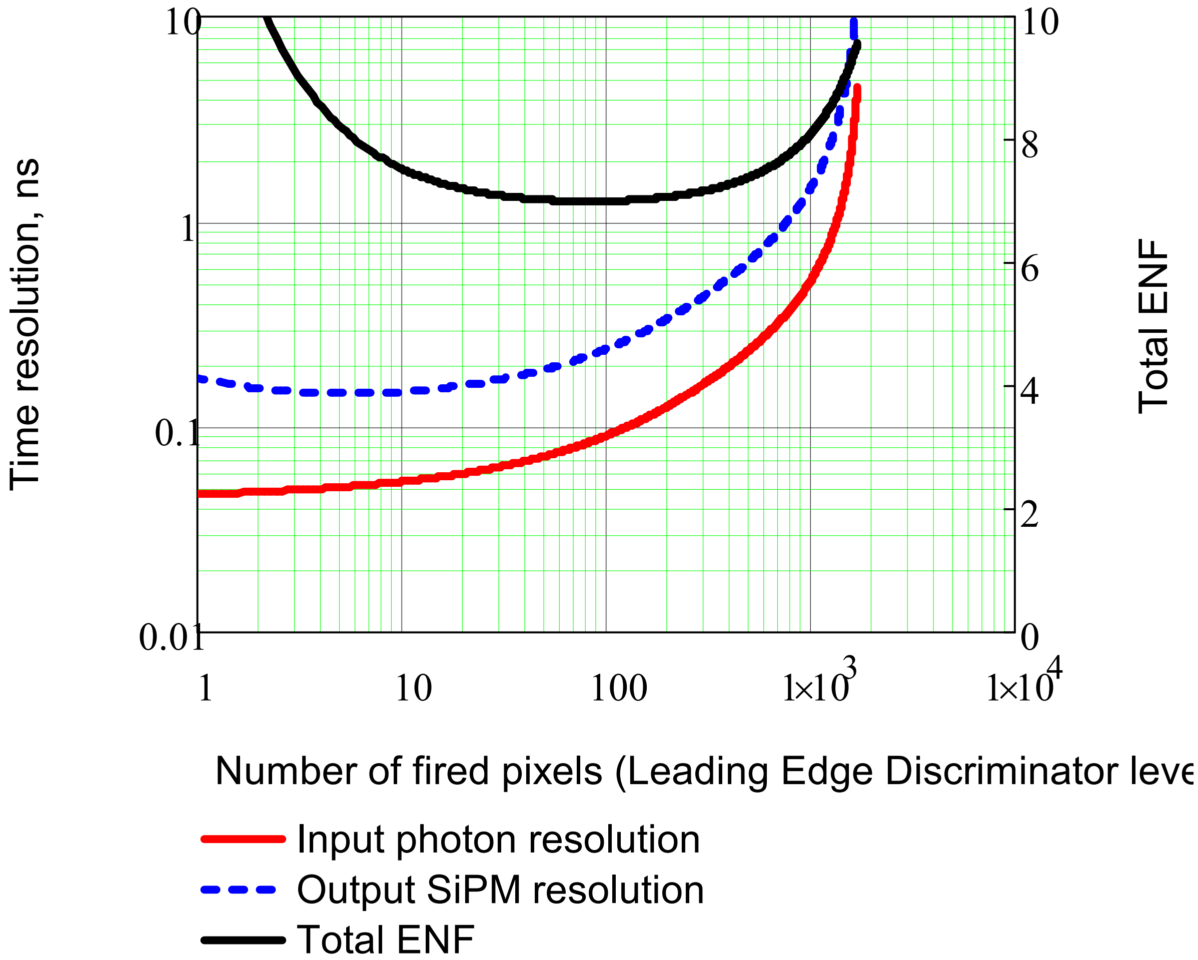
SiPM:

PDE = 25%; Npix = 3600;

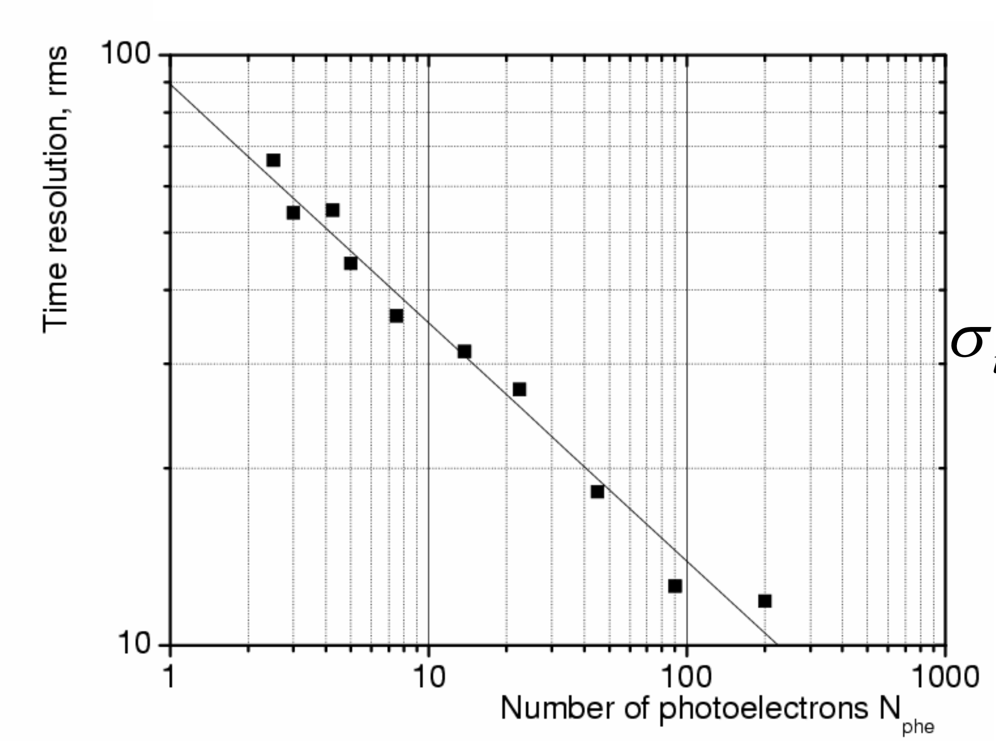
DCR = 1 Mcps; Pdup = 30%

TTS and electronic noise are not included





SiPM's jitter vs light intensity



$$\sigma_t \sim \frac{\sigma_{sptr\_of\_one\_fixed\_cell+tts}}{\sqrt{N_{phe}}}$$

ADVANCED TECHNOLOGY & PARTICLE PHYSICS Proceedings of the 7th International Conference on ICATPP-7
Villa, Olmo, Como, Italy, 15 - 19 October 2001

B.Dolgoshein et al."THE ADVANCED STUDY OF SILICON PHOTOMULTIPLIER"

Cherenkov light timing resolution in case if $\sigma_{sptr+tts}$ has been measured for this SiPM

A. Ronzhin et al.,Study of Timing Properties of SiPMs at Fermilab

2012 IEEE Nuclear Science Symposium
and Medical Imaging Conference Record (NSS/MIC)

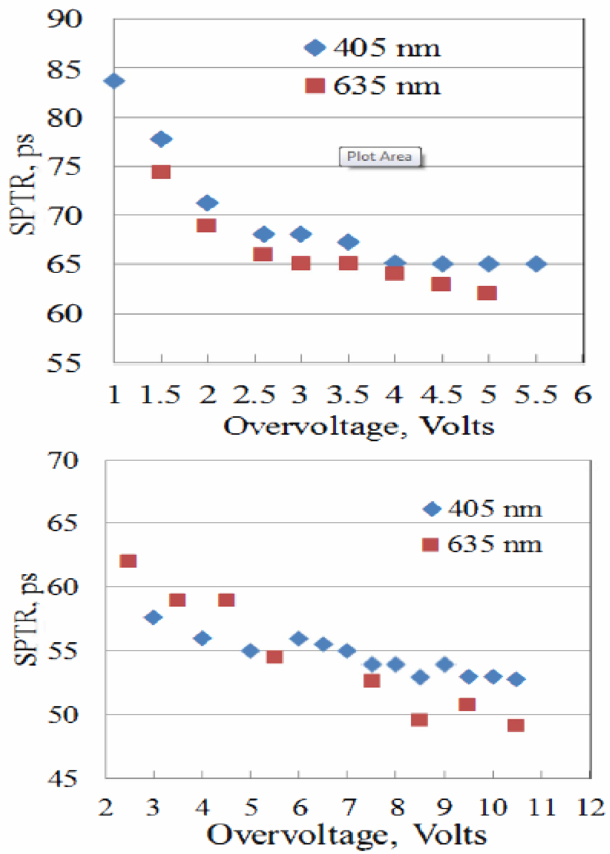


Fig. 6, top: SPTR for STM, P on N, 3.5x3.5 mm^2, 3,600 pixels, 58 um pitch. Bottom: The SPTR for STM, P on N, 1x1 mm^2, 324 pixels, 58 um pitch.

S.Cova, A.Lacaita, M.Ghioni, G.Ripamonti, T.A.Louis:
"**20 ps timing resolution with single-photon avalanche diodes**"
Rev.Sci.Instrum. **60**, 1104-1110 (1989)

Summary

Transistion in SiPM time resolution (SPTR) from 120ps to 20 ps is

a question of proper signal readout of a fired cell

(suitable connecting network and FE electronics)