State of the art in SiPM’s

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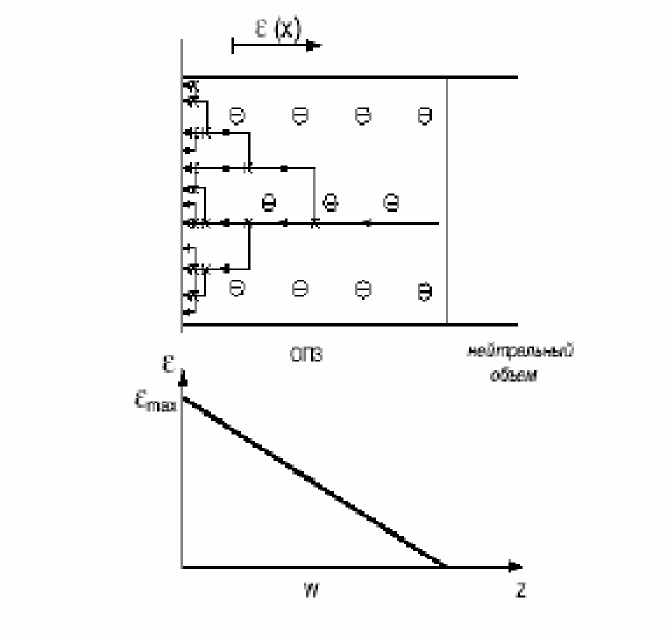
Outline

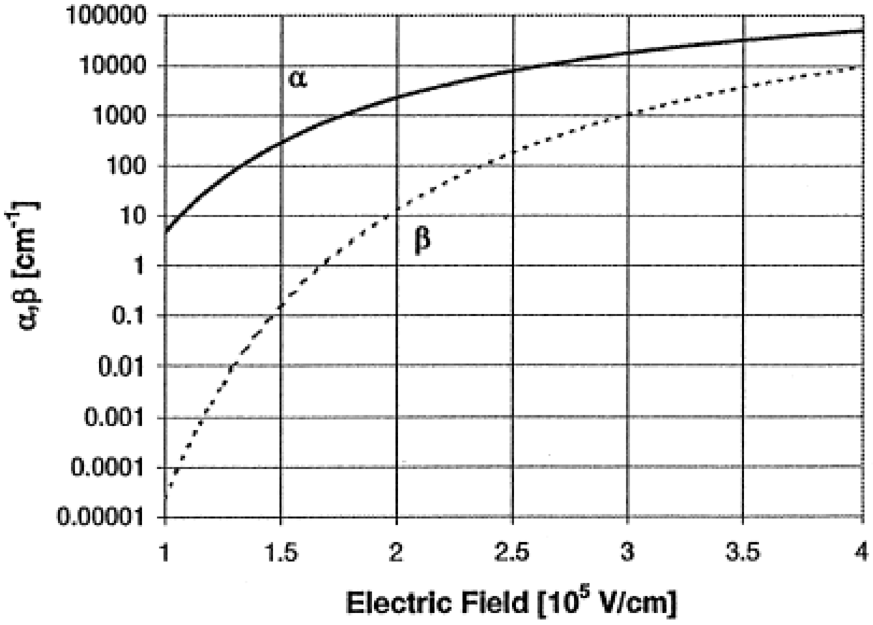
- History of SiPM development
- Principle of operation
- SiPM parameters, important for HEP and medical applications
- Overview of new developments
- SiPMs in HEP (T2K, CMS)
- Future of SiPMs

Avalanche multiplication

Applying high electric field in uniform p-n junction may cause an avalanche multiplication of electrons and holes created by absorbed light (K.G. McKay, K. J. McAffe "Electron multiplication in silicon and germanium", Phys.Rev. v91 (1953))

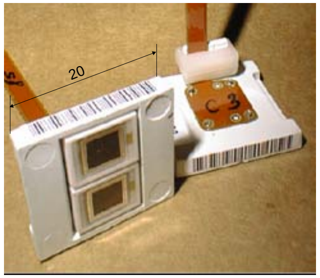


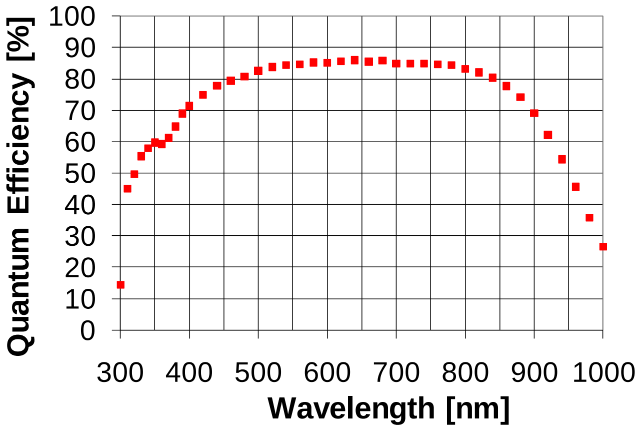
Ionization coefficient s of electrons and holes in Si (at room temperature)

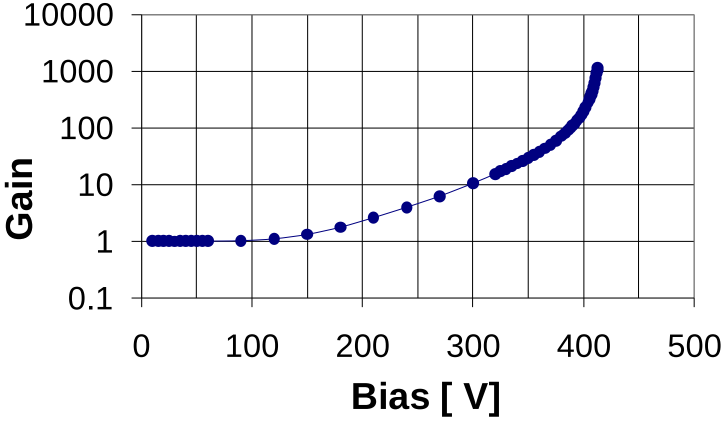


Silicon is a good material for APD construction: high sensitivity in visible and UV range, significant difference between ionization coefficients for electrons and holes – smaller positive feedback and smaller multiplication noise

Linear APD parameters (CMS APD)







Avalanche multiplication is a stochastic process → multiplication noise

Excess noise factor : $F=k*M+(1-k)(2-1/M)$

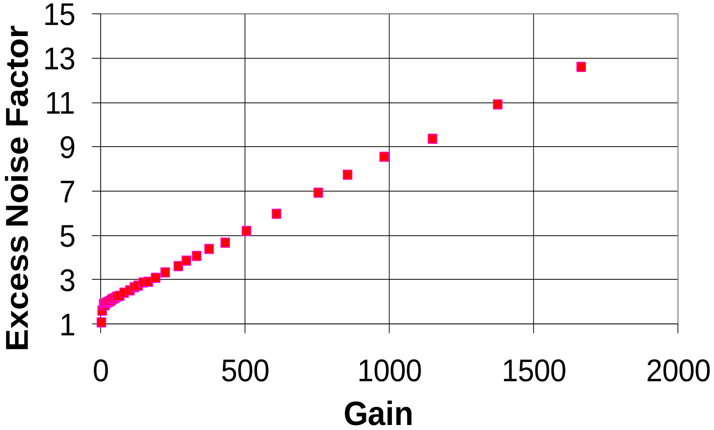
$k=\beta/\alpha$ (k-factor)

M- average multiplication coefficient

β- ionization coefficient of holes

α- ionization coefficient of electrons

(R.J. McIntyre, IEEE Tr. ED-13 (1972) 164)



Advantages: high QE, gain up to 1000, area up to 2 cm^2

Disadvantages: ENF and temperature coefficient increases with increasing gain

Devices with high multiplication noise are not good for single photon counting

Single photon counting is possible, but at low temperature (T~77K) and with slow electronics (PDE~20%)

(see A. Dorokhov et.al.,Journal Mod.Opt. v51 2004 p.1351)

APDs operated in Geiger mode

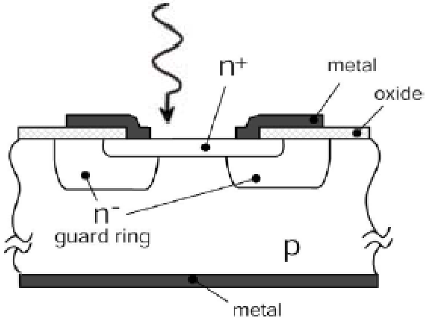
Photon counting with high efficiency → operate APDs over breakdown → Geiger mode APDs

Single pixel Geiger mode APDs were developed a long time ago

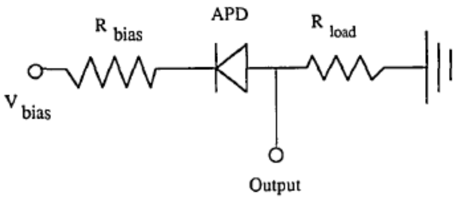
(see for example: *R. Haitz et al, J.Appl.Phys. (1963-1965)*

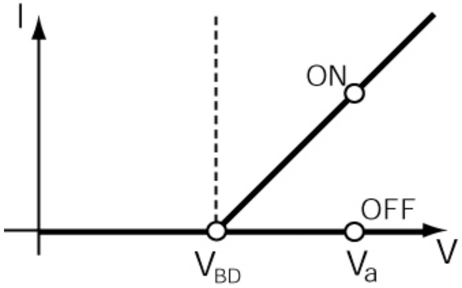
R. McIntyre , J.Appl.Phys. v. 32 (1961))

Planar APD structure



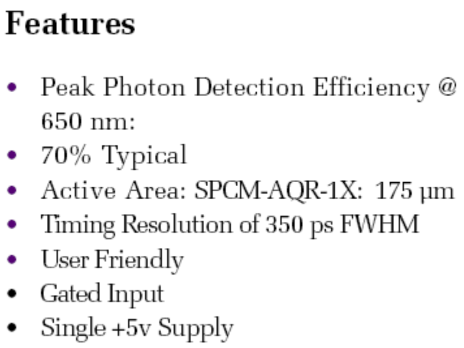
Passive quenching circuit





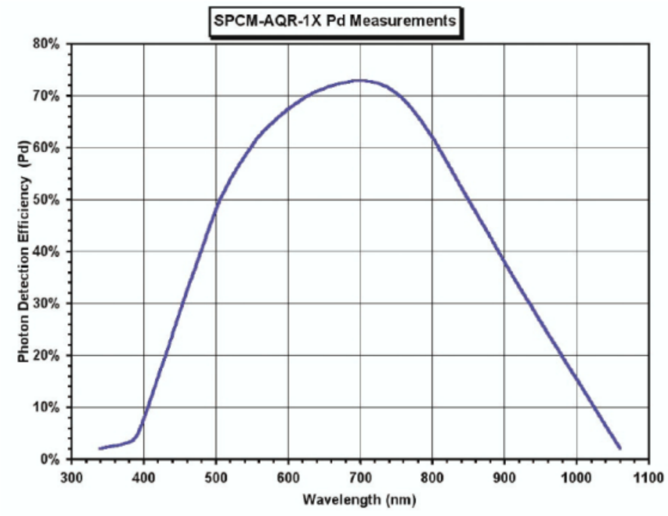
GAPD- photon detection efficiency

Photon counting module (Perkin Elmer)



Features

- Peak Photon Detection Efficiency @ 650 nm:
- 70% Typical
- Active Area: SPCM-AQR-1X: 175 µm
- Timing Resolution of 350 ps FWHM
- User Friendly
- Gated Input
- Single +5v Supply



Dark count rate – 500 Hz (25 Hz -selected)

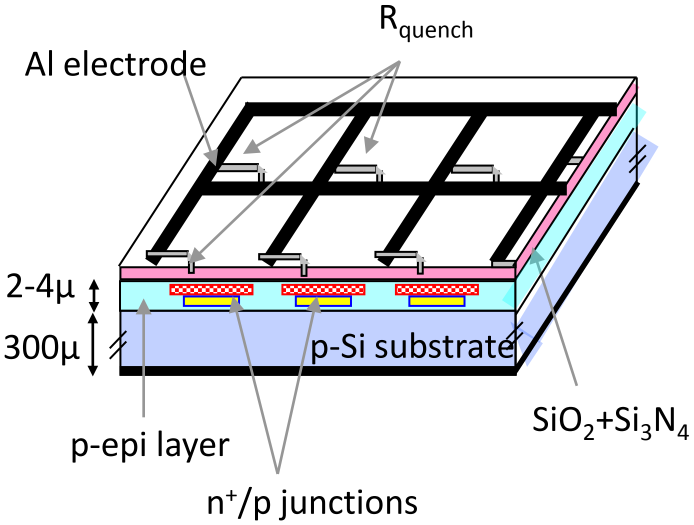
- Very high PDE (up to 70 %) of APDs operated in Geiger mode

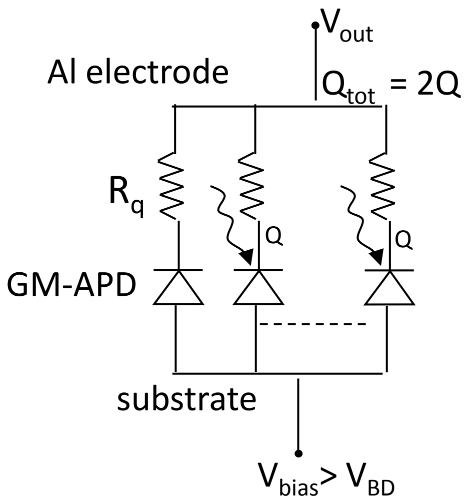
but:

- Single pixel devices are not capable of operating in multi-photon mode
- Sensitive area is limited by dark count and dead time (few mm^2 Geiger mode APD can operate only at low temperature, needs “active quenching”)

Solution: Multi-cell Geiger mode APD (or Silicon Photomultiplier)

SiPM structure and principles of operation





(EDIT-2011, CERN)

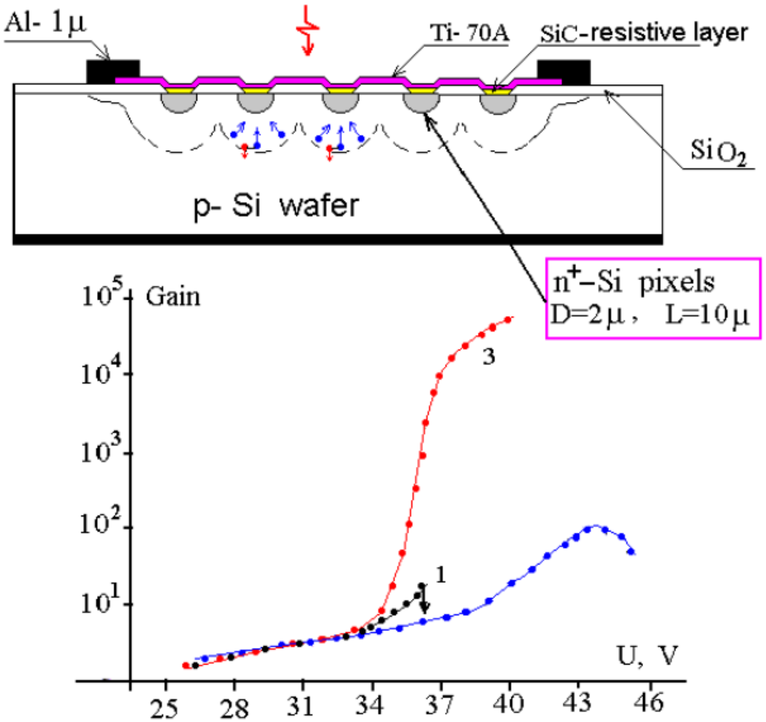
- *SiPM is an array of small cells (SPADs) connected in parallel on a common substrate*
- *Each cell has its own quenching resistor (from 100kΩ to several MΩ)*
- *Common bias is applied to all cells (~10-20% over breakdown voltage)*
- *Cells fire independently*
- *The output signal is a sum of signals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

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

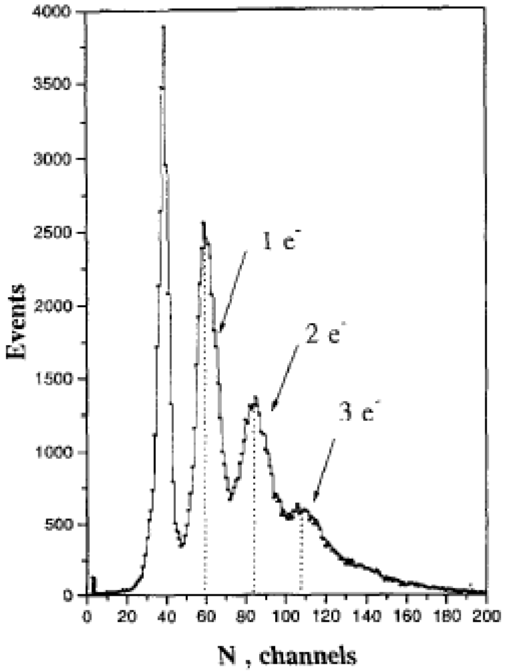
First design (MRS APD, 1989)

The very first metall-resitor-smiconductor APD (MRS APD) proposed in 1989 by A. Gasanov, V. Golovin, Z. Sadygov, N. Yusipov (Russian patent #1702881, from 10/11/1989). APDs up to 5x5 mm^2 were produced by MELZ factory (Moscow).

Geometric factor was low. Only few % photon detection efficiency for red light was measured with 0.5x0.5 mm^2 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

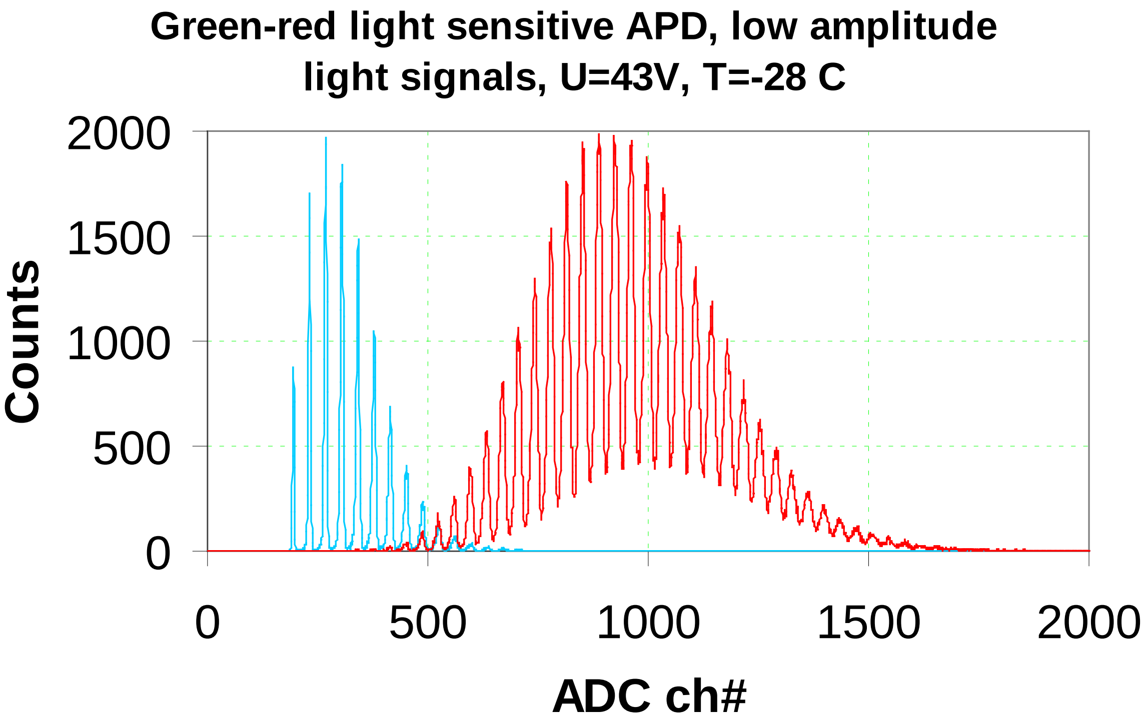
Since 1989 many Multi-cell Geiger mode APD structures were developed by different developers:

- CPTA (Moscow)
- Zecotek (Singapore)
- MEPhI/Pulsar (Moscow)
- Amplification Technologies (Orlando, USA)
- Hamamatsu Photonics (Hamamatsu, Japan)
- SensL (Cork, Ireland)
- FBK-irst (Trento, Italy)
- STMicroelectronics (Italy)
- KETEK (Munich)
- RMD (Boston, USA)
- MPI Semiconductor Laboratory (Munich)
- Novel Device Laboratory (Beijing, China)
- Excelitas Technologies (former PerkinElmer)
- ……

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

SiPM properties

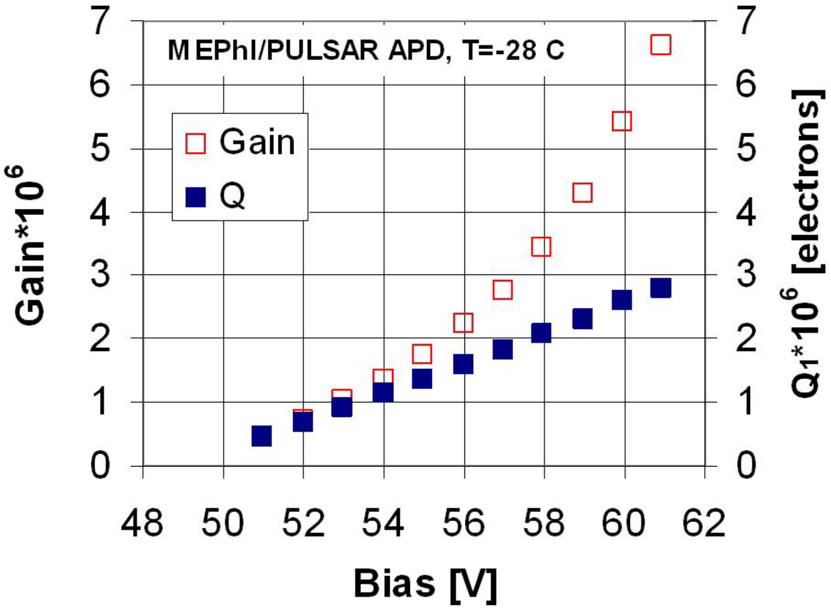
Pixel-to-pixel uniformity



SiPMs have very good pixel-to-pixel signal uniformity (uniform VB). Pedestal is well separated from the signal produced by single fired pixel $Q_1=C_{pixel}*(V-V_b)$.

Gain and Single Pixel Charge

Each pixel works as a digital device – several photons hitting the same cell (and at the same time) produce the same signal $Q_1=C_{pixel}*(V-V_b)$ (or Single Pixel Charge).



For linear device a measured output charge :

$Q_{output}=N_{pe}*Gain$

For SiPM Gain=Q_1 only for small V-VB → more than 1 pixel is fired by one primary photoelectron!

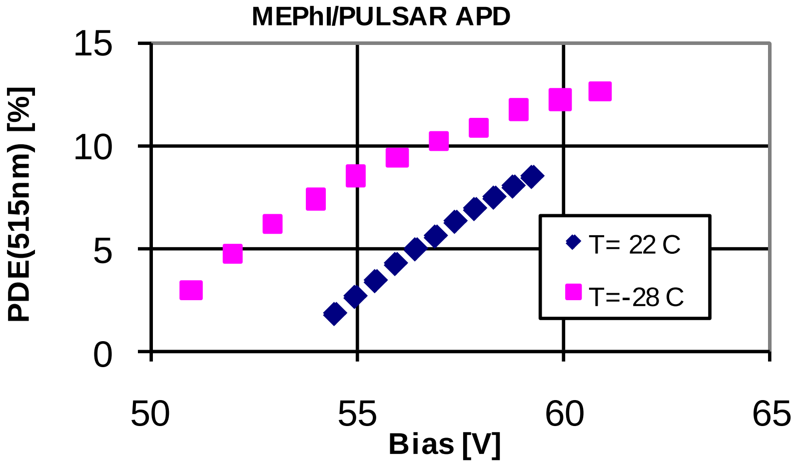
$Gain=Q_1*n_p$,

where n_p is average number of pixels fired by one primary photoelectron. There are 2 reasons for this:

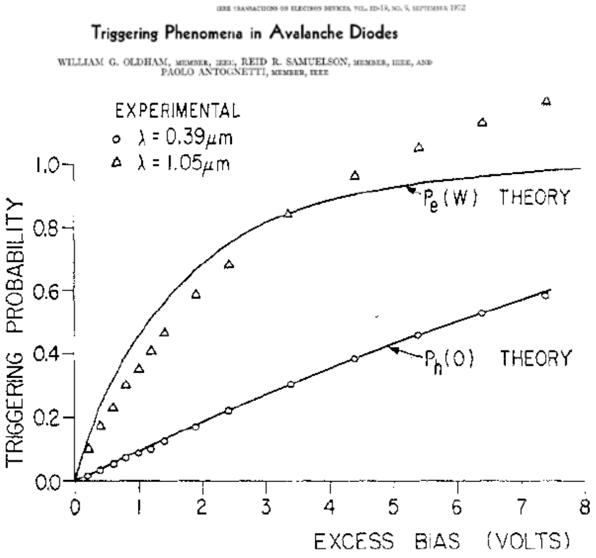
- optical cross-talk between pixels
- after-pulsing (one pixel can be fired more than 1 time during light flash)

(Y. Musienko, NDIP-05, Beaune)

Photon detection efficiency



(Y. Musienko, NDIP-05, Beaune)


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

Photon detection efficiency (PDE) is the probability to detect single photon when threshold is < Q1 . 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) .

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

To determine $\langle N_{pe} \rangle$ in light pulse one can use well known property of the Poisson distribution :

$$\langle N_{pe} \rangle = -\ln(P(0))$$

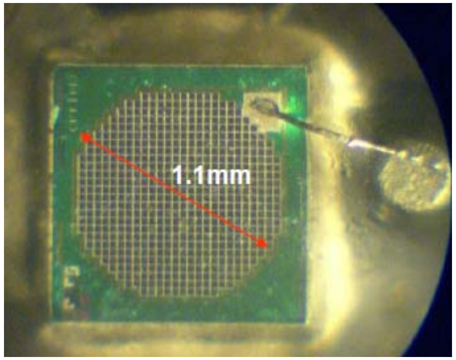
Average number of photons $\langle N_\gamma \rangle$ in LED pulse can be measured using calibrated photo-sensor . Then:

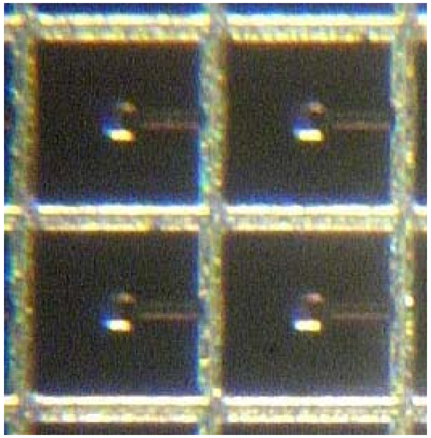
$$PDE(\lambda) = \langle N_{pe} \rangle / \langle N_\gamma \rangle$$

Geometric factor

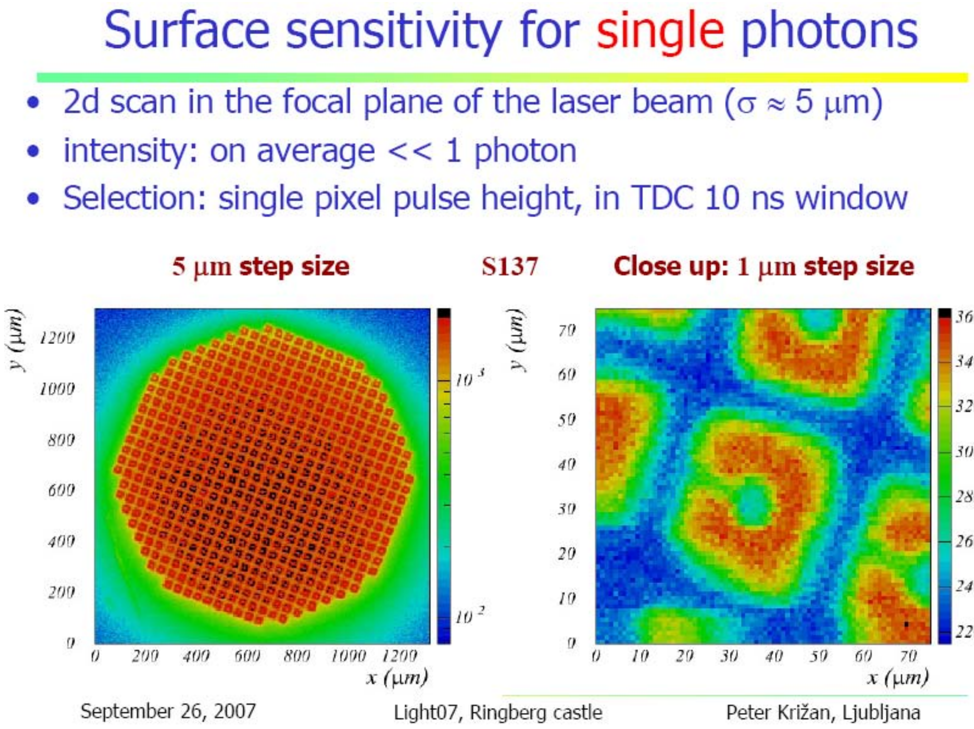
Non-sensitive zones between cells reduce PDE

CPTA SSPM





SSPM 2d scan with focused laser beam



Surface sensitivity for single photons

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

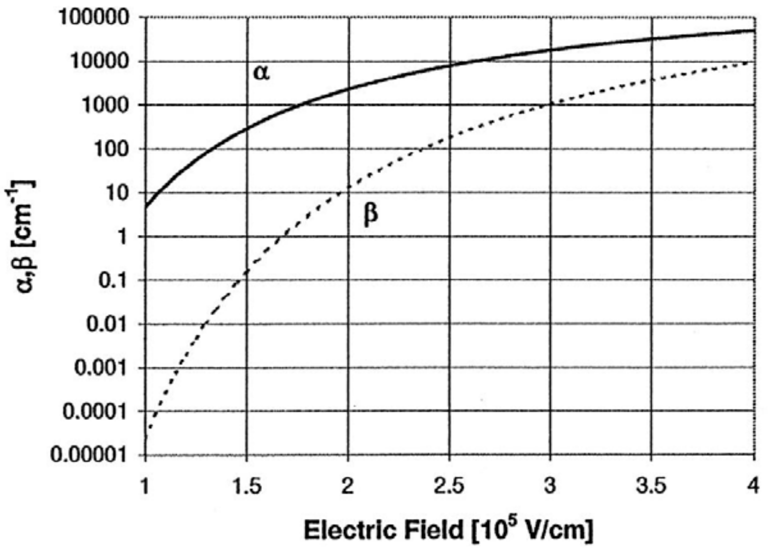
5 µm step size S137 **Close up: 1 µm step size**

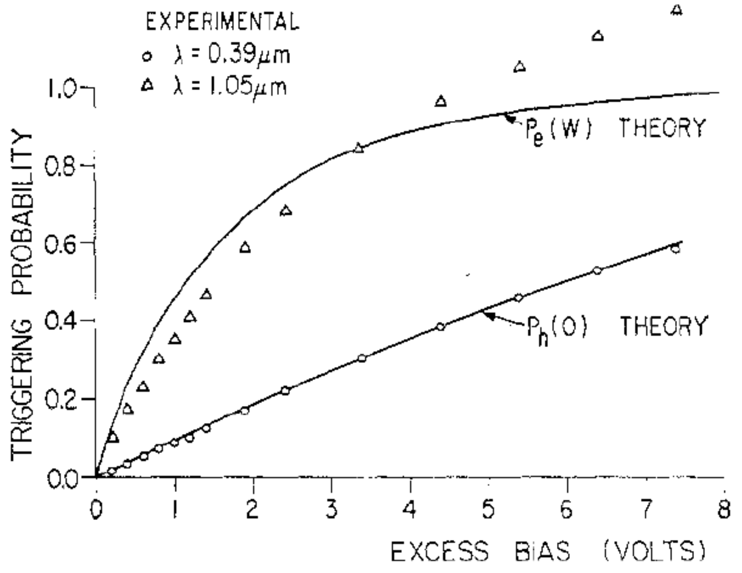
September 26, 2007 Light07, Ringberg castle Peter Križan, Ljubljana

SiPMs with 60-80% geometric factor (for 50-100 µm cell pitch) were produced

Breakdown initiation probability

Ionization coefficients for electrons and holes in silicon





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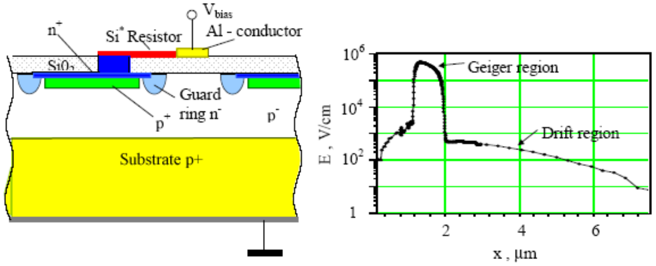
Because of the higher ionization coefficient, the electron triggering probability is always higher than that for holes

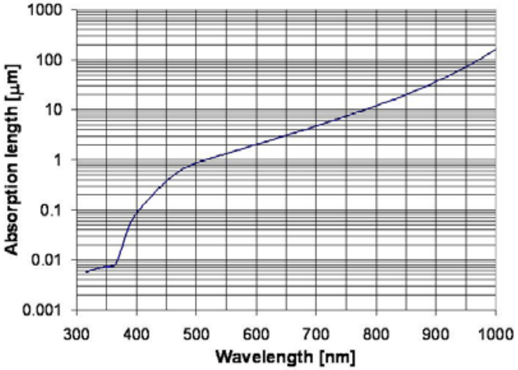
Structure for green/red light (n on p)

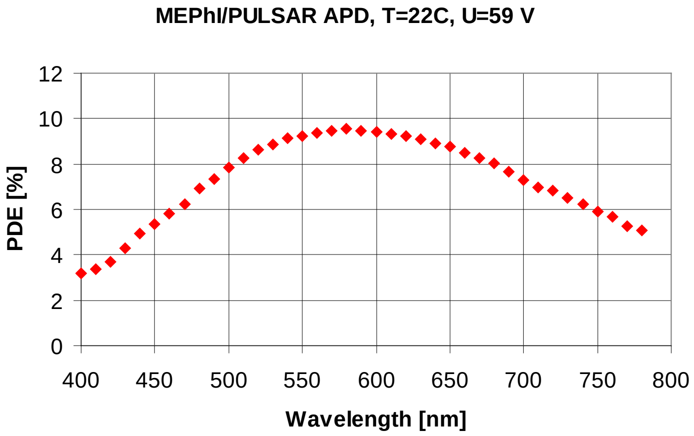
Sensitivity for blue light is low. Blue light is absorbed close to the SiPM surface – holes initiate an avalanche



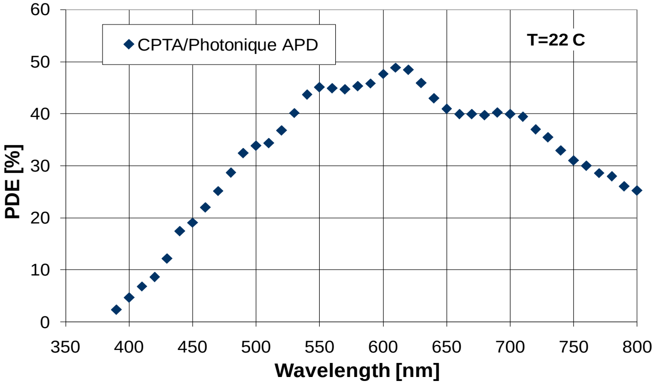
B. Dolgoshein et. al., “An advanced study of silicon photomultiplier”, ICFA-2001

Absorption length for light in silicon





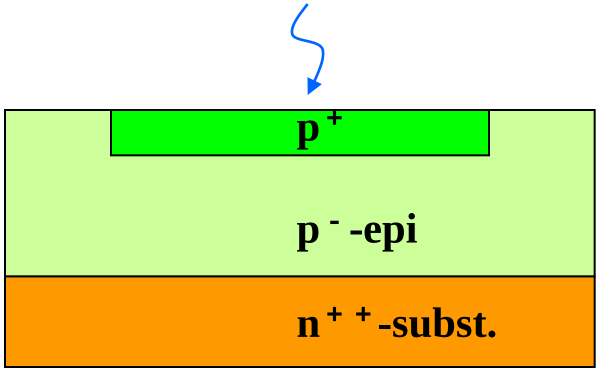
(Y. Musienko, NDIP-05, Beaune)



(Y. Musienko, PD-07, Kobe)

Blue/UV light sensitive SiPMs (p on n)

Solution for UV/blue light detection is a “p on n” structure. In this structure electrons initiate the avalanche breakdown

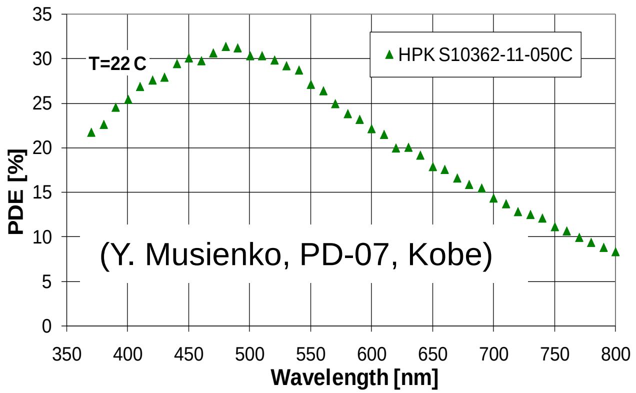


p^+

p^--epi

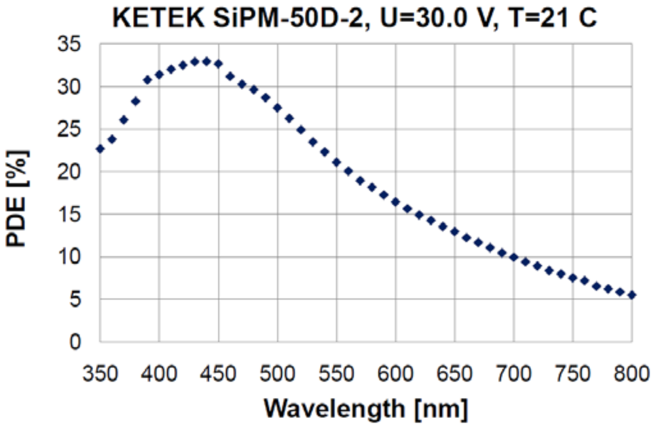
n^{++}-subst.

Hamamatsu MPPC (50 μm cell pitch)

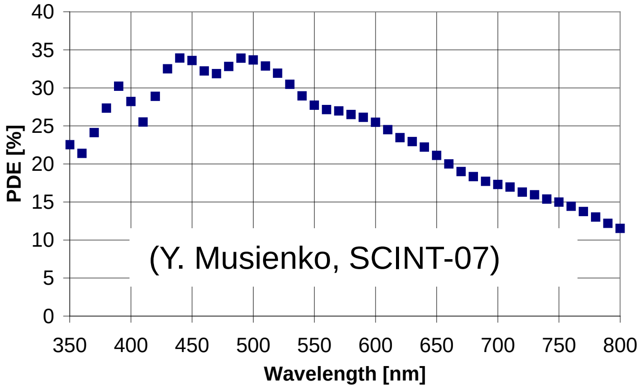


(Y. Musienko, PD-07, Kobe)

KETEK SiPM (50 μm cell pitch)



CPTA SSPM (43 μm cell pitch)

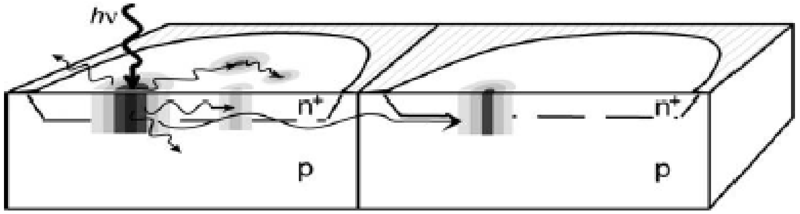


(Y. Musienko, SCINT-07)

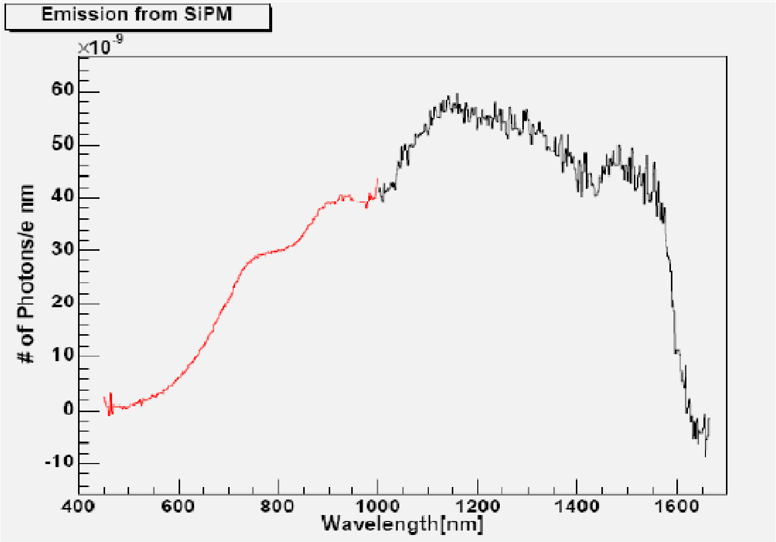
Optical cross-talk

SiPM is not an ideal multiplier!

Light emission spectrum from SiPM



A. Lacaita et al, IEEE TED (1993)



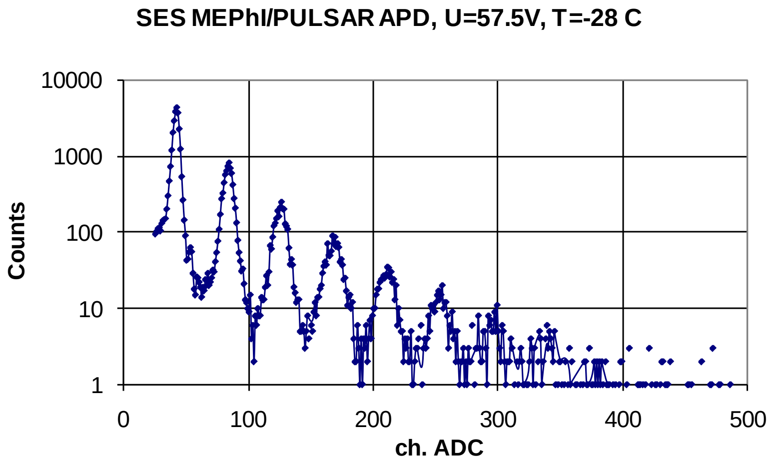
Light is produced during cell discharge. Effect is known as a hot-carrier luminescence: 10^5 carriers produce ~3 photons with an wavelength less than 1 μm

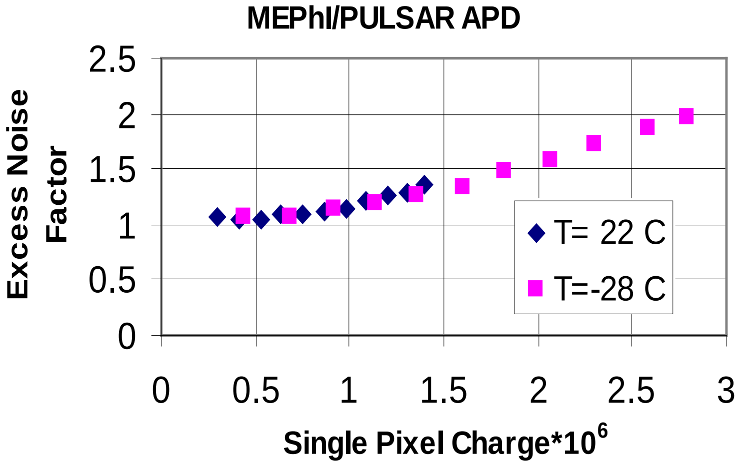
(R. Mirzoyan, NDIP08, Aix-les-Bains)

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 $V\text{-}V_b$>>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



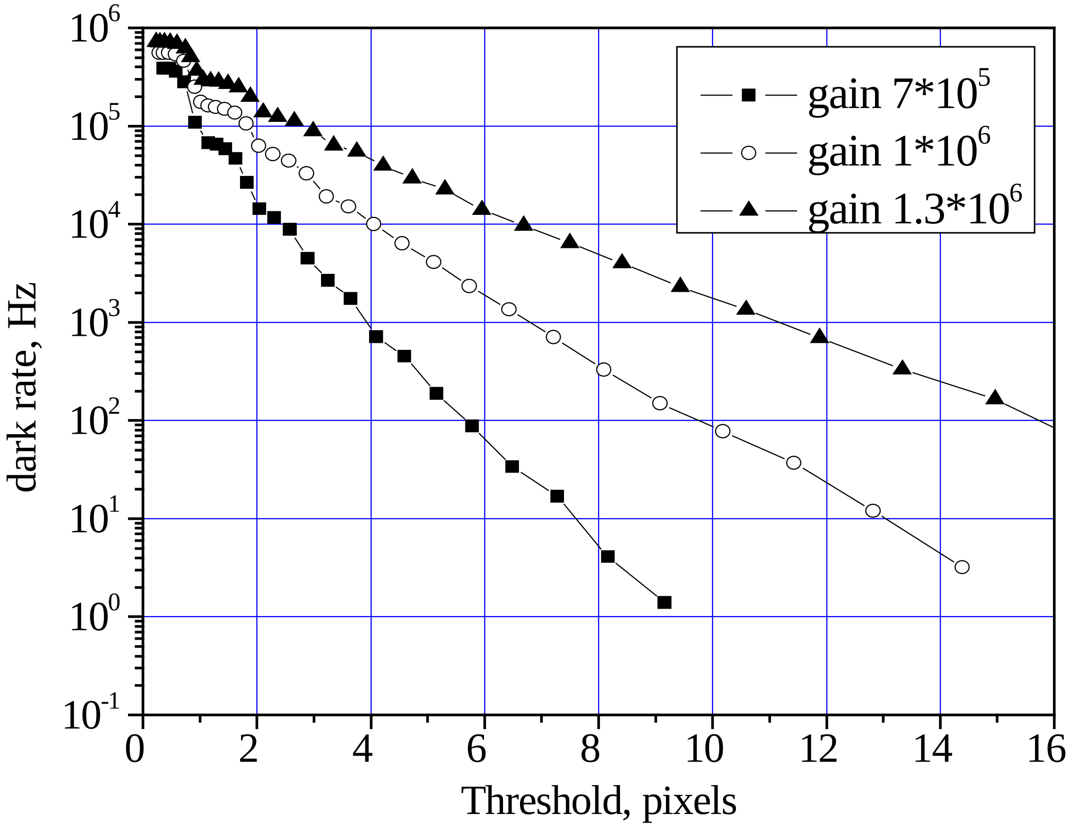


(Y. Musienko, NDIP-05, Beaune)

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

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

Dark count rate vs. electronics threshold



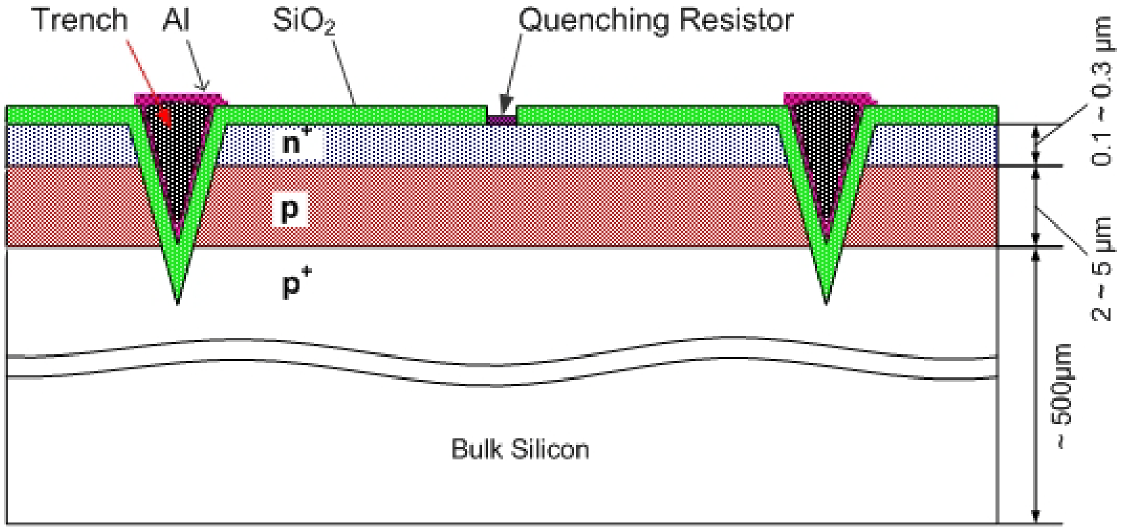
Optical cross-talk also increases the dark count at high electronics thresholds

(E.Popova, CALICE meeting)

This effect is more pronounced at high SiPM gain!

Optical cross-talk reduction

Solution: optically separate cells trenches



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

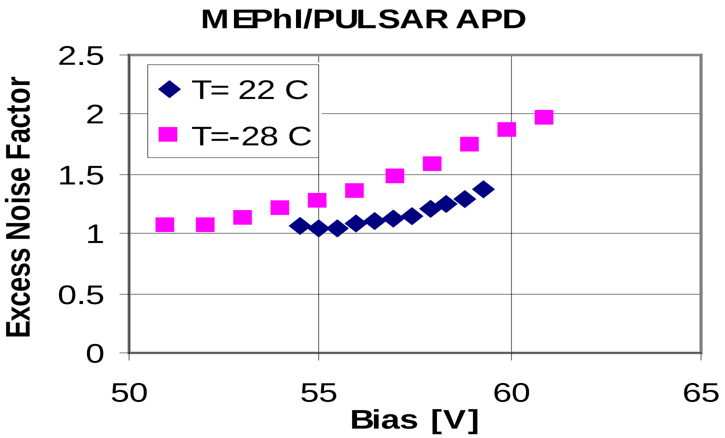
To reduce optical cross-talk CPTA /Photonique was the first to introduce trenches separating neighbouring pixels

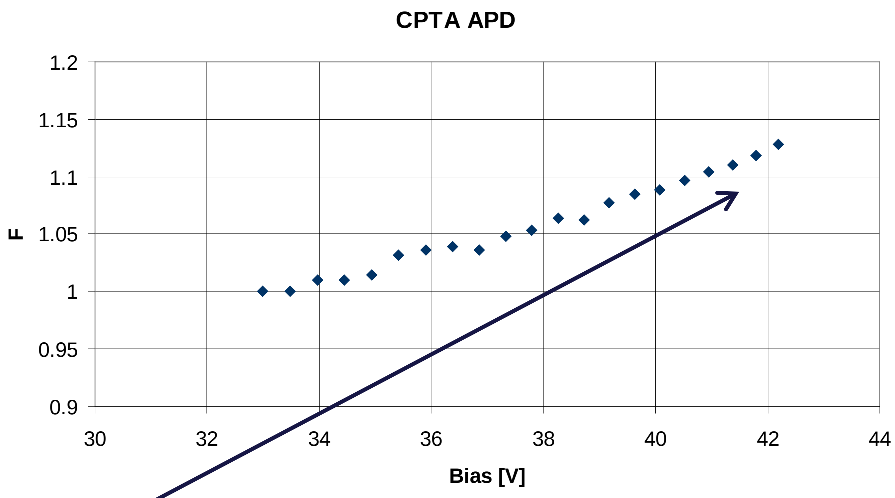
SiPMs with reduced optical cross-talk

It really helps …

MEPhI/Pulsar SiPM without trenches

CPTA/Photonique SSPM with trenches



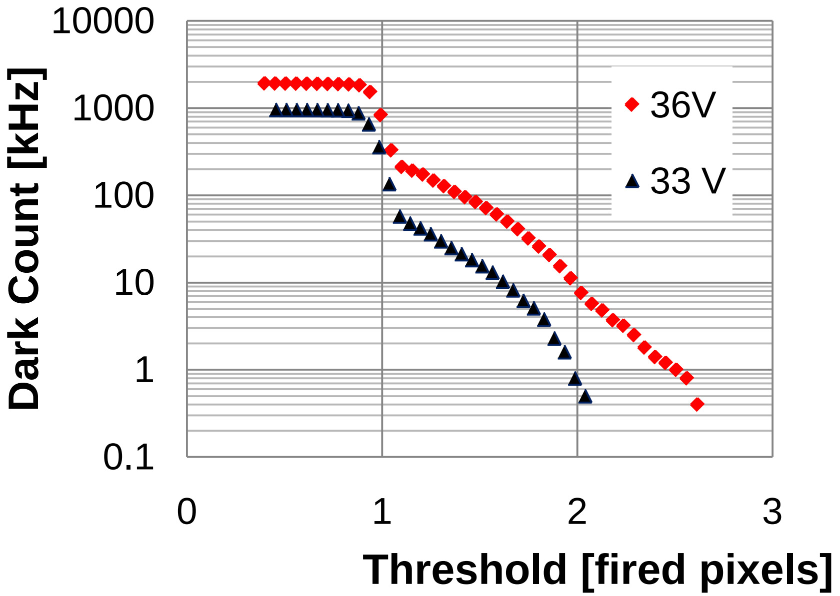


The excess noise factor is small even at V-VB~10 V !

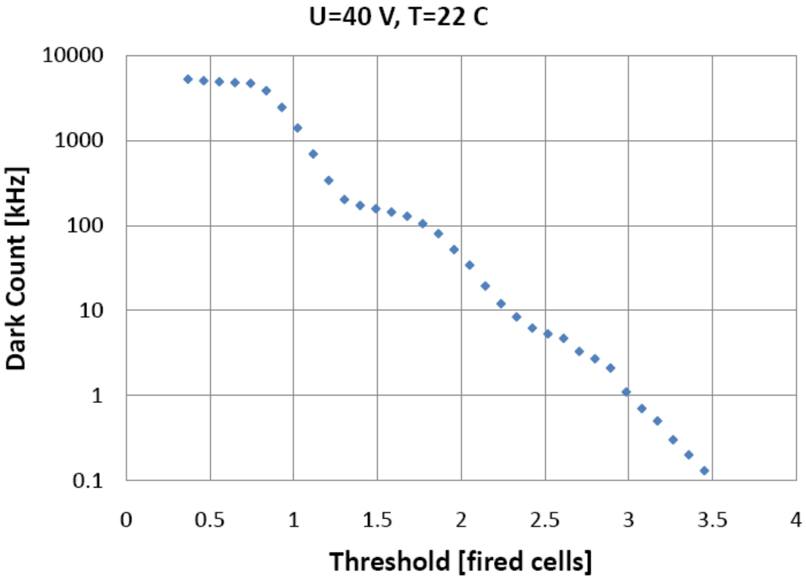
Dark count rate of the SiPMs with trenches vs. electronics threshold

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

CPTA/Photonique SSPM with trenches



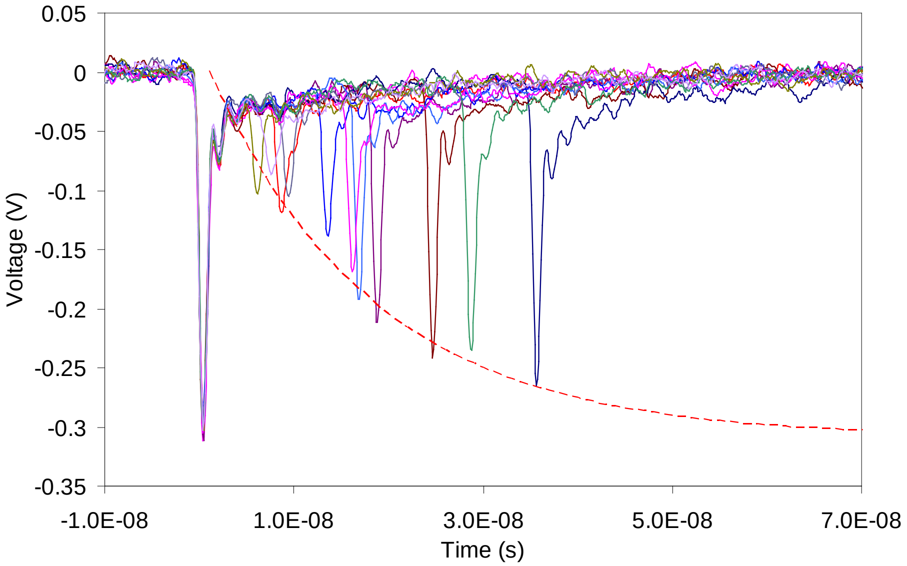
ST-Micro SiPM with trenches

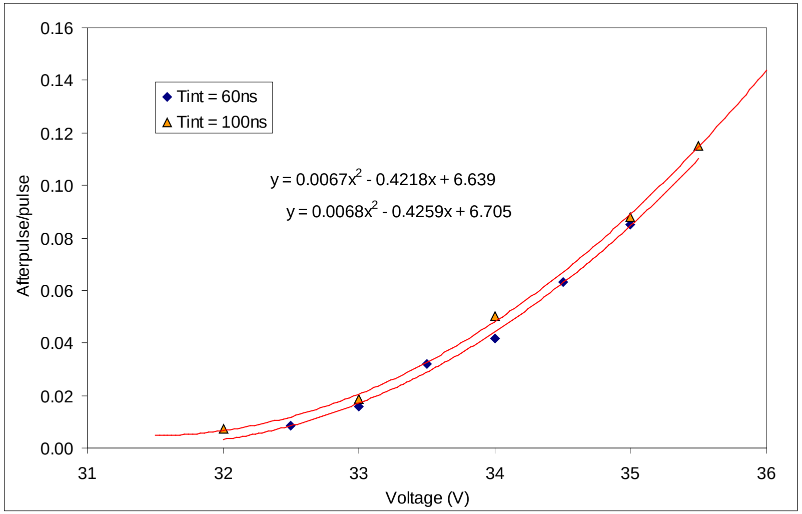


SiPMs with trenches can have an optical cross-talk as low as 1-2%

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.

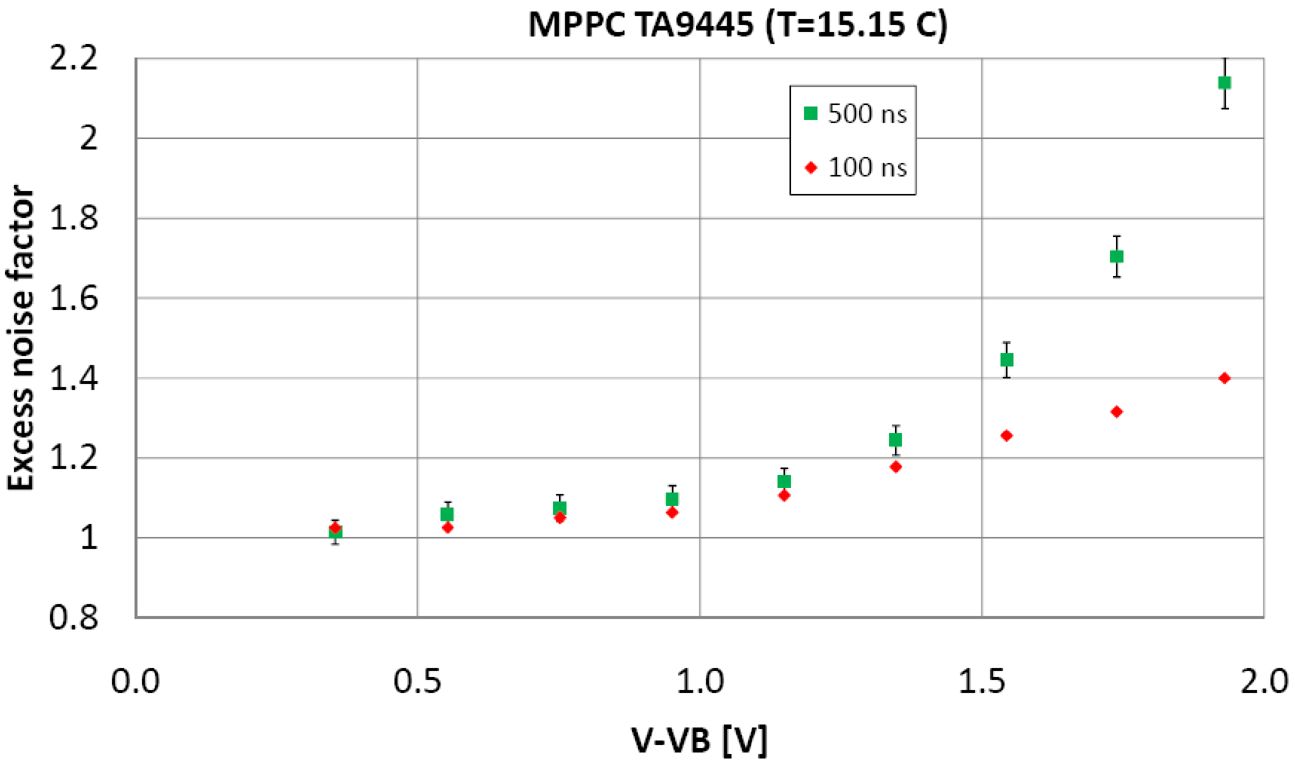
After-pulse probability increases with the bias

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

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

After-pulses and the Excess Noise Factor

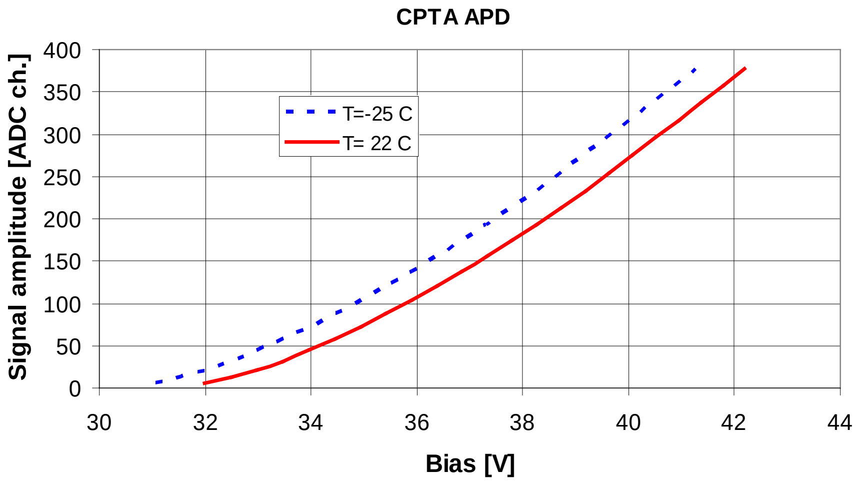
After-pulses cause an increase of the SiPM dark count rate. They also increase the excess noise factor if the signal integration time is long

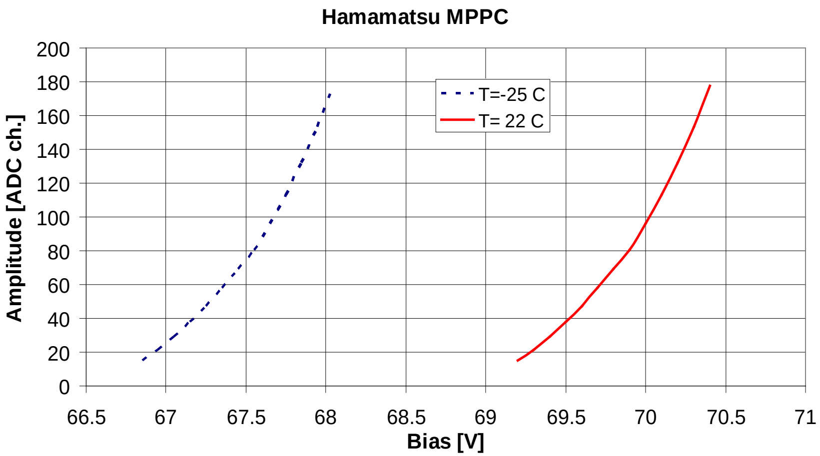


Y. Musienko (Iouri.Musienko@cern.ch)

SiPM response vs. temperature

SiPM gain and PDE depend on the temperature



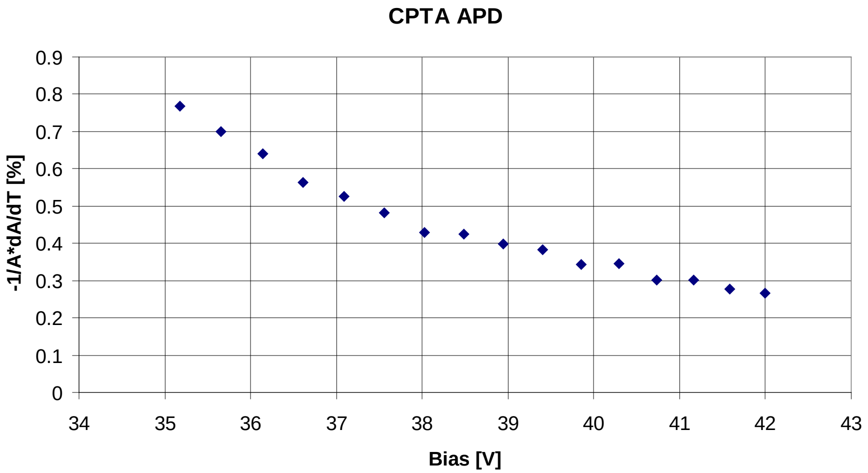


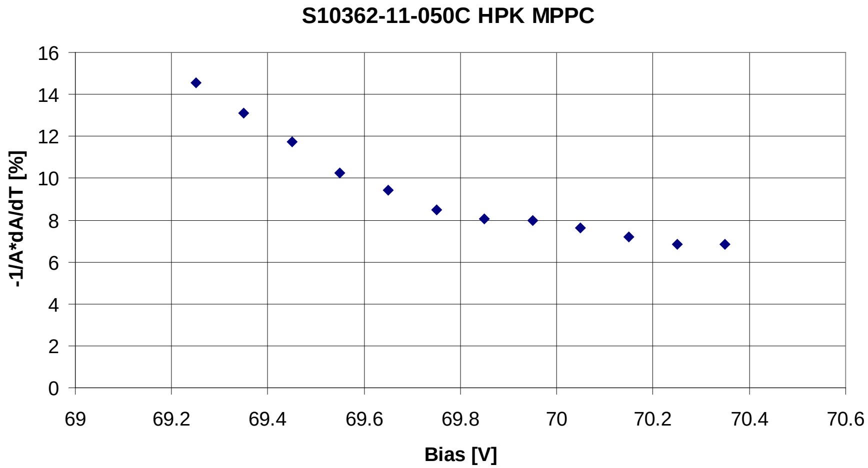
LED signal was measured in dependence on bias at 2 temperatures for SiPMs from 2 producers

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

(Y. Musienko, PD-07, Kobe)

Temperature coefficient





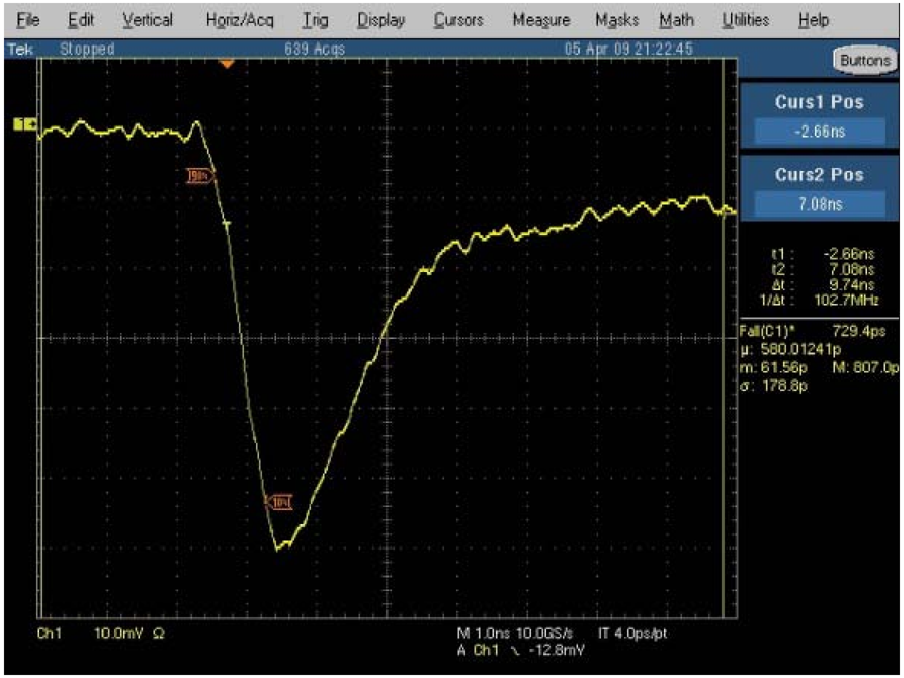
k_T=dA/dT*1/A, [%/°C]

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

(Y. Musienko, PD-07, Kobe)

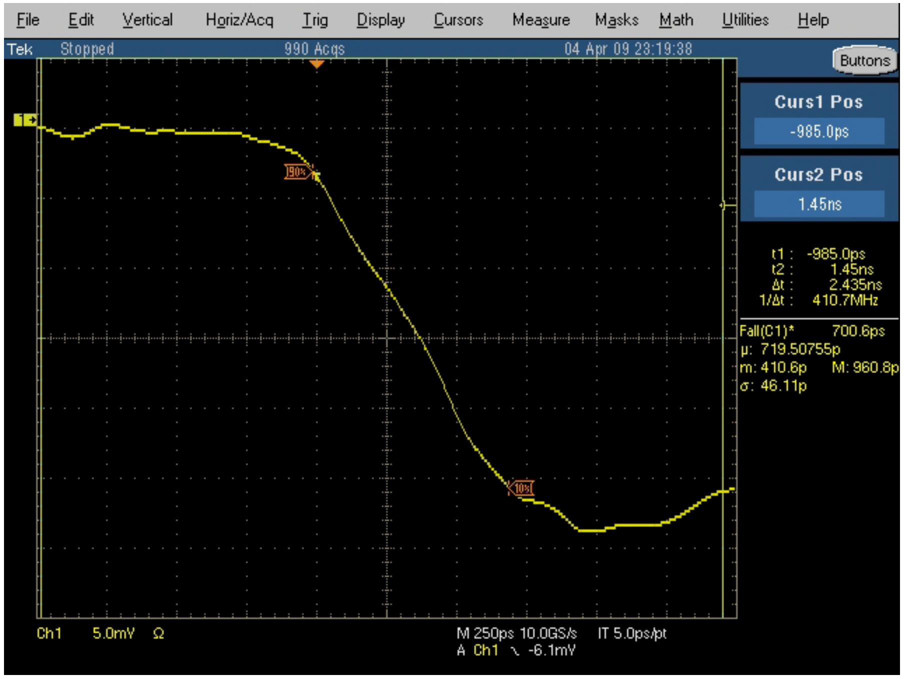
Signal rise time

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



```
Tek  Stopped        639 Acqs        05 Apr 09 21:22:45

Curs1 Pos
-2.66ns
Curs2 Pos
7.08ns

    t1 :    -2.66ns
    t2 :     7.08ns
    Δt :     9.74ns
  1/Δt :   102.7MHz

Fall(C1)*        729.4ps
µ: 580.01241p
m: 61.56p     M: 607.0p
σ: 178.8p

Ch1   10.0mV  Ω          M 1.0ns 10.0GS/s    IT 4.0ps/pt
                         A  Ch1  \  -12.8mV
```

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

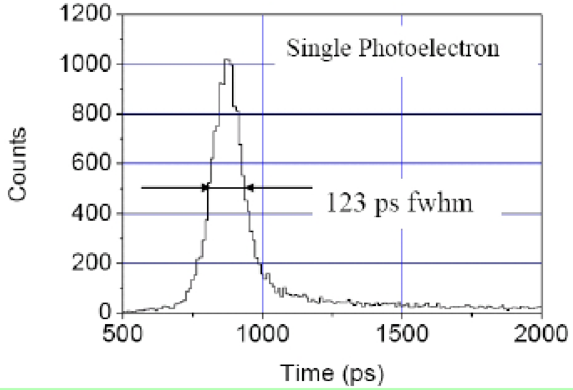


```
Tek  Stopped        990 Acqs        04 Apr 09 23:19:38

Curs1 Pos
-985.0ps
Curs2 Pos
1.45ns

    t1 :  -985.0ps
    t2 :     1.45ns
    Δt :    2.435ns
  1/Δt :   410.7MHz

Fall(C1)*        700.6ps
µ: 719.50755p
m: 410.6p     M: 960.8p
σ: 46.11p

Ch1   5.0mV  Ω           M 250ps 10.0GS/s    IT 5.0ps/pt
                         A  Ch1  \  -6.1mV
```

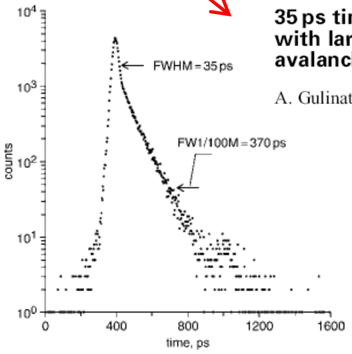
~700 psec rise time was measured (limited by circuitry)

Single photon time resolution

SiPMs have excellent timing properties

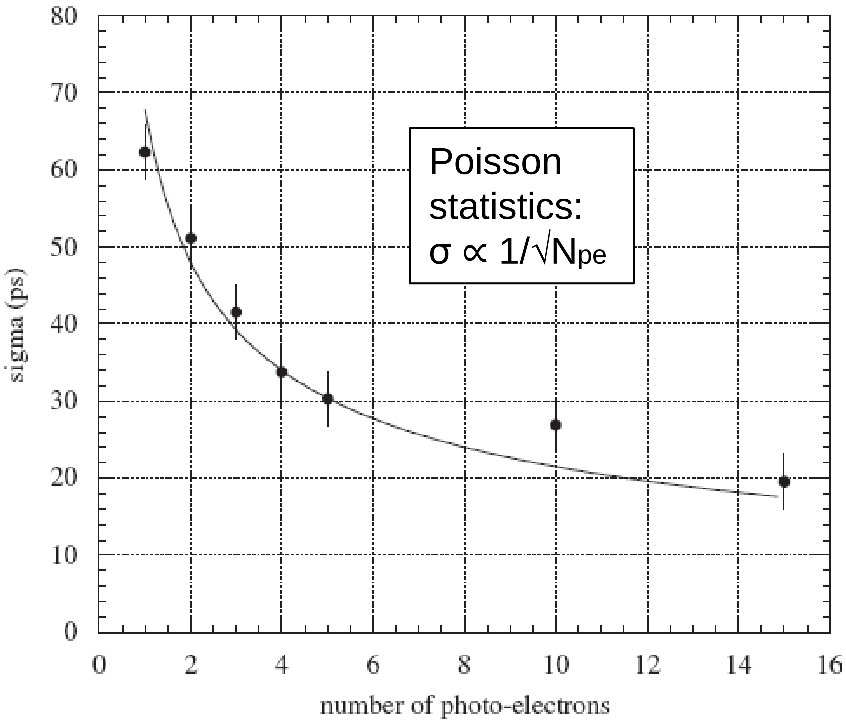


123 psec FWHM time resolution was measured with MEPhI/Pulsar SiPM using single photons (B. Dolgoshein, Beaune-02). And this can be improved …



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



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

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

Linearity and dynamic range

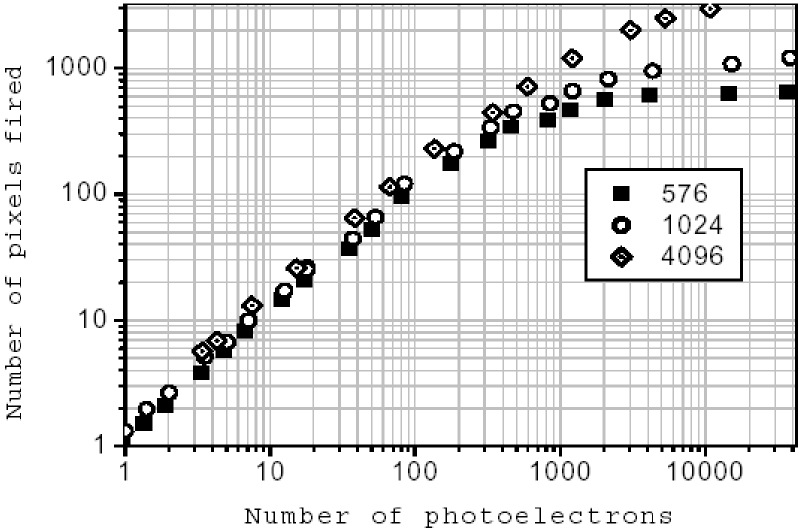
SiPM linearity is determined by its total number of cells

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)

Response functions for the SiPMs with different total pixel numbers measured for 40 ps laser pulses



(B. Dolgoshein, TRD05, Bari)

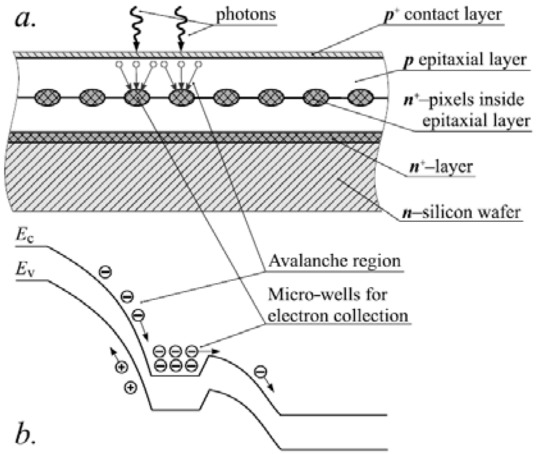
For correct amplitude measurements the SiPM response should be corrected for its non-linearity !

New SiPM developments

Large dynamic range Micro-pixel APDs from Zecotek

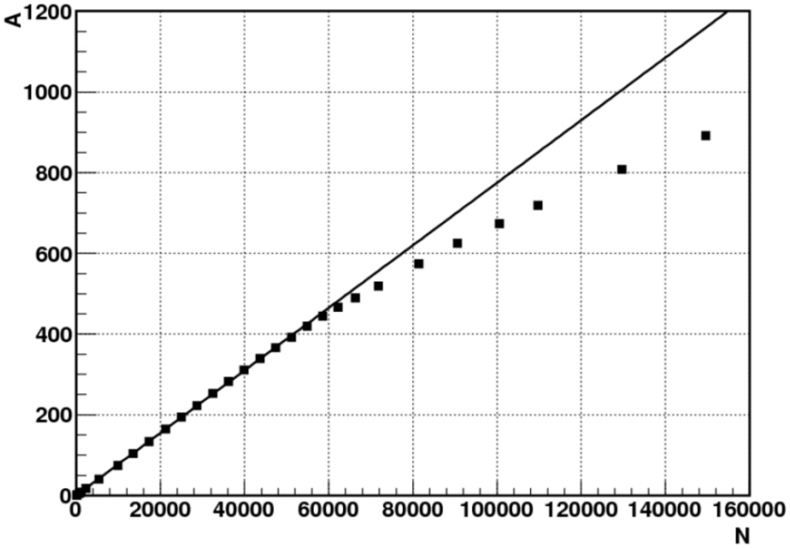
Micro-well structure with multiplication regions located in front of the wells at 2-3 µm depth was developed by Z. Sadygov. MAPDs with 10 000 – 40 000 cells/mm^2 and up to 3x3 mm^2 in area were produced by Zecotek (Singapore).

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)

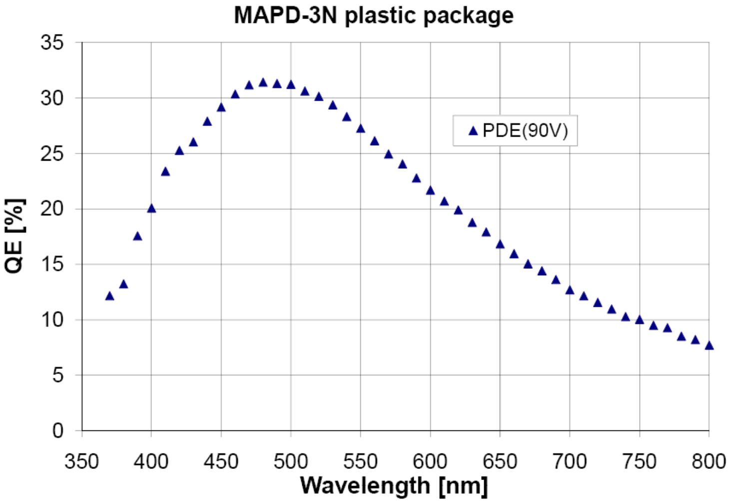
Micro-pixel APDs for the CMS HCAL Upgrade

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

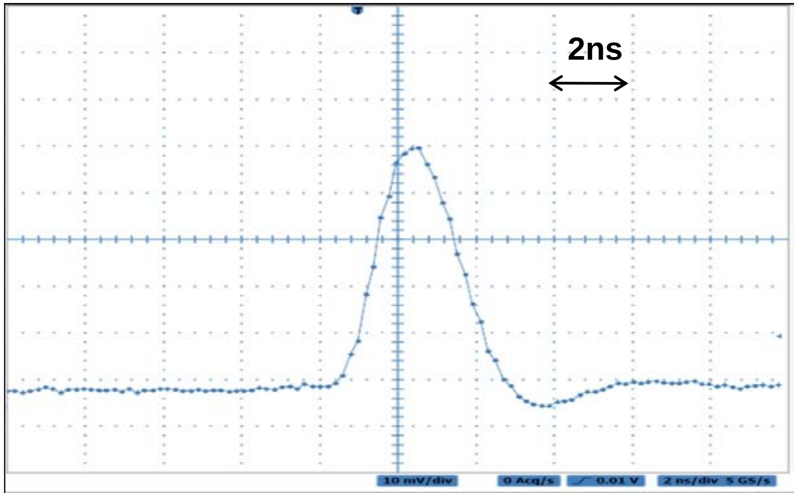
Linear array of MAPDs (18x1 mm^2 , 15 000 cells/mm^2) produced by Zecotek for the CMS HCAL Upgrade project.

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

PDE vs. wavelength



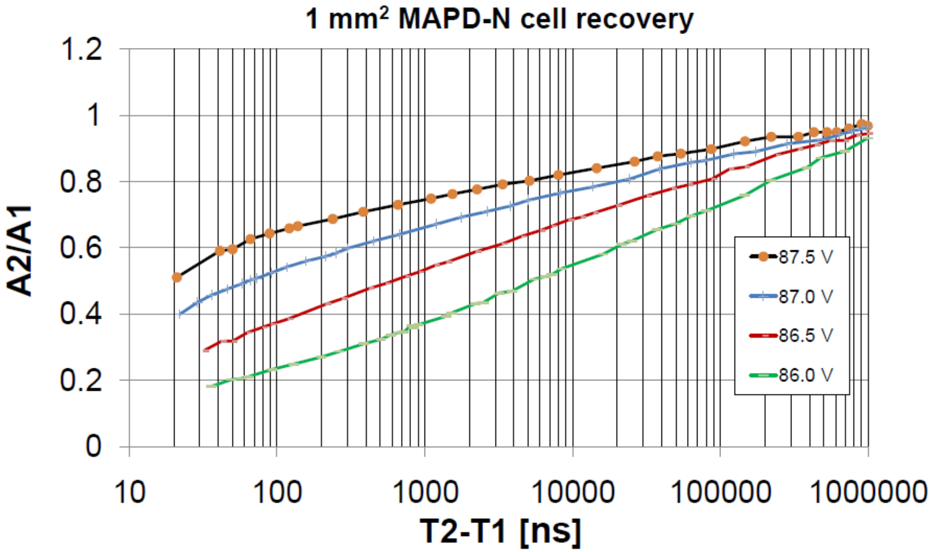
1 mm^2 MAPD response to a 35 psec (FWHM) laser pulse



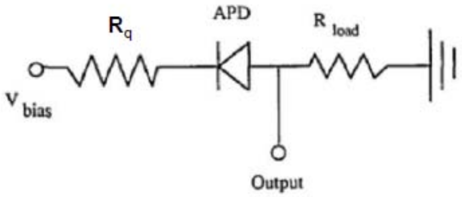
MAPD cell recovery

MAPD cell recovery is not exponential

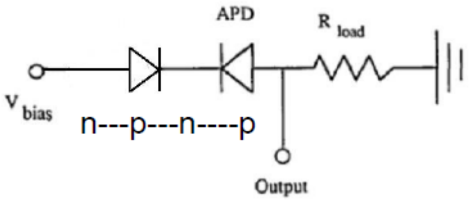
MAPD (3N type) cell recovery (measured using 2 LED technique)



SiPM cell equivalent circuit

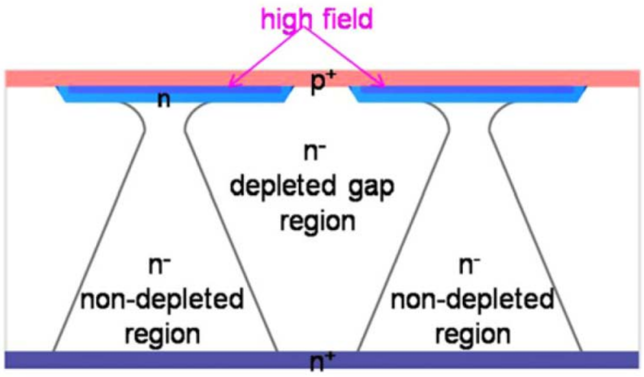


MAPD cell equivalent circuit



SiPMs with bulk integrated quenching resistors from MPI (SiMPI concept)

Schematic cross-section of two neighboring cells



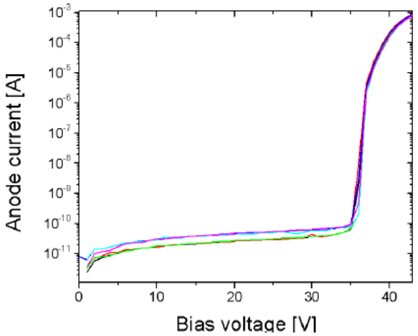
Advantages:

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

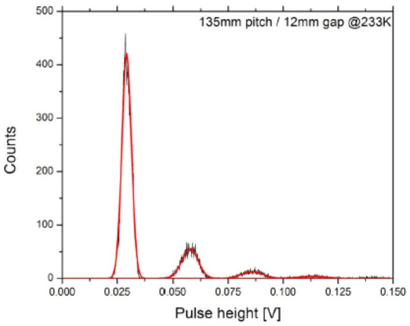
Drawbacks:

- ➔ **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 ??**

Static measurements



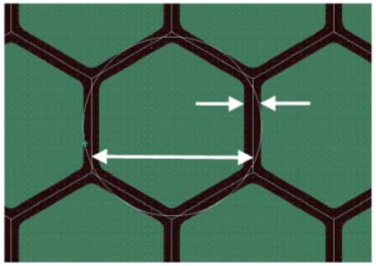
Dynamic measurements

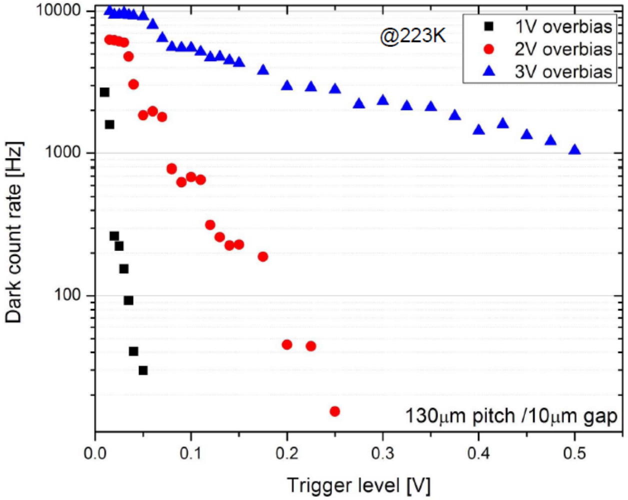


(J. Ninkovic et al., NIM A628 (2011))

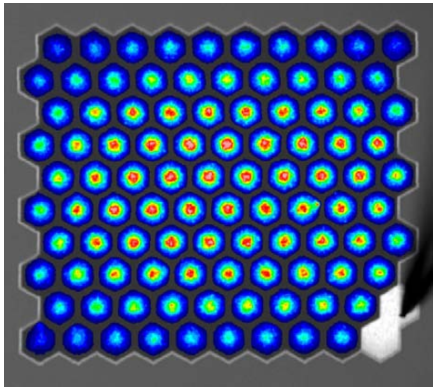
SiMPl results

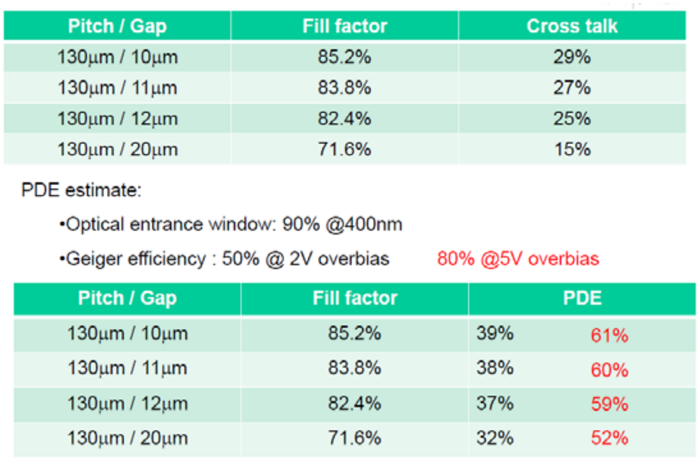
Prototype structure was recently produced





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

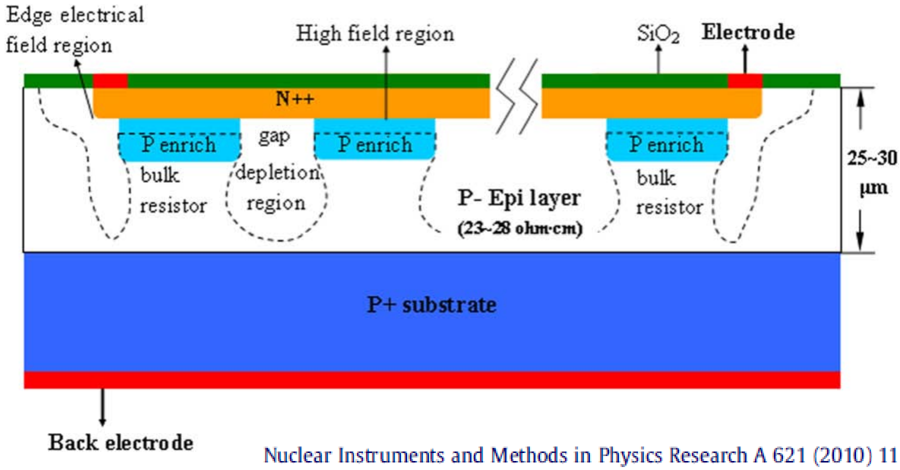
Pitch / Gap	Fill factor	PDE	
130µm / 10µm	85.2%	39%	61%
130µm / 11µm	83.8%	38%	60%
130µm / 12µm	82.4%	37%	59%
130µm / 20µm	71.6%	32%	52%

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

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

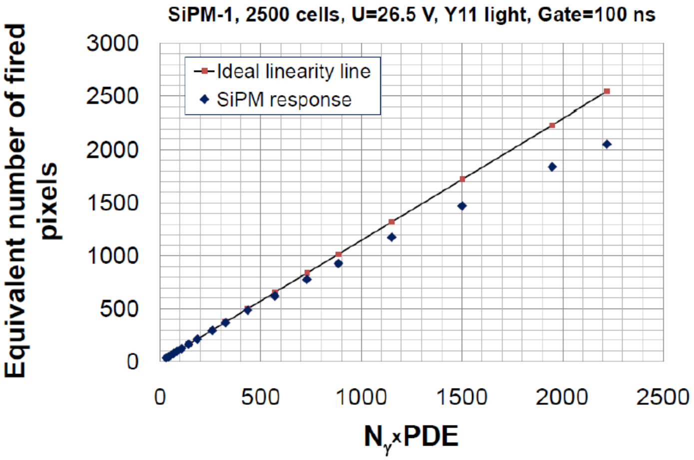
Large dynamic range SiPMs with bulk integrated quenching resistors from NDL(Beijing)

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



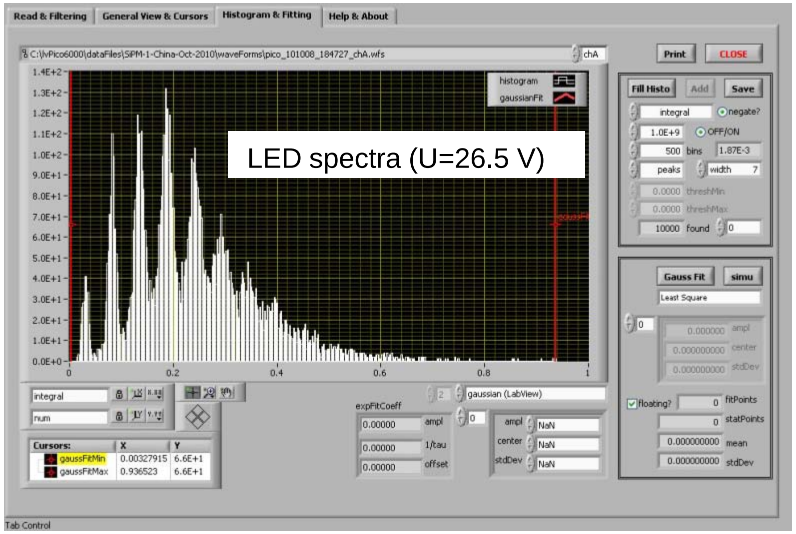
Nuclear Instruments and Methods in Physics Research A 621 (2010) 116–120

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



LED spectra (U=26.5 V)

C:\lvPico6000\dataFiles\SiPM-1-China-Oct-2010\waveForms\pico_101008_184727_chA.wfs chA

integral ○ negate?
1.0E+9 ○ OFF/ON
500 bins 1.87E-3
peaks width 7
0.0000 threshMin
0.0000 threshMax
10000 found 0

Least Square
0
0.000000 ampl
0.000000000 center
0.000000000 stdDev
☑ floating? 0 fitPoints
0 statPoints
0.000000000 mean
0.000000000 stdDev

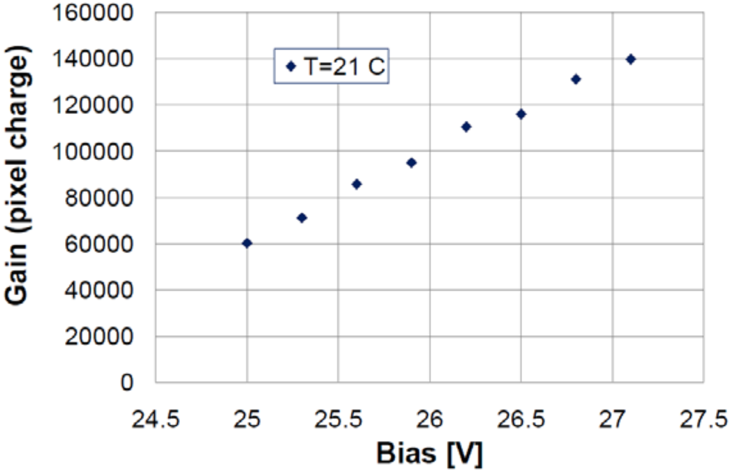
integral
num

2 gaussian (LabView)

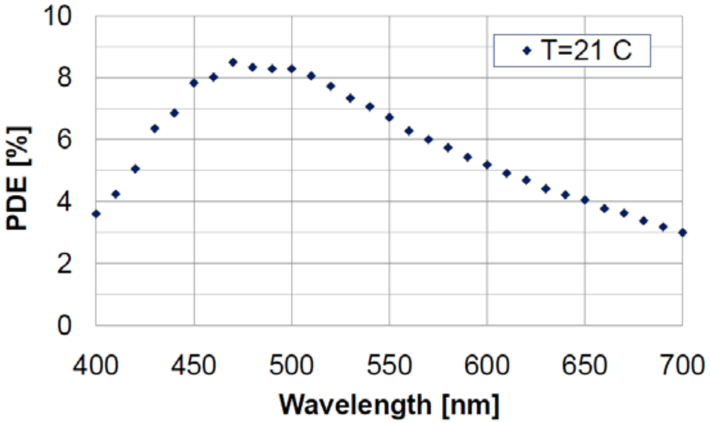
expFitCoeff
0.00000 ampl
0.00000 1/tau
0.00000 offset

0
ampl NaN
center NaN
stdDev NaN

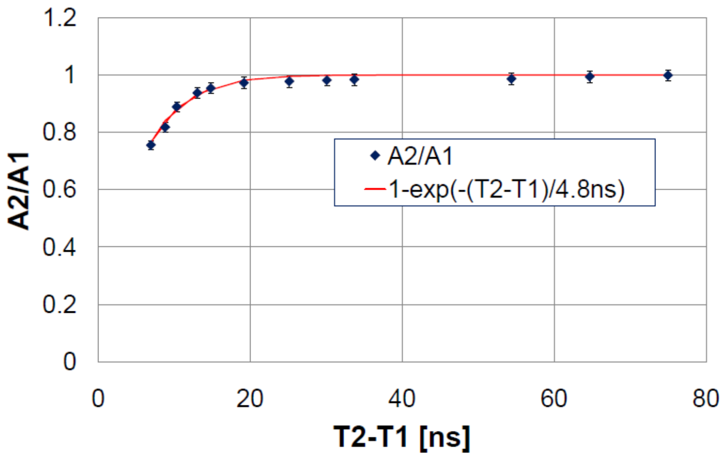
Cursors:	X	Y
gaussFitMin	0.00327915	6.6E+1
gaussFitMax	0.936523	6.6E+1



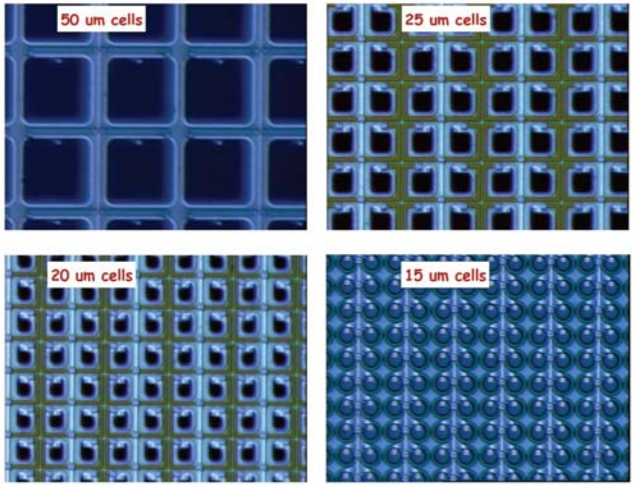
SiPM (U=26.5 V, 2 500 cells, 0.25 mm²)

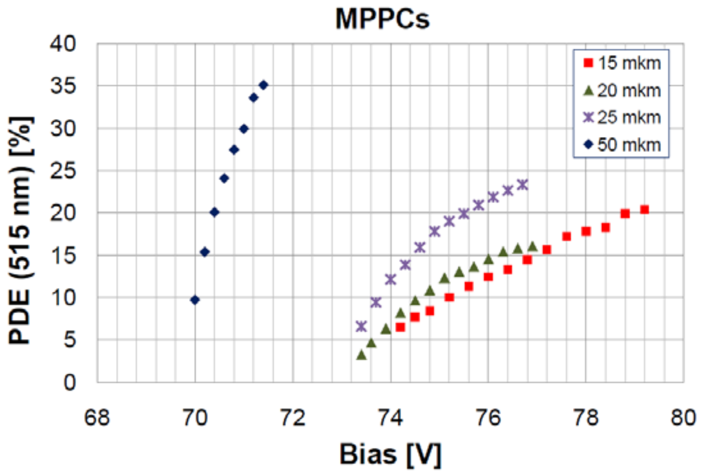


SiPM pixel recovery (U=26.5 V, double pulse, $N_\gamma > 10^6$ 1/mm²/pulse)

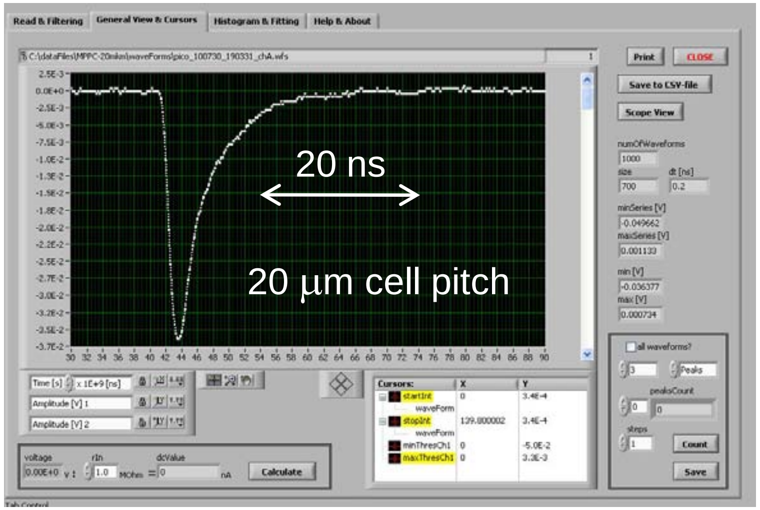


Large dynamic range MPPCs





MPPC responses to a fast (35 psec FWHM) laser pulse



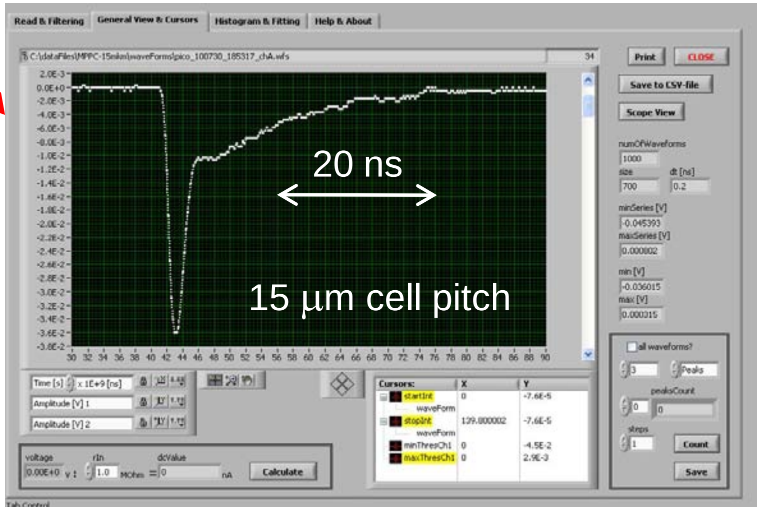
C:\dataFiles\MPPC-20mkm\waveForms\pico_100730_190331_chA.wfs 1

numOfWaveforms 1000
size 700
dt [ns] 0.2
minSeries [V] -0.049662
maxSeries [V] 0.001133
min [V] -0.036377
max [V] 0.000734
☐ all waveforms?
3
Peaks
peaksCount 0 0
steps 1

Time [s] x 1E+9 [ns]
Amplitude [V] 1
Amplitude [V] 2

voltage 0.00E+0 V rIn 1.0 MOhm = dcValue 0 nA

Cursors:	X	Y
startInt	0	3.4E-4
waveForm		
stopInt	129.000002	3.4E-4
waveForm		
minThresCh1	0	-5.0E-2
maxThresCh1	0	3.3E-3



C:\dataFiles\MPPC-15mkm\waveForms\pico_100730_185317_chA.wfs 34

numOfWaveforms 1000
size 700
dt [ns] 0.2
minSeries [V] -0.045393
maxSeries [V] 0.000802
min [V] -0.036015
max [V] 0.000315
☐ all waveforms?
3
Peaks
peaksCount 0 0
steps 1

Time [s] x 1E+9 [ns]
Amplitude [V] 1
Amplitude [V] 2

voltage 0.00E+0 V rIn 1.0 MOhm = dcValue 0 nA

Cursors:	X	Y
startInt	0	-7.6E-5
waveForm		
stopInt	129.000002	-7.6E-5
waveForm		
minThresCh1	0	-4.5E-2
maxThresCh1	0	2.9E-3

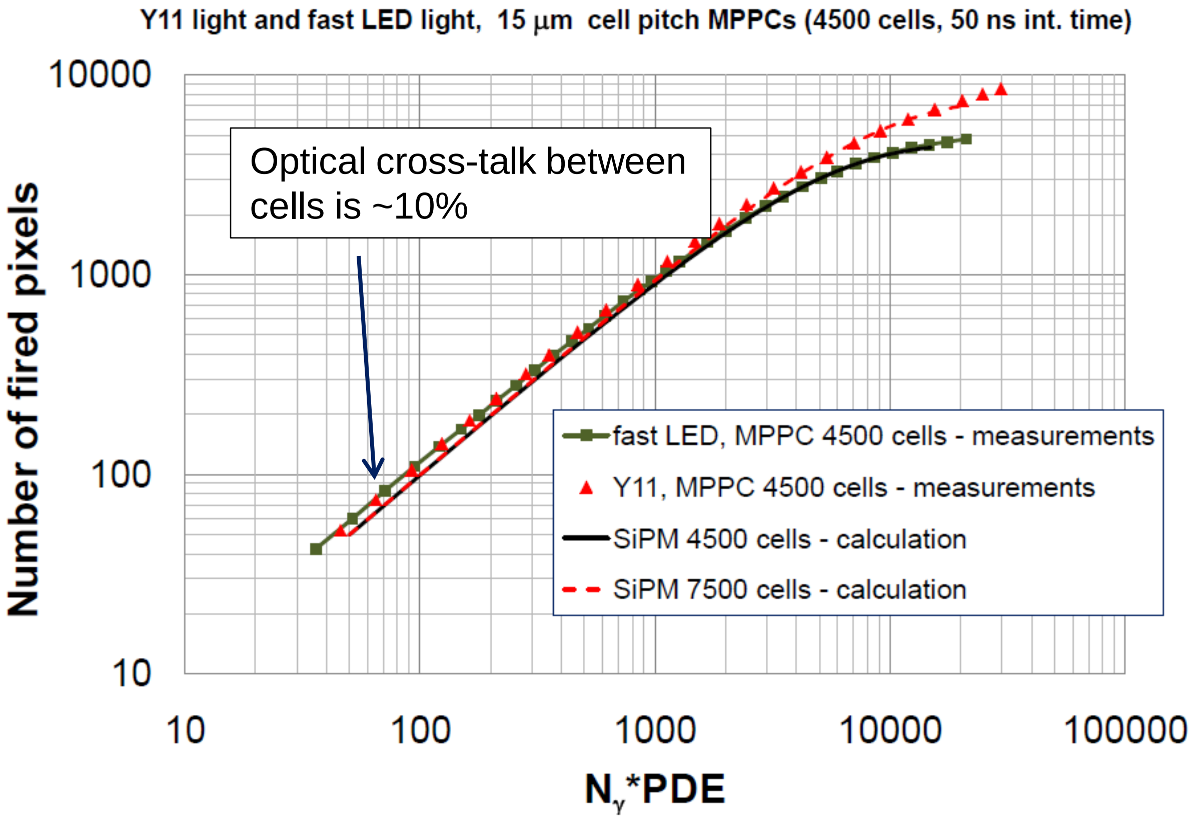
New MPPC parameters

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	1690	6.75	11.4	72.75	76.4	2.0
20 μm pitch	2500	31	305	12.4	3.8	73.05	75.0	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

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

SiPM linearity measurements (MPPC with 4 500 cells)



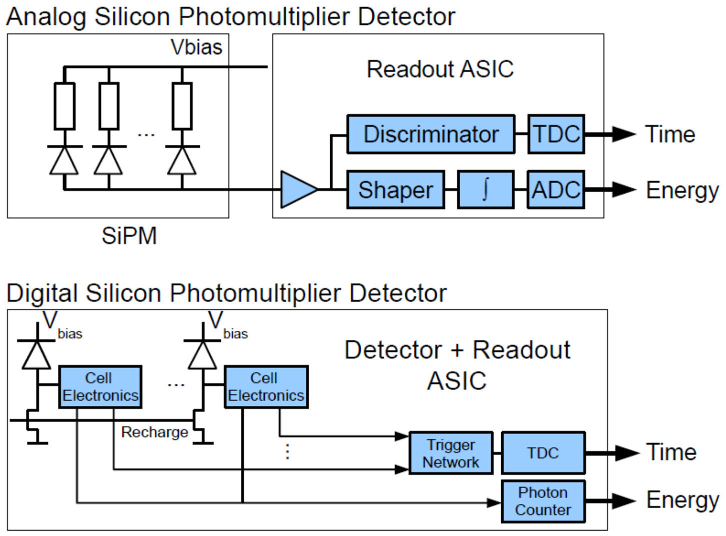
Optical cross-talk between cells is ~10%

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: τ~11 ns.

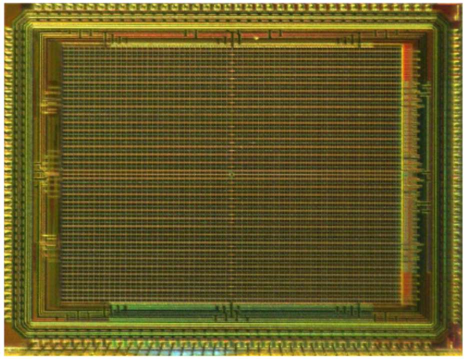
dSiPM (Philips)

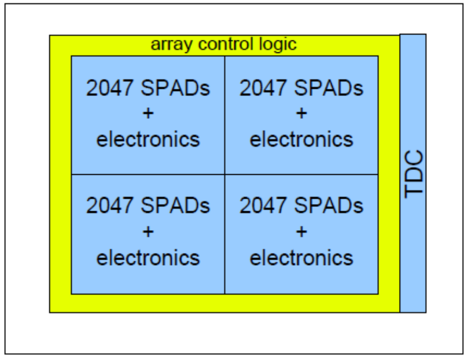
dSiPM - array of SPADs integrated in a standard CMOS process. Photons are detected and counted as digital signals using a dedicated cell electronics block next to each diode. This block also contains active quenching and recharge circuits, one bit memory for the selective inhibit of detector cells. A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

Digital SiPM – The Concept



Digital SiPM – Test Chip Architecture

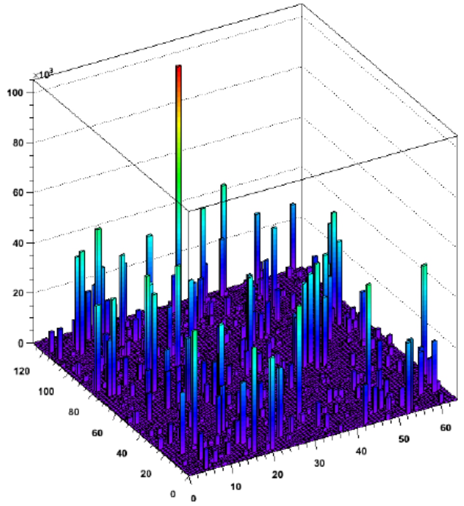


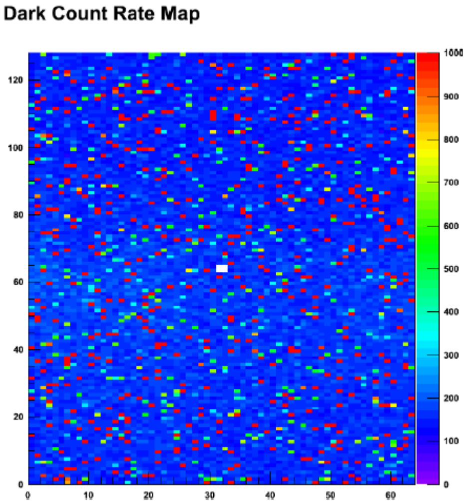


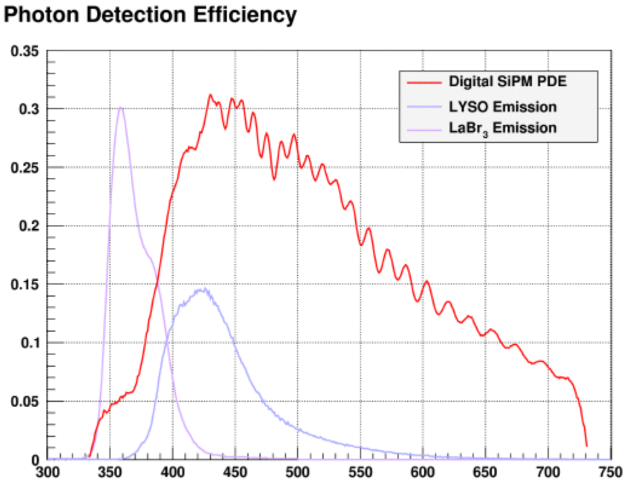
- Pixel composed of 4 identical sub-pixels with 2047 microcells each
- Microcell size 30µmx52µm, 50% fill factor including electronics
- A 1 bit inhibit memory in each microcell to enable/disable faulty diodes
- Active quench & recharge, on-chip memory and array controllers
- Integrated time-to-digital 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







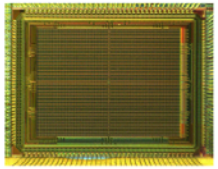
Only 5 to 10% of the diodes show abnormally high dark count rates due to defects. These diodes can be switched off. The average dark count rate of a good diode at 20 °C is approximately 150 cps (or ~100 kHz/mm^2).
Digital signal – only PDE varies with the temperature → low temperature sensitivity ~0.33%/C

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

dSiPM – new development

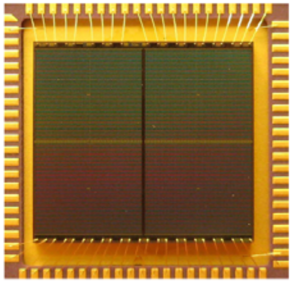
Digital SiPM Prototype

DLD8K Technology Demonstrator:

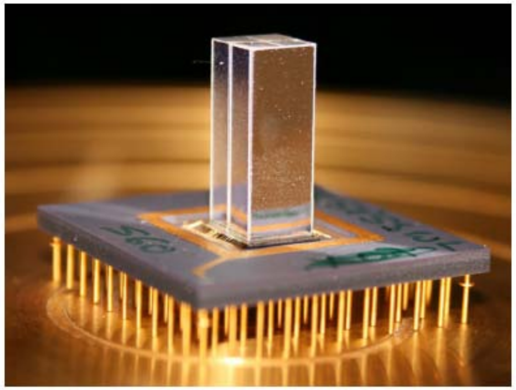


- *8192 Geiger-mode cells*
- *Integrated time-to-digital converter*
- *On-chip inhibit memory controller and first-level photon accumulators*
- *Off-chip acquisition controller*
- *160 bond wires*

DLS-6400-22 DSiPM Prototype:

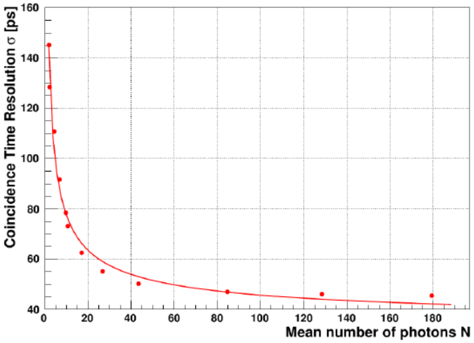


- *25600 Geiger-mode cells*
- *Two complementary TDCs*
- *Integrated acquisition controller*
- *JTAG for configuration & test*
- *Two serial data outputs*
- *48 bond wires*

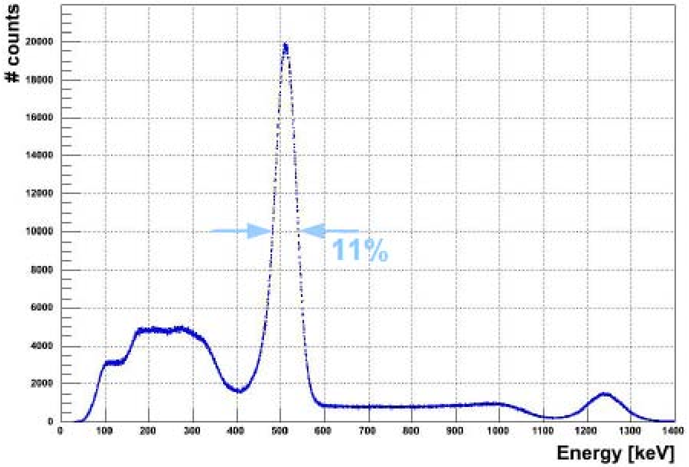


- *2x2 Array of 3x3x15mm³ LYSO*
- *1:1 coupling using MeltMount*
- *Illuminated by ²²Na source*
- *Corrected only for saturation*
- *dE/E = 11% (combined)*

Digital SiPM – Coincidence Time Resolution



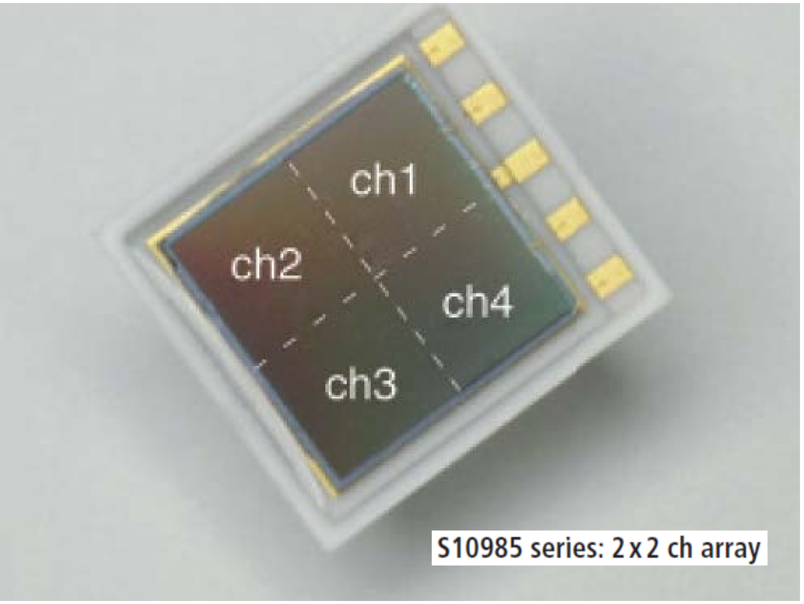
- *Two DLS-6400-22 Digital SiPMs in coincidence*
- *Triggered by attenuated picosecond laser pulses (σ = 36ps)*
- *Both sensors see approximately the same number of photons*

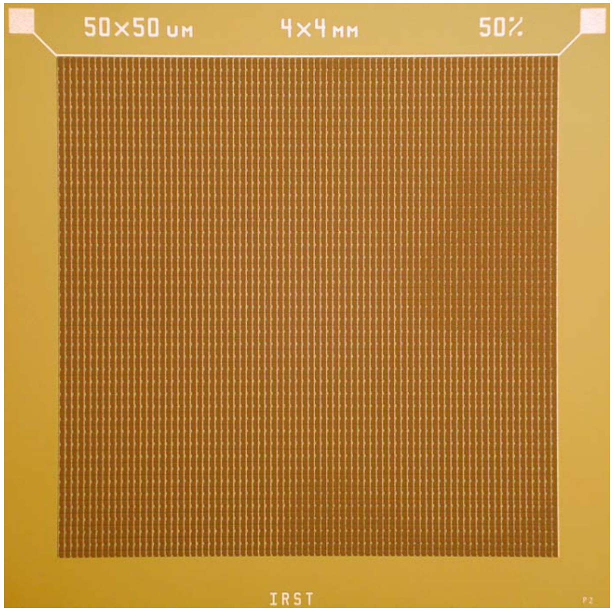


(T. Frach , IEEE-NSS/MIC, Knoxville, Nov. 2010)

Large area SiPMs

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





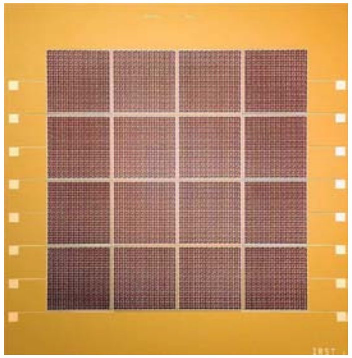
Hamamatsu MPPC, 6x6 mm^2, 14 400 cells

FBK SiPM, 4x4 mm^2, 6400 cells

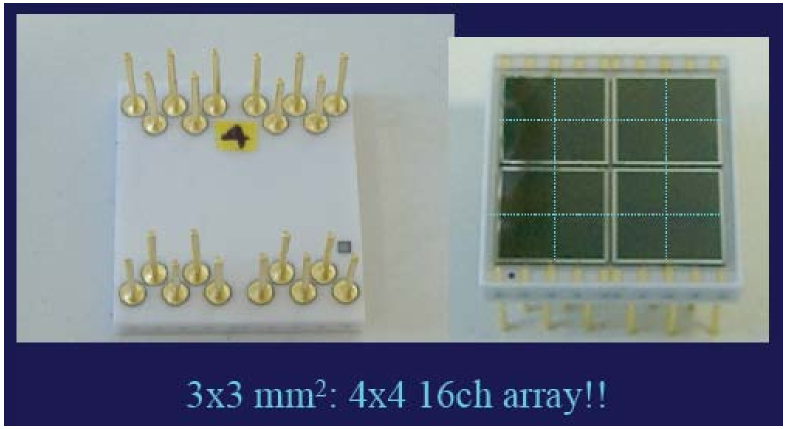
SiPM arrays

SensL array for PET/MRI (16x9 мм^2)

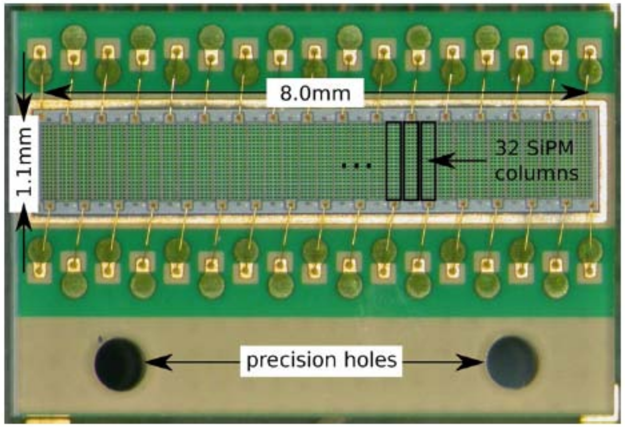
FBK MPPC array for PET (16x1 мм^2)



MPPC array for MAGIC telescope



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



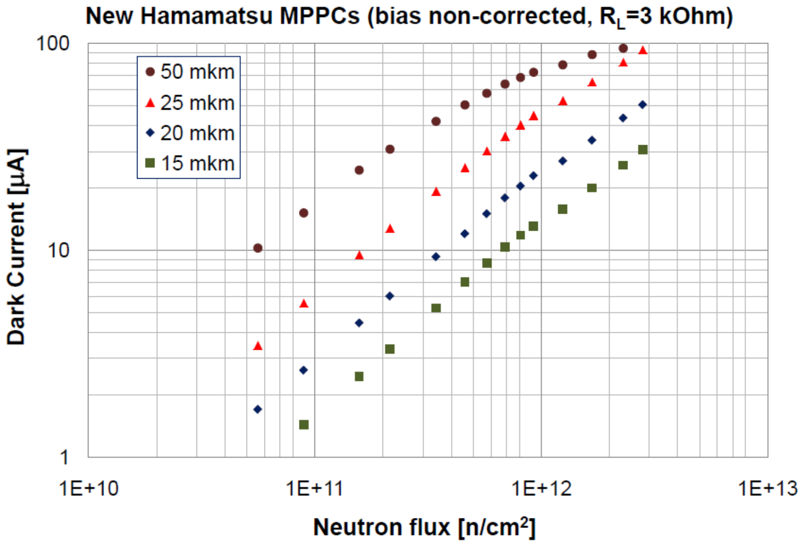
Radiation hardness studies

Motivation: G-APDs will be used in HEP experiments

Radiation may cause:

- Fatal G-APDs damage (G-APDs can't be used after certain absorbed dose)
- Dark current and dark count increase (silicon …)
- Change of the gain and PDE vs. voltage dependence (G-APDs 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:

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

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

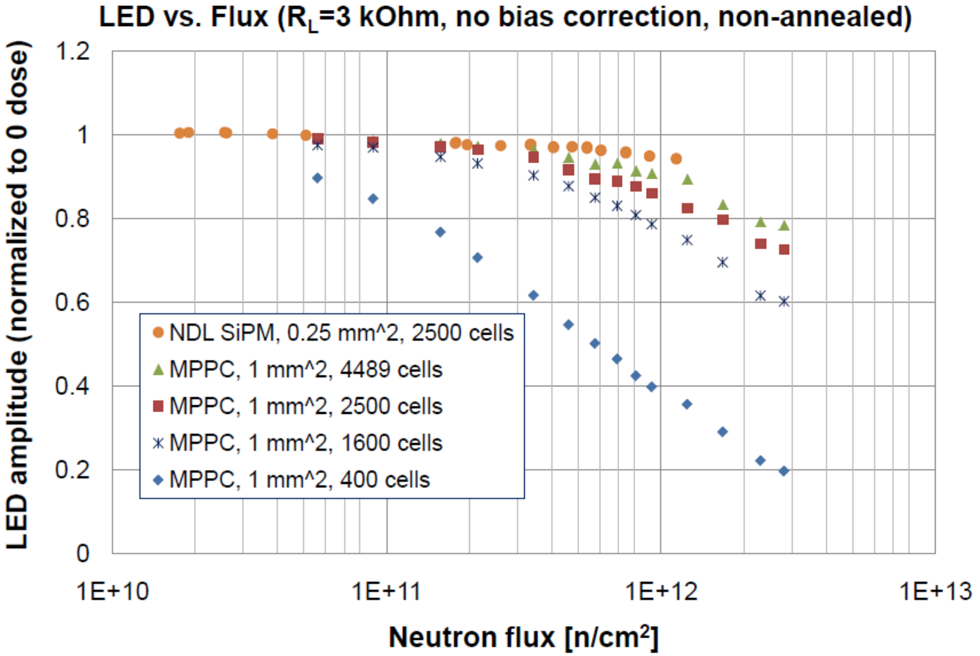
α_{Si} ~$4*10^{-17}$ A*cm after 80 min annealing at T=60 C (measured at T=20 C)

- 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

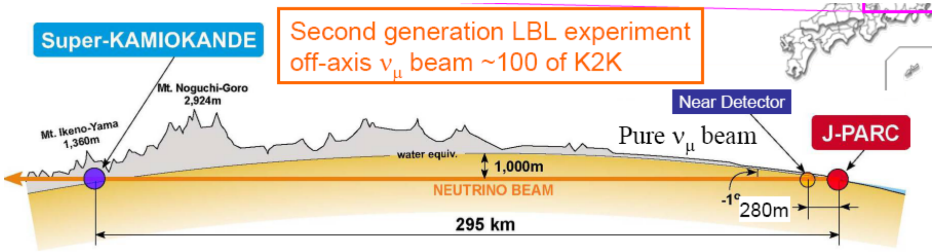


SiPMs with high cell density and fast recovery time can operate up to 3*10^{12} neutrons/cm^2 (gain change is< 25%).

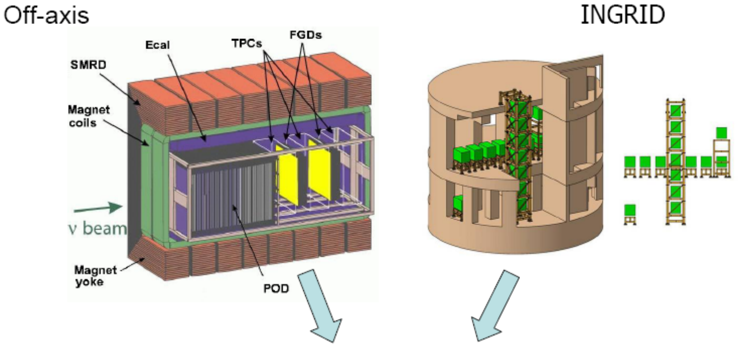
SiPMs for HEP experiments

(SiPMs are used in large quantities now!)

T2K neutrino experiment



Second generation LBL experiment
off-axis ν_μ beam ~100 of K2K

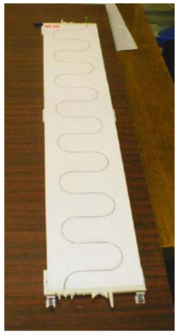


Scintillator detectors with WLS fibers

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

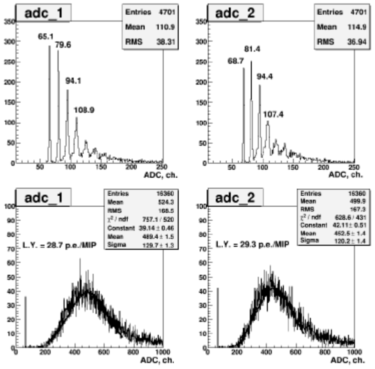
SMRD detectors

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



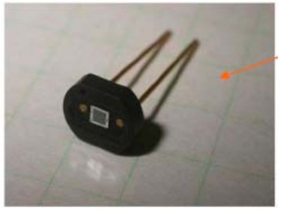
MIP detection efficiency	**> 99.9%**
σ_t (MIP)	**~ 0.7 ns**
Spatial resolution	**~ 7 cm**

Light yield



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

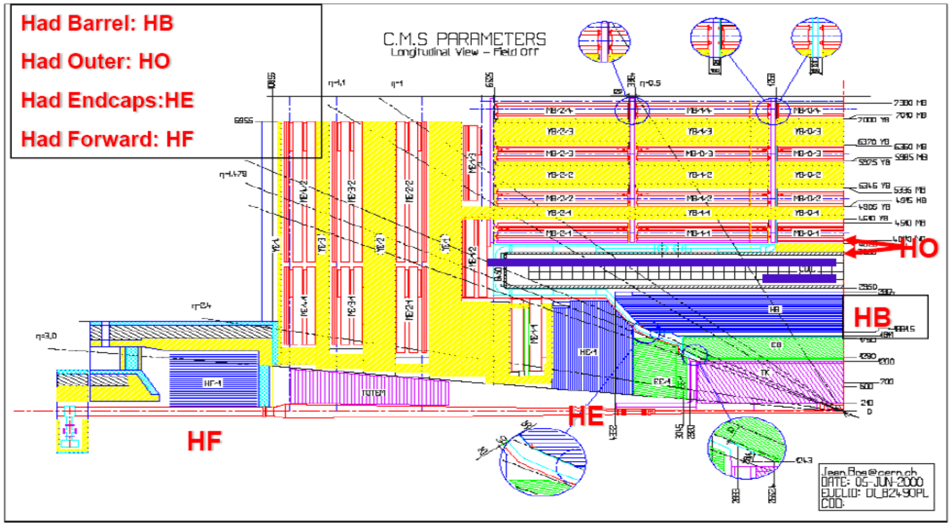
Hamamatsu MPPC: active area 1.3×1.3 mm^2



Number of pixels	667
Pixel size	50×50 μm
Gain	~0.7×10^6
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%

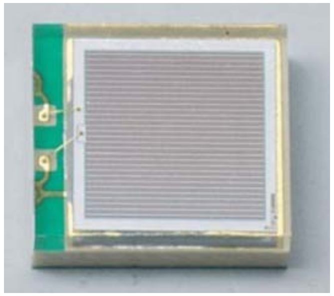
(Yu. Kudenko, G-APD workshop, GSI, Feb. 2009)

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



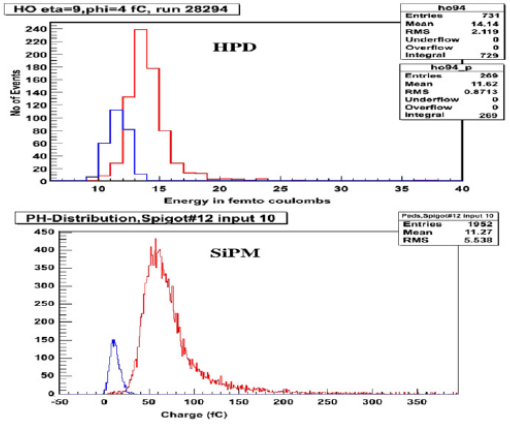
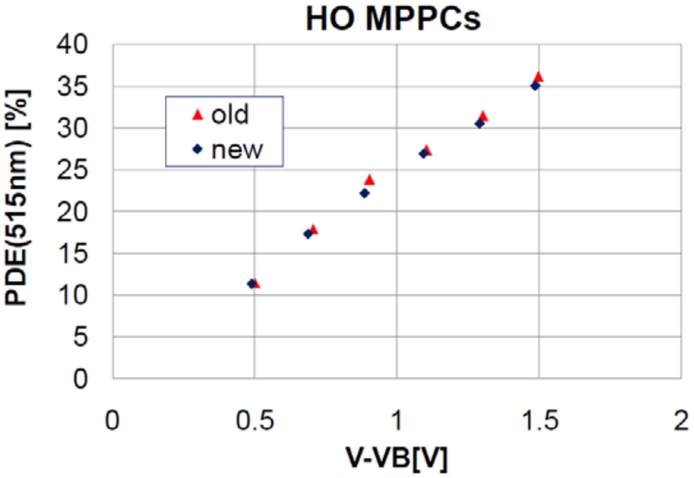
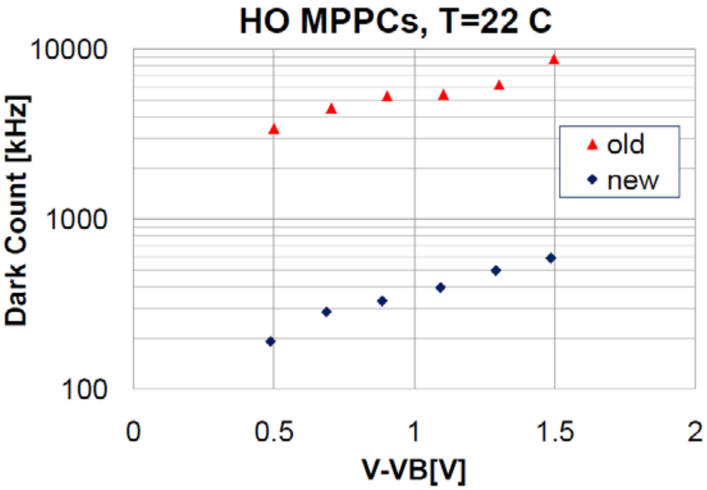


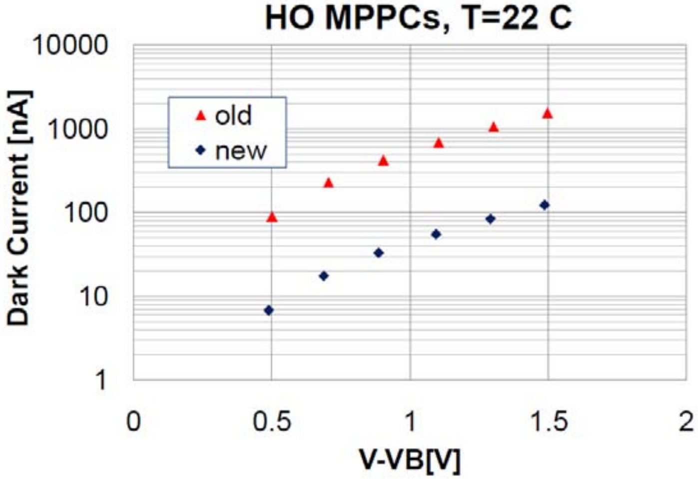
Fig. 3. Pedestal and muon signal distributions for HPD and SiPM [3].

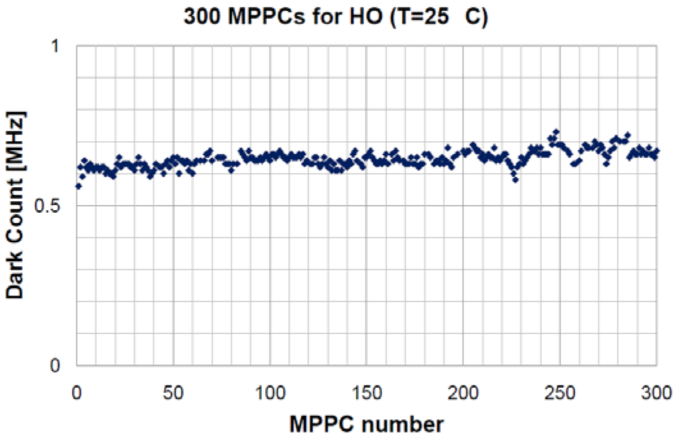
HO SiPM readout module – 18 channels

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 !

Summary

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

- High PDE~30-40% for blue-green light (CPTA/Photonique, Hamamatsu, Zecotek, KETEK, Philips …)
- Reduction of dark count at room temperature (~70 kHz/mm^2, Hamamastu)
- Low cross-talk (<1-3%, CPTA/Photonique, STMicroelectronics)
- Low temperature coefficient (~0.3%/C – CPTA, Philips)
- Fast timing (~50 ps (RMS) for single photons)
- Large dynamic range (10 000 – 40 000 pixels/mm^2, Zecotek, NDL)
- Large area (≥3x3 mm^2 - Hamamatsu, FBK, SensL, Zecotek, STMicroelectronics CPTA, KETEK, Philips …)
- SiPM arrays: 4x4, 8x8

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 SSPMs (my dreams…)

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

- PDE > 50-60% for 350-650 nm light
- dark count rate <50 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%)
- very fast CCDs operated in Geiger mode
- super radiation hard G-APDs - up to $10^{14} \div 10^{15}$ n/cm^2 (new materials: diamond?, GaAs?, SiC?, GaN? …)
- production cost <1 $/мм^2
- ….