Status and Perspectives in Silicon Photomultiplier developments

Jelena Ninkovic for the HLL avalanche team

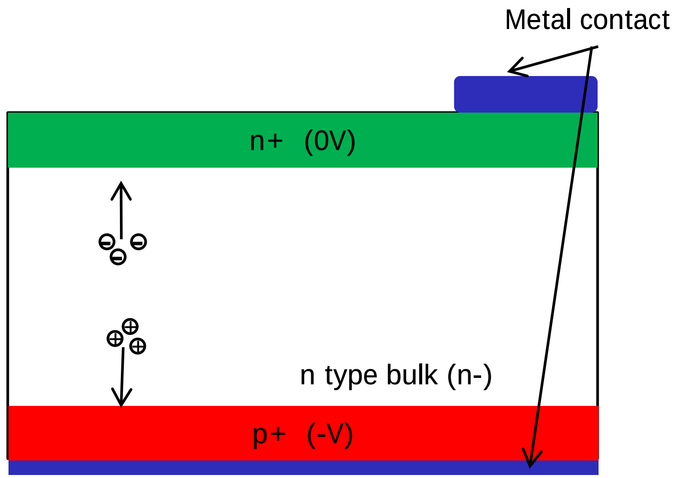
- Some properties and problems of SiPMs
- SiPM development at MPI Semiconductor Laboratory

532. WE-Heraeus-Seminar, Bad Honnef, Germany, 23-25 May 2013

P(i)N Diode

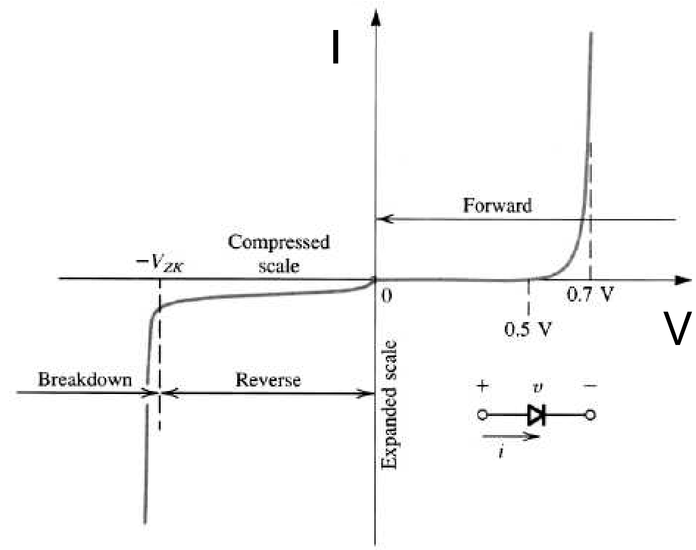
Material: silicon
germanium
compound semiconductors
(CdTe, CZT, ...)

Geometry
size: 5 mm² ... 1 cm²
thickness: 300, 500 µm, 1 mm



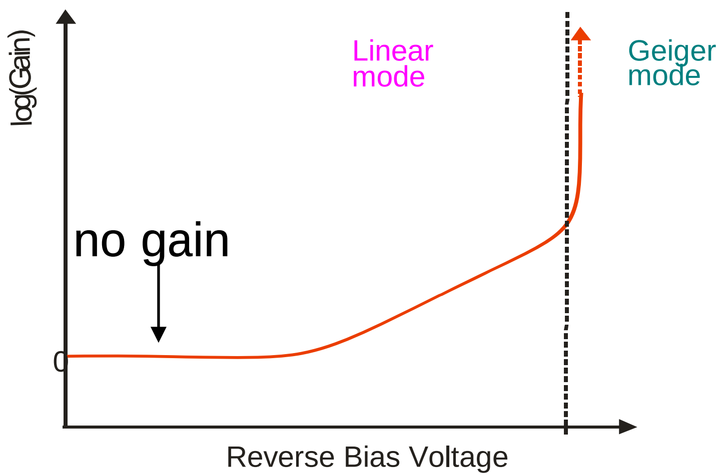
Sensitive to light but no single photon sensitivity.

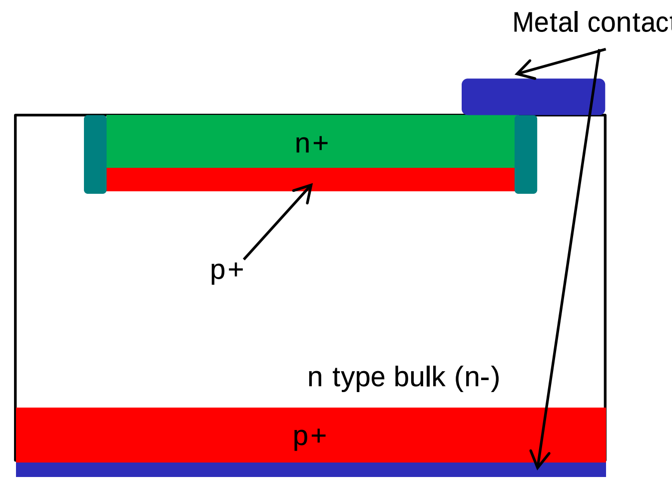
example: $N_D = 2 \cdot 10^{12} / cm^3$
d = 250, 500 µm
↳ V = 75, 300 V



Avalanche PhotoDiode - APD

An **avalanche photodiode (APD)** is a photodiode that internally amplifies the photocurrent by an avalanche process.





Linear/ Proportional mode

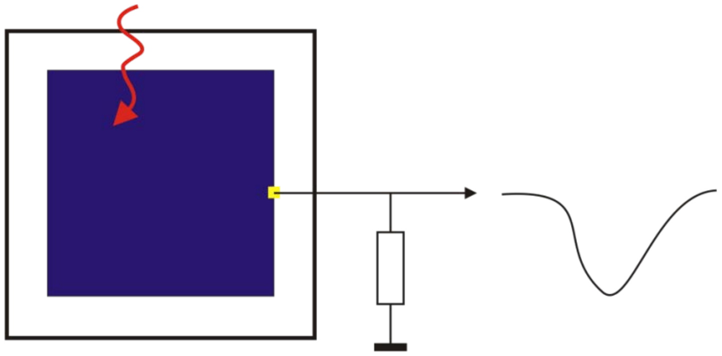
Bias: slightly ***BELOW*** breakdown
Linear-mode: it's an ***AMPLIFIER***
Gain: limited < 300 (1000)
High temperature/bias dependence
No single photo electron resolution

Geiger mode

Bias: (10%-20%) ***ABOVE*** breakdown voltage
Geiger-mode: it's a ***BINARY*** device!!
Count rate limited
Gain: **"***infinite***"** !!

The Silicon Photomultiplier

An avalanche photodiode (APD) in Geiger mode is a highly efficient single photon counting device



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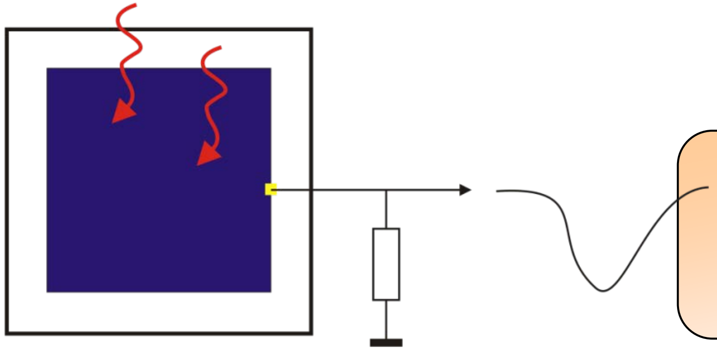

BUT:
Output signal of a single Geiger APD is independent of number of incident photons

The Silicon Photomultiplier

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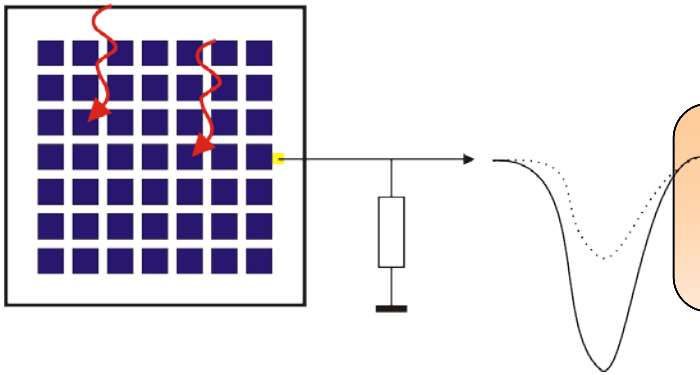
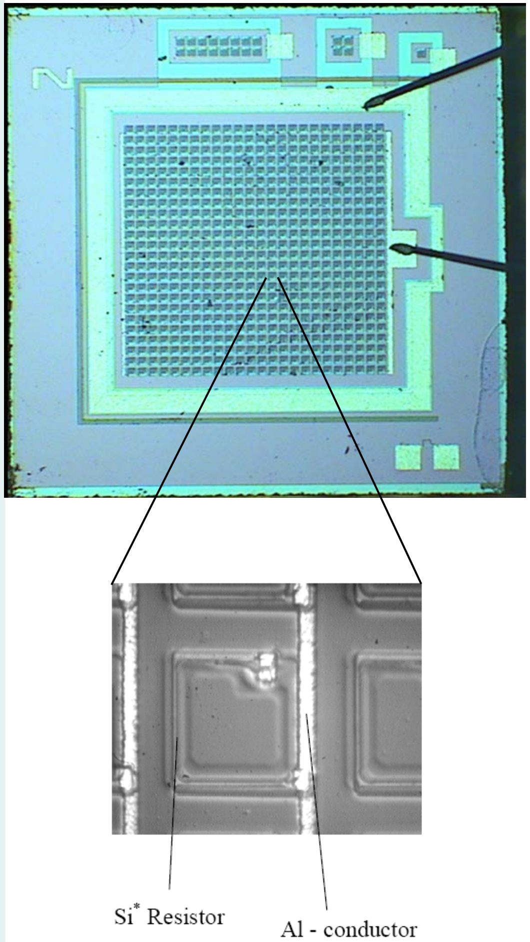


BUT:
Output signal of a single Geiger APD is independent of number of incident photons

Solution:
Combine an array of small Geiger APDs onto the same substrate and connect all cells in parallel

The Silicon Photomultiplier



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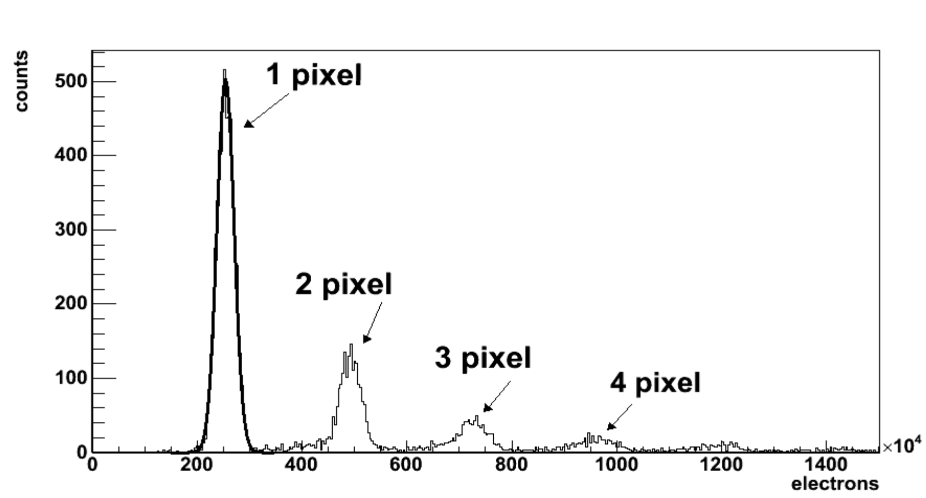
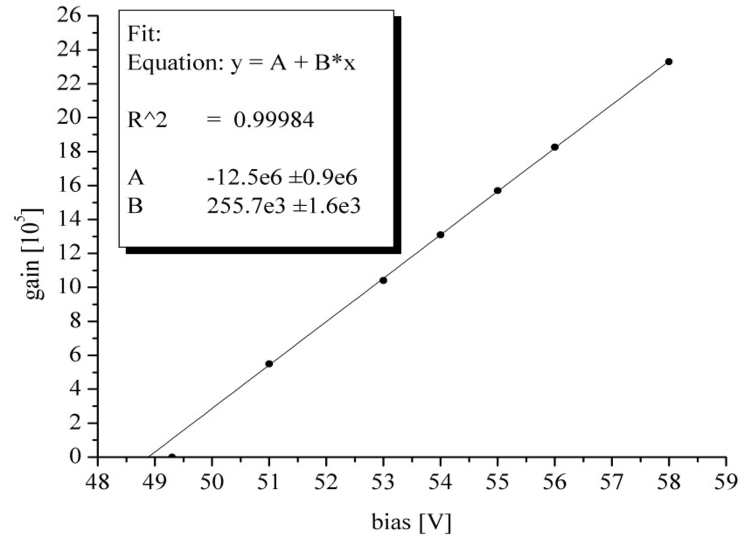
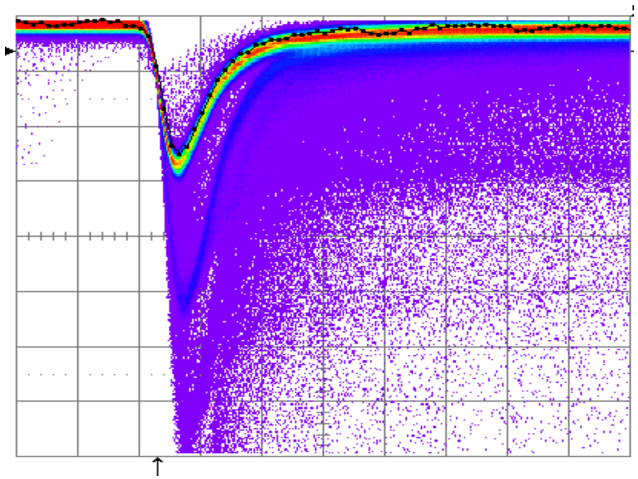
Characteristics







Operating voltage: «100 V
Gain: 10^5 up to 10^7
dependence of Gain on Temp.: 0.5% dG/dT

What is available

MEPhI/Pulsar (Moscow) - Dolgoshein

CPTA (Moscow) - Golovin

Zecotek(Singapore) - Sadygov

Amplification Technologies (Orlando, USA)

Hamamatsu Photonics (Hamamatsu, Japan)

SensL(Cork, Ireland)

AdvanSiD (former FBK-irst Trento, Italy)

STMicroelectronics (Italy)

KETEK (Munich)

RMD (Boston, USA)

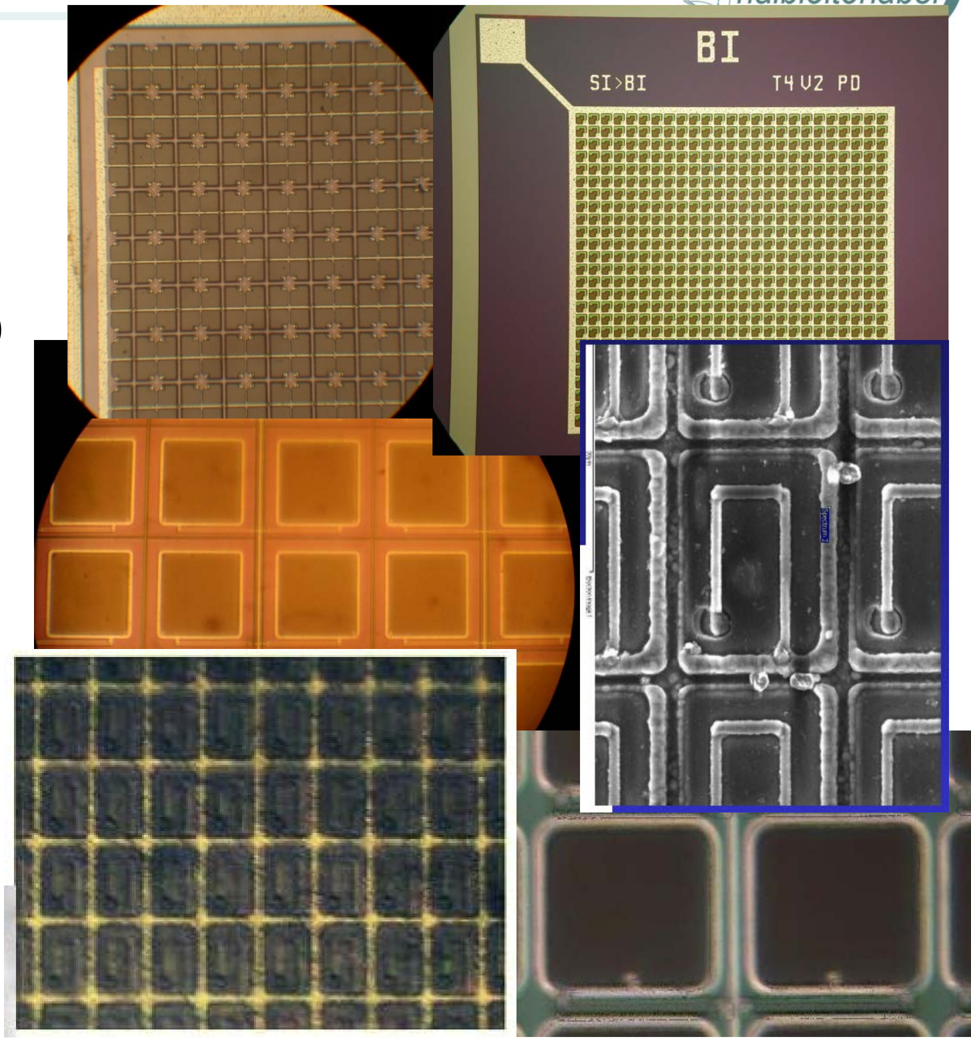
ExcelitasTechnologies (former PerkinElmer)

MPI Semiconductor Laboratory (Munich)

Novel Device Laboratory (Beijing, China)

Philips (Netherlands)

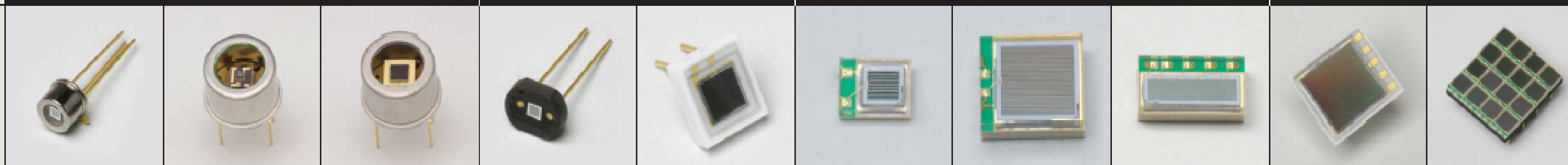
....



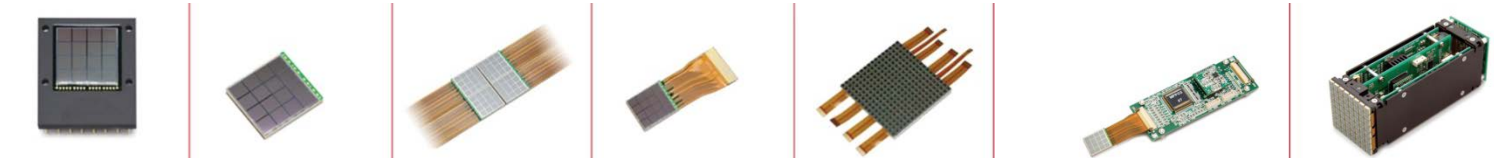
......Every producer uses its own name for this type of device: MRS APD, MAPD, SiPM, SSPM, MPPC, SPM, DAPD, PPD, SiMPl , dSiPM...

Hamamatsu – MPPC (Multi Pixel Photon Counter)

■ MPPC lineup (conventional type)

Type	Metal type			Ceramic type		Plastic package (Surface mount type)				2D array type	
		TE-cooled							Array	Array	Array
Image											
Type no.	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Effective active area	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Pixel size (μm)	25 × 25	25 × 25	25 × 25	25 × 25	25 × 25	25 × 25	25 × 25	25 × 25	25 × 25	25 × 25
	50 × 50	50 × 50	50 × 50	50 × 50	50 × 50	50 × 50	50 × 50	50 × 50	50 × 50	50 × 50
	100 × 100	100 × 100	100 × 100	100 × 100	100 × 100	100 × 100	100 × 100	100 × 100	100 × 100	
Package	Metal (TO-18)	Metal (TO-8)	Metal (TO-8)	Ceramic	Ceramic	Plastic	Plastic	Plastic	Ceramic	Plastic

Just as an illustration … no personal preference



4x4ch monolithic array	4x4ch monolithic array	4x4ch monolithic array	4x4ch monolithic array	8x8ch discrete array	4x4ch module	8x8ch module
PWB package S11827-3344MG	SMD package buttable S11828-3344M	with FPC (15 cm) buttable S11829-3344MF	with FPC (5 cm) buttable S11830-3344MF	with FPC buttable S11834-3388DF	C11206-0404FB	C11206-0808FA

Peak sensitivity : 440nm, Typical V_b= 70V, Typical operating voltage: V_b+1.5V (102%V_b)

Dynamical range & Saturation

The output signal is ~ to the number of fired cells as long as the number of detected photons (N_{photon} x PDE) is significantly smaller than the number of cells N_{total}.

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

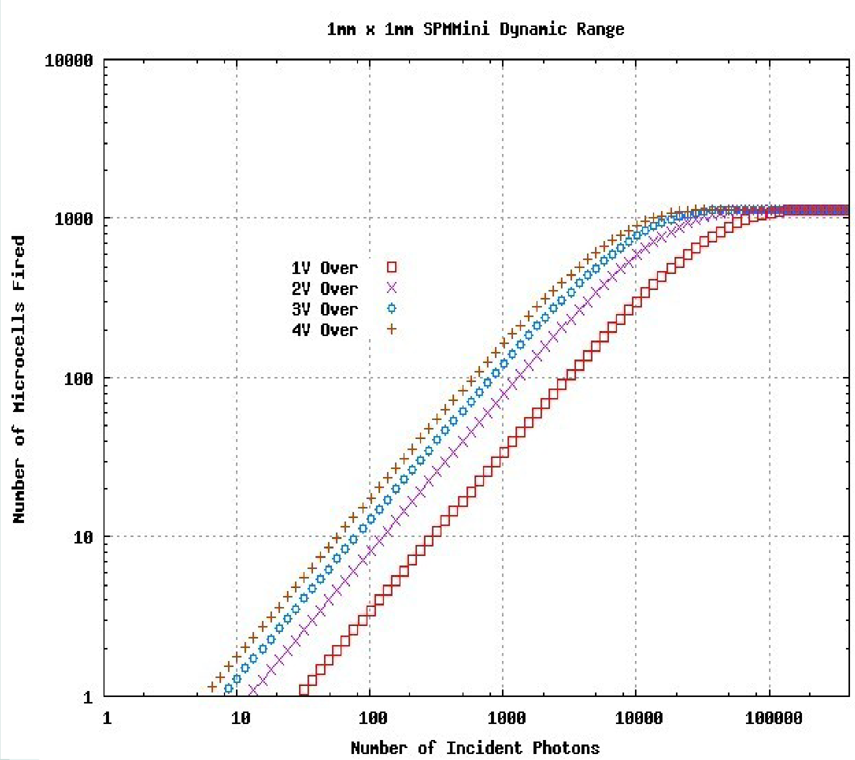
correct for an “ideal” SiPM (no cross-talk and no after-pulsing) as long as light pulses are shorter than pixel recovery time

Hint: 2 or more photons simultaneously in 1 cell look exactly like 1 single photon

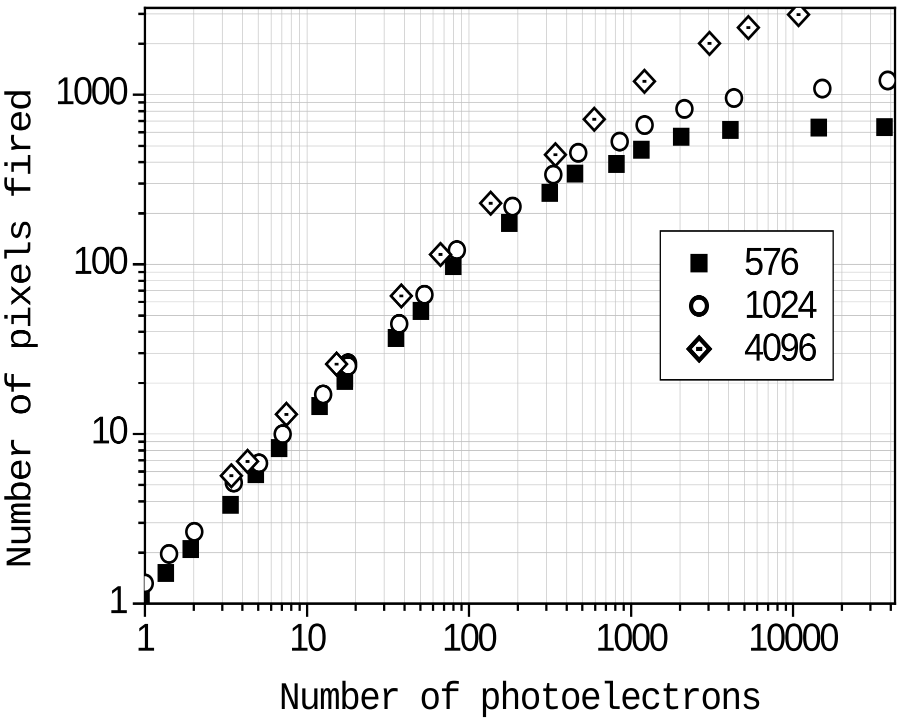
Hint: *For correct amplitude measurements the SiPM response should be corrected for its non-linearity !*

Saturation

SensL



MEPhI/Pulsar



Dark counts

A breakdown can be triggered by an incoming photon or by any generation of free carriers within the detector.

Dark count rates of 100 kHz... 10MHz/mm^2@25°C

Strong function of overbias voltage

Solution:

cooling (factor 2 reduction every 8°C)

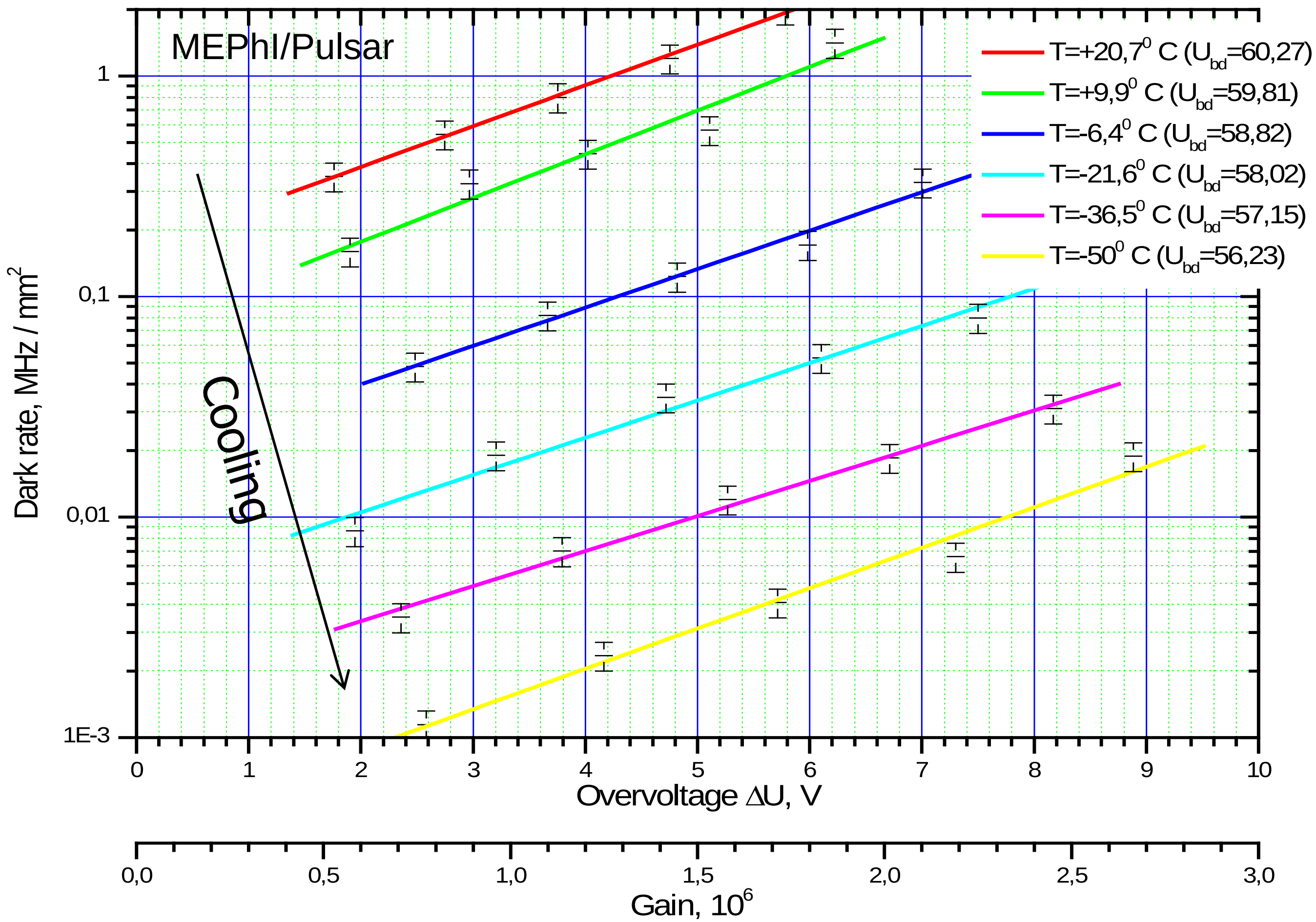
smaller electric field (lower gain)

better/cleaner technology

Dark counts

Dark Rate(DR)

SiPM 1x1 mm^2 , 10^3 pixels



B.Dolgoshein,LIGHT06

High gain

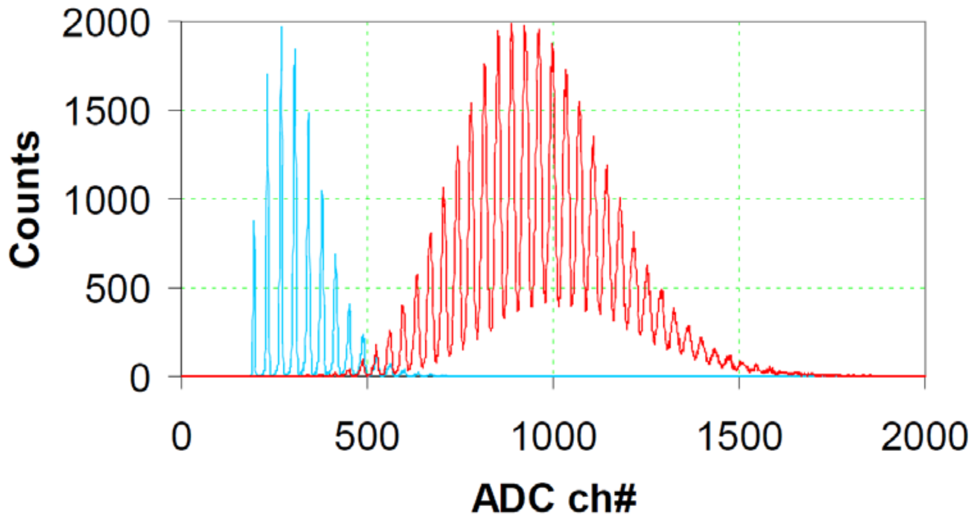
The gain is in the range of 10^5 to 10^7. Single photoelectrons produce a signal of several mV on a 50 W load.

A simple amplifier is needed.

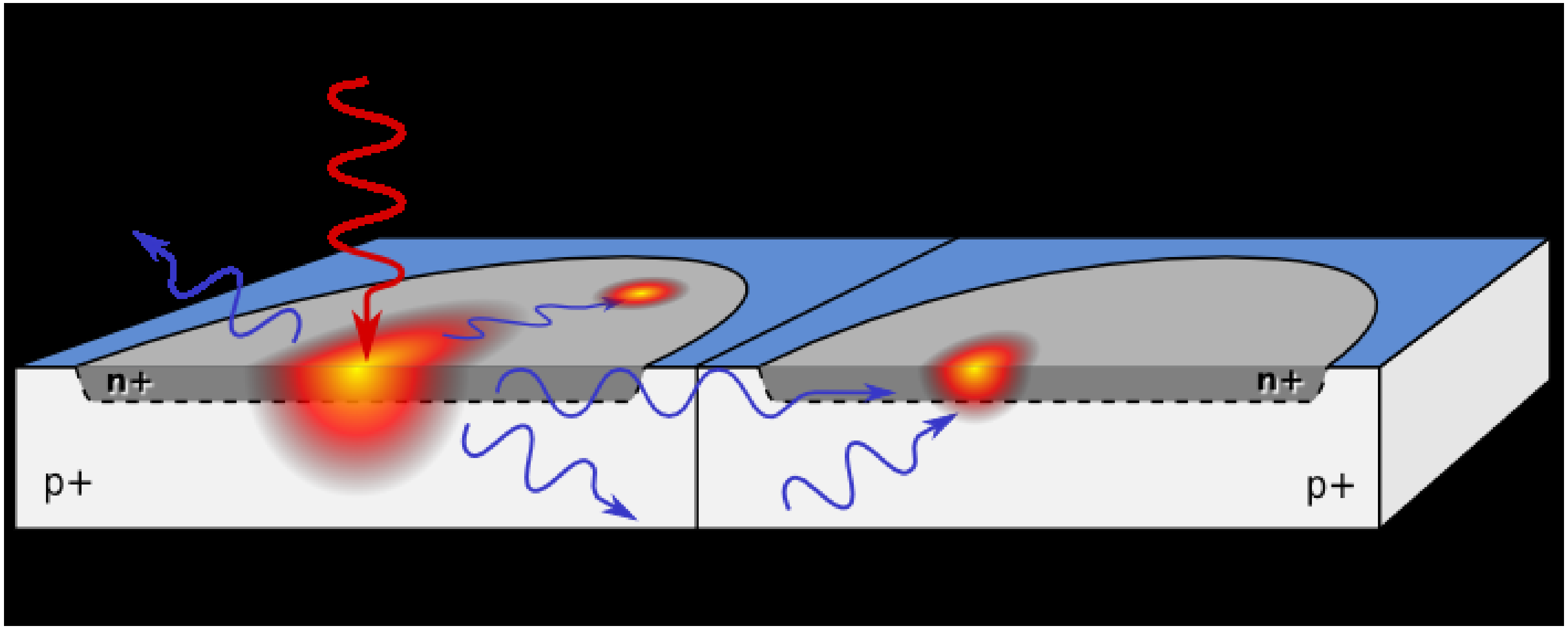
Hint: Gain ~ overbias

Gain can be tuned with implantations of the high filed region

If homogenous within the array gives nice separation between detected peaks



Optical Crosstalk (OCT)



Optical Crosstalk (OCT)

Hot-Carrier Luminescence:

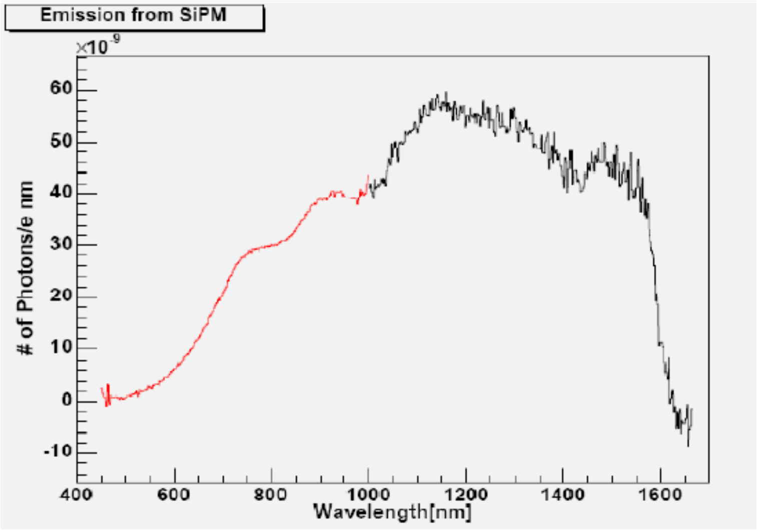
In an avalanche breakdown 10^5 carriers emit in average 1 photon with E > 1.14 eV. *A. Lacaita et al, IEEE TED (1993)*

OCT becomes >1 for a Gain > few times$\times10^7$ ... self-sustaining discharge

Excess Noise Factor becomes too large.

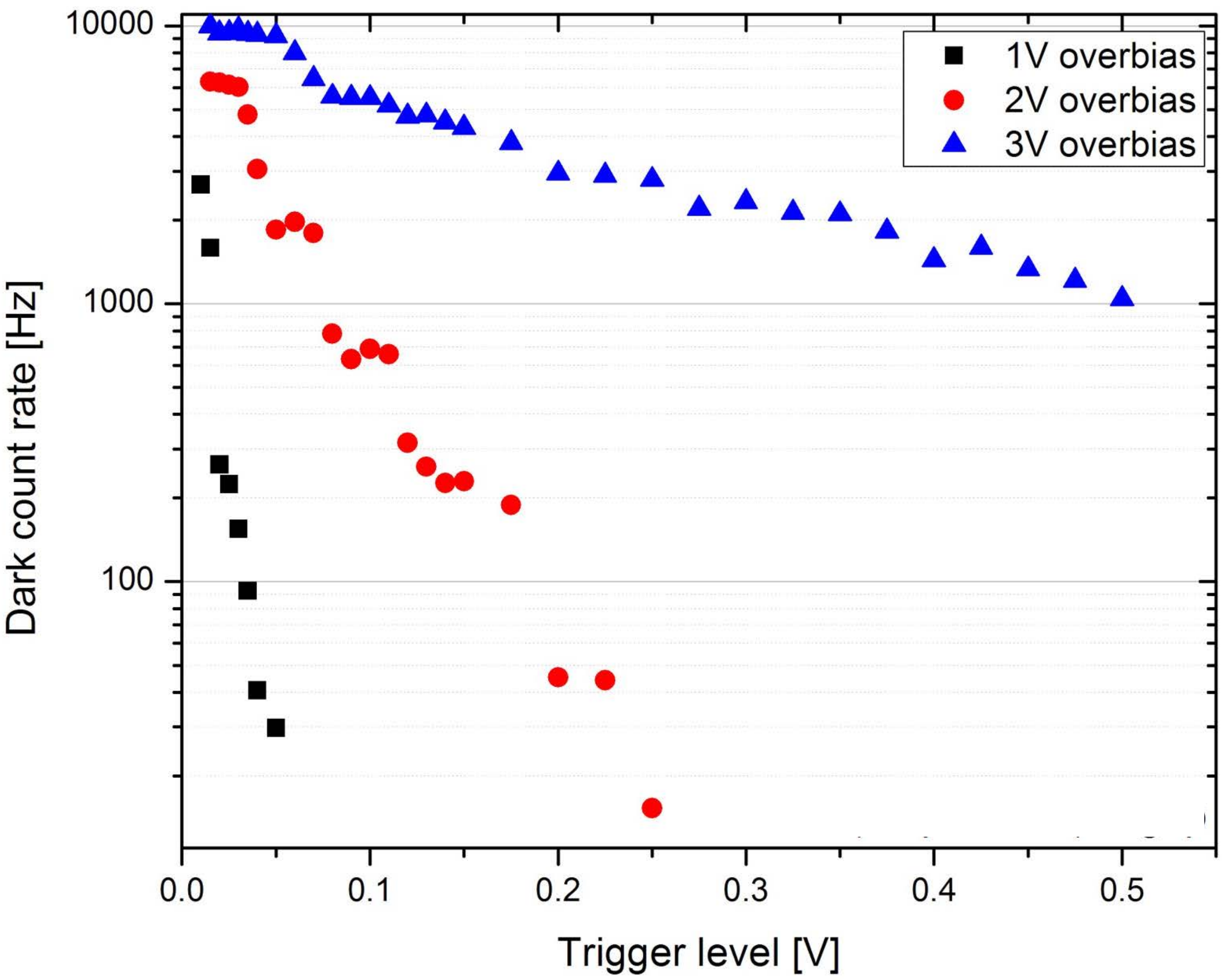
Solution:

- Optical isolation between pixels
- Operate at relative low gain

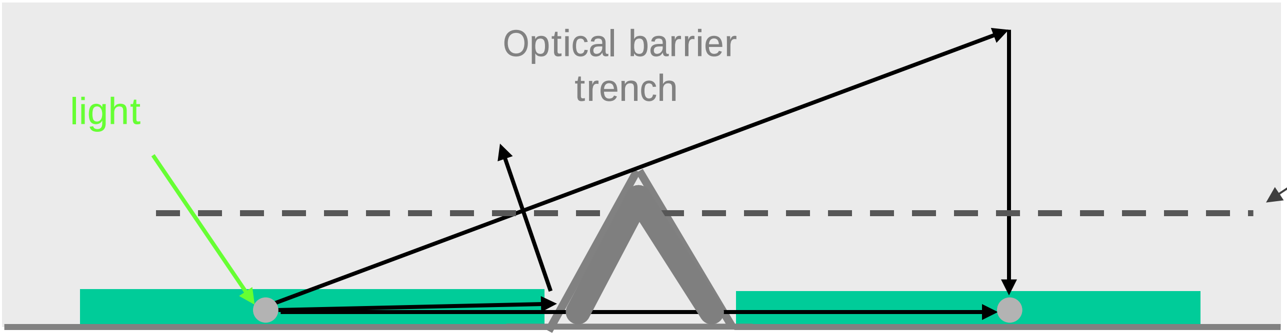


(R. Mirzoyan, NDIP08, Aix-les-Bains)

Optical cross talk



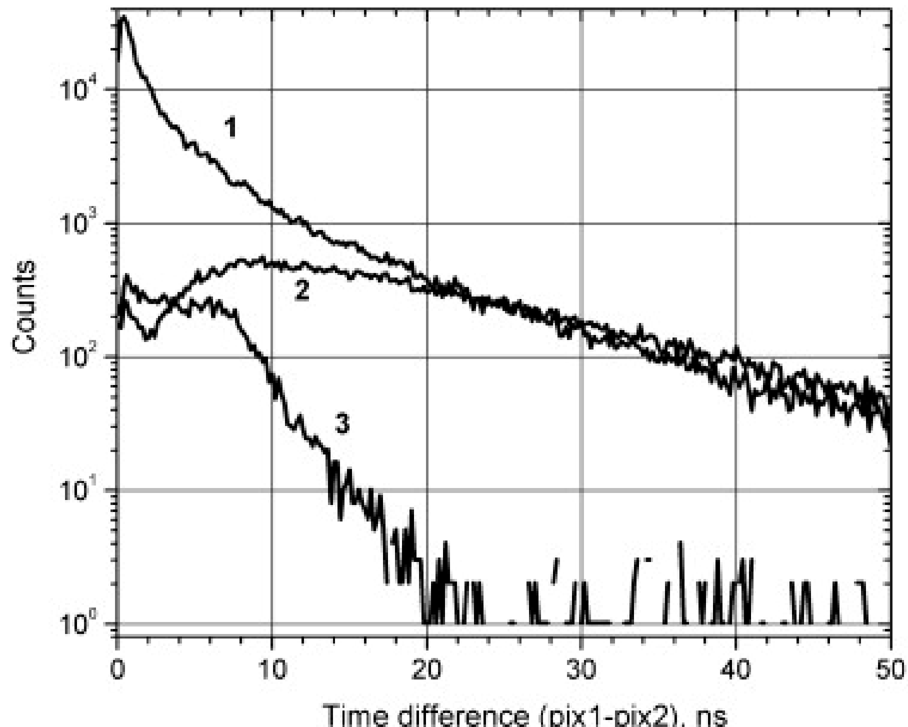
Optical cross talk suppression



1: without optical crosstalk suppression

2: suppression by optical barrier

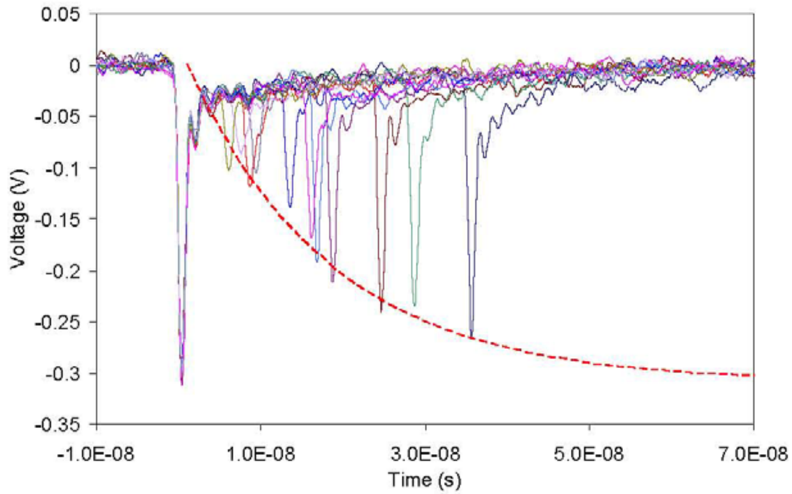
3: suppression by optical barrier and second *pn*-junction

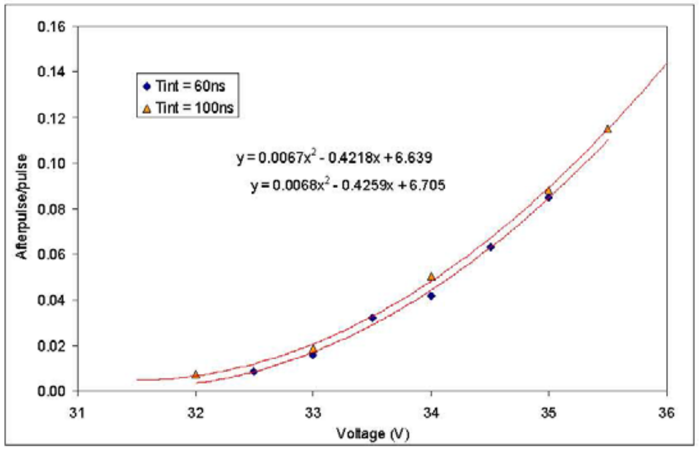


Buzhan et al., NIM A 610 (2009)

Afterpulsing

carriers can be trapped during the avalanche discharge and then released
→ trigger a new avalanche during a period of several 100 ns after the initial breakdown





Events with after-pulse measured on a single micropixel.

After-pulse probability increases with the bias

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

Solution:

- Cleaner/better technology
- Longer recovery time
- Lower gain

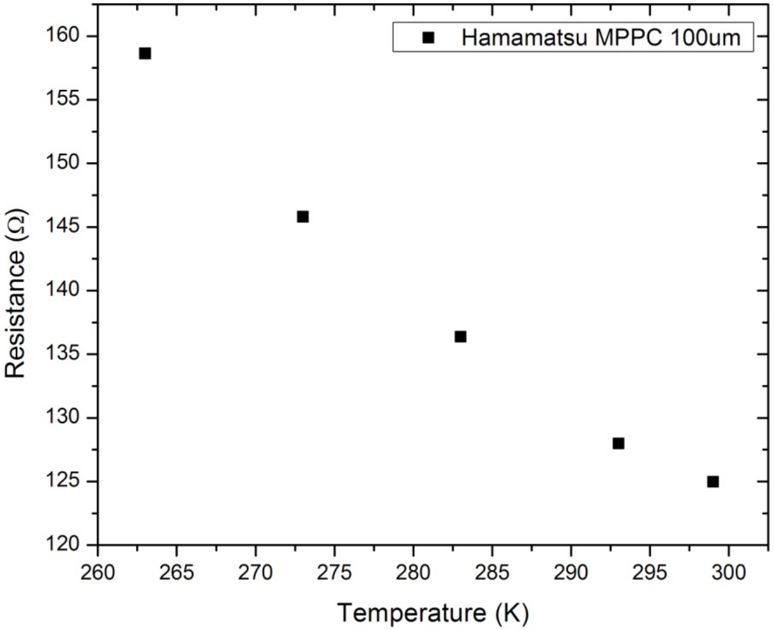
Recovery time

The time needed to recharge a cell after a breakdown depends mostly on the cell size (C) and the quenching resistor (R).
Recovery time of SINGLE pixel:
C(pix)xR(pix) → 20ns.....a few μs

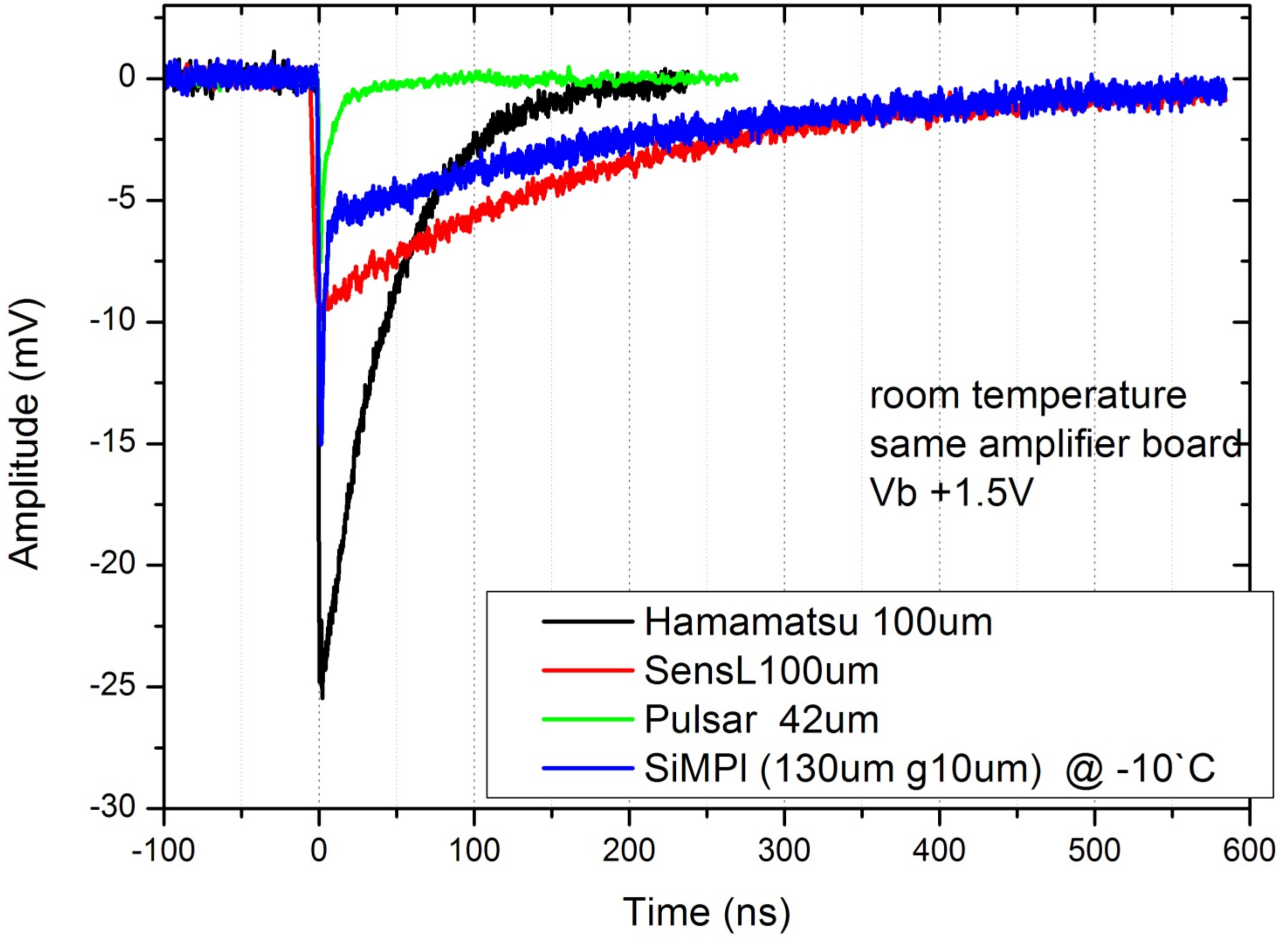
Polysilicon resistors that are used up to now are temperature dependent. Therefore there is a strong dependence of the recovery time on the temperature.

Solution: Go to a metal alloy with high resistivity

.



Recovery time



Timing

Avalanche breakdown process is fast and the signal amplitude is big.
$\Rightarrow$very good timing properties even for single photons.

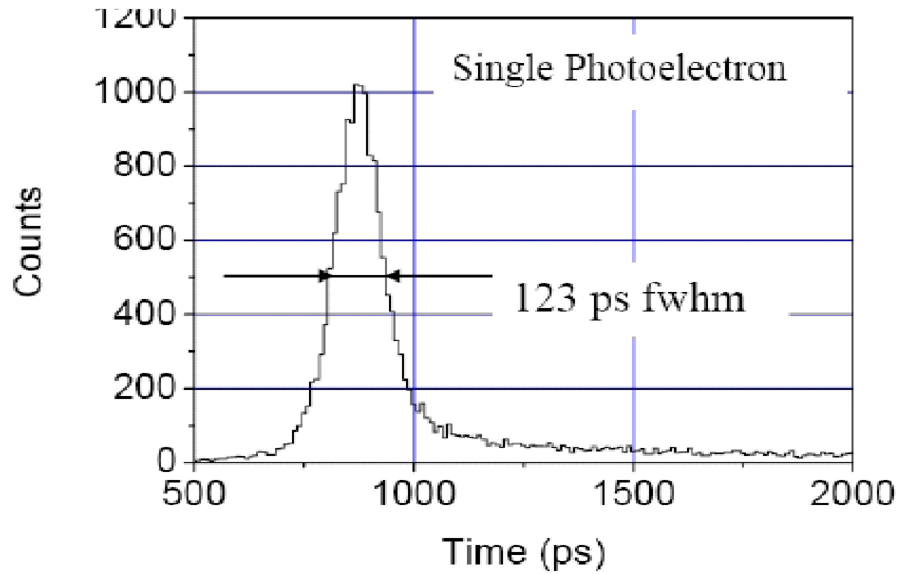
Fluctuations in the avalanche are mainly due to a lateral spreading (~10 ps) by diffusion and by the photons emitted in the avalanche.

A. Lacaita et al., Apl. Phys. Letters 62 (1992) A. Lacaita et al., Apl. Phys. Letters 57 (1990)

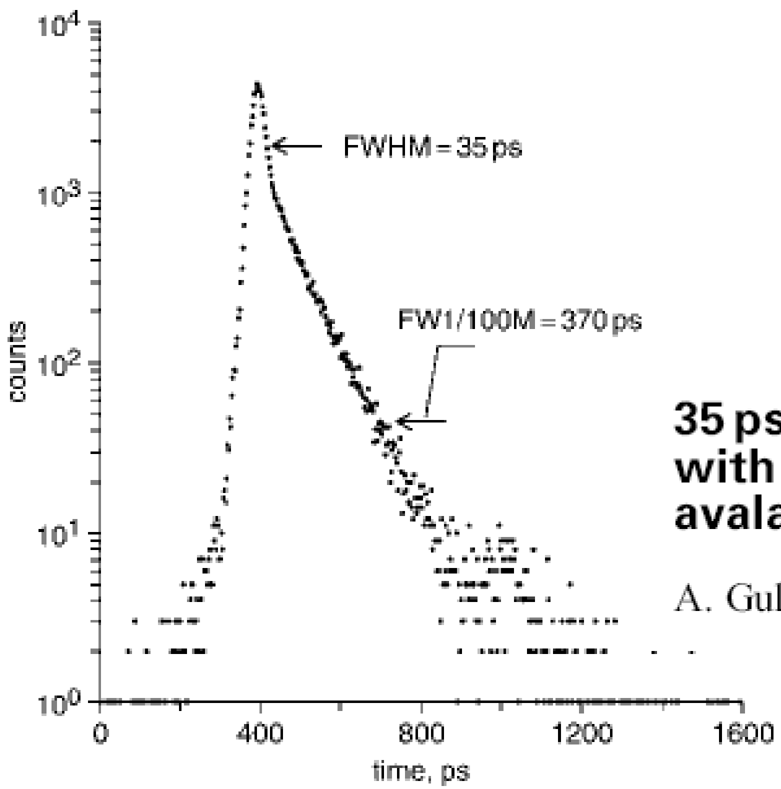
Hint: High overvoltage (high gain) may slightly improve the time resolution.

Timing

B. Beaune 2002 (NIM A 504 (2003) 48)



Contribution from the laser and the electronics is 40 ps each. time resolution 100ps FWHM



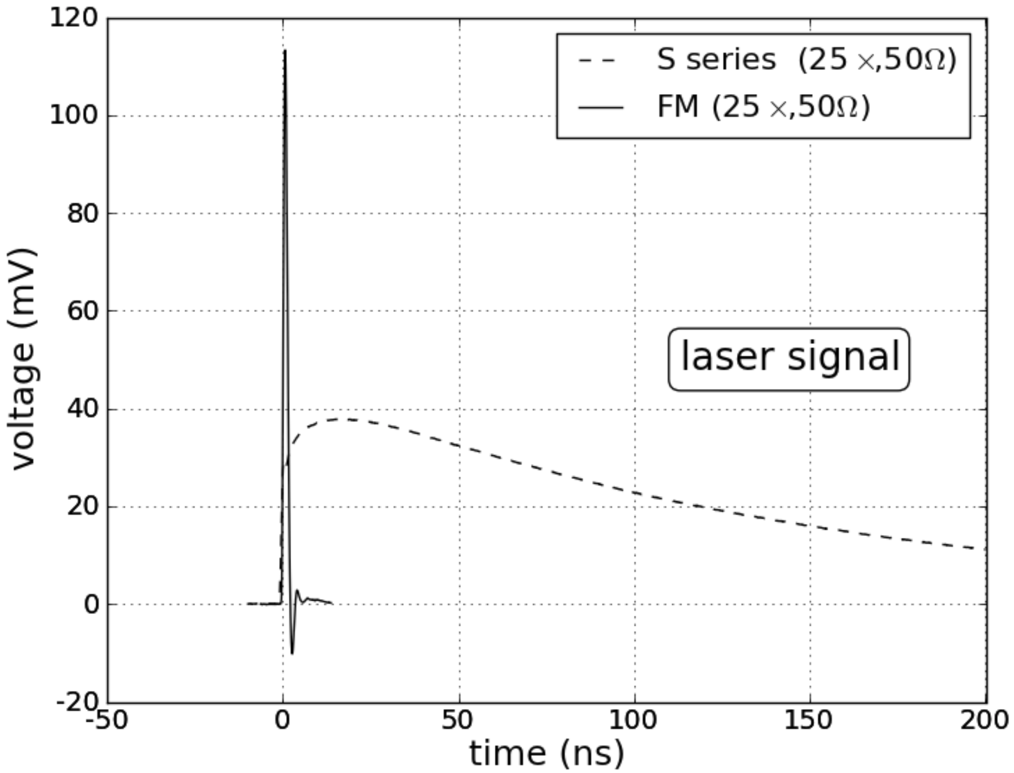
35 ps time resolution at room temperature with large area single photon avalanche diodes

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

SensL - New Fast Timing SPM

SensL's new technology creates fast pulses without sacrificing PDE

- This new technology is described in SensL's international patent application no. WO2011117309
- MicroFM family sampling now with general availability Q3 2012



SensL presentation NDIP2012

Photon Detection Efficiency

PDE = Fill Factor * QE * Geiger probability

Main limitations:

Geometrical occupancy of the Geiger diodes (max 80%)

Reflection losses on the SiPM surface (<10% possible)

Can be tuned by coating

λ_{min} determined by thickness and quality of surface implantation
λ_{max} determined by thickness of active volume

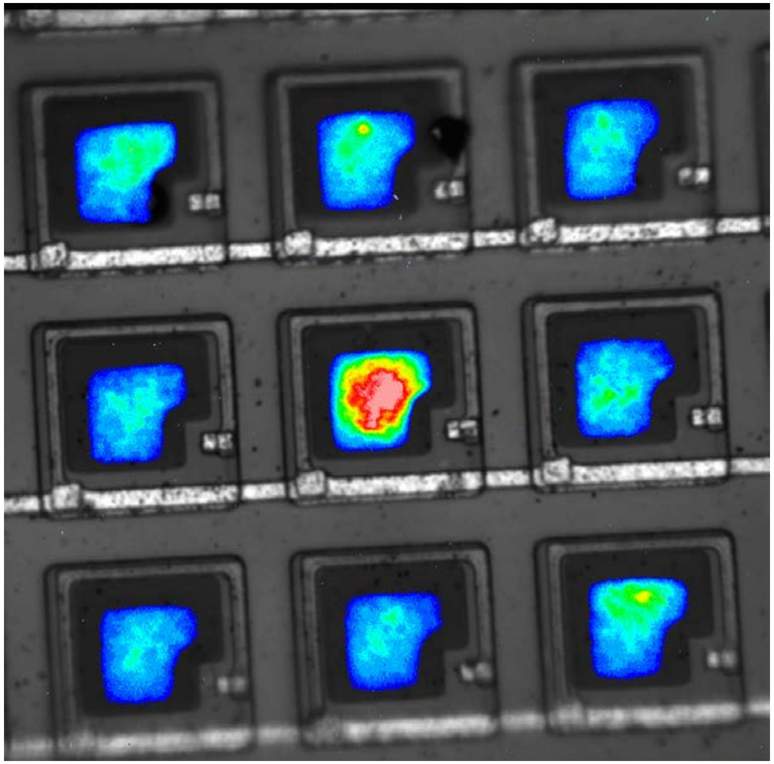
Breakdown Initiation Probability (~90%)

Function of the electric field in the avalanche region

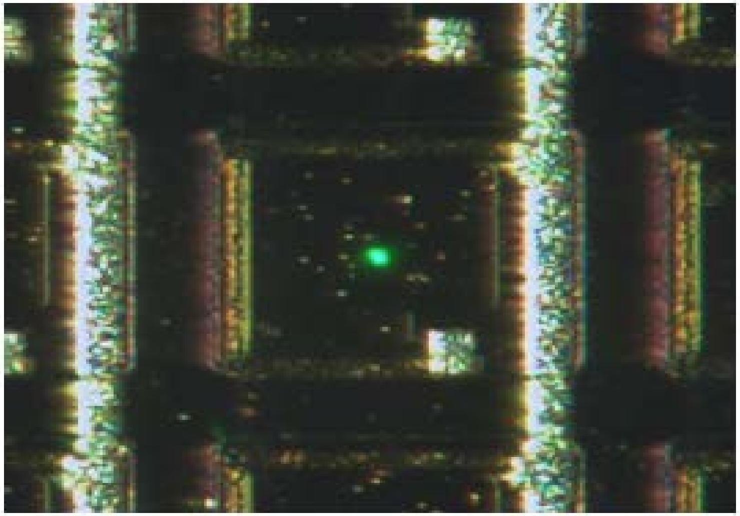
→ End up with 50…60% PDE

Fill factor

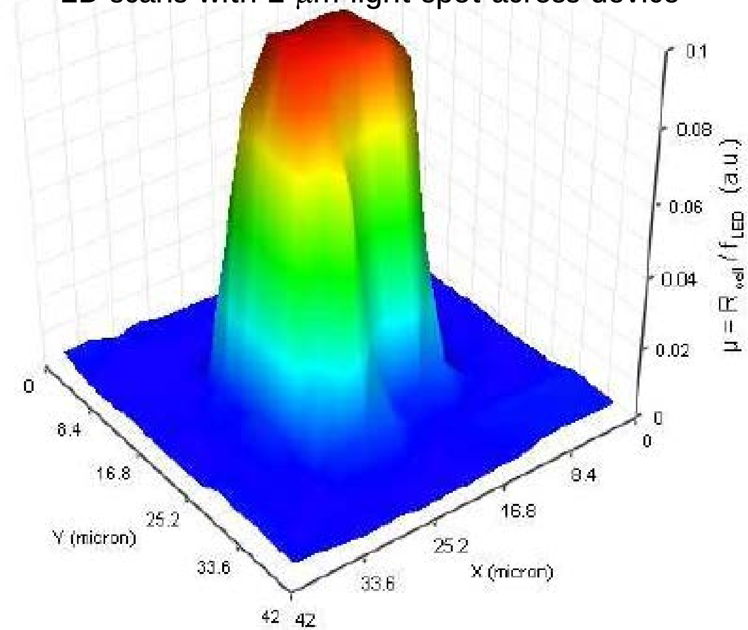
Photoemission image



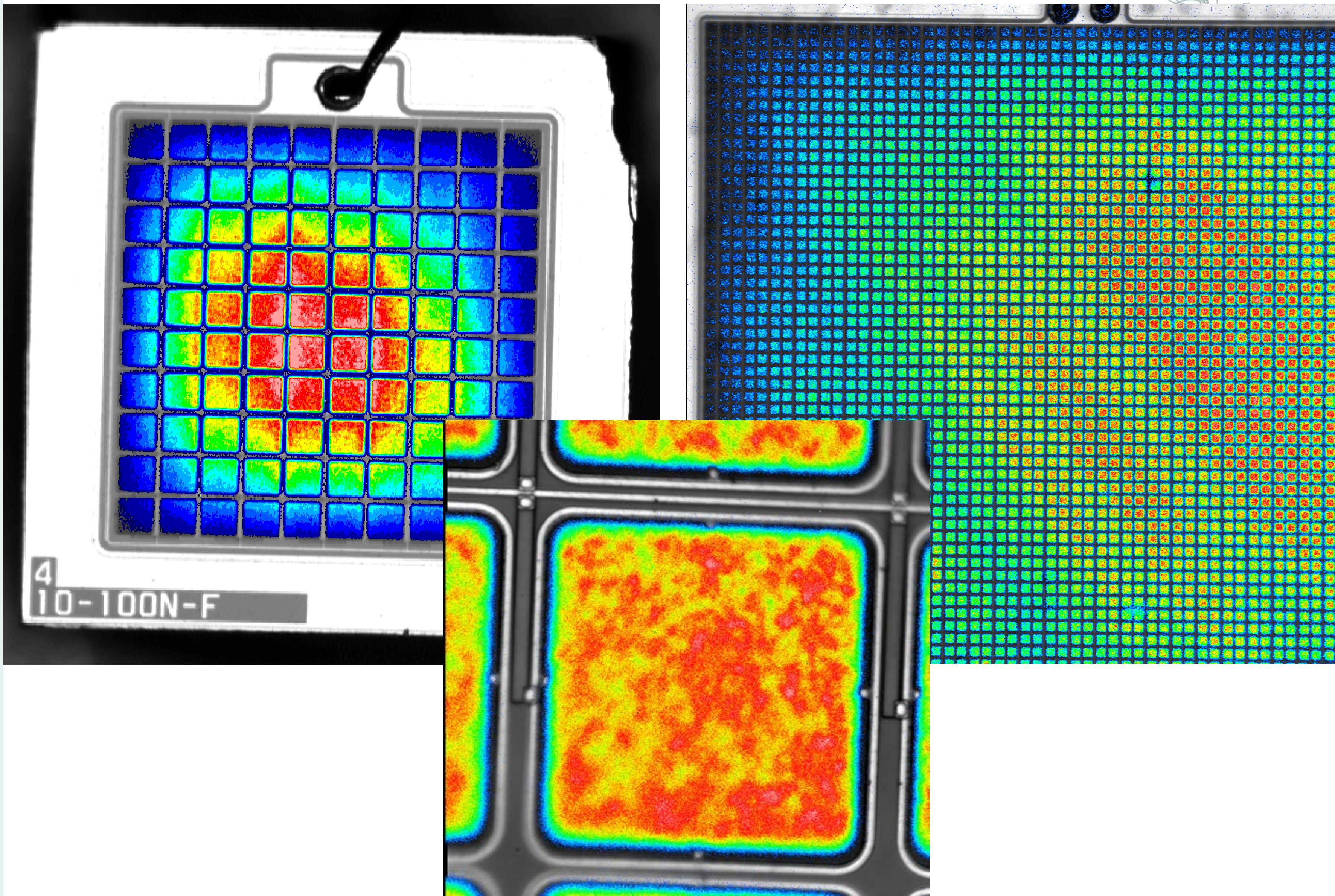
Old (2007) MEPHI device 42μm pitch size



2D scans with 2 μm light spot across device



Hamamatsu MPPC



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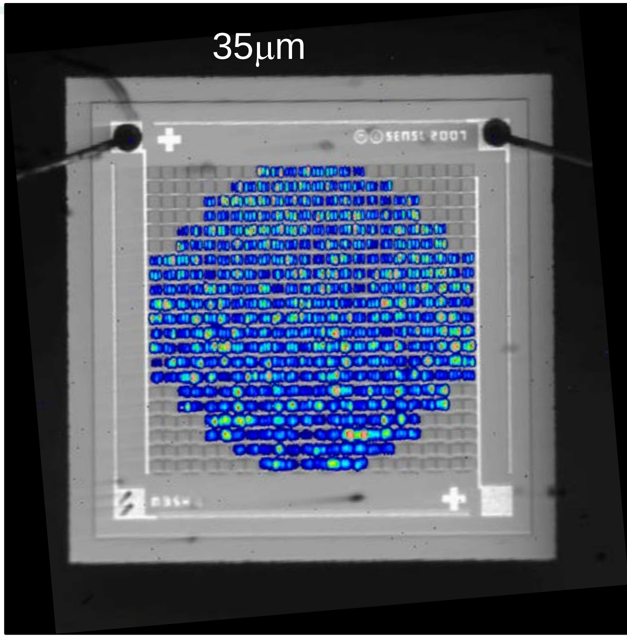
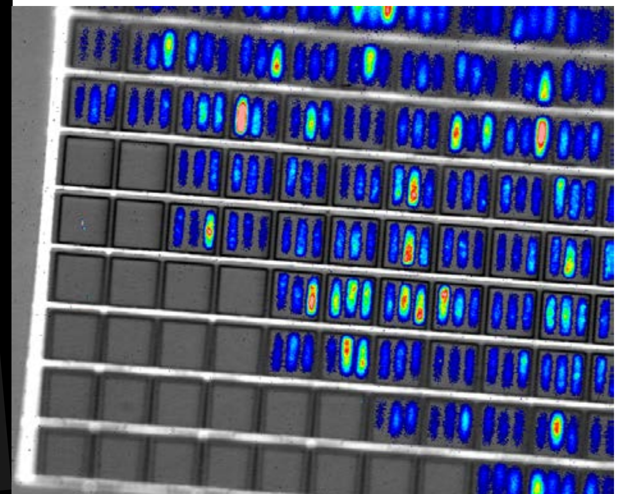
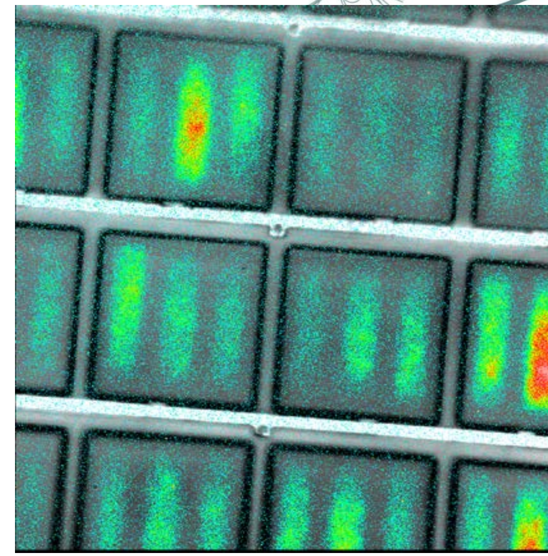
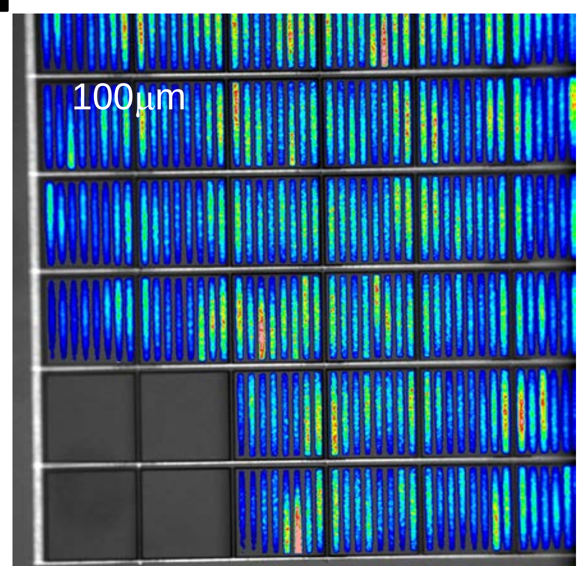
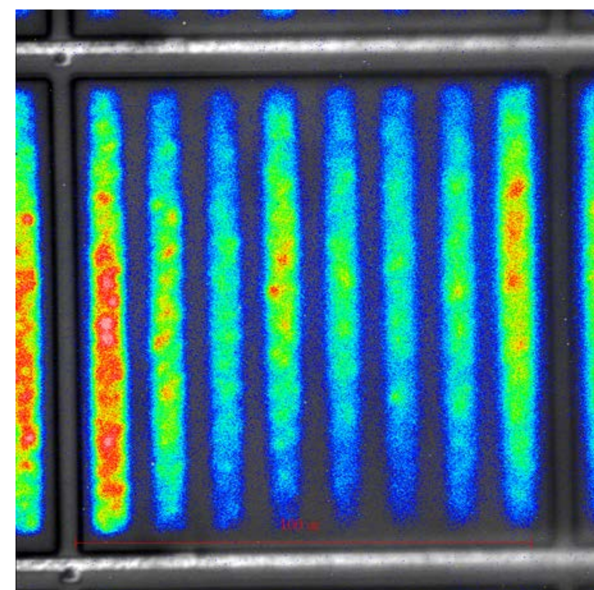






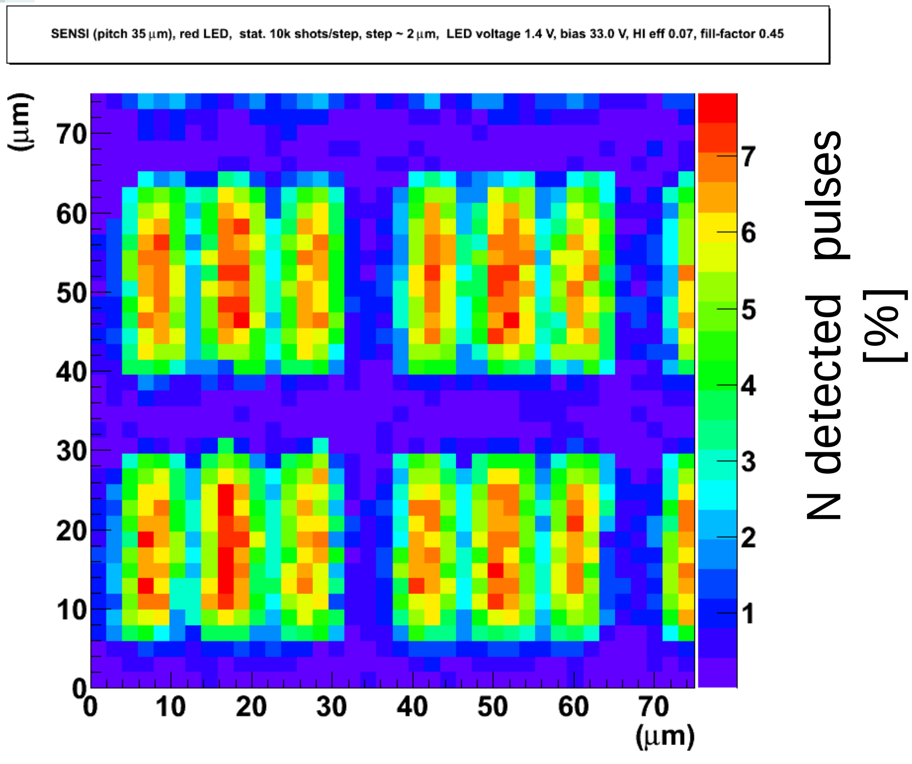


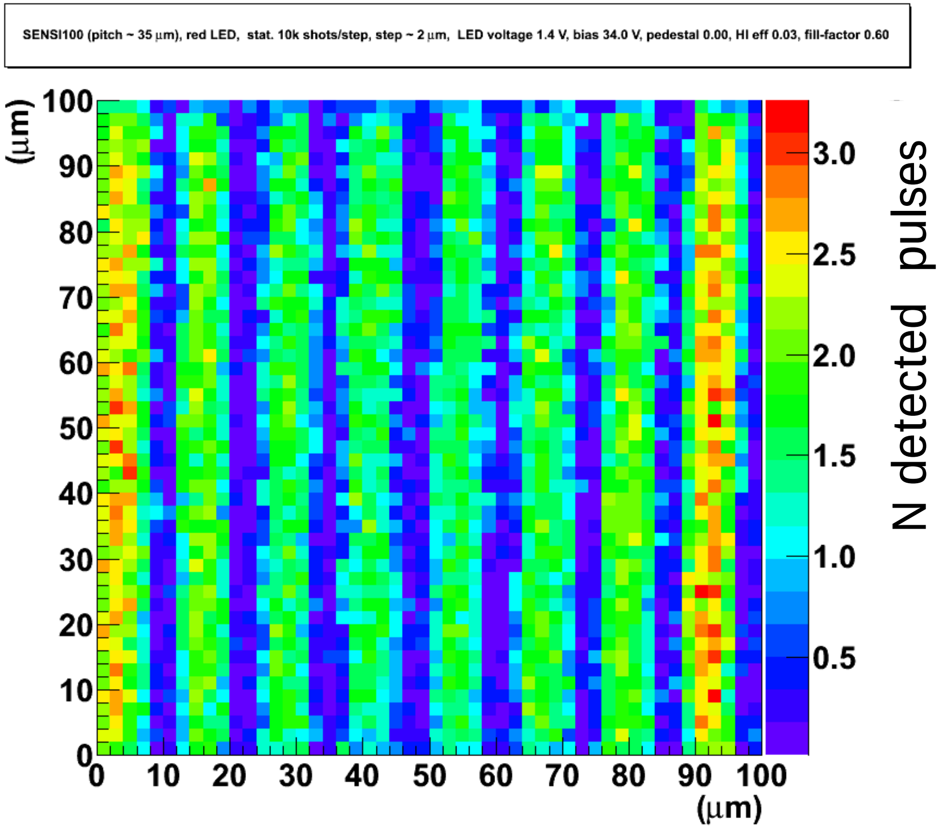


High filed regions structured !!!!

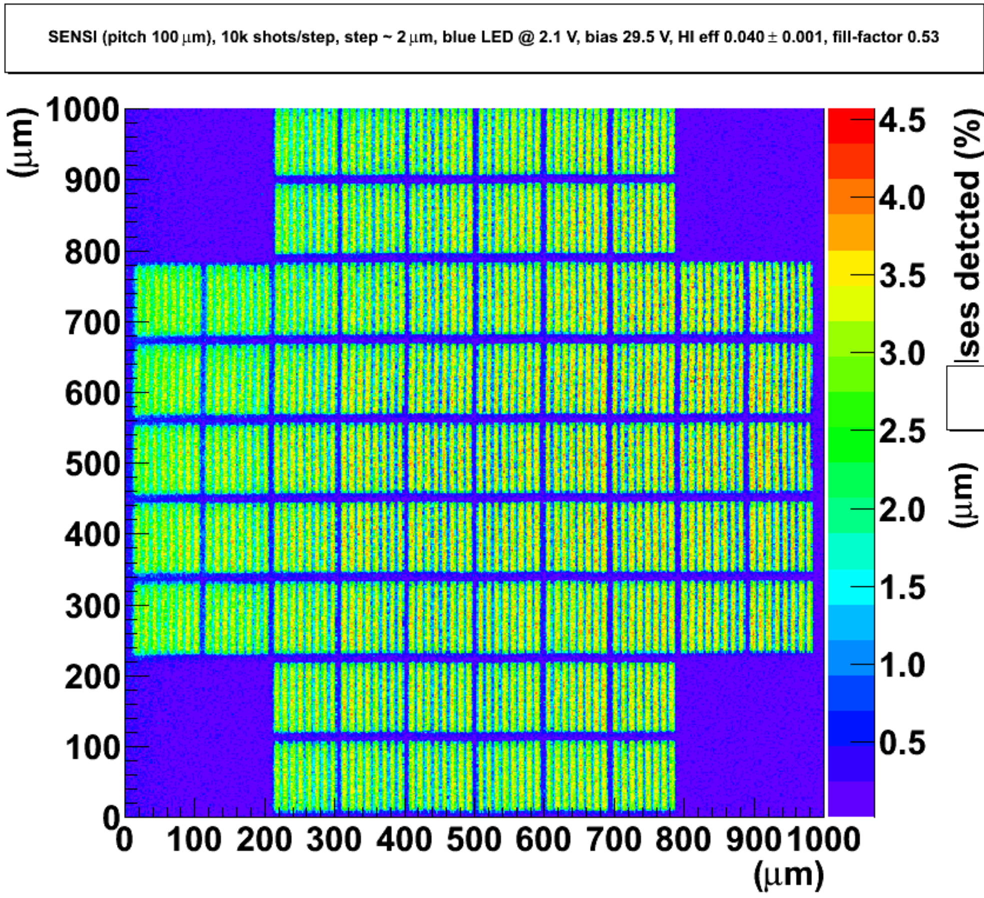
Reduced fill factor!

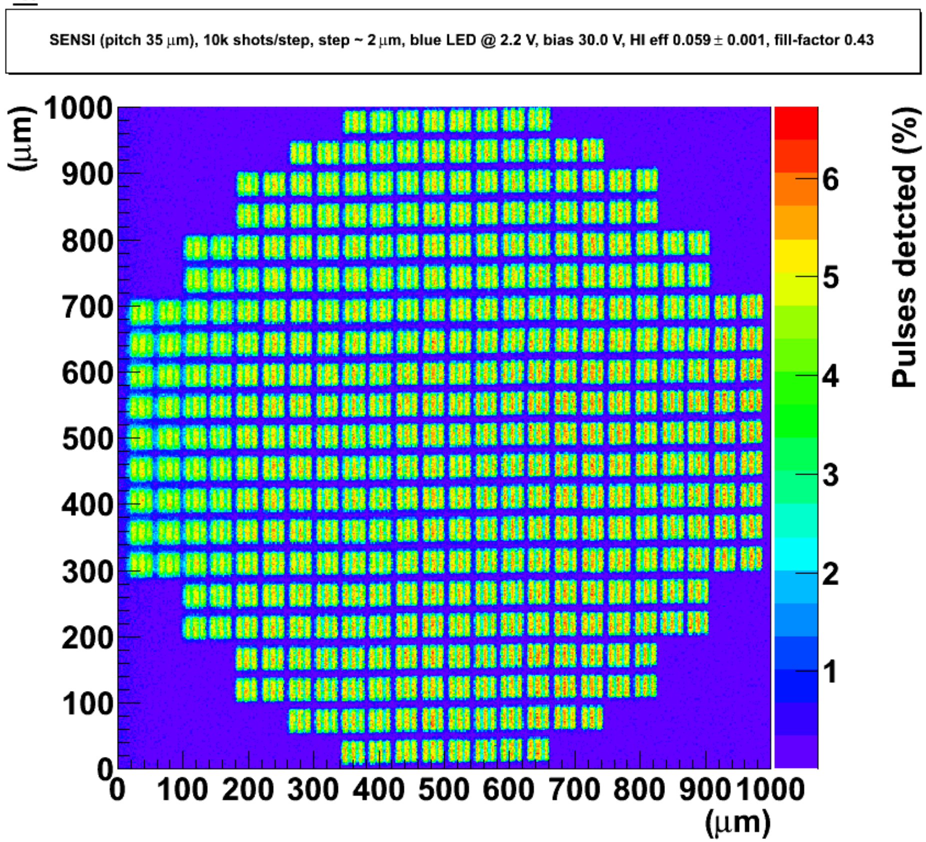
SensL – 2D scans with blue LED





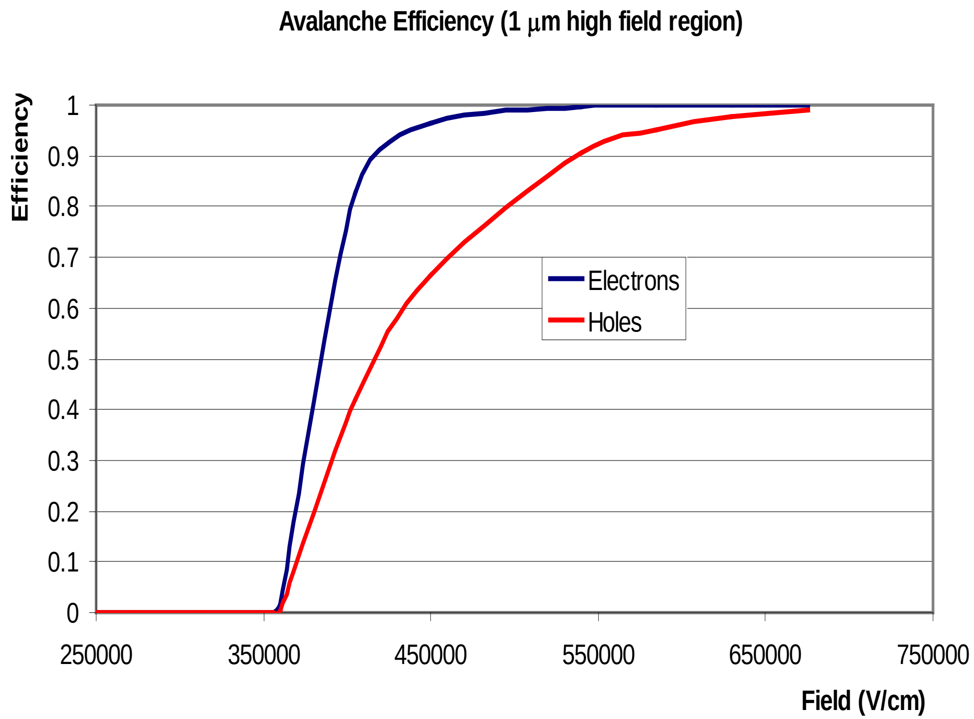
SensL – 2D scans with blue LED





Blue/UV sensitivity

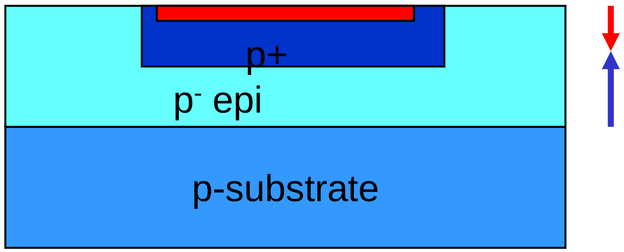
Electrons have a higher probability to trigger an avalanche breakdown then holes

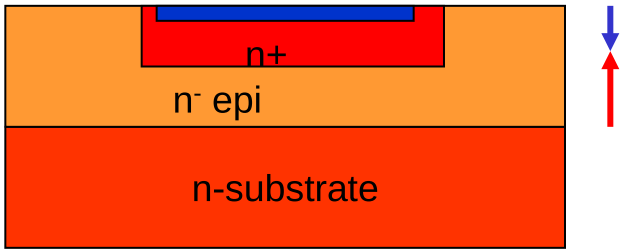


Solutions:

-Increase overvoltage

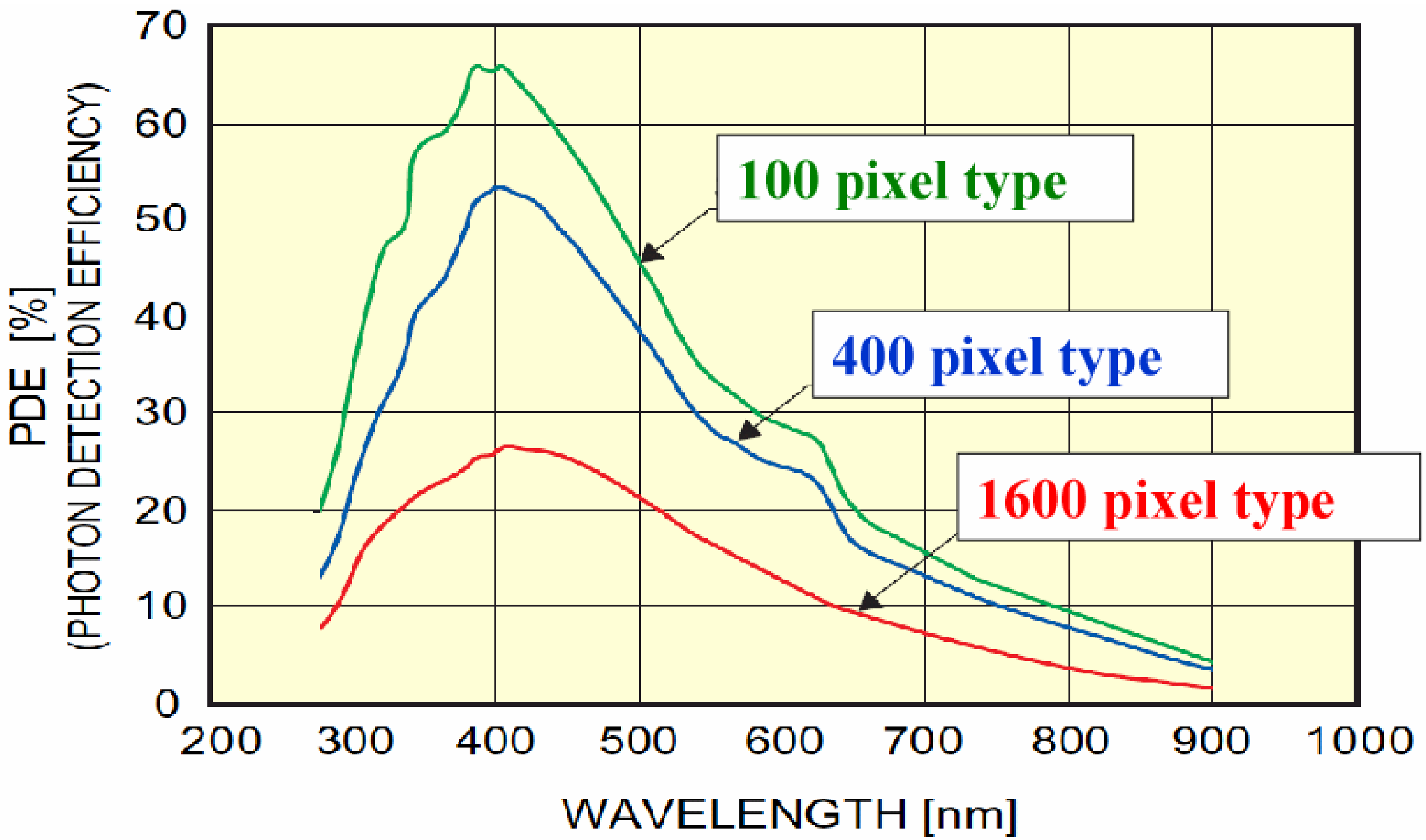
-Inverted structures





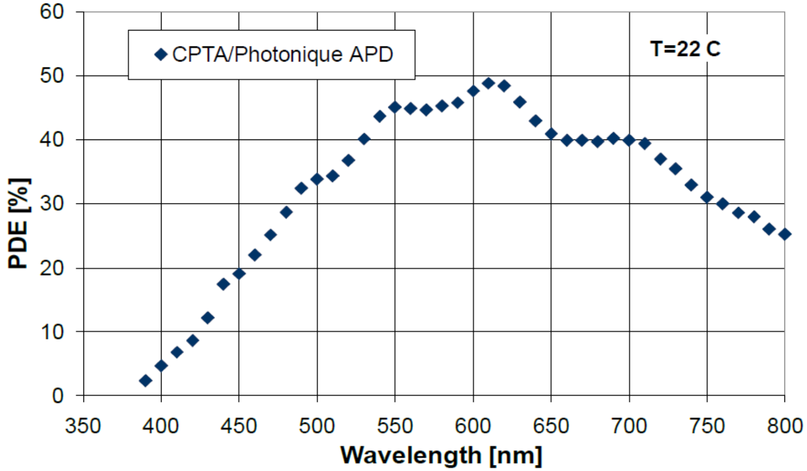
PDE

Hamamatsu Datasheet

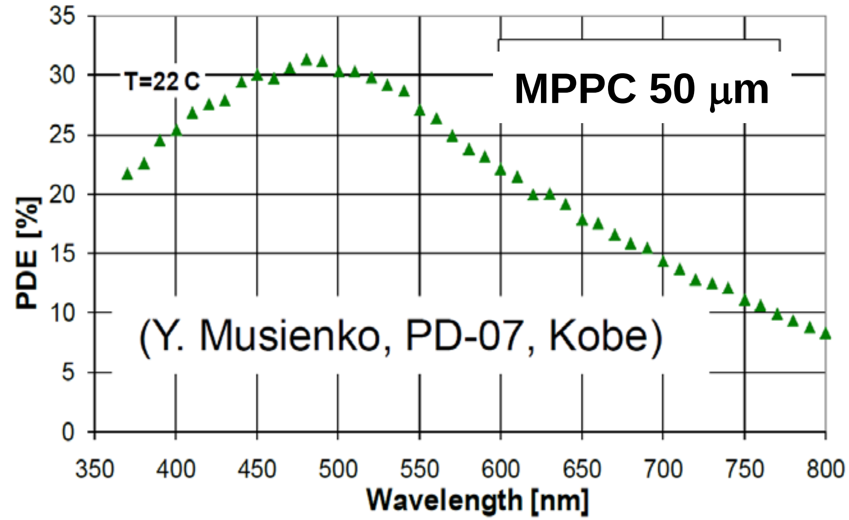


NOTICE!!! PDE measured including Cross talk and afterpulses

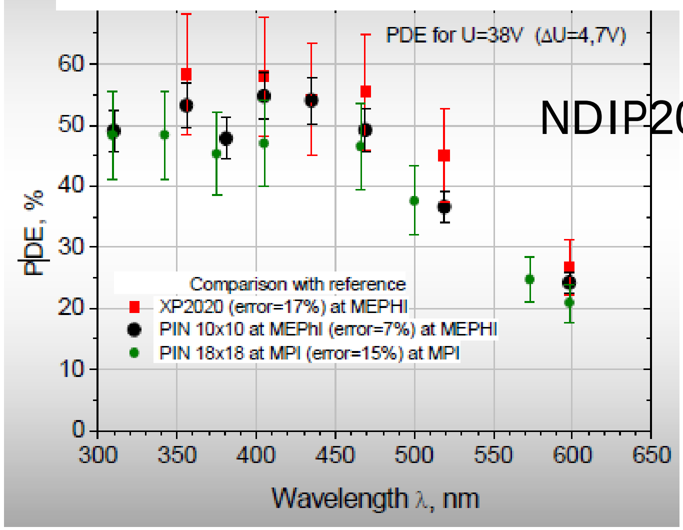
PDEs

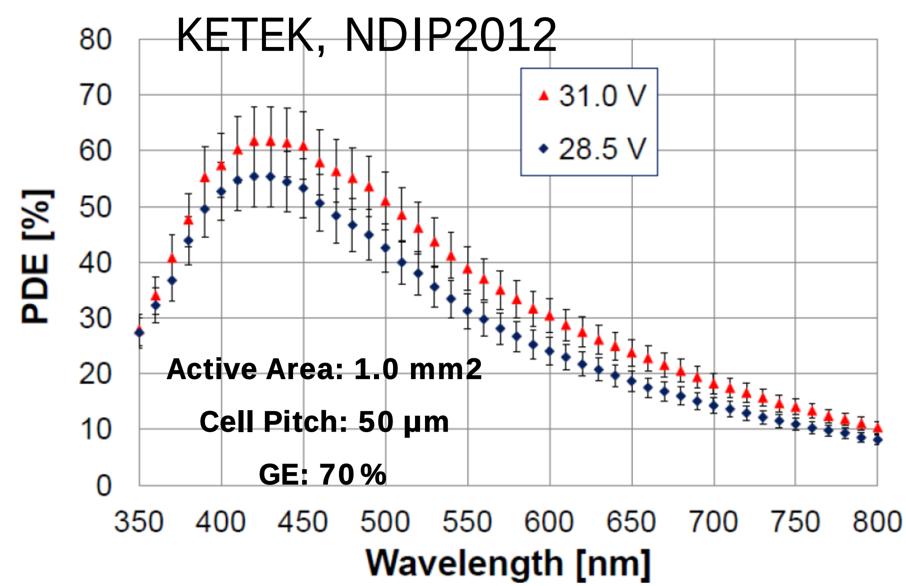


(Y. Musienko, PD-07, Kobe)



MEPhI/MPI/Excelitas collaboration





Current R&D

- Understanding and improving the radiation tolerance of SiPMs
- Large dynamic range: Hamamatsu R&D down to 15μm pitch
- Lowering of dark rate : all
- Increasing PDE @ 400nm : all
- Large area SiPMs : SiPMs with Area ≥ 3x3 mm^2 produced by many companies: Hamamatsu, CPTA, Pulsar, Zecotek, SensL, FBK, STMicro...
- SiPM Arrays → further increase of sensitive area

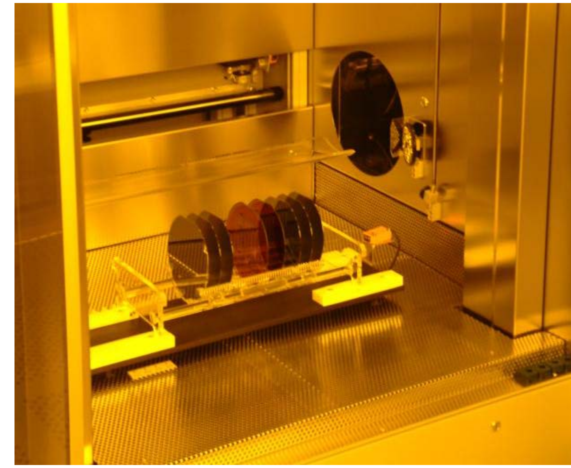
Non conventional SiPM developments

- MAPDs from Zecotek
- SiMPl – MPI Semiconductor Lab
- dSiPMs from Philips

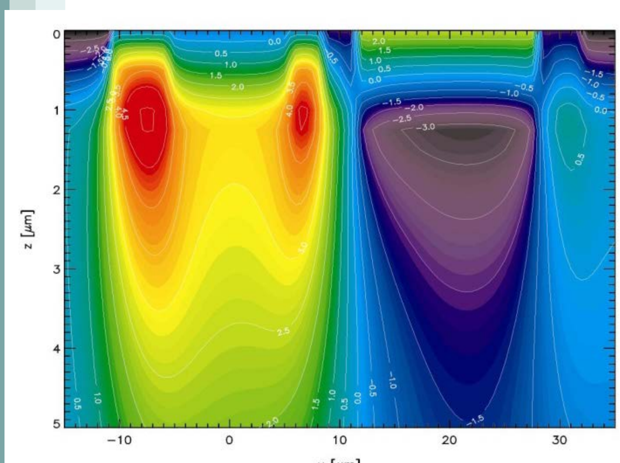
MPG semiconductor laboratory

800m^2 clean room up to class 1

6 inch silicon process line



with custom made equipment

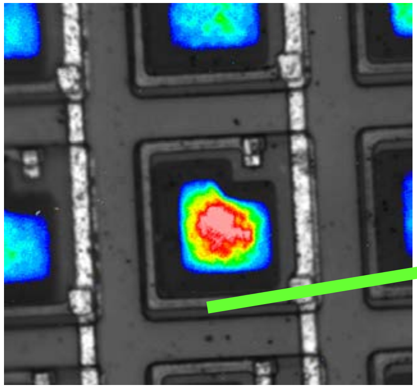


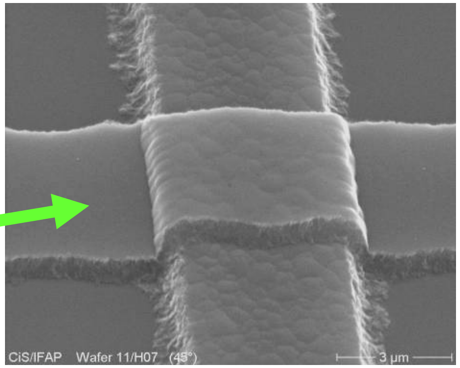
design and simulation tools

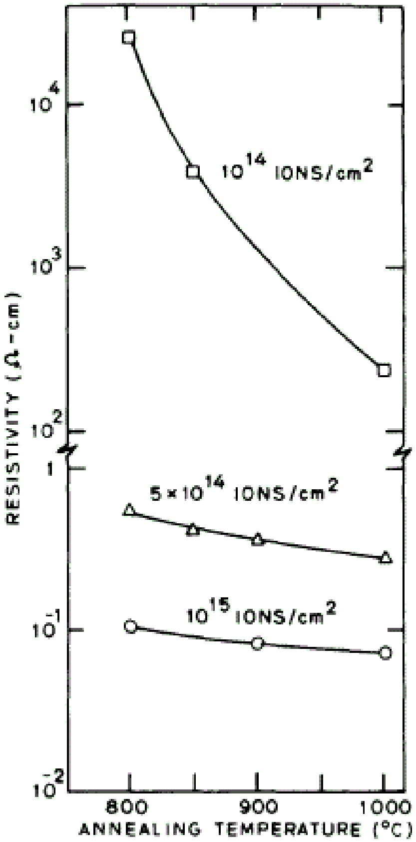
testing & qualification

mounting capabilities

Polysilicon Quench Resistors







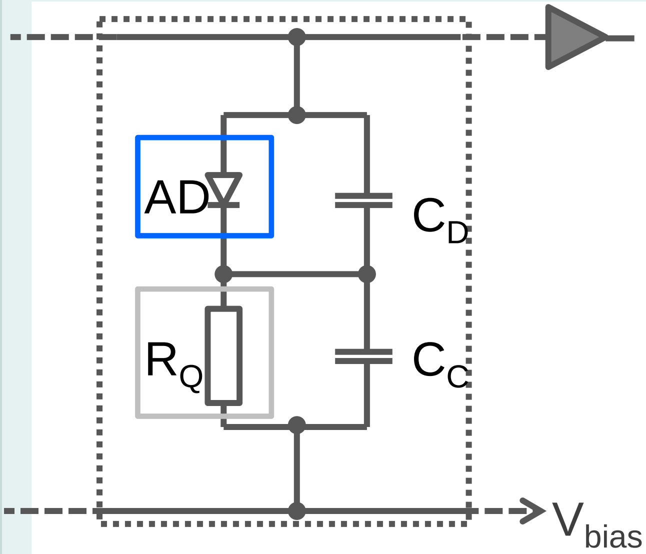
M. Mohammad et al.
'Dopant segragation in polycrystalline silicon',
J. Appl. Physics, Nov.,1980

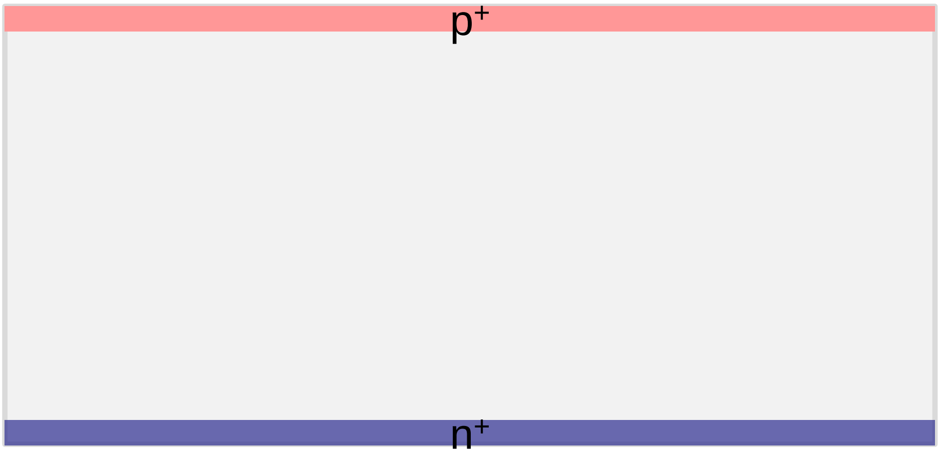
Critical resistance range

influenced by: grain size, dopant segregation in grain boundaries, carrier trapping, barrier height

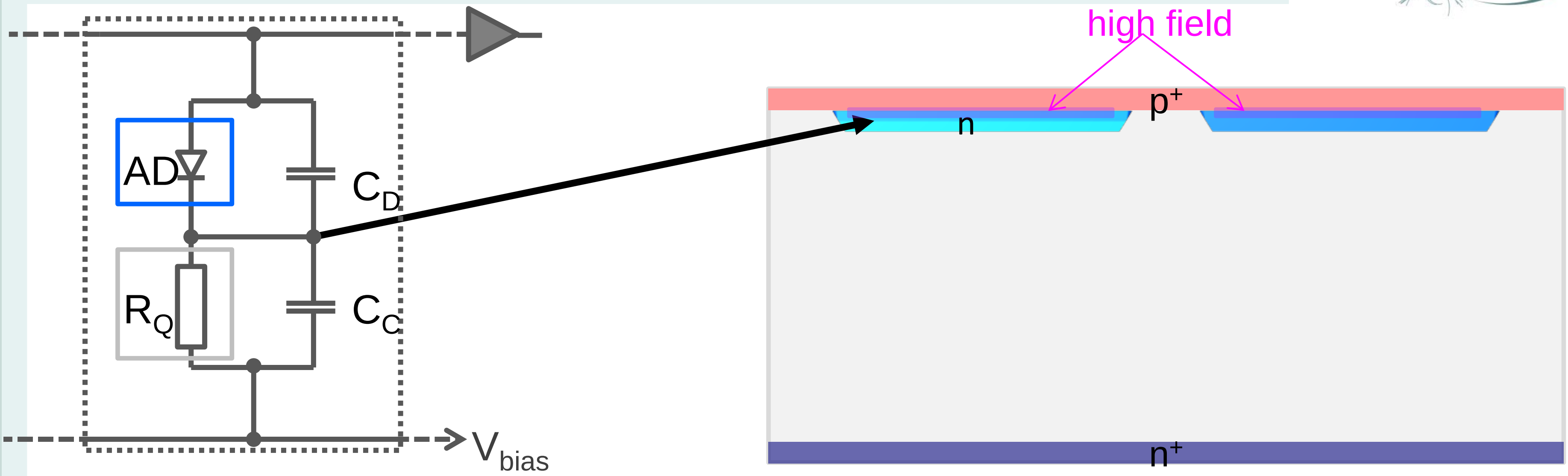
Rather complex process step and an obstacle for light

SiPM cell components → SiMPl approach

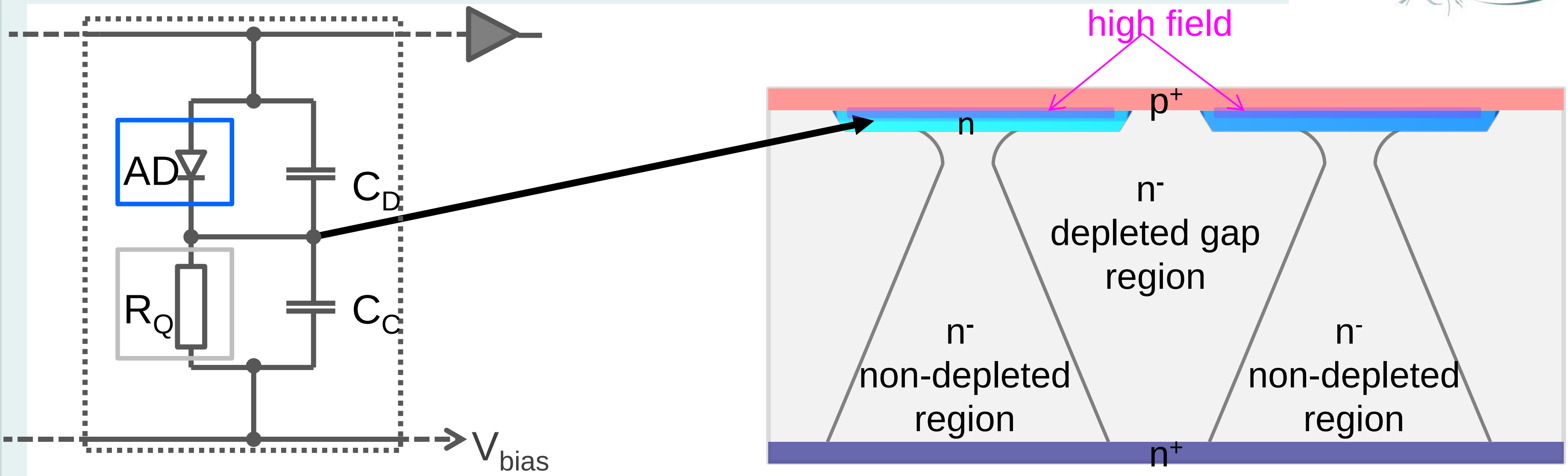




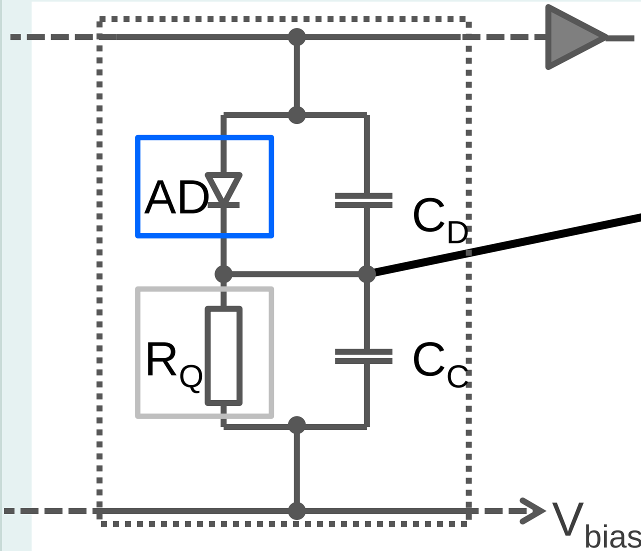
SiPM cell components → SiMPl approach

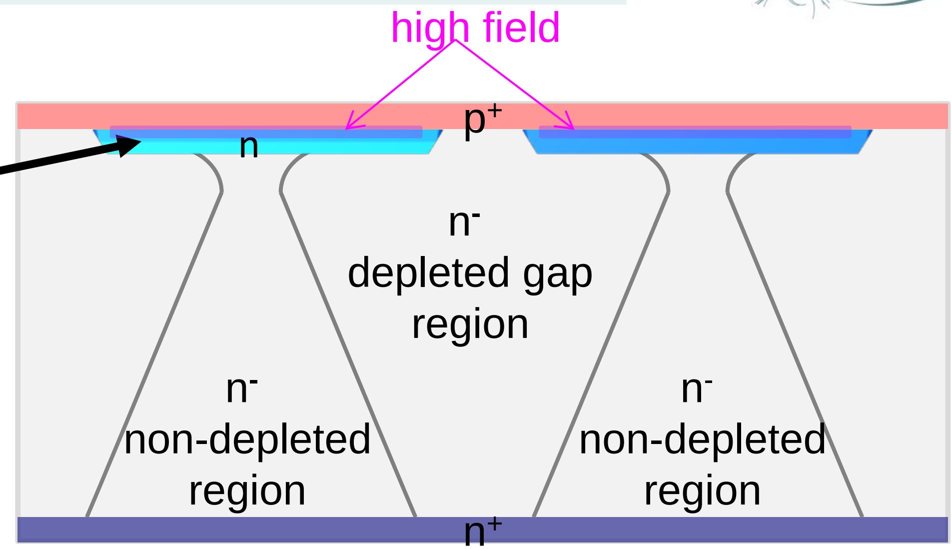


SiPM cell components → SiMPl approach



SiPM cell components → SiMPl approach

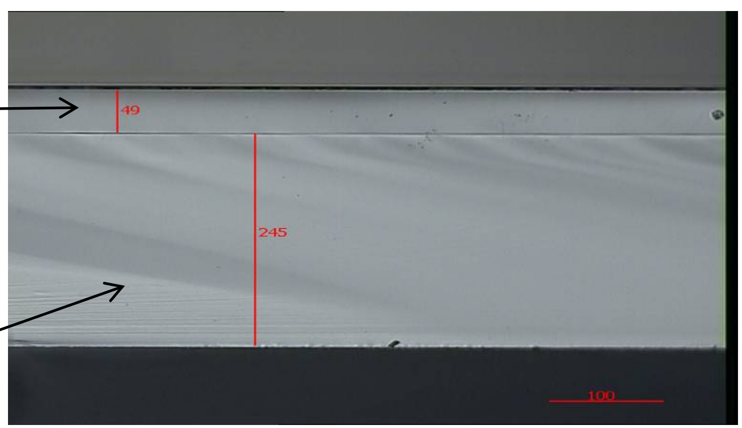




SOI wafers

Sensor wafer

Handle wafer



Advantages and Disadvantages

Advantages:

- no need of polysilicon
- free entrance window for light, no metal necessary within the array
- coarse lithographic level
- simple technology
- inherent diffusion barrier against minorities in the bulk -> less optical cross talk

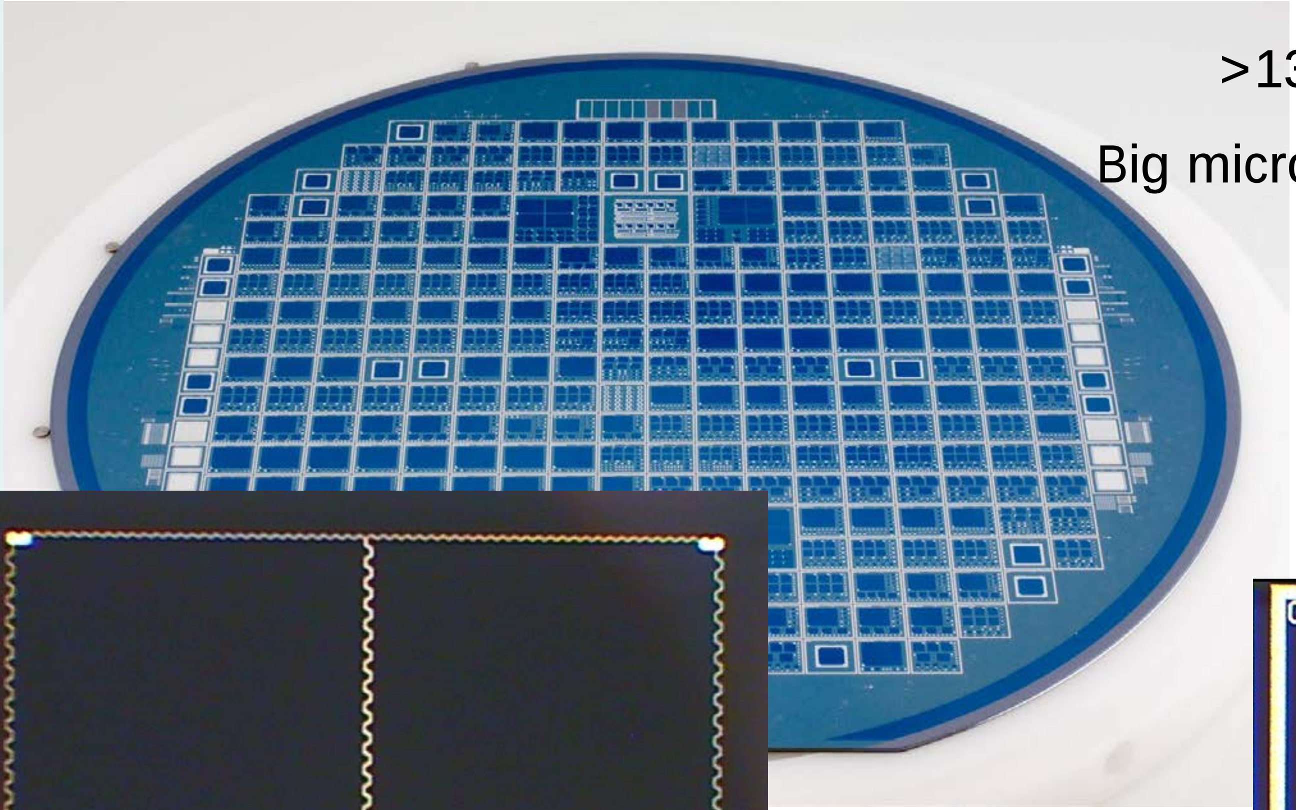
Drawbacks:

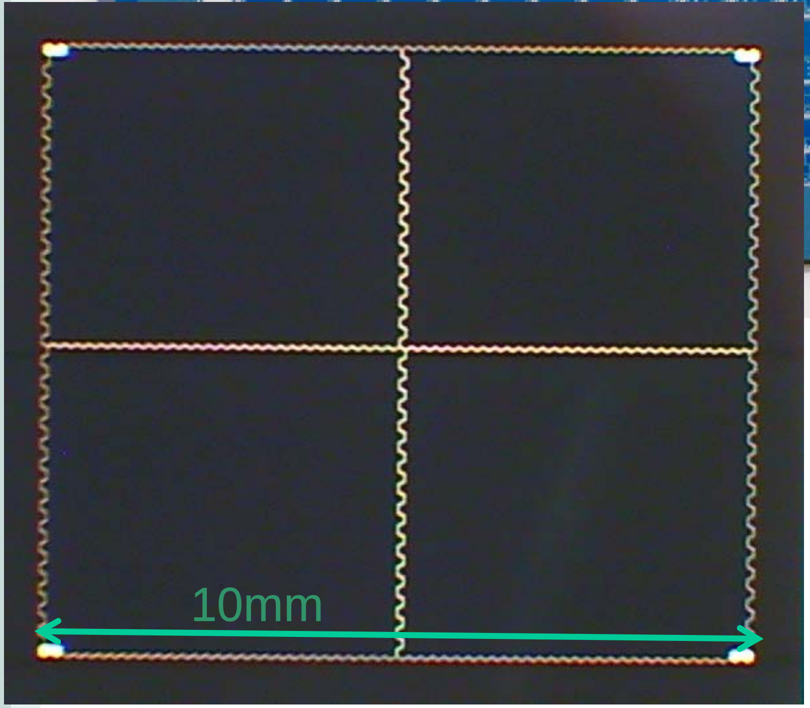
- required depth for vertical resistors does not match wafer thickness
- wafer bonding is necessary for big pixel sizes
- significant changes of cell size requires change of the material
- vertical ‘resistor‘ is a JFET -> parabolic IV -> longer recovery times

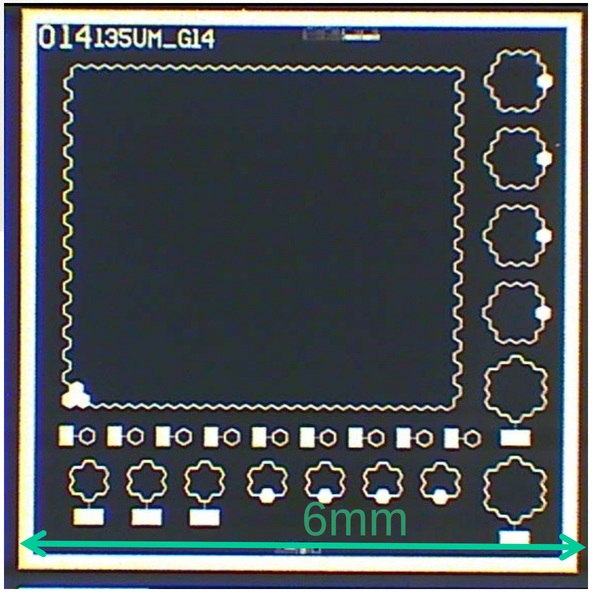
Prototype production

>130 different chips

Big microcell sizes 90-160μm

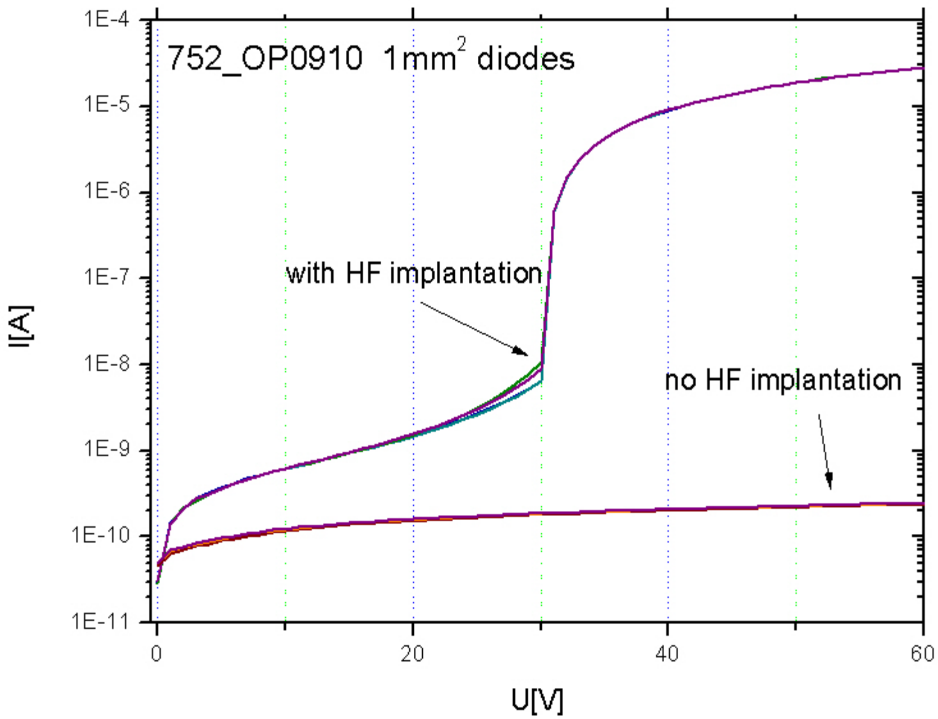




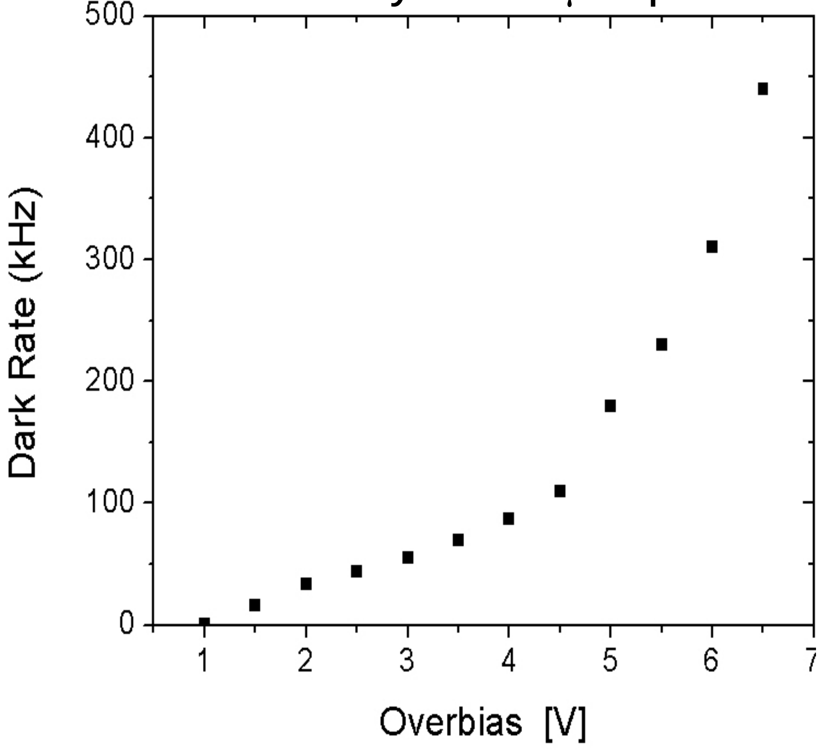


Dark rate

Due to the non optimal process sequence of the high field processing ~10MHz @300K for 4V overbias

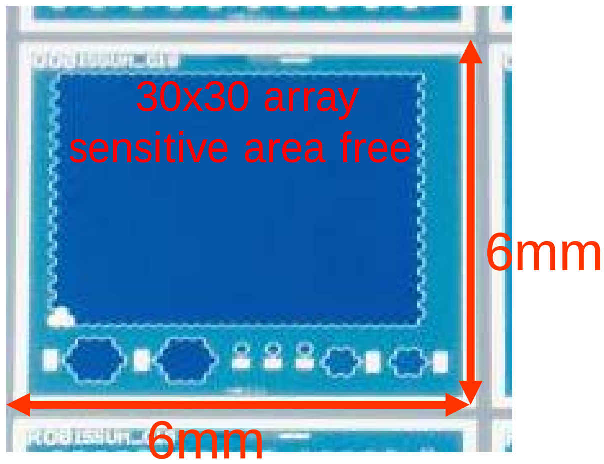


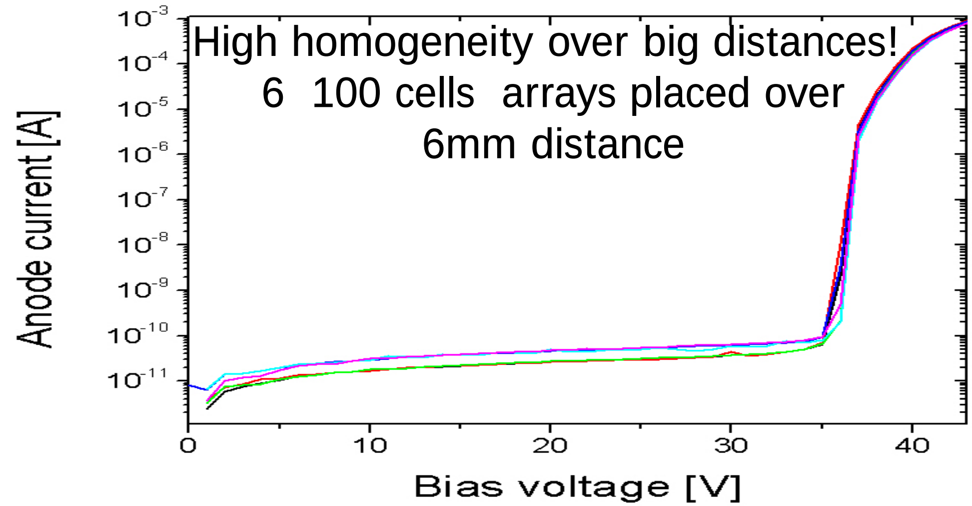
10x10array of 130μm pitch

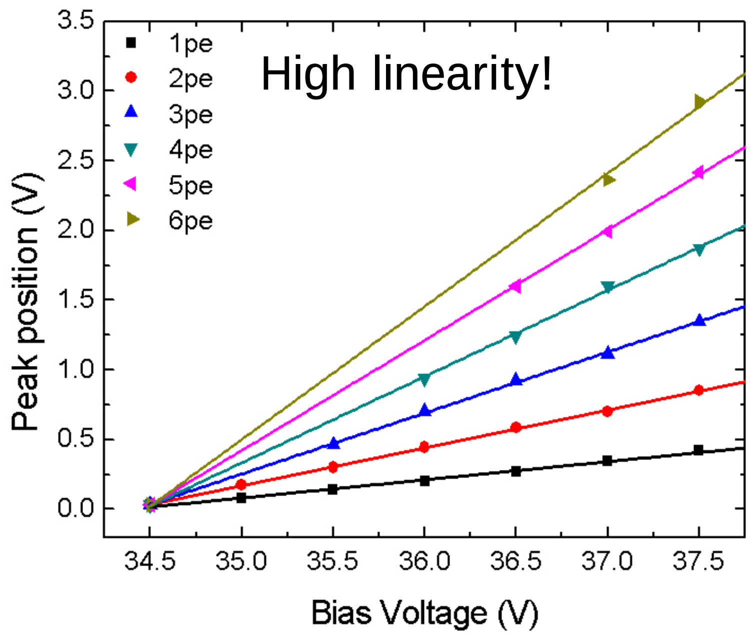


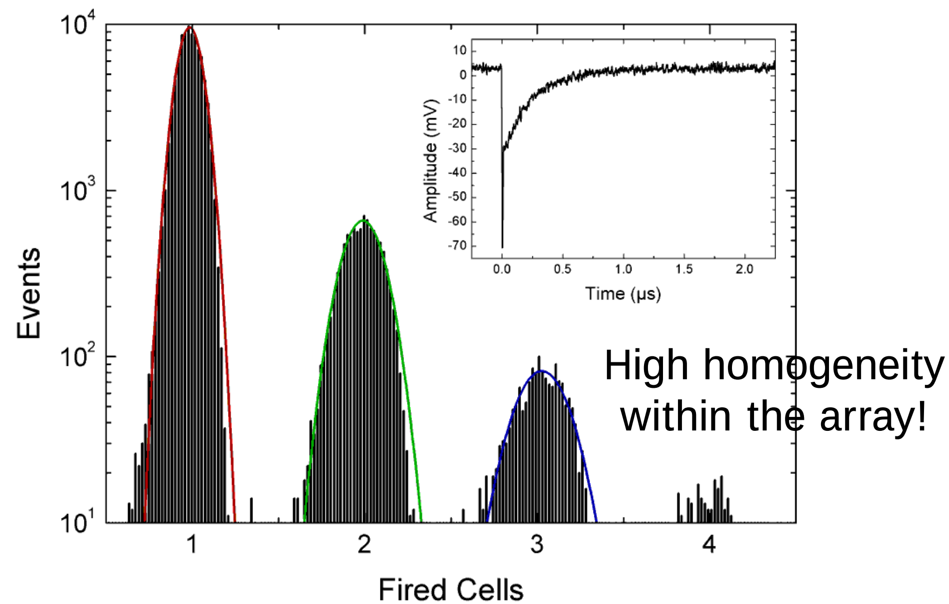
Normal operation up to 4.5V overbias @227K

Prototype production

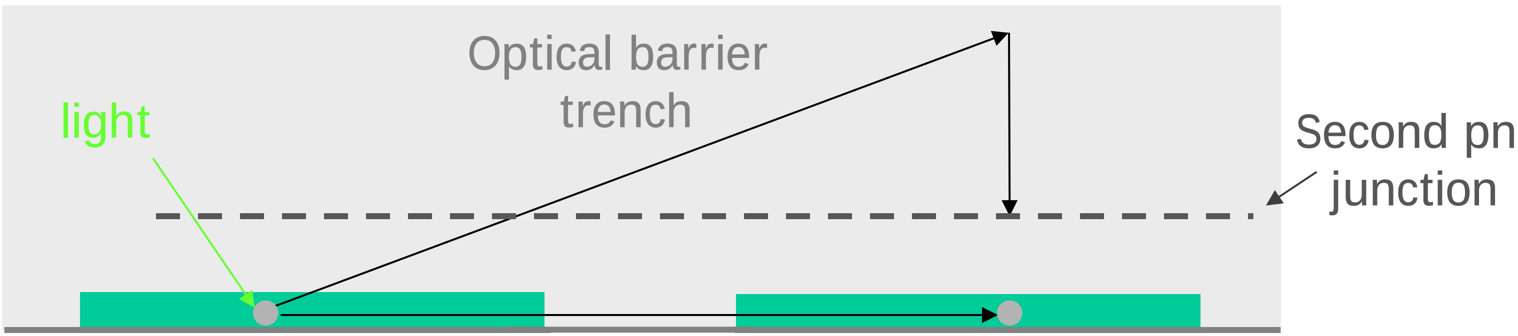




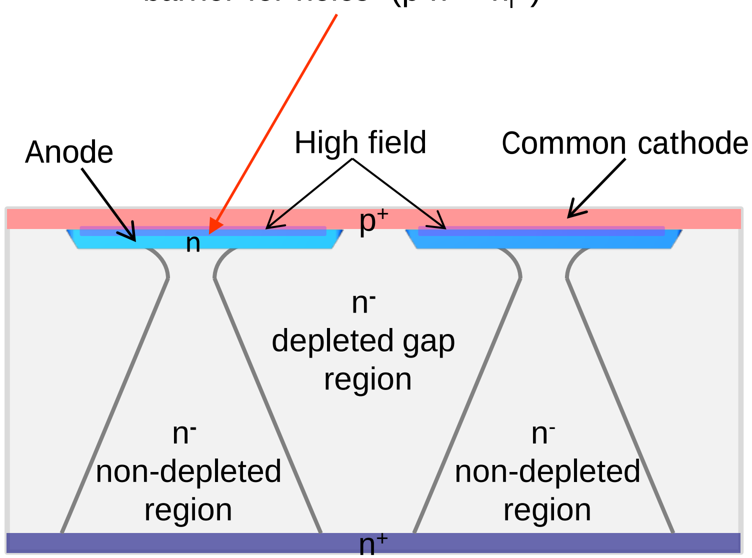




Optical cross talk suppression



Highly doped high field region is a diffusion
barrier for holes (p n = n_i^2)

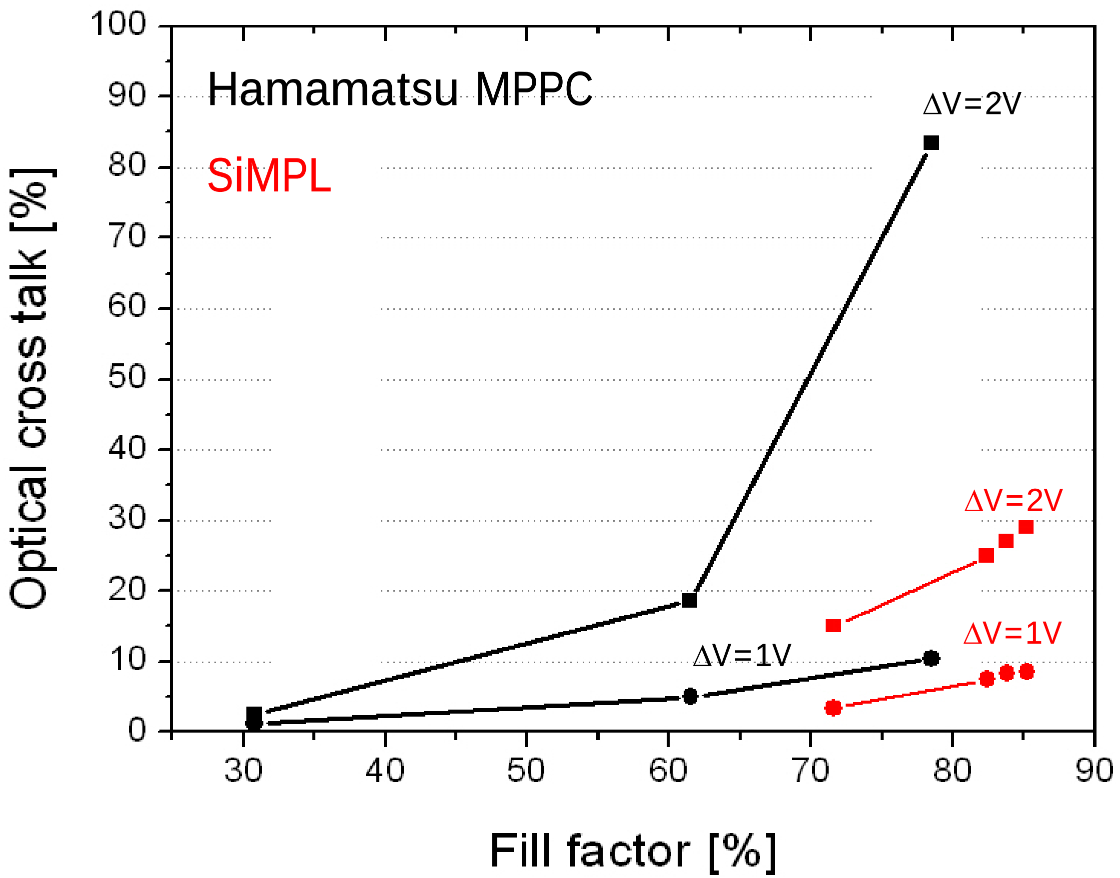


Produced SiMPI devices have very high fill factors!

Pitch / Gap	Fill factor	Cross talk meas. ($\Delta V=2V$)
130μm / 10μm	85.2%	29%
130μm / 11μm	83.8%	27%
130μm / 12μm	82.4%	25%
130μm / 20μm	71.6%	15%

Fill factor & Cross Talk

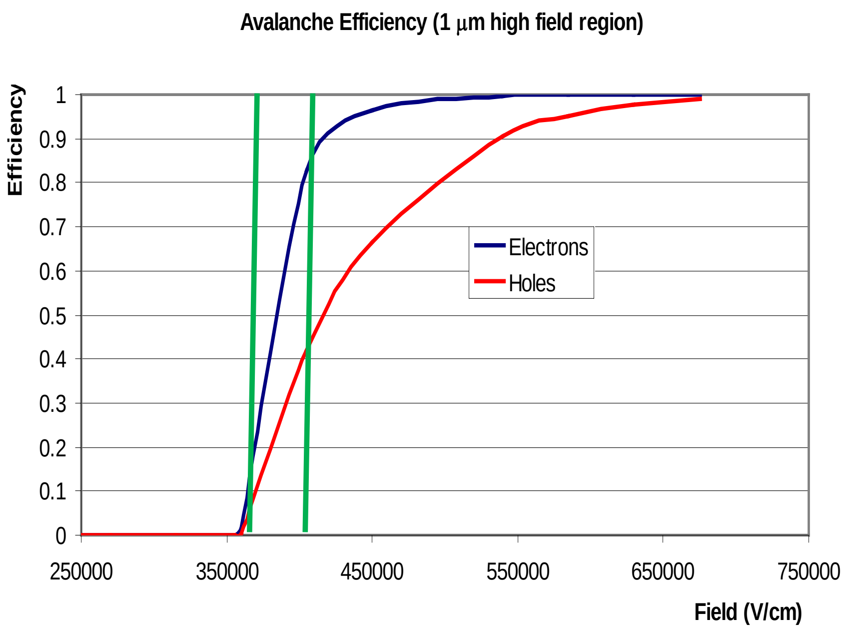
No special cross talk suppression technology applied just intrinsic property of SiMPl devices

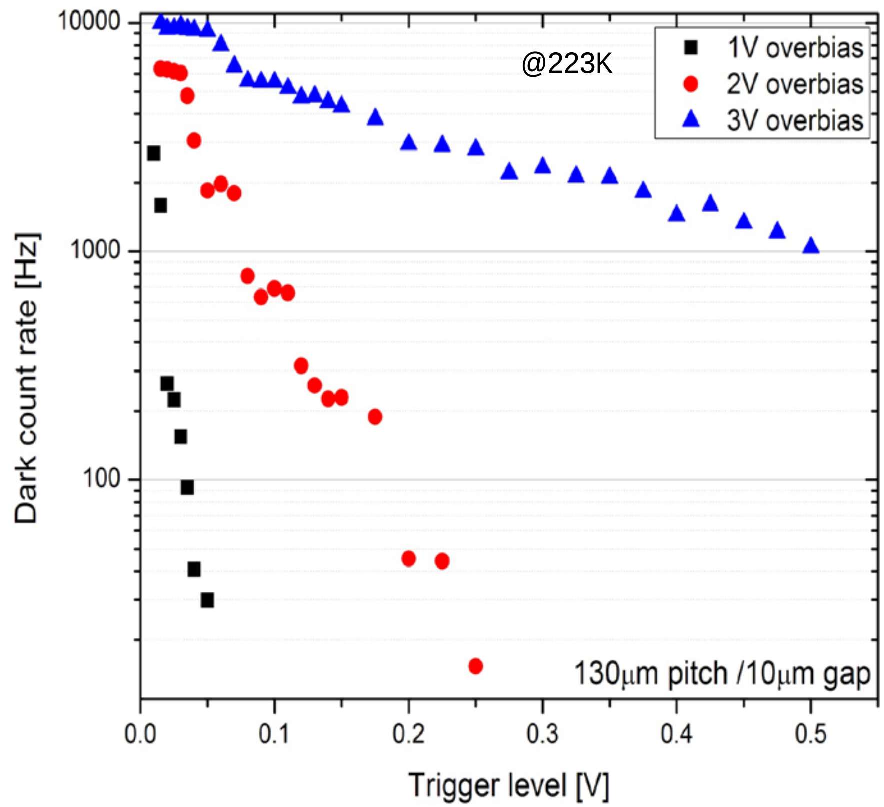


Detection of particles

Excellent time stamping due to the fast avalanche process (<1ns)

MIP gives about 80pairs/μm → huge signal in SiPM→ allows operation at small ΔV





Reduction of dark rate and cross talk by order of magnitude

Detection of particles

Dark rate: 1 MHz/mm² = 1 hit/µm²/s = O(Belle II)

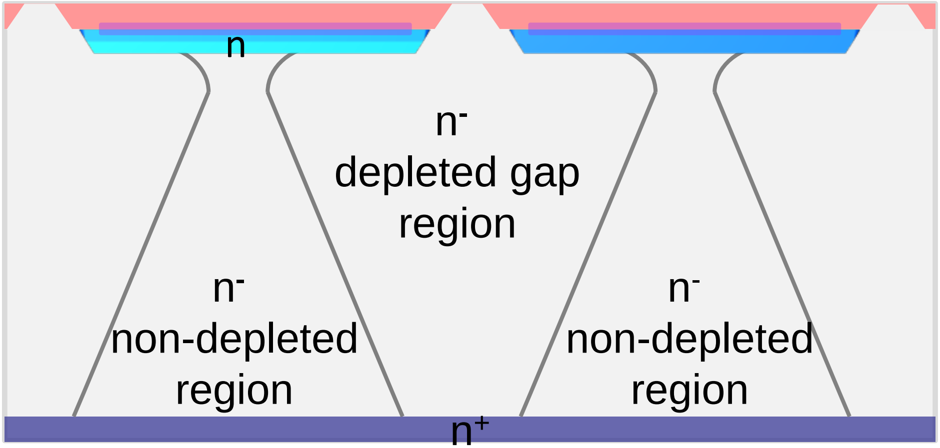
With 20 µm pitch and 12 ns time stamp: occupancy: 2.5 x10^{-6}

Power (analogue): ~ 5 µW/cm²
Dominated by dark rate

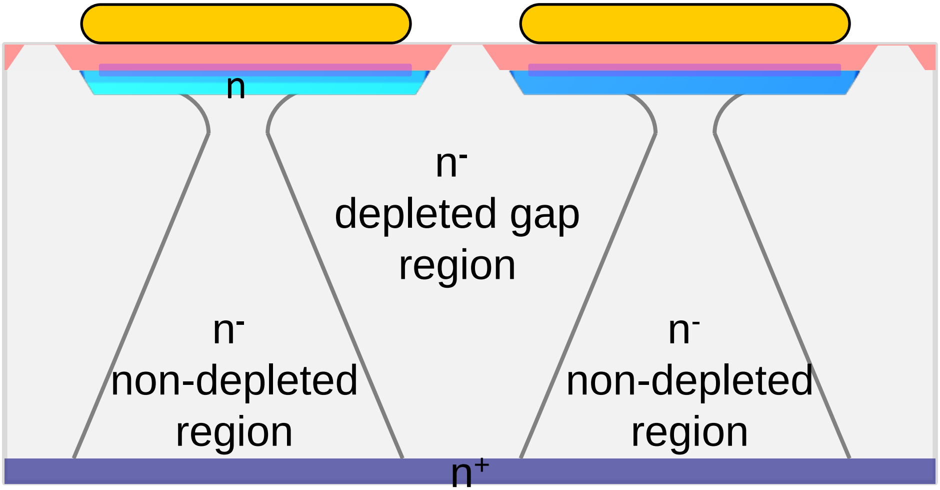
Possible concerns :

- Radiation hardness (dark rate increases due to bulk damage)
- Cross talk – low with low overbias
- Efficiency (fill factor)
- Digital power

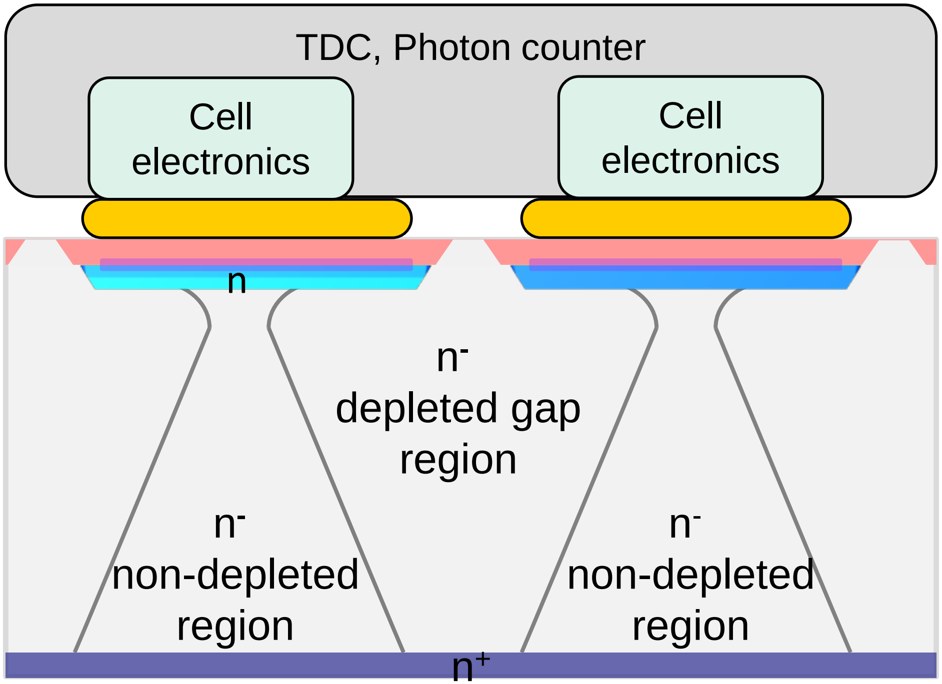
Next generation SiMPl devices



Next generation SiMPl devices



Next generation SiMPl devices



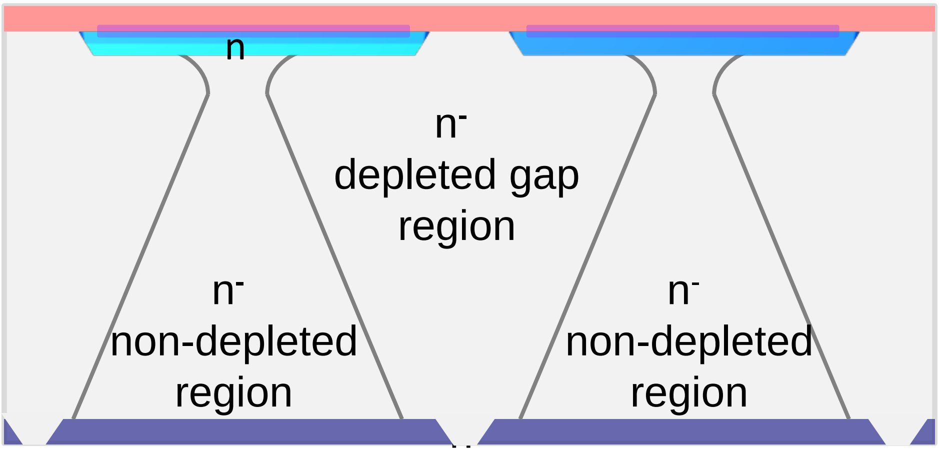
Topologically flat surface

High fill factor

Adjustable resistor value, active recharge

Pitch limited by the bump bonding

Next generation SiMPl devices

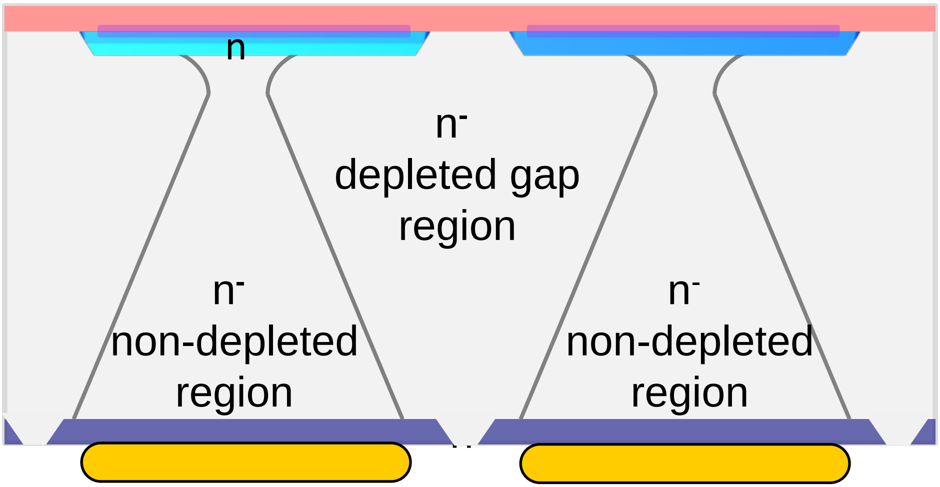


Topologically flat and free surface

High fill factor

Sensitive to light

Next generation SiMPl devices

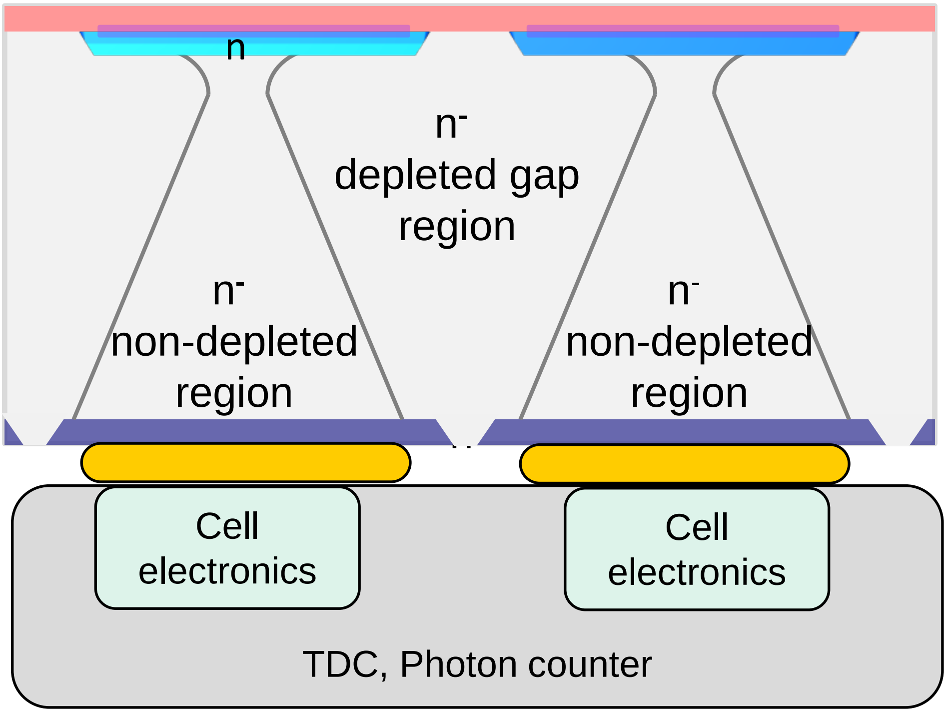


Topologically flat and free surface

High fill factor

Sensitive to light

Next generation SiMPl devices



Topologically flat and free surface

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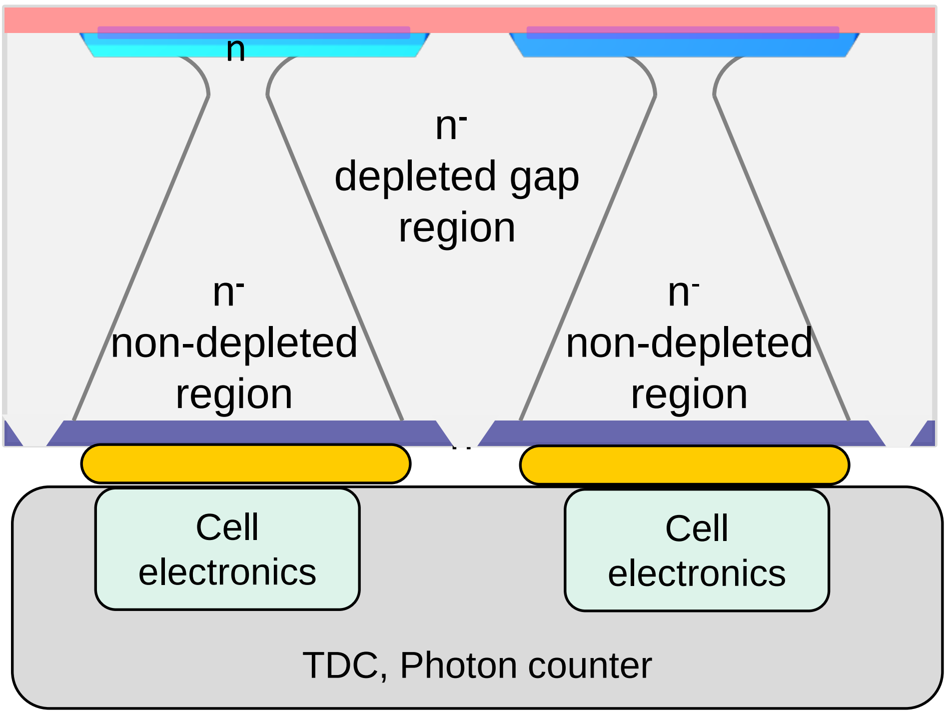


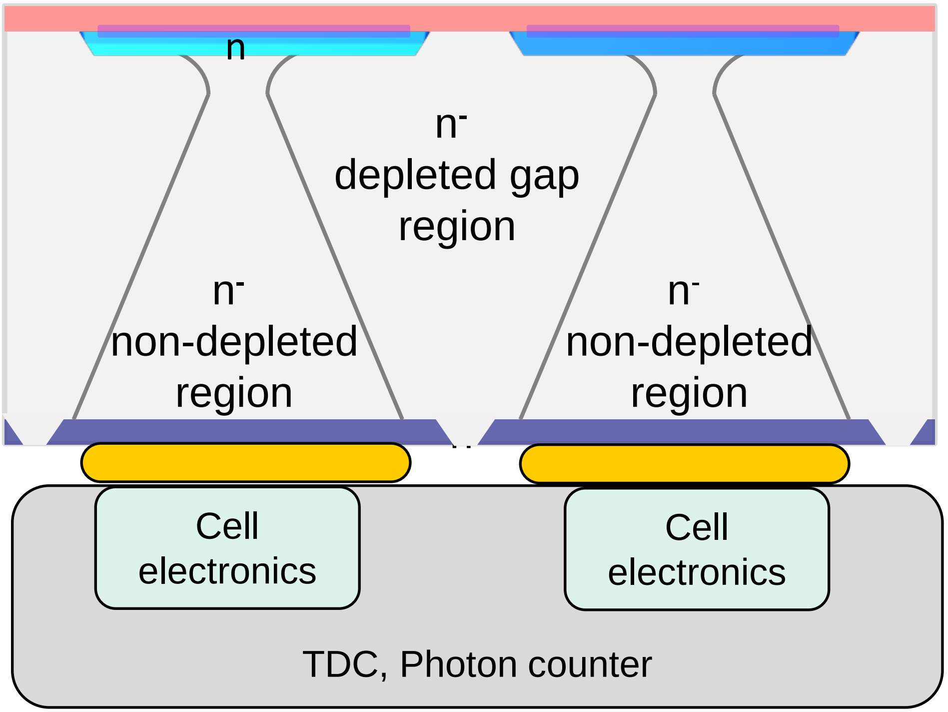
Topologically flat and free surface

High fill factor

Sensitive to light

1. Structured implant on backside on sensor wafer
2. bond sensor wafer to handle wafer
3. thin sensor side to desired thickness
4. process SiMPl arrays on top side

Next generation SiMPl devices



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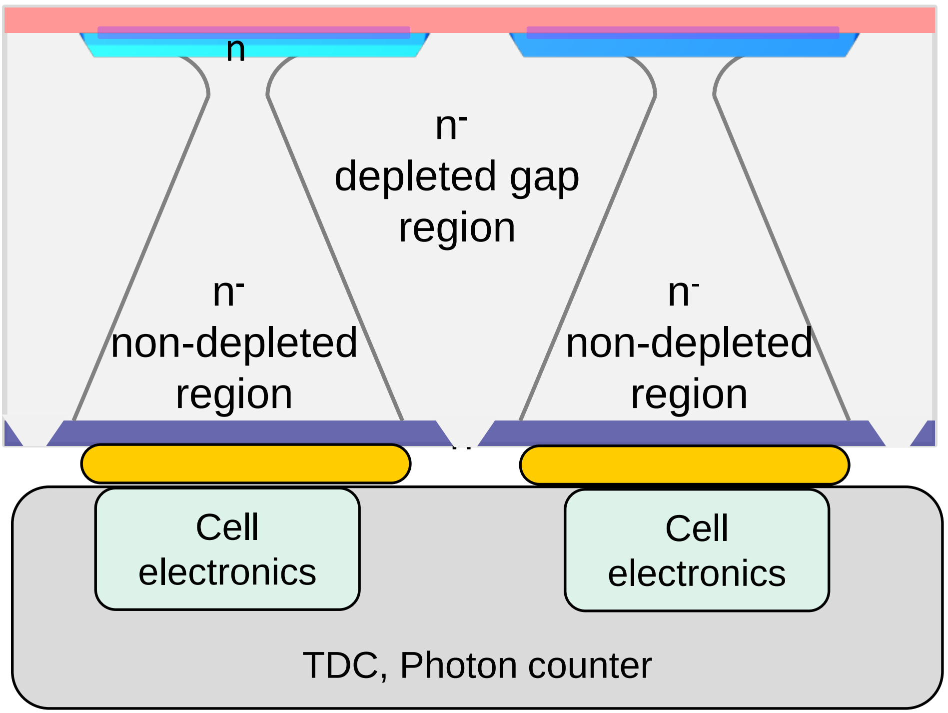

Topologically flat and free surface

High fill factor

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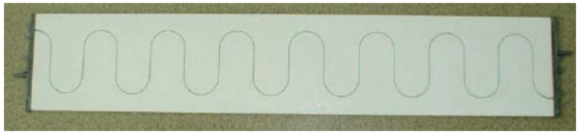
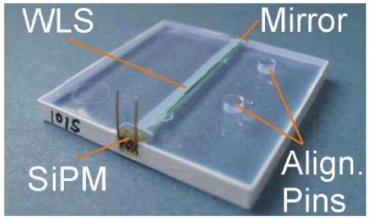
Summary

SiPMs have capacity to replace PMTs in many applications.



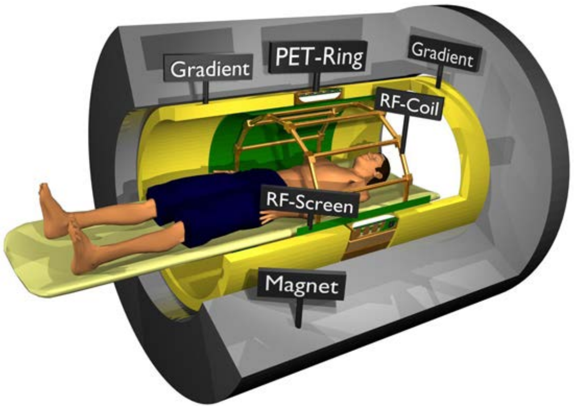
Optimization of properties can be/must be done for every application.

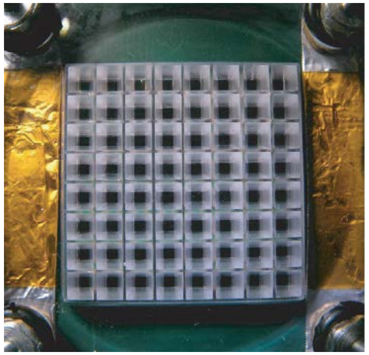


Experiments already using SiPMs:

- T2K ND280 – 60000 SiPMs in the experiment
- Calice Hadronic calorimeter – 8000 SiPMs
- FACT – small camera with 1440 SiPMs
- ...
- studies for Belle II particle ID upgrade
- studies for CMS outer Hadron Calorimeter upgrade

Medical applications are driving a lot of developments
→ Goal to have PET-MR scanner ...





Summary II

There is still room from improvement ...

Ongoing developments - radiation hardness
- higher PDE
- UV sensitivity
- low temperature operation

New concepts which open doors for new applications : SiMPl, dSiPMs ...

Thanks for your attention ...

Questions ???