Silicon Photomultipliers
Properties and Perspectives

J. Ninković

Max Planck Institute for Physics, Semiconductor Laboratory, Munich, Germany

Outlook

- Conventional Silicon Photomultiplier - properties
- Digital SiPMs
- SiPMl concept - Concept of Avalanche Diode Array with Bulk Integrated Quench Resistors for Single Photon Detection

Why do we need new photon sensor?

Many future experiments will use >> 100,000 photon detectors

robust and stable
easy to calibrate
blue sensitive
low cost (+ low peripheral costs)
compact
low power consumption
insensitive to magnetic field
…
highest possible photon detection efficiency

Avalanche PhotoDiode - APD

Linear/ Proportional mode

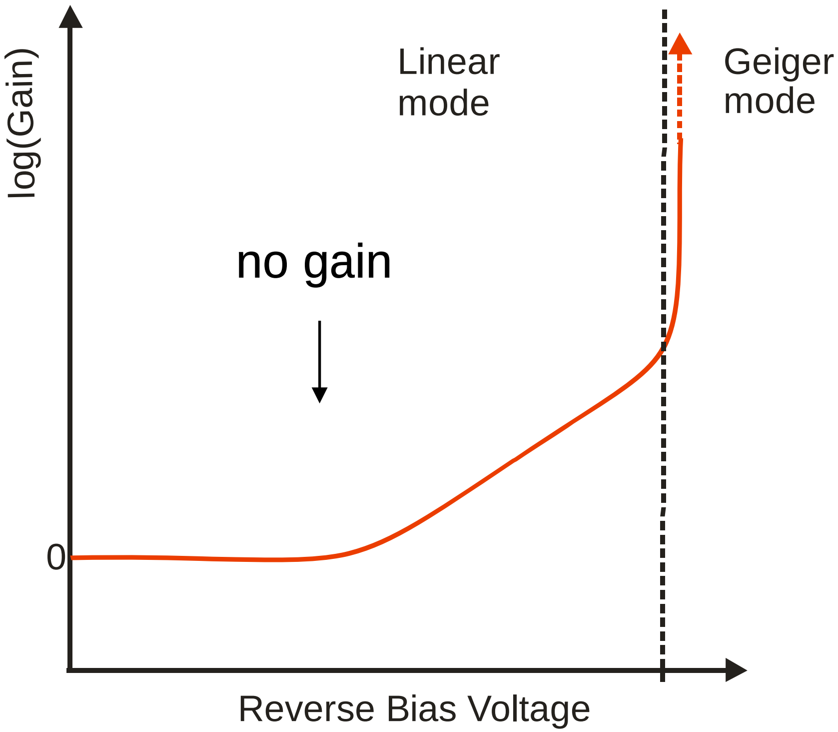
Bias: slightly ***BELOW*** breakdown

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***"** !!

Advantages of Geiger mode APDs

Large standardized output signal

high immunity against pickup

High sensitivity for single photons

Excellent timing even for single photo electrons (<<1ns)

Good temperature stability

Low sensitivity to bias voltage drifts

Devices operate in general < 100 V

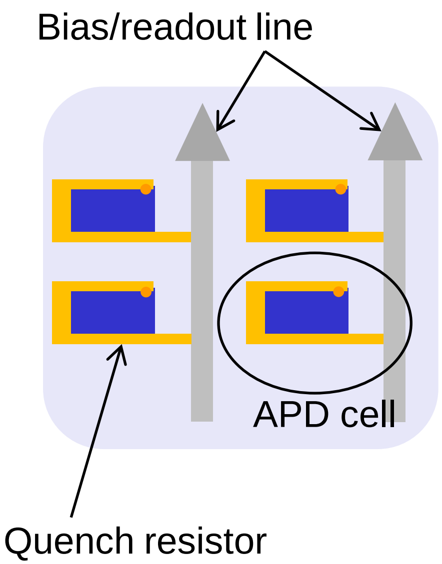
Complete insensitive to magnetic fields

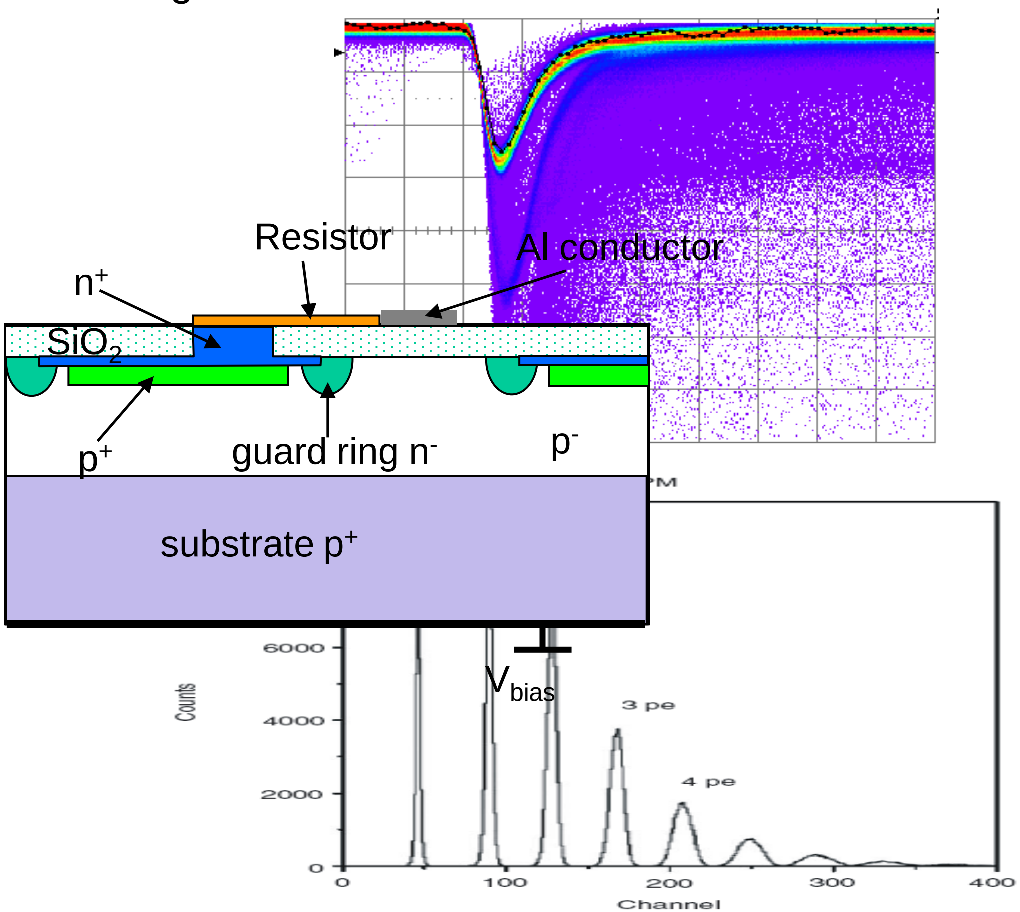
but it is a binary device ...

Conventional Silicon Photomultiplier – SiPM

•An array of avalanche photodiodes

- operated in Geiger mode
- passive quenching by integrated resistor
- read out in parallel → signal is sum of all fired cells



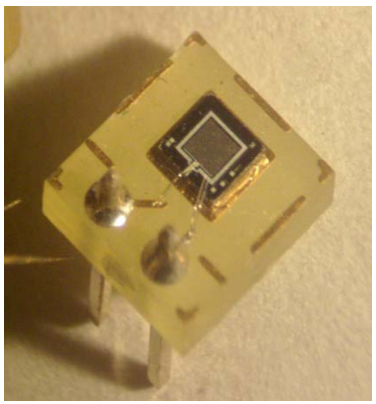


What is available?

Conventional SiPM

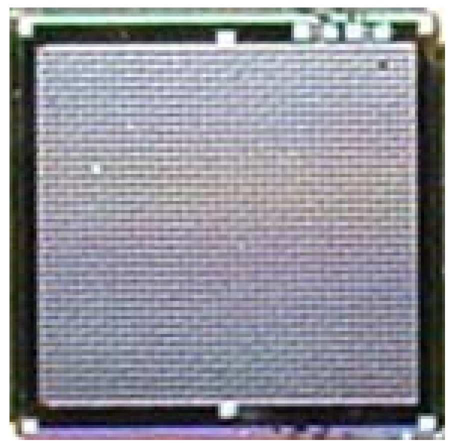
MEPhI / SensL / Hamamatsu / FBK …

1x1mm²



3x3mm²

5x5mm²



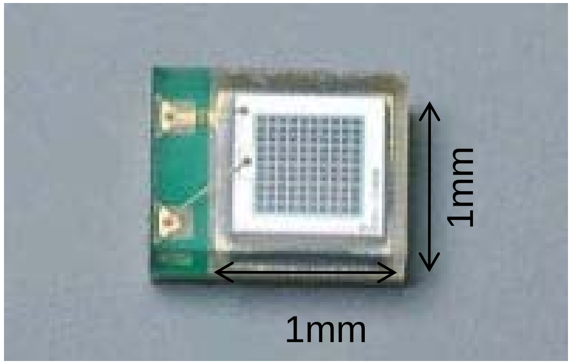
- Single cell sizes ~ 20µm x 20µm
- Geometrical occupancy ~ 25%
- Photon Detection Efficiencies ~ 10%

- Single cell sizes ~ 100µm x 100µm
- Geometrical occupancy 70%
- Photon Detection Efficiencies ~ 40%

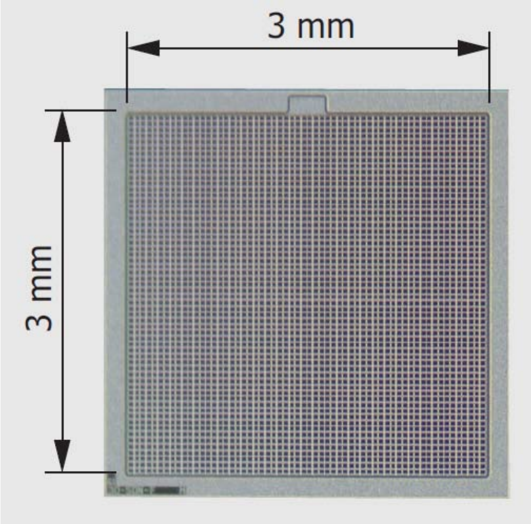
What is available?

Conventional SiPM

MEPhI / SensL / Hamamatsu / FBK…



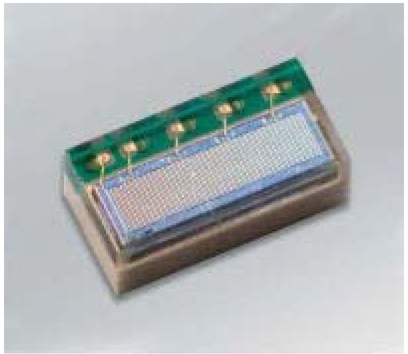
MULTI-PIXEL PHOTON COUNTERS (MPPC)



- Single cell sizes ~ 25µm x 25µm … 100µm x 100µm (1600cells ... 100 cells)
- Geometrical occupancy ~ 20-50%
- Photon Detection Efficiencies ~ 35%

What is available?

Hamamatsu (MPPC)



SenSL

•SiPM Arrays ~ 1x4, 2x2, ….4x4

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 Ω load.

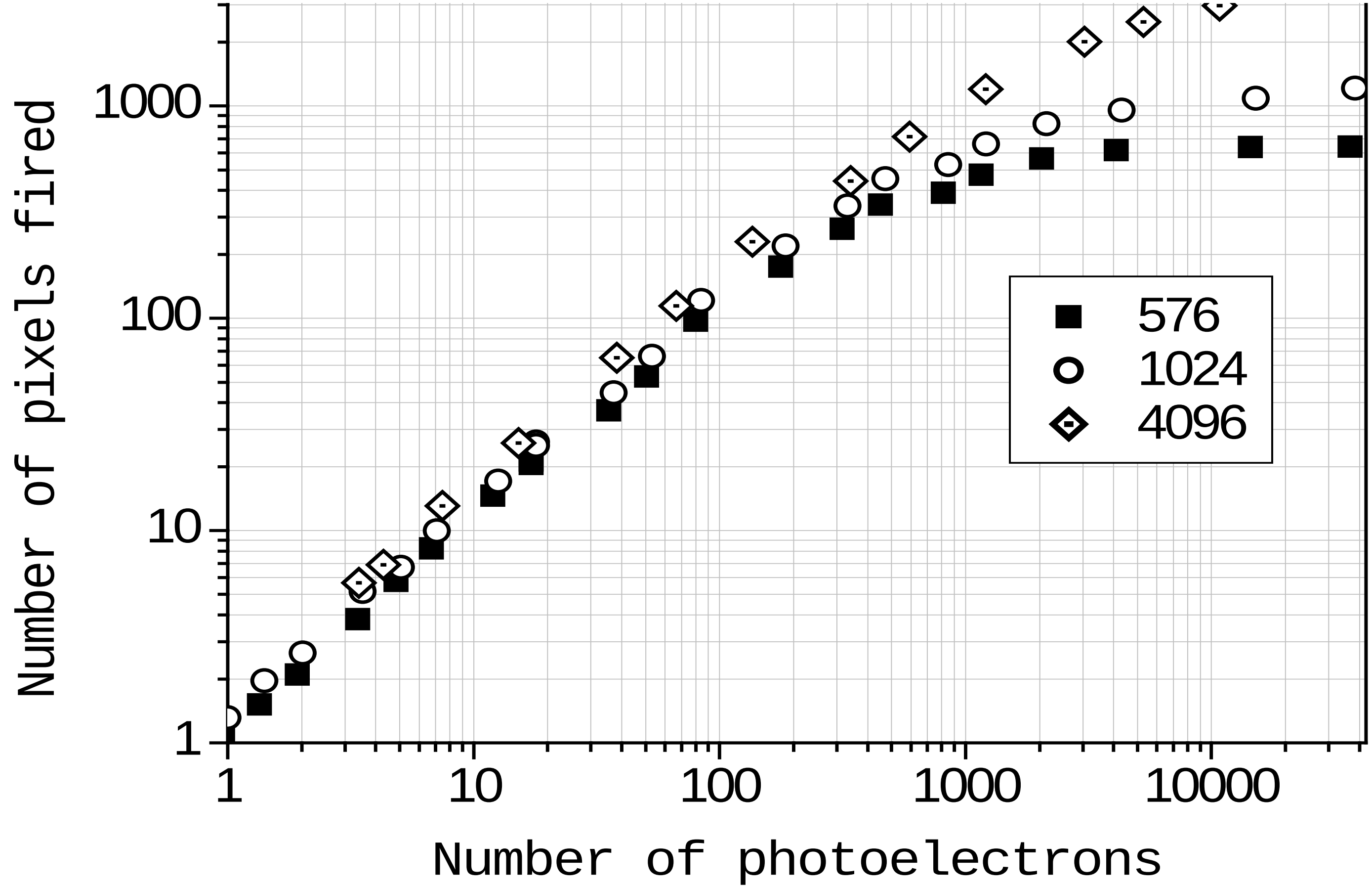
A simple amplifier is needed.

Saturation

The ... ber of ... ne

2 or

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



B.Dolgoshein,LIGHT06

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

Solution:

cooling (factor 2 reduction every 7-8°C)

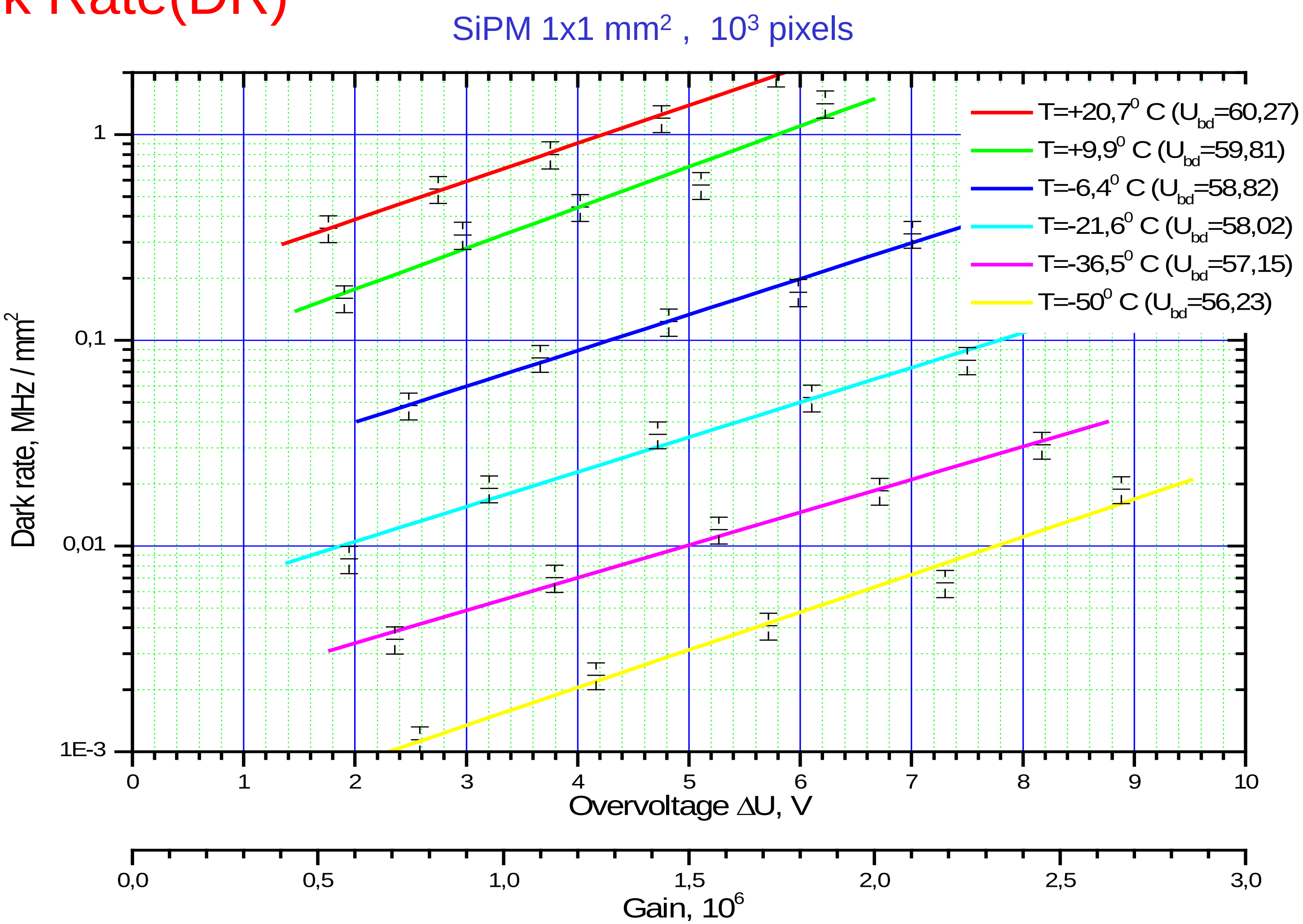
smaller electric field (lower gain) → disadvantage lower PDE

Field-assisted generation (tunneling) depends on the design of the avalanche structure.

DR increases with overvoltage (tunneling) → deep cooling doesn't help!

Dark counts

Dark Rate(DR)



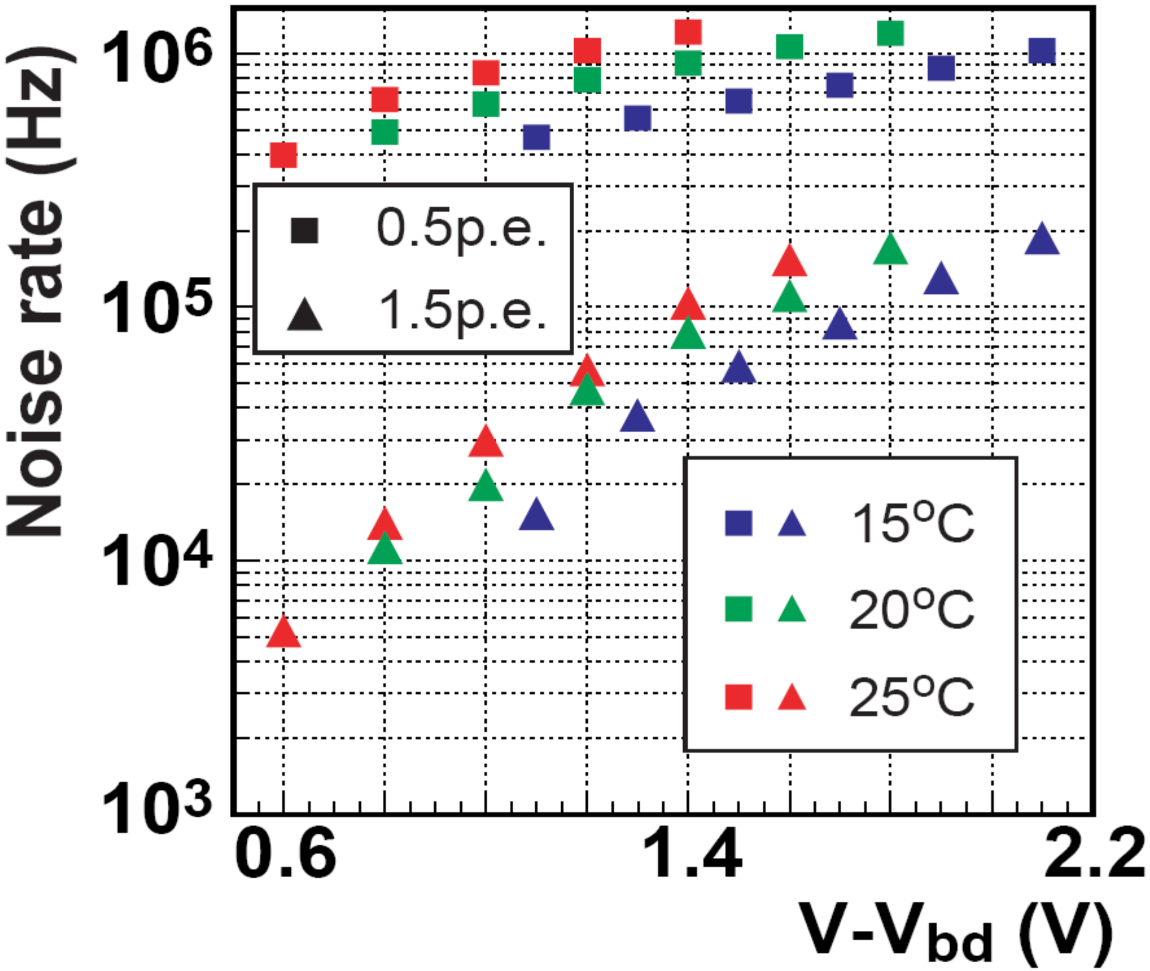
B.Dolgoshein,LIGHT06

Dark counts

Hamamatsu

$1mm^2$ device

Operation @low overvoltage



Yokoyama et al. **physics/0605241**

Optical Crosstalk (OCT)

Hot-Carrier Luminescence:

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

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

OCT becomes >1 for a Gain > few times$\times 10^7$ … self-sustaining discharge

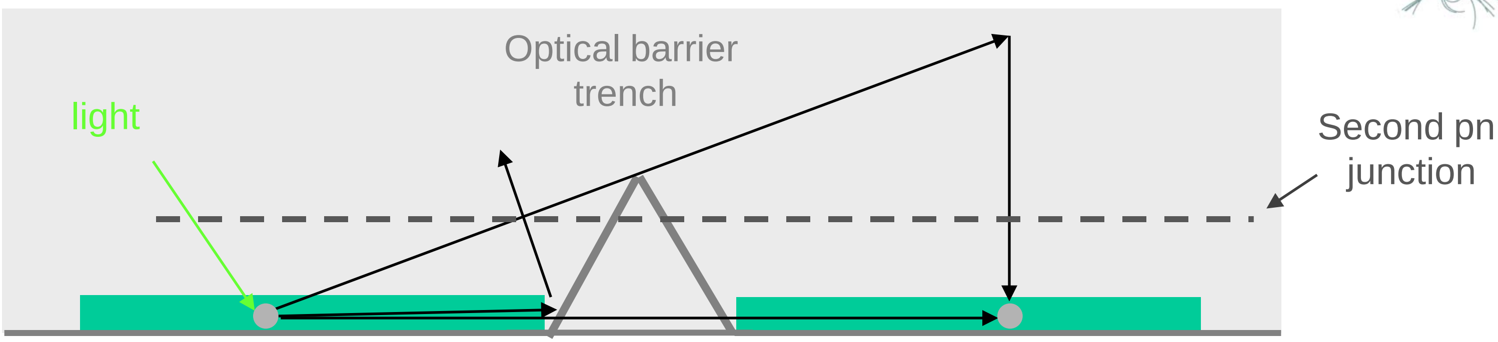
Excess Noise Factor becomes too large.

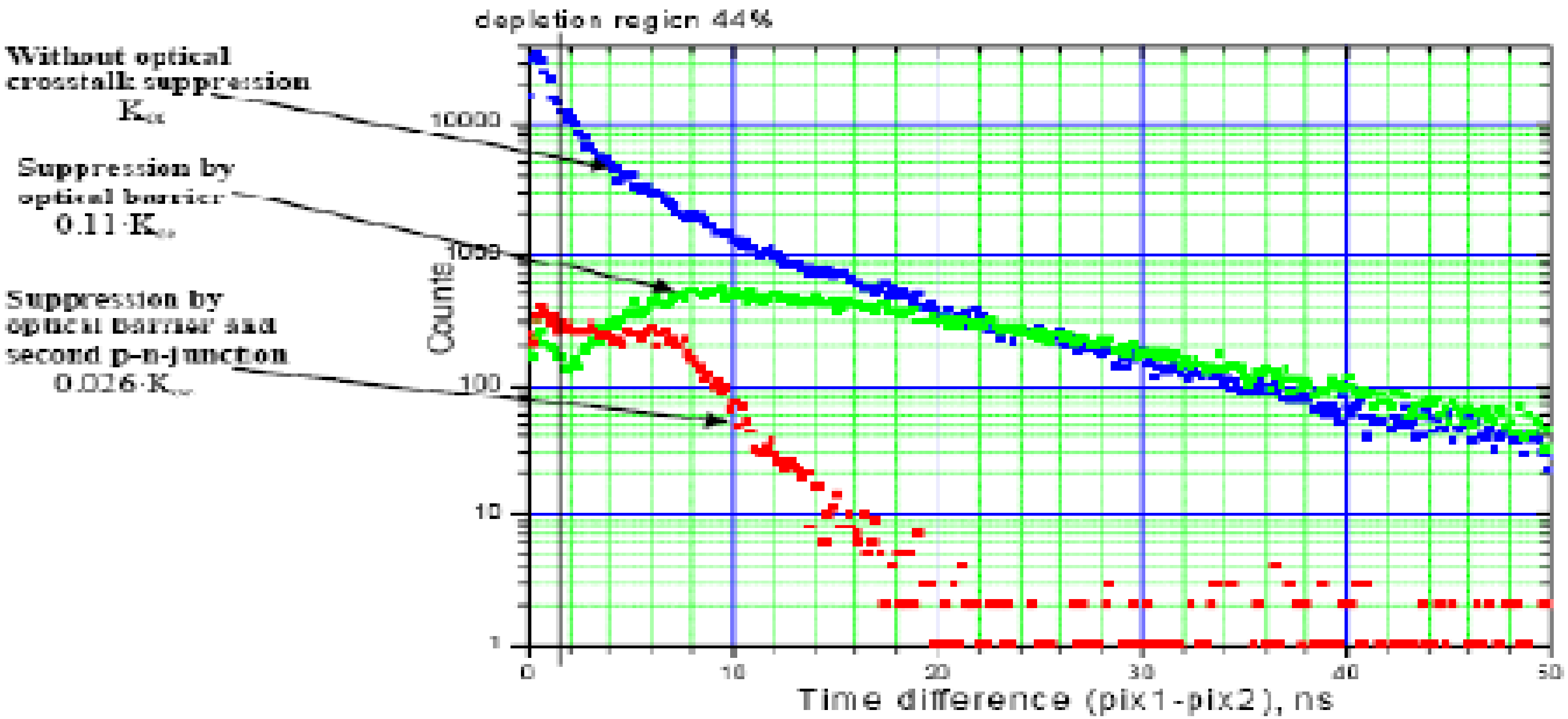
:

Optical isolation between pixels

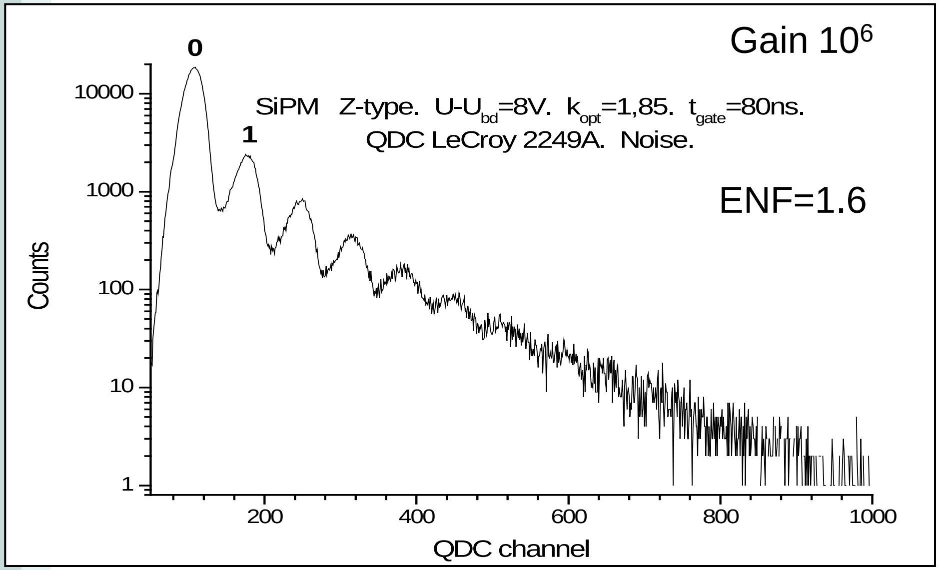
Operate at relative low gain → disadvantage lower PDE

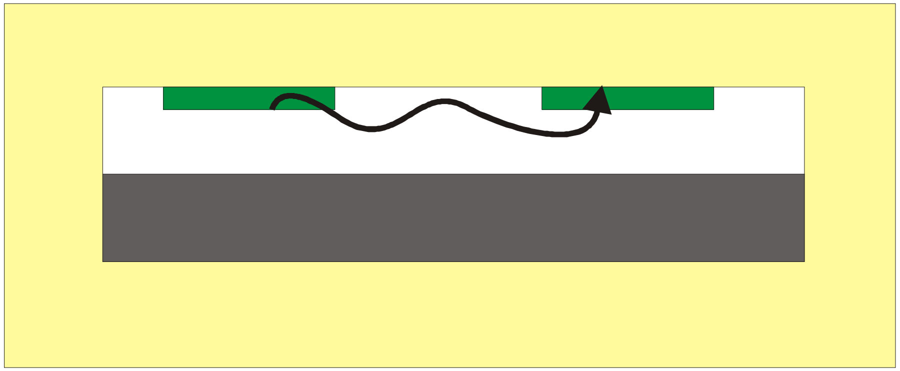
Optical cross talk suppression

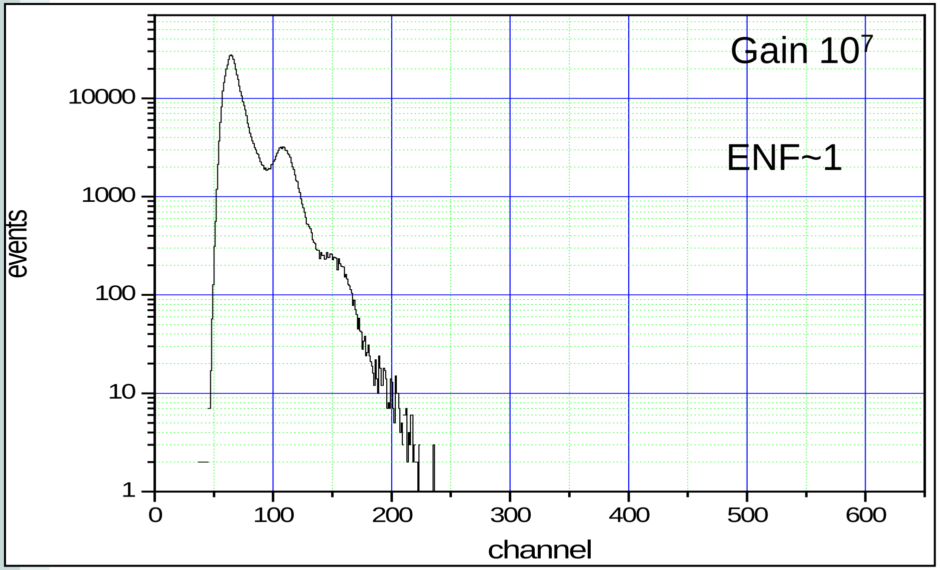


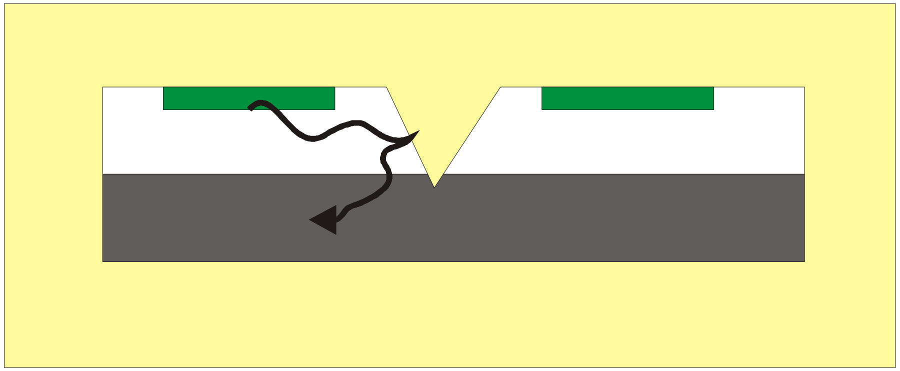


Optical crosstalk, SiPM 1.4x1.4 mm2,dark noise



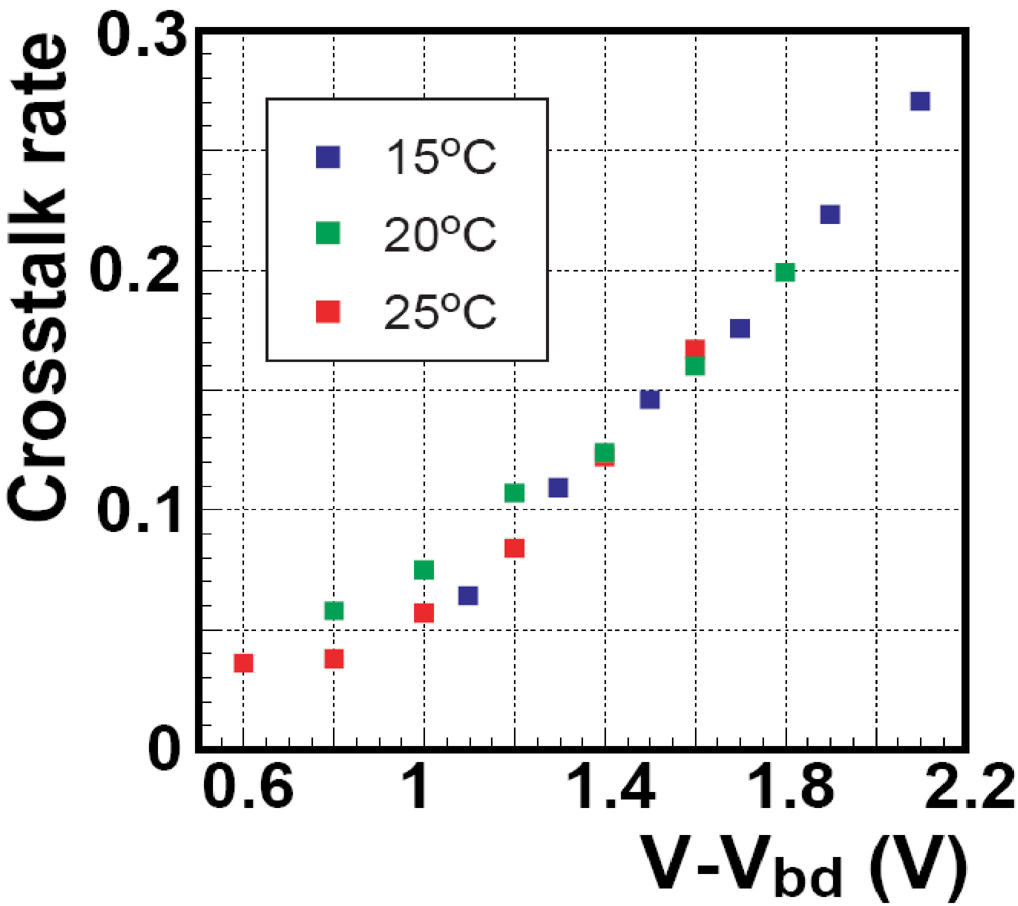






B.Dolgoshein,LIGHT06

Optical cross talk – Hamamatsu



Yokoyama et al. **physics/0605241**

Recovery time

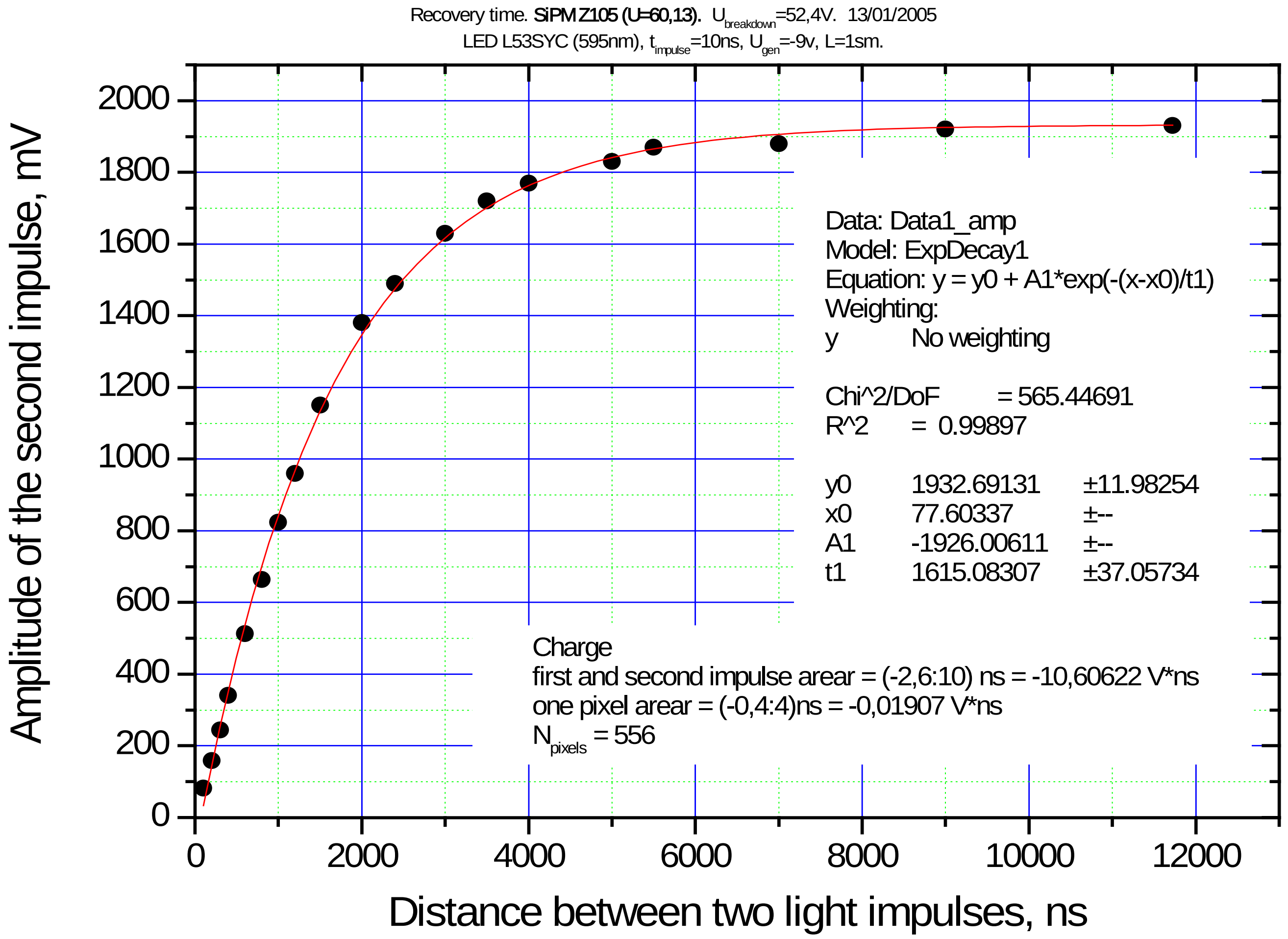
The time needed to recharge a cell after a breakdown depends mostly on the cell size (capacity) and the quenching resistor (RC).

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

Recovery time of SINGLE pixel: C(pix)xR(pix)-->20ns…..a few microsec



B.Dolgoshein,LIGHT06

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.

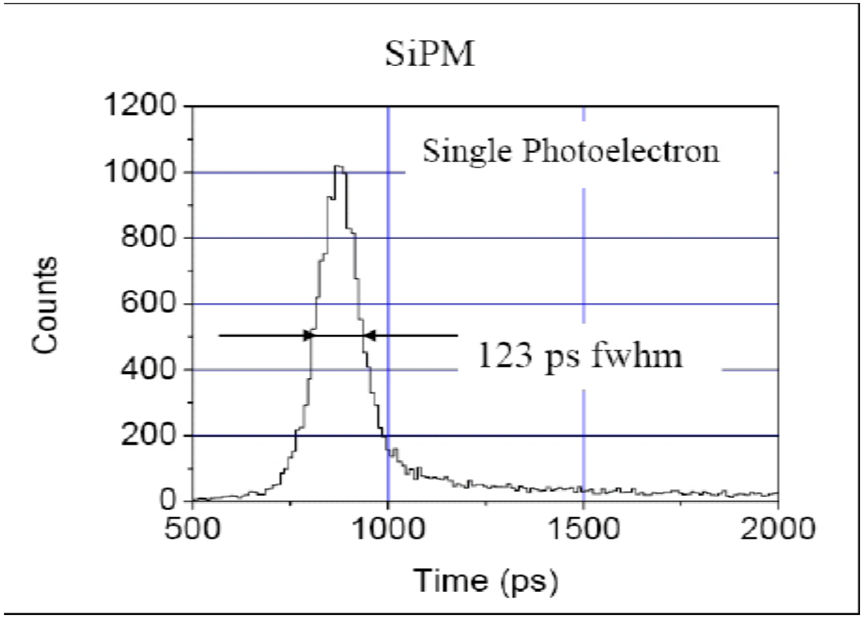
A. Lacaita et al., Apl. Phys. Letters 62 (1992) A. Lacaita et al., Apl. Phys. Letters 57 (1990)

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

Timing

taken from B. Dolgoshein's presentation in Beaune 2002 (NIM A 504 (2003) 48)

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



Photon Detection Efficiency

Main limitations:

Geometrical occupancy of the Geiger diodes (aimed at 70%)

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

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

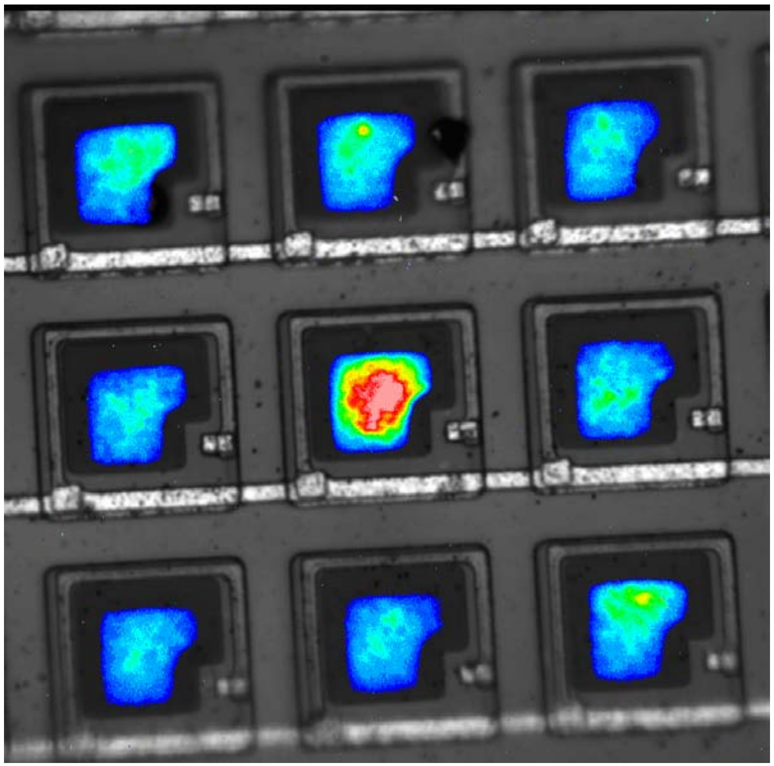
Classical Quantum efficiency (~100%)

Breakdown Initiation Probability (~90%)
Function of the electric field in the avalanche region

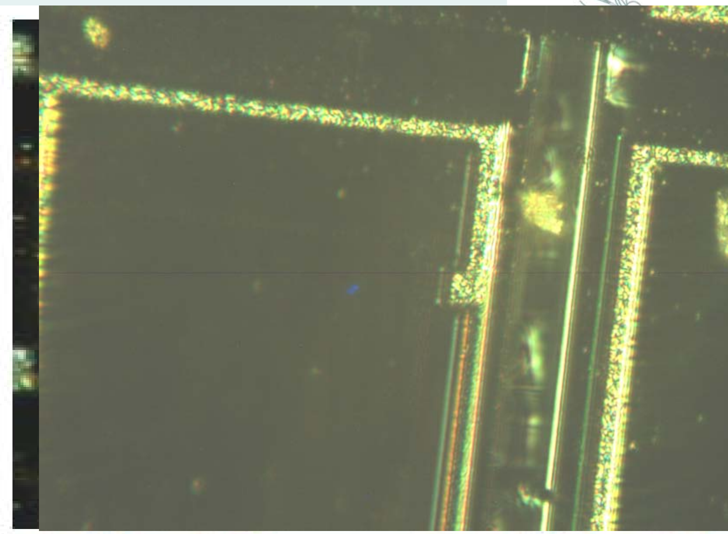
→ End up with 50…60% PDE

Fill factor

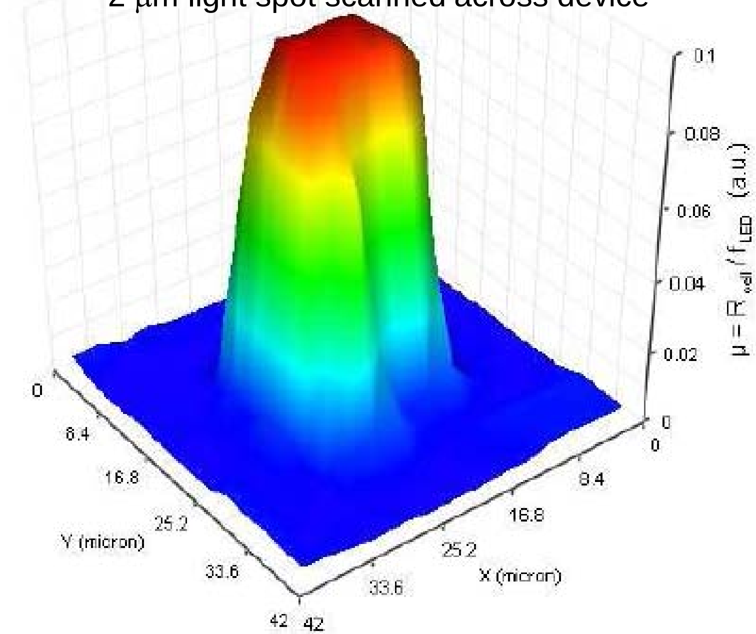
MEPhI



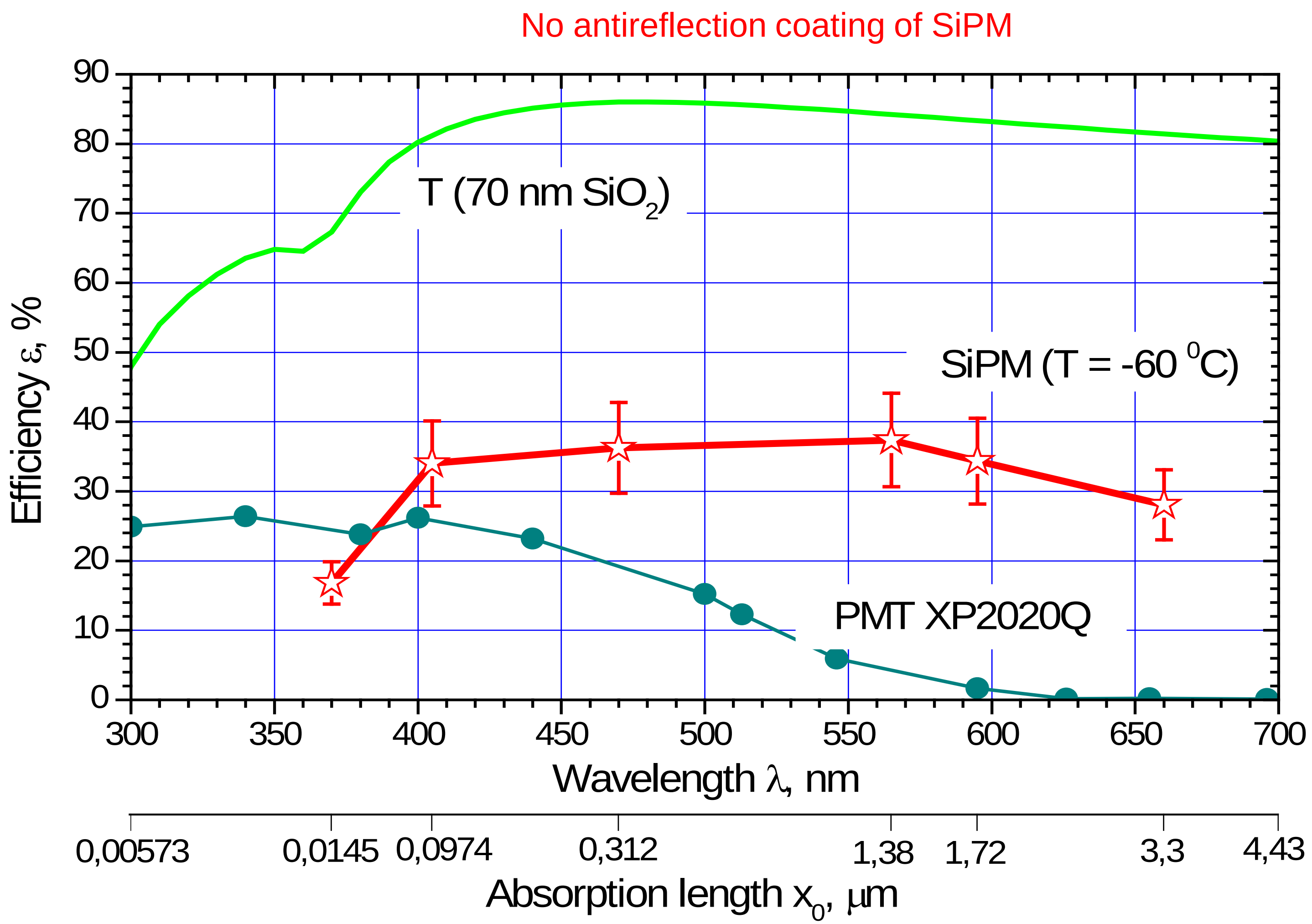
Pitch size 25µm



2 µm light spot scanned across device



Photon Detection Efficiency



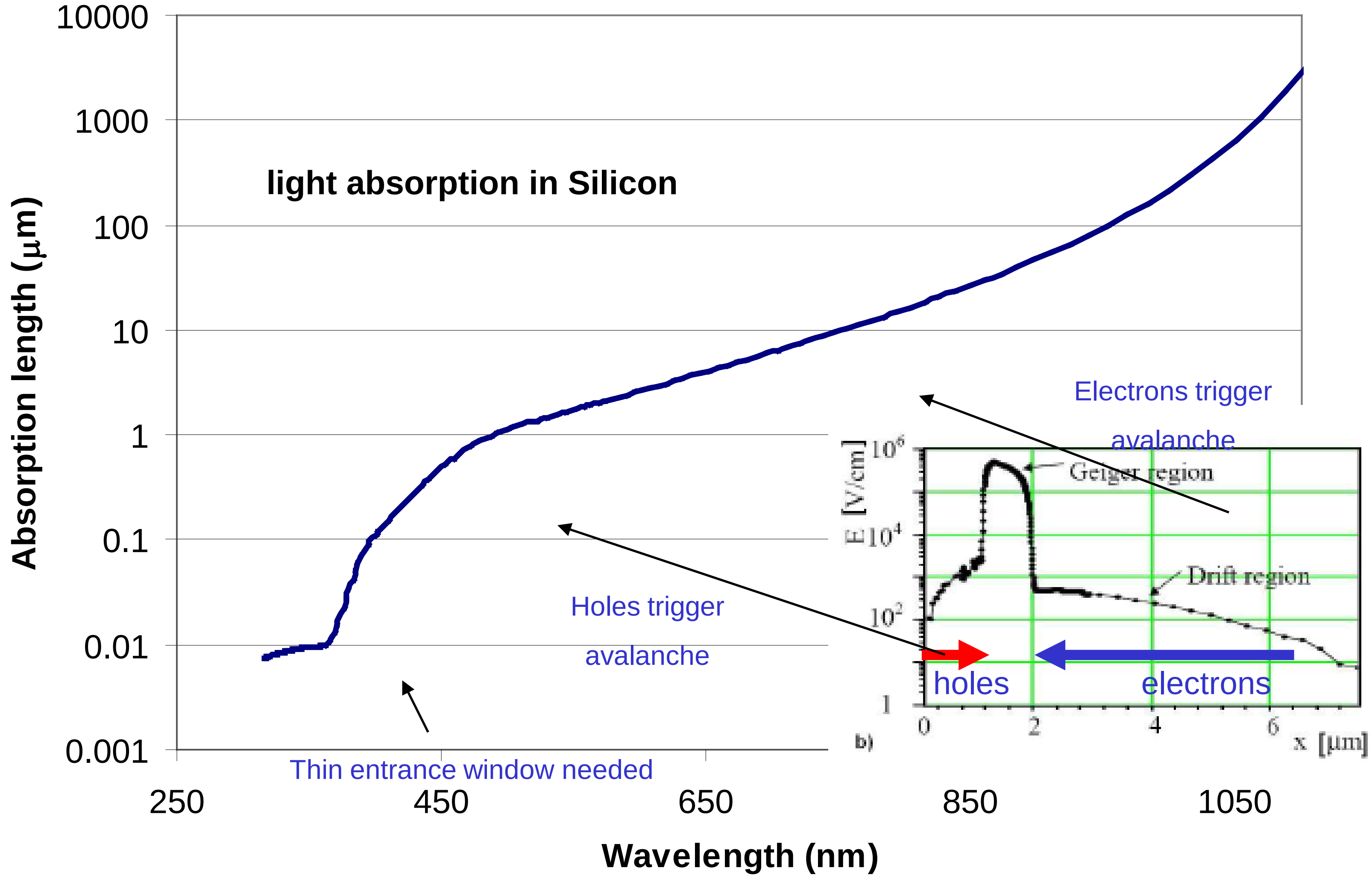
$$PDE = T_{SiO_2} \cdot \varepsilon_{packing} \cdot \varepsilon_{Geiger} \cdot QE$$

$\varepsilon_{packing} = 0.5$

$\varepsilon_{Geiger} \approx 1$

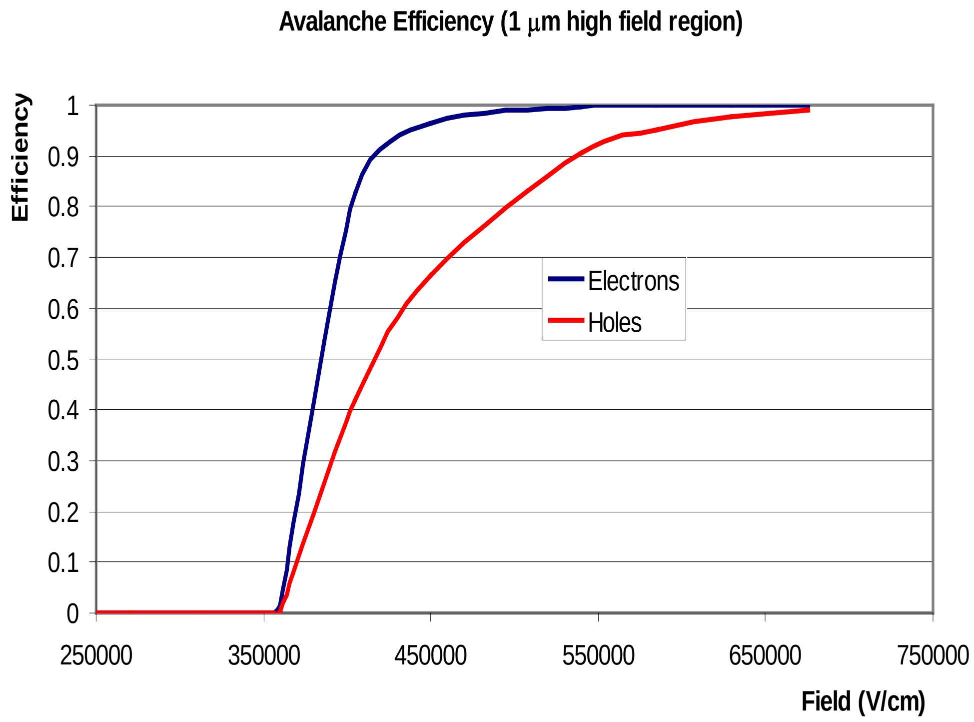
B.Dolgoshein,LIGHT06

Blue/UV sensitivity



Blue/UV sensitivity

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

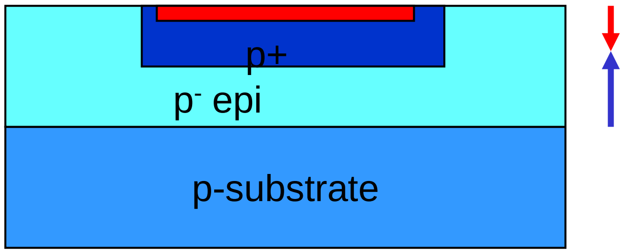


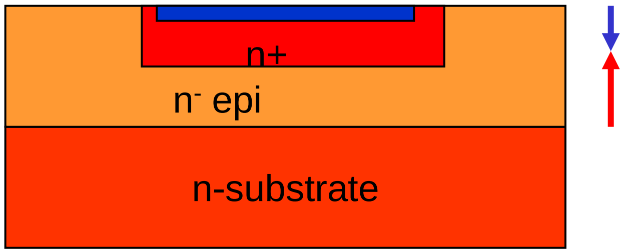
Solutions:

-Increase overvoltage

-Inverted structures

(prototypes produced at MEPhI/Pulsar & Hamamatsu)

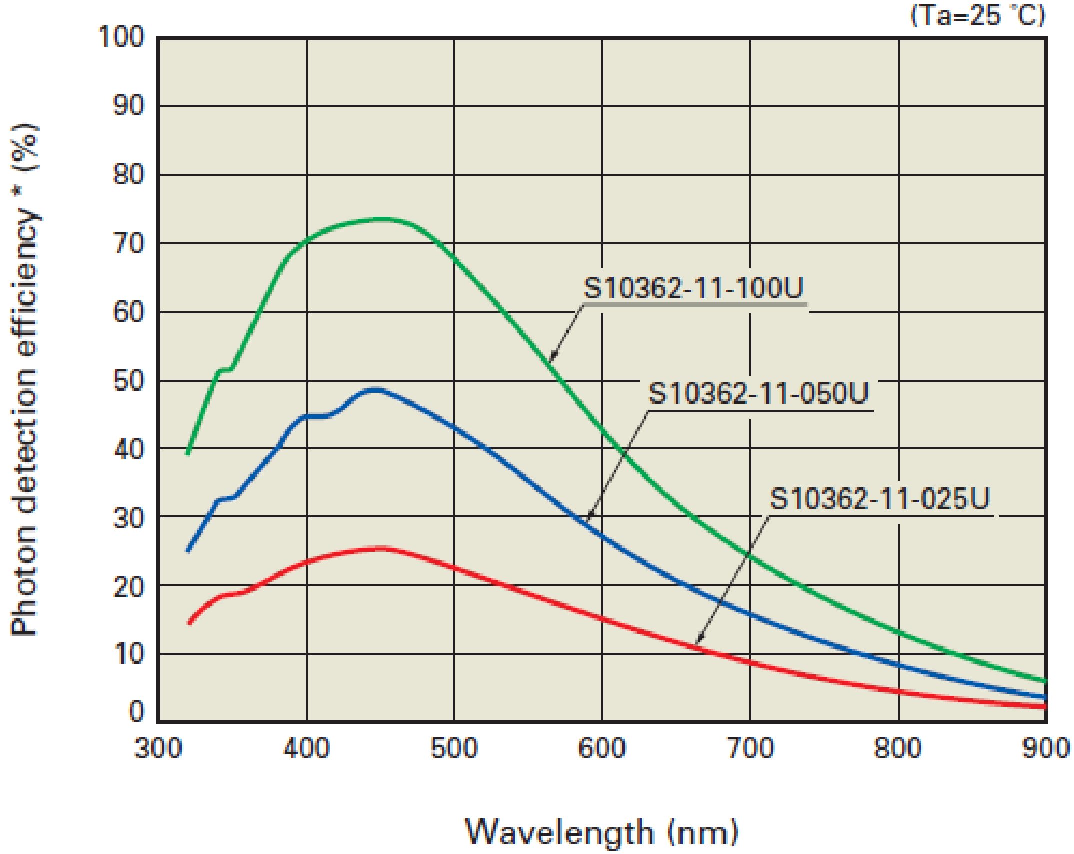




PDE - Hamamatsu

[Figure 12] Photo detection efficiency (PDE)* vs. wavelength (measurement example) –

(a) S10362-11-025U/-050U/-100U



* Photon detection efficiency includes effects of crosstalk and afterpulses.

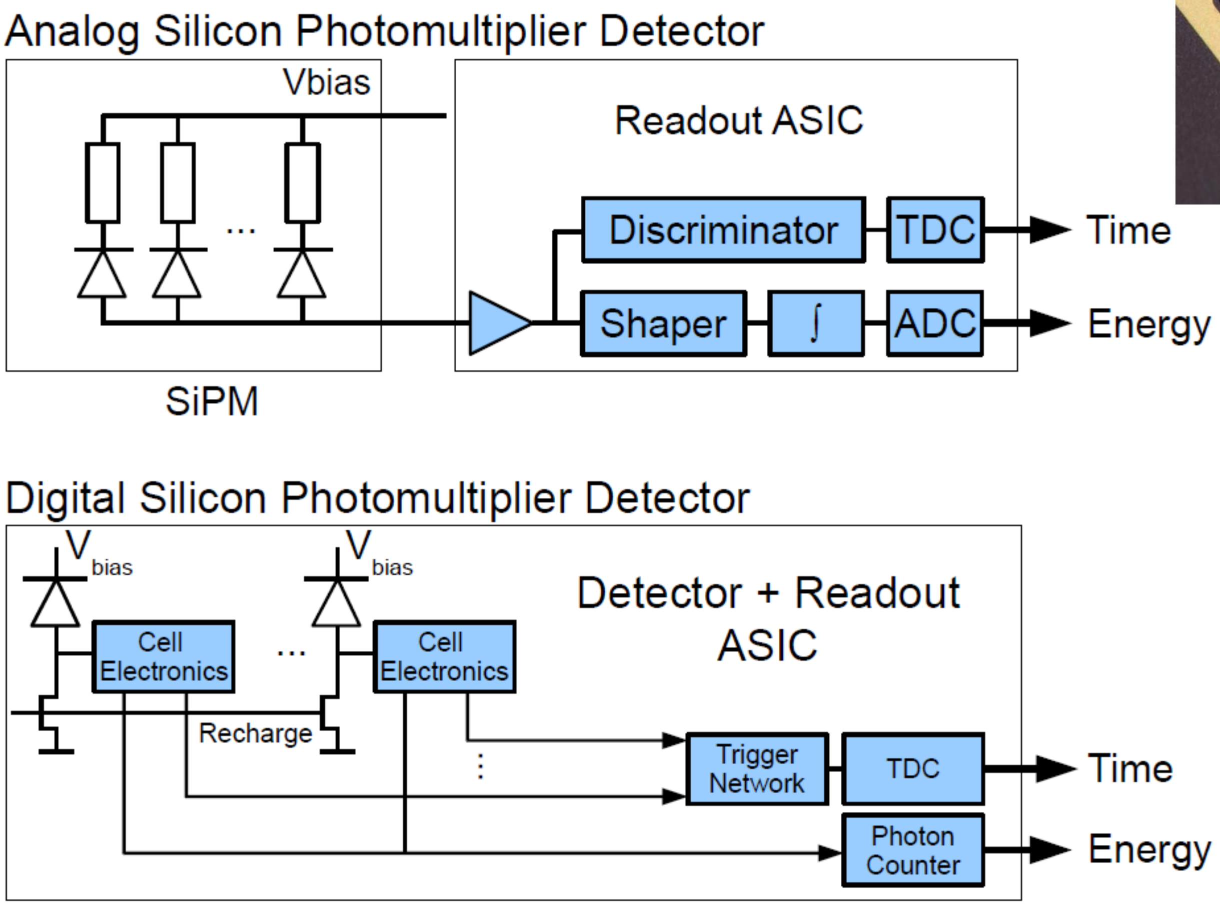
KAPDB0170EA

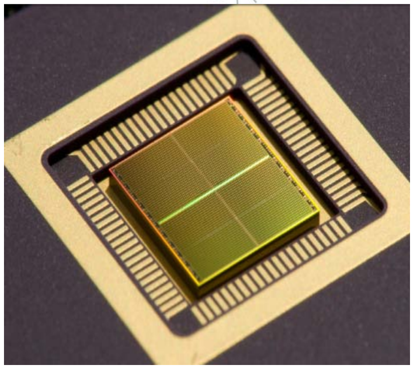
9

Digital SiPMs

PHILIPS

Digital SiPM – The Concept

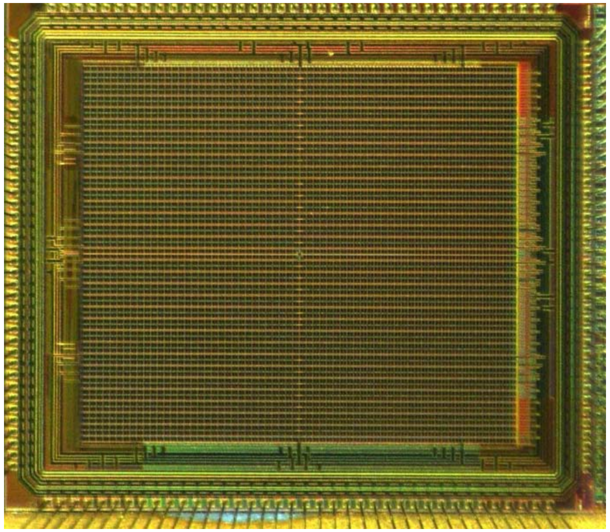




IEEE Nuclear Science Symposium / Medical Imaging Conference, Orlando, FL October 28, 2009

2

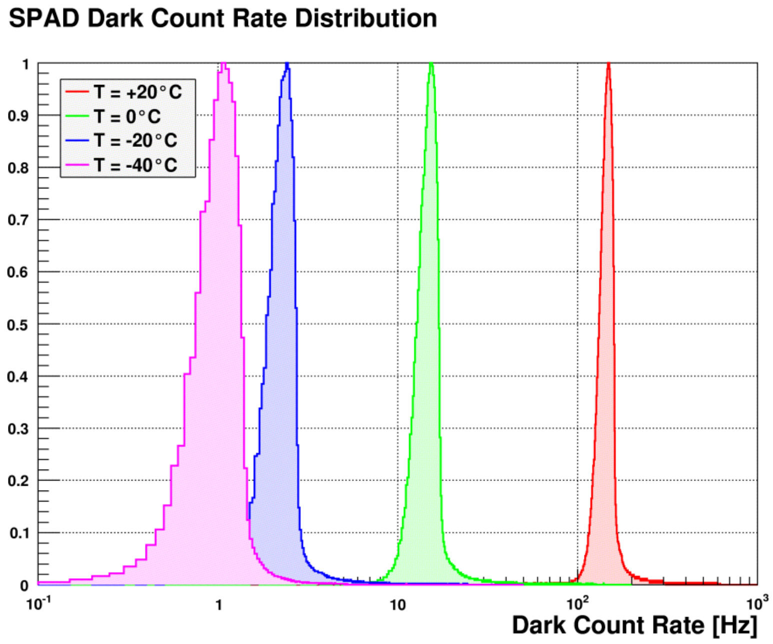
Digital SiPMs

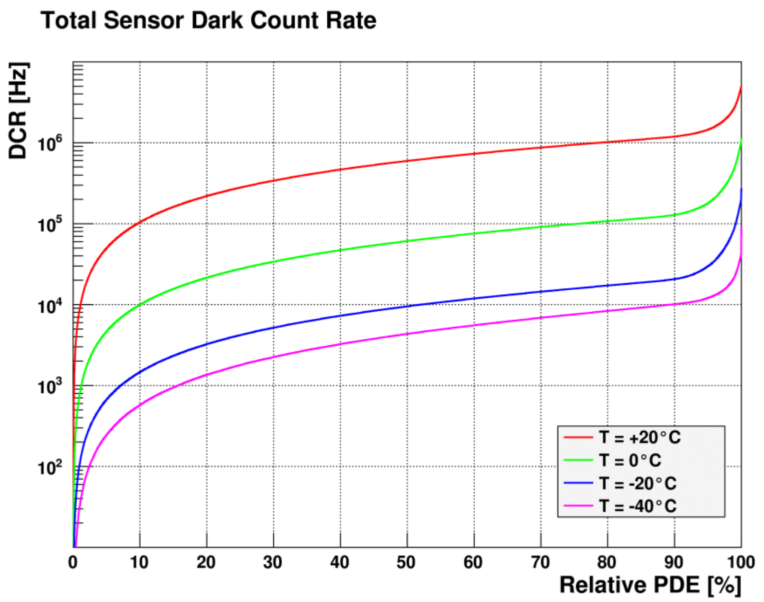


4 identical sub-pixels with 2047 microcells each

- Microcell size 30μmx52μm, 50% fill factor including electronics
- 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

Digital SiPMs





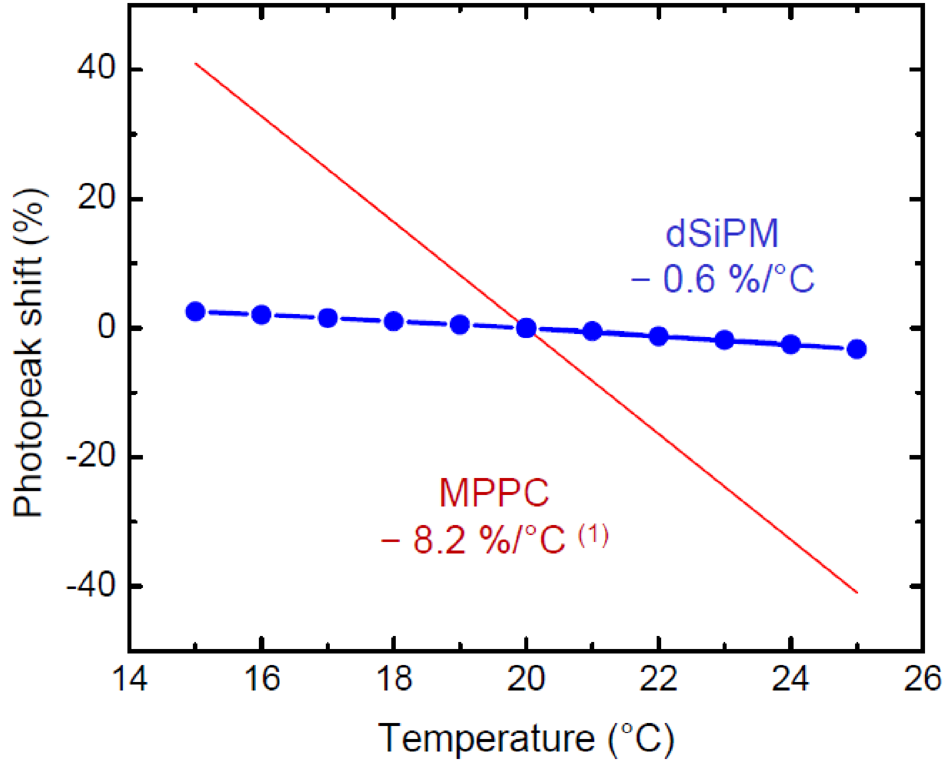
Digital SiPM – Dark Count Rate

- 90 – 95% good diodes (dark count rate close to average)
- Typical dark count rate at 20°C and 3.3V excess voltage: ~150Hz / diode
- Dark count rate drops to ~1-2Hz per diode at -40°C

Digital SiPMs

PHILIPS

Temperature Dependence



Temperature dependent light output of LYSO:

– 0.2 %/°C [2]
– 0.45 %/°C [3]

[1] K. Burr et al, Nuclear Science Symposium Conference Record, N18-2, 2007
[2] R. Mao et al, IEEE Transactions of Nuclear Science, vol. 55, 2008
[3] C. Kim, Nuclear Science Symposium Conference Record, M07-113, 2005

www.philips.com/digitalphotoncounting Philips Digital Photon Counting, October 27th, 2009

Digital SiPMs

PHILIPS

Summary

Digital SiPM operational

- Integrated electronics at cell level
- Integrated time-to-digital converter and photon counter
- Fully digital interface

Main benefits of the dSiPM

- Best possible timing due to first photon trigger
- Low dark count rate, high yield
- No additional ASICs needed
- Low sensitivity to temperature variations
- Low power consumption
- Easy system integration

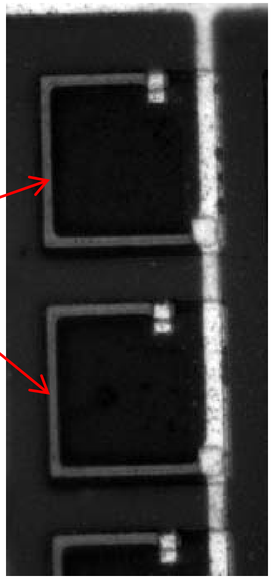
www.philips.com/digitalphotoncounting   Philips Digital Photon Counting, October 27th, 2009

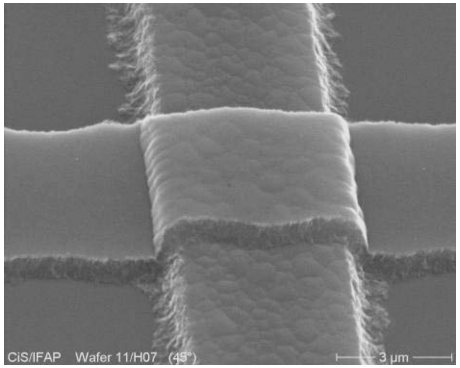
SiMPl concept

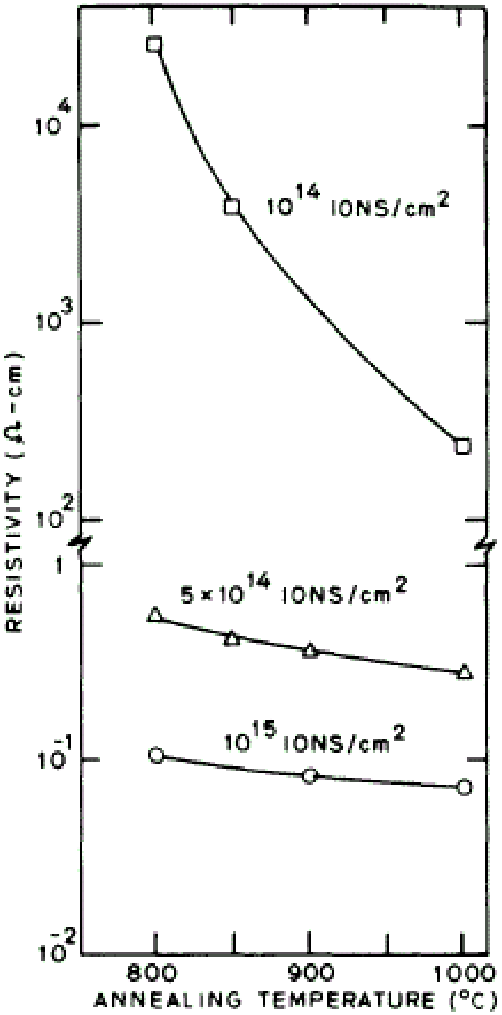
- Concept of Avalanche Diode Array with Bulk Integrated Quench Resistors for Single Photon Detection – SiPMl concept
- SiPMs developed @ MPI Semiconductor Laboratory Munich

Polysilicon Quench Resistors

polysilicon







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

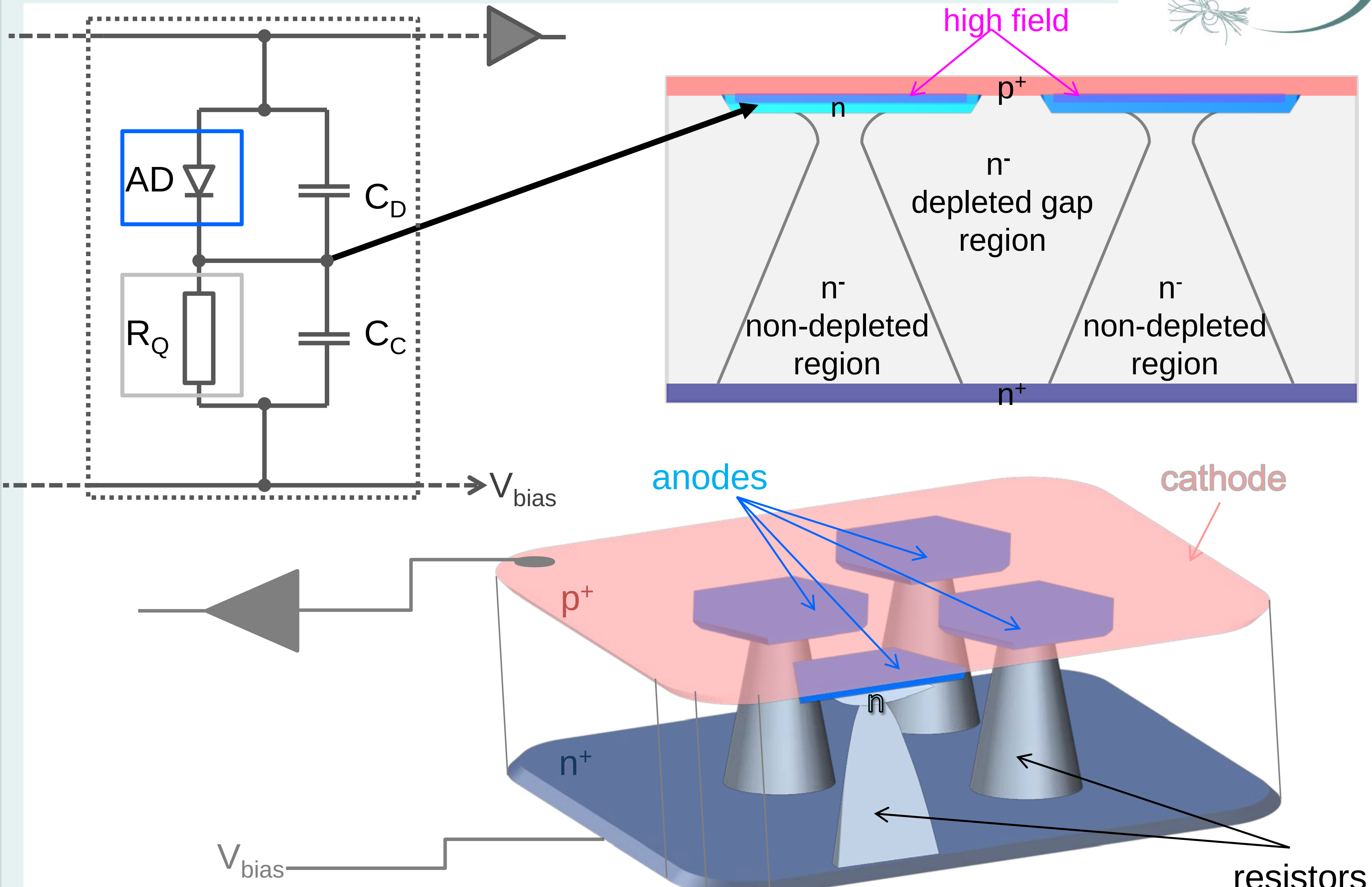
Complex production step

Critical resistance range

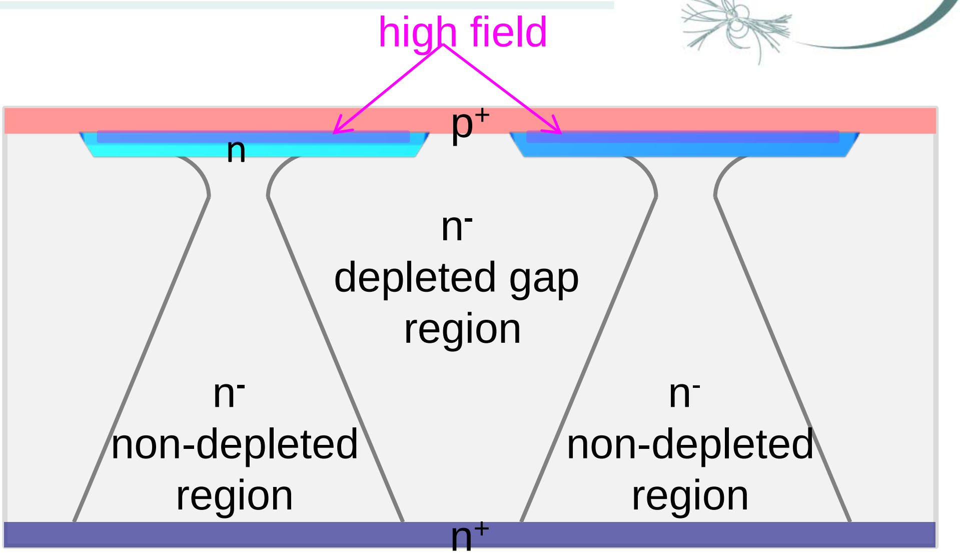
influenced by: grain size, dopant segregation in grain boundaries, carrier trapping, barrier height

Rather complex process step and an absorber for light

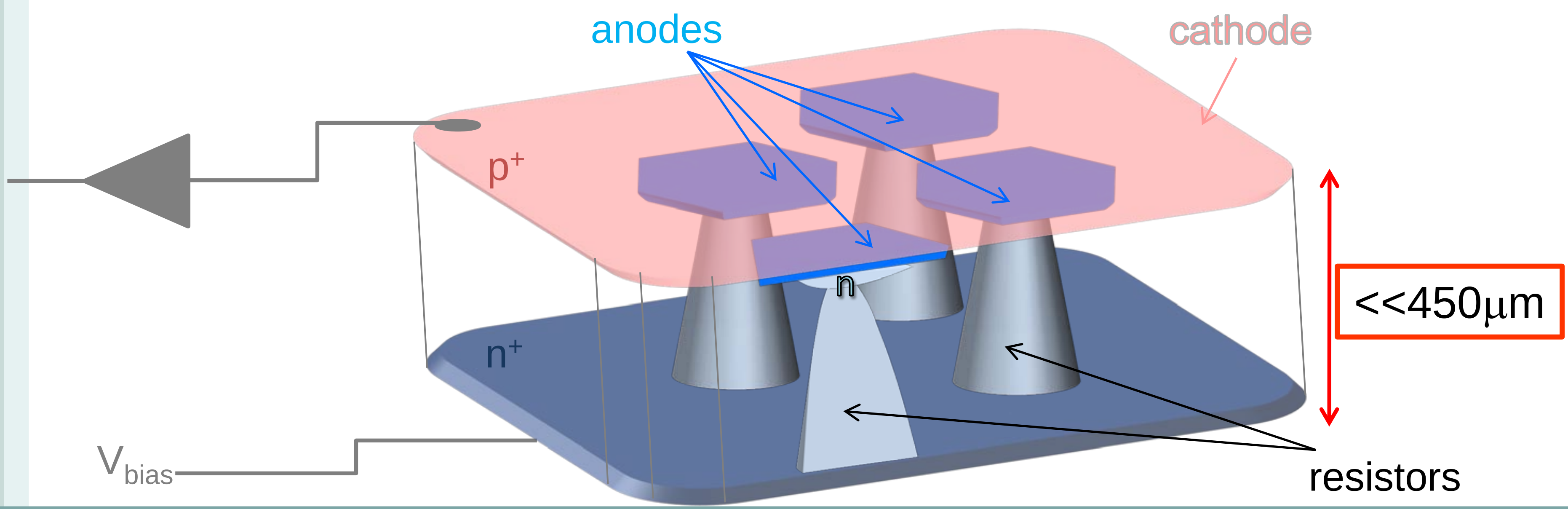
SiPM cell components → SiMPl approach



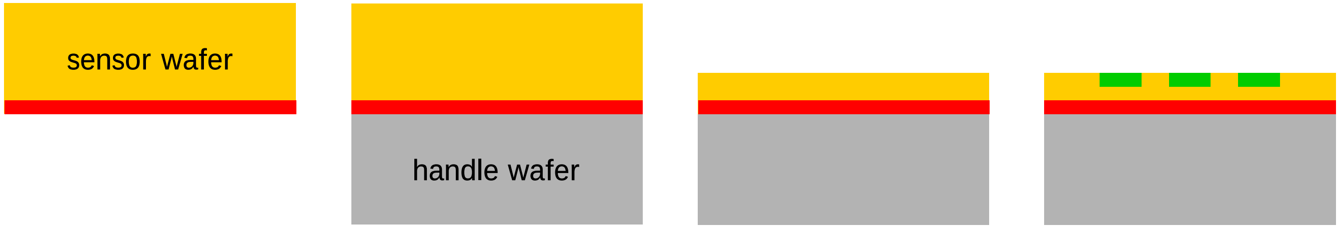
SiPM cell components → SiMPl approach



Resistor matching requires thin wafers !

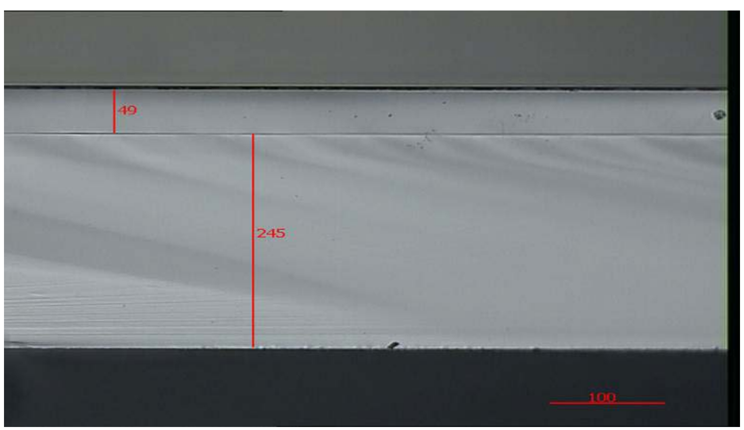


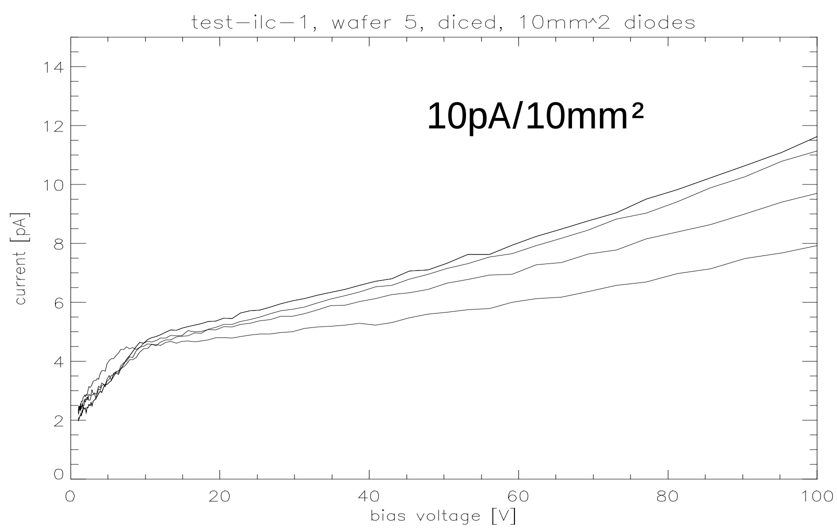
SOI wafers



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

Industrial partners → MPI Sem. Lab





Simulations

Not a simple resistor problem

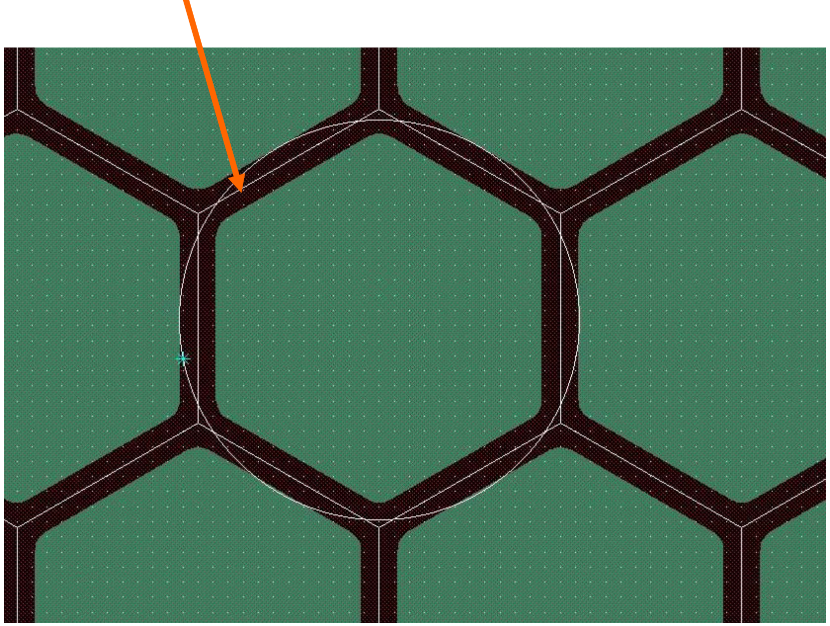
- bulk resistivity
- sensor thickness
- pitch size
- gap size

Influence

- carrier diffusion from top and bottom layer into the resistor bulk
- sideward depletion

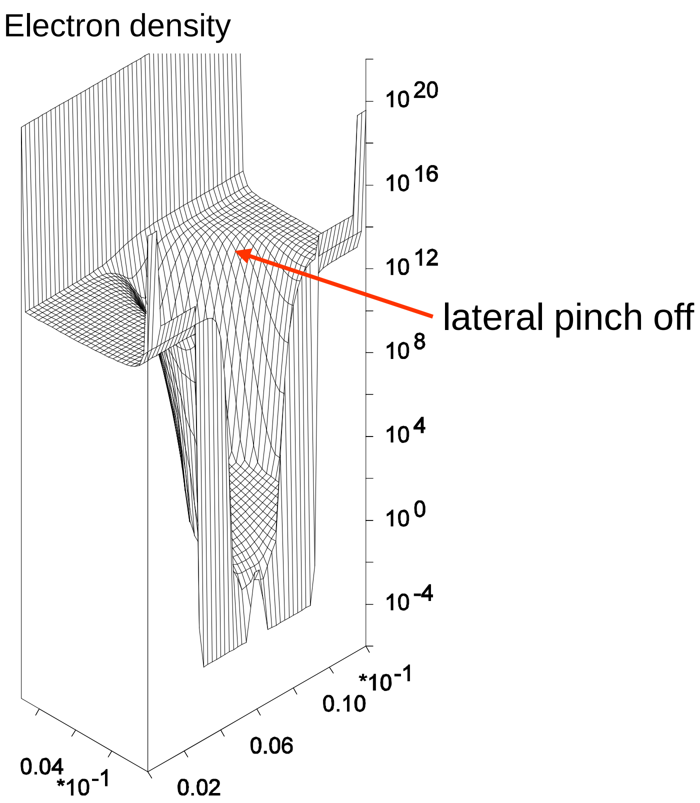
➔Extended device simulations performed and showed promising results for both small (25µm) and big (100µm) cells.

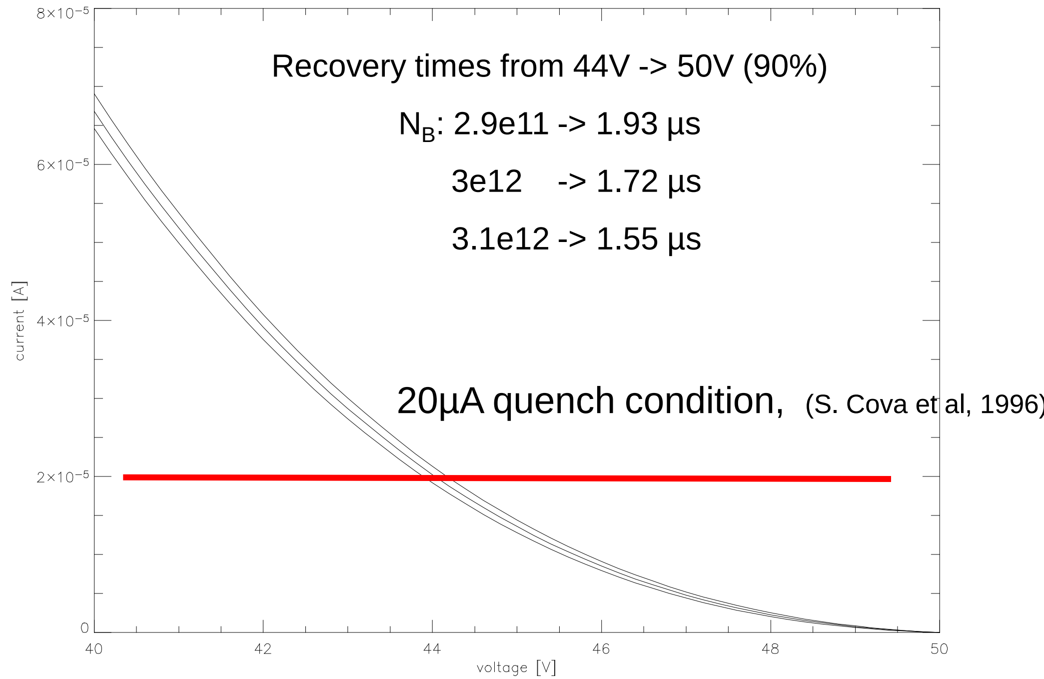
cylindrical approximation of hexagons for quasi 3d simulation



Ninkovic et al., NIM A, 610, Issue 1

Quench resistor – parasitic JFET behavior





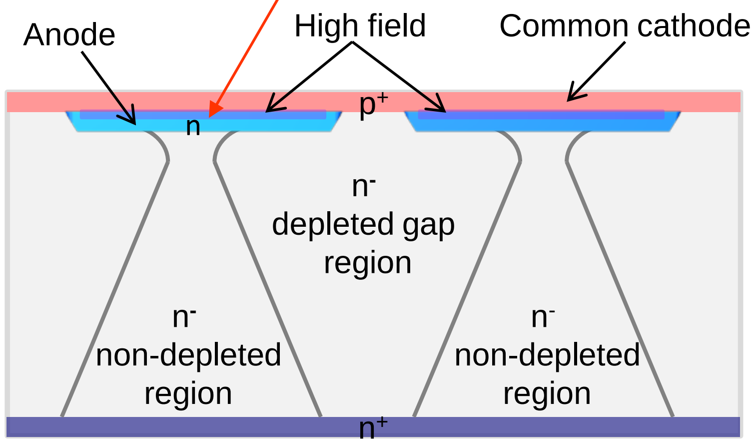
Recovery times by a factor 3 - 4 longer compared to optimally adjusted polysilicon resistor

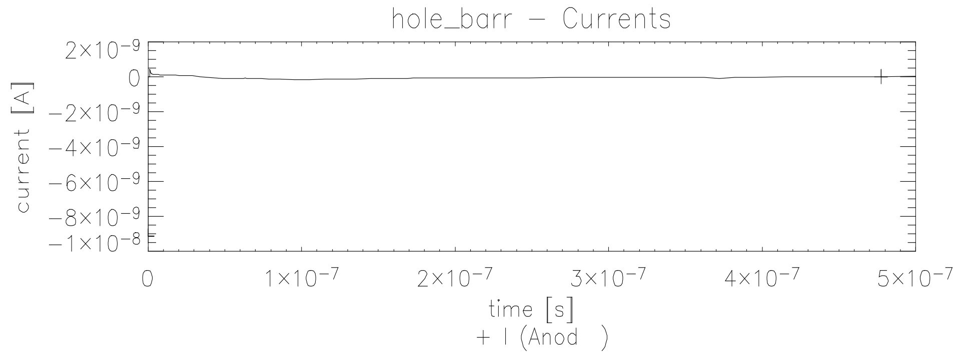
Cross talk – bulk contribution

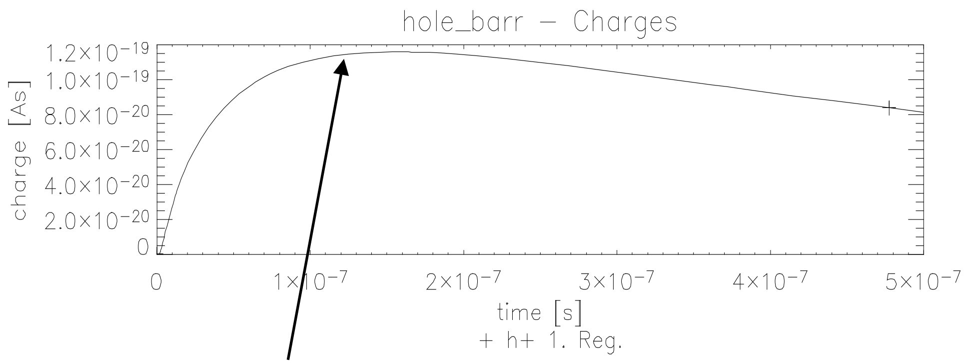
device simulation

generation of 1000e/h pairs in the bulk

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







Less than 1 hole in the high field region

PDE estimation

Hexagonal design pitch 150µm(50µm), isolation gap 40µm(15µm) ➔
geomatrical fill factor 75%

Optical entrance window: 90% @400nm

Geiger efficiency : 90%

➔ PDE: 61% (depends strongly on gap size)

PDE estimation

Hexagonal design pitch 150µm, isolation gap 20µm ➔ geomatrical fill factor 87%

Optical entrance window: 90% @400nm

Geiger efficiency : 90%

➔ PDE: 70% (depends strongly on gap size)

Remarks on radiation hardness

Bulk damage -> increase of darkrate, and afterpulsing
no difference to classical devices

Surface damage at Si/SiO_2 interface
can become significantly already in the krad range
- fixed positive oxide charge generation
  -> flatband voltage shift, higher fields, edge breakdown
- generation of interface states (breaking of hydrogen bonds)
  -> increased leakage current, amphoteric traps

Avoid depleted interfaces

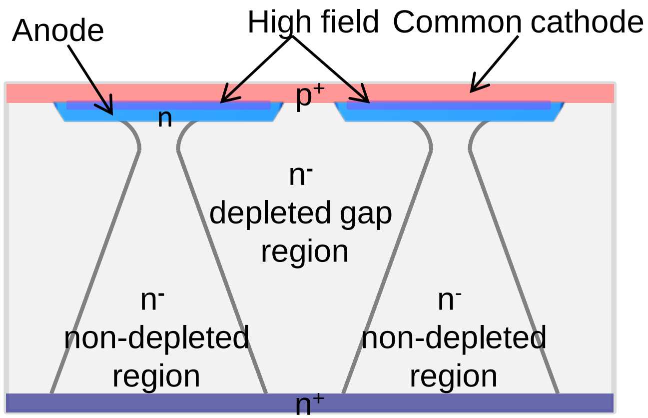
Free carriers (high doping densitys) neutralize radiation induced oxide charges, and occupies interface states preventing them from SRH generation

Ideal situation:

Highly doped surface within the array

no edges -> no lateral high field regions

(At the edge of the matrice is space enough for guard structures)



Advantages and Disadvantages

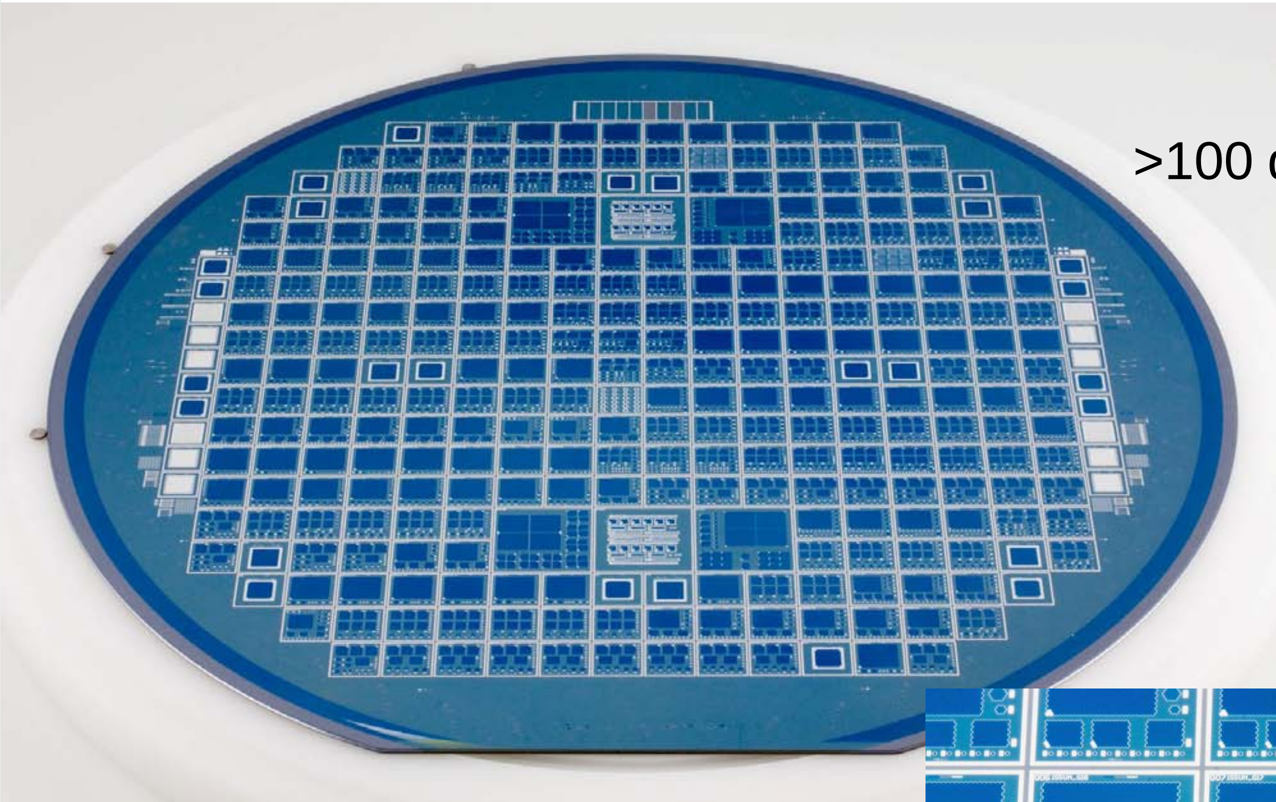
Advantages:

- 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
- hopefully better radiation hardness
- No Al lines needed for biasing of the cells and therefore smaller parasitic capacitance

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

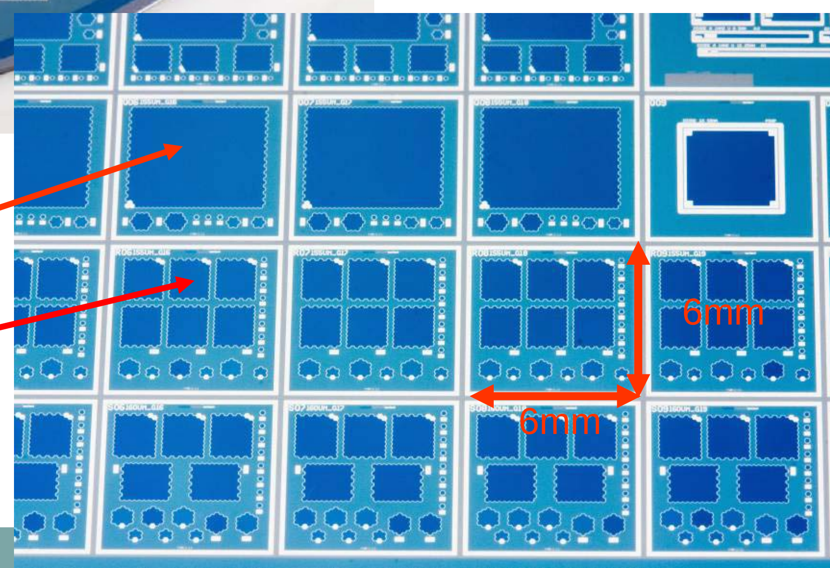
Prototype production



>100 different geometrical combinations

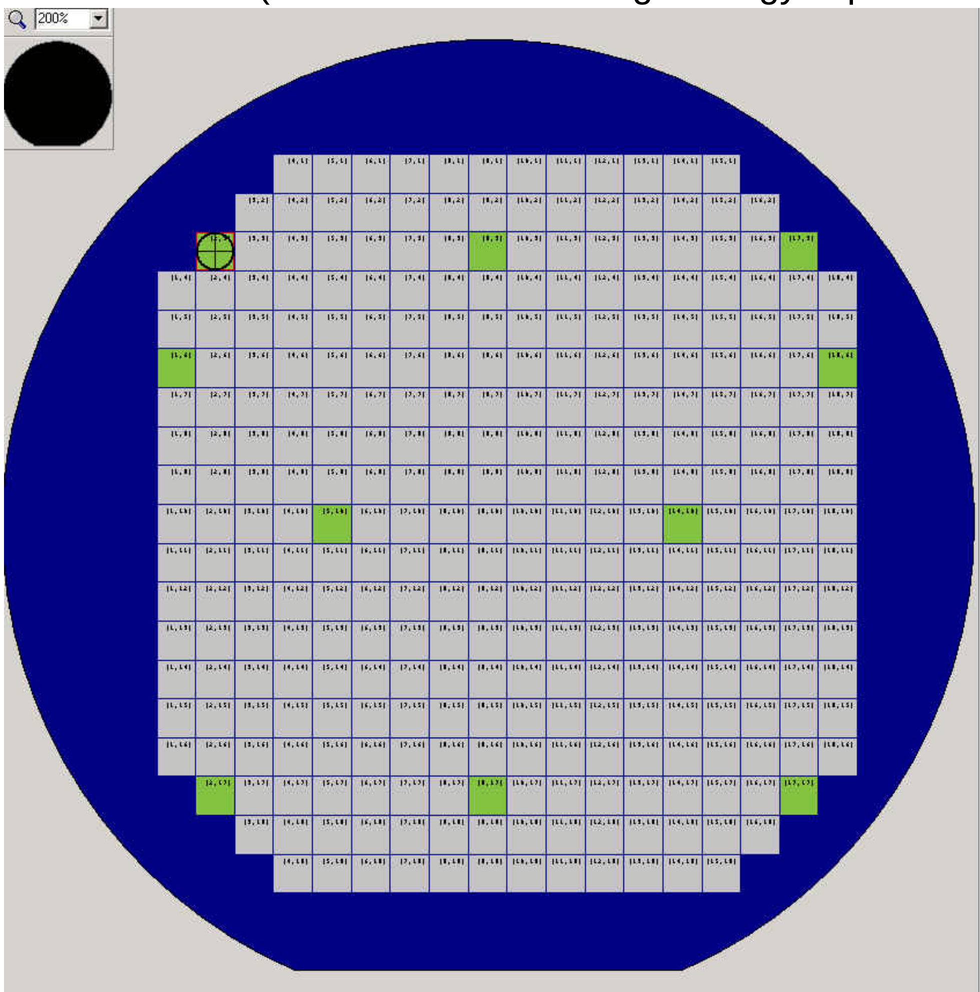
30x30 arrays

10x10 arrays



Bulk doping

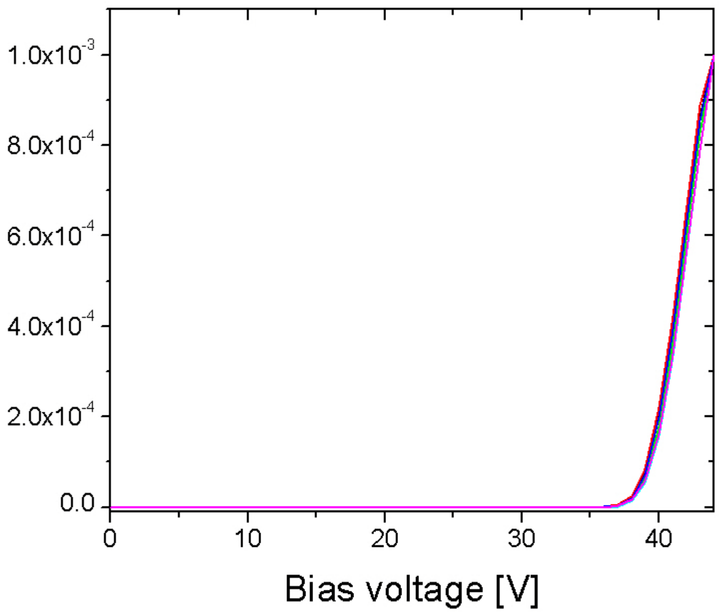
- Critical parameter
- Bulk doping variation of the top wafers measured on 10 diodes*/wafer (CV)
  (*test diodes without high energy implantation)

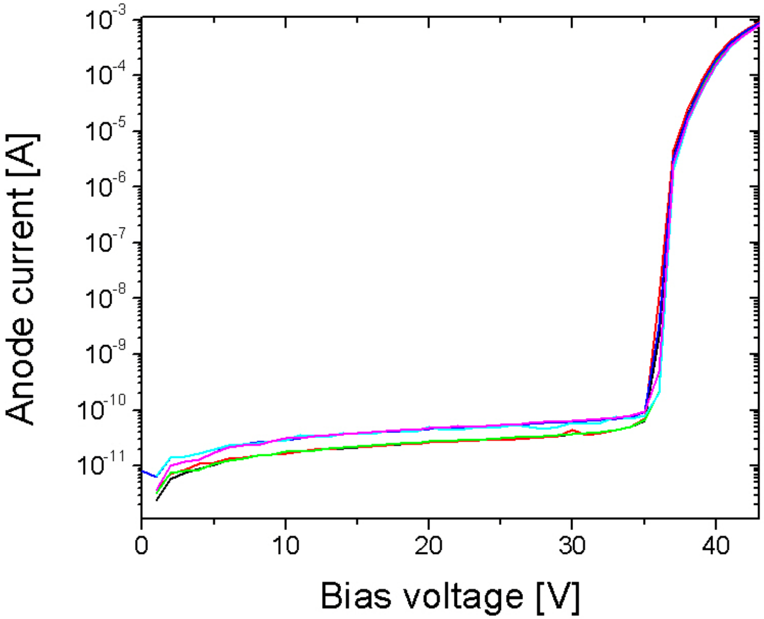


Standard deviation
1—2% of the mean value
over the wafer

Static wafer measurements

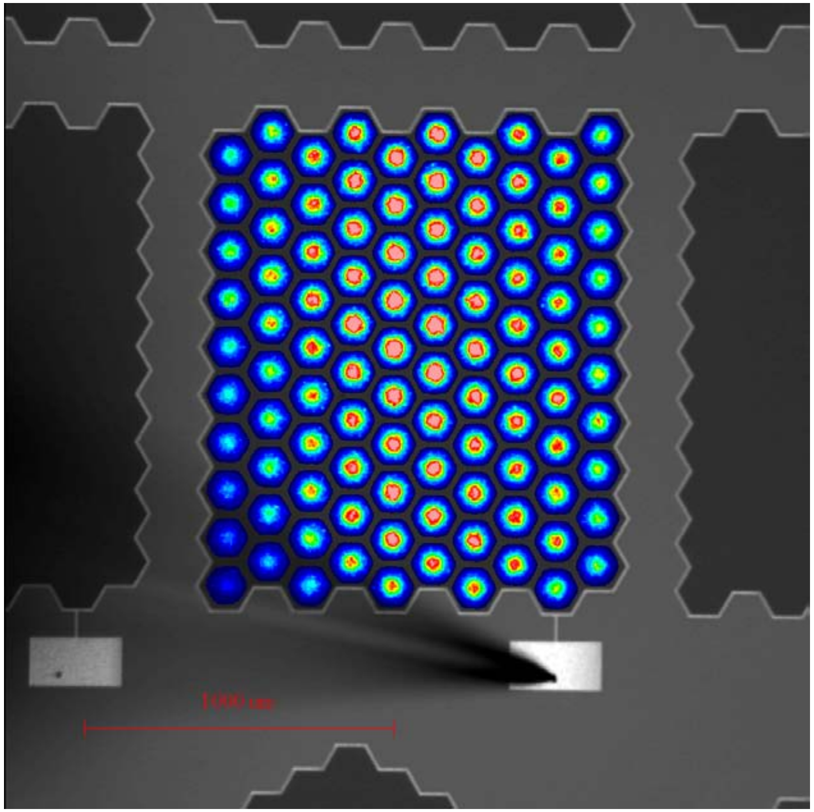
Homogeneous break down voltage

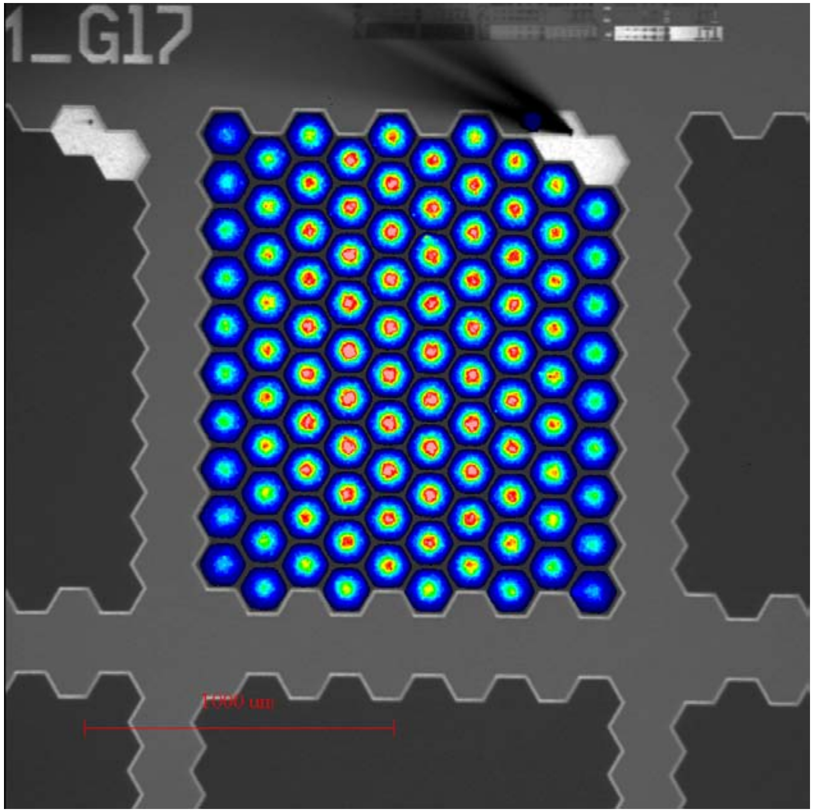




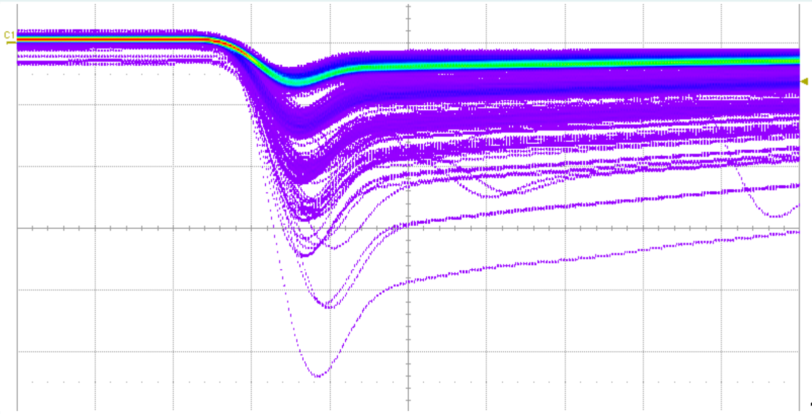
6 (10x10) arrays placed over 6mm distance

Photoemission images



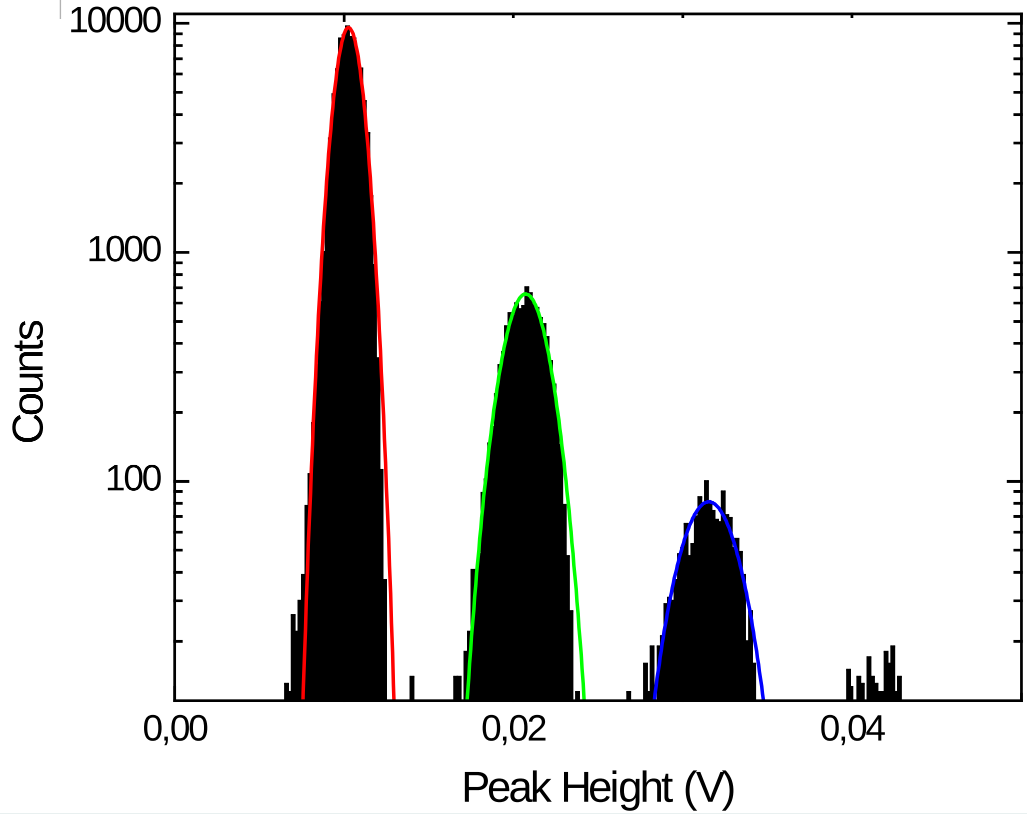


Dynamic measurements

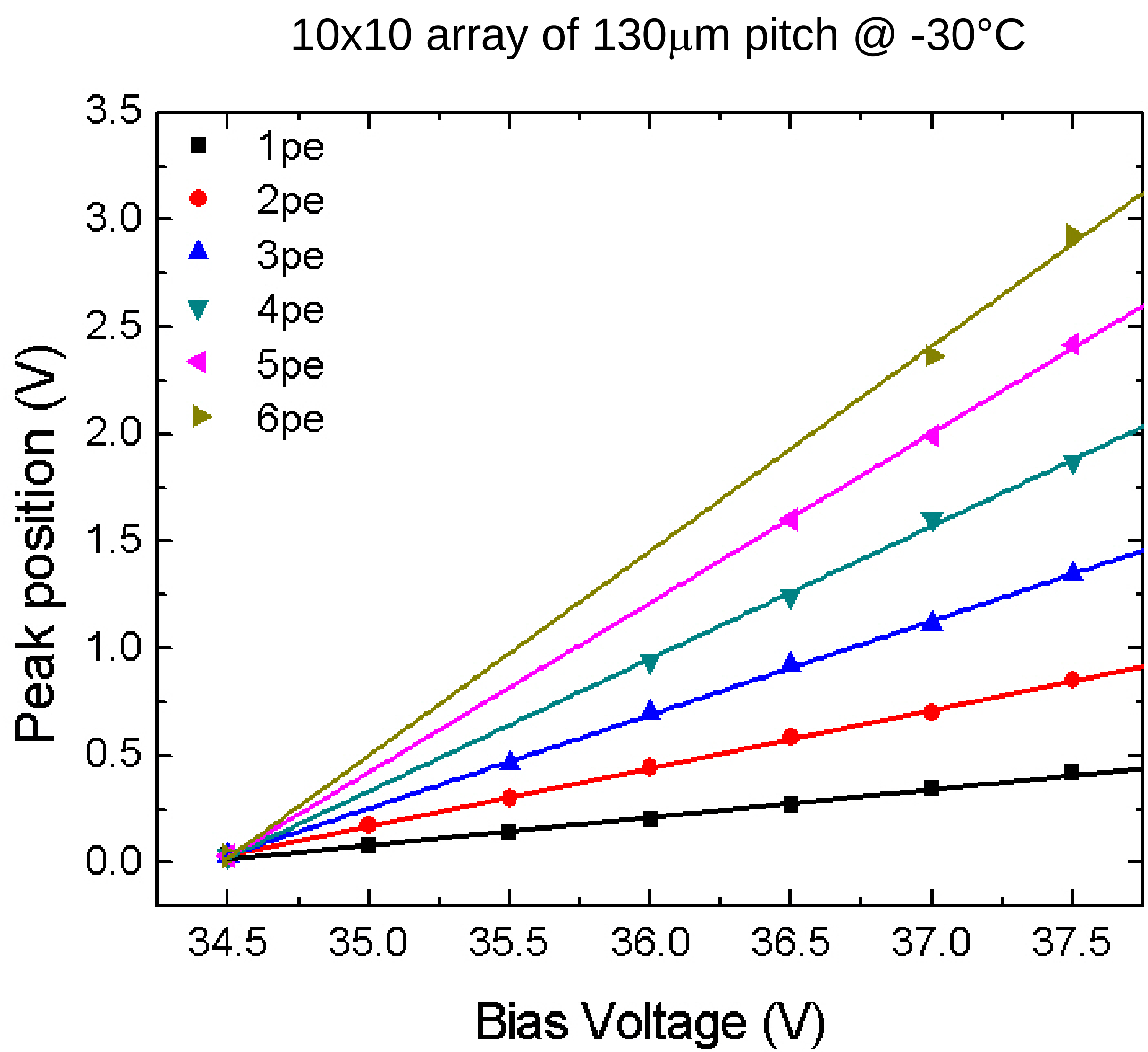


20mV/div and 10ns/div

10x10 array of 135μm pitch @ -20°C



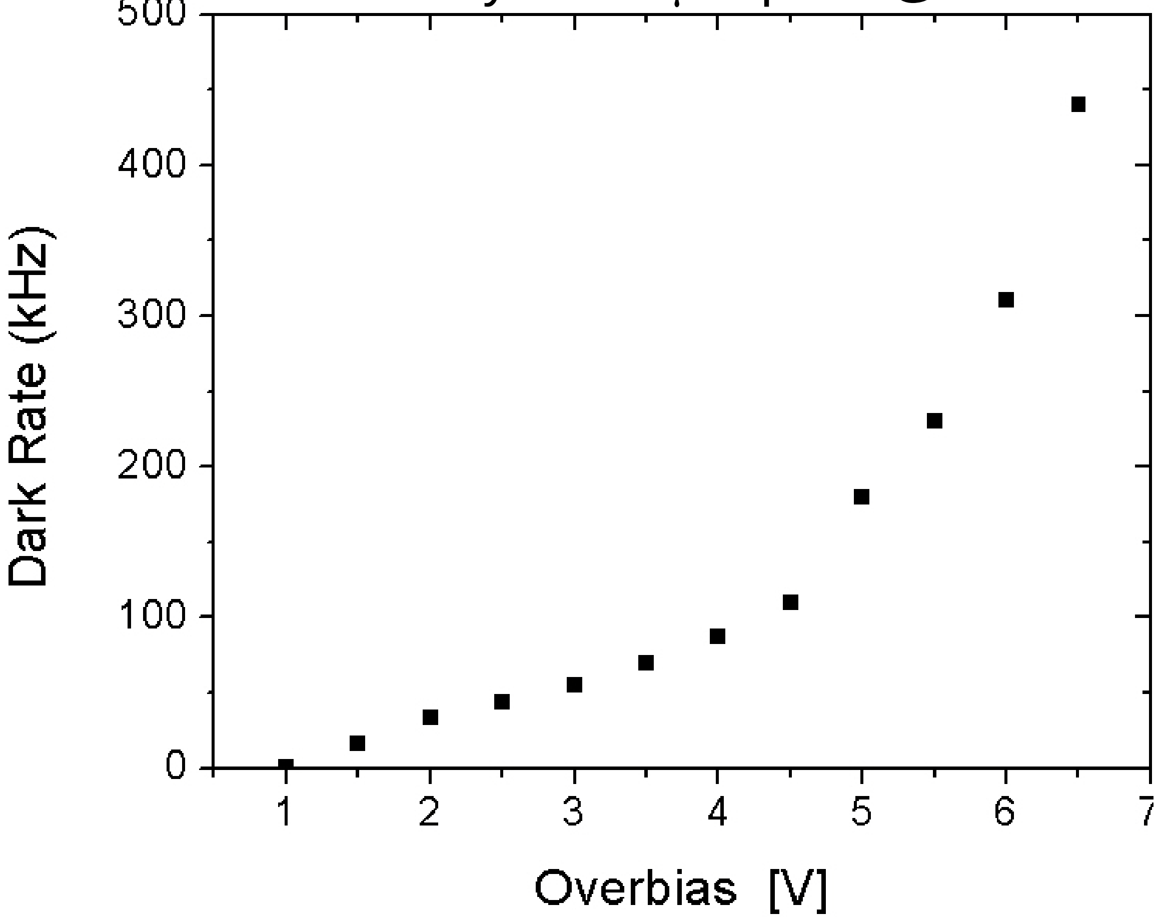
Gain linearity



Dark rate

Due to the non-optimized process sequence
~10MHz/1mm^2 @300K for 4V overbias

10x10array of 135μm pitch @ 227K

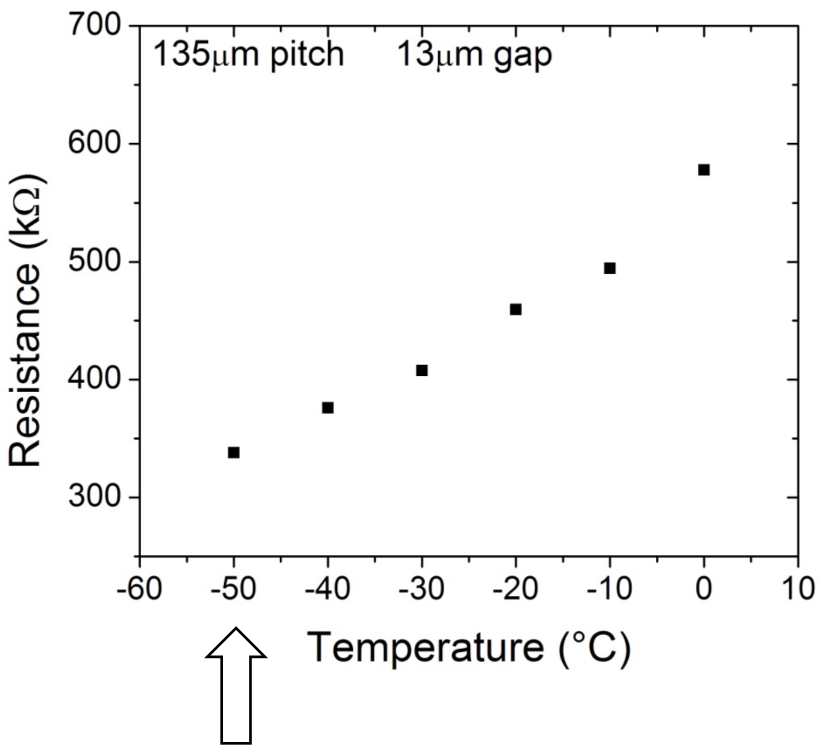


Normal operation up to 4.5V overbias @227K

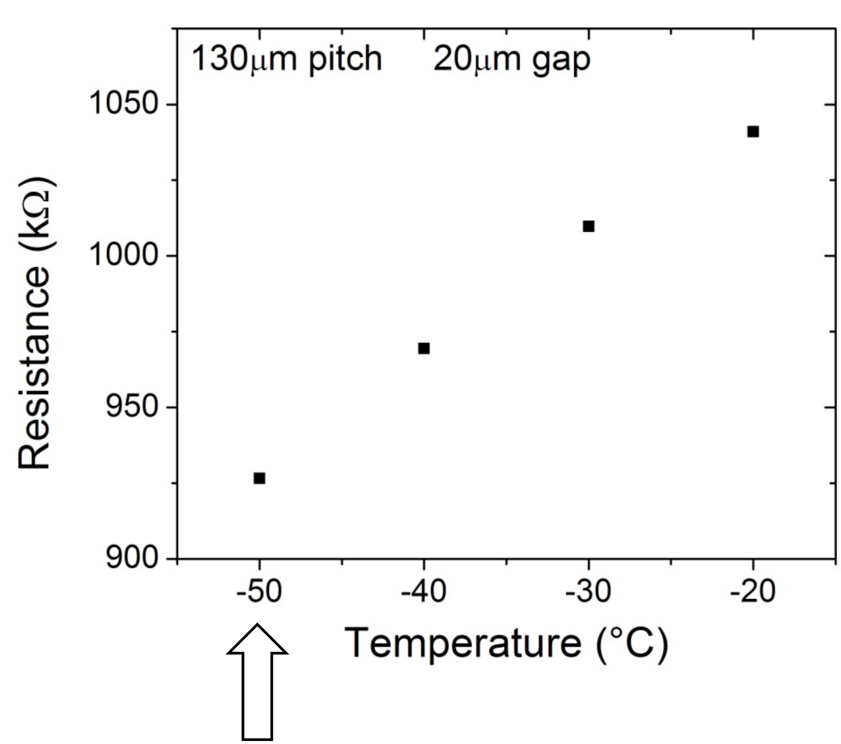
@ΔV > 4.5V non quench condition due to the small resistor value

Resistor behavior

Resistor value designed for the room temperature operation



350kΩ @ -50°C



920kΩ @ -50°C

Summary

Conventional SiPMs:

- Are already an alternative to PMTs in many applications.
  T2K, the Tokai-to-Kamioka second generation long-baseline neutrino oscillation experiment uses 60000 MPPCs.
- Many of the parameters are already in the mature state.
- Radiation tolerance still has to be improved for many applications.
- Front side contact is not desirable for coupling to scintillators.

Digital SiPMs :

- demonstrator implemented in conventional CMOS process
- Flexible architecture allows to optimize sensor performance for application
- Micro-lenses could be used to effectively increase fill factor
- Low sensitivity to temperature variations
- Fault-tolerant, high yield and low power design
- Integrated data processing will enable future detector-on-chip concepts

Summary

SiMPl concept :

- Required flexibility for quench resistor adjustment comes with wafer bonding technique (for small pixels an epitaxial layer is also suitable)
- No polysilicon resistors, contacts and metal necessary at the entrance window
- Geometrical fill factor is given by the need of cross talk suppression only
- Very simple process, relaxed lithography requirements

Prototype production finished – quenching works, first measurements very promising

Thanks !