New developments of SiPM for visible and near UV light at FBK

Alessandro Ferri

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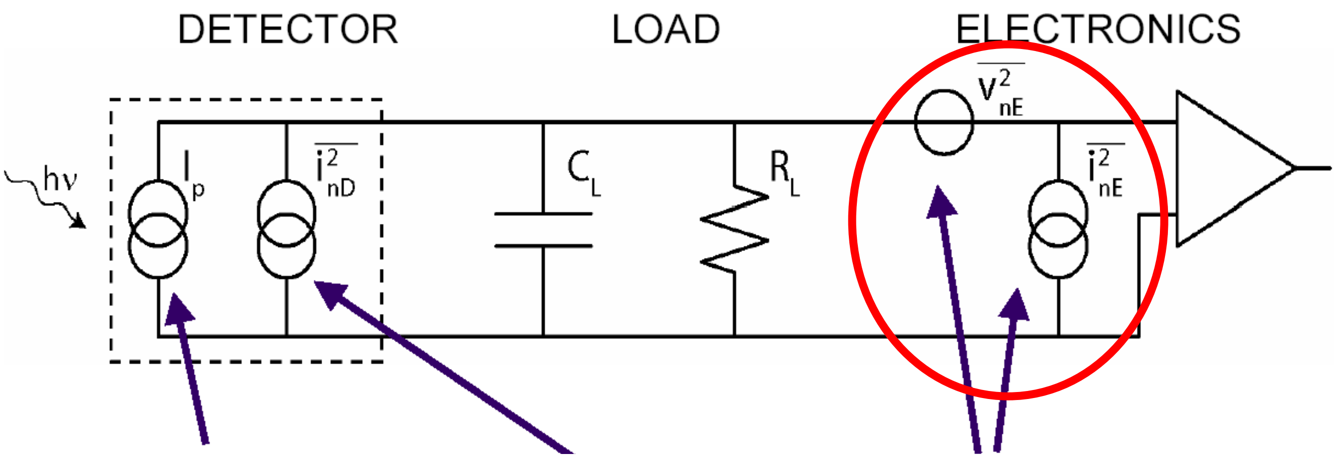
Internal gain

The problem: detection of extremely low intensity light down to the single photon



Current signal: 1 pair/photon

Detector noise: fluctuation of leakage current

Electronics noise: shot + thermal noise

Need of a detector with internal amplification to reduce the impact of electronic noise.

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PMT

Today, it is the most used sensor
for low-level light detection.

Features:

- high gain
- single photon sensitivity
- low noise
- large sensitive area
- high frequency response
- good QE from UV to nearIR
- low cost

Issues:

- bulky and fragile
- influenced by magnetic fields
- damaged by high-level light

Applications:

physics experiments astronomy
medicine biology material analysis

Difficult to compete with this technology!!

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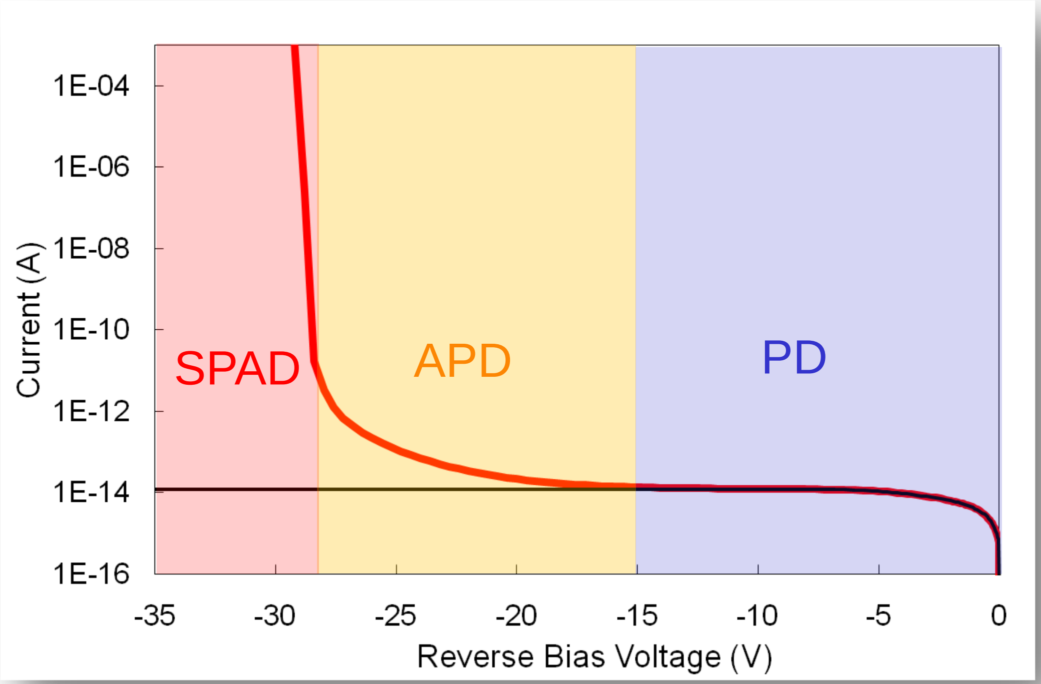
Solid-state technology: SPAD

Devices with internal gain based on carrier multiplication via impact ionization



AVALANCHE PHOTODIODE
- Gain ~100
- Timing ~ ns/ 10ph.e.
- Bias voltage ~500V
- Sensitivity ~10 ph. e.
- QE ~ high in all spectrum

SPAD / Geiger-mode APD
- Gain ~10^6
- Timing ~ 10ps /10ph.e.
- Bias voltage <100V
- Sensitivity ~1 ph. e.
- QE ~ medium

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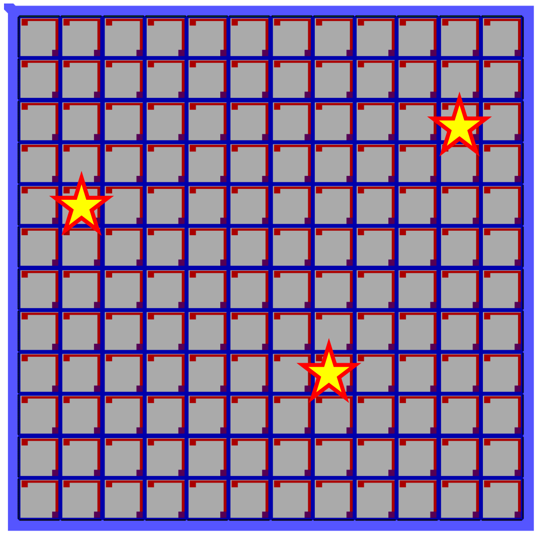
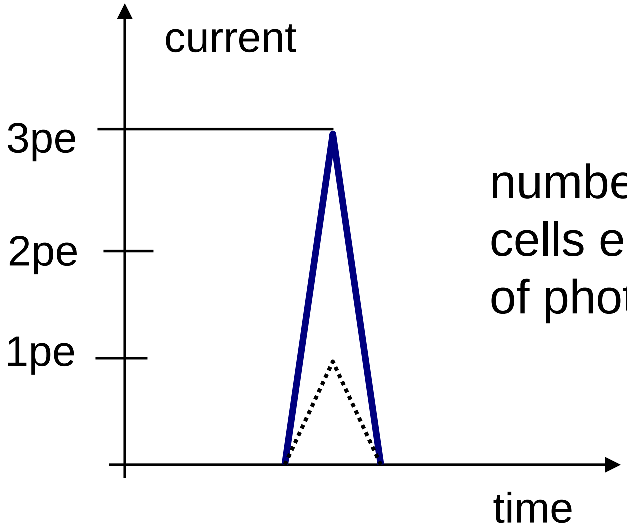
SPAD → SiPM

When the application requires (also) the estimation of the number of photons in a short light flash the SPAD is not enough.

SiPM: array of SPADs tightly packed and connected in parallel.
(first proposed by Golovin and Sadygov in the ’90s)





number of activated cells equal to number of photons (PDE=1)

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SPAD → SiPM

The transition from SPAD to SiPMs is not just design.

New issues are:

• a third factor enters in the photo-detection efficiency: the **fill factor** that for small cell size can be quite low

• how to control the **dark rate** because
  - limited space for gettering techniques
  - high probability to include noisy cells in a device

• optical cross-talk

• yield, uniformity

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Main parameters

- Gain
  - Number of electrons per detected photon
- Primary Noise
  - Thermally generated events
- Correlated Noise
  - after-pulse, optical cross-talk
- Photo-detection efficiency (PDE)
  - Number of detected photons over total incident photons
- Dynamic range
  - Linearity of response
- Time resolution
  - Precision in the determination of photon arrival time

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Wish list

Parameter	Wish	Comment
Gain	High	Usually not a problem (~1e6)
Primary Noise	Low	Hard to reach PMT levels!!
Correlated Noise	Low	Good options to reduce it
PDE	High	>50% feasible, wavelength?
Dynamic range	High	Up to 5-10000/mm2
Time resolution	Low	~100ps FWHM

- Today, we do not find a device with all the parameters optimized.
  Trade-off among them (e.g. PDE *vs* dynamic range)!!

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Other important features

(at the system level)

- Breakdown voltage uniformity
- Temperature stability
- Packaging type (dead border region, TSV)
- **COST!!**

Solutions to improve performance must be cost-effective.

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FBK experience

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SiPM R&D

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- **Process/Device Simulation – Layout**

  1/2 people

- **Process development and implementation**

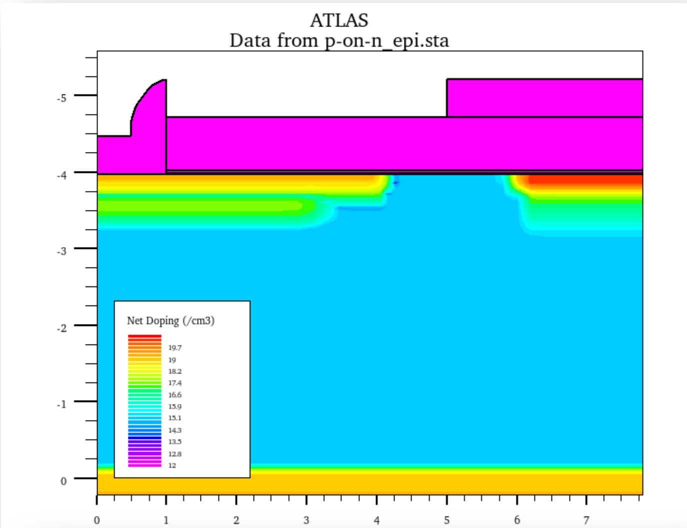
  2 people

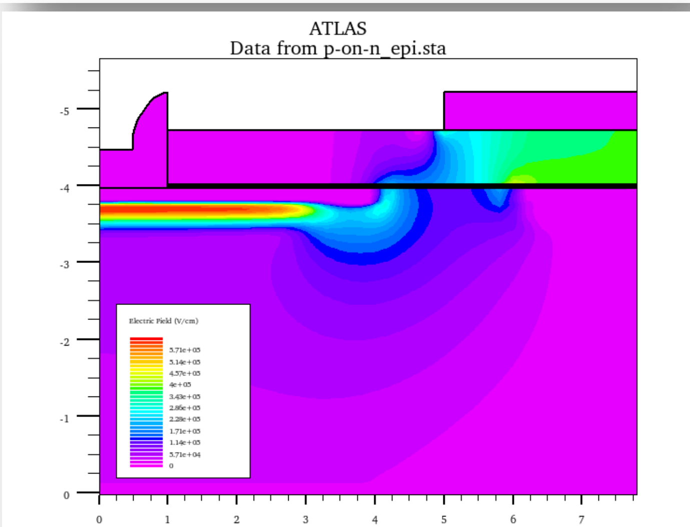
- **Device characterization**

  4 people

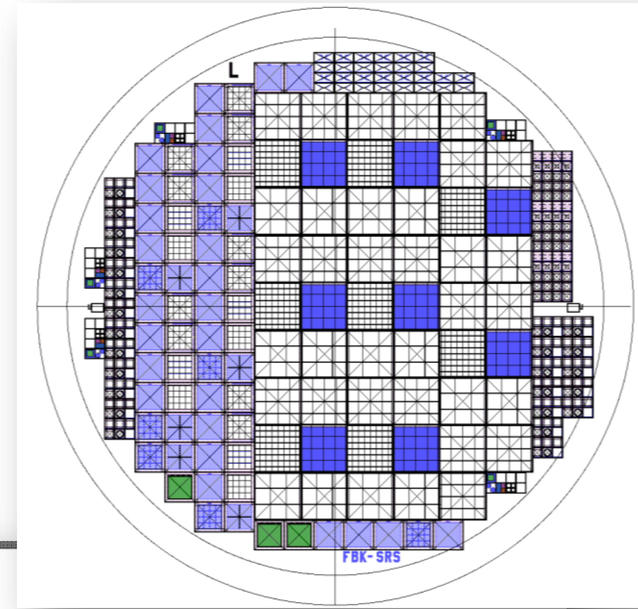
Simulation & Layout

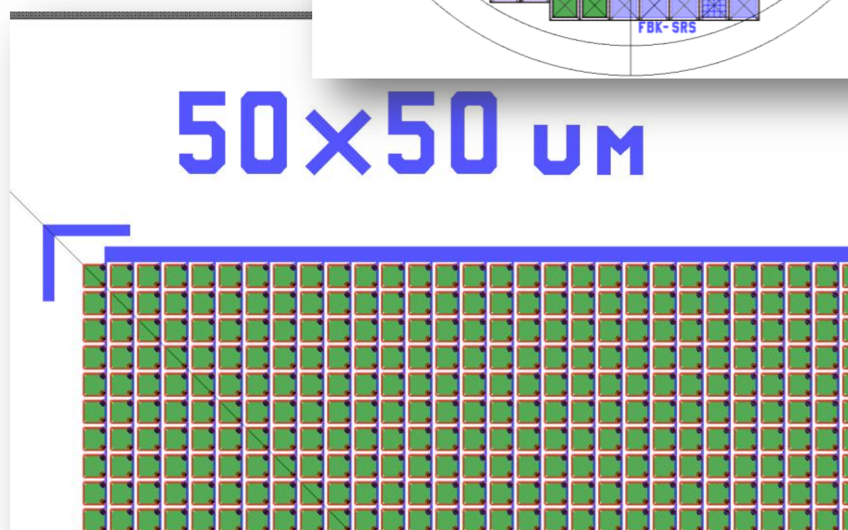
TCAD for process and device





CAD for device design





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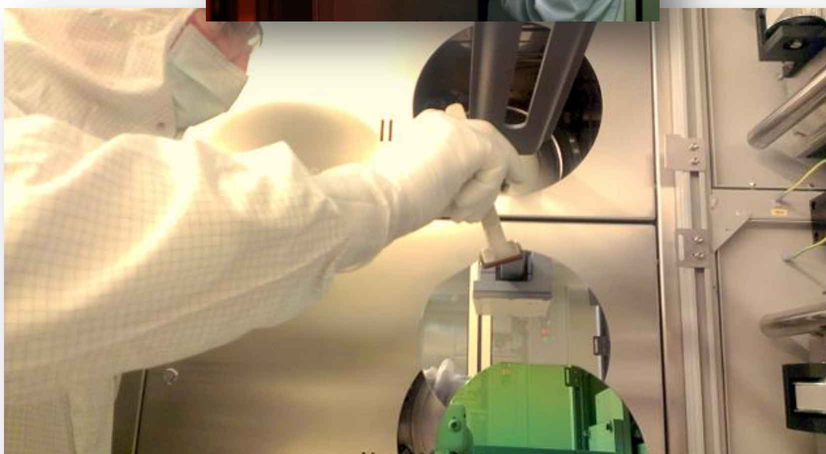
FBK Technolgy


Clean room «Detectors»:

- 500m^2
- 6'' wafers
- Equipped with:
  - ion implanter
  - 8 furnaces
  - wet etching
  - dry etching
  - lithography
    - stepper
    - mask aligner
  - Deep RIE
  - Plasma-enhanced CVD
  - sputtering

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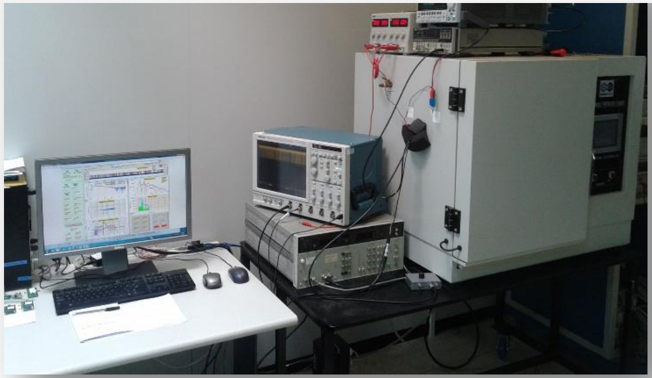
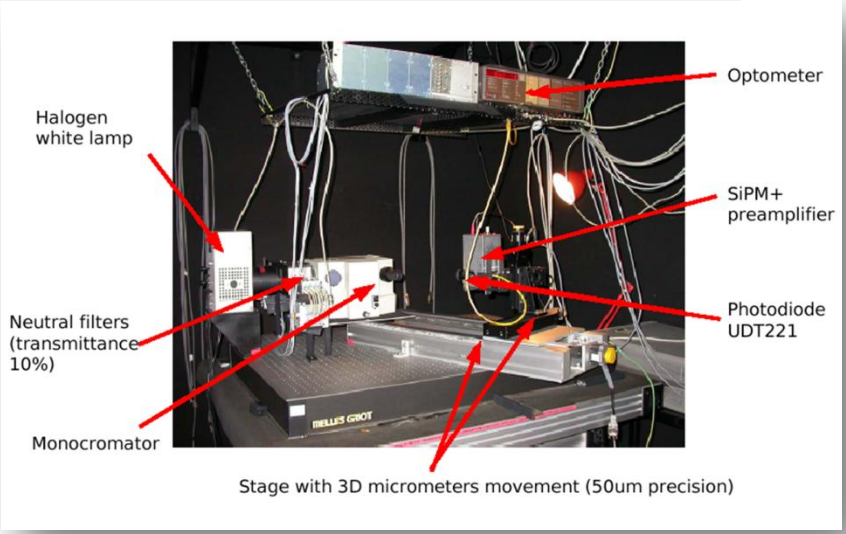
SiPM Characterization

1. IV measurement

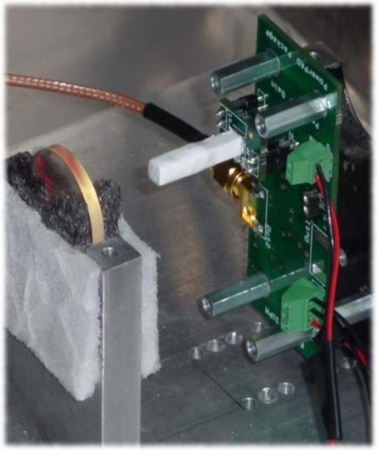
2. Dark characterization



3. Optical characterization



4. Functional charact.



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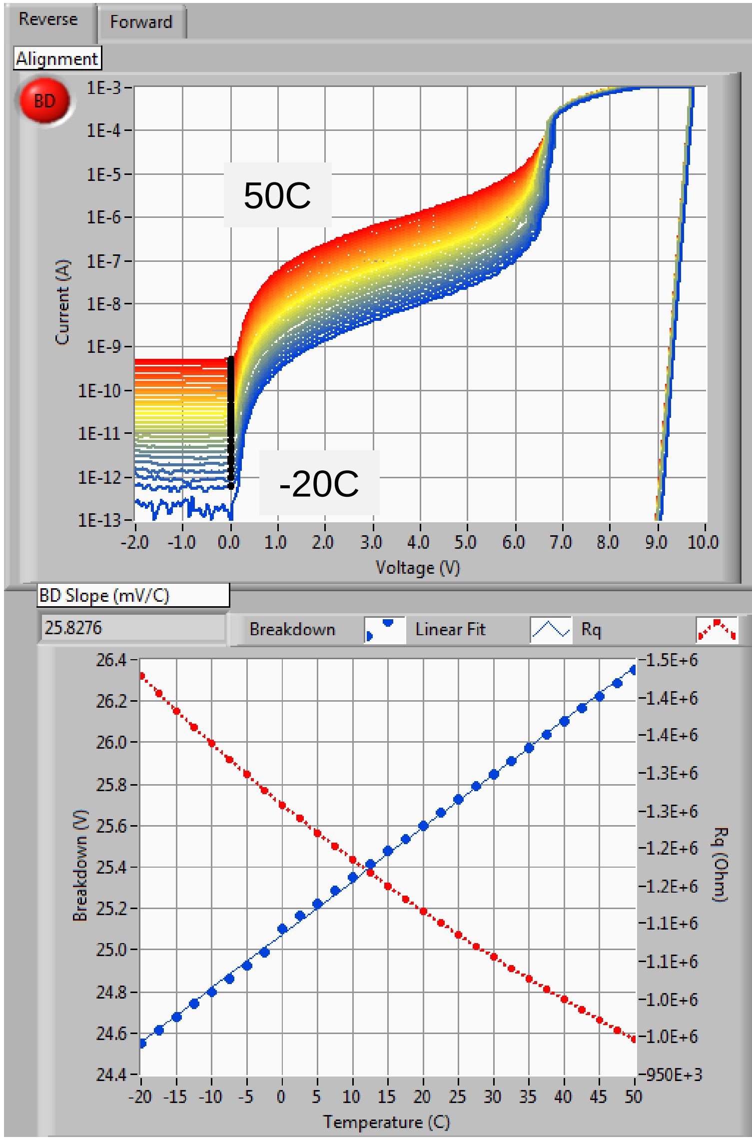
SiPM Characterization



IV measurement

Reverse IV

Reverse IV:
→ BD voltage vs T

Forward IV:
→ R_Q vs T

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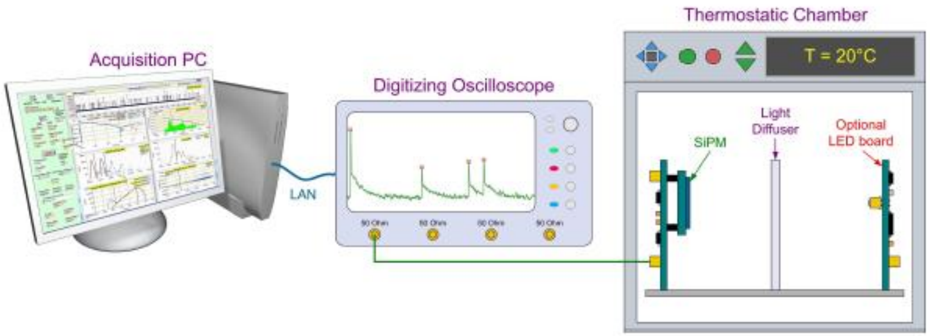
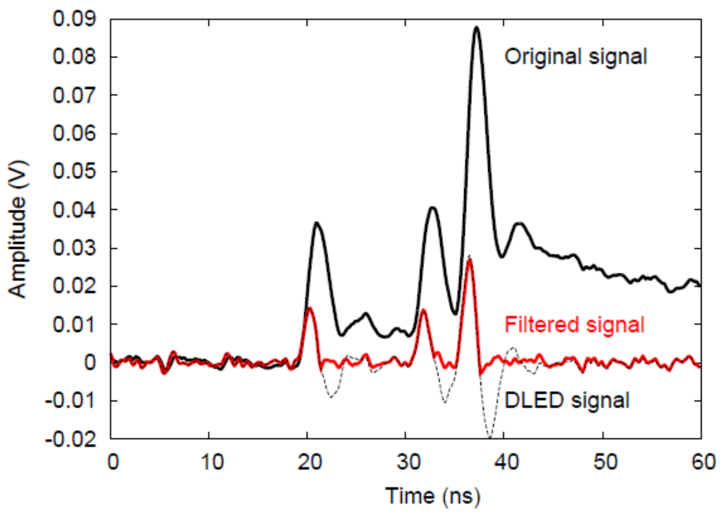
Dark measurement



We acquire ms-long waveforms

Signal filtered to reduce its length



→ time delay array
→ amplitude array

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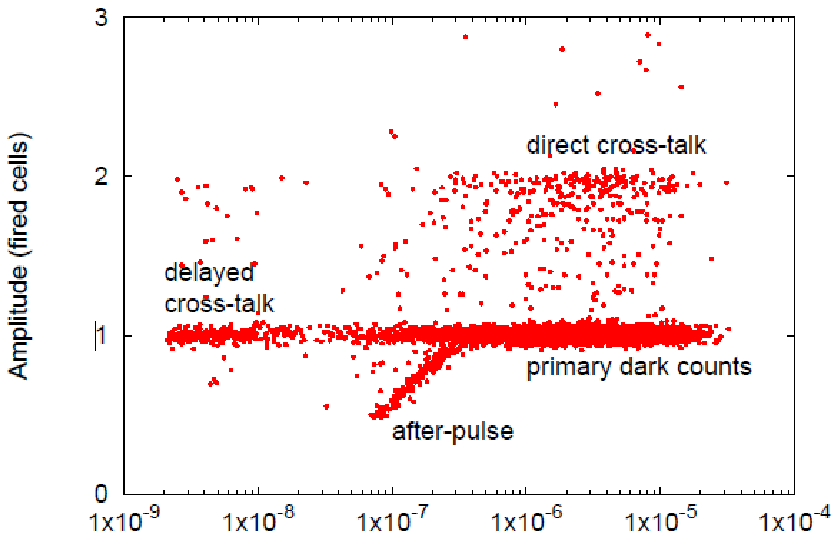
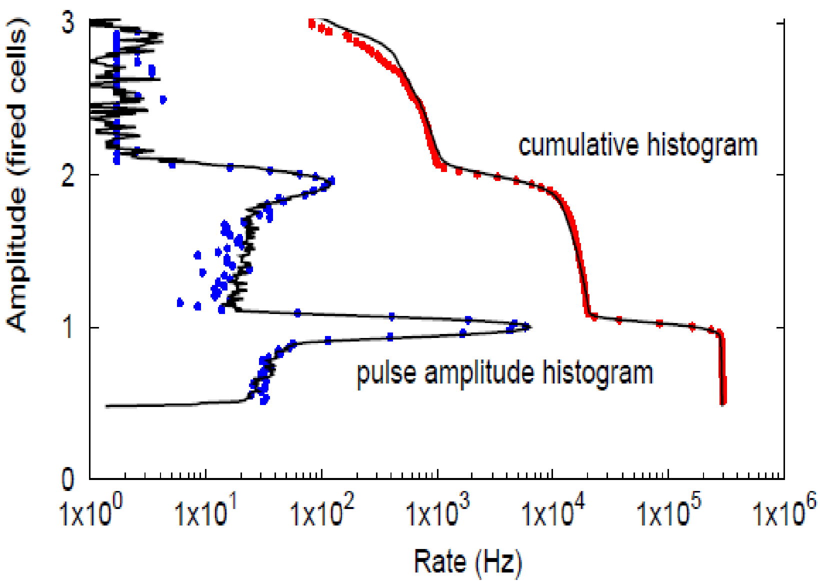
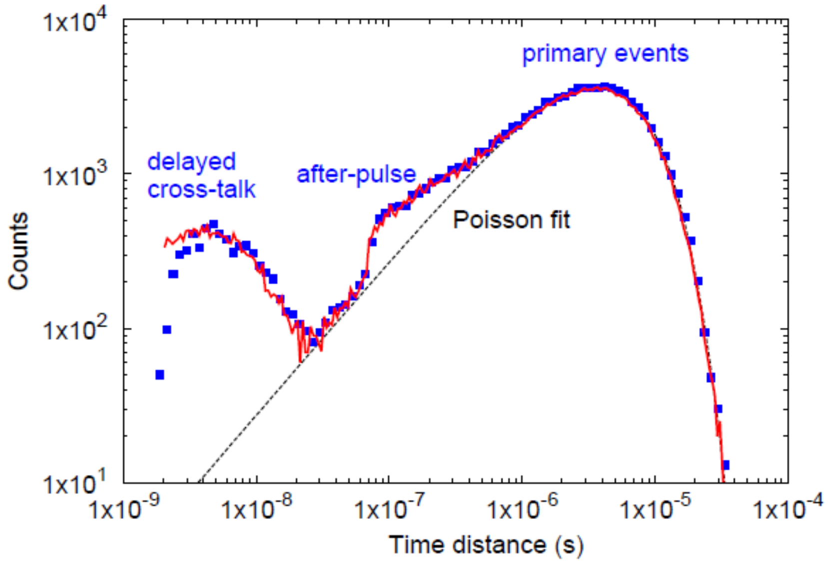
Dark measurement







→ primary dark rate (DCR)
→ direct cross-talk
→ delayed correlated components

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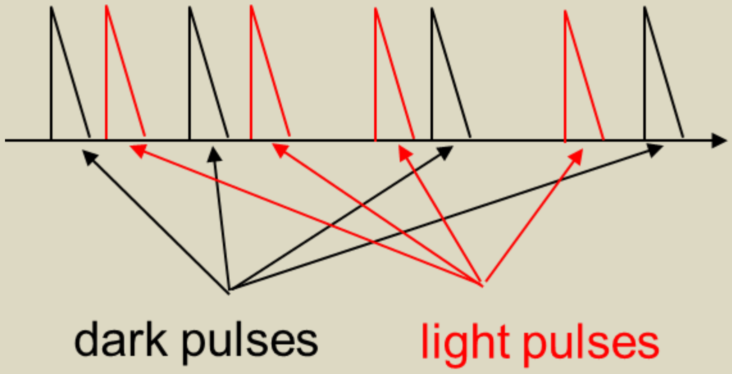
Optical characterization

Usually done on single-cell SiPM:
- less dark noise
- no optical cross-talk

photon counting under continous illumination



Light count rate = Poisson fit
(same program used in dark)

Light intensity determined with calibrated photodiode

pulsed mode with much less than 1 photon average

Light source = LEDs with different λ

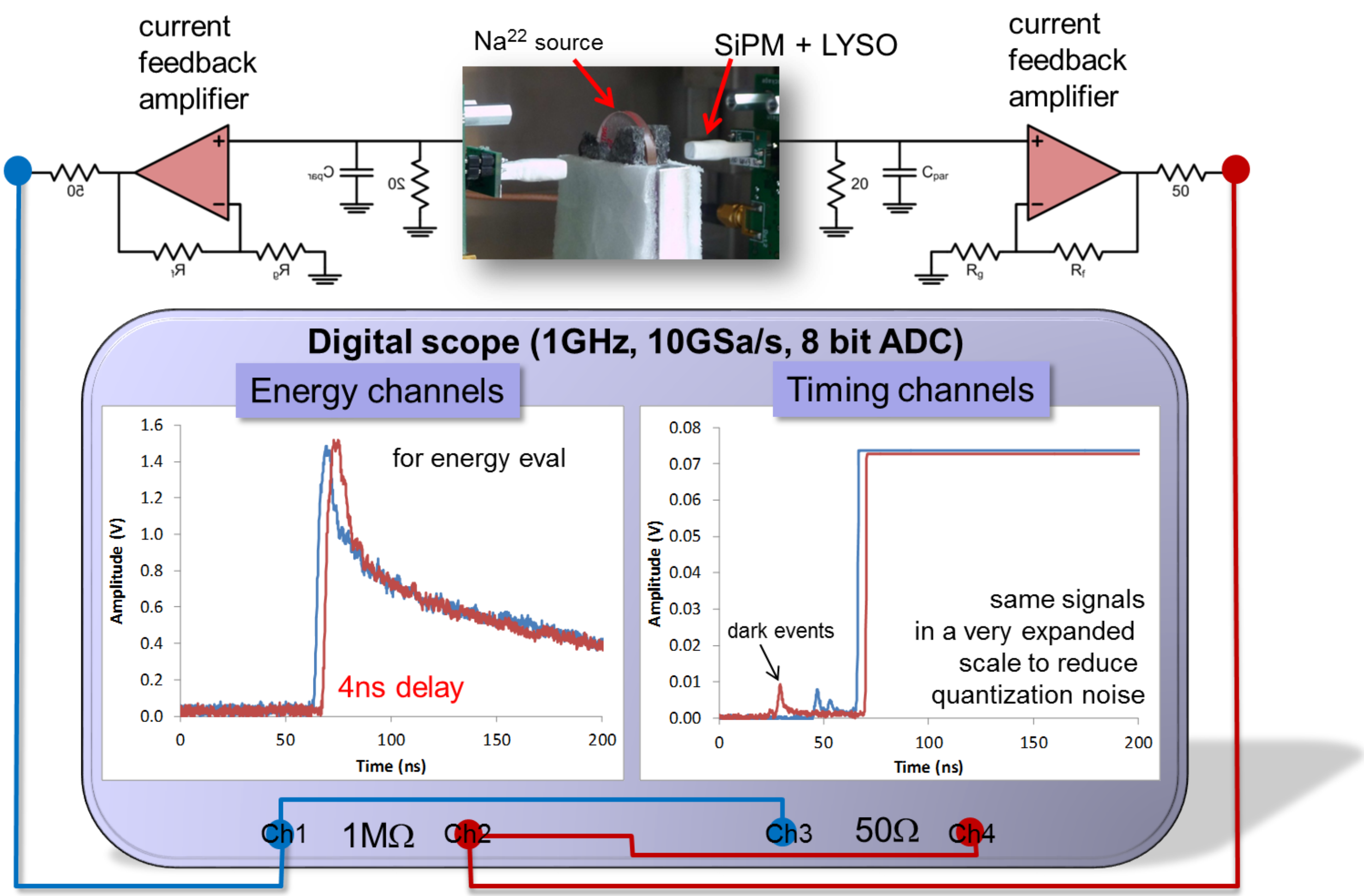
Light inensity determined with a calibrated SPAD.

We count the positive events and compare with reference SPAD.

Very fast measurement, free form AP, can be done in climatic chamber.

Functional characterization

- gamma ray spectroscopy
- coincidence time measurement



FBK technology evolution

Original technology 2006

2010-11

RGB-SiPM
(Red-Green-Blue SiPM)

- excellent breakdown voltage uniformity
- low breakdown voltage temperature dependence
- higher efficiency
- lower noise

electric field engineering

2012

NUV-SiPM
(Near-UV SiPM)

new junction

- excellent breakdown voltage uniformity
- low breakdown voltage temperature dependence
- high efficiency in the near-ultraviolet
- very low dark noise

2012

RGB-SiPM_HD
(Red-Green-Blue SiPM – high density)

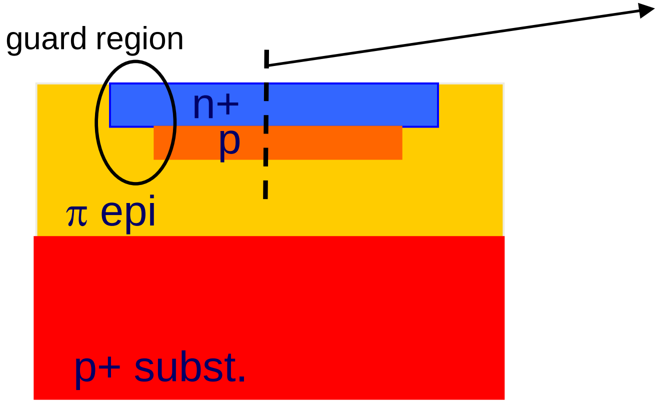
- small cell size with high fill factor:
  - high dynamic range
  - low excess noise factor

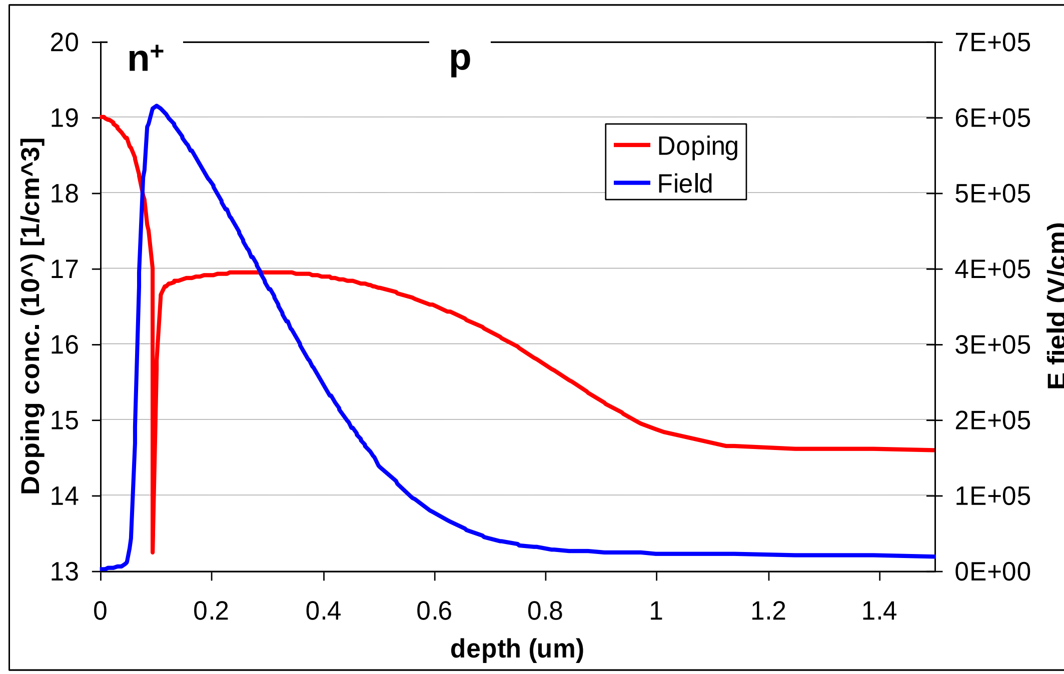
new cell border

Original technology

[C. Piemonte
"A new Silicon Photomultiplier structure for blue light detection"
NIMA 568 (2006) 224-232]

Shallow-Junction SiPM





High field region ← | → Drift region

1) Substrate: p-type epitaxial
2) Very thin n+ layer
3) Polysilicon quenching resistance
4) **high electric field**

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Main parameters

50um cell
45% FF

	Original n+/p
Breakdown voltage	33V
Breakdown voltage uniformity on wafer	~3V
Max over-voltage	~8V
V_{BD} temp. coeff.	75mV/C
Max primary dark rate (20C)	several MHz/mm^2
Peak PDE	450-600nm
Wavelength range	300-900
Peak PDE	25%
ECF (at max PDE)	1.5

good gain temp. dependence even if VBD temp. dep. is not very small

Gain pulse: extracted from area of single cell signal
Gain current: extracted from ratio between DC current and primary dark rate

ECF = Gc/Gp

From measurements with scintillator: good energy and timing resolution!!

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RGB

Re-design of the active area: electric field engineer.

Lower electric field, thicker high-field region

+

partially depleted epi at breakdown voltage

Next slide: comparison between two SiPMs 1x1mm2 50x50um2 having exactly the same layout (FF ~45%).

N.Serra: «Characterization of new FBK SiPM technology for visible light detection", JINST 2013 JINST 8 P03019

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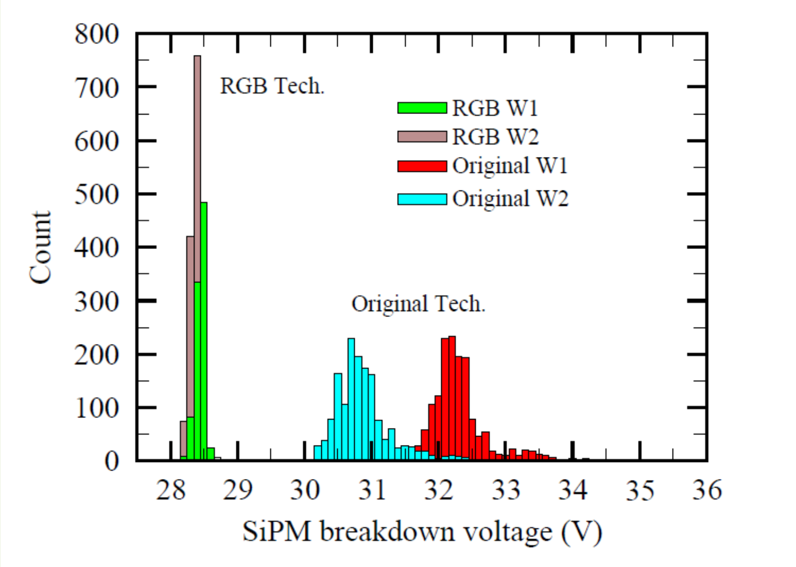
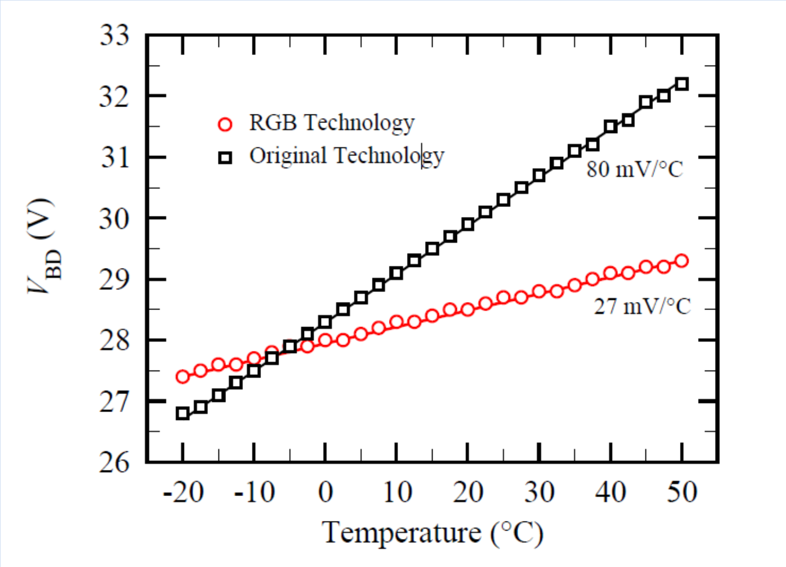
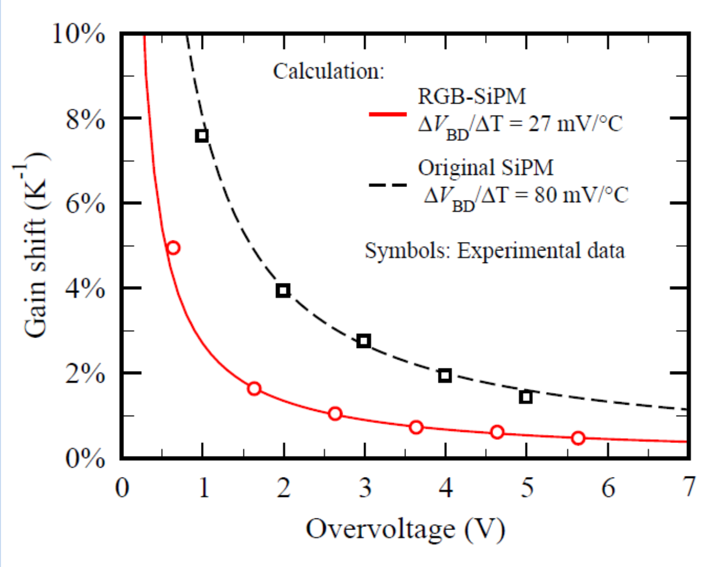
RGB: breakdown voltage



breakdown voltage non-uniformity strongly reduced both at wafer level and from wafer to wafer

breakdown voltage temperature dependence





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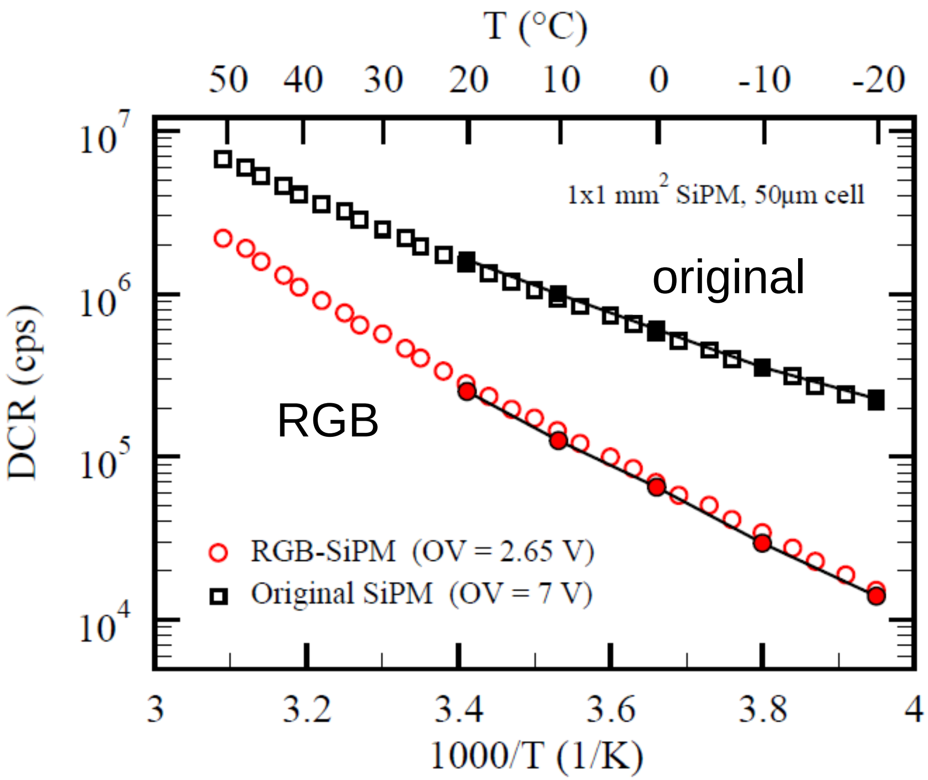
RGB: DCR



RGB has a much lower noise and a steeper temperature dependence:

→ **less tunneling**

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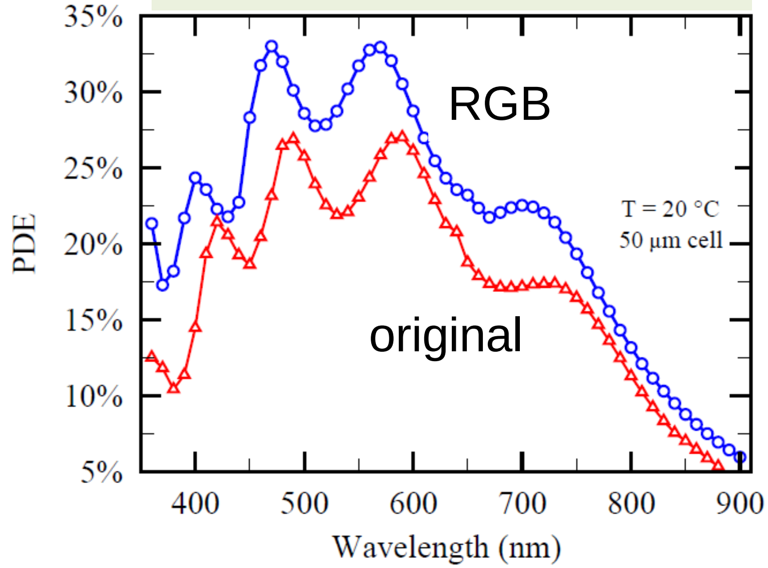
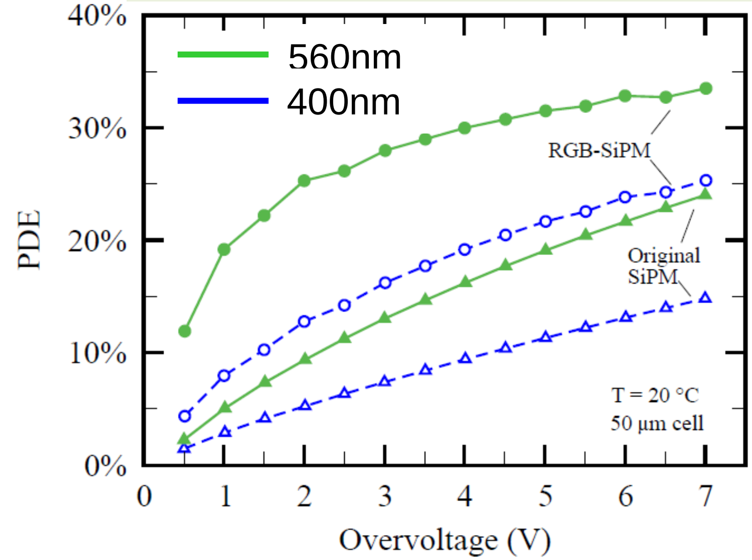
RGB: photo-detection efficiney

PDE *vs* wavelength



PDE *vs* over-voltage



RGB:

→ Much faster increase of efficiency vs over-voltage.

→ As in original, peak is at green, consistent with junction type

RGB vs original

	Original n+/p	RGB-SiPM (Upgraded n+/p)
Breakdown voltage	33V	28V
Breakdown voltage uniformity on wafer	~3V	**<0.2V**
Max over-voltage	~8V	~6V
V_{BD} temp. coeff.	75mV/C	**25mV/C**
Max primary dark rate (20C)	several MHz/mm^2	~500kHz/mm^2
Peak PDE	450-600nm	450-600nm
Wavelength range	300-900	300-900
Peak PDE	25%	33%
ECF (at max PDE)	1.5	1.8

50um cell
45% FF

From measurements with
scintillator: comparable or slightly better for RGB

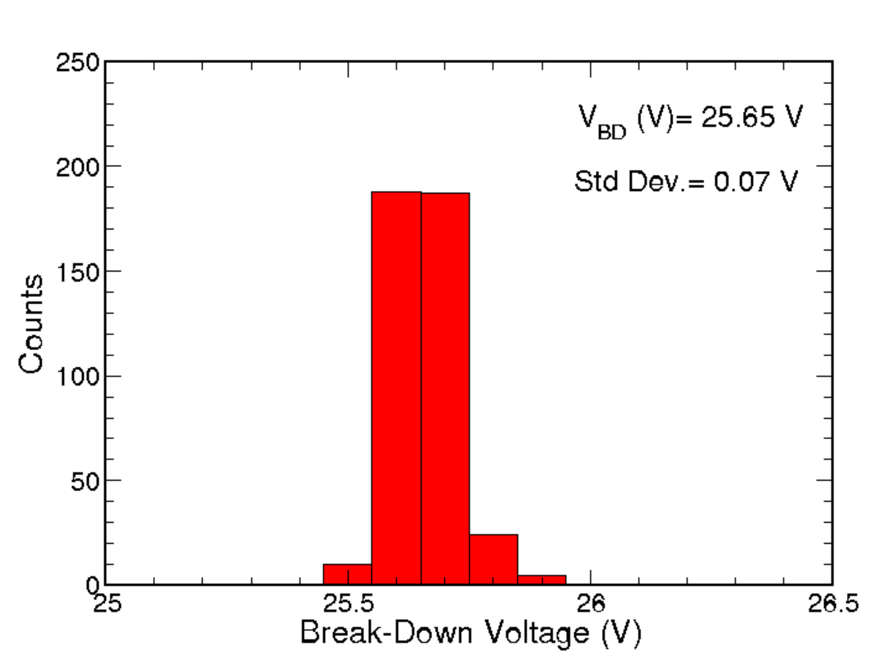
NUV SiPM

Same electric field configuration of RGB technology but with opposite sign.

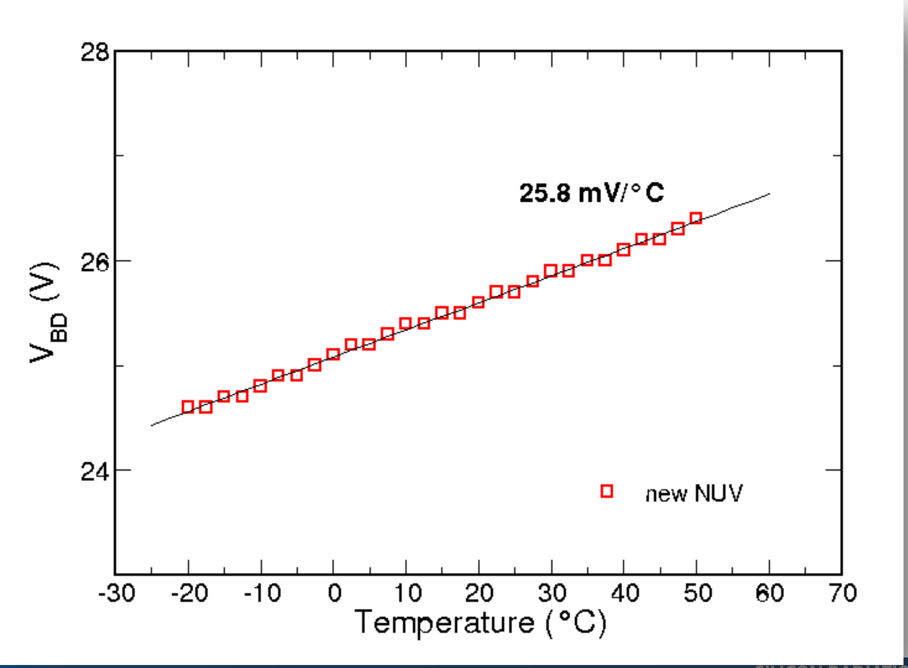
↓

Objective: maintain the advantages of RGB but with peak efficiency in the near-UV

Breakdown voltage

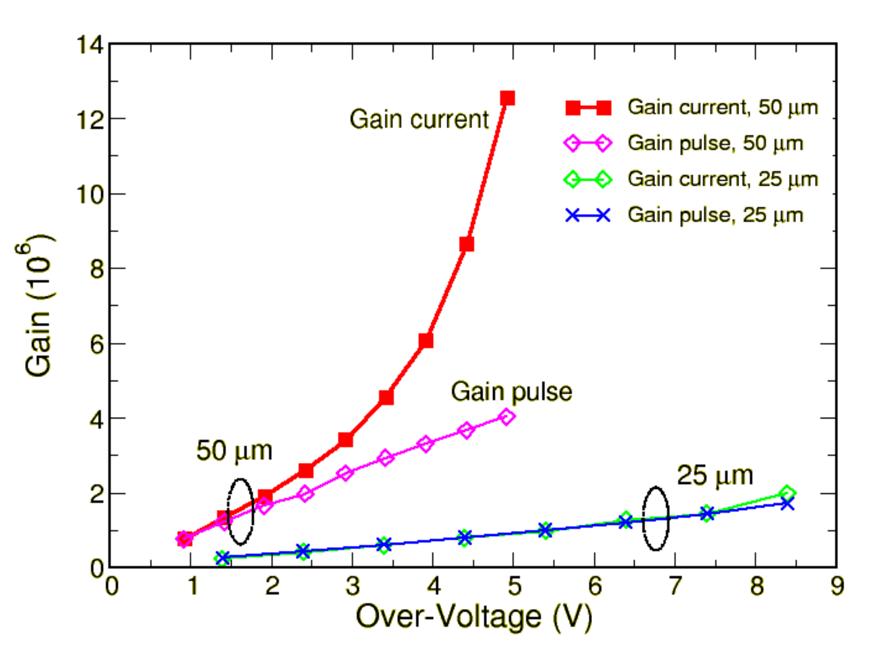


Breakdown voltage uniformity on a wafer.



Temperature dependence of the breakdown voltage.

Gain and noise



Gain of 50x50 and 25x25um^2 cells.
Gain pulse: extracted from area of single cell signal
Gain current: extracted from ratio between DC current and primary dark rate

NUV-SiPM: 1x1mm^2 50x50um^2.
Total and *primary* dark count rate at 0.5 p.e.

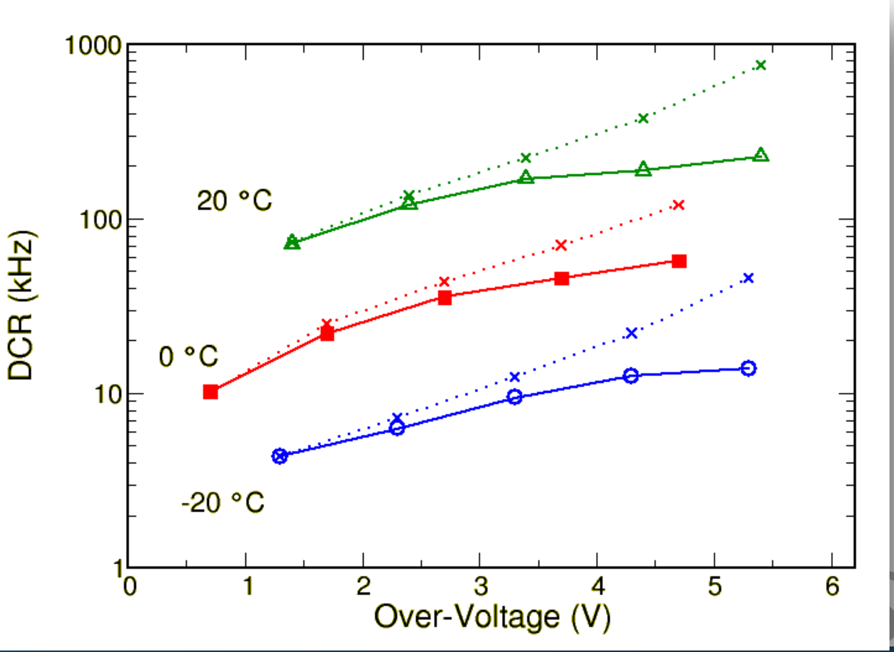
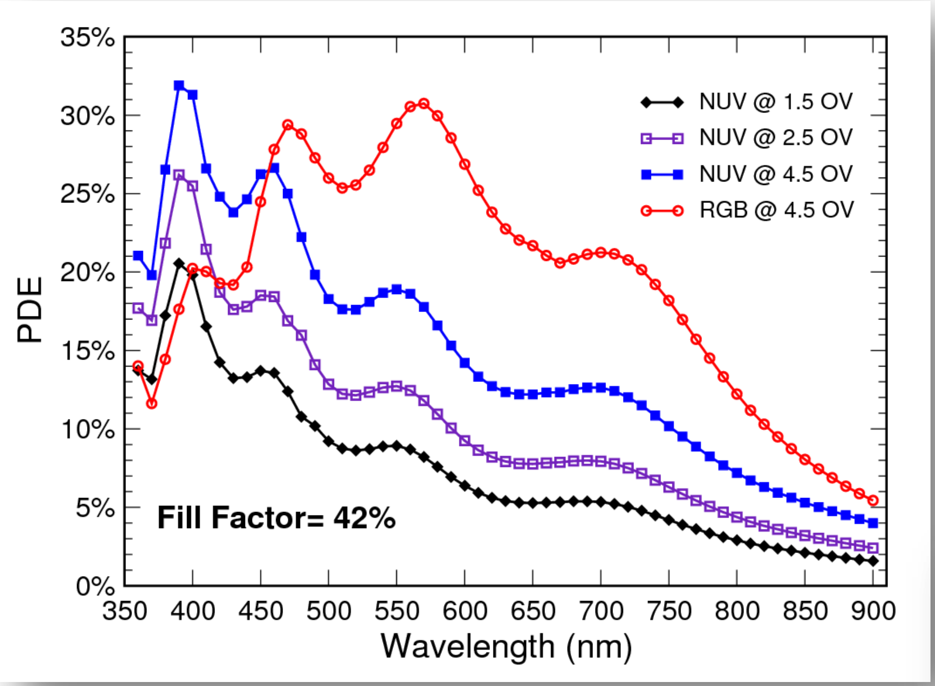
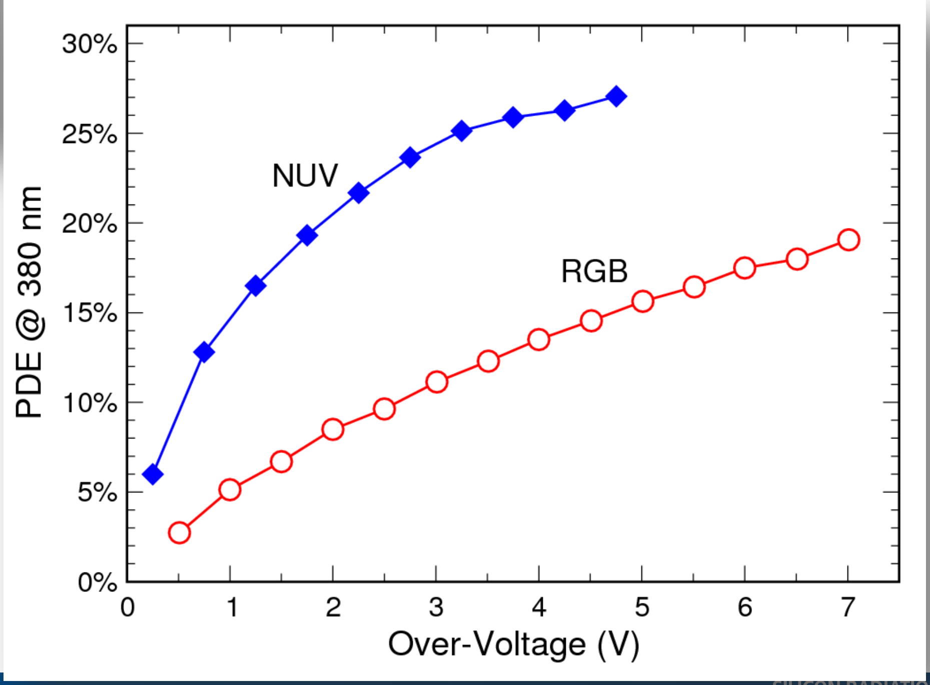


Photo-detection efficiency

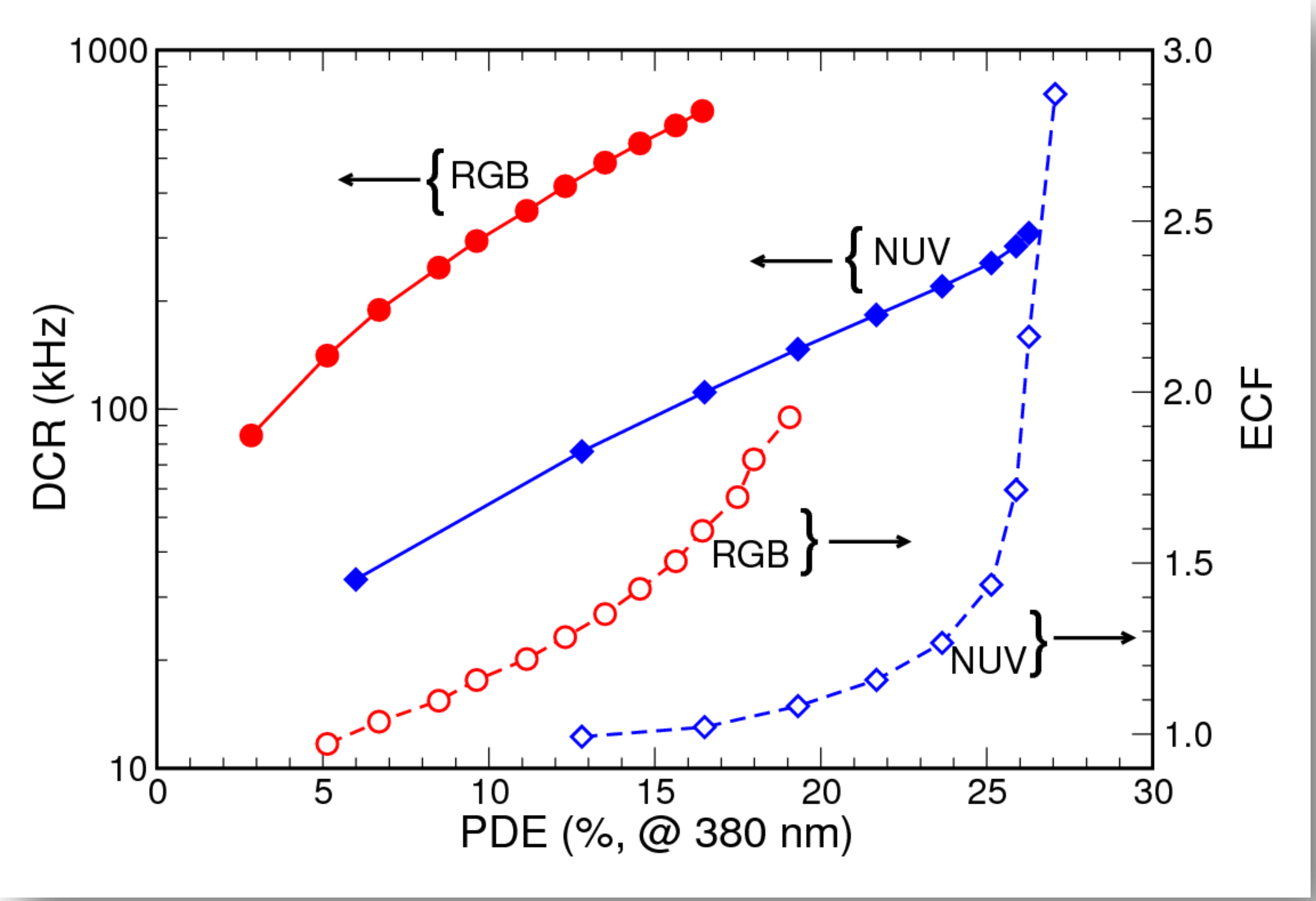


PDE vs wavelength
for a NUV-SiPM and RGB-SiPM
with 50x50um^2 cell, 42% fill factor.



PDE@380nm vs Overvoltage
for a NUV-SiPM and RGB-SiPM
with 50x50um^2 cell, 42% fill factor.

Summary



ECF = $\frac{\text{Gain current}}{\text{Gain pulse}}$

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NUV vs RGB

	Original n+/p	RGB-SiPM (Upgraded n+/p)	NUV-SiPM
Breakdown voltage	33V	28V	26V
Breakdown voltage uniformity on wafer	~3V	**<0.2V**	**<0.2V**
Max over-voltage	~8V	~6V	~5V
V_{BD} temp. coeff.	75mV/C	**25mV/C**	**25mV/C**
Max primary dark rate (20C)	several MHz/mm^2	~500kHz/mm^2	**~150kHz/mm^2**
Peak PDE	450-600nm	450-600nm	**390nm**
Wavelength range	300-900	300-900	300-600
Peak PDE	25%	33%	32%
ECF (at max PDE)	1.5	1.8	2

50um cell 45% FF

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What's next?

- Fill factor: 50x50um^2 cell only 45%

so far we used the mask aligner which has a limited alignment and resolution capability.
We produced functional devices with the «stepper» obtaining a fill factor of 65%...
…good, but also the ECF is much higher!!

→ for higher PDE we <u>must</u> find a way to reduce optical cross-talk and after-pulsing

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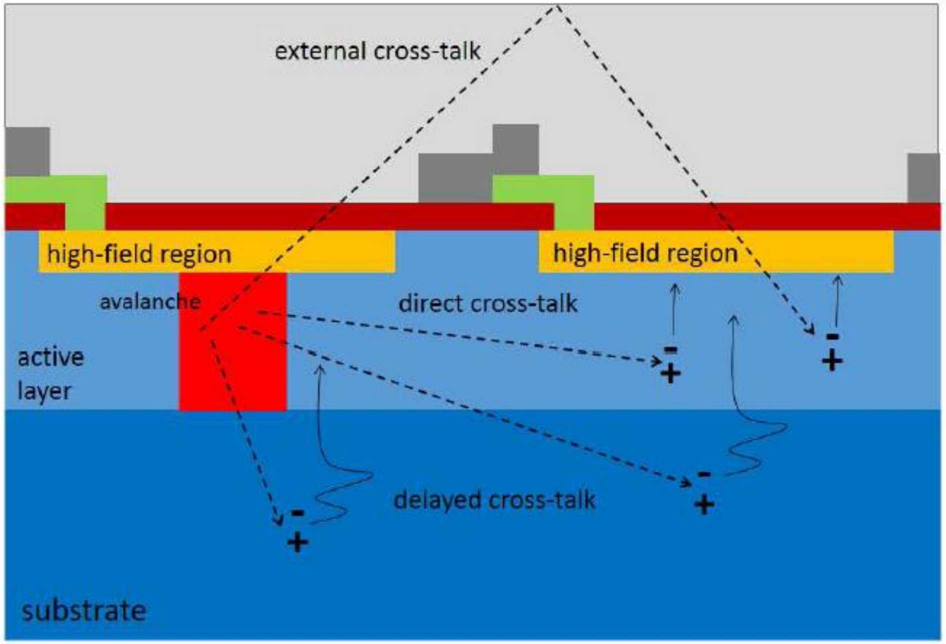
Correlated noise



Some paths for optical cross-talk

- Trenches to avoid direct and delayed cross-talk…
- buried junction to avoid out-diffusion…
- **lower gain!**

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Small cells!

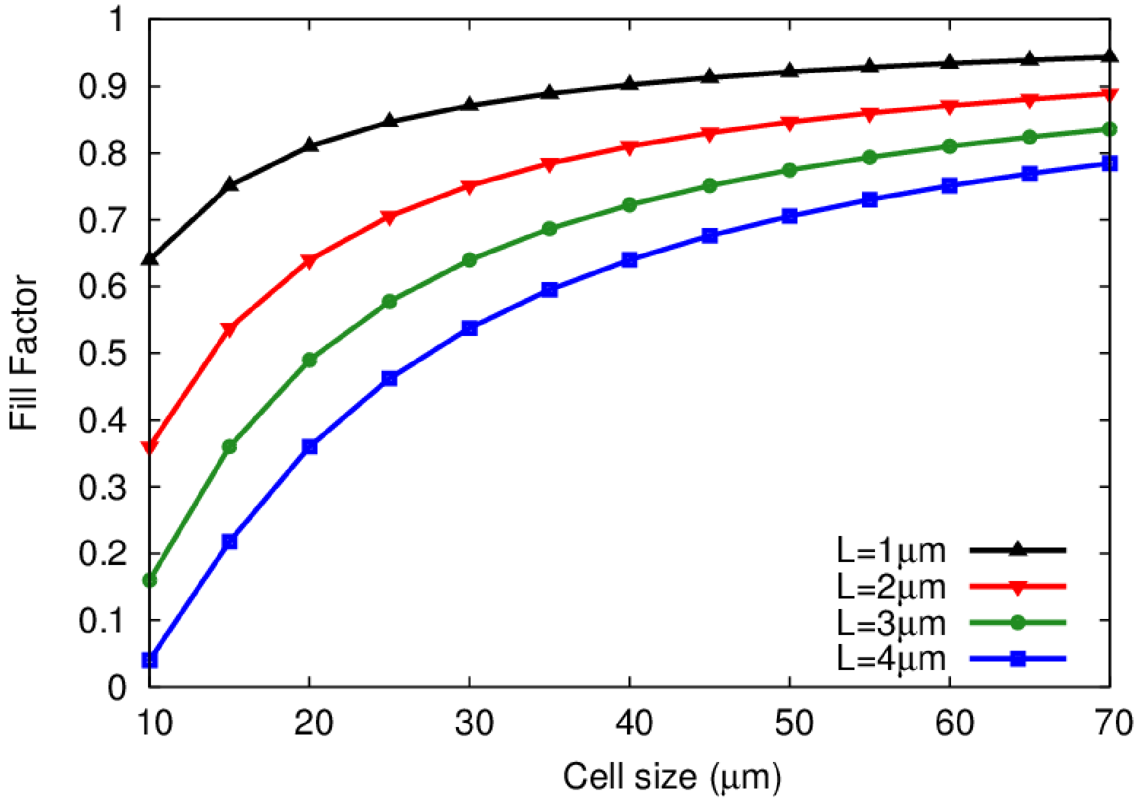
1. Lower correlated noise, because of lower gain:
   - lower after-pulse
   - lower direct and delayed OCT
   - lower external OCT

2. Higher dynamic range

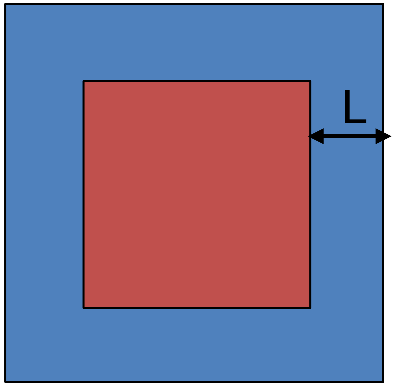
3. Faster recharging time

All are important to optimize spectroscopic and timing performance, but not only...

Difficult? Yes.

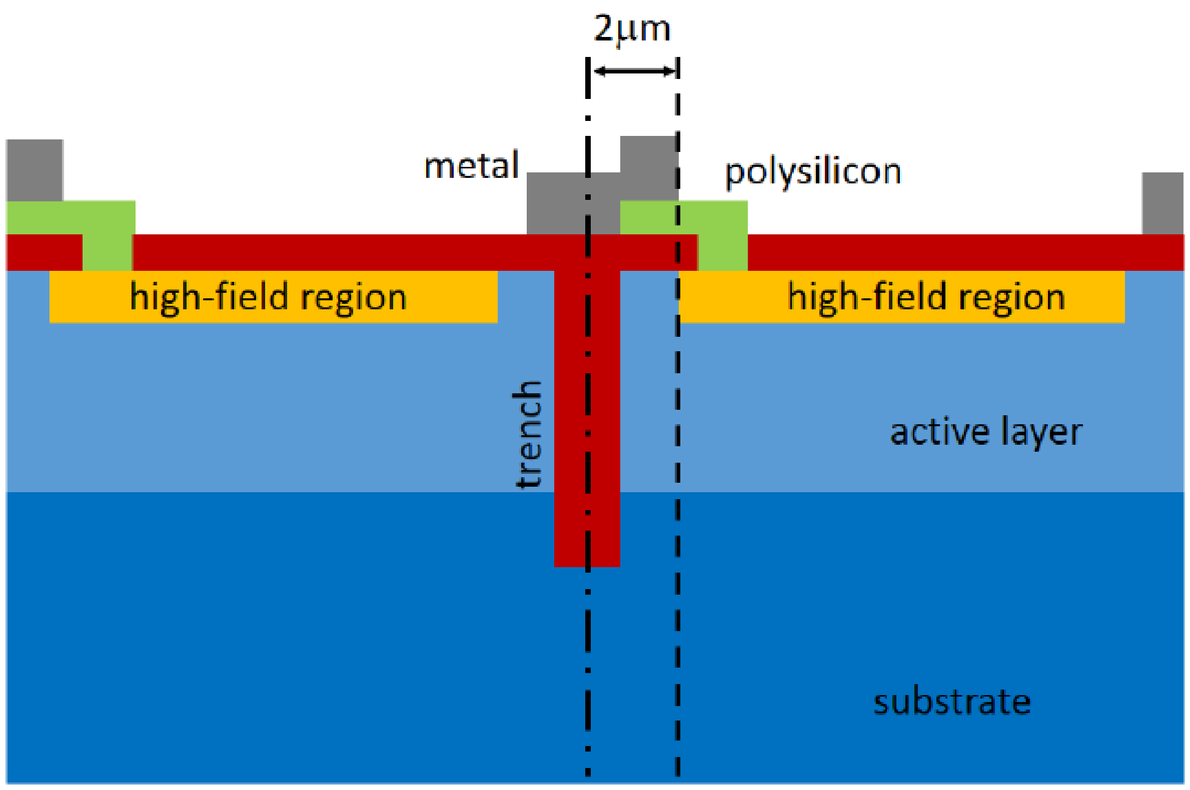


L is the dead border region around a cell



RGB-HD

We completely re-designed the cell border structure of RGB tech. to have small cells with high fill factor,



L = 2um. In the previous technology it was 6/7um

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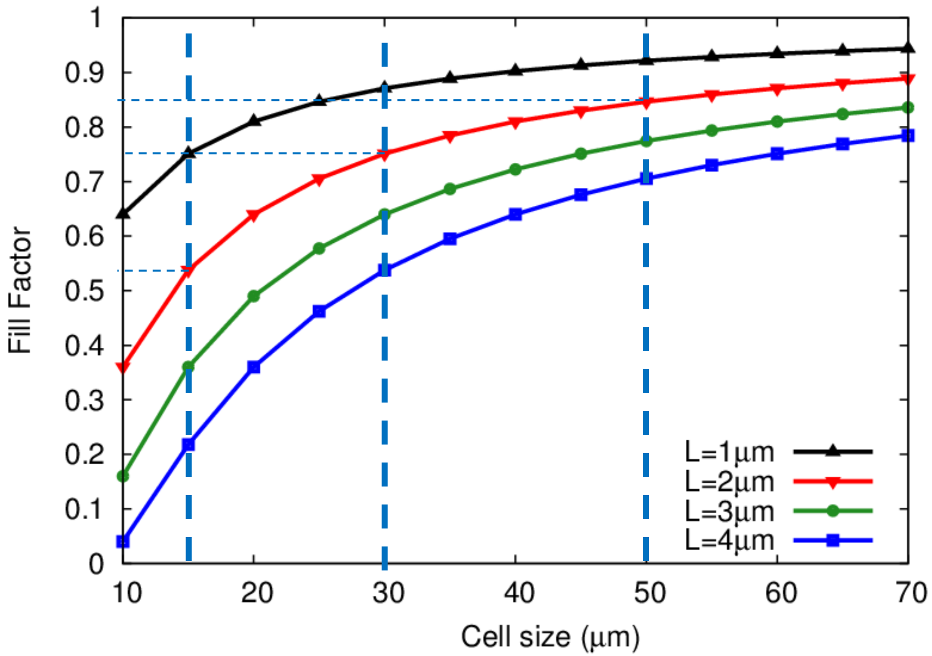
RGB-HD-SiPM

SiPM:
size: **4x4mm^2**
cell size: **30x30um^2**
cells: ~1000cells/mm^2

Nominal FF = 74%

SiPM:
size: **2.2x2.2mm^2**
cell size: **15x15um^2**
cells: 4400cells/mm^2

Nominal FF = 48%



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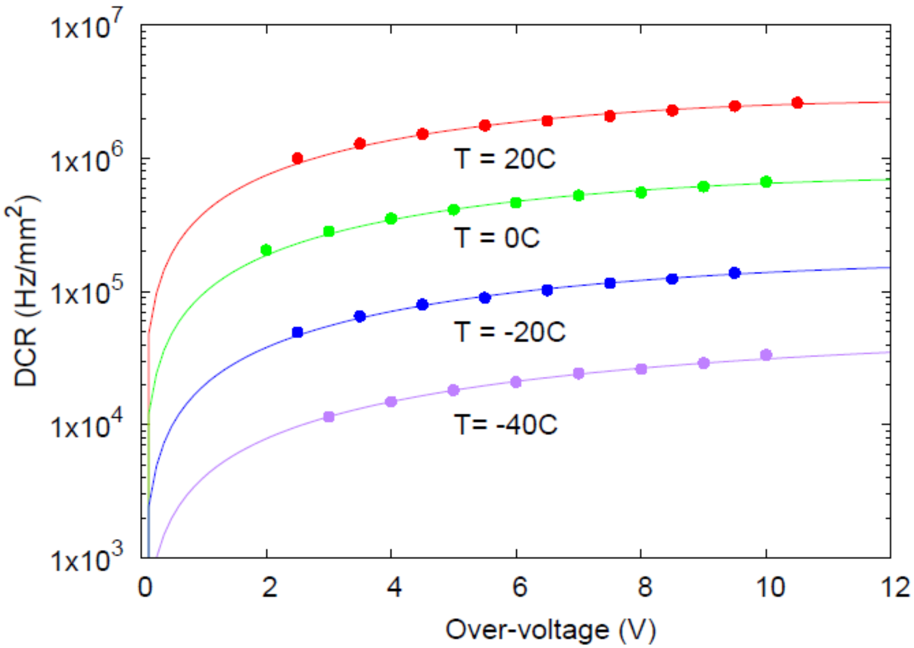
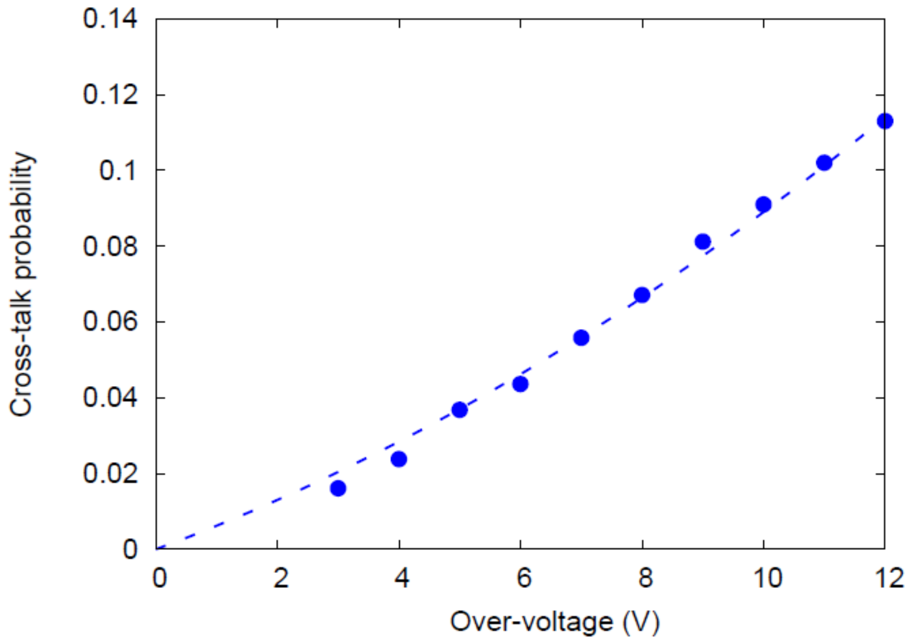
Cell size: 15x15um^2



Dark rate 4 times higher than normal RGB.
We have to check with further productions.

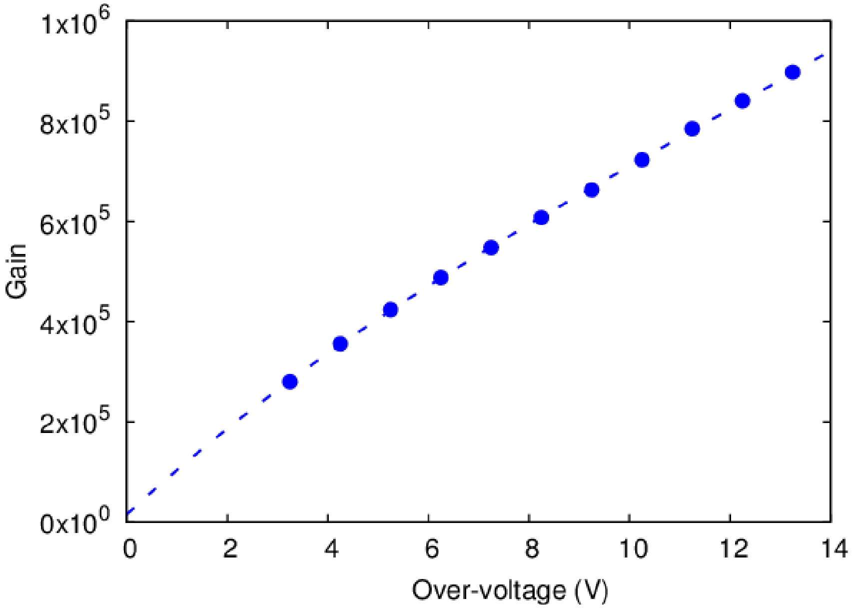


Low cross-talk.
Very low AP prob. (~1%)

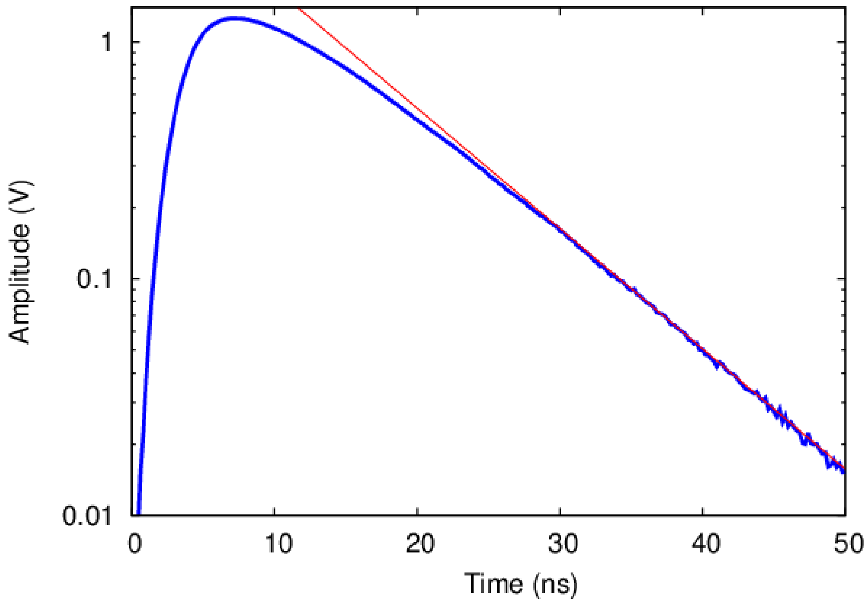
=> ENF ~1.1 at 10V

FONDAZIONE BRUNO KESSLER

Cell size: 15x15um^2



Gain always below 1million



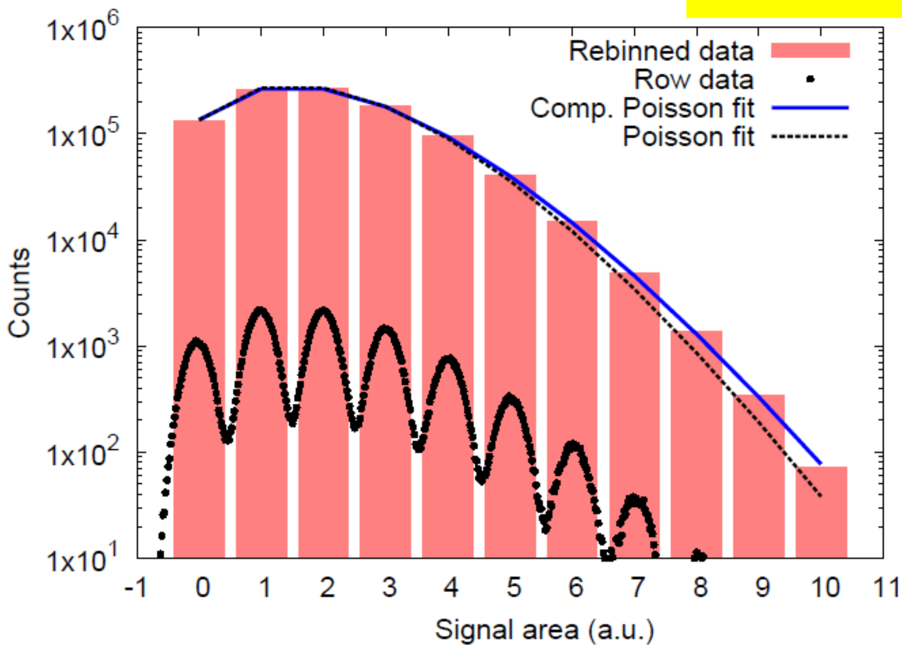
Recharge time constant of 9ns!!

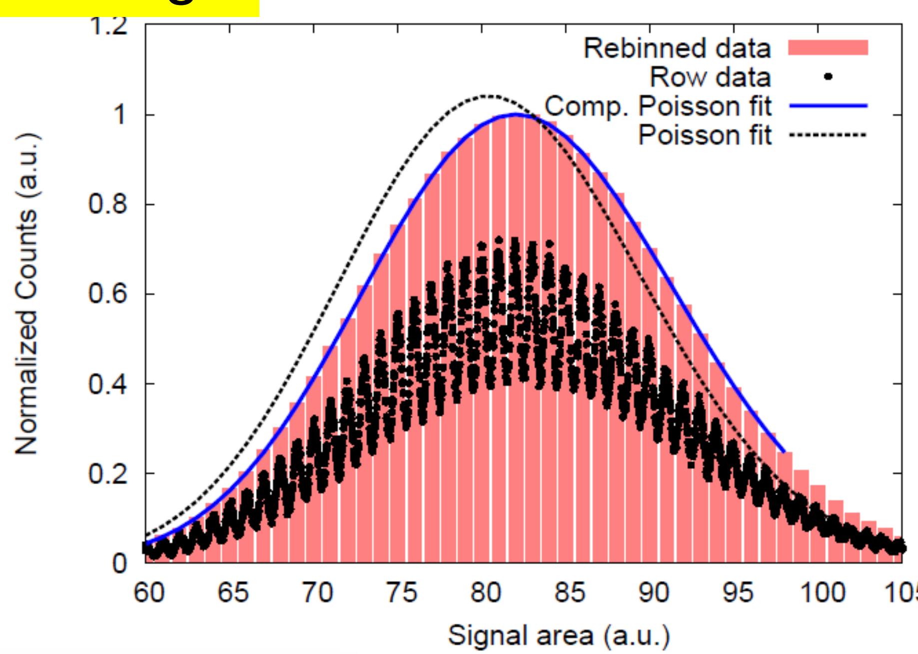
(With a quenching resistor of ~1Mohm)

Cell size: $15x15um^2$

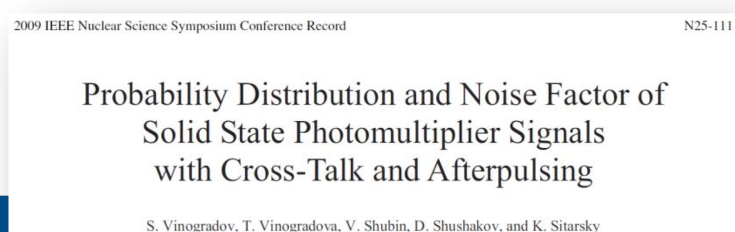
SiPM irradiated with pulsed light from LED.
Signal integrated for 100ns to include delayed correlated components

3V over-voltage





$\lambda = 2.3$
p=2%


2009 IEEE Nuclear Science Symposium Conference Record N25-111

Probability Distribution and Noise Factor of Solid State Photomultiplier Signals with Cross-Talk and Afterpulsing

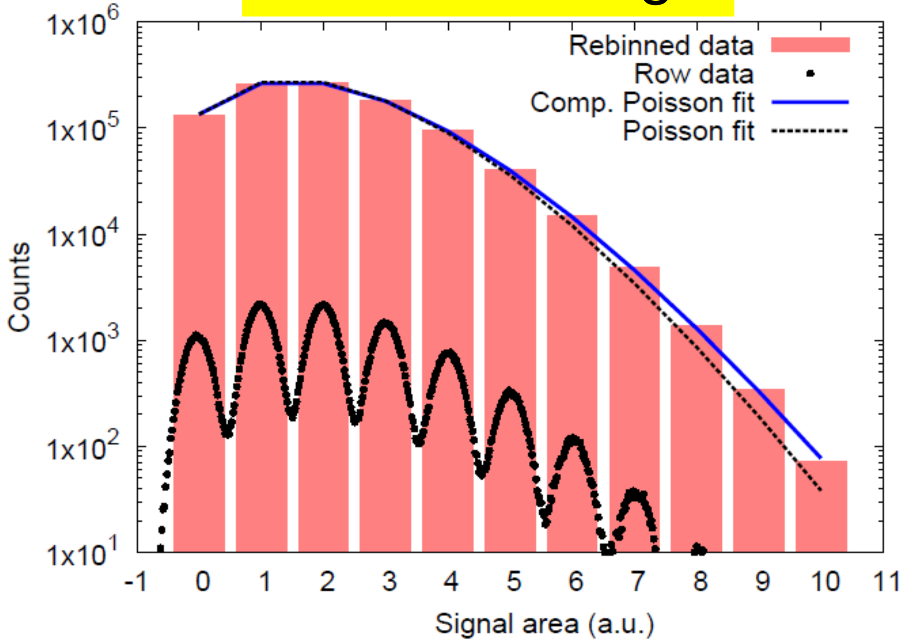
S. Vinogradov, T. Vinogradova, V. Shubin, D. Shushakov, and K. Sitarsky

$\lambda = 80$
p=2%

Cell size: 15x15um^2

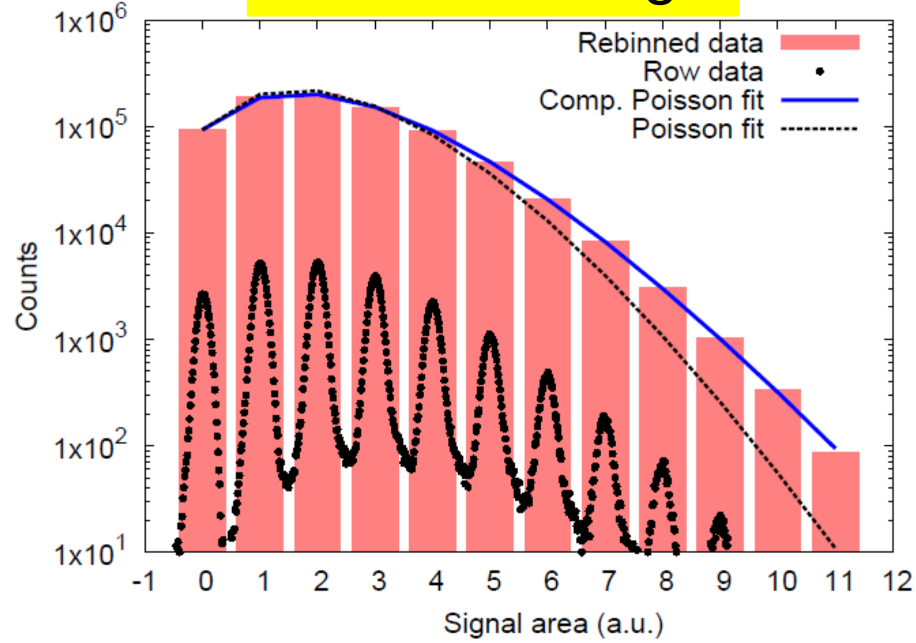
SiPM irradiated with pulsed light from LED.
Signal integrated for 100ns to include delayed correlated components

3V over-voltage



$\lambda = 2.3$
p=2%

7V over-voltage



$\lambda = 3$
p=7%

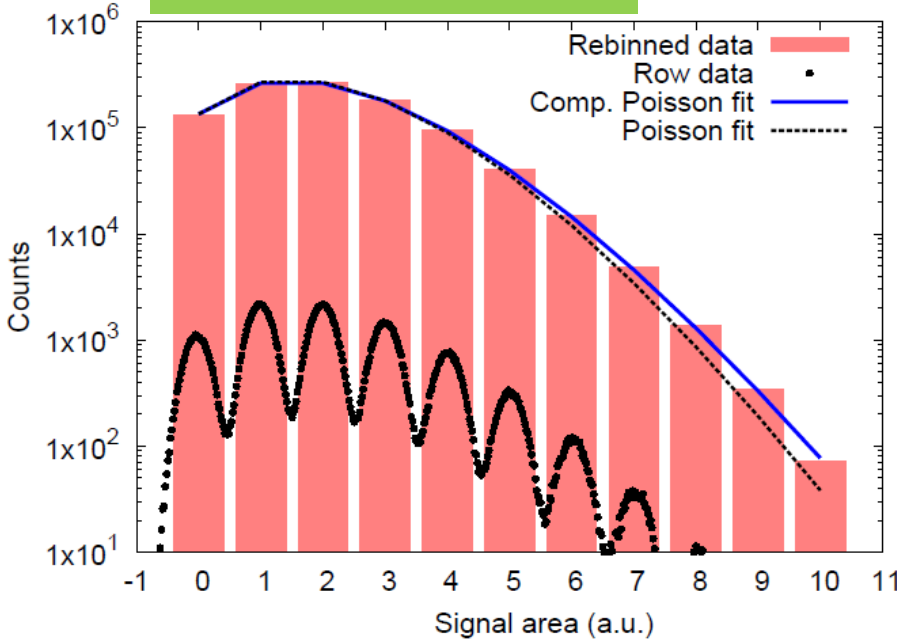
Cell size: 15x15um^2

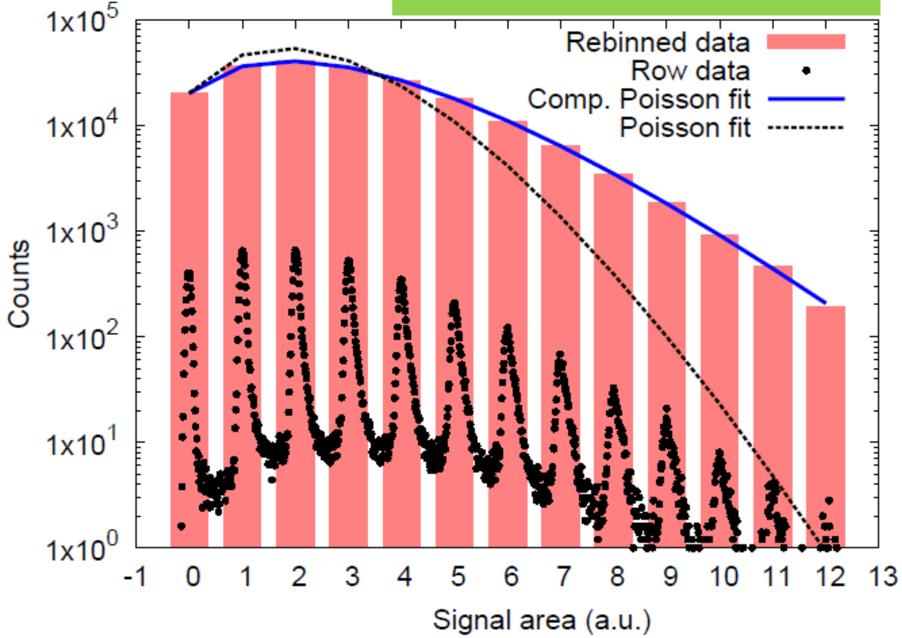
SiPM irradiated with pulsed light from LED.
Signal integrated for 100ns to include delayed correlated components

RGB-HD
15x15um2 – 48% FF

3V over-voltage

RGB
50x50um2 – 45% FF



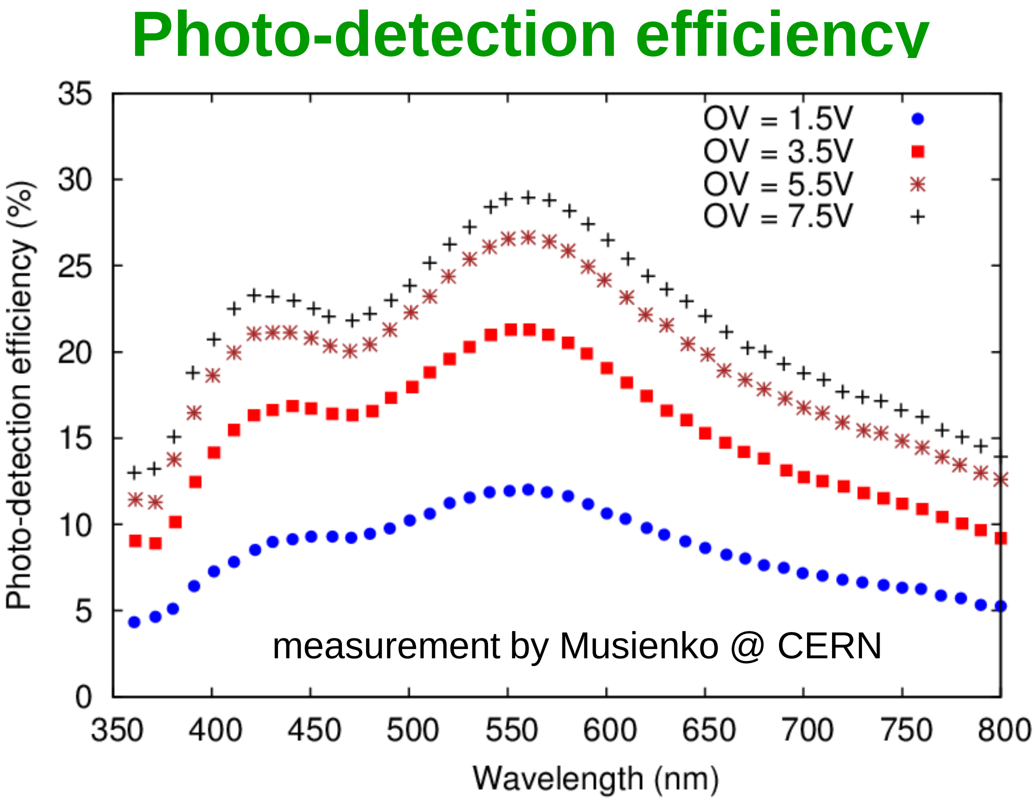


$\lambda = 2.3$
p=2%

$\lambda = 3$
p=20%

FONDAZIONE BRUNO KESSLER

Cell size: 15x15um^2



Quenching resistor is high allowing high bias voltage.

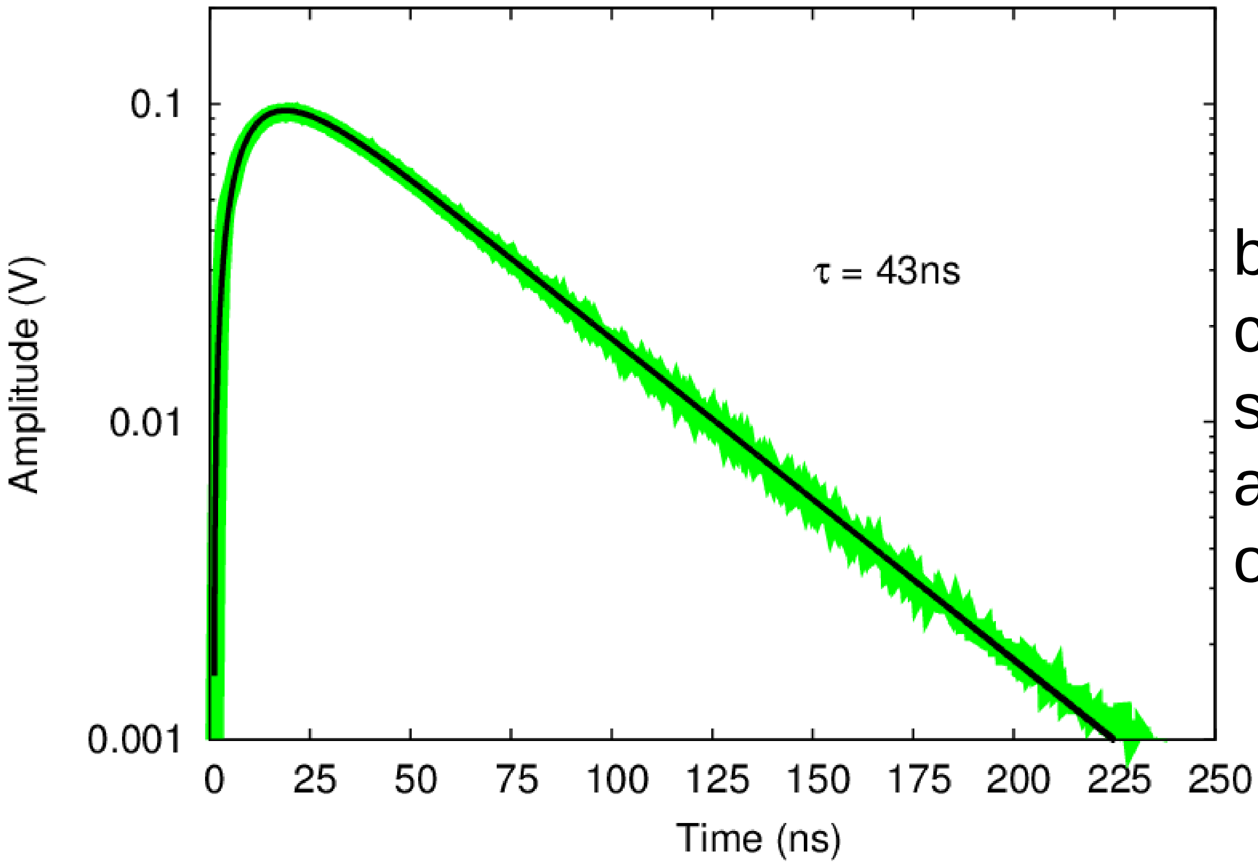
This make the device operation more stable in temperature.

- PDE comparable to our old 50x50um2 cell!!
- Estimated PDE of 30um cell is ~50%!

SRS SILICON RADIATION SENSORS

Cell size: 15x15um^2

Response to LYSO (511keV)

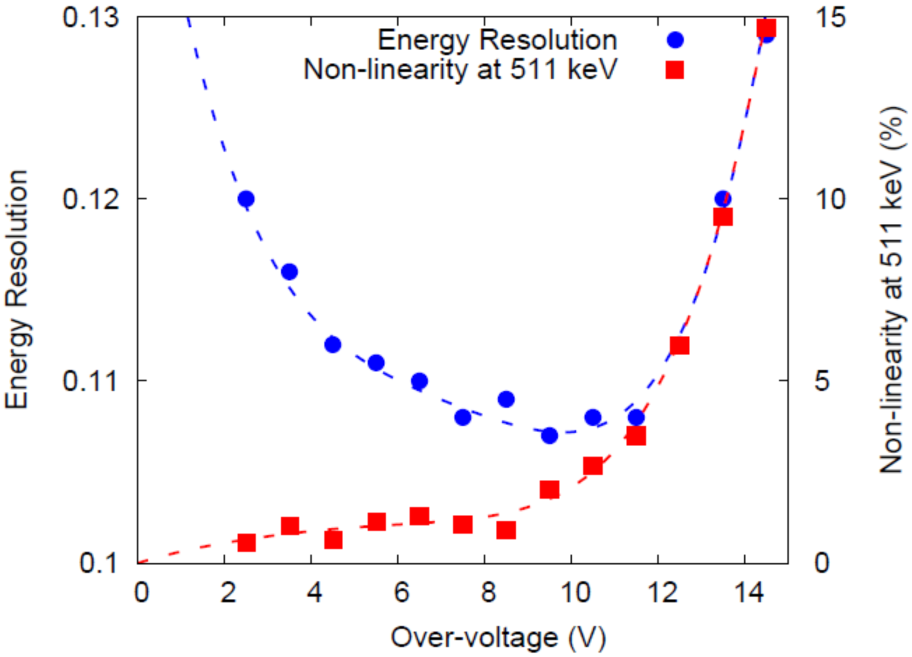


black line is the convolution of the sipm signal (tau=9ns) and LYSO light output (tau=43ns)

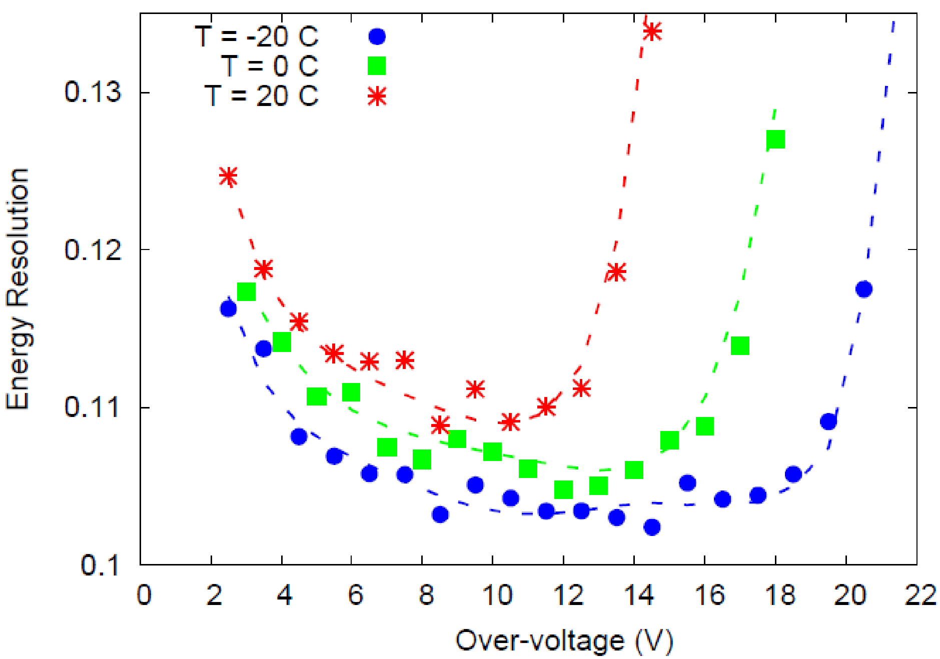
FONDAZIONE BRUNO KESSLER

Cell size: 15x15um^2

LYSO 2x2x10mm^3



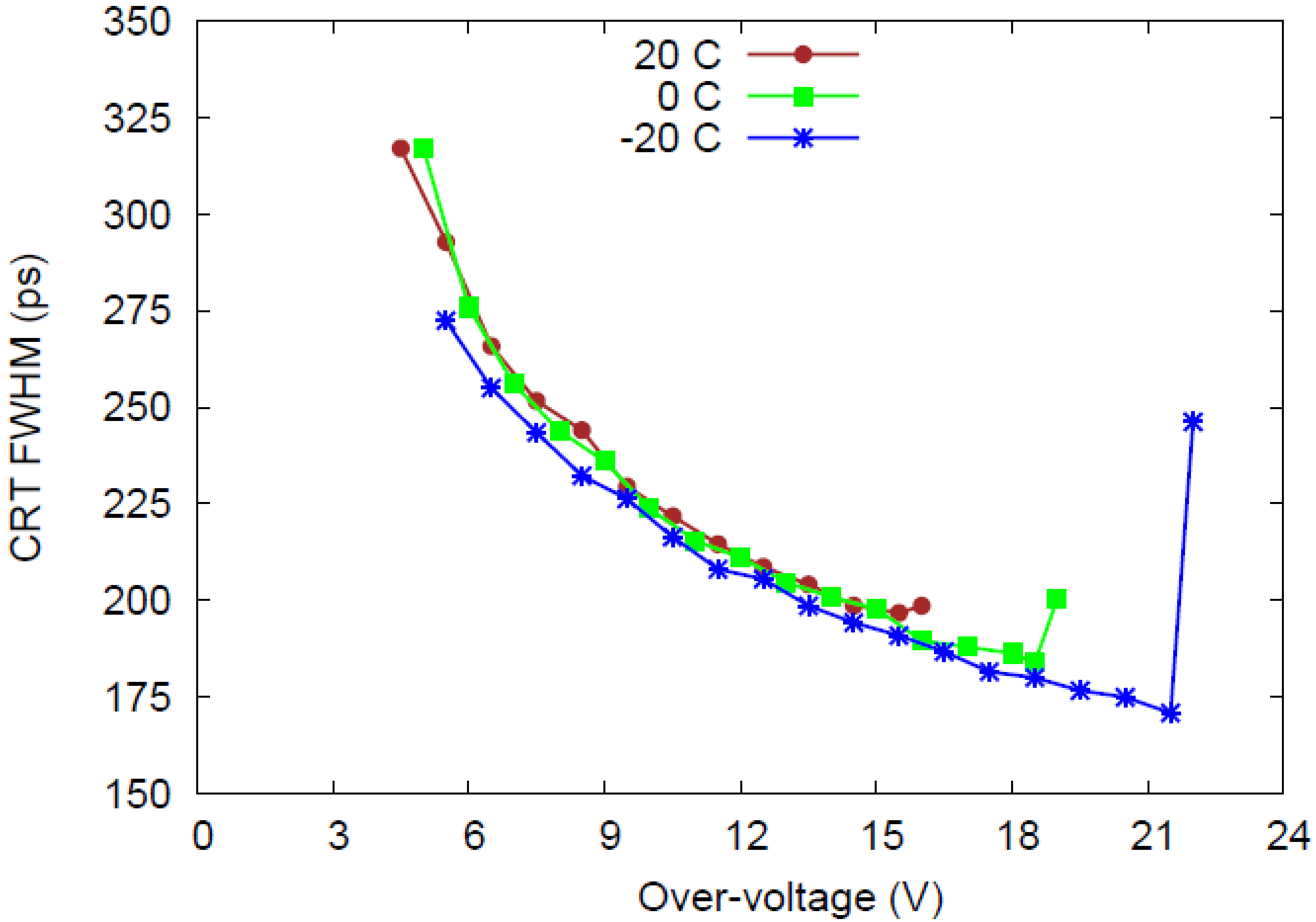
Non-linearity = deviation of the peak position from expected one (@ 511keV)



extremely wide operation range
at low temperature,
not limited by OCT.

Cell size: 15x15um^2

LYSO 2x2x10mm^3



FONDAZIONE BRUNO KESSLER

NUV vs RGB

	Original n+/p	RGB-SiPM New n+/p	RGB-HD-SiPM New n+/p	NUV-SiPM p+/n
Cell size	50µm	50µm	15µm	50 µm
Breakdown voltage	33V	28V	28V	26V
Breakdown voltage uniformity on wafer	~3V	**<0.2V**	**<0.2V**	**<0.2V**
Max over-voltage	~8V	~6V	~8V	~5V
V_{BD} temp. coeff.	75mV/C	**25mV/C**	**25mV/C**	**25mV/C**
Max primary dark rate (20C)	several MHz/mm^2	~500kHz/mm^2	~2MHz/mm^2	**~150kHz/mm^2**
Typical FF	45%	45%	**48%**	45%
Peak PDE	450-600nm	450-600nm	450-600nm	**390nm**
Wavelength range	300-900	300-900	300-900	300-600
Maximum PDE	25%	33%	30%	32%
ECF (at max PDE)	1.5	1.8	**1.1**	2

SRS SILICON RADIATION SENSORS

Conclusion

SiPM technology is evolving quickly.

It outclasses PMT in many aspects except from dark count rate.

High competition: → better performance
→ lower price