FONDAZIONE
BRUNO KESSLER

Development of Ultra-High-Density (UHD) Silicon Photomultipliers with improved Detection Efficiency

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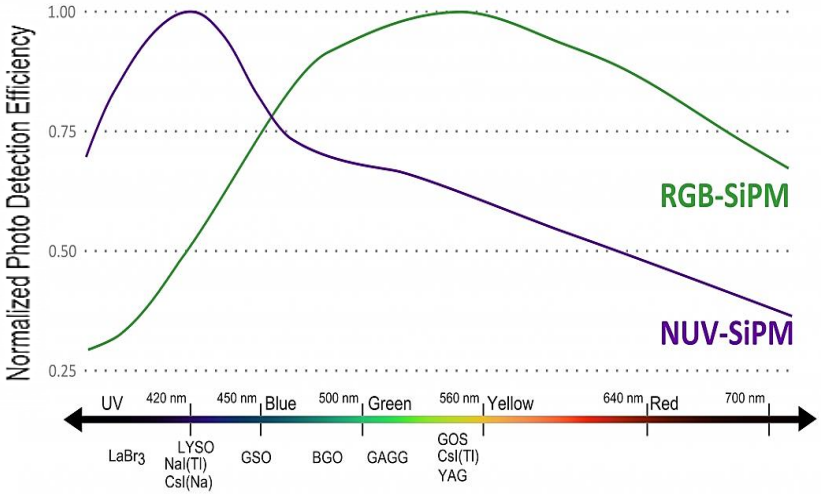
Claudio Piemonte, Nicola Zorzi

http://iris.fbk.eu/silicon-photomultipliers
http://srs.fbk.eu

FBK SiPM technologies



RGB
NUV

SPAD size: 40÷50μm
Fill factor: 45÷60%

New cell border (trenches)

RGB-HD
NUV-HD

SPAD size: 15÷40μm
Fill factor: 55%÷80%

Trench filling

RGB-HD-LowCT
NUV-HD-LowCT

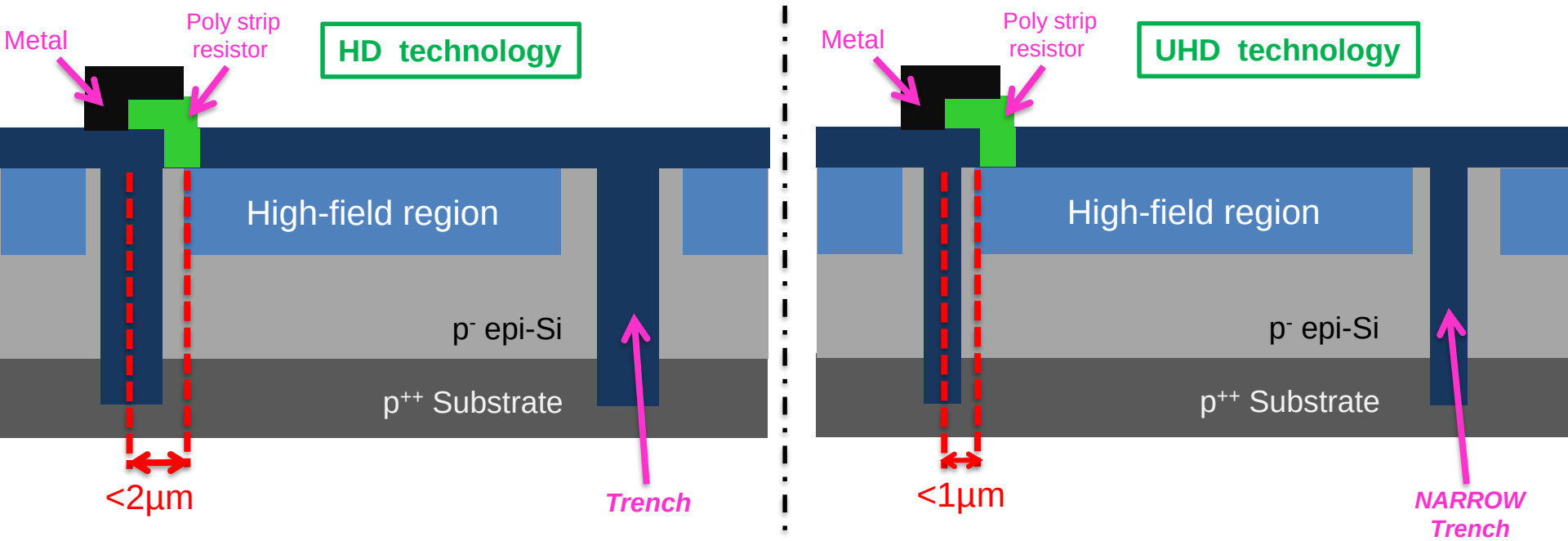
Very-small cells

RGB-UHD

ULTRA-High cell density

SPAD size: 5 ÷ 12μm

HD and UHD technology



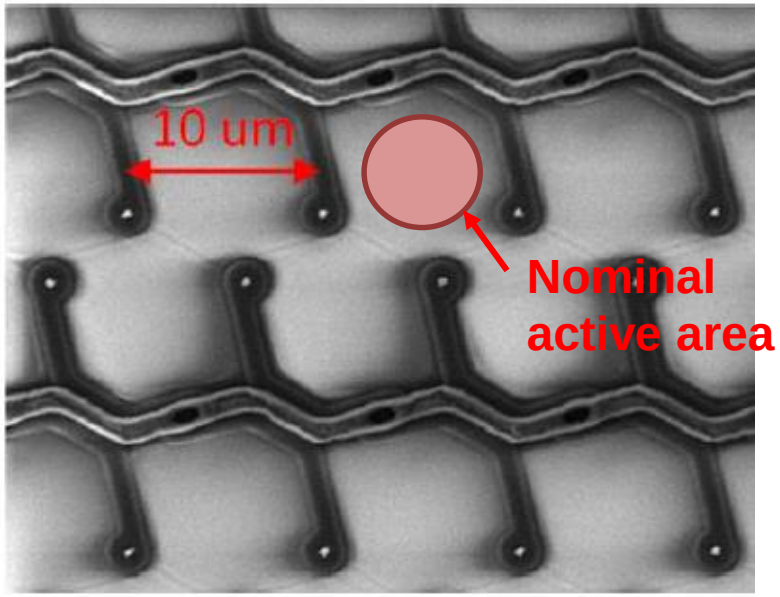
- **Trenches between cells**
  - **Optical and electrical cell isolation**
  - Smaller dead border → increased FF
- **Small cells**
  - **Gain reduction → afterpulsing and CT reduction**
  - Faster cell recharge

But, HD and UHD tech. → also have HIGH FF → HIGH PDE !

UHD Technology

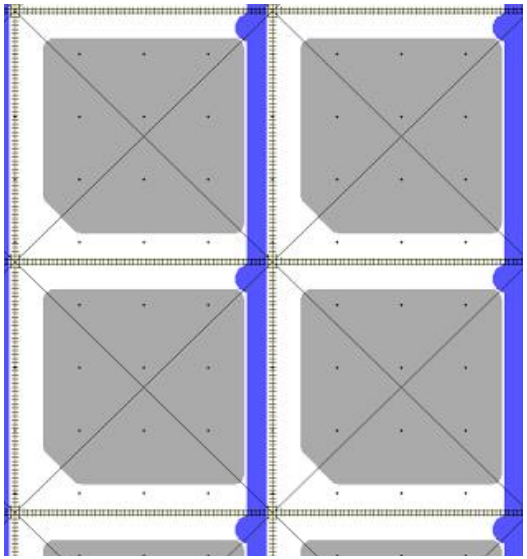
- **Reduction of all the feature sizes**
  - Contacts
  - Resistor
  - ..
- **Reduction of the active-to-border distance** (L)
  - Higher FF
- **Circular active area**
  - No corners (with lower field)
  - Hexagonal cells in honeycomb configuration
- **Lower Rq**
  - For faster recharge

AGGRESSIVE LAYOUT



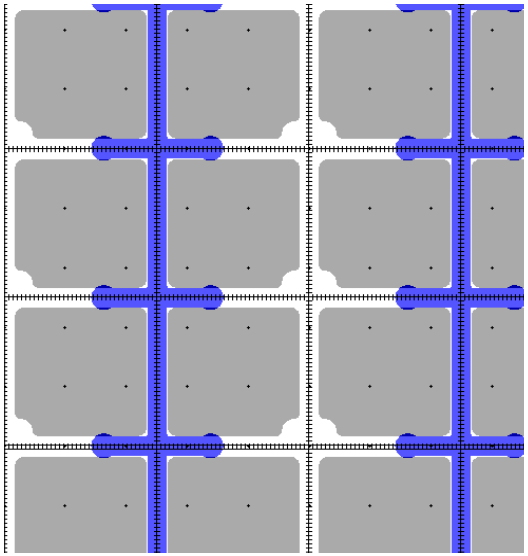
FBK Technology comparison

RGB



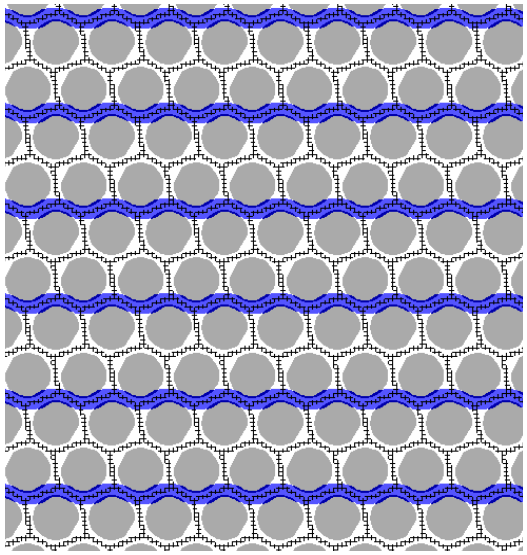
Example with
40 um cell

RGB-HD



Example with
25 um cell

RGB-UHD



Example with
7.5 um cell

Applications of very-small-cell SiPM

- **Calorimetry**
  - CMS calorimeter Phase II Upgrade → *R&D funding.*
  - Reduced non-linearity at high energy ← *high cell density and fast recharge*
  - Reduced correlated noise.

- **Prompt Gamma Imaging in Proton Therapy**
  - **Larger dynamic range** with respect to typical SiPM

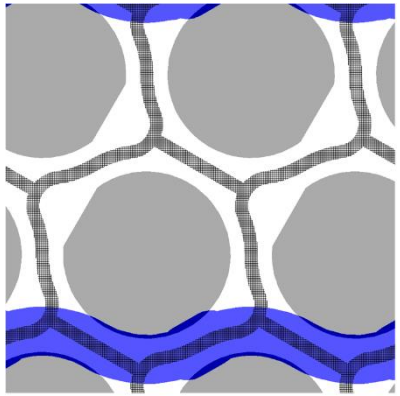
- **Applications requiring radiation hardness**
  - Small cells → **less sensitive to the effects of radiation damage.**

- **… … … others … … …**

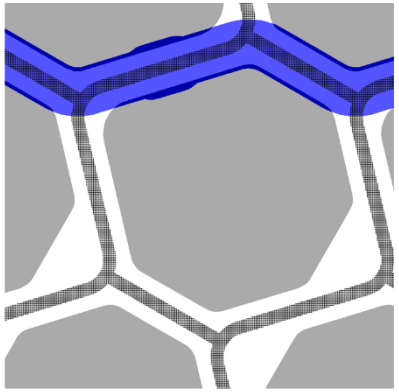
Radiation Damage in small-cell SiPMs

- Increase in the primary noise (DCR).
- Increased afterpulsing (increased number of traps). → Smaller cell → Lower gain reduces afterpulsing (for a given number of traps).
- PDE loss due to cells busy triggering dark counts. → Many, smaller cells with faster recharge → less PDE loss.
- Increased power consumption due to higher DCR. → Smaller cell → Lower gain less current (for a given DCR).

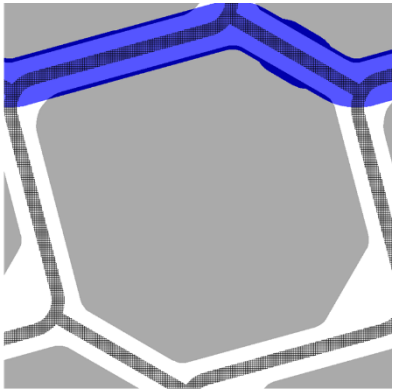
UHD SiPM: first production



7.5 um



10 um



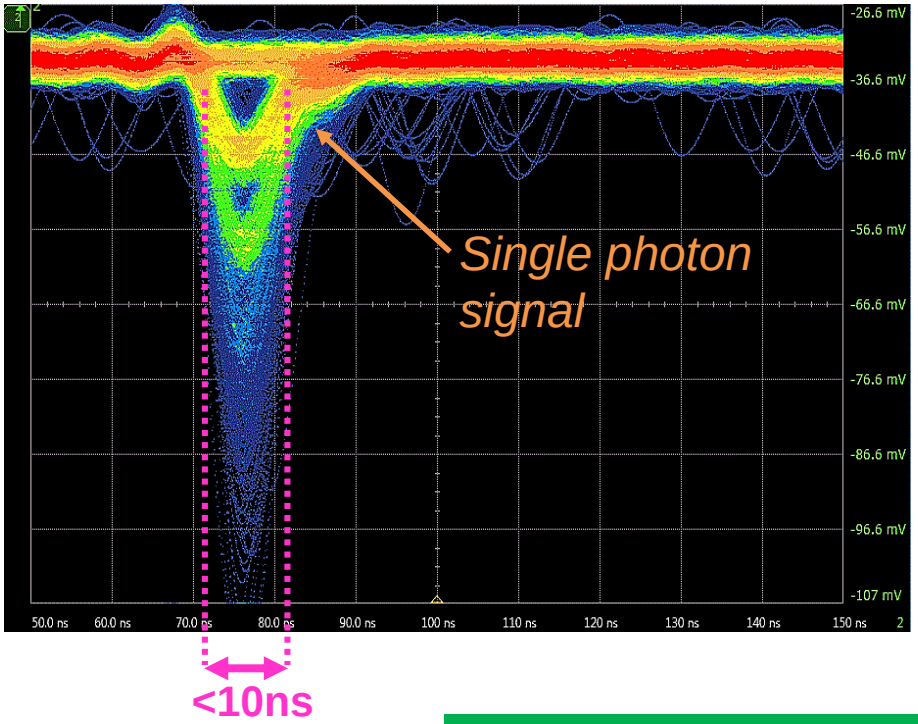
12.5 um

Cell size (µm)	Cell density (cells/mm^2)	Fill Factor *(L = 0.75 um)*
7.5	20530	57.1%
10	11550	68.1%
12.5	7400	74.5%

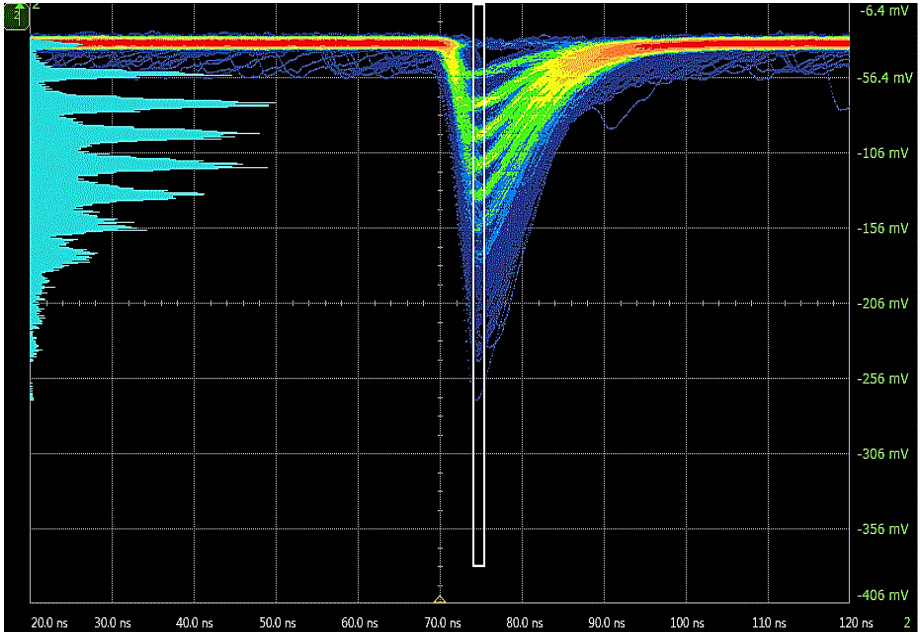
Oscilloscope waveforms
(pulsed low-level light source)

UHD SiPM
1st production

7.5 µm cell

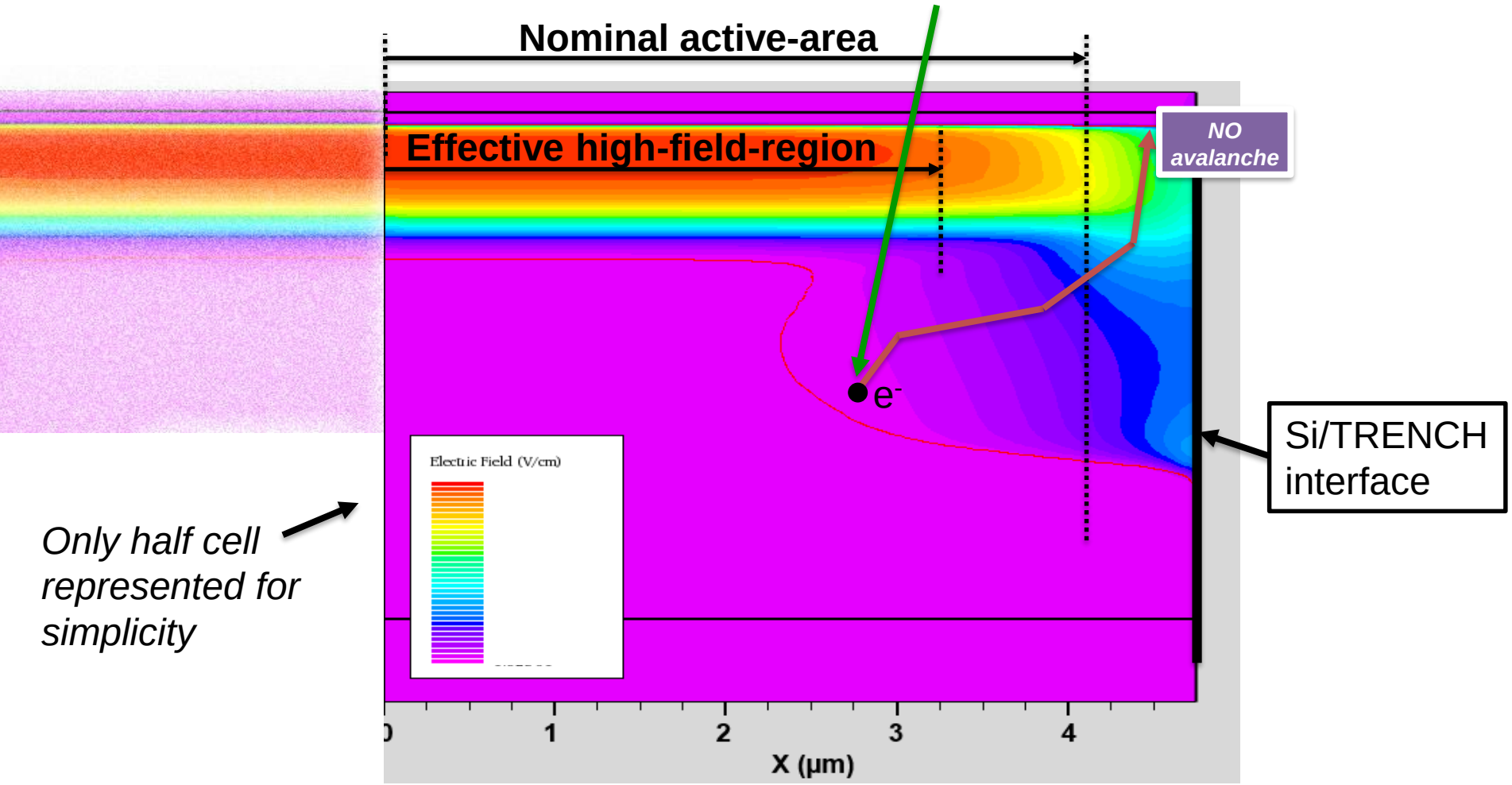


10 µm cell



- **Very fast signals**
- Good photon number resolution

Problem of very-small cell: border effect



TCAD Simulation: Electric Field
10µm cell @ 2V excess bias

border effect → new guard ring (NGR)

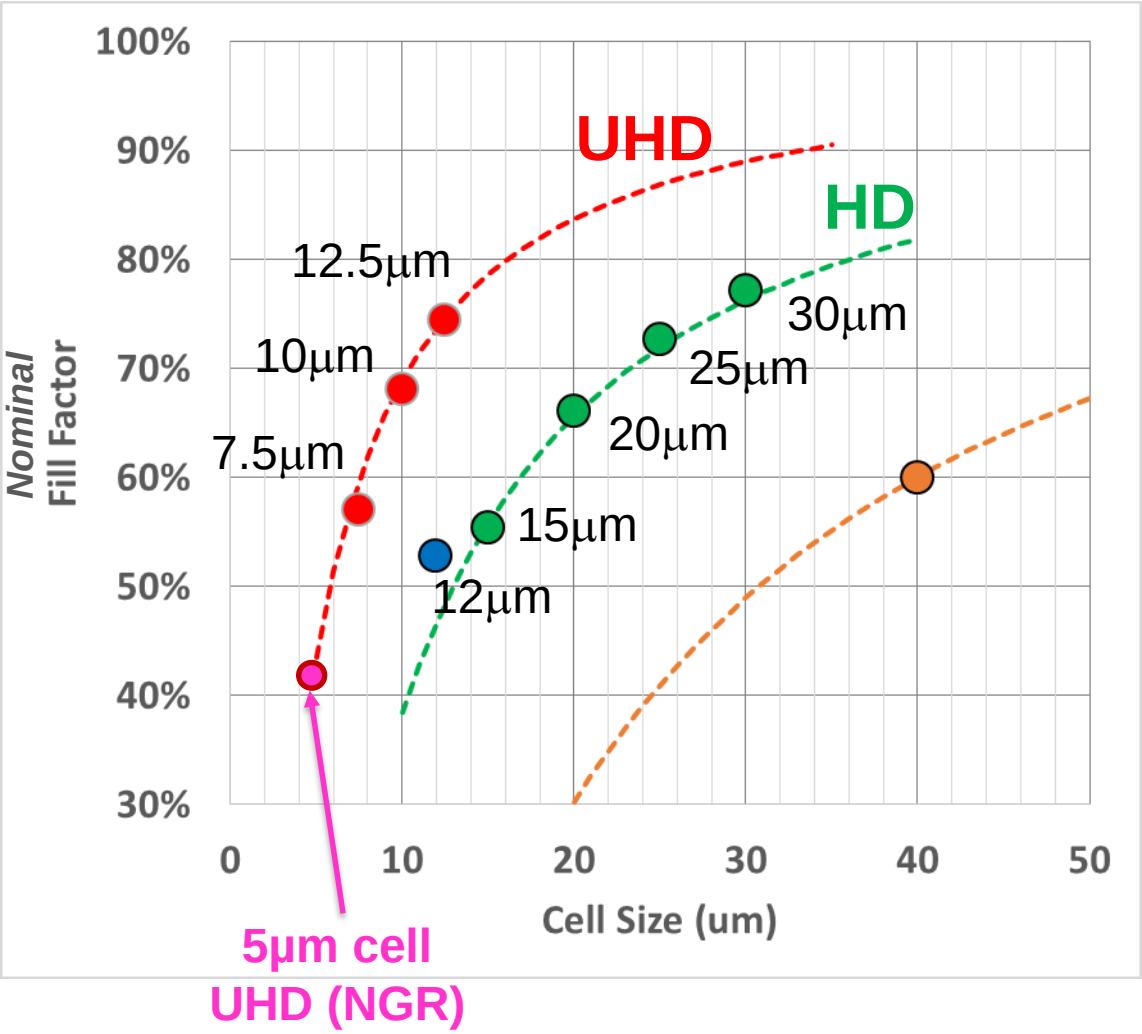
- **Border effect more and more important reducing cell dimension**
  - 7.5µm cell: half of the cell
  - 5µm cell: ALL the cell → prevent correct working of the SPAD

- **Border effect need to be reduced to improve effective FF → improve PDE**

- **NGR: new guard ring → <u>modified doping profile</u> in the SiPM cell**
  - Enhancement of electric field near the border
  - Reduction of depletion in the center of the cell

- **Simulation → functioning 5µm cell**

New UHD technology: std and NGR



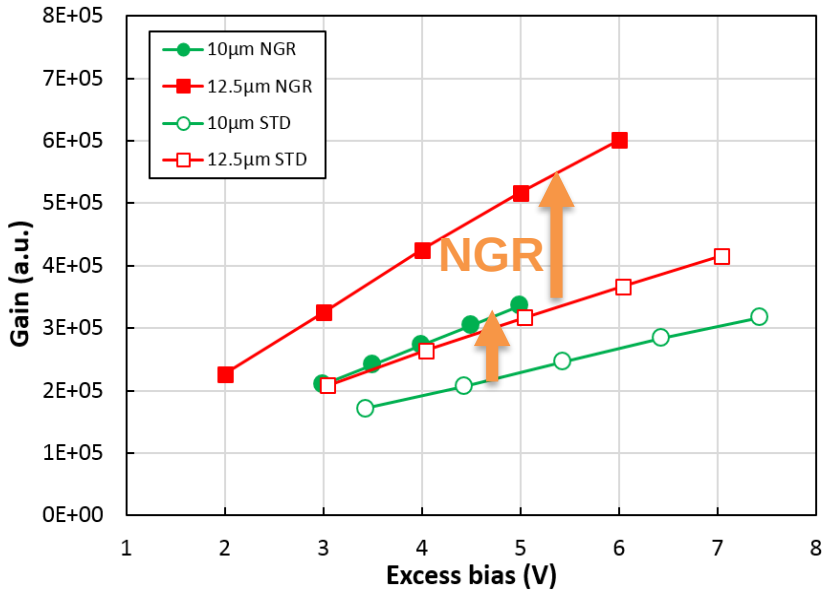
RGB-HD

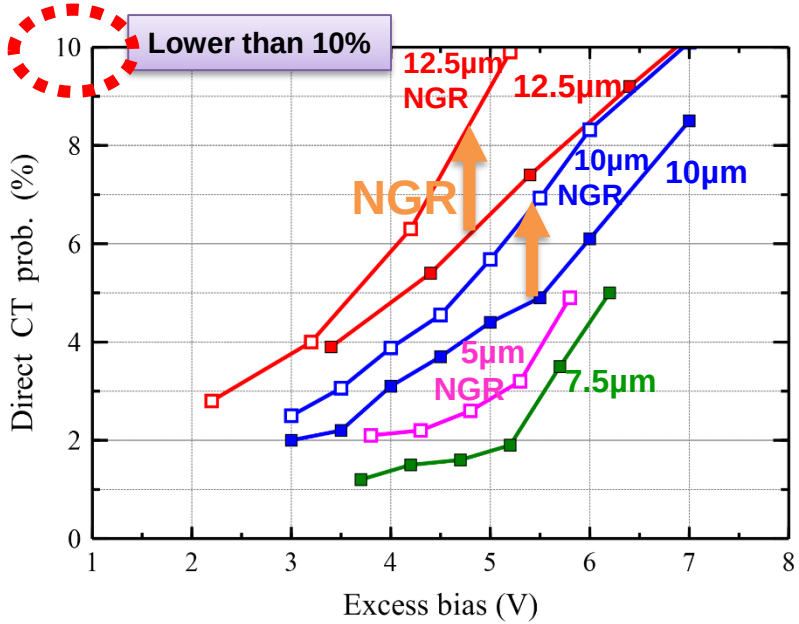
cell pitch (µm)	cells/mm²
30	1100
25	1600
20	2500
15	4500
12	7000

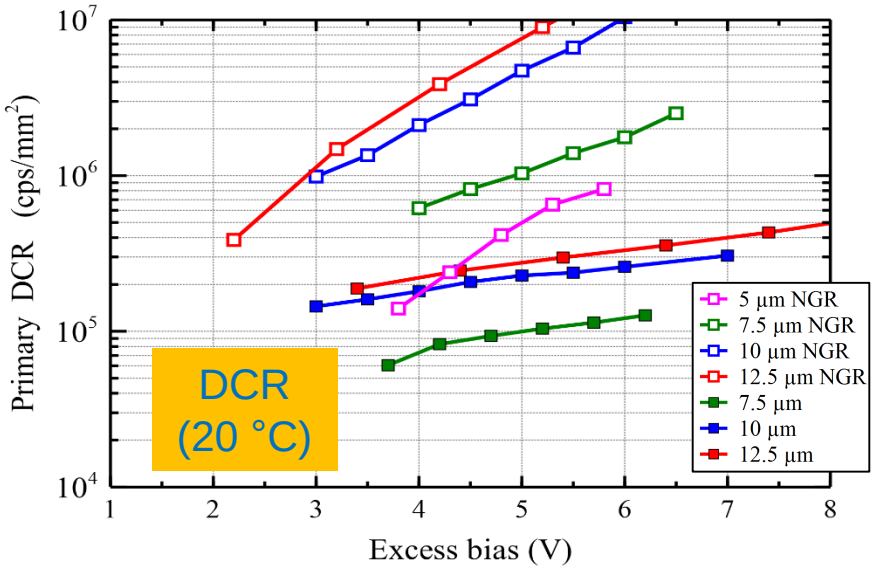
RGB-UHD

cell pitch (µm)	cells/mm²
12.5	7400
10	11550
7.5	20530
5	*46190*

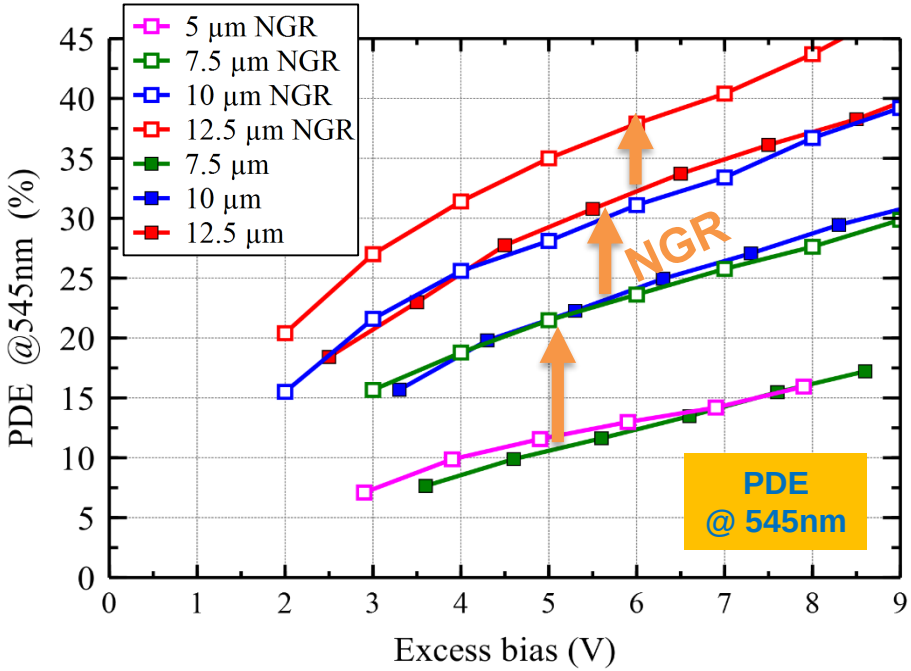
Cell GAIN & Cross-talk probability







Detection efficiency



- **Visible PDE improvement with NGR:**
  - 5µm-cell-NGR → same PDE of 7.5µm std
  - 7.5µm-cell-NGR → same PDE of 10µm std

Measurements after Irradiation

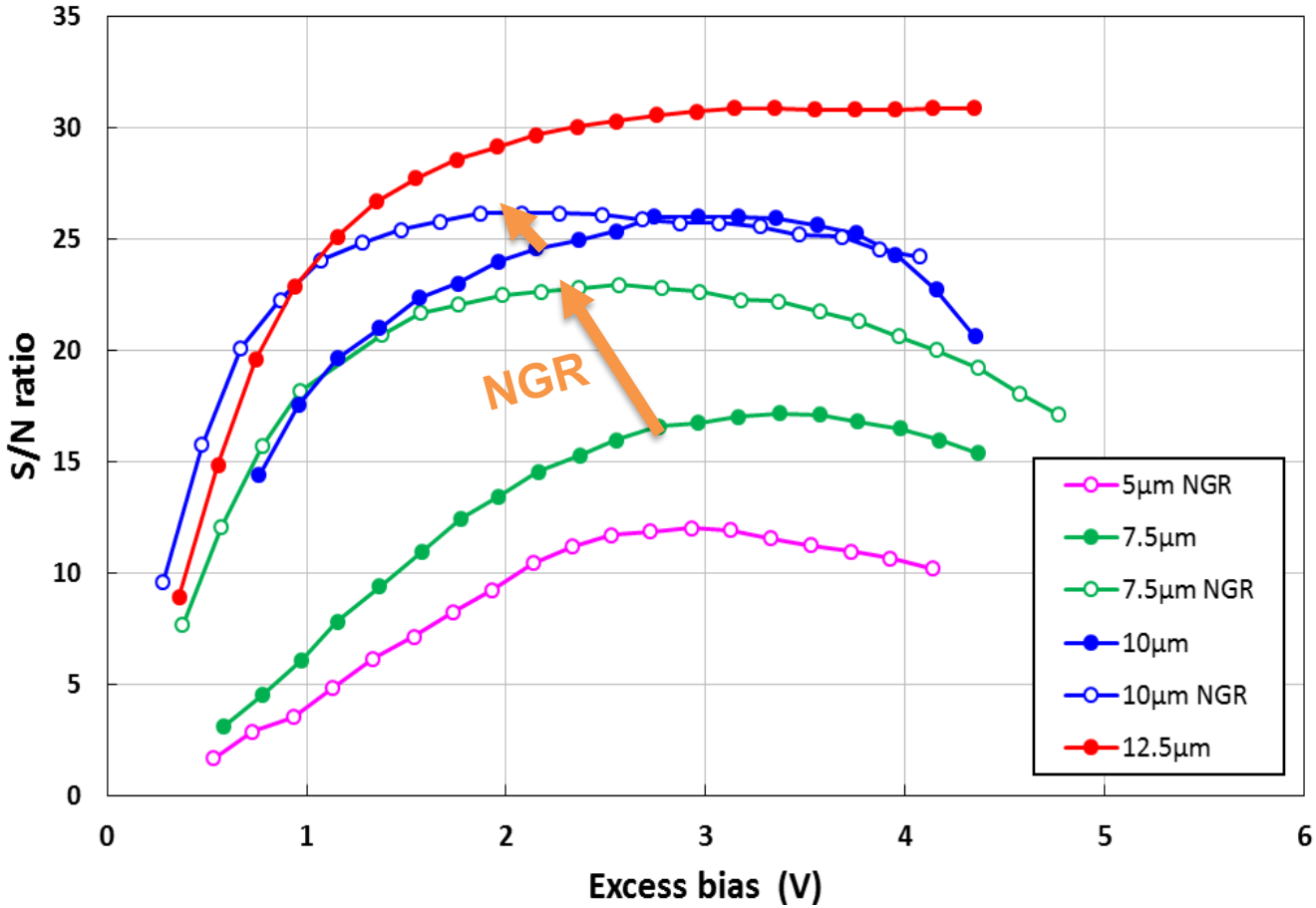
Measurements carried out by Y. Musienko and A. Heering @CERN, with a dose of **4E11 n/cm²**

with a controlled pulsed illumination

Signal defined as:
Npe/ENF

In dark conditions:

Noise defined as:
ENC(in 50ns)



Conclusions

- **Demonstrated the functionality of FBK UHD SiPM technology**
- **Improvement of "Novel guard ring" (NGR) approach increasing the effective-Fill-Factor → increasing the PDE**
- **5µm-cell SiPM working → with promising performances**
- **UHD-SiPM technology:**
  - *Very short recovery time constant: <10 ns*
  - *Good PDE: > 25% (7.5 um) and > 40% (12.5 um).*
- **Good potential for:**
  - future calorimeters, like CMS calorimeter Phase II Upgrade
  - Many other high-dynamic-range applications

Next Steps

- **New development → avoid DCR increment, but with high PDE**

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