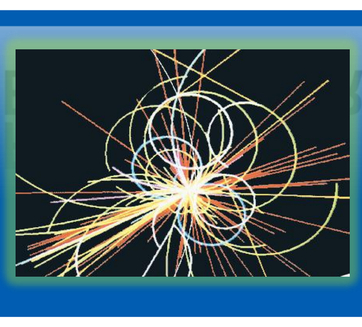
New Ultra-High cell-Density Silicon Photomultipliers (UHD-SiPM) with improved performance



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14th Pisa meeting on advanced detectors

Summary

In the recent years, FBK developed "high-density" silicon photomultipliers (HD-SiPMs) → deep trenches, obtaining small cells, high fill-factor (FF) → high photon detection efficiency (PDE).
New development → **Ultra-High Density SiPM** (RGB-**UHD**), with very small cell size. → **Cell pitches: 5 µm, 7.5 µm, 10 µm, 12.5 µm, 15 µm**.
Problem: in a very small cell, the "border effect" dramatically reduces the effective FF (much smaller than the nominal FF) → it is important to overcome this issue.
First solution: UHD-NGR: we **modified the doping profiles inside the cell** (i.e. the SPAD), developing the "new guard ring" (NGR) structure. → PDE is significantly improved but much higher DCR.
New solutions: based on new TCAD simulation we developed 2 new technological solution + cell layout optimization → **newest version of UHD-SiPM**, with **high PDE but lower DCR**.

UHD-SiPM technology

- **Aggressive layout** and technological features:
  - Non-active region reduced to ~1µm (including half of trench width)
  - SPAD with circular active area
  - Honeycomb configuration of cells

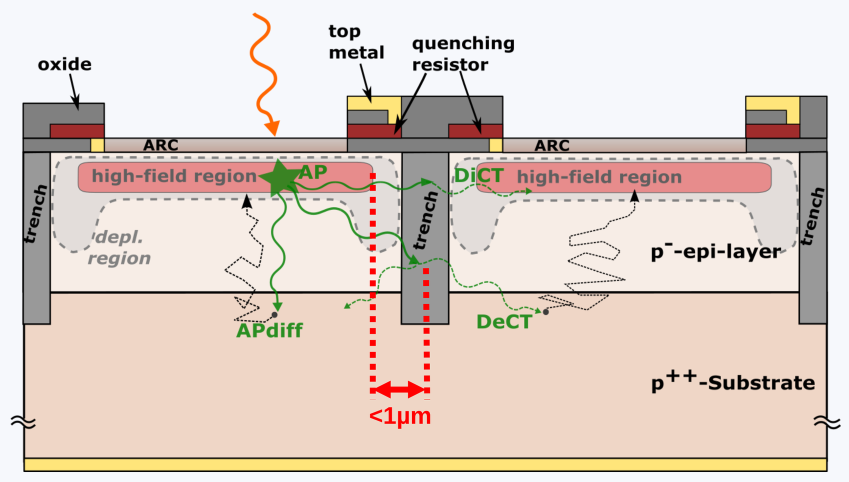

Fig.1: Cross-section of the UHD-SiPM cells, with trench separation

- Very **high cell density + fast cell recovery**
  - **5.0 µm cell → ~40000 cell/mm²**
  - **12.5 µm cell → ~7400 cells/mm²**
  - Very high dynamic range achievable

- High FF despite the very small cell pitch

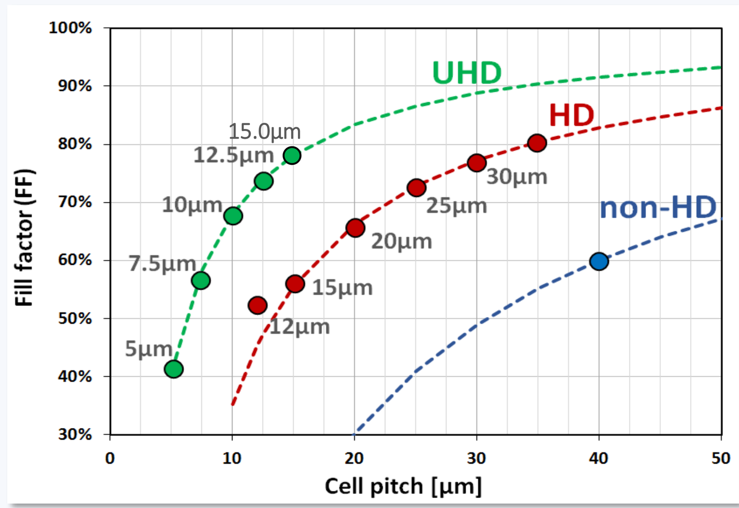

Fig.3: Nominal FF vs. cell pitch, for different technologies

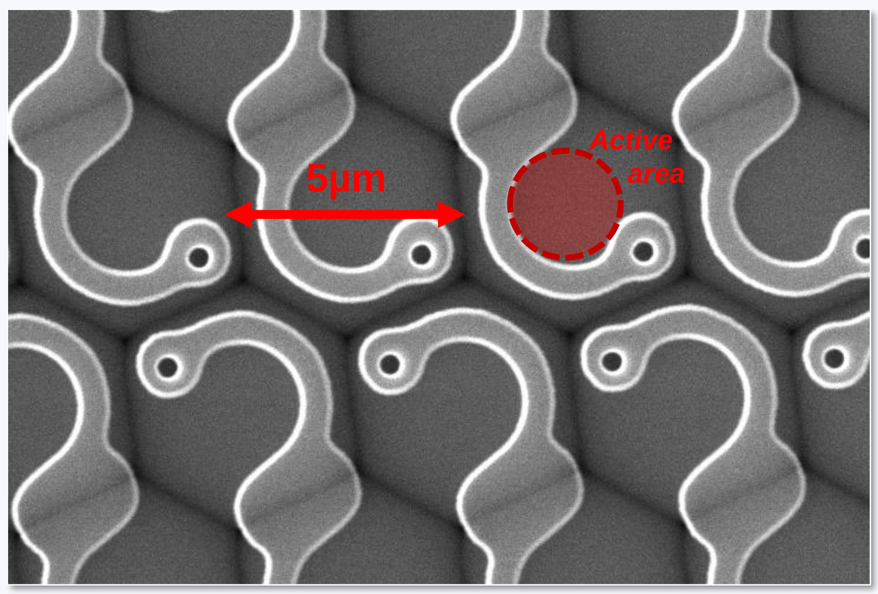

Fig.2: SEM image of 5µm pitch SiPM, showing hexagonal cells and polysilicon resistors on top

- **Applications: calorimetry** (high linearity + radiation hardness); gamma imaging in **proton therapy** (high linearity), **high-energy physics experiments** (radiation hardness), etc.

Problem: important dead-border

- UHD SiPMs have very small cell-pitch → very small SPAD size
  - Border region becomes very important.
  - *Effective active area significantly smaller* than design active area, eventually preventing correct working of the 5µm cell.

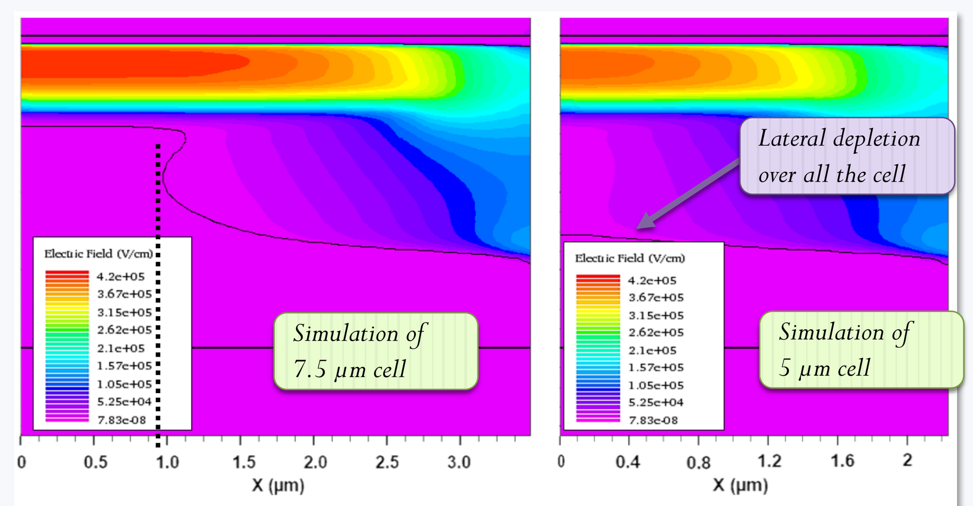

Fig.4: TCAD simulation of electric field in the SPADs (at breakdown voltage): SiPM with 7.5-µm cell pitch (left) and 5 µm cell pitch (right). In 5-µm cell case, the "central active area" is no more present

- 1st optimization with TCAD simulation → "new guard ring" structure has been developed in Q4-2016:
  - PDE significantly improved but primary noise was also significantly higher.
  - This was probably due to high electric field very close to the silicon/trench interface.

- *2nd (new) optimization of the structure* and fine tuning of high-field region distance from trenches.
  Results:
  - *New UHD NGR2 version*
  - *UHD low-field (LF) version*

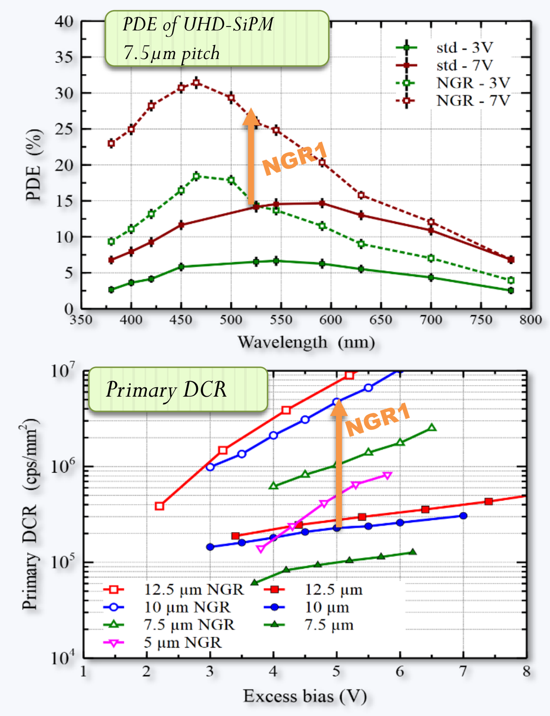

Fig.5: PDE (545nm) and DCR of old "std." and NGR1 SiPMs

New UHD SiPMs: optimized structures

- Tested and compared different structures, new low-field (LF) and the new "new guard ring 2" (NGR2) UHD-SiPMs → **RESULTs: optimized structures with low dark count rate, good PDE and fast signals.**

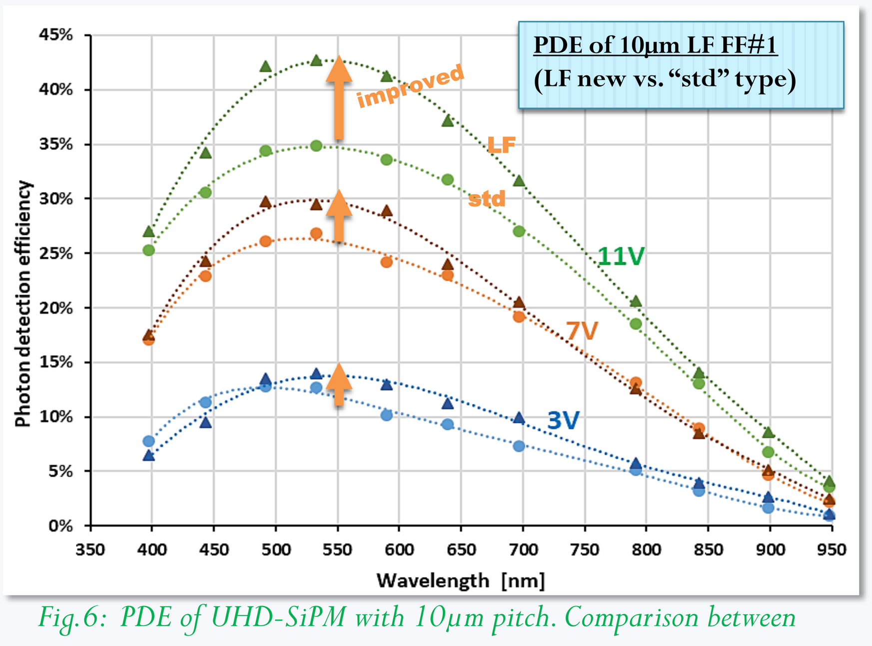

Fig.6: PDE of UHD-SiPM with 10µm pitch. Comparison between new LF vs. old std. version at 3V, 7V and 11V of excess bias.

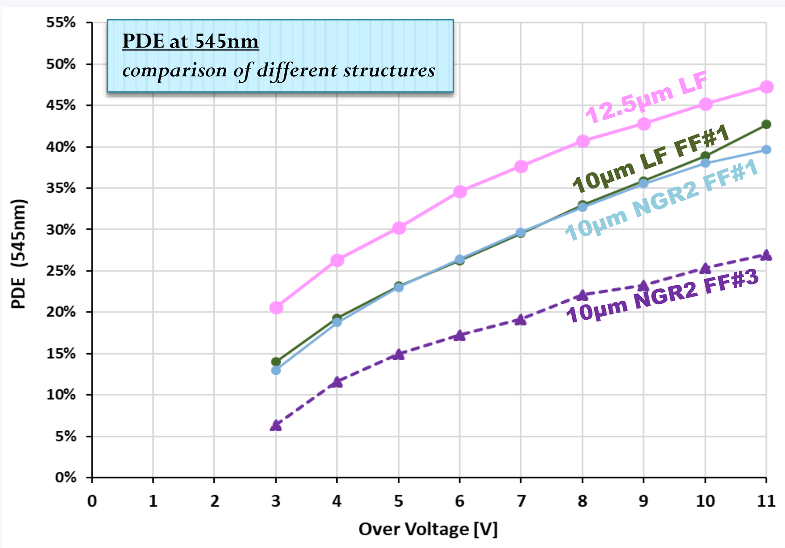

Fig.7: PDE comparison (at 545nm) of different UHD SIPMs: 10µm FF#1 SiPMs; 12µm LF SiPM and 10µm FF#3 SiPM.

Tested SiPMs

- *12.5µm LF SiPM*
- *10µm SiPM LF & NGR2 SiPMs*
  (tested different layouts → find best tradeoff PDE vs noise)
  FF#1=68%   FF#2=60%   FF#3=54%
- *7.5µm LF SiPM*
- *5µm NGR2 SiPM*

Optimization result: DCR comparable with "std" version, but PDE has been improved

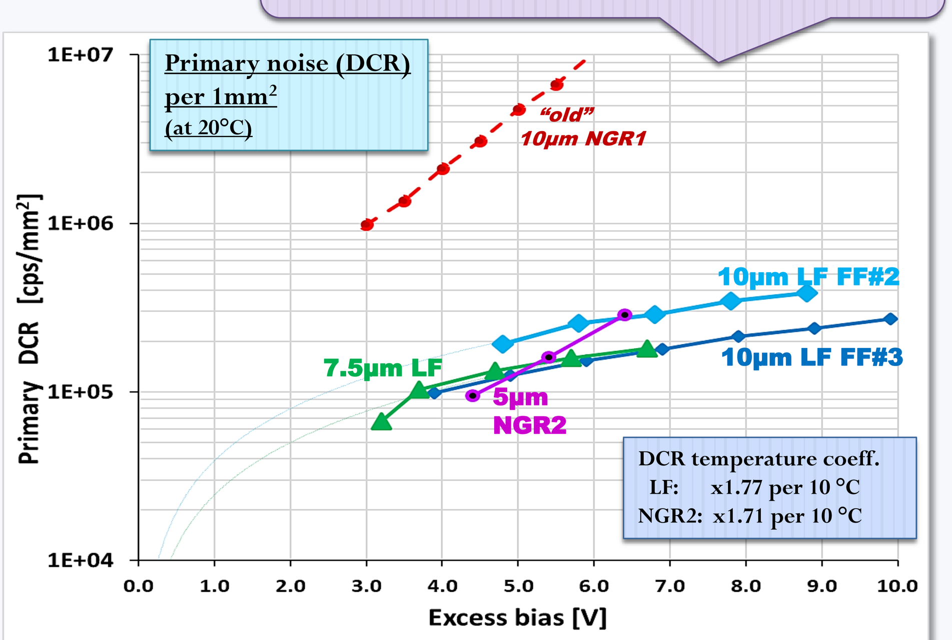

Fig.8: Primary dark count rate of UHD SIPMs (LF and NGR2), compared to "old" NGR1.

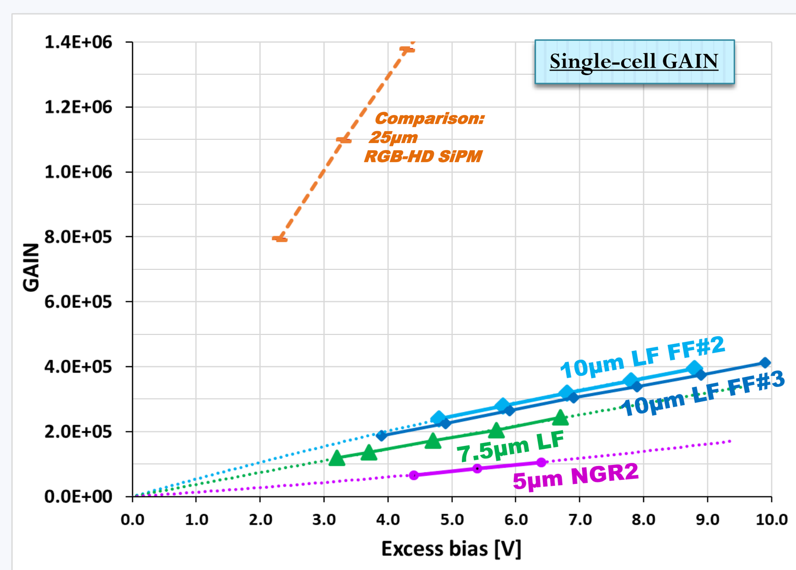

Fig.9: Single-cell gain of UHD SiPMs (compared with FBK high-density 25µm SiPMs.

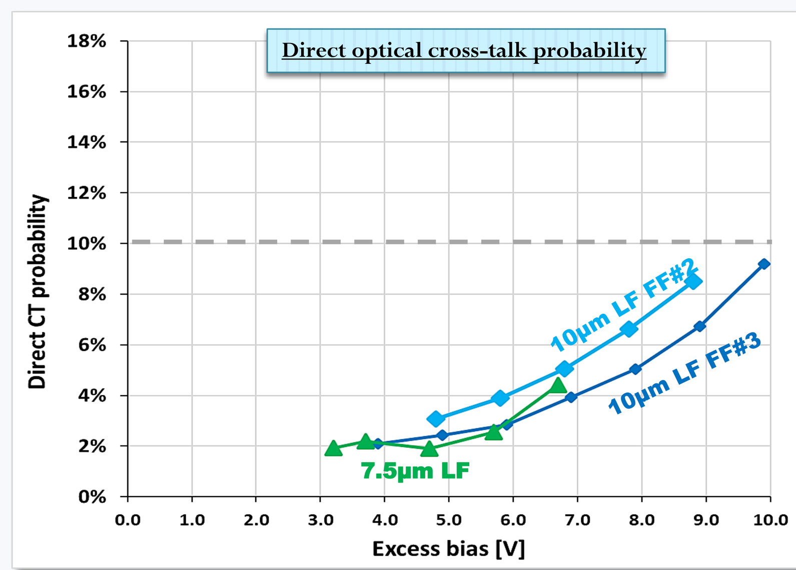

Fig.10: Direct crosstalk probability of UHD SiPMs

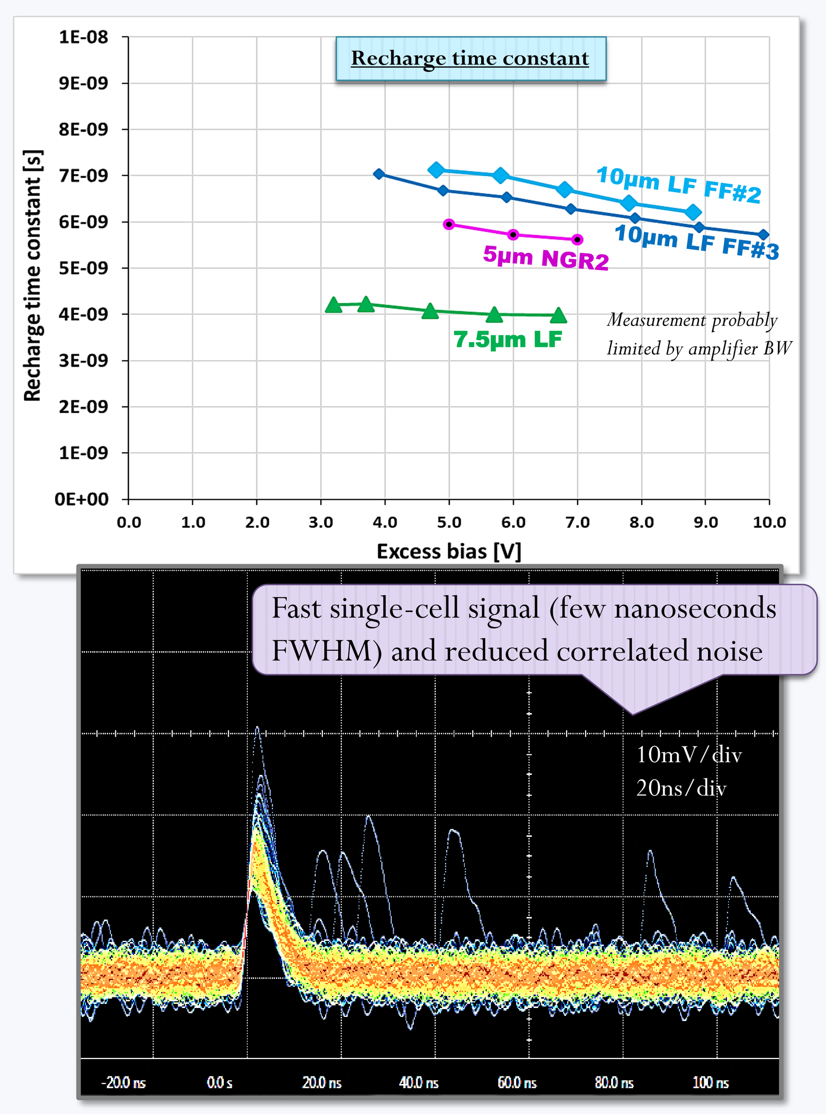

Fig.11: Recharge time constants (top) and screenshot from oscilloscope of single-cell signal of 7.5µm pitch SiPM (bottom).

Conclusions

- Ultra high density (UHD) SiPM technology has been developed and optimized during last years.
- The goal was to increase the effective FF, thus the detection efficiency, while not increasing the noise (dark count rate).
- As a result of the optimization → new upgraded versions, featuring modified edge structure and lower overall electric fields at the junction.
- Small cells provide increased radiation hardness. R&D is ongoing to reduce electric field in the cell, for further improved resistance to radiation damage.

References

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- F. acerbi et. al., IEEE j. of Selec. Topic. quant. Elect., v.24, n.2, p. 3800608, 2018.