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

Fabio Acerbi, Alberto Gola, Giovanni Paternoster, Claudio Piemonte, Nicola Zorzi

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

SPAD size: 5 ÷ 12μm

Very-small cells
ULTRA-High cell density

RGB-UHD

Normalized Photo Detection Efficiency

UV 420 nm 450 nm Blue 500 nm Green 560 nm Yellow 640 nm Red 700 nm

LaBr3 LYSO NaI(Tl) CsI(Na)
GSO BGO GAGG CaSO4(Tl) YAG
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
FBK Technology comparison

Example with 40 um cell

Example with 25 um cell

Example with 7.5 um cell
Applications of **very-small-cell** SiPM

- **Calorimetry**
  - CMS calorimeter Phase II Upgrade $\rightarrow$ *R&D funding.*
  - Reduced non-linearity at high energy $\leftarrow$ *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 $\rightarrow$ *less sensitive to the effects of radiation damage.*

- ... ... ... others ... ... ...

22/02/2017
Radiation Damage in small-cell SiPMs

- Increase in the primary noise (DCR).
- Increased afterpulsing (increased number of traps).
- PDE loss due to cells busy triggering dark counts.
- Increased power consumption due to higher DCR.

- Smaller cell  →  Lower gain reduces afterpulsing (for a given number of traps).
- Many, smaller cells with faster recharge  →  less PDE loss.
- Smaller cell  →  Lower gain less current (for a given DCR).
### UHD SiPM: first production

<table>
<thead>
<tr>
<th>Cell size (µm)</th>
<th>Cell density (cells/mm²)</th>
<th>Fill Factor (L = 0.75 um)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>20530</td>
<td>57.1%</td>
</tr>
<tr>
<td>10</td>
<td>11550</td>
<td>68.1%</td>
</tr>
<tr>
<td>12.5</td>
<td>7400</td>
<td>74.5%</td>
</tr>
</tbody>
</table>

Cell size: 7.5, 10, 12.5 µm

Cell density and fill factor data for different cell sizes.
Oscilloscope waveforms
(pulsed low-level light source)

7.5 µm cell
10 µm cell

• Very fast signals
• Good photon number resolution
Problem of very-small cell: border effect

Nominal active-area

Effective high-field-region

Only half cell represented for simplicity

Si/TRENCH interface

TCAD Simulation: Electric Field
10µm cell @ 2V excess bias
border effect $\rightarrow$ 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 $\rightarrow$ prevent correct working of the SPAD

- Border effect need to be reduced to improve effective FF $\rightarrow$ improve PDE

- **NGR: new guard ring** $\rightarrow$ modified doping profile in the SiPM cell
  - Enhancement of electric field near the border
  - Reduction of depletion in the center of the cell

- Simulation $\rightarrow$ functioning 5µm cell

22/02/2017
New UHD technology: std and NGR

### RGB-HD

<table>
<thead>
<tr>
<th>Cell Pitch (μm)</th>
<th>Cells/mm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>1100</td>
</tr>
<tr>
<td>25</td>
<td>1600</td>
</tr>
<tr>
<td>20</td>
<td>2500</td>
</tr>
<tr>
<td>15</td>
<td>4500</td>
</tr>
<tr>
<td>12</td>
<td>7000</td>
</tr>
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</table>

### RGB-UHD

<table>
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</tr>
<tr>
<td>7.5</td>
<td>20530</td>
</tr>
<tr>
<td>5</td>
<td>46190</td>
</tr>
</tbody>
</table>

**Nominal Fill Factor** vs **Cell Size** (μm)

- **UHD**
  - 12.5 μm
  - 10 μm
  - 7.5 μm
- **HD**
  - 25 μm
  - 20 μm
  - 15 μm
  - 12 μm
- **5 μm cell**
- **UHD (NGR)**
Cell GAIN & Cross-talk probability

Lower than 10%

DCR (20 °C)
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/cm$^2$

with a controlled pulsed illumination

Signal defined as: $N_{pe}/ENF$

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 \( \rightarrow \) increasing the PDE

• 5µm-cell SiPM working \( \rightarrow \) 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 \( \rightarrow \) avoid DCR increment, but with high PDE
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