Radiation damage on FBK SiPMs

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Silicon Photomultipliers

What is a SiPM?

What is a SiPM?

Anna Rita Altamura

16th TREDI
FBK SiPM technologies

RGB

RGB-HD

RGB-UHD

Optimized for cryogenic applications

NUV

NUV-HD

NUV-HD-LF

Ultra high cell density (Very small cells)
SiPM and radiation damage

High fluences in HEP experiments ...

... but losing performance in sensors

Irradiation test to check SiPMs radiation hardness

<table>
<thead>
<tr>
<th>Fluence</th>
<th>$I_{\text{dark/DCR}}$</th>
<th>GAIN</th>
<th>PDE</th>
<th>Rq</th>
<th>$V_{\text{bd}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium $\phi &lt; 10^{12}$ cm$^{-2}$</td>
<td>x(↑)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High $\phi &gt; 10^{12}$ cm$^{-2}$</td>
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</tbody>
</table>
Irradiation tests with protons

Proton irradiation tests → 2019, LNS Catania (Italy)

Gaussian beam at 61MeV with a non uniform irradiation along the sensors surface

Energy shift between the first and the last SiPM in the block
Irradiation tests with protons

- 10 technologies in a fluence range \((1.7 \times 10^8 \div 1.7 \times 10^{12}) \) n_{eq}/cm²

- SiPM type:
  - 1x1mm² \div 1.75mm² active area
  - Placed on bigger chip (test chip)
  - Different pitches

- All SiPMs have been annealed at room temperature for \(~1\) month before measurement

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>Characteristics</th>
<th>Cell pitch [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUV – HD lowCT 2015</td>
<td>N-type substrate. Peak sensitivity 400nm.</td>
<td>25 30 35 40</td>
</tr>
<tr>
<td>RGB – UHD LF 2017</td>
<td>Ultra high density. Lower electric field.</td>
<td>7.5 10 12 15</td>
</tr>
<tr>
<td>NUV-HD ULF 2019</td>
<td>Lower electric field. Small cell pitch.</td>
<td>12 15</td>
</tr>
</tbody>
</table>
Main investigation parameters

CURRENT
• **Leakage**: pre-breakdown current
• **Dark current**: post-breakdown current

DARK COUNT RATE
Primary noise due to deep-levels into the silicon, thus crucially affected by the damage

PHOTON DETECTION EFFICIENCY
\[ \text{PDE} = Q_e \times P_t \times \text{FF} \]

CORRELATED NOISE
• **Cross-Talk (optical)** between cells
• **Afterpulsing**
Results – Current

- Significant increase from $1 \times 10^9$ p/cm$^2$
- Dark current increasing of 2.5 decades after $1 \times 10^{11}$ p/cm$^2$
Results – Dark current increment

Useful information from the increase of dark current at excess bias 5V at +20C

\[ r = \frac{I_{after}}{I_{before}} \]

- Linear, then more than linear increment.
- Saturation at high fluences.
- More than factor $10^5$ increment in noise at $10^{11}$ proton/mm$^2$
Results – Dark Count Rate (primary noise)

Method → analysis of pulses: **Inter-arrival times**

- Peaks identification
- Amplitude calculation
- Inter-arrival time estimation

Method widely used in SiPM characterization,
BUT **no longer usable** when pulses are no more clearly distinguishable!
Results – Dark Count Rate (primary noise)

Current method

\[
DCR (V) = \frac{I_{dark}(V)}{q \times G(V) \times ECF(V)} = \frac{1}{q} \frac{I_{dark}(V)}{G_c(V)}
\]

- Pulsed 420nm LED connected to a fiber at -20C
- Charge integration Q
- Number of photons counting

\[
n_{ph} = \frac{Q}{PDE \times G_c}
\]

\(G_c\) steady up to \(3.4 \times 10^9\) p/mm² at least

Proved effectiveness of the current method

To estimate DCR from \(I_{dark}\) the assumption of \(G_c\) not changing with fluence must be verified
Results – Optical Crosstalk between cells

- Evidence of a slight increase of the DiCT due to the high noise
- Low efficiency in the program for highly damaged SiPM
- Correction factor useful to fix the issue
  \[ p = 1 - \left[ 1 - \frac{DCR_{1.5}}{DCR_{0.5}} \right] \cdot \exp(DCR_{0.5} \cdot \tau) \]
- Clear improvement visible in the results
Results – Photon Detection Efficiency

PDE constant up to $1.2 \times 10^8$ p/mm$^2$

Still no efficient method for estimation of PDE at high fluences due to the noise

From Gc measure PDE not changing with fluence up to $\sim 10^9$ p/mm$^2$
Results – Breakdown voltage

Interesting to determine if breakdown voltage is changing after irradiation:
used several methods to identify $V_{bd}$

1. Maximum of First Logarithmic Derivative (FLD)
2. Maximum of Second Logarithmic Derivative (SLD)
3. Minimum of Inverse Logarithmic Derivative (ILD)
4. Maximum of Normalized First Derivative (NFD)
5. Bias at Amplitude equal to zero ($A$)
6. Bias at Gain equal to zero with only two points ($G_2$)
7. Bias at Gain equal to zero with all points ($G_{all}$)

$V_{bd}$ constant up to $2.3 \times 10^9$ p/mm$^2$
Results – Arrhenius plot and Activation Energy

Activation energy extracted from linear fit of Current vs 1000/T in range (-15÷15)°C

At least two $E_a$ levels and clear saturation effects
Results – Emission Microscopy

Secondary photons emission

Hot carrier luminescence (HCL) due to accelerated carriers suddenly losing their energy in high electric field regions.

In SPADs secondary photons emission in avalanche multiplication process.

Single cell 35µm x 35µm
Results – Emission Microscopy

Counting of points inside and outside the internal circle changing the intensity thresholds
Results – Emission Microscopy

- Hotspots mostly located on the border of the cells
- Further upgrades of the study will hopefully lead to a full localization of the defects in the cell
Conclusions

- Significantly worsening of the CURRENT between $10^8$ and $10^{11}$ p/mm$^2$

- Trend of $I_{after}/I_{before}$
  - No linearity with fluence $I_{after}/I_{before}$
  - Possible saturation effect starting between $10^{10}$ and $10^{11}$ p/mm$^2$

- Increase of the DCR as expected from literature
  - Up to 6 order of magnitude increment between 0 –$10^{11}$ p/mm$^2$
  - Significant bulk damage
  - No changes in gain current

- No significant changes in DiCT, $V_{bd}$ and Gain
  - No significant variation in doping concentrations.

- Decrease of the activation energy with some saturation effects at high fluences

- High defect concentration on the border of the cells from EMMI measurement
THANK YOU