SiPM characteristics after very high Radiation at low Temperature for the SLHC CMS PHASE II upgrade

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- 2 future CMS sub detectors which are planning on using SiPMs

- General experience from last > 10 years of R&D on raddam on SiPMs

- Results of latest Wafer run with FBK on thin epitaxial layer substrate

- Main effects of raddam at very high doses > 5E13 n/cm2 1 Mev eq
CMS - CEH EndCap for Phase II

Active Elements:
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H

Key Parameters:
- CE covers 1.5 < η < 3.0
- ~215 tonnes per endcap
- Full system maintained at -30°C
- ~600m of silicon sensors
- ~500m² of scintillators
- 6M Si channels, 0.5 or 1 cm² cell size
- ~27000 Si modules
- Power at end of HL-LHC: ~110 kW per endcap

Electromagnetic calorimeter (CE-E): Si, Cu & CuW & Pb absorbers, 28 layers, 25 X₀ & ~1.3λ.
Hadronic calorimeter (CE-H): Si & scintillator, steel absorbers, 24 layers, ~8.5λ.

1 MeV eq Neutron fluence up to 8E13 n/cm²

We expect a signal of ~ 40 p.e/MIP

Signal to Noise is very important for calibration

SiPM-on-Tile in the biggest part of CE for high granularity to compliment CE-E
Bench measurement of the timing dependence of the $N_{\text{phe}}$ and DCR using an LED with a pulse of 390 p.e. and time spread of 350 ps rms. At $2E14$ n/cm$^2$ eq. the DCR is expected to rise to 40–60 GHz even at an operating temperature inside the tracker tube of -30C. The DCR noise term will quickly be the dominating factor in the timing resolution.
DCR or Noise increase in SiPMs due to rad

Leakage current increase in Si-PIN diodes for 1 MeV equivalent dose

slope = 3.5E-17 A/cm

Measurements show ~4X more noise

We expect the dark count rate:
Dark Count = 1/q * V * \( \Phi \) * slope * G.F. * \( P_{(V)} \)

\( V = \) cell size * \( d_{epi} \) (few microns in case of SiPM)

The dark noise generation rate in APDs/SiPMs is dominated by high electric field effects mainly by tunneling via radiation-induced defects or traps in Si
**Before Irradiation:**
Primary dark count rate is due to the thermal generation of carriers; $1/T$ (reduction of $2.4 \times$ every 10°C)

**After irradiation** we find that temperature reduction coefficient drops to as low as $1.6 / 10°C$ depending on the internal electric field structure of the SiPM

General trend is that SiPMs with higher Vbr have larger reduction with T
In 2018 we chose the best 3 SiPMs with the best performance vs irradiation for the BTL as a TDR baseline. All cell sizes are 15x15 micron to avoid saturation due to high DCR. This also reduces the recovery time.
FBK wafer split for optimization

<table>
<thead>
<tr>
<th>Wafer n.</th>
<th>Substrate</th>
<th>Technology</th>
<th>DI dose</th>
<th>Meas Vbr (RT)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Thin Epi</td>
<td>Low Field</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Thin Epi</td>
<td>Low Field</td>
<td>1</td>
<td>38.0</td>
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<tr>
<td>3</td>
<td>Thin Epi</td>
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<td></td>
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<tr>
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<tr>
<td>10</td>
<td>Thin Epi</td>
<td>Low Field</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

In addition each wafer has 2 different micro cell versions one aggressive for better FF

15 micron STD : 51.2 %
15 micron HFF : 60.1 %
Irradiation in ceramic Package of the wafers

We packaged the 8 different Types in a 8ch ceramic package

3 of these arrays were sent to JSI for passive irradiation for a total dose of 1E13, 2E14 and 4E14

For direct comparison we also included 3 HPK 3x3 mm HDR2 for each dose
Average number of photons in LED pulse is measured using XP2020 calibrated: PMT (QE(410 nm)=25.0 %, ENF=1.15), and waveforms recorded by DSO
To measure S/N after irradiation we use constant light illumination from 405 nm LED source (calibrated uniform over the 8ch):

\[ I_{\text{total}} = I_{\text{ph}} + I_{\text{dark}} = (I'_{\text{ph}} + I'_{\text{dark}}) \times \text{Gain} \times \text{ENF} \quad \text{with ENF} \approx 1 \]

\( I'_{\text{ph}} \) and \( I'_{\text{dark}} \) are the primary generated currents (before amplification)
\( I_{\text{total}} \) and \( I_{\text{dark}} \) are measured simultaneously (LED On and LED off)

\[
\text{Phcurrent} = \frac{I'_{\text{ph}}}{1.6 \times 10^{-19}} \\
\text{DCR} = \frac{I'_{\text{dark}}}{1.6 \times 10^{-19}} \\
S/N = \frac{\text{Phcurrent}}{\text{DCR}}
\]
Silicon Annealing vs temperature

- We use 60C for 80 min to simulate RT annealing
I(\text{ph}) measured before and after irradiation

Dose = 1.4E13 n/cm eq.

I(\text{ph}) is unchanged after irradiation and annealing:
Hence PDE, Gain and ENF are unchanged at this dose
DCR after irradiation of $1.4 \times 10^{13}$ n/cm$^2$

Currents reach 2 mA at 3V over voltage which starts to cause self heating of the SiPM.
405 nm, T=-31 °C

$S/N$ ratio

$0.0E+00$ $1.0E+04$ $2.0E+04$ $3.0E+04$ $4.0E+04$ $5.0E+04$ $6.0E+04$

V-VB [V]

- HDR2, $S/N$
- W9C
- W7C
- W4C
- W2C
Previously measured Vbr shift with rad

Using the CERN IRRAD 24 GeV proton beam we irradiated a 8 ch Array with 10 micron HPK S12572 SiPMs

Due to Change of the doping concentration:
VB shift with fluence reaches 4 V at 2.2E14 n/cm²

Vbr = 66 V at zero dose
Measured Breakdown voltage shift at 2E14

HDR2-3015 SiPM (T= -29.4 °C)

<table>
<thead>
<tr>
<th>Fluence [n/cm²]</th>
<th>36</th>
<th>5E+13</th>
<th>1E+14</th>
<th>2E+14</th>
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<td>∆VB at 2E14n/cm² [V]</td>
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<td>0.25</td>
<td>0.5</td>
<td>0.75</td>
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</table>

VB at RT [V]

![Graph showing the relationship between fluence and breakdown voltage shift.]

**FBK Wafer 9,7,4,2 HHF (C) (T= -31°C)**

DI dose

Bari oct. 2019

A. Heering, CMS collaboration
Other EFFECT we found at 2E14 is QE loss

This could be a combination of; Recombination of e-h in top p+ layer and Browning of protective resin used (under investigation)
FBK thin epi after 2E14

FBK with thinner top p+ layer
R&D on the use of mini peltiers

Power consumption vs $\Delta T$

- $\Delta T$ of -20C without extra power
- Annealing at +60C during LHC shutdowns

Advantage of the use of mini peltiers:

Power consumption vs $\Delta T$

- Before irradiation
- After 4E14 n/cm$^2$
Summary

After successful replacement of HPDs with SiPMs in the CMS HCAL in the last 6 years with a neutron dose of max $2 \times 10^{12} \text{n/cm}^2$

We now plan to also use them in two more sub-detectors in CMS: HGCAL and BTL.
This bring significant new challenges due to the large fluence of $2 \times 10^{14} \text{n/cm}^2$ 1MeV eq. (Even though we will operate at -30C)

- Large DCR linear with the fluence
- Breakdown voltage shift due to change in doing concentration
- Self heating of the SiPMs due to the large gain
- Loss of PDE in front p+ layer and/or the protective resins used

We like to thank FBK and Hamamatsu for the commitment to this project and the progress made in the last years to improve the SiPMs for these projects

R&D will continue.....
SiPM, T=22 C

\[ y = 0.4198x^3 - 4.8388x^2 + 21.277x + 3.6737 \]