Performance of irradiated FBK 3D sensors for the ATLAS ITk pixel detector

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Inner Tracker (ITk): a new silicon tracking detector in preparation for the ATLAS upgrade at the HiLumi-LHC

Pixel: R&D phase to find the best solution, as a compromise between radiation tolerance and performance

Details of the latest design version: https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/ITK-2020-002/

5 layer of pixels:
- L4: Planar sensors
- L3: Planar sensors
- L2: Planar sensors
- L1: Planar sensors
- L0: 3D sensors
  - Barrel: 25x100 μm²
  - Endcap: 50x50 μm²

Barrel at 34 mm from collisions
- Dose up to 1.8e16 n_{eq}/cm²

L0 triplet modules
- barrel: 288
- endcap: 900
L0 of the ITk Pixel detector will be equipped with 3D sensors:
- 25x100 µm$^2$ in the barrel → linear triplet modules to be placed on stave
- 50x50 µm$^2$ in the endcap → curved triplet modules to be placed on ring

In the last years, several R&D production of wafers by FBK:
- Batch 2: Mask aligner, 130 µm active thickness
  - 5 wafers: 2 to Leonardo and 3 to IZM
- Batch 3: Stepper, 150 µm active thickness
  - 11 wafers: 2 to Leonardo and 2 to IZM

Sensors 1x2 cm$^2$ compatible with the RD53A chip
- Assembled in modules (3D sensor + RD53A chip) on card (SCC)

In this talk, a summary of results from FBK 3D sensor irradiated modules:
- Moreover, also diodes test structures irradiated and tested
- Meanwhile FBK, CNM and SINTEF foundries are preparing for pre-production
- ATLAS institutes are preparing for ITk module assembly and test
  - Briefly introducing the triplet module and an assembly method (Genoa)

18/02/2021
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Recent results from 6 RD53A modules built from batch 3 sensors (150 µm active thickness)
- Irradiated uniformly at CYRIC (70 MeV protons)
- Fluence: 1.0e16 n_{eq}/cm^2
- TID: 700 Mrad

2 sensors from wafer 27 (thinned)
- F03_27_25x100-1E_D4.1 → damages to chip WBs → in lab, measured IV
- F03_27_50x50-1E_E6.5 → damages to chip WBs → in lab, measured IV

2 sensors from wafer 27 (thinned)
- F03_27_25x100-1E_D10.4 → sensor OK, but problematic chip → only IV
- F03_27_25x100-1E_D11.2 → sensor high current, while chip OK → only IV

2 sensors from wafer 30 (not thinned)
- F03_30_50x50-1E_E3.3 → sensor and chip OK → IV and testbeam data →
- F03_30_25x100-1E_D9.5 → sensor and chip OK → IV and testbeam data →

Testbeam data results shown today for E3.3 and D9.5
- Data taking at DESY in October 2020
• Data taking at DESY II 6 GeV electron beam
• Chip tuning: Differential Front End
• Top right corner: bumps damaged → no hits recorded there
• Hit detection efficiency higher than 97% above 90 V bias
  • Confirmation of many experimental results from other pixel modules irradiated to $1.0\times10^{16} \text{n}_{\text{eq}}/\text{cm}^{2}$
  • Testing modules irradiated to $1.0\times10^{16} \text{n}_{\text{eq}}/\text{cm}^{2}$ has become a routine
  • Planning an irradiation campaign up to $2.0\times10^{16} \text{n}_{\text{eq}}/\text{cm}^{2}$ at Los Alamos in June 2021

• Unexpected behaviour of D9.5
  • Decreasing efficiency at higher $V_{\text{eff}}$
  • Let’s take a look at the charge collection!

18/02/2021
• D9.5 (25x100 µm²) module, ToT tuning: 10ke @ 10BC
• ToT vs charge calibration extrapolated by injecting 3-to-10ke charge
• Cluster ToT converted in charge exploiting the calibration
• Higher V bias $\rightarrow$ cluster ToT $\rightarrow$ collected charge $\rightarrow$ efficiency
  • At 97% efficiency, collected 8.5 ke charge (75% of 11ke expected)

$V_{\text{eff}} = 36$ V
Eff = 84.9 %

$V_{\text{eff}} = 85$ V
Eff = 97.5 %
• Again, exploiting the calibration curve, the collected charge was extrapolated from the cluster ToT
• Tuning of D9.5 was not effective: ToT & charge decreased when increasing V bias \(\rightarrow\) could explain eff. drop

<table>
<thead>
<tr>
<th>(V_{\text{eff}}) [V]</th>
<th>Cluster ToT MPV</th>
<th>Charge [ke]</th>
<th>Eff [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>75.4</td>
<td>4.8</td>
<td>4.2</td>
<td>88.9</td>
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<tr>
<td>87.6</td>
<td>5.7</td>
<td>6.1</td>
<td>93.8</td>
</tr>
<tr>
<td>96.0</td>
<td>6.4</td>
<td>7.5</td>
<td>97.8</td>
</tr>
</tbody>
</table>

(70% of 11ke expected in 150 µm)

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</thead>
<tbody>
<tr>
<td>71.4</td>
<td>6.7</td>
<td>6.8</td>
<td>96.5</td>
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<tr>
<td>80.6</td>
<td>6.6</td>
<td>6.8</td>
<td>95.4</td>
</tr>
<tr>
<td>86.0</td>
<td>6.0</td>
<td>5.2</td>
<td>93.7</td>
</tr>
</tbody>
</table>
- 3D sensor + RD53A chip modules
- Irradiated at different facilities
- Different annealing times

IV of irradiated 1x2 cm² sensors
• 3D sensor + RD53A chip modules
• Irradiated at different facilities
• Different annealing times

• IV measured in different conditions:
  • Dots: in lab, -25°C
  • Squares: at testbeam, -45°C
• 3D sensor + RD53A chip modules
• Irradiated at different facilities
• Different annealing times

• IV measured in different conditions:
  • Dots: in lab, -25°C
  • Squares: at testbeam, -45°C

• Not visible effect of active thickness:
  • Blue: Batch 2, 130 µm a.t.
  • Red: Batch 3, 150 µm a.t.
• 3D sensor + RD53A chip modules
• Irradiated at different facilities
• Different annealing times

• IV measured in different conditions:
  • Dots: in lab, -25°C
  • Squares: at testbeam, -45°C

• Not visible effect of active thickness

• Negligible effect of additional dose:
  • Blue: 0.5e16 n_{eq}/cm^2
  • Red: 1.0e16 n_{eq}/cm^2
• 3D sensor + RD53A chip modules
• Irradiated at different facilities
• Different annealing times

• IV measured in different conditions:
  • Dots: in lab, -25°C
  • Squares: at testbeam, -45°C

• Not visible effect of active thickness

• Negligible effect of different dose

• Not significant effect of pixel size:
  • Blue: 25x100
  • Red: 50x50
• 3D sensor + RD53A chip modules
• Irradiated at different facilities
• Different annealing times

• IV measured in different conditions:
  • Red dots: in lab, -25°C
  • Blue squares: at testbeam, -45°C

• Power dissipation:
  • Not possible to disentangle effects
  • Some early breakdowns → avoid!
  • Most IVs increase around 100-150 V
    • Power diss. still below 20 mW/cm²
2 mm² diodes (n⁺ columns shorted together) were produced together with modules inside FBK wafers
- Irradiated to 1.0 and 1.5e16 nₑq/cm² with neutrons at JSI reactor, Lubiana
- IV measured at -25°C (ITk operation temperature) in climate chamber
- Spread between different diodes higher than the effect of higher dose (1.0 to 1.5e16 nₑq/cm²)
- 25x100 µm² performs better with respect to 50x50 µm² (lower current → lower power dissipation)
- Power dissipation around 20 mW/cm² in the range 100-150 V of bias voltage (> 97% effic. since 80-90 V)
- Small size diodes, contribution of the edges → 20 mW/cm² limit is therefore conservative
While FBK, CNM and SINTEF produce pre-production sensors

ITk institutes involved in the R&D on module assembly & test

6 teams: Genoa, Milan, Trento, Barcelona, Oslo, Bergen

Assembly is done by gluing 3 bare modules to a flexible PCB

- High precision in the bare module placement: ~50 µm
- Uniform layer of Araldite 2011
  - Achieved by stamping the glue on the flexible PCB
- Flexible PCB is placed on top of the 3 bare modules

As soon as the assembly procedure is verified

- First production of triplet modules (sensor + RD53A)
- Then, modules with 3D sensor + ITkPixV1 chip will follow
Summary

• In the last years, several 3D sensor wafers were produced by FBK for R&D towards HiLumi-LHC application
• 1x2 cm² sensors bonded to RD53A chips were irradiated and tested
• Both 25x100 and 50x50 µm² sensors irradiated to 1.0e16 n_{eq}/cm² reach 97% detection efficiency at ~90V
• 97% efficiency is reached when the sensor collect at least ~8ke
  • This corresponds to a charge collection efficiency of the 70% (11ke deposited in 150 µm a.t. sensor)
• Leakage current very similar between 0.5 and 1.0e16 n_{eq}/cm²
  • Seen also in diodes irradiated to 1.0 and 1.5e16 n_{eq}/cm² (spread larger than effect of the radiation)
• At 1.0e16 n_{eq}/cm², operating voltage would be around 100-150 V
  • At this voltage, power dissipation below 20 mW/cm²
• More systematical study with diodes (small area 2x2 mm²)
  • Clearly visible that 25x100 dissipate less than 50x50 µm²
• INFN Genoa started R&D for assembling triplet modules
• In the next months few triplet prototypes will be assembled
• Then, the pre-production of ITkPixV1 chip modules will follow
  • Ongoing pre-production of 2x2 cm² 3D sensors
    • FBK and SINTEF focusing on 50x50 µm²
    • CNM focusing on 25x100 µm²

Some of these results in a summary paper just accepted: https://www.frontiersin.org/articles/10.3389/fphy.2021.624668/abstract