Performance of Edgeless Silicon Pixel Sensors on p-type substrate for the ATLAS High-Luminosity Upgrade

G.Calderini$^1$, A.Bagolini$^2$, M.Bomben$^1$, M.Boscardin$^2$, L.Bosisio$^3$, J.Chauveau$^1$, A.Ducourthial$^1$, G.Giacomini$^2$, A.La Rosa$^4$, G.Marchiori$^1$, N.Zorzi$^2$

$^1$LPNHE Paris  $^2$FBK-CMM
$^3$Università Trieste and INFN  $^4$Uni-Geneva

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Edgeless or active edge pixel sensors are critical in configurations such as innermost layers or tiled modules, where not enough space (or too much complicated) to design an overlap.

Example: ATLAS IBL overlap in phi but not along z

Just as a factoid: in original ATLAS pixels, guard ring region is 1.1 mm wide!

In the ATLAS IBL (n-in-n) the guard-ring region reduced to 450um and pixels pushed below GRs to recover efficiency.
Many techniques developed in the years to extend the efficient region to the sensor edge.

- **Scribe-Cleave-Passivate**
  - NRL + SCIPP (UCSC)

- **Diffusion**
  - FBK

- **Implantation**
  - VTT
FBK/LPNHE productions: n-in-p active edge pixel sensors

Deep trench diffusion (to prevent electrical field on the damaged cut)

Cut line

Uniformity of trench filling is critical.

4.5 μm wide
200 μm deep trench

Deep trench diffusion (to prevent electrical field on the damaged cut)
First active edge production we did with FBK dates back to 2013

- 9 FE-I4 type Sensors (50μm x 250μm Pixels)
  - 0, 1, 2, 3, 5, 10 GRs
  - Different $n^+ \rightarrow$ trench distances
- 4 FE-I3 Sensors (50μm x 400μm Pixels)
  - 1 or 2 GRs
- TestPixels/Pad
  - 0, 1, 2, 3, 5, 10 GRs
  - Different $n^+ \rightarrow$ trench distances
- DC Strip Sensors
Electrical characterization

P-spray dose: $3 \times 10^{12}/\text{cm}^2$

P-spray dose: $5 \times 10^{12}/\text{cm}^2$

PARIS PAE w216 with FP -- without FP

Bump-bonded to FE-I4 at IZM (Sr90)
Example: LPNHE5, featuring 100 µm pixel-to-trench distance and no GRs
2 more modules available; not enough beam-time to measure them

Configurations tested

<table>
<thead>
<tr>
<th># Events</th>
<th>$V_{bias}$</th>
<th>Seuil</th>
<th>angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>2M</td>
<td>-30 V</td>
<td>2000 e</td>
<td>0</td>
</tr>
<tr>
<td>2M</td>
<td>-40 V</td>
<td>2000 e</td>
<td>0</td>
</tr>
<tr>
<td>2M</td>
<td>-40 V</td>
<td>1600 e</td>
<td>0</td>
</tr>
<tr>
<td>4M</td>
<td>-40 V</td>
<td>1600 e</td>
<td>15</td>
</tr>
</tbody>
</table>
Tested on beam (I): DESY
(4 GeV electrons)

Example: LPNHE5, featuring 100 µm pixel-to-trench distance and no GRs
2 more modules available; not enough beam-time to measure them

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<td>0</td>
</tr>
<tr>
<td>2M</td>
<td>-40 V</td>
<td>1600 e</td>
<td>0</td>
</tr>
<tr>
<td>4M</td>
<td>-40 V</td>
<td>1600 e</td>
<td>15</td>
</tr>
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</table>
In-pixel efficiency

- Analysis limited by multiple scattering

> 95% almost everywhere

No inefficiency due to bias rail (temporary metal, see next slide)
Some inefficiency due to charge sharing
Temporary metal at FBK

Technical solution allowing to remove the metal grid used to bias pixels during tests. After the metal removal, no inefficiency left due to bias network.
Hit-efficiency at the edge

- Hit-efficiency above 90% up to 40 µm outside the last pixel
- No good tracks beyond -50 µm ➔ this is also due to track quality cuts in testbeam reconstruction
Space resolution

- Analysis limited by the multiple scattering: $\sigma_{\text{MS}} \sim 30 \mu m$

- X: RMS $\sim 80 \mu m$; pitch/$\sqrt{12} \sim 72 \mu m$

- Y: RMS $\sim 34 \mu m$; pitch/$\sqrt{12} \sim 14 \mu m$

- Results consistent with expectations

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Charge sharing

- Analysis limited by multiple scattering

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Irradiation at KIT
One sample irradiated to a dose = $1 \times 10^{15}$ neq/cm$^2$
(26 MeV protons)
Tested on beam (II): CERN

Measured at SPS (120 MeV protons)

We were hoping to show the plot of hit-efficiency at the edge or the x and y resolution with high energy protons but ...

... the testbeam was only two weeks ago and the data is still being analyzed.

Qualitative elements (integrated maps, correlations telescope-DUT etc. look ok)
Among other things, production used as test-bench to develop Power Board architectures

These sensors are used in the framework of a EU program of collaboration between University and Industry (IAPP). We have setup a common test-bench in C.A.E.N. at Viareggio (Italy) for the development of new HV power supply boards, in particular we optimized the architecture/specs of the new A1541/1542 cards.

It was a prototype last year

Now it is in production
New productions: FBK-AE-2 (collaboration INFN-FBK-LPNHE)

2014-15: FBK moved to 6”: first test production Silicon on Silicon (SiSi) wafers.

- No active edge, just preparation
- Sensor wafer thicknesses: 100 µm and 130 µm
- Shared ATLAS and CMS production
  10 FEI4 (ATLAS) + 30 PSI46 (CMS)
  + test structures
- Production finished, electrical tests ok
- Flip-chip almost completed
New productions: FBK-AE-3 (collaboration INFN-FBK-LPNHE)

- Late 2015, early 2016: new planar active production
- Based on DWB wafers of the same kind as mentioned in the previous slide

- Layout similar to previous production
- More aggressive designs for single FEI4 chip sensors
- Some RD53 chip-compatible sensors
- ATLAS: 1 double FEI4 chip sensor per wafer for the ALPINE layout

Detail of a “Mountain” sensor, specific for the Alpine layout
Alpine stave
Conclusions and future developments

- Active-edge sensors production in 4” at FBK finished and tested
- Un-irradiated and irradiated modules on testbeams (DESY/CERN)
- Data rather consolidated, positive results
- CERN high energy proton data still missing

- FBK 6” first production (no active-edge) delivered and tested. Flip-chip underway

- FBK 6” first production (active-edge) ready to go as soon as we’ll have feedback from the other one
Additional material
FBK/LPNHE active edge

<table>
<thead>
<tr>
<th>Doped region</th>
<th>impurity</th>
<th>function</th>
<th>peak value (cm(^{-3}))</th>
<th>reference value (cm(^{-3}))</th>
<th>rolloff (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel and CR</td>
<td>D</td>
<td>gaussian</td>
<td>$2 \times 10^{19}$</td>
<td>$10^{16}$</td>
<td>1.0</td>
</tr>
<tr>
<td>Back</td>
<td>A</td>
<td>gaussian</td>
<td>$2 \times 10^{19}$</td>
<td>$10^{16}$</td>
<td>1.0</td>
</tr>
<tr>
<td>Trench</td>
<td>A</td>
<td>erf</td>
<td>$2 \times 10^{19}$</td>
<td>$10^{12}$</td>
<td>2.0</td>
</tr>
<tr>
<td>Bias tab</td>
<td>A</td>
<td>gaussian</td>
<td>$2 \times 10^{19}$</td>
<td>$2 \times 10^{16}$</td>
<td>0.5</td>
</tr>
<tr>
<td>P-spray</td>
<td>A</td>
<td>gaussian</td>
<td>$5 \times 10^{16}$</td>
<td>$7 \times 10^{15}$</td>
<td>0.5</td>
</tr>
<tr>
<td>P-stop</td>
<td>A</td>
<td>gaussian</td>
<td>$5 \times 10^{17}$</td>
<td>$7 \times 10^{16}$</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 3: Implant parameters for simulated detectors; A (D) is for acceptor (donor) impurities.

<table>
<thead>
<tr>
<th>Multiplicity</th>
<th>Number of GRs</th>
<th>pixel-to-trench distance (µm)</th>
<th>Type</th>
<th>Energy (eV)</th>
<th>$\sigma_p$(cm(^2))</th>
<th>$\sigma_h$(cm(^2))</th>
<th>$\eta$(cm(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>100</td>
<td>A</td>
<td>$E_G$ -0.42</td>
<td>$9.5 \times 10^{-15}$</td>
<td>$9.5 \times 10^{-14}$</td>
<td>1.613</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>100</td>
<td>A</td>
<td>$E_G$ -0.46</td>
<td>$5.0 \times 10^{-15}$</td>
<td>$5.0 \times 10^{-14}$</td>
<td>0.9</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>100</td>
<td>D</td>
<td>$E_V$ +0.36</td>
<td>$3.23 \times 10^{-13}$</td>
<td>$3.23 \times 10^{-14}$</td>
<td>0.9</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>200</td>
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<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>300</td>
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<td></td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>400</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Table 4: Relevant parameters for acceptors (A) and donor (D) deep levels in the bandgap, describing the radiation damage.

Qox = $10^{11}$ cm\(^2\), $3 \times 10^{12}$ cm\(^2\)
Global hit efficiency

Average efficiency vs V_bias

- Threshold = 2000 e
- Threshold = 1600 e

✓ Above 98% for all configurations
✓ Best configuration: above 99%

Example of eff. map
Cluster and collected charge properties

- Lower threshold and larger bias voltage $\Rightarrow$ larger clusters

- $15^\circ$ data $\Rightarrow$ more than 60% of clusters with more than 1 pixel

- Lower threshold and larger bias voltage $\Rightarrow$ more charge

- $15^\circ$ data $\Rightarrow$ significant correlation between cluster size and cluster charge

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Setup

**Mainframe Crate:** CAEN SY4527
16-boards capacitance, controlled by A4528 CPU Full

**HV board:** A1541N

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of Channels</td>
<td>32 (Common Floating Return)</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>0÷500 V</td>
</tr>
<tr>
<td>Max. Output Current</td>
<td>10 mA</td>
</tr>
<tr>
<td>Voltage Set Resolution</td>
<td>10 mV</td>
</tr>
<tr>
<td>Voltage Monitor Resolution</td>
<td>1 mV</td>
</tr>
<tr>
<td>Current Set Resolution</td>
<td>200 nA</td>
</tr>
<tr>
<td>Current Monitor Resolution</td>
<td>10 nA</td>
</tr>
<tr>
<td>VMAX hardware</td>
<td>0÷500 V common for all the board channels</td>
</tr>
<tr>
<td>VMAX hardware accuracy</td>
<td>1 V</td>
</tr>
<tr>
<td>VMAX software</td>
<td>0÷500 V settable for each channel</td>
</tr>
<tr>
<td>VMAX software resolution</td>
<td>1 V</td>
</tr>
<tr>
<td>Ramp Up/Down</td>
<td>1÷50 Volt/sec, 1 Volt/sec step</td>
</tr>
<tr>
<td>Voltage Ripple</td>
<td>&lt; 10 mVpp (Max) full load</td>
</tr>
<tr>
<td>Maximum output power</td>
<td>5 W per channel</td>
</tr>
<tr>
<td>Power consumption</td>
<td>A1541: 320 W @ full power</td>
</tr>
<tr>
<td></td>
<td>A1541L, A1541S: 240 W @ full power</td>
</tr>
<tr>
<td></td>
<td>A1541D: 120 W @ full power</td>
</tr>
</tbody>
</table>

**Readout:** ATLAS USBPix