Sub-pixel characterization of innovative 3D trench-design silicon pixel sensors using ultra-fast laser-based testing equipment

A. Lampis on behalf of the TimeSPOT team

16th (Virtual) "Trento" Workshop on Advanced Silicon Radiation Detectors
Outline

- Sensor non uniformity contribution to a charged particle detector time resolution

- Laser based setup

- Sensor characterization:
  - Amplitude maps
  - Time of Arrival maps

- Comparison between trench sensor and column sensor
Sensor non-uniformity $\sigma_{un}$

The sensor signal is produced by the drift of the charge carriers created along the path of the (charged) particle across the pixel volume, this charge motion induces an instantaneous current at the readout electrode defined as

$$i = q \vec{E}_w \cdot \vec{v}_d$$

If $\vec{E}_w \cdot \vec{v}_d$ is as uniform as possible inside the active volume the signals do not depend on where the charged particle has crossed the detector:

- $\vec{E}_w$ uniform by design
- work in a velocity saturation regime
The trench-type TimeSPOT 3D pixels

- **55µm x 55µm pixels** (to be compatible with existing FEE, for example the Timepix family)

- In each pixel a **40µm long n++ trench** is placed between continuous p++ trenches used for the bias

- **150µm-thick active thickness**, on a 350µm-thick support wafer

- The collection electrode is **135µm deep**
TimeSPOT silicon sensor

First batch produced in 2019 at Fondazione Bruno Kessler (FBK, Trento, Italy)

Many devices fabricated (single, double pixels, pixel-strips, 256x256 pixel matrices)
Laser-based setup

Laser setup allows to emulate the energy deposit of a MIP passing through the sensor

- Pulsed laser:
  - IR Laser (1030 nm), FWHM < 200 fs

- Optical fiber from laser to microscope.

- Focused spot of $\sim 5 \mu m$

- Observation camera

- XY closed loop stages

- Optical laser time reference: accuracy $<1ps$
The time reference is itself a TimeSPOT 3D sensor but stimulated with high intensity (∼10 MIP).

\[ \Delta t \]

\[ \sigma_t = \sqrt{\sigma_{laser}^2 + \sigma_{detector}^2} \]

\[ \sigma_t = \frac{\sigma}{\sqrt{2}} = 0.9 \text{ ps} \]
The sensor scan

- Labview software to perform the sensor scan:
  - XY closed loop stages move the sensor with respect to the laser beam → **scanning step 1 μm**
  - Oscilloscope acquires sensor’s waveforms and perform the measurements

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Measurements

- Measurements performed via 8 GHz oscilloscope 20 GSa/s
- Averaged waveform to reduce electronic noise contribution:
  \[ \sigma = \sqrt{\sigma_{un}^2 + \sigma_{ej}^2} \]
- For each position we measured:
  - Sensor signal amplitude
  - Time of Arrival (ToA) of laser pulses

\[ \text{ToA} = t_{\text{sensor}} - t_{\text{ref}} \]

\( t_{\text{sensor}} \) and \( t_{\text{ref}} \) by CFD @ 50% of amp

<table>
<thead>
<tr>
<th>Meas Group 1</th>
<th>Current</th>
<th>Max</th>
<th>Min</th>
<th>Mean</th>
<th>RMS</th>
<th>( \sigma ) (5-dev)</th>
<th>Event count</th>
<th>Wave count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>91.7 mV</td>
<td>94.862 mV</td>
<td>89.328 mV</td>
<td>90.58 mV</td>
<td>90.582 mV</td>
<td>496.03 pV</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Area</td>
<td>-12.591 pV*s</td>
<td>-2.5543 pV*s</td>
<td>-26.863 pV*s</td>
<td>-12.772 pV*s</td>
<td>12.843 pV*s</td>
<td>1.3498 pV*s</td>
<td>500</td>
<td>500</td>
</tr>
<tr>
<td>Delay</td>
<td>-645.96 ps</td>
<td>-641.93 ps</td>
<td>-649.33 ps</td>
<td>-647.41 ps</td>
<td>647.41 ps</td>
<td>916.77 ps</td>
<td>500</td>
<td>500</td>
</tr>
</tbody>
</table>
Why a sensor scan?

In a test beam characterization you only look to the signals that fulfil a trigger condition (in general a threshold in the DUT signal amplitude)

- How do you ensure you are looking at all the sensor active region?

- For trench design we don’t expect high disuniformity but is it true also for a more classic 3D geometry?

The laser scan allows to measure the **detailed response of the full sensor active area**
**Device Under Test**

**PIXEL STRIP:** 10 pixels with readout electrodes shorted together

**Front End Electronic board**

- **Electronic** optimized for the TimeSPOT sensors
- Two stages of **transimpedance amplifier** with ultra low noise SiGe Bjt allows to read very fast sensor’s current

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ToA map

ToA extremely uniform

Biassing trench

Metal

Readout trench

20 ps

50 V
- Slower regions near the readout trench due to holes drift velocity

- Trend confirmed: as the sensor bias increases the slower zones become faster (the holes drift velocity get closer to saturation)

Trench pixels produce extremely uniform ToA but increasing the bias voltage they become even more uniform

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Device Under Test: Hexagonal pixel

3D column electrodes

- Guard ring
- Hexagonal pixel
- 30μm
- Wire bonding
- Same front end electronic board

Sultan, D M S. (2017). Development of Small-Pitch, Thin 3D Sensors for Pixel Detector Upgrades at HL-LHC. DOI: 10.13140/RG.2.2.36253.82403/1

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Amplitude Map: 3D Hexagonal
ToA map: 3D Hexagonal

Standard 3D geometry has a very high spread in ToA

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Trench vs Hexagonal

For good timing, it’s not important to be fast but to be uniform!
- Electric field maps for several 3D sensors geometries

Electric field maps are less uniform for all column geometries with respect to trench design.
Conclusion

- We built a setup that allows to accurate study the timing performances of different sensors geometries

- Unlike test beam and radioactive source characterizations we measured a detailed response of the full sensor active area

- The 3D trench TimeSPOT sensors have shown an excellent timing performance with respect to more classic 3D geometry
Outlook

- New sensor production at FBK is completed:
  - New test structures, to continue the characterization of these innovative 3D pixels
  - Matrix of pixels for bump bonding
- Characterization of pixels matrix read with optimized VLSI electronics (CMOS 28nm)

S. Cadeddu’s talk

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