First characterization of TI-LGAD technology in a test beam setup

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The TI-LGAD technology

Goal: Sensor with small pixels (<= 100 um) and high Fill Factor (> 80%).

TI-LGAD FBK RD50 production:

- Trenches: 1 or 2.
- Contact type: “Ring” or “dot”.
- Pixel border: “V1” < “V2” < “V3” < “V4”.
- Trench depth: “D1” < “D2” < “D3”.
Test beam setup

Simplified diagram:

- CERN H6 beamline (120 GeV pions)
- Mimosa telescope
- Chubut 2, 4 channels readout board¹
- CAEN DT5742 digitizer, 500 MHz @ 5 GS/s
- Cold box for irradiated DUTs, down to -12 °C
- Tracks reconstruction using Corryvreckan²

¹ https://github.com/SengerM/Chubut_2
² https://project-corryvreckan.web.cern.ch/project-corryvreckan/
Test beam setup

Some photos:
Waveforms analysis

We record the waveforms, then process them offline*. Example:

* https://github.com/SengerM/signals
Tested devices

- All from FBK RD50 TI-LGAD production
- Same physical layout and connection →
- 8 DUTs, details in table below ↓

<table>
<thead>
<tr>
<th>device_name</th>
<th>wafer</th>
<th>trench process</th>
<th>trench depth</th>
<th>trenches</th>
<th>pixel border</th>
<th>contact type</th>
<th>Fluence (neq/cm²)</th>
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</thead>
<tbody>
<tr>
<td>T1116</td>
<td>16</td>
<td>P2</td>
<td>D3</td>
<td>1</td>
<td>V3</td>
<td>dot</td>
<td>0.0E+0</td>
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<td>V3</td>
<td>ring</td>
<td>1.0E+15</td>
</tr>
</tbody>
</table>

* Devices were irradiated with reactor neutrons at JSI, Ljubljana.
** “device_name” can be ignored, it is shown here for curious readers who may want to see details from the examples.
Results
Waveforms distribution and events selection

- Each dot is one waveform
- Color denotes channel

* This example is for one DUT, they all look similar.

Example: This waveform has amplitude = 100 mV and \( t_{50} = 125 \) ns
Waveforms distribution and events selection

- Hits have large amplitude and well defined time.
- Empty waveforms have small amplitude (noise) and random time.
Waveforms distribution and events selection

A threshold in amplitude defines what we consider a hit in a pixel:
Tracks and hits on DUTs

- Each dot is a track
- Colored according to which channel was hit
- Tracks reconstruction using Corryvreckan¹

* This example is for one DUT, they all look similar.

¹ Corryvreckan - CERN

This gap is due to the trigger device
Charge sharing in TI-LGADs

We look at the cluster size, i.e. number of active pixels per hit.

Example for two DUTs:

- W16 D3 1T V2 ring, 0 n\textsubscript{eq} cm\textsuperscript{-2}
- W16 D3 1T V3 ring, 0 n\textsubscript{eq} cm\textsuperscript{-2}

* This example is for two DUTs, they all look similar.
Charge sharing in TI-LGADs

Only ~1% of events share charge, low value consistent with expectation.

Example for two DUTs (similar for all of them):

- W16 D3 1T V2 ring, 0 $n_{eq} \text{ cm}^{-2}$
  - Count: 8280

- W16 D3 1T V3 ring, 0 $n_{eq} \text{ cm}^{-2}$
  - Count: 7770

* This example is for two DUTs, they all look similar.
Efficiency vs position

Efficiency = \frac{\text{Number of detected particles}}{\text{Number of particles that went through}}

This DUT was measured as a control DUT, knowing it has a larger inter-pixel distance. Here we can see it.

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W16 D3 1T V2 ring, 0 \( n_{\text{eq}} \) cm\(^{-2} \)

W16 D3 1T V3 ring, 0 \( n_{\text{eq}} \) cm\(^{-2} \)

Larger no-gain area
Efficiency profile

What’s the efficiency profile along two pixels?
Efficiency profile

Select tracks within these strips and project along x and y
Efficiency profile

- W16 D3 1T V3 ring
- 0 $n_{eq}$ cm$^{-2}$
- 230 V
- Room T
Efficiency profile

- W16 D3 1T V3 dot
- $0 \text{n}_{\text{eq}} \text{ cm}^{-2}$
- 230 V
- Room T

![Efficiency Profile Diagram]

- [Zoom in]
Irradiated TI-LGADs
Waveforms distribution for irradiated TI-LGAD

- **W7 D2 1T V3 ring**: Low noise, amplitude threshold at -5 mV ✓ (same as non irrad)
- **W16 D3 1T V2 ring**: Noisier → higher amplitude threshold & less gain → lower efficiency 😞

* During the test beam a single voltage point was taken, it is possible that if e.g. 490 V instead of 500 V would have been applied, the noise would be greatly reduced.
Efficiency profile

- W7 D2 1T V3 ring
- $1 \text{n}_{\text{eq}} \text{ cm}^{-2}$
- 525 V
- -12 °C
Effective efficiency
Effective efficiency

Efficiency measured in an area of the same size as a pixel. To avoid edge effects, take it close to the center:

- Global efficiency that a large area sensor would have
- Thanks to DUT symmetry, it is translation invariant
- Higher statistics
Effective efficiency

Two graphs are shown, comparing the effective efficiency at different fluences for two pixel borders, V2 and V3. Each graph contains data points representing different contact types: ring and dot. The x-axis represents fluence in units of $10^{15}$ $n_{eq}$ cm$^{-2}$, and the y-axis represents the effective efficiency in percentage. The graphs show a comparison of the efficiency between the two contact types and pixel borders.
Effective efficiency

Before irradiation, inefficiency is only due to inter-pixel distance, ordering is consistent with TCT studies.*

Inter-pixel distance (IPD)

Assuming all inefficiency before irradiation is due to fill factor, we can estimate an "effective IPD"

$$\text{fill factor} = \frac{(\text{pitch} - \text{IPD})^2}{\text{pitch}^2}$$
Effective efficiency

After irradiation, gain loss contributes to inefficiency, in the same way as for the standard LGAD technology.
Effective efficiency

Pixel border V2 is better when new, but after irradiation it may suffer more due to higher voltage.*

* Unfortunately only one voltage point was taken for V2, it may happen that reducing the voltage a bit fixes this issue and efficiency goes up again.
Conclusions

- TI-LGAD samples were characterized in a test beam setup.
- Before irradiation, $99.2 \pm 0.2 \%$ efficiency measured.
- After $1 \times 10^{15} \text{n}_{eq} \text{cm}^2$ with reactor neutrons, $97.4 \pm 0.6 \%$ efficiency measured.
- Charge sharing between neighboring pixels very small.

Future work

- FBK AIDAinnova TI-LGAD production: Addition of carbon co-implantation for enhanced radiation hardness.
  - Laboratory testing.
  - Test beam testing.
Acknowledgements

This project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement No 101004761.
Backup slides
TCT characterization

Almost all design patterns from the FBK RD50 TI-LGAD production were ranked according to their inter-pixel distance as measured with laser TCT, more details in https://doi.org/10.3390/s23136225.
Time resolution

Measured in laboratory beta source setup as well as in test beam setup, see https://doi.org/10.3390/s23136225 for more details.