Time and space characterization of novel TI-LGAD structures before and after irradiation

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Previous talk on this project: 39th RD50 Workshop @ Valencia (link)
LGAD

- Low Gain Avalanche Detector (LGAD)
- Solid state diode:
  - Very thin active thickness ~40 µm.
  - Gain layer provides gain ~10.
  - Time resolution for 1 MIP ~10-30 ps.

LGAD technology and (x,y,z,t) tracking

- "Plain LGAD": mature technology.
  - CMS ETL
  - Atlas HGTD
- Outstanding time resolution.

Issue: Fill factor
- Inter-pixel distance (IPD) is on the order of 20-50 µm.¹

The “RD50 TI-LGAD Project”

- **Goal:** “Design and production of TI-LGAD with small pixels (<= 100 um) and high Fill Factor (> 80%).”¹

**Design patterns**

1) **Trenches:**
   - 1.
   - 2.
2) **Contact type:**
   - Ring.
   - Dot.
3) **Pixel border:**
   - trench-gain layer distance.
4) **Trench depth.**

*These design patterns are constant within each sample, here they are drawn all together as in a single sample just to illustrate.

**These cartoons show a simplified/idealized picture and are meant for visualization purposes.

Experimental setup and procedures
TCT setup @ UZH

- Particulars Scanning TCT:
  - Infrared laser (1064 nm).
  - Laser spot Gaussian with\(^1\) \(\sigma \approx 9 \mu m\).
  - Laser splitting+delay\(^2\) with optic fiber for timing measurements provides two pulses separated by 100 ns.

- Custom made passive readout board.
  - Temperature + humidity close to DUT.

- Cividec C2HV amplifier.
  - 2 GHz, 40 dB.

- Oscilloscope WaveRunner 640Zi or 9254M.
  - 4 GHz, 40 GS/s.

- Keithley 2470 bias voltage source.

\(^1\) https://msenger.web.cern.ch/a-spacial-characterization-of-the-tct/
\(^2\) https://msenger.web.cern.ch/laser-delay-system-for-the-scanning-tct/
Low temperature system

- Used for irradiated devices.
- Chiller + peltier cells.
- Temperature and humidity measured on board, 5 mm away from DUT.
- PID control implemented in the computer.

Measurements conditions:
- $T = -20.00 \pm 0.02 \, ^\circ C$
- $H < 1 \%$RH at all times

Example from one of the scans
Samples geometry and laser scans

- 1D linear scan.
- From metal to metal crossing through the window.
- Two geometries:
  1) 2×2 big pixels.
  2) 4×4 small pixels.
- Window is identical in both.
Inter-pixel distance (IPD)

- IPD: Distance between 50% of normalized collected charge of each channel.
- Linear interpolation, not “S function”.
  - Observed deviations from “S”, different for each design pattern and dependent on the bias voltage.

Example from a random scan (non irradiated device)
Scanning at different bias voltages

Example from a random scan (non-irradiated device)
Scanning at different bias voltages

Example from a random scan (non-irradiated device)

Normalize

Bias voltage (V)
- 55
- 73
- 91
- 109
- 127
- 145
- 163
- 181
- 200

Collected charge (V/s)

Normalized collected charge

Laser position (m)
Scanning at different bias voltages

Inter-pixel distance (IPD) depends on bias voltage¹.

Time resolution

- Constant fraction discriminator.
- Time resolution vs laser position.

\[ \text{Time resolution} = \frac{\sigma_{\Delta t}}{\sqrt{2}} \]

- Within window (laser in silicon):
  - \( \sim 10 \text{ ps} \) ✔️

Outside window (laser in metal):
- > 10 ns because the software is measuring noise ✔️
Results for non irradiated TI-LGAD
Interpixel distance and time resolution

- Border V2 is always better.
- Deeper trenches are better.
- Contact type “ring” is better.
- Time resolution does not seem to depend systematically on these design parameters.
IV curves

⇒ All devices with “2 trenches” & “pixel border V3” & “contact type ring” went into breakdown at very low voltages (<10 V).

Measurement conditions:
- Devices installed in readout boards.
- All pixels grounded or 50Ω terminated.
- Room temperature (not controlled).
- Light/laser off.
Irradiation campaign
Our irradiation campaign at UZH

- TI-LGADs aimed towards future trackers.
  - Possible replacement of pixel disks of the CMS experiment in Phase-3, with fluence range $3-5 \times 10^{15}$.

- We irradiated with reactor neutrons at JSI to 3 fluences:
  1) $1.5 \times 10^{15}$ n$_{eq}$/cm$^2$
  2) $2.5 \times 10^{15}$ n$_{eq}$/cm$^2$
  3) $3.5 \times 10^{15}$ n$_{eq}$/cm$^2$

- Irradiated devices were kept all the time at -20 °C except for handling, to avoid annealing effects.
Scanning along irradiated devices

- Same procedure and analysis as for non irradiated devices.
- Gain is significantly reduced.
  - SNR worse, still can measure.
- Behavior in inter-pixel area is “washed out”, all look similar now.

Example from one random family of design patterns
(non irrad @ 200 V, irradiateds @ 500 V)
Scanning along irradiated devices: Pixel isolation

Pixel isolation is not affected by radiation.

Example from one random family of design patterns (non irrad @ 200 V, irradiateds @ 500 V)
Time resolution (TCT) vs position

- Time resolution degraded by radiation (yes, that was expected...)
- Still uniform until the edges (the plateaus are not deformed)

![Graph showing time resolution vs laser position]

The time resolution is the value within the plateau. For this example:

- Non irrad: ~ 5 ps
- Irrads: ~ 15-30 ps

Example from one random family of design patterns (non irrad @ 200 V, irradiateds @ 500 V)
Results after irradiation
Collected charge after irradiation

- Before irradiation 8-12 fC @ 200 V (using same calibration).
  - 5-20 times smaller.
- Pixel border V2 seems to be slightly more degraded after irradiation.
Gain after irradiation

- Before irradiation 30-50 @ 200 V (using same calibration).

(Could not measure gain up to highest voltages because the PIN did not withstand. At 600 V the lowest gain is probably ~ 2.)
Time resolution (TCT) after irradiation

- Before irradiation: 4-6 ps @ 200 V.
- Radiation exposure severely affects time resolution.
• IPD “converges” faster to lower values after irradiation.

• IPD is still good.
IV curve after irradiation

- Breakdown voltage moved from ~250 V → ~600 V.

- "Pixel border V3" & "1 trench" showed earlier and smoother breakdown.

- All devices died with current compliance of 10 µA shortly after ~620 V. Before irradiation compliance of 20 µA @ ~250 V did not killed them.
Beta source measurements
Beta setup

- Assembled inside climate chamber at -20 °C.
- DUT mounted in same readout board and with same amplifier as in TCT.
- Reference detector: Calibrated single pad LGAD mounted in “Chubut board”*.
- 74 kBq Sr-90 beta source.
- Oscilloscope triggering in coincidence of DUT and reference.

* Almost a clone of the Santa Cruz board in a smaller layout, the same performance was observed [https://github.com/SengerM/ChubutBoard](https://github.com/SengerM/ChubutBoard).
Time resolution with beta source

- Time resolution of same devices in TCT setup: 35-50 ps @ 500 V.
- Landau contribution: ~30 ps.
Conclusions

- A comprehensive characterization of novel TI-LGAD devices was performed using a scanning TCT setup.
  - Pixel isolation by trenches is good before and after irradiation.
  - Inter-pixel distance < 4 µm was observed both before and after irradiation, which allows for fine segmentation.
  - Gain performance severely affected by radiation levels studied.
  - Time resolution after irradiation also degraded.

- In samples tested with beta source setup:
  - Time resolution ~50-65 ps values observed using beta setup on most irradiated samples.

- **TI-LGAD is still, after 35 n_{eq}/cm² of neutrons, a promising candidate towards 4D-pixels.**
Acknowledgments

Part of this work has been performed in the framework of RD50 CERN collaboration and the AIDAinnova project.
That’s all,

thank you for your attention
Extra slides
Laser scans

- Trenches provide good isolation.
- Shared signal in the middle is shared due to the size of the laser spot.
- Qualitative similar behavior for all devices.
• Processing in Python using this [https://github.com/SengerM/signals](https://github.com/SengerM/signals).
• Signal is linearly interpolated.
Laser scans

- Steps of 1 µm.
- ~ 50 events at each position.
- Metal-silicon interface as reference:
  - Check laser shape/size.
  - Distance scale correction (2-5%).

Example from a random scan (non-irradiated device)
Collected charge

The value is the average of each scan within the plateau.

BEFORE IRRADIATION

Contact type:
- ring
- dot

Pixel border:
- V2
- V3

Trenches:
- D1
- D2
- D3

Collected charge (C)

Bias voltage (V)
Gain

\[ \text{Gain} = \frac{Q_{\text{LGAD}}[V_s](V_{\text{bias}}, \text{laser intensity})}{Q_{\text{PIN}}[V_s](V_{\text{bias}}, \text{laser intensity})} \]

- “Border V2” & “contact ring” show ~ 20% more gain.
Charge calibration

Deposited MPV charge by $e^-$ in silicon:\(^1\):

$$Q_{MPV} = e \cdot \left( 31 \ln \left( \frac{d}{1 \, \mu m} \right) + 128 \right) \frac{d}{1 \, \mu m} \frac{d}{3.65}$$

\(\Rightarrow 1\text{MIP} \approx 0.49 \, \text{fC}\)

$\beta$ source

$D=45 \, \mu m$ (for all devices of this production)

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PIN @ 100 V, beta source

$[\text{Coulomb}] \approx [\text{Vs}] \frac{0.49 \, \text{fC}}{32 \, \text{pVs}}$

Laser intensity calibration

PIN used: Wafer 7, P250_4×4_1, 45 µm, D2, 1 trench, V3, dot

From the fit:
\[ x_{\text{MPV}} = 32 \text{ pVs} \equiv 1 \text{ MIP} \]
Annealing

A set of 3 devices sharing the same design patterns, each with a different fluence, was annealed at room temperature for 7 days.

- Slight improvement of bias current.
- Less gain.
Annealing: Time resolution and IPD

- Time resolution is worse after annealing (see plot).
- Inter-pixel distance shows no changes after annealing.
Data example from one beta scan

- Same constant fraction discriminator algorithm applied to TCT data was used here.
- This time “pulse 1” and “pulse 2” were “pulse DUT” and “pulse reference”.

![Graph showing probability density and collected charge](image1)

![Graph showing amplitude over time](image2)

- Check the langauss distribution is not cut.
- Reference

- Fit Gaussian & extract sigma

- Repeat for every $k_1, k_2$ and pick the best.