FEASIBILITY STUDY OF USING FEMTOSECOND LASER- BASED SPA AND TPA FOR THE INTERPAD STUDY IN TI-LGAD

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Outline

- Aim
- Motivation
- Materials and Methods
- Results
- Conclusion and Outlook

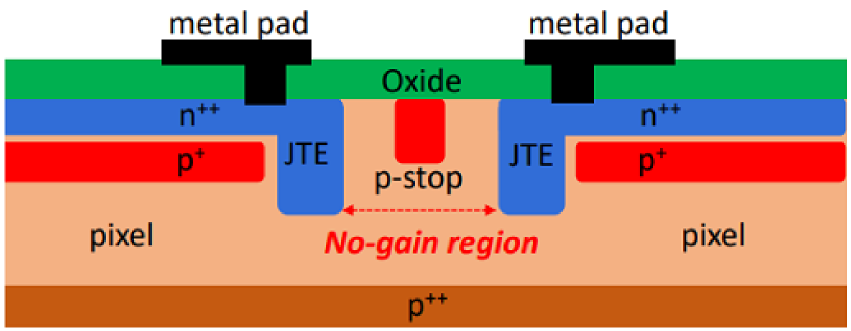
Aim

Threefold:

- ❑ To experimentally investigate the feasibility and prospect of using Femtosecond TCT and TPA – TCT in measurements of Interpixel distance (IP)
    - **to our best knowledge the fs-SPA and TPA were not utilized for IP up to now.**
- ❑ To learn more about TI-LGAD (we have been recently (for the first time) introduced to this technology
    - **interpixel distance study by performing X-scan with SPA and TPA**
- ❑ To broaden our understanding about advantages and drawbacks of TPA in comparison to SPA:
    - **to compare the results from SPA (800 nm) and TPA (1550 nm) using femtosecond laser, from the point of perspective of TPA technique**

Motivation: to contribute to R&D pixeled LGAD

Traditional LGAD

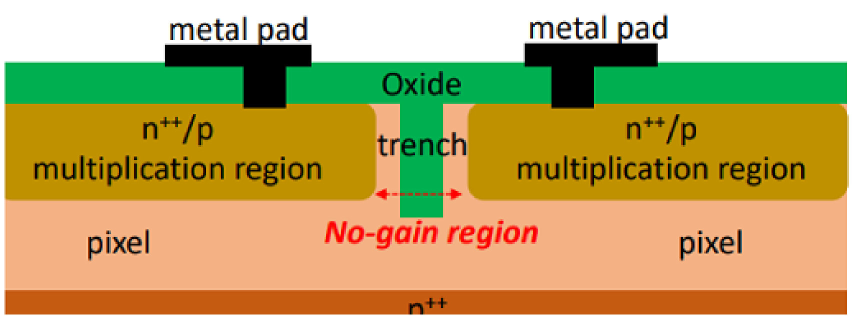


Standard segmentation based on:

- ➢ Junction Termination Extension (JTE)
- ➢ p-stop implant

No-gain region of 60-120 μm

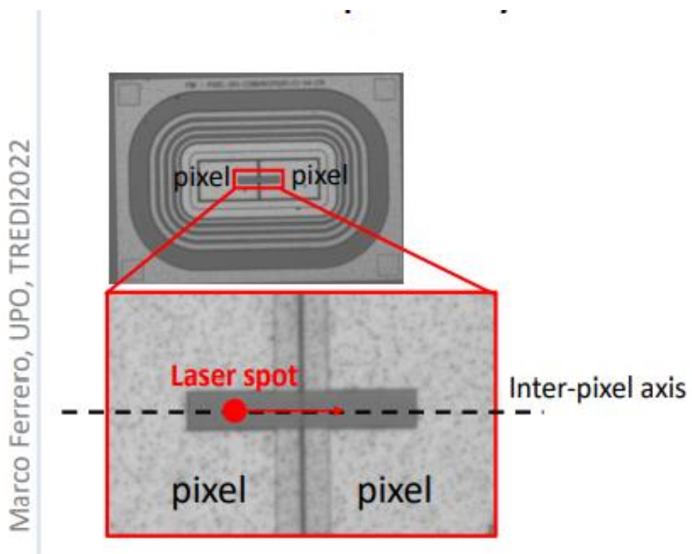
Trench-Isolated LGAD (TI-LGAD)

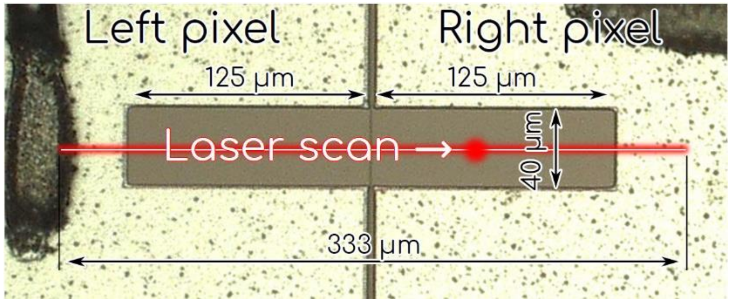


Segmentation based on Depth Trenches filled with Oxide

No-gain region of ~10 μm (Fill Factor improvement)

Research task & Method



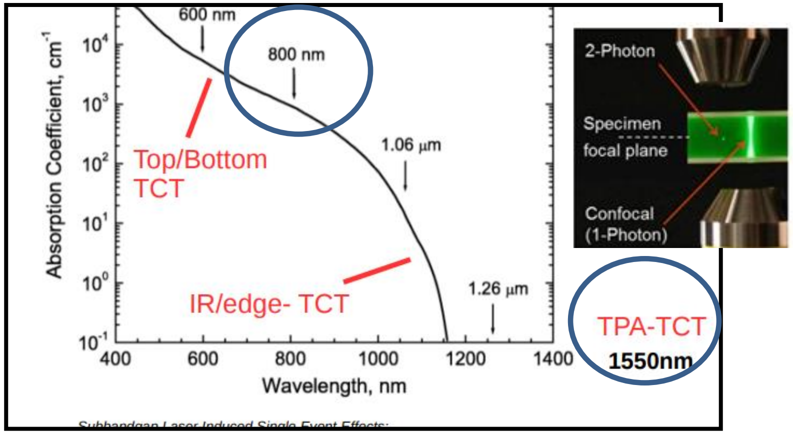


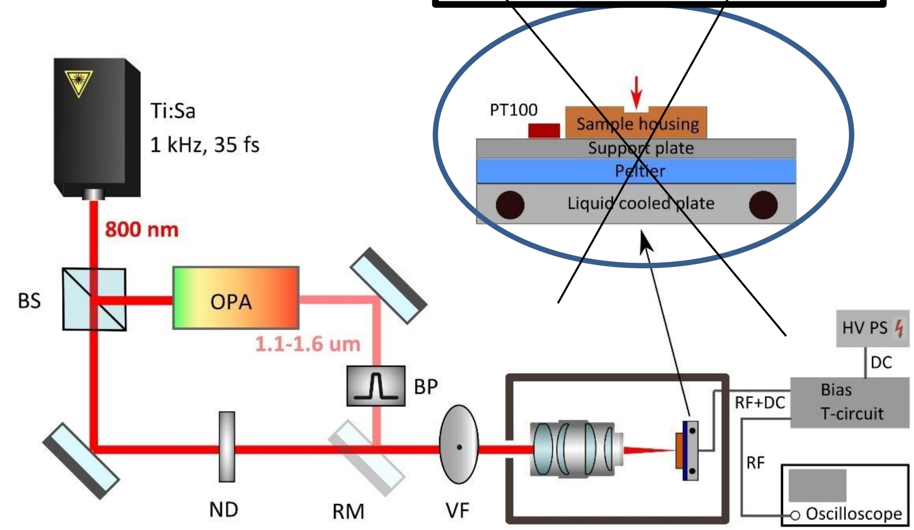
- **Purpose**: monitoring interpixel distance by performing X-scan with SPA and TPA
- **Method:** X-scan: laser is moved through the center of opening windows with the step of 1 um
- **Scientific experimental tool:** Femtosecond laser based TCT set-up we built at laser facility ELI Beamlines specifically to test radiation hardness of LGAD (SEB) and to characterize LGAD (R&D)
- **Project:** ELI open user call (2022)

Fs-Laser beam Experimental SETUP

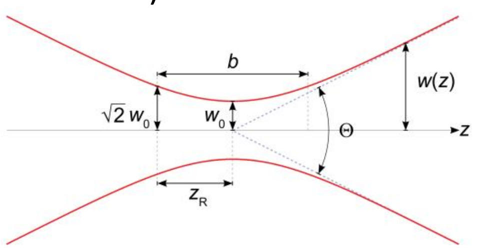
- ✓ No 1st amplifier
- ✓ No 2nd amplifier
- ✓ No cooling

➢ Unique femtosecond laser based TCT with both, SPA and TPA





Schematic view of the setup for TCT-SPA and TCT-TPA measurements at ELI Beamlines (BS – beam splitter, OPA – optical parametric amplifier, BP – bandpass filter, ND – neutral density filter, RM – removable mirror, VF – variable filter).



SPA:
$w_0 = 0.85m$
$Z_R = 3.31\mu m$

TPA:
$w_0 = 1.52\ \mu m$
$Z_R = 7.74\ \mu m$

TI-LGAD Samples: General info

Process parameters:
- Three trench depths: **D1 < D2 < D3**
- Three trench processes: **P1; P2; P3**

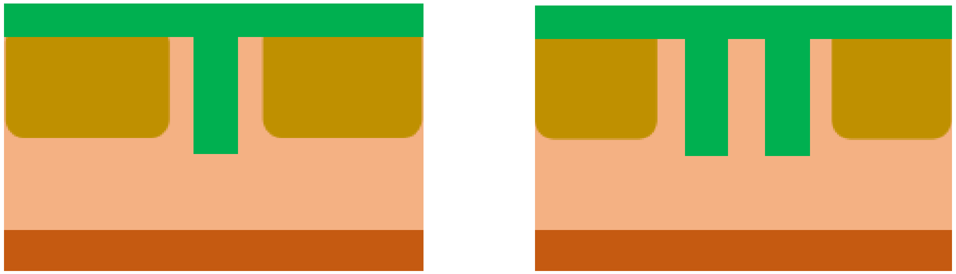
Additional Information:
- Active thickness of 45 µm
- p-bulk inverted (in new sensors)
- Boron High Diffusion gain implant
- No carbon co-implantation

Inter-pixel layout:
- **One/Two trenches (1TR/2TR)** to separate pixels
- Four pixel borders: (most aggressive) **V1<V2<V3<V4** (least aggressive)

Sample we analysed

Wafer	Trench depth	Trench process
1	D2	P1
7	D2	P2
9	D2	P3
11	D1	P1
16	D3	P2

Pixel border Layout



Marco Ferrero, UPO, TREDI2022

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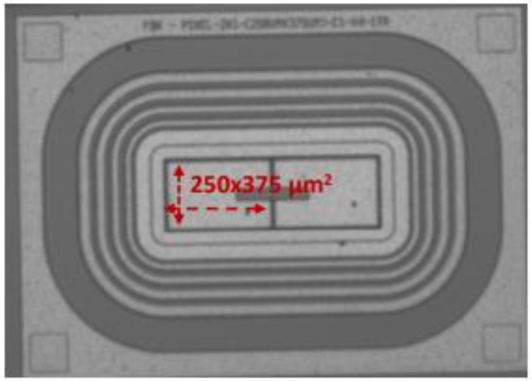
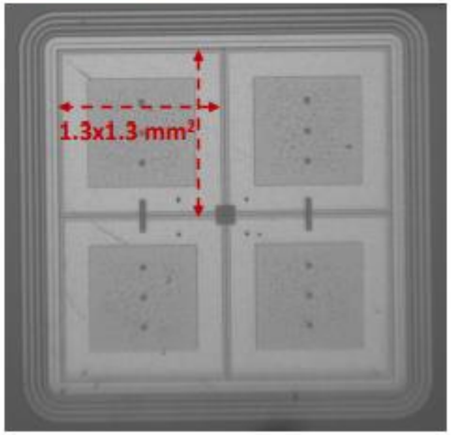
Sensors geometry:
- 1x2 array with several inter-pixel flavours
- 2x2 array, with pixel-border V3-1TR

Wafer	Trench depth	Trench process
1	D2	P1
7	D2	P2
9	D2	P3
11	D1	P1
16	D3	P2

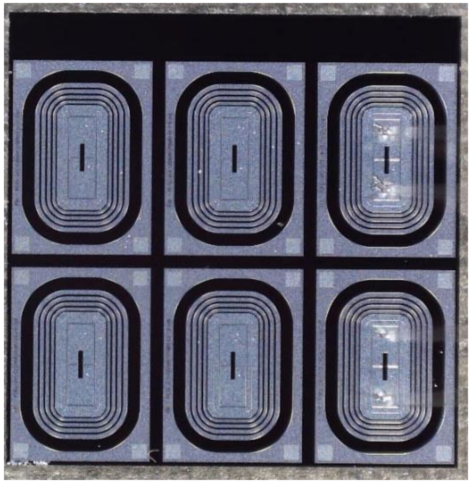




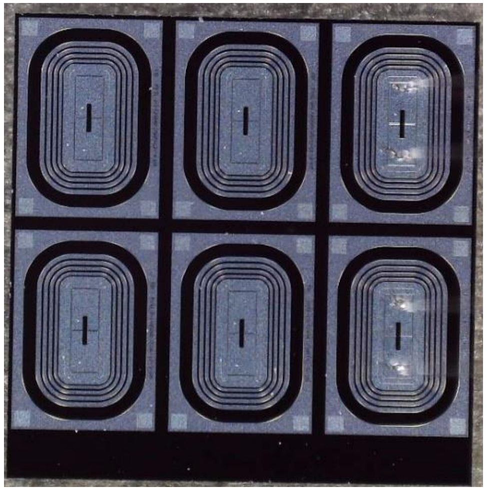
Samples we investigated

- We got 4 samples from Gregor that were already wirebonded and mounted in our standard housings. They are labelled: A1 pos, A3 pos, A6 pos and A9 pos.
- Every sample is an array of 6 LGADs (2 x 3) where only 2 LGADs are wirebonded. Every wirebonded LGAD is divided into 2 pixels separated by trench.
- There is one exception in A9 sample where one of the LGADs has 2 trenches.
- The samples A1 and A3 give very unstable signal (very jumpy and shape changing waveforms). Sample A6 also exhibits some instabilities especially at higher bias (>100V). Sample A9 gives stable signal and was used for further studies.

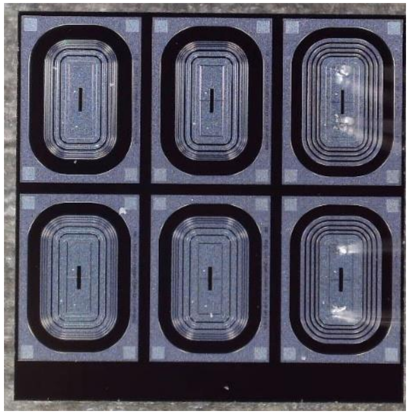
A1 pos



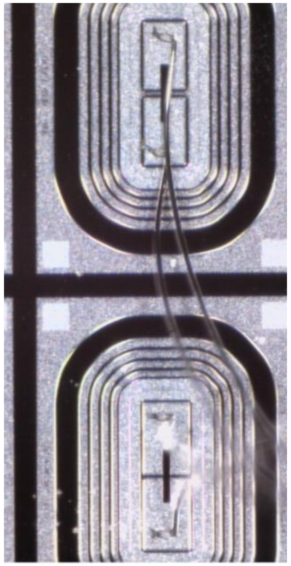
A6 pos



A3 pos



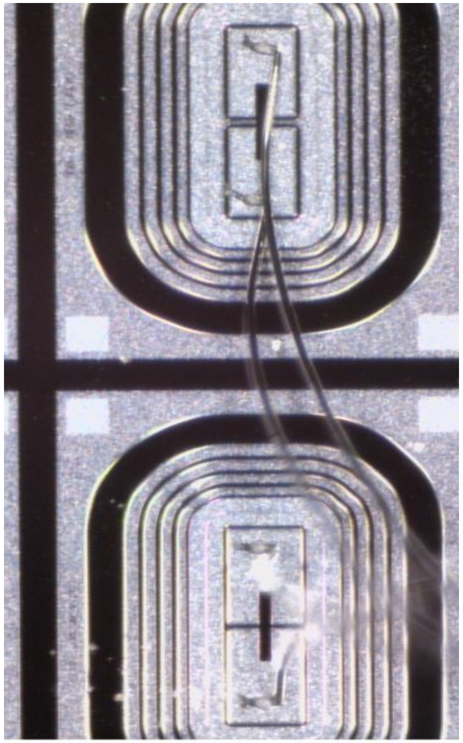
A9 pos



https://cernbox.cern.ch/index.php/s/uMZMxQC7VmT52ap

The selected pot: Sample A9

- This sample is only one which exhibits stable signal under constant laser illumination.
- It has two wire-bonded LGADs.



Upper LGAD: double trench separated pixels

Lower LGAD; single trench separated pixels

Measurements condition

SPA

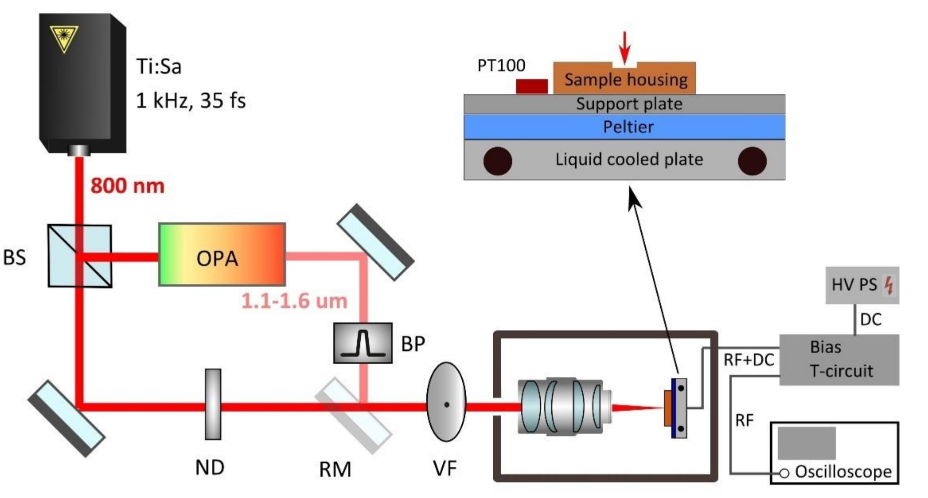
- Wavelength 800 nm
- spatial resolution 1 μm
- room temperature: 20°C
- bias levels: 50 V, 100 V, 150 V, 180 V, 200 V, 215 V and 230 V
- pulse energy: 10pJ

SPA:
$w_0 = 0.85\text{m}$
$Z_R = 3.31\mu\text{m}$

TPA:
$w_0 = 1.52\ \mu\text{m}$
$Z_R = 7.74\ \mu\text{m}$

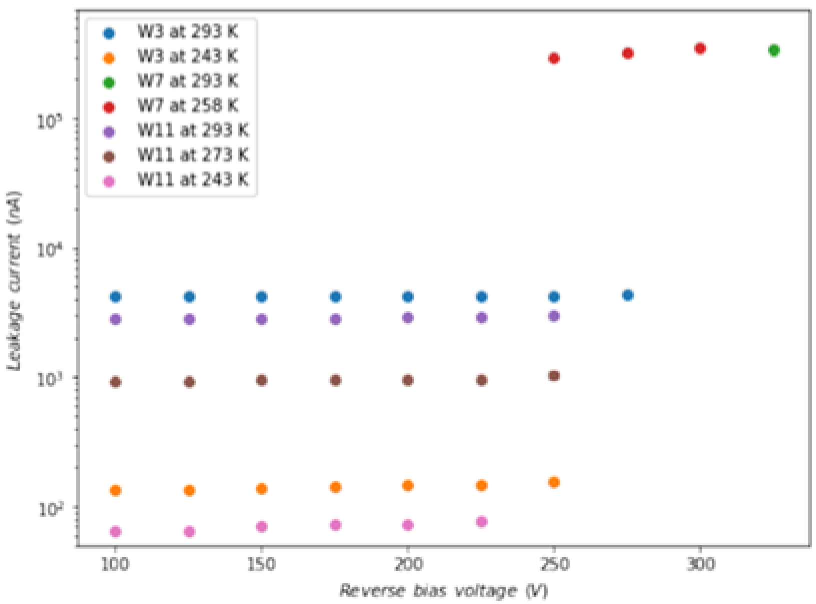
TPA

- Wavelength 1550 nm
- spatial resolution 1 μm
- room temperature: 20°C
- bias levels: 100 V and 200
- pulse energy: 5 nJ

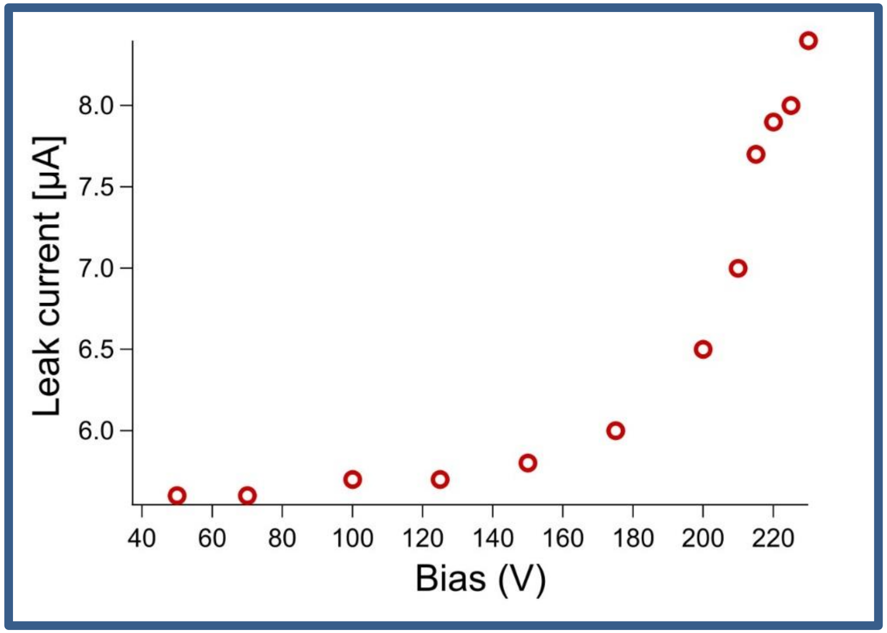


Leakage current

- Leakage current increases significantly above 200 V, thus, for safety reasons the HV bias of 230 V has never been exceeded.



Measured at JSI



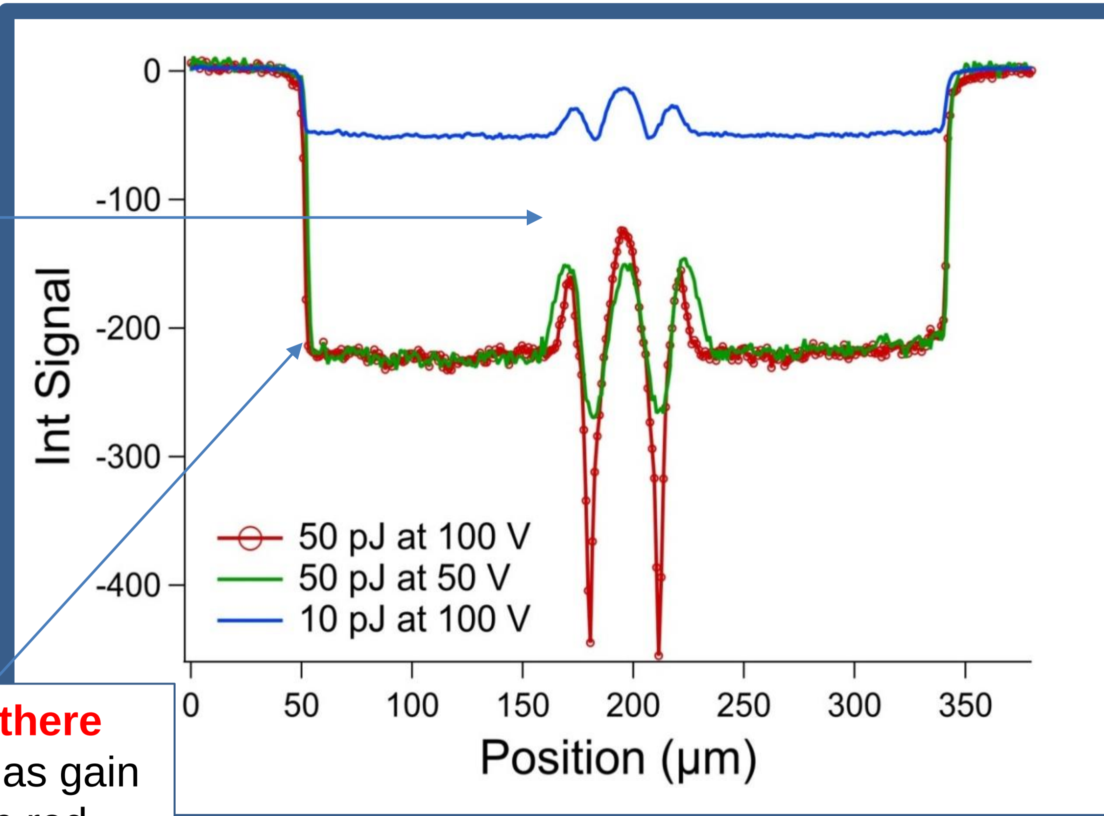
Measured at ELI

Results: Trench Structure well visible

- Preliminary studies on **X-scan (A9)** were performed **by SPA at 50 pJ and bias 50 V or 100 V.**

- Trench region very well visible in X-scan.

- **No change of gain vs HV Effect of gain suppression!**
  - For further studies only lower pulse energy 10

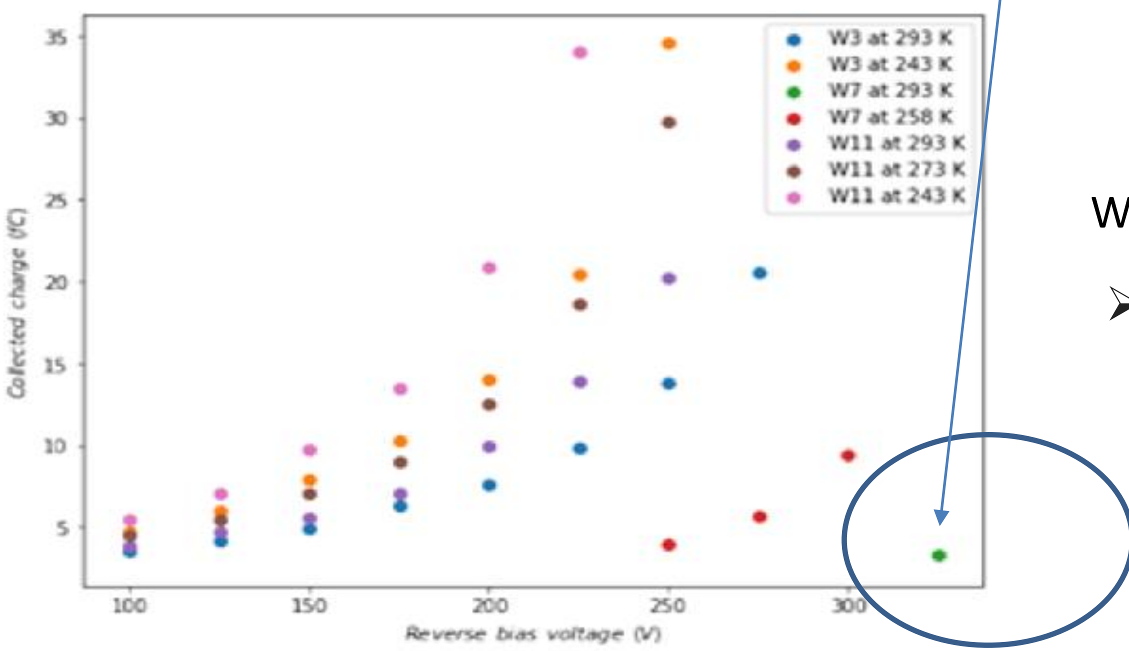


Example preliminary X-scans performed on double trench LGADs under 10 and 50 pJ.

✓ Apparently, **on the edge of Si-SiO2, there is difference in the field** – at 100 V as gain occurs (look at the difference between red and green)-> very likely “thermal generation” origin, at the trench (SiO2) – silicon interface; It doesn’t depend on bias so it is not gain related

Collected charge

Collected charge (fC) vs Bias (V)-
Small gain!



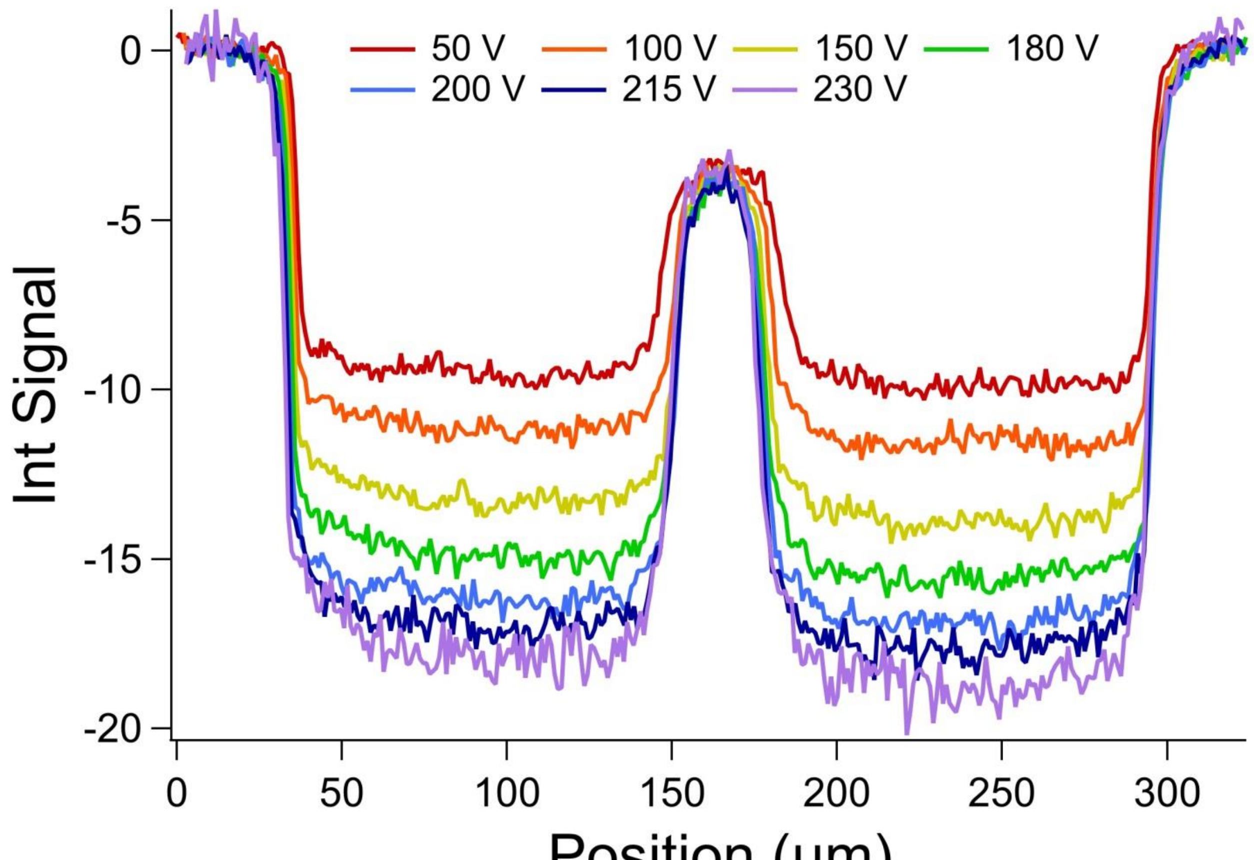
- **W7 has less doped gain layer, hence smaller gain**.
- Notes: **We did not cool the sensor**. The impact ionization depends on the temperature and if we want to see the gain at lower bias voltage it has to be cold.
- Cooling was not done in these preliminary tests since we did not expect low gain or thermal "generation" effect (highly possible we deal with it in W7), Also sensors are non-irradiated so we thought not needed.
- What we see in **W7 is high current**.
- It doesn't depend on bias so it is not gain related. It scales with temperature so it is of "thermal generation" origin, very likely at the trench (SiO2) – silicon interface.

W7-wafer: marked by green dots

- cooling down means larger gain at the same voltage

W7, Single Trench, SPA: IP

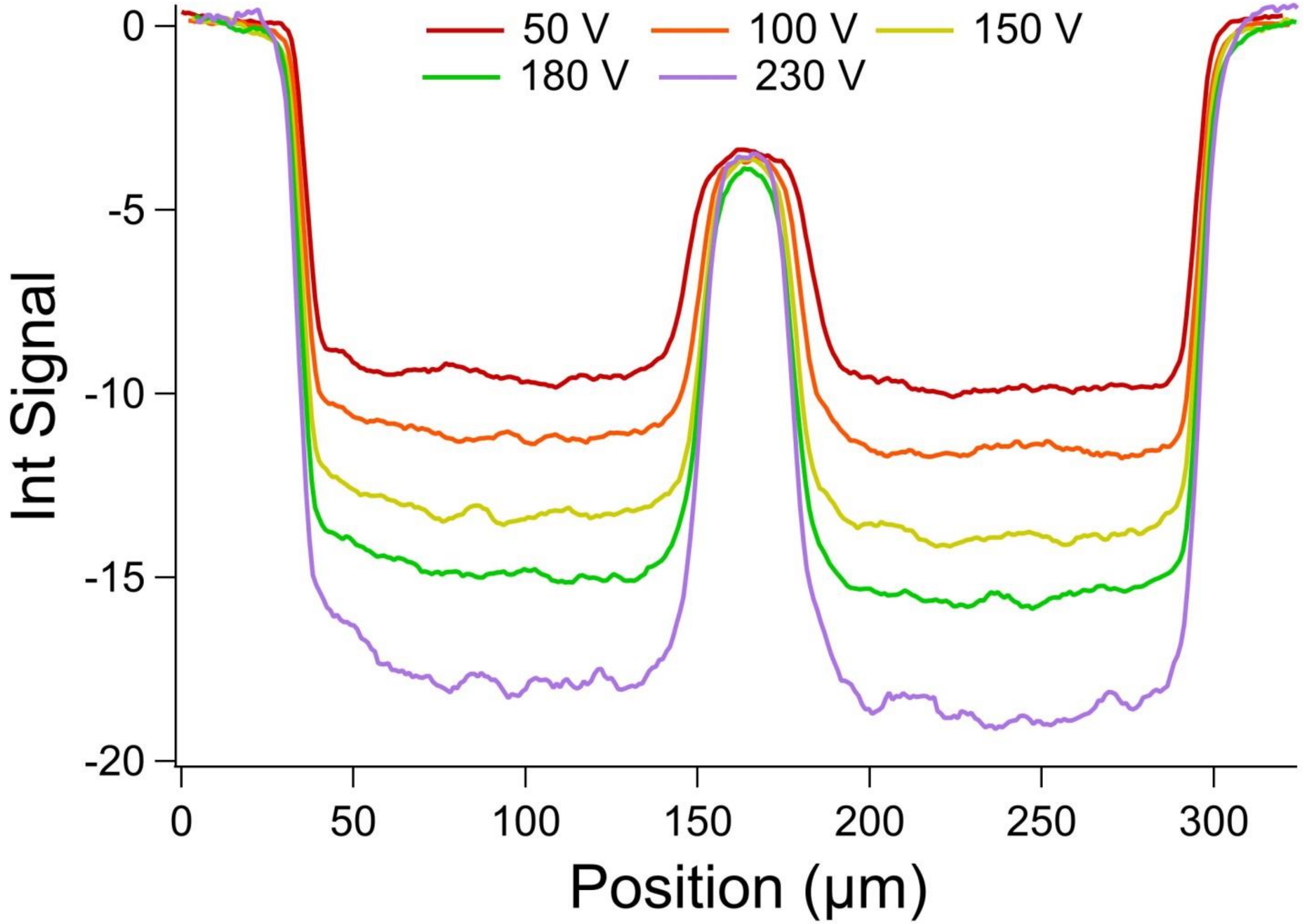
- X-scan on A9 single trench LGAD was performed at 10 pJ for different bias values.
- Signal was obtained by integration waveforms over 8 ns.
- The signal is a bit noisy (especially for higher bias) but a trench region (with no gain) is well visible.
- **It is also quite clear that interpixel distance decreases for higher bias.**



IP: around 20 µm

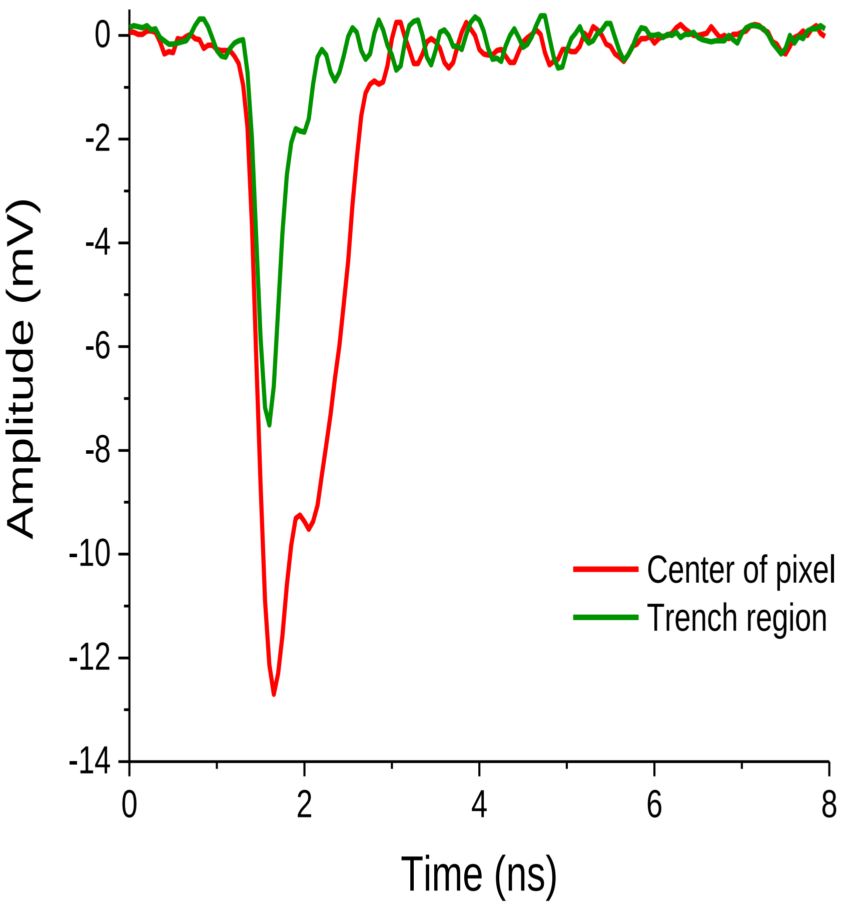
W7, Single Trench, SPA: IP

- To improve a bit quality of data we smoothed the profiles (binomial smoothing).
- The same data like in previous slide (just smoothed).

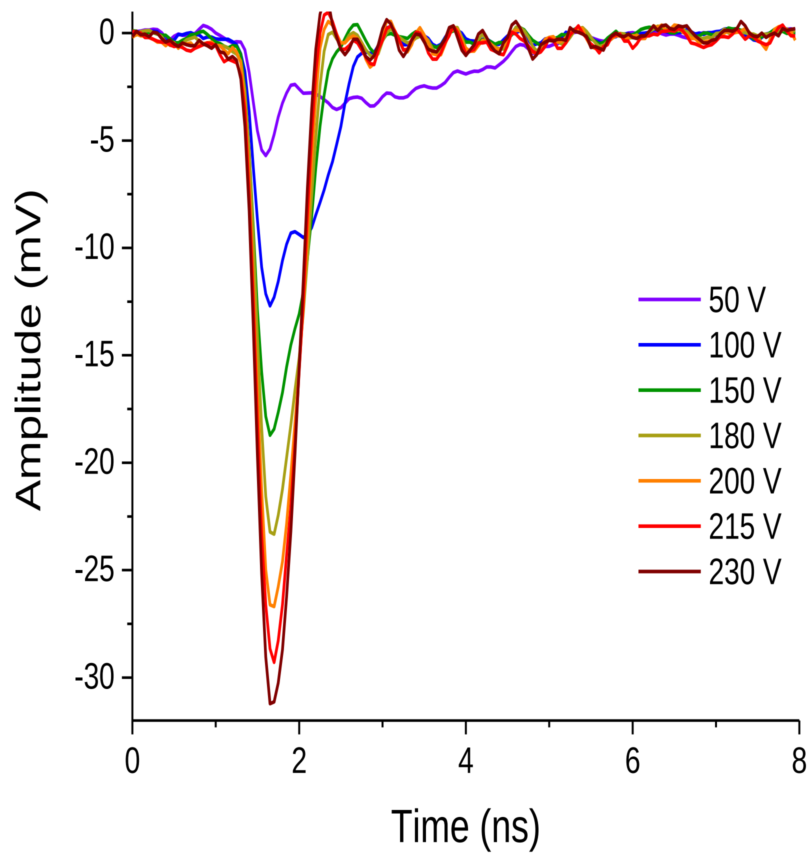


Single Trench, SPA: Waveforms

Example of waveforms measured at the center of the pixel and in the trench region (10 pJ/100V).

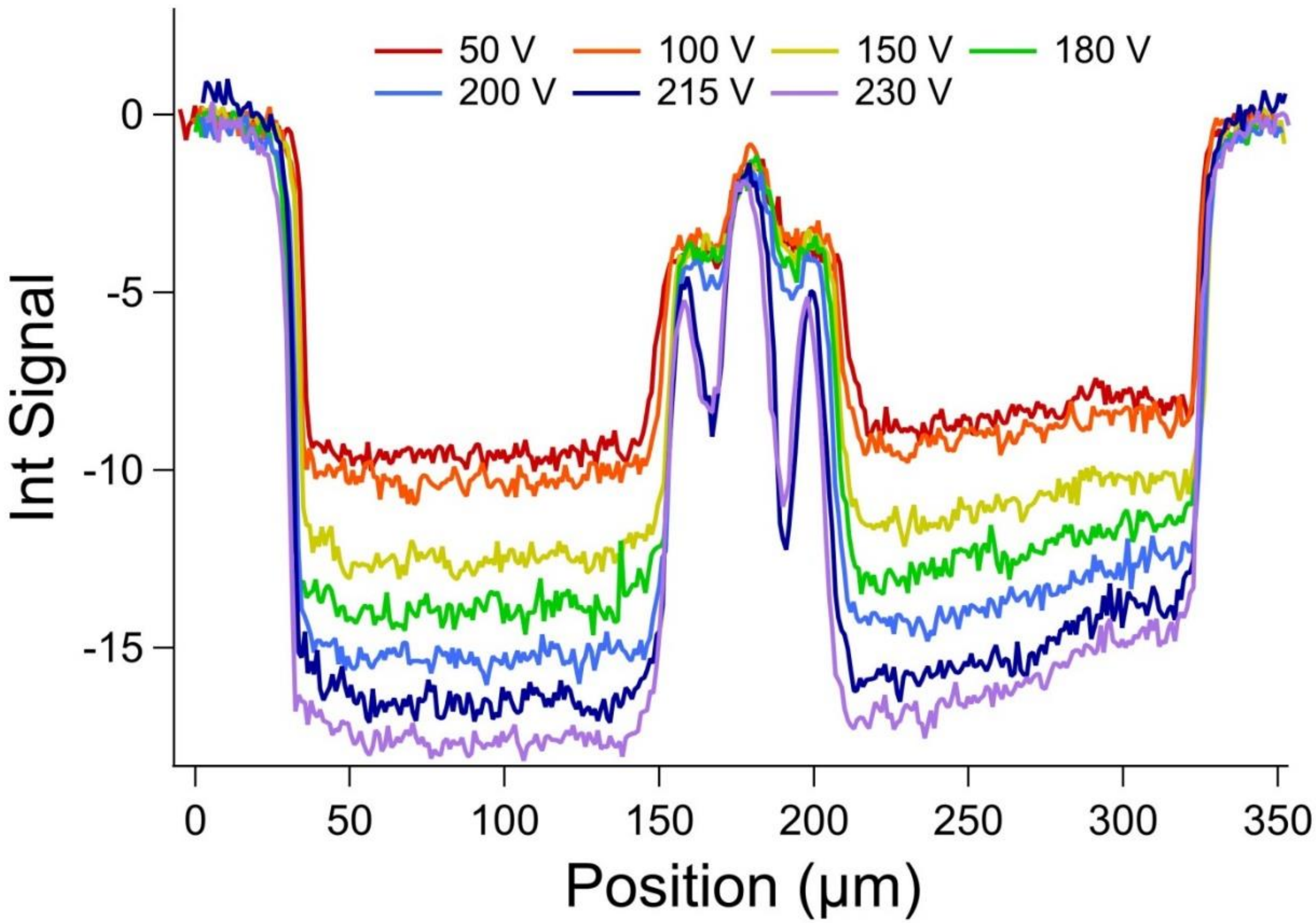


Example waveforms measured at the center of the pixel for different bias



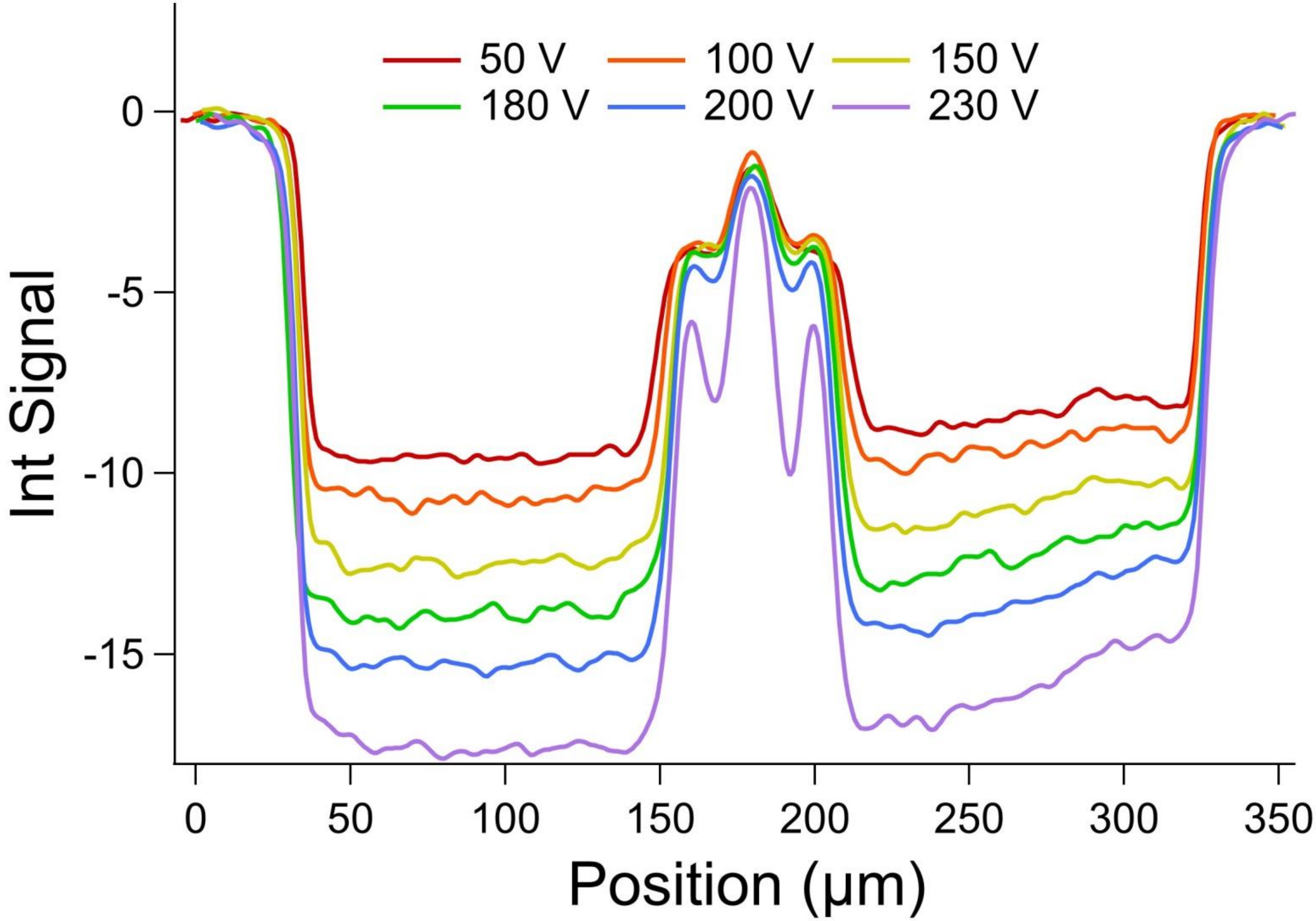
Double trench, SPA: IP

- **Double trench region is well visible in the scans.**
- An effect of HV is also clearly demonstrated
  - When the effect of trench is not seen this is because there is no gain and the CCE has no “hole”.
  - The higher the bias the larger the “hole” effect and this is due to gain.



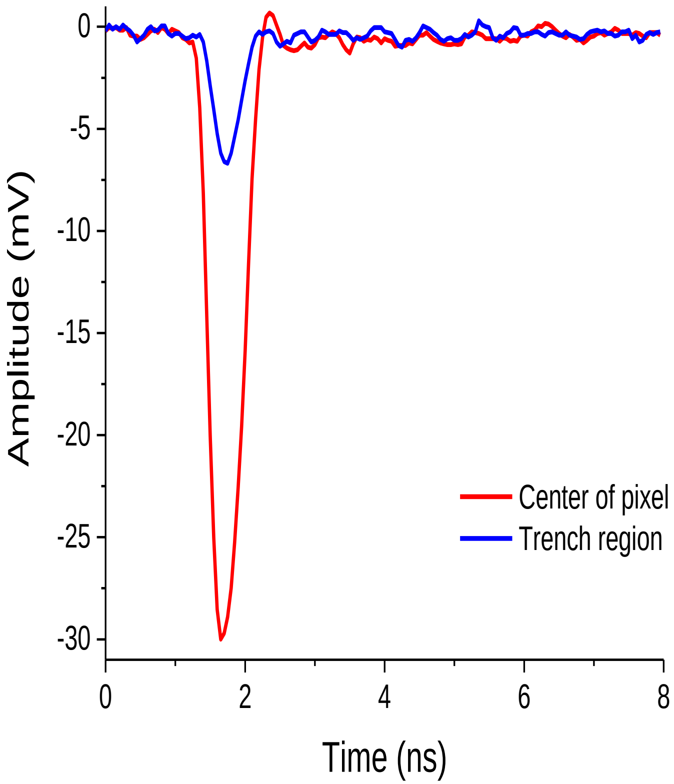
Double trench: SPA data

The same data were smoothed for better visualization.

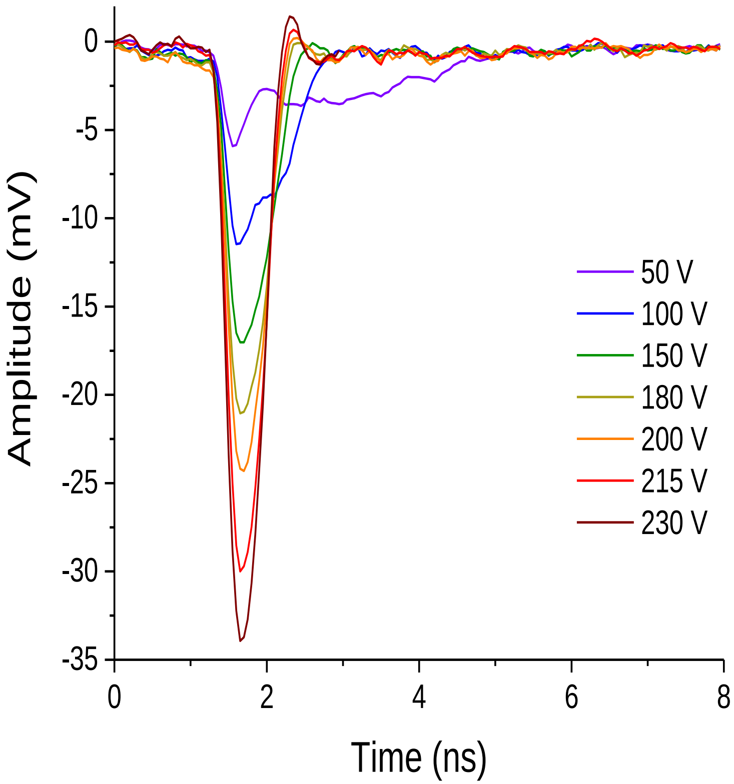


Double trench, SPA: Waveform

Example waveforms measured at the center of the pixel and in the trench region (10 pJ/100V).



Example waveforms measured at the center of the pixel for different bias



Single trench: TPA data

- X-scan on A9 single trench LGAD was also performed using TPA technique, at the different depths in the sample.
- The laser power for this measurement was adjusted to generate the same amplitude of the signal to what is measured with 10 pJ in SPA study.
- Since these measurements are very time consuming only 2 bias values was tested in those first tests: 100 and 200 V.
- First Z-scans were performed to probe the range of depth that can be studied. Then, for a few selected depths, X-scans were performed for 100 and 200 V.

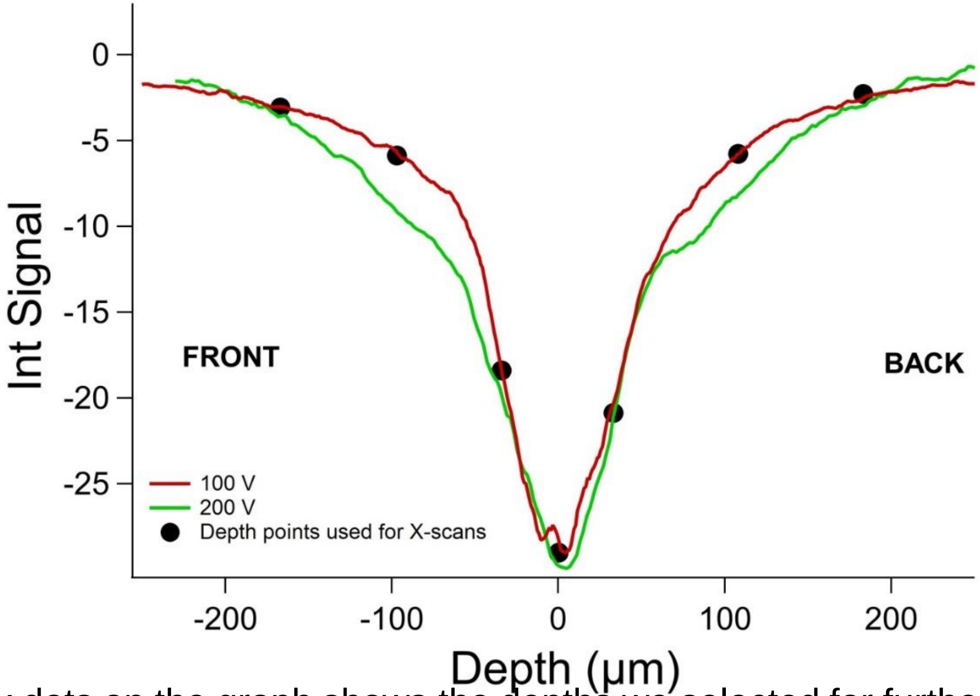
Z-scans

- ❑ Z-scan a bit intriguing;
- ❑ Difficult to say what is the reason; higher pulse power may enhance “cigar” effect.

We see the quadratic dependence for Charge versus laser power, so it must be something else

Hypotheses:

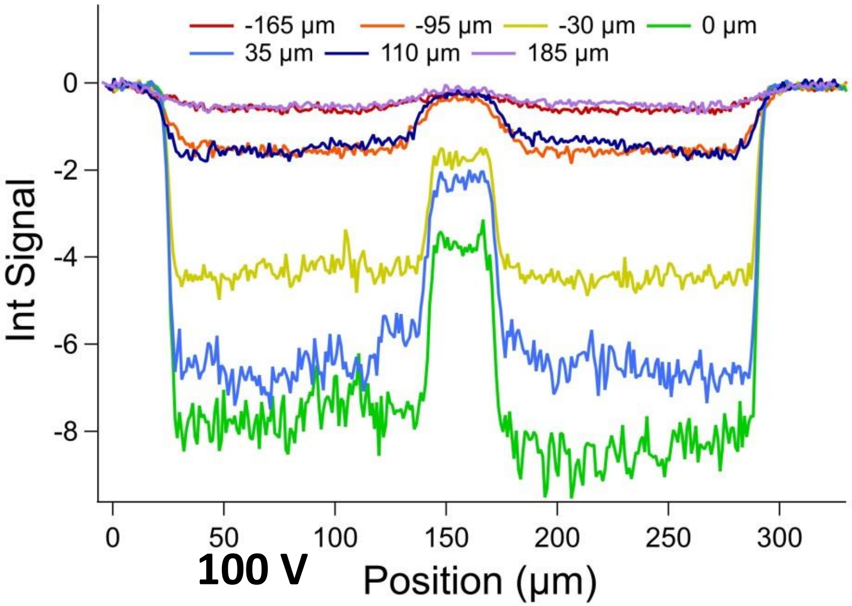
- ➢ Z-scan, affected by light propagation and/or focal condition in silicon (not clear)?
- ➢ Plasma effect (very probable) ->we will reduce laser pulse power in next campaign
- ➢ **Widening the charge cloud with depth**; this may affect CCE, and gain-> **gain increases** with depth
- ➢ ➔ see next page

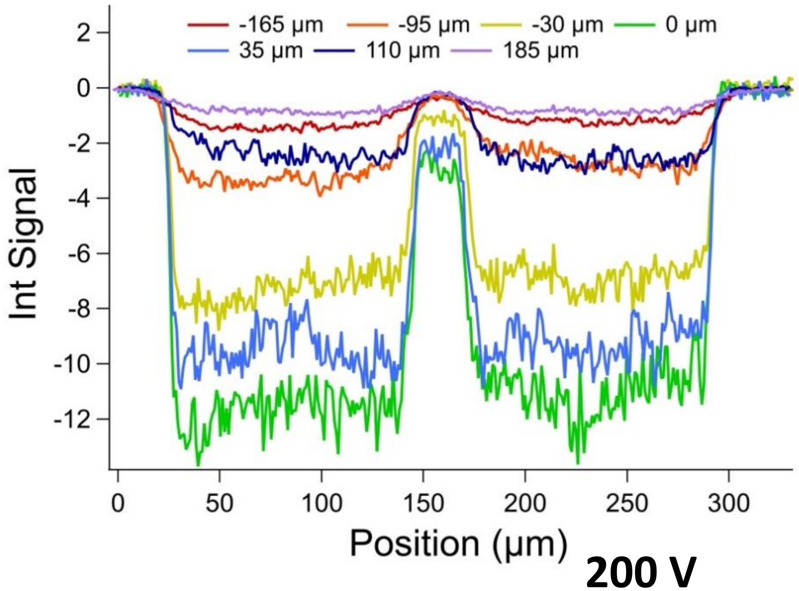


Black dots on the graph shows the depths we selected for further X-scans. Idea was to take scan at maximum (arbitrary marked as zero point) and also in few points before and after this point.

Single trench: TPA data

- X-scan for 7 different depths and two bias values (100 and 200 V) were performed under 5 nJ illumination.
- the signal is noisier than in SPA (the stability of laser at 1550 nm is always worse than at native 800 nm laser wavelength). This problem can be circumvented but requires much longer acquisition time (more averaging).
- Nevertheless, in all scans the trench region is clearly visible.
- Interpixel distance is less affected at HV >100 V as expected (this study will be extended to lower HV)
- Gain increases with HV

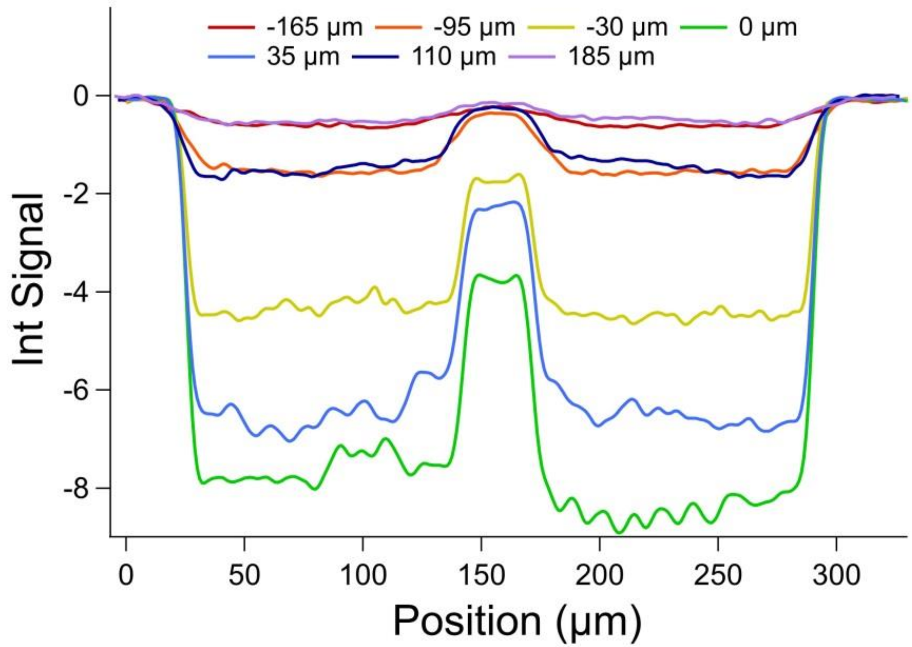




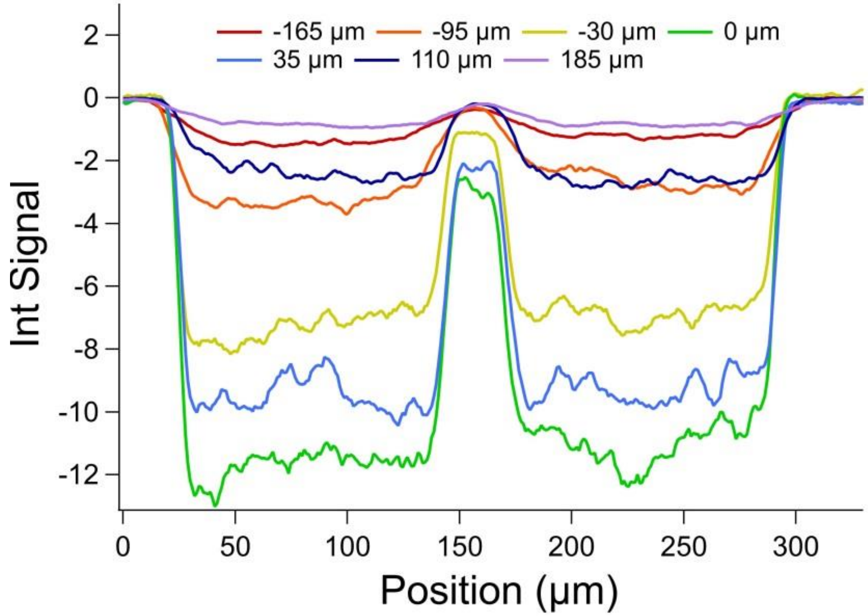
- IP is larger close to surface then when probing LGAD’s depth deeper;
- Likely not related to IP but to TPA behaviour. Charge cloud widening at different depths and laser power

A9 single trench: TPA data

Data are smoothed



100 V

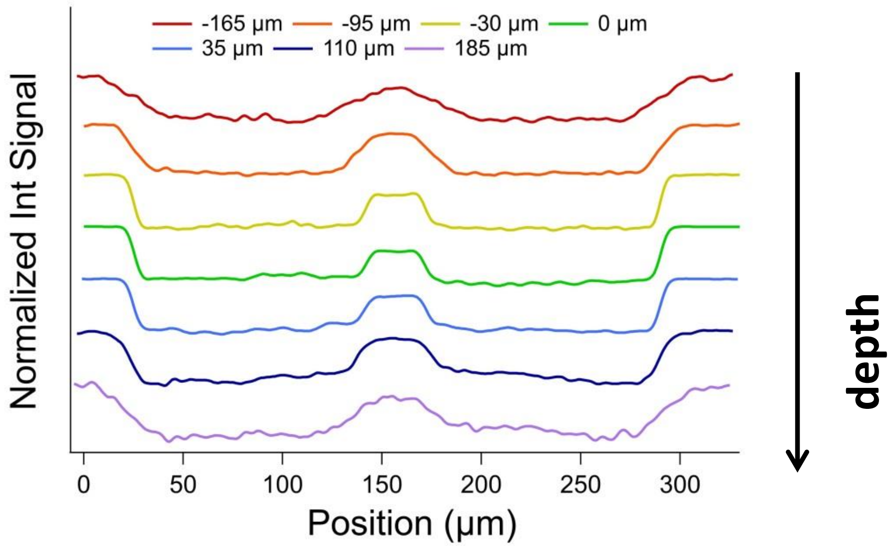


200 V

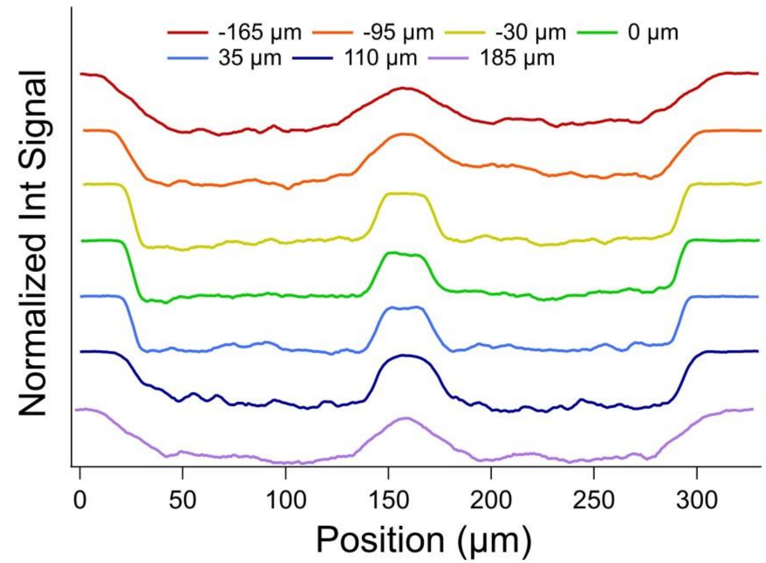
- Gain increases with depth due to widening of the charge cloud (reduce screening effect)?
- -> the only way to check it is do reduce the laser power and repeat the measurements.

A9 single trench: TPA data

✓ from data show in previous slide but normalized and shifted, so the observed tendency is better observed



100 V



200 V

✓ Charge increases with depth → gain increases with depth (less screening?)

- ➢ Could it be sign that gain increases with depth (widening of the charge cloud; less screening? -very possible; -> scanning over laser power and LGAD's depth has to be done.)

➡ We can speculate; some indicators exists, but comprehensive study has to be done (subject of our next campaign in July)

Lessons learnt/Open Q

Q: **Can noise/thermal excitation of holes at the surface level (TPA) make IP larger at smaller depth and spoil the measurement?**

A:Yes, we have seen the widening, less square shape, of the IP. It is not clear why. We have to think and to do some tests.

Q: **IP study affected with TPA charge transport dynamic mechanisms under high injection level of deposited energy?**

Yes, we see this effect; This will be studied in details in future.

Conclusion

- We show that Fs-laser SPA and TPA study are fully feasible with our setup. Many interesting Q opened!
- It probably requires more optimization and better knowledge of the system's "interaction" with the deposited energy and generated charge in LGAD (very much true when higher laser power is applied).
- TPA set up is one thing (get good optics and good TPA signal), but how to use it very much depends on specific conditions, and sensitivity of device; we deal with very tiny and thin sensors (45 microns!).
- SPA: IP dependence on HV bias is seen although IP looks a bit wide (charge transport mechanism will be studied by doing fine scans over laser power); it might be also effect of "thermal generation" at surface we saw.
- TPA: IP shows inverse effect that we expected → it decreases with depth (the most probable effect of charge transport behavior, widening of charge cloud, laser power) -> fine scanning over laser power will be performed soon and all noisy sources will be carefully taken into consideration.

Outlook/Future experiments

- more optimized conditions and longer acquisition time to get better quality data
- **measurements at low temperature**
- more samples/different samples needed for conclusive statements
- two outputs for separate pixels?
- Charge transport mechanism (including plasma effect /charge widening cloud, screening etc..) and its effect on IP in TPA studies

It seems many questions are opened for the moment; typical when the experiment is performed for the first time. More question opened now → more targets to be achieved later ☺