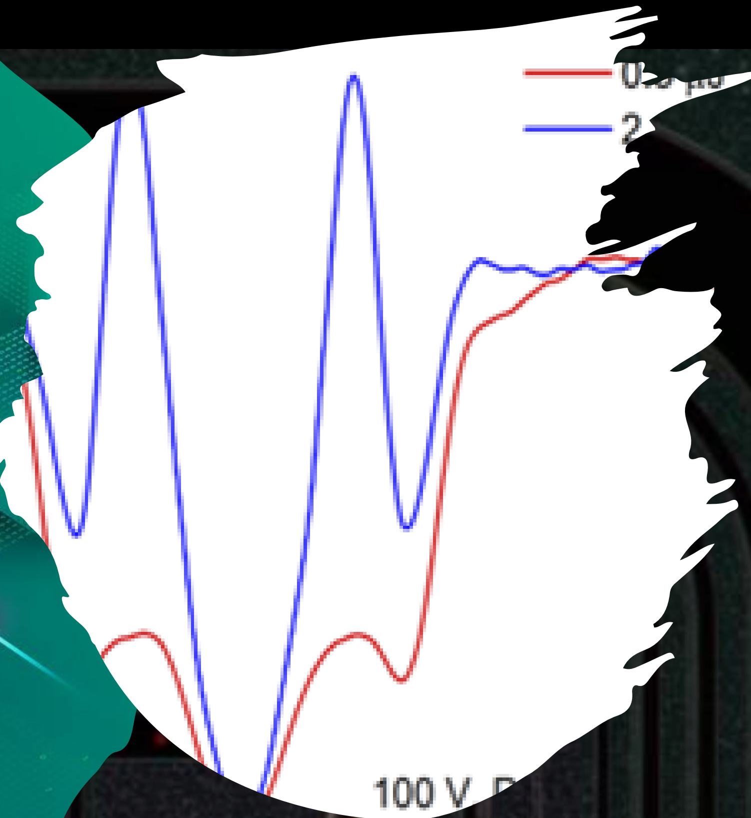
TREDI 2024: 19th Workshop on Advanced Silicon Radiation Detectors, 20-22 February 2024, Torino



EXPLORING INTERPIXEL LAYOUT IN TI-LGAD: INSIGHTS INTO THE GHOST AND AVALANCHE MULTIPLICATION USING FS-LASER BASED SPA AND TPA AT ELI

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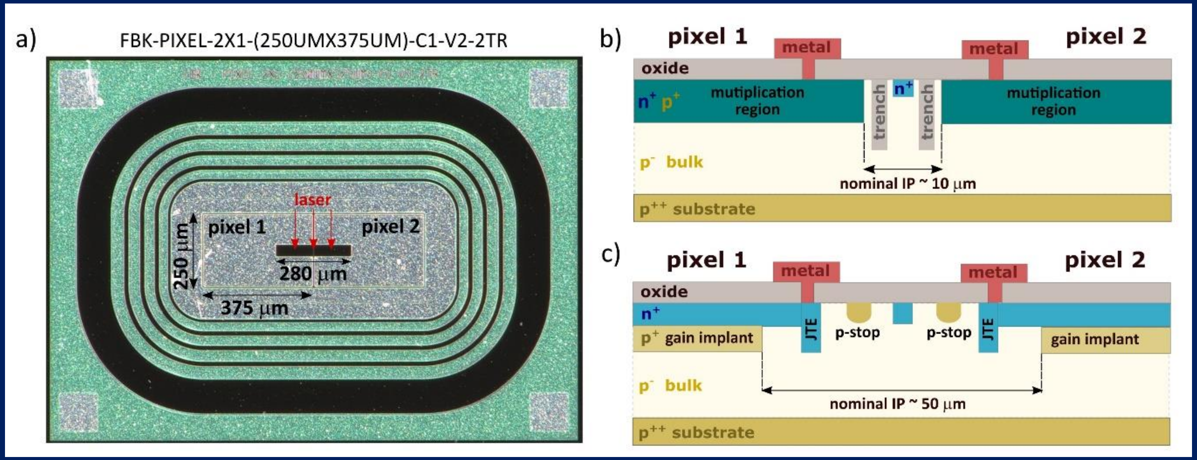
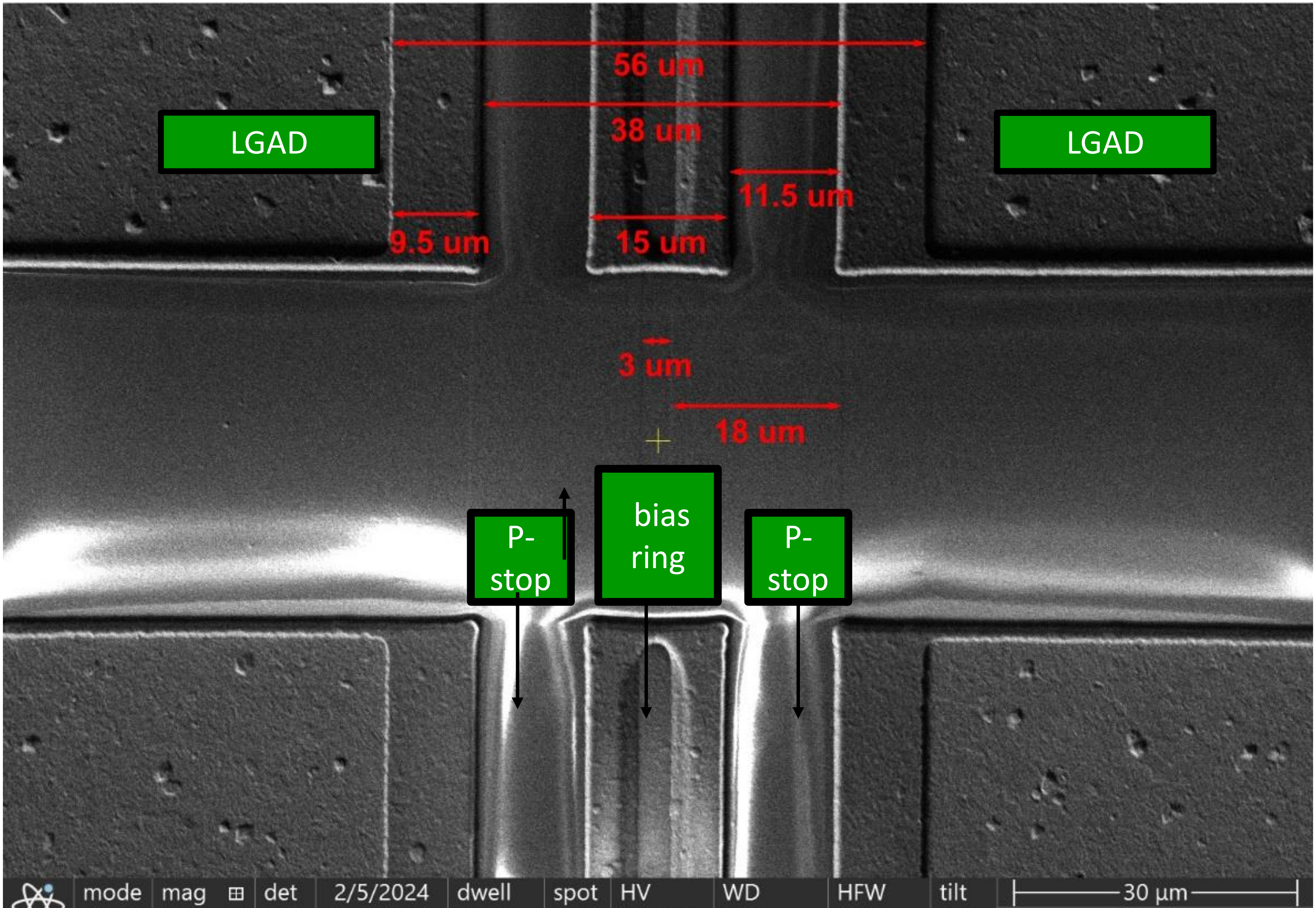
OUTLINE

- ❑ Introduction (Motivation)
  - ➢ Study on Ti-LGAD Type 10 , IPD=49 µm
    - ➢ strong CM observed in inter-pad region in vicinity of p-stops
    - ➢ Cross-check with UFSD 4.0, IPD=61 µm
- ❑ Microscopic images of sensors with focus on the IP region and isolation structures
- ❑ Study on Double Trenched Ti-LGAD : W7, W11, W16 (C1- C2, V1-4 V3, D1-D3)
  - ➢ Ghost signals & very strong signals
- ❑ Summary



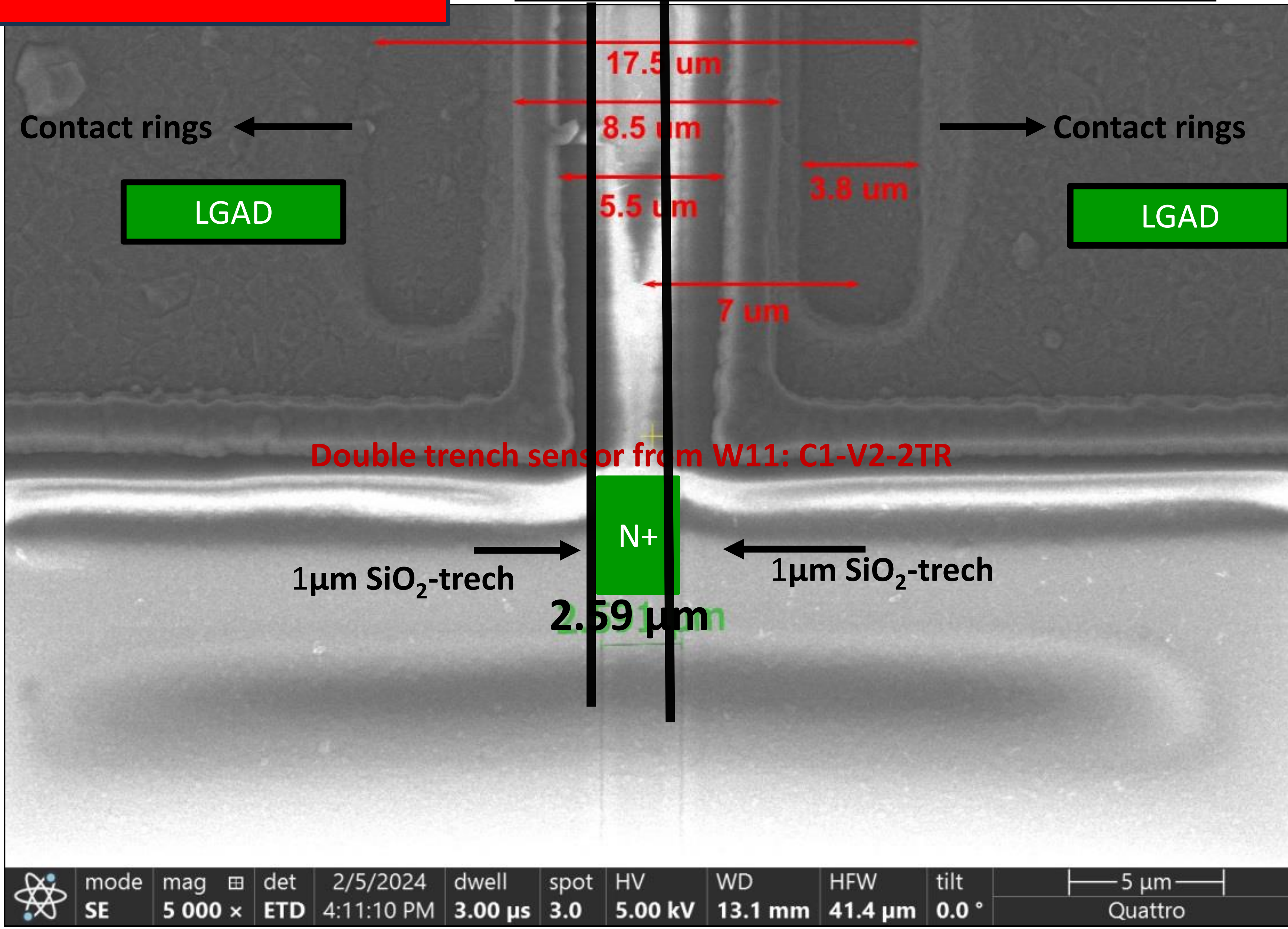
Measured sensors seen under microscope

Type10 sensor from W16



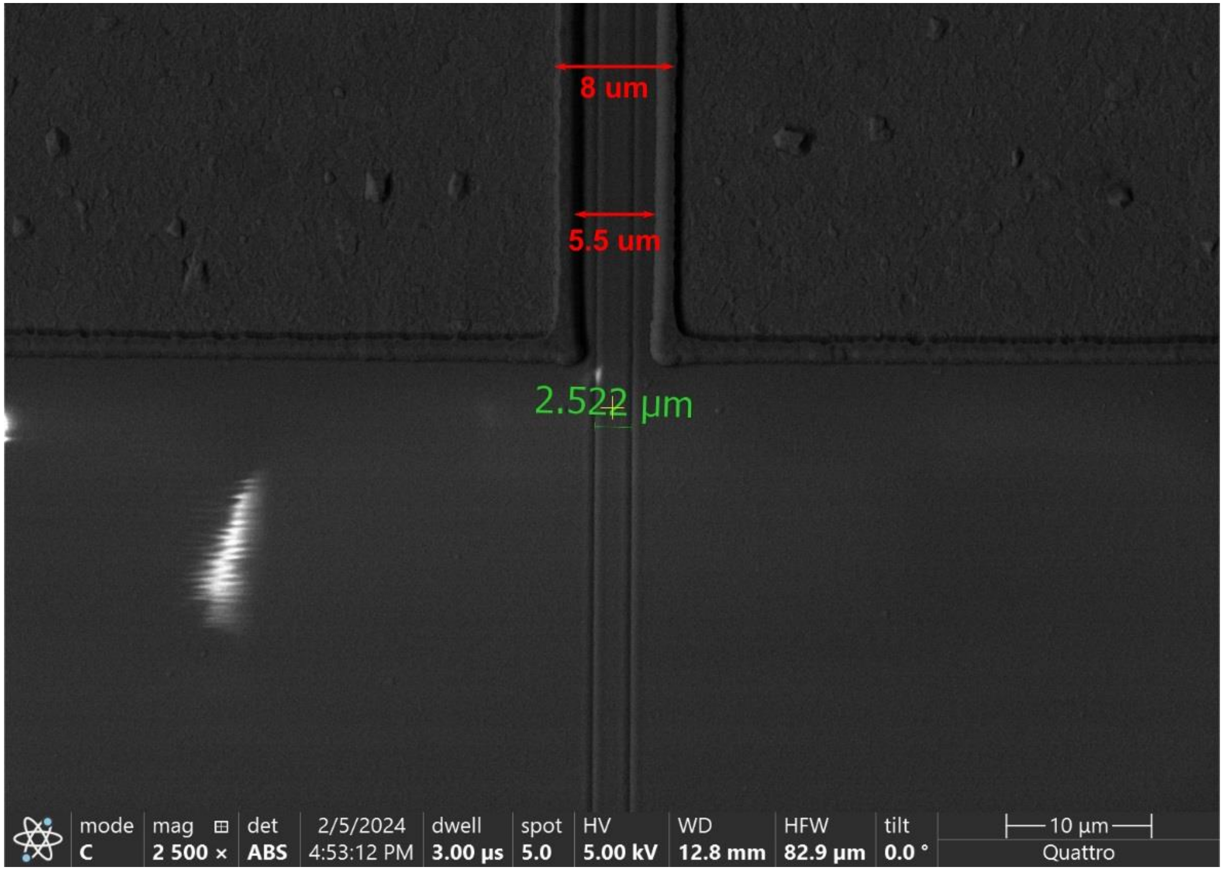
Microscopic image of sensors

Double trench sensor from W11: C1-V2-2TR



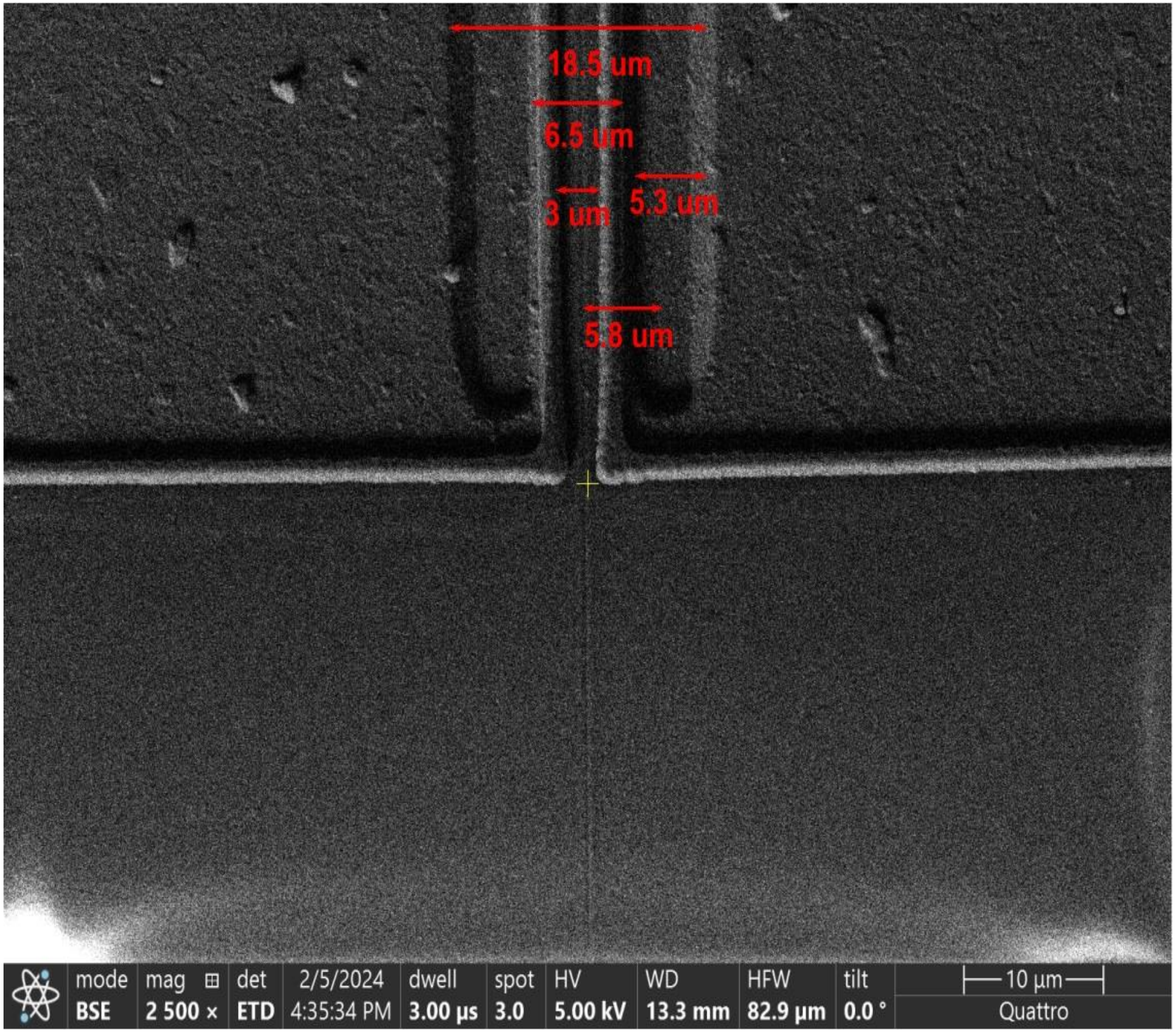
Microscopic image of sensors

Double trench sensor from W16: C2-V3-2TR-CRT2



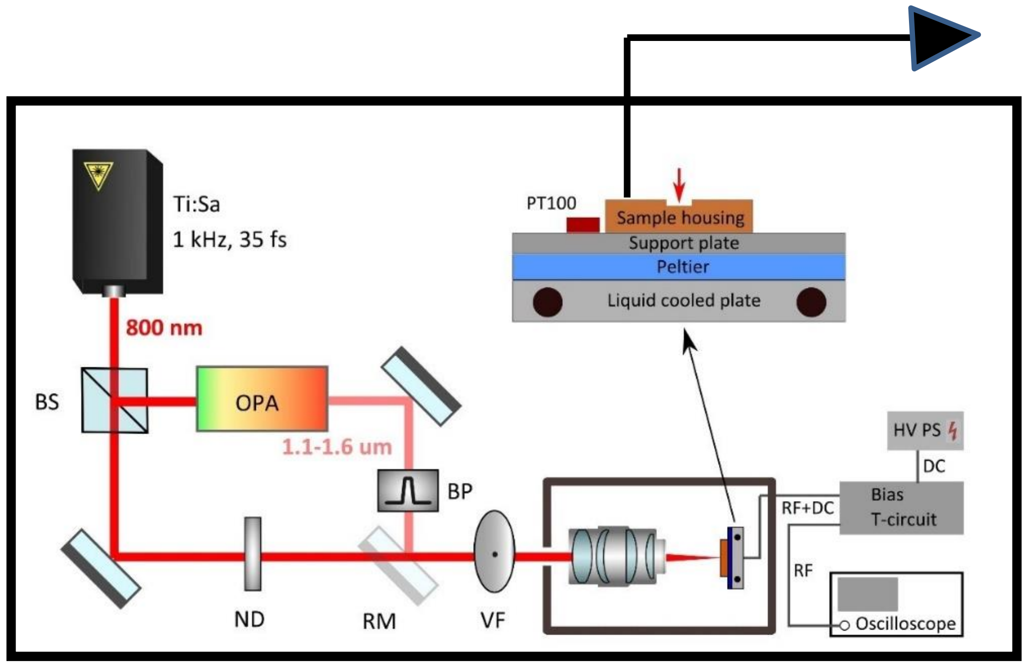
Single trench sensor from W11: C1-V4-1TR

Measured sensors



Experimental Technique: fs-laser based TCT at ELI

Place	ELI Beamlines
Operational modes	Single and two photon absorption (SPA and TPA)
Pulse energy on sample	Variable by ND filters (accuracy: 0.2 pJ)
Wavelength	800 nm (SPA), 1550 nm (TPA)
Pulse width in sensor	1550 nm, ~ 150 fs 800 nm, ~ 50 fs
Focus waist radius	0.85 μm (SPA), 1.5 μm (TPA)
Rayleigh length	3.31 μm (SPA), 7.74 μm (TPA)
Sample cooling	Down to -25 deg. C
Sample movement	X, Y, Z
Bias voltage	up to or > 720 V
Detection	6 GHz (20 GSa) oscilloscope and leakage current measurement (accuracy: 0.1 μA)

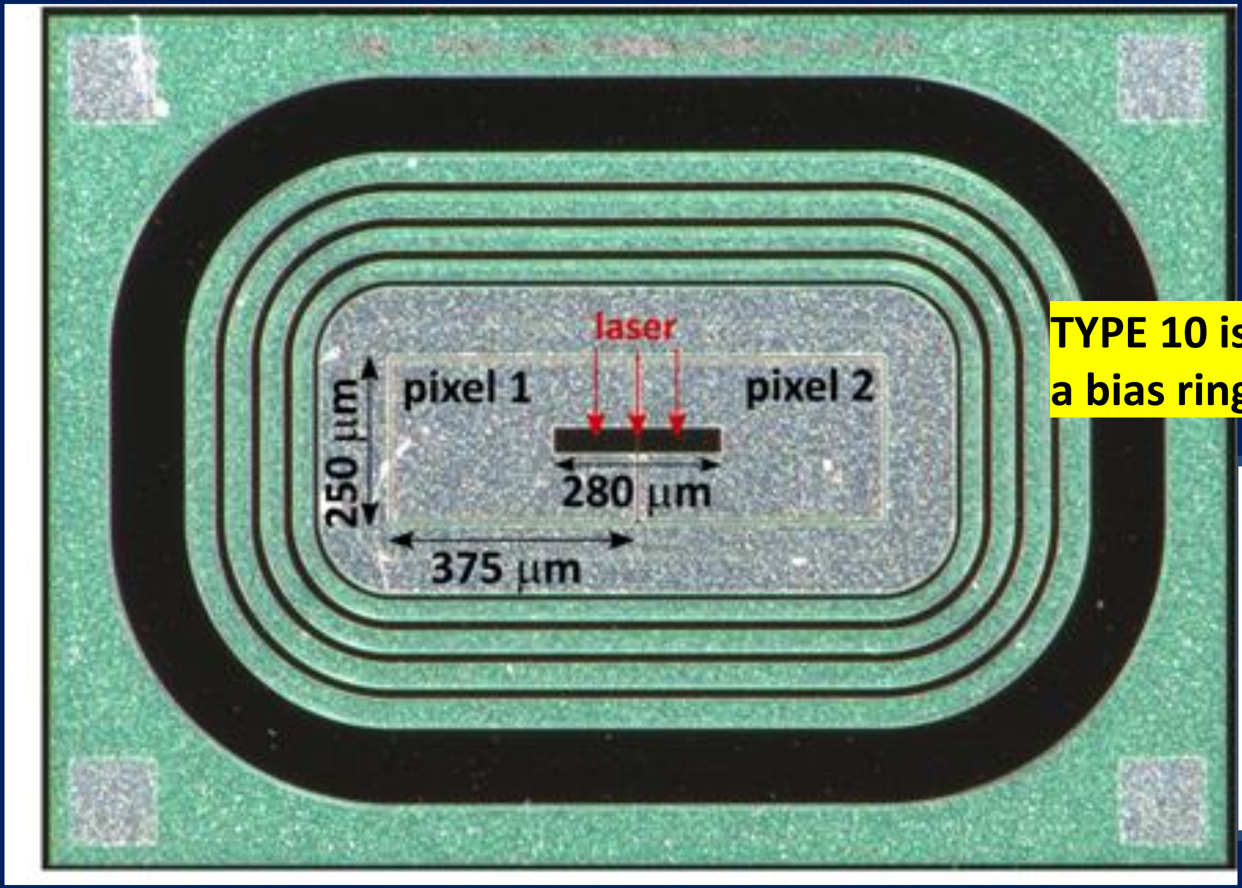


Schematic view of the setup for TCT-SPA and TCT-TPA measurements at ELI Beamlines (BS – beam splitter, OPA - optical parametric amplifier, BP - bandpass filter, ND - neutral density filter, RM - removable mirror, VF - variable filter)

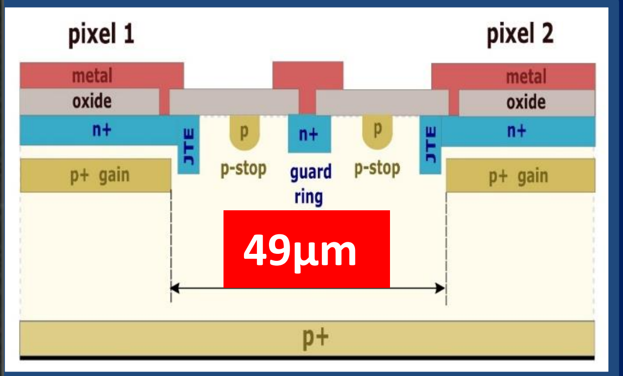
In study presented here we did not use amplifier.

Ref: G. Lastovicka-Medin et al, Femtosecond laser studies of the Single Event Effects in Low Gain Avalanche Detectors and PINs atELI Beamlines, Nuclear Inst. and Methods in Physics Research, NIM A, 2022

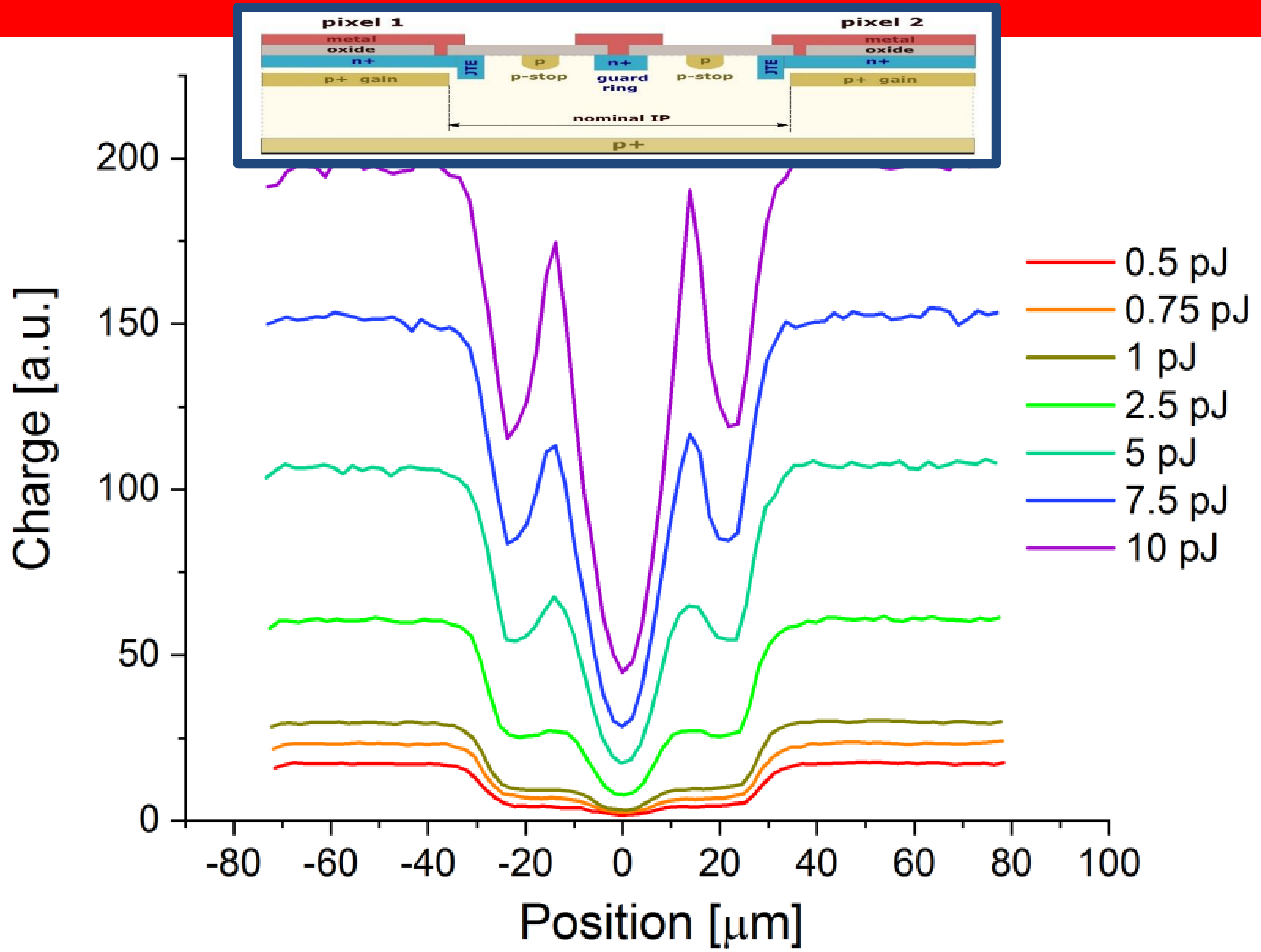
Motivation: Observed strong charge enhancement in IP region in Ti-LGAD TYPE10



TYPE 10 isolation layout: 2p-stops and a bias ring at the center



Strong charge enhancement in IP region

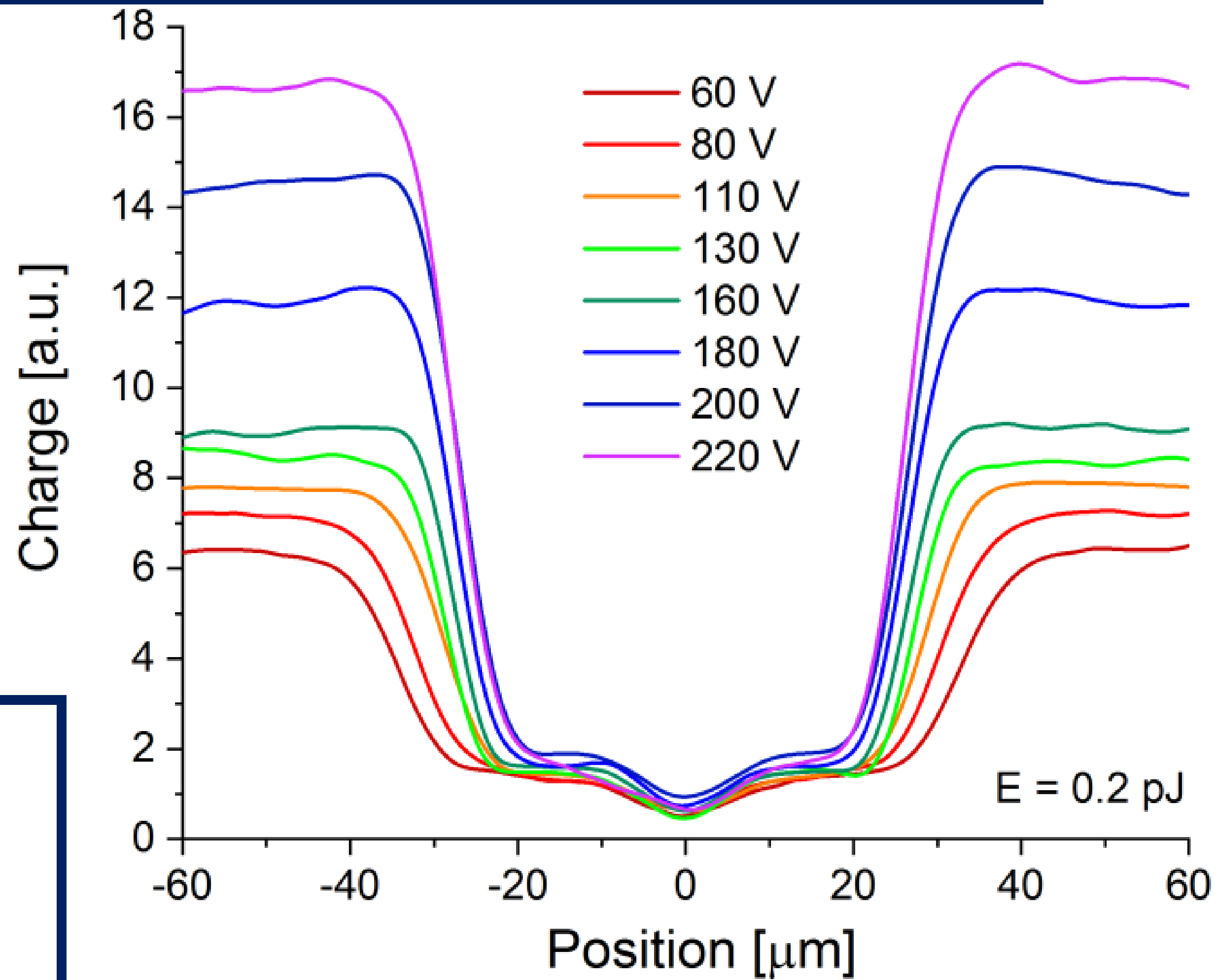


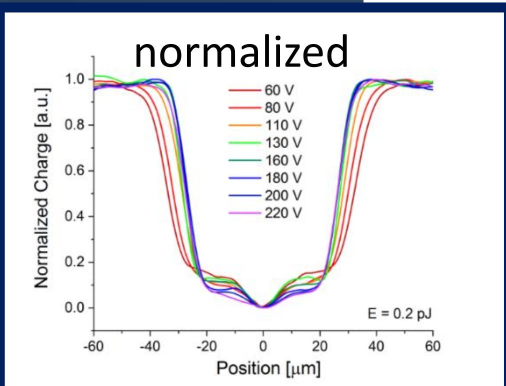
Space-charge profile vs laser pulse energy)

- ❑ Spikes observed in space charge profile in no-gain region; more enhanced with increased laser power.
- ❑ They appears on the sides of the central hollow (more or less at +/- 15 μm).

at low laser power

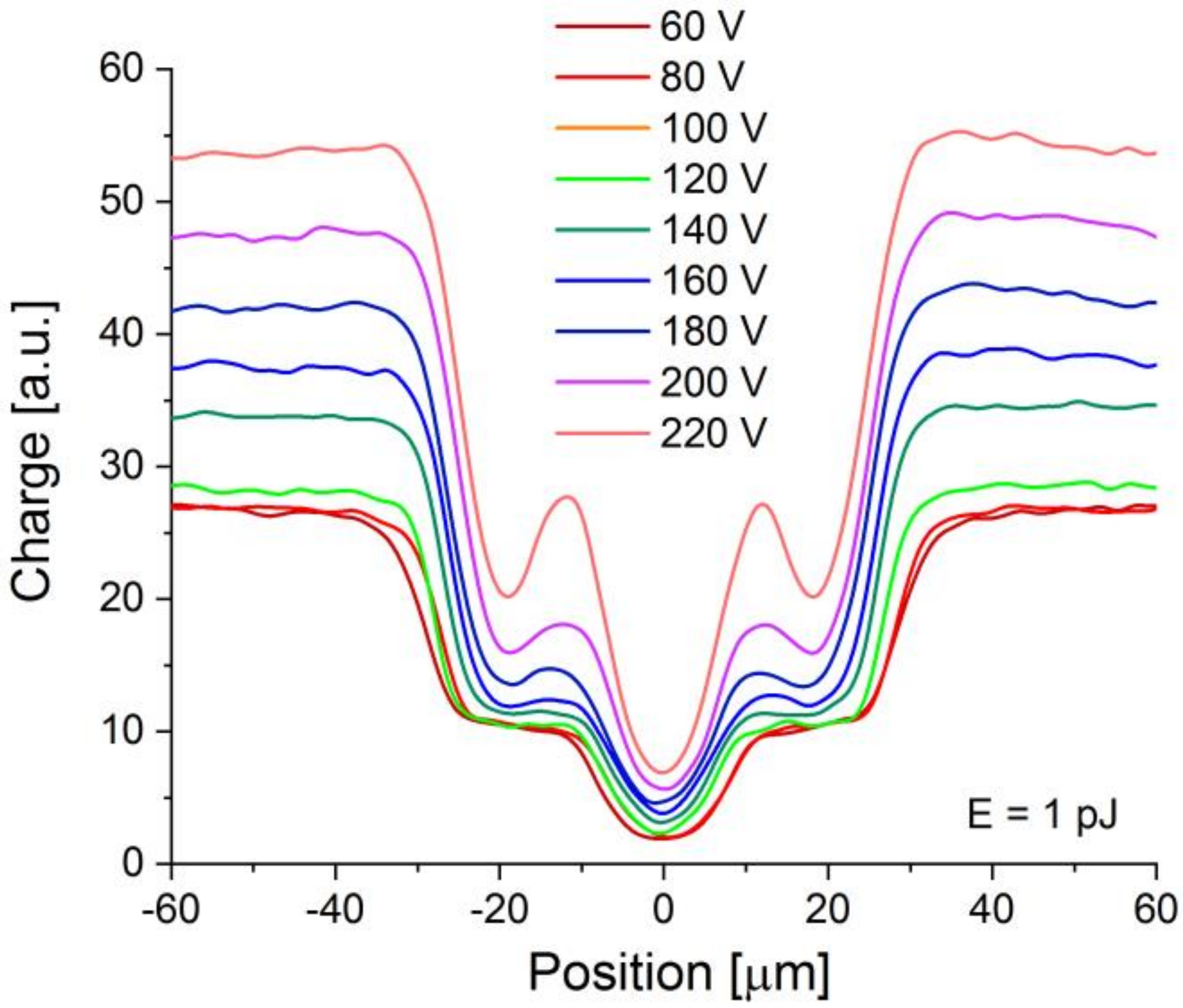
Same data as above but normalized for better compariso





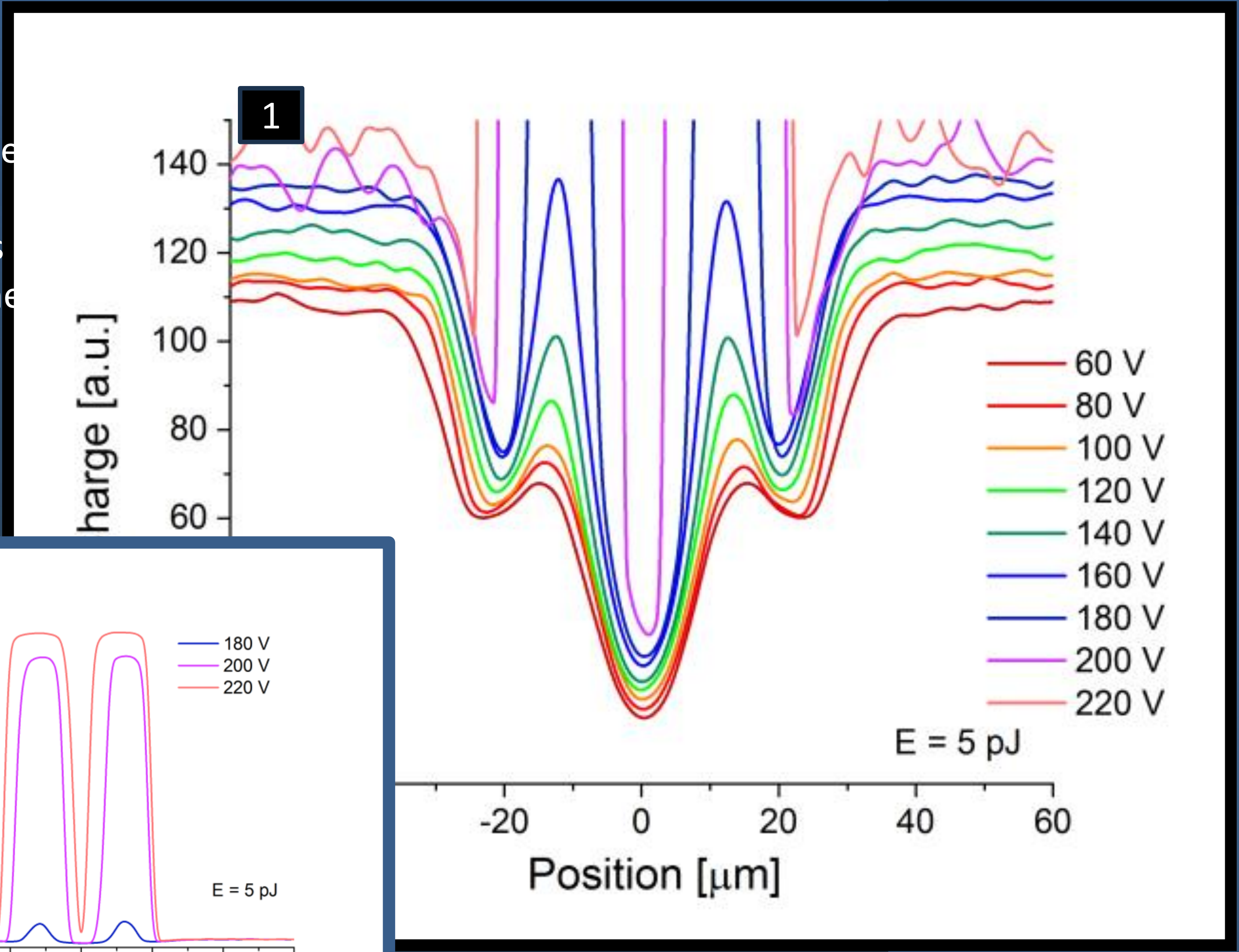
IP distance decreases with increasing bias.

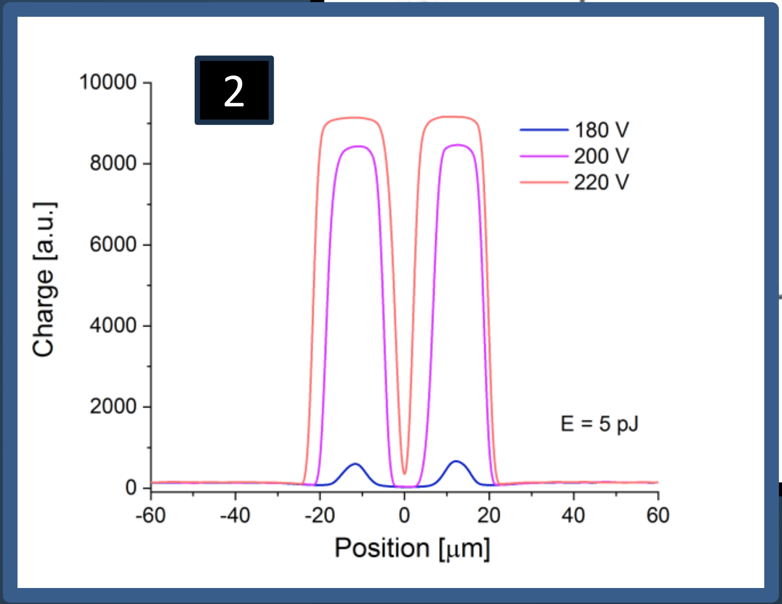
at medium laser power



at high laser power

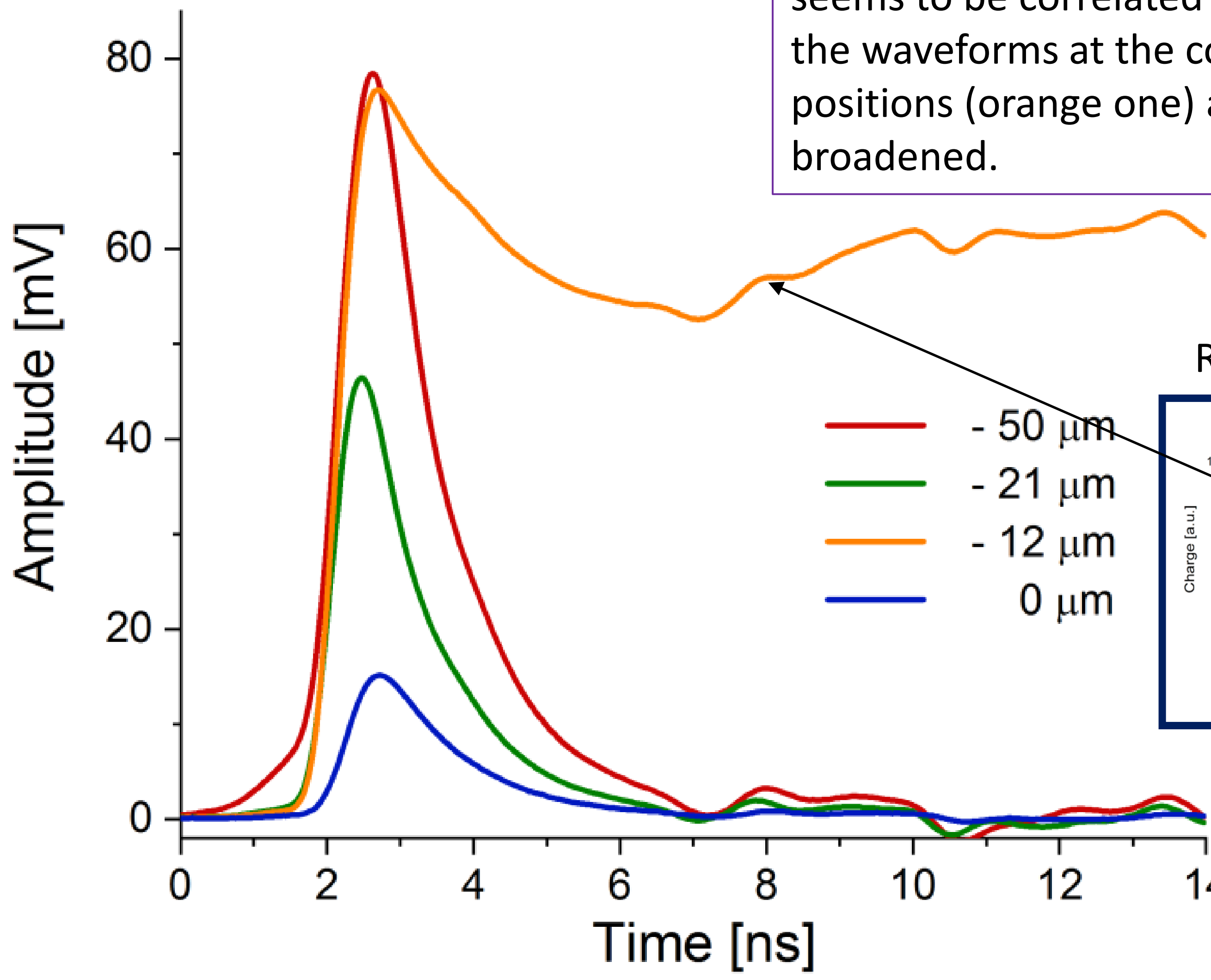
At high laser power (5 pJ) extremely strong side bands appear around the central hollow.



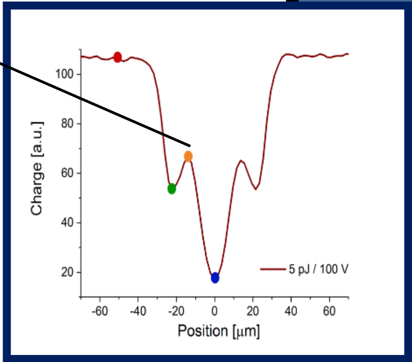


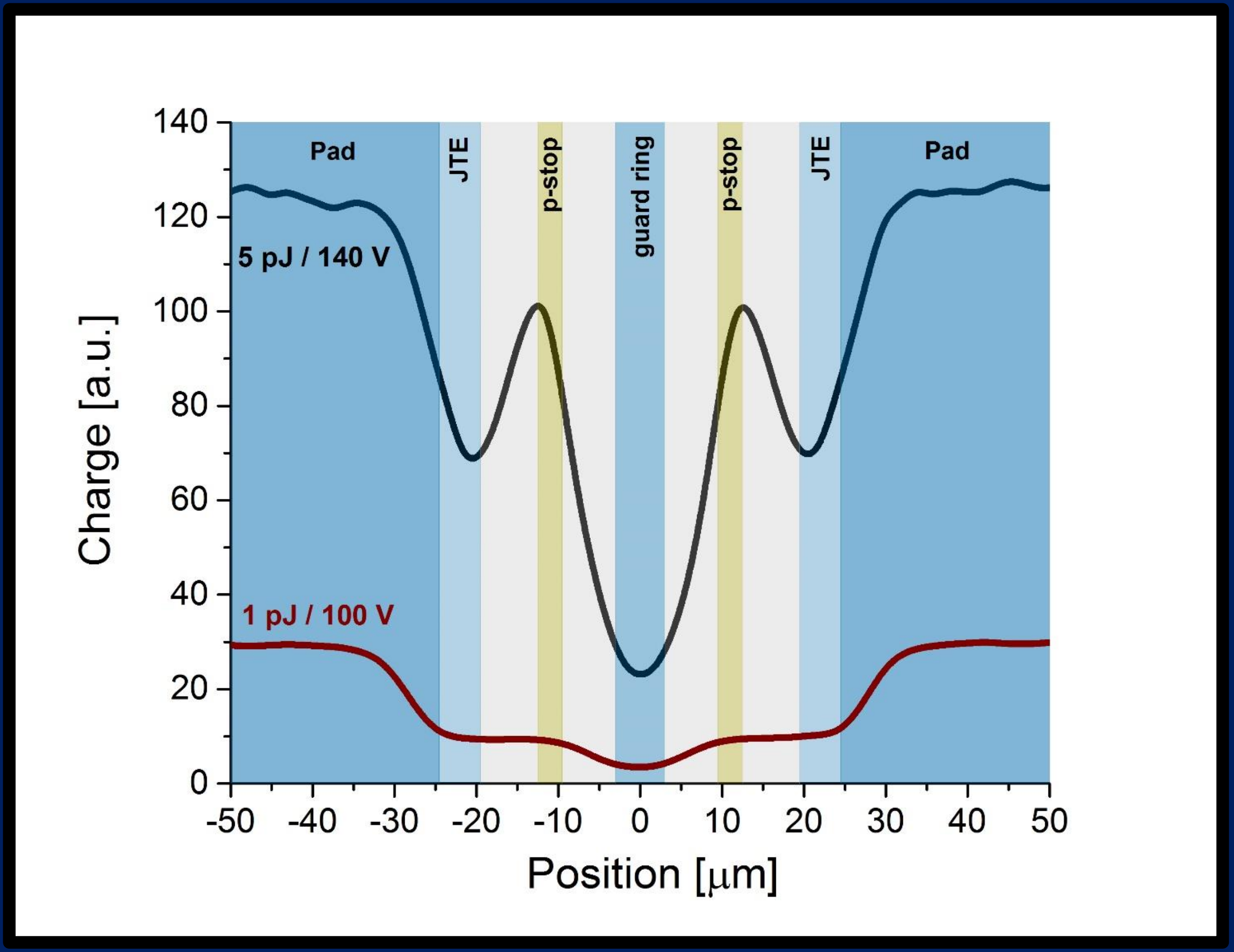
Waveforms recorded at high power and bias (5 pJ/180 V) at selected positions

When we look at the waveforms it is visible that the very strong side bands seems to be correlated to the fact that the waveforms at the corresponding positions (orange one) are extremely broadened.



Reminder:

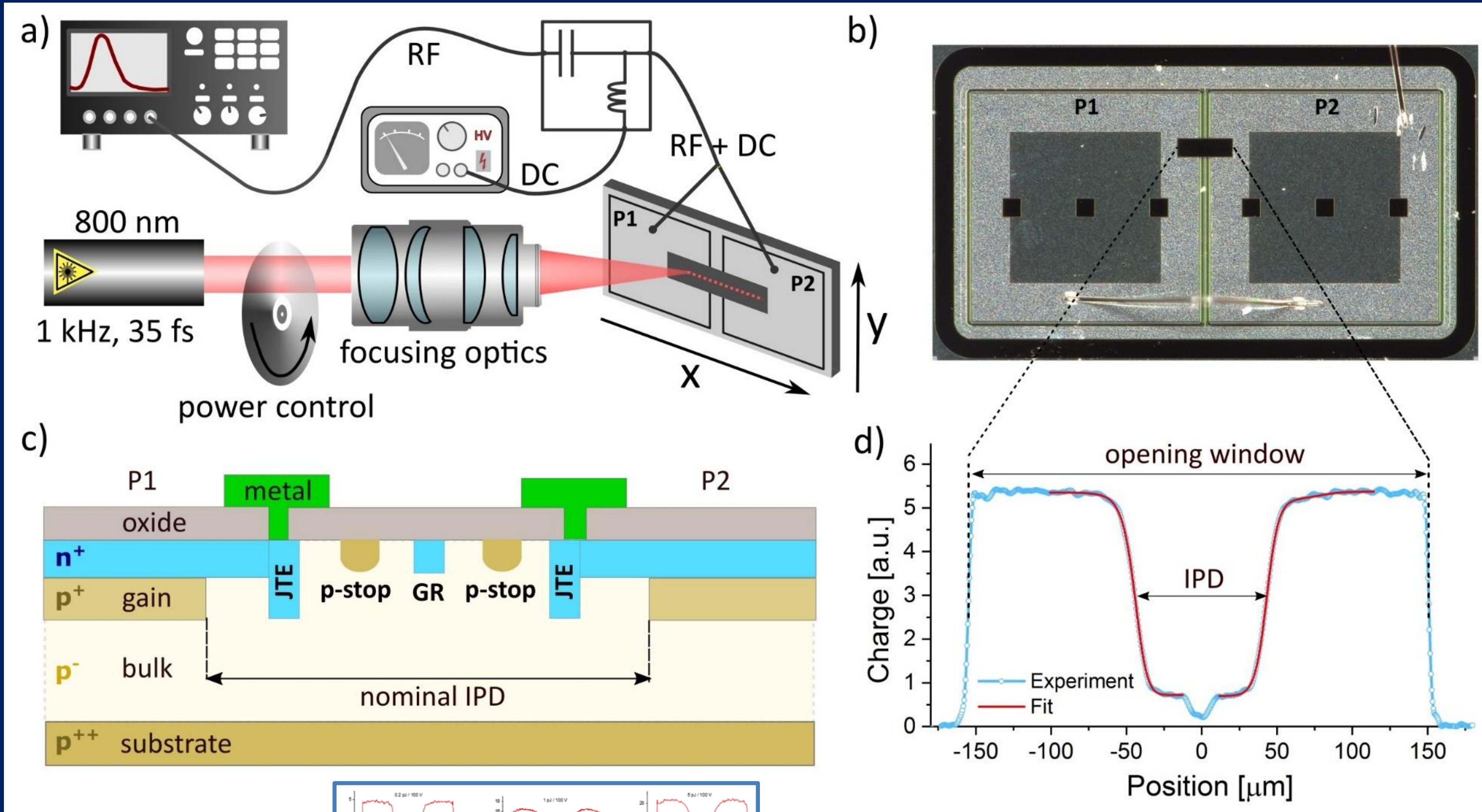




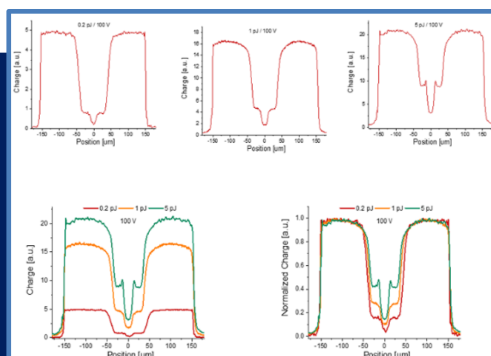
Published in Sensor:

G. Laštovička-Medin et al., Exploring the Interpad Gap Region in Ultra-Fast Silicon Detectors: Insights into Isolation Structure and Electric Field Effects on Charge Multiplication, Sensors 23, No. 15 (2023) 6746.

Cross-Check: UfSD4, IPD = 61µm



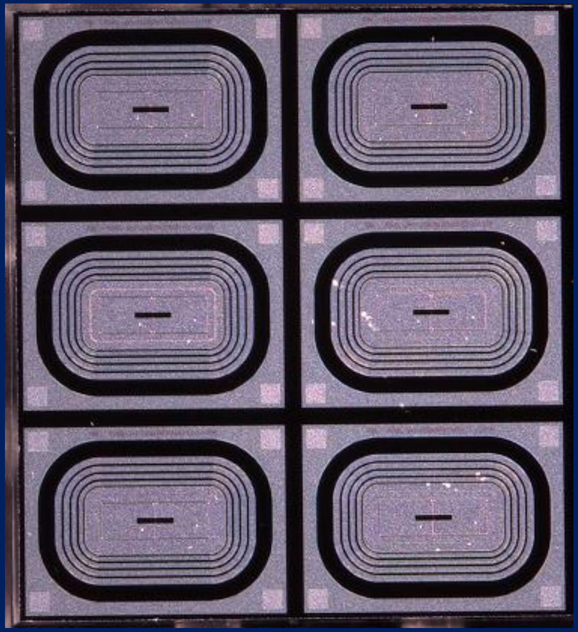
Submitted to Radiation protection and Isotopes

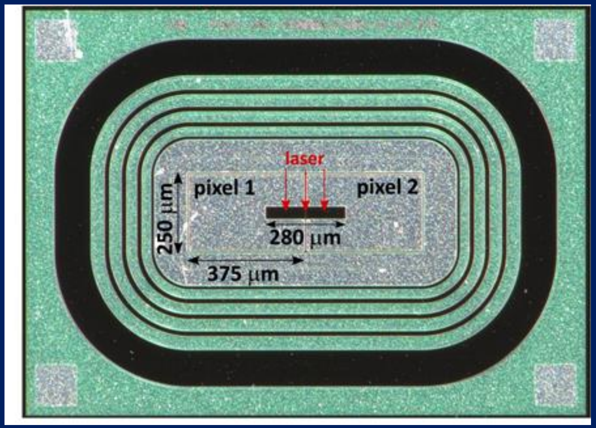


No enhancement has been seen in IP region.

- Lower p-stop doping in ufsd 4.0
- Larger distance between p-stop and JTE
- No field plates used in TI-LGAD type 10

Double Trenched LGAD : Main topic

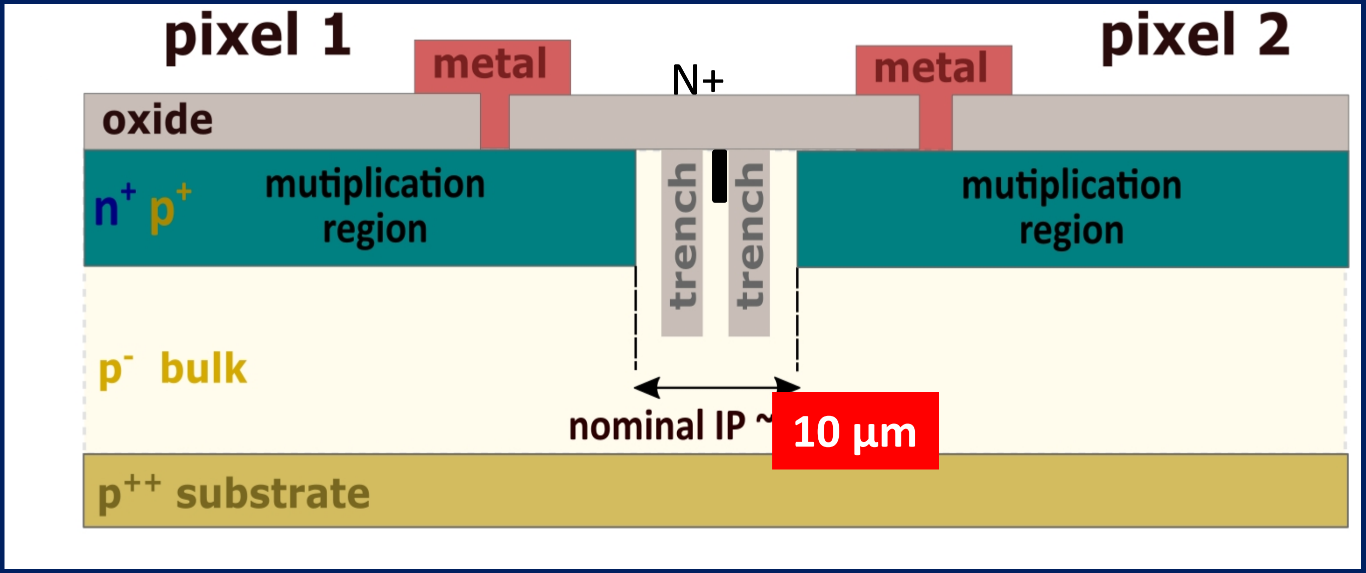




- W7: C2-V3-2TR-GRT2
- W11: C1-V2-2TR
- W16: C1-V4-2TR and C2-V2-2TR

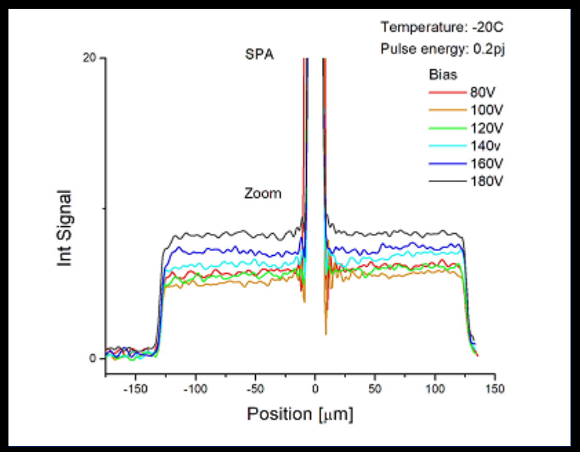
W7, lower gain, higher leakage current
W11: shallower trench
W16: deepest trench

(V_{GL}=25 V, V_{FD} =30 - 35 V, G = 5-10



Example of Space-Charge profile & Comparison of signals from different sensor's regions

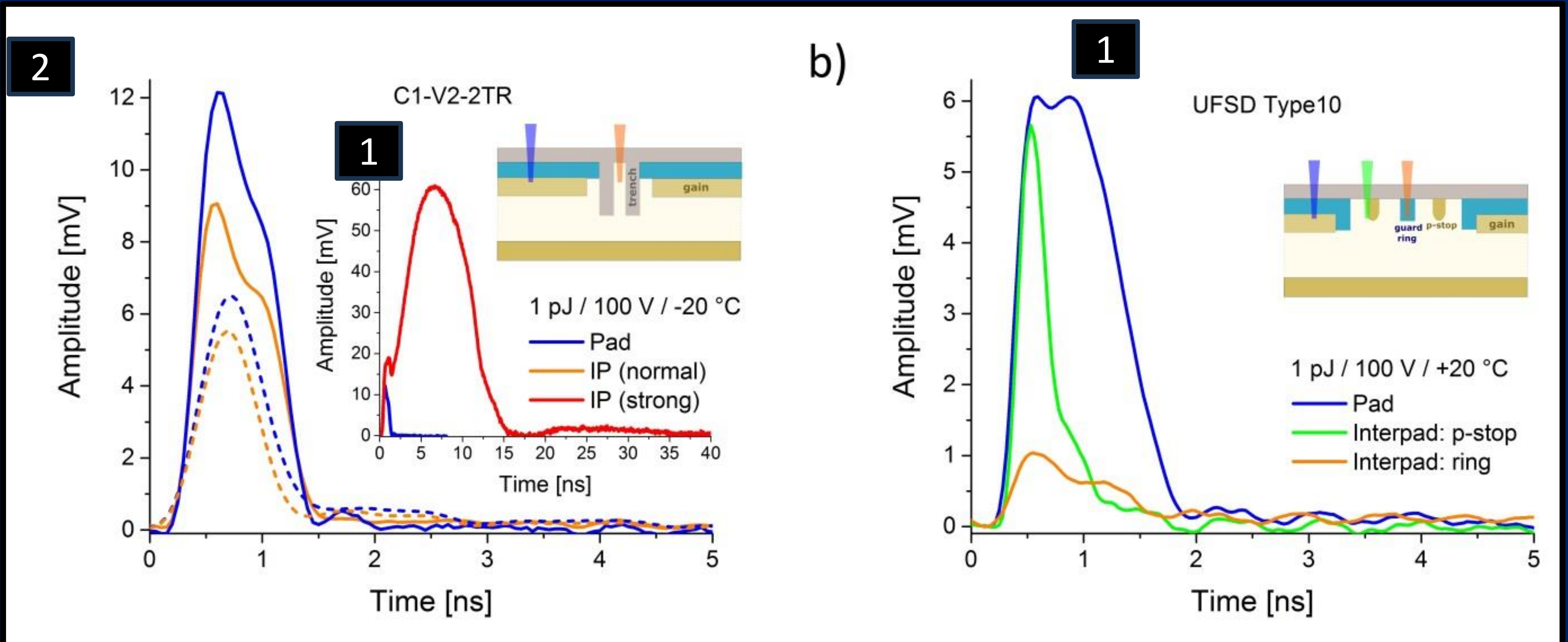
1



2

1

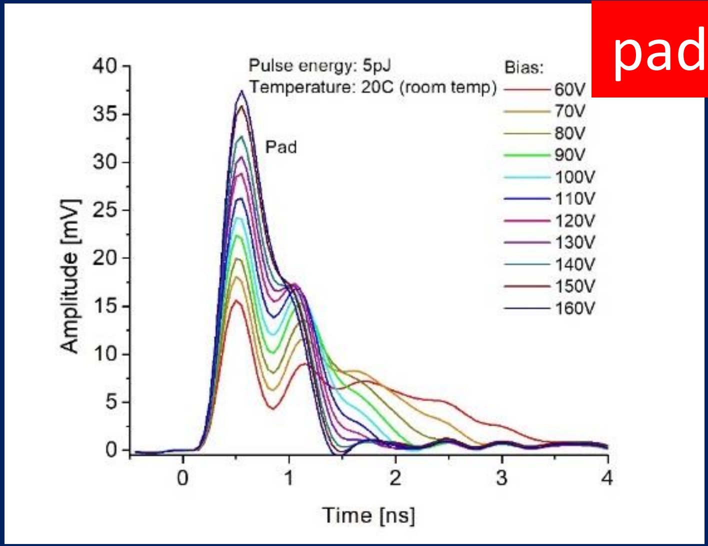
1



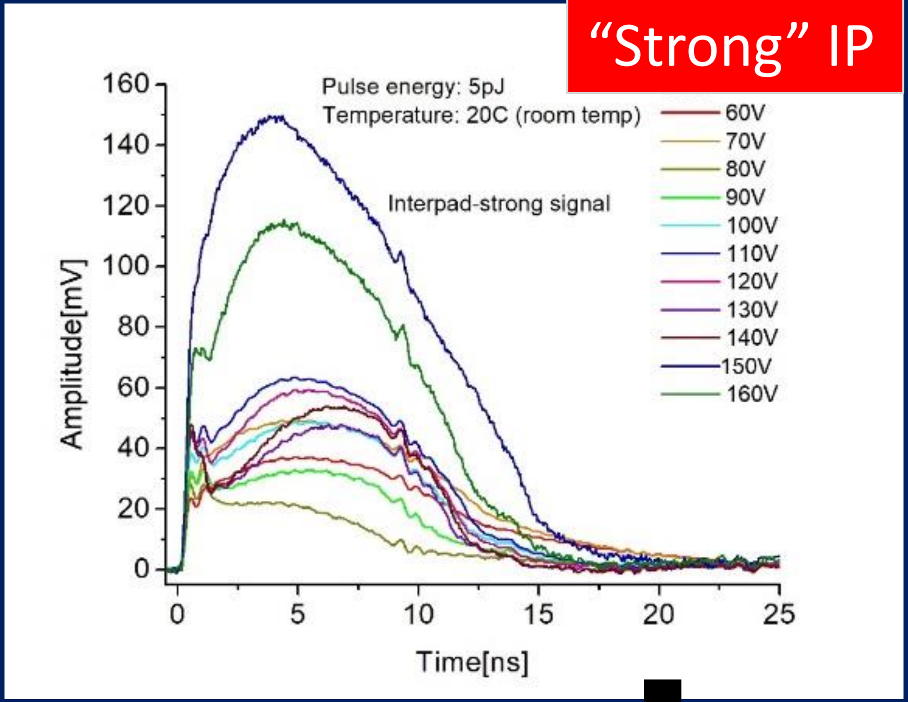
Many type of signals in IP region

Sample from W7, T=20^0C

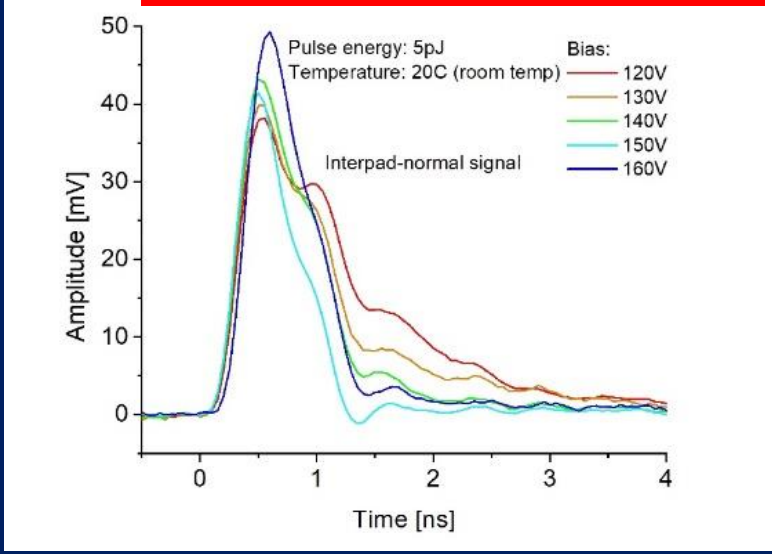
pad

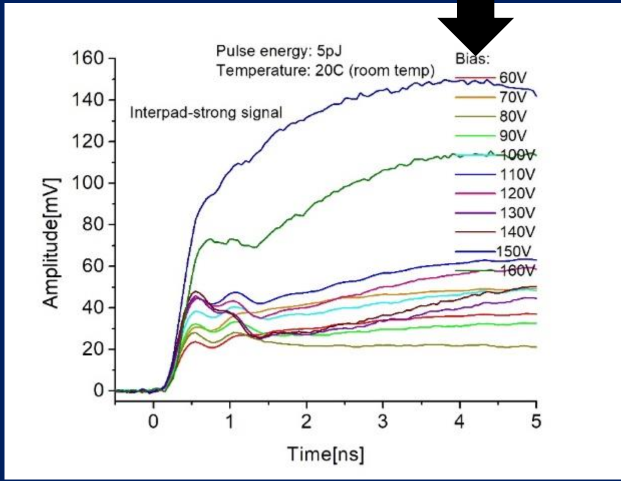


“Strong” IP



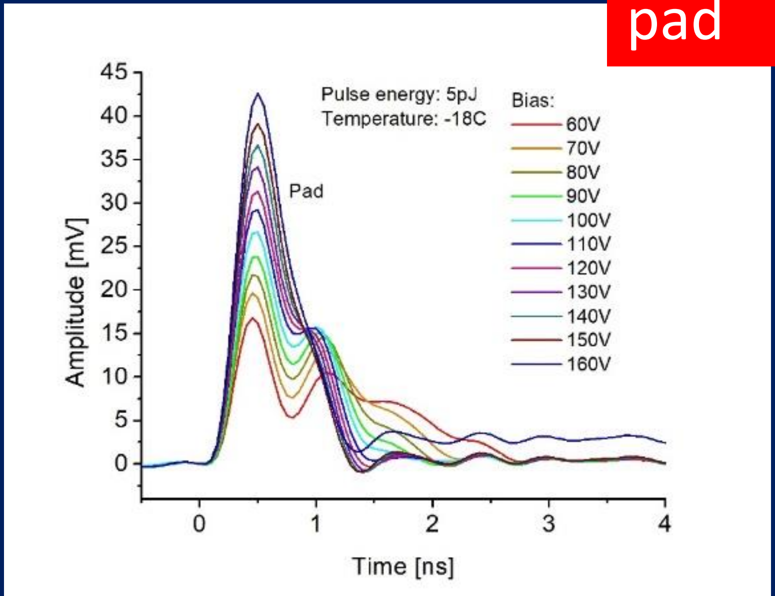
“Expected”(normal) IP



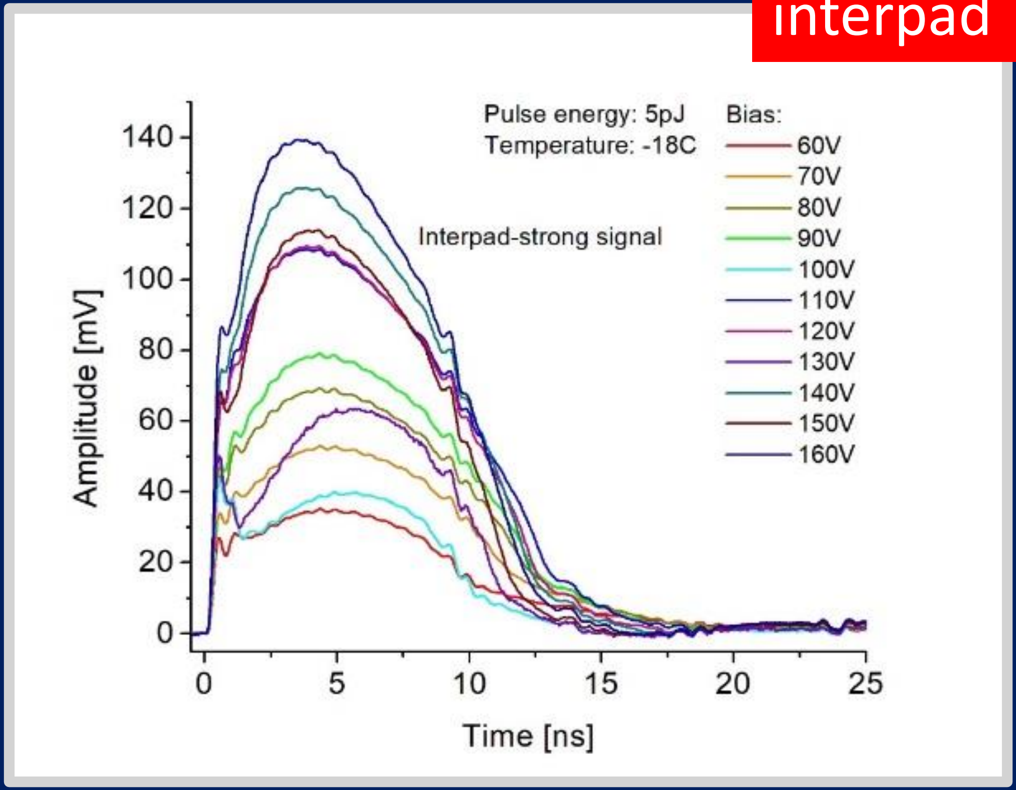


W7, T=-20^{0}C

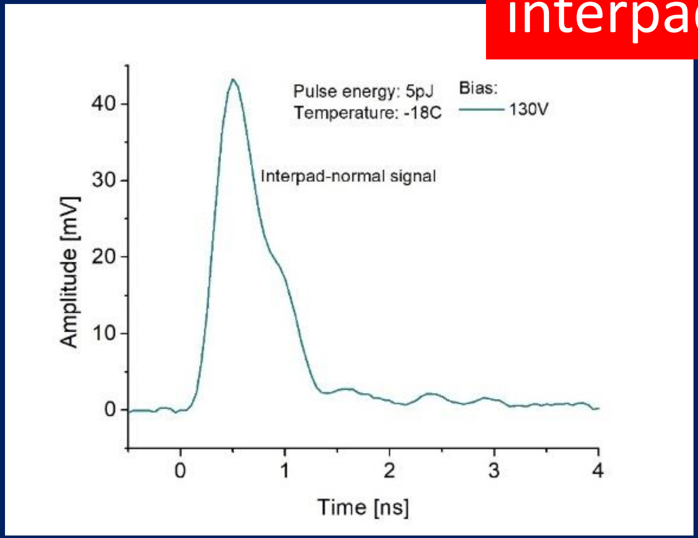
pad



interpad

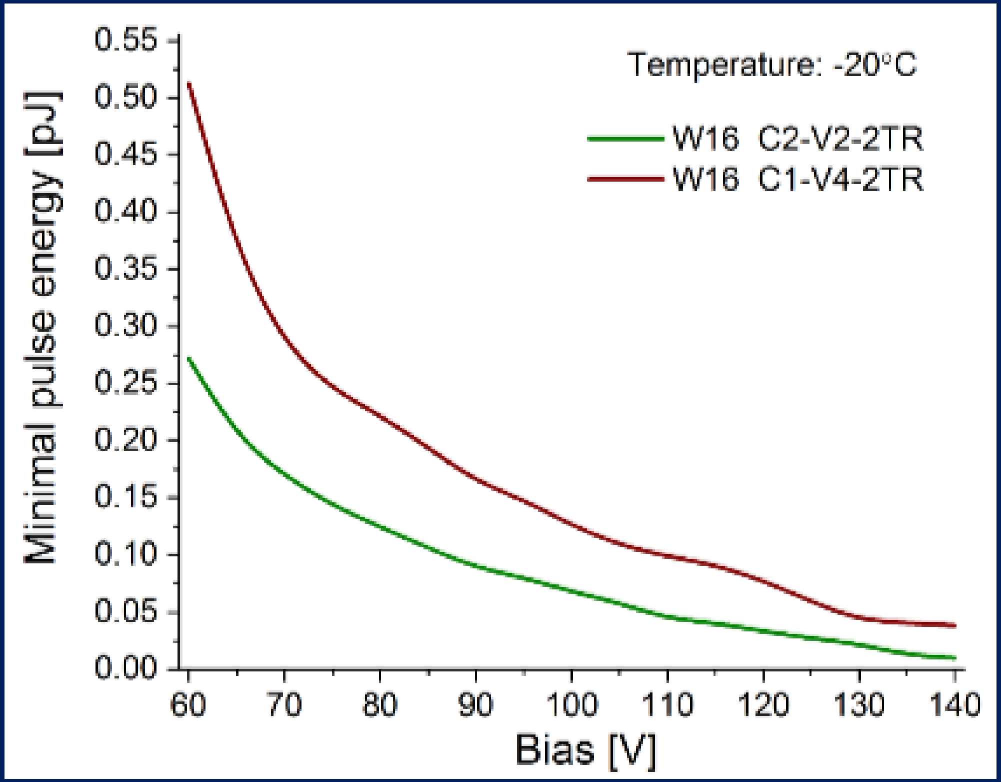


interpad



Threshold conditions for strong IP signals:
The Minimal laser pulse energy vs bias

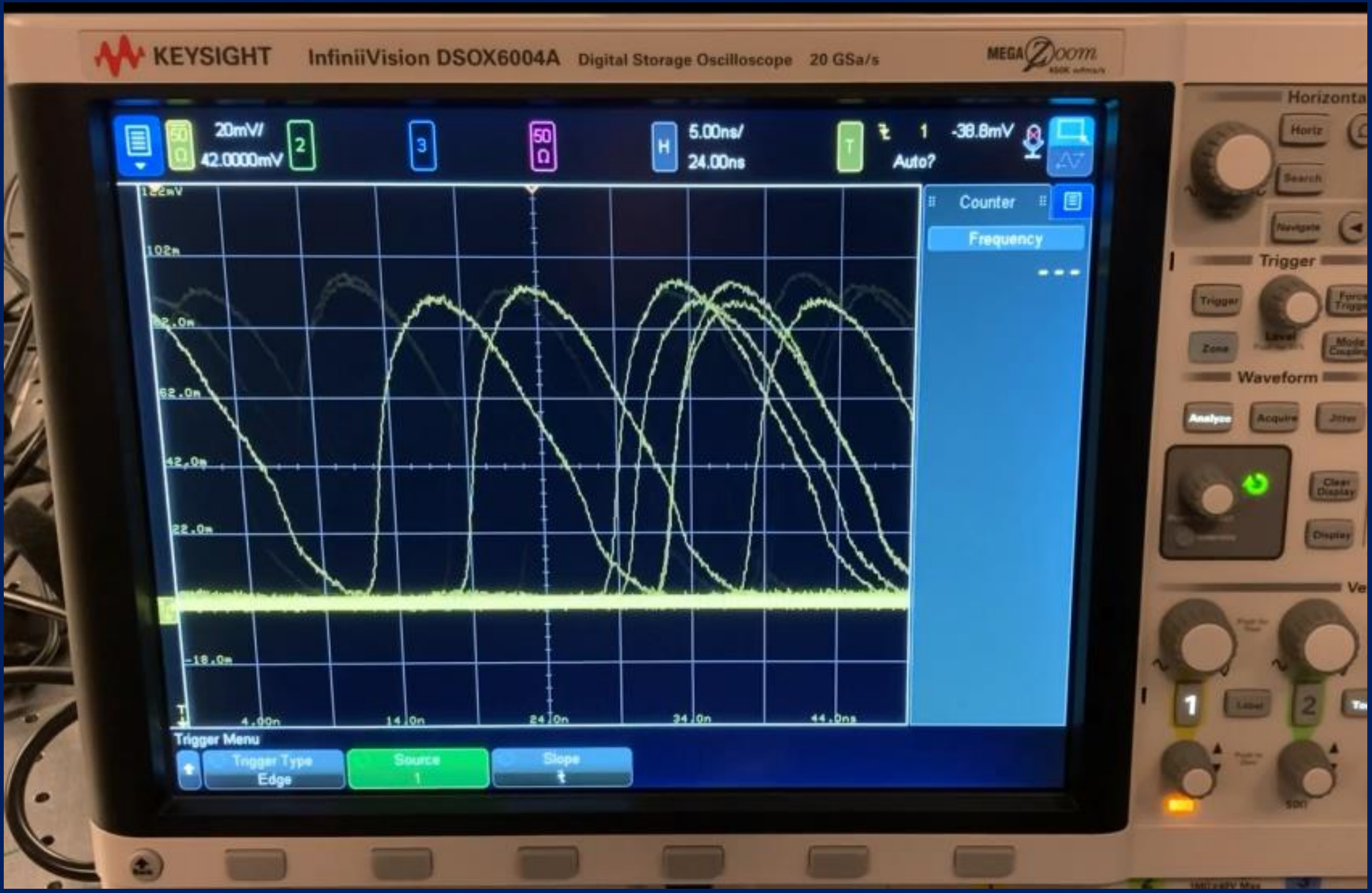
- W16 sample;
- Measurements conducted at -20C temperature.

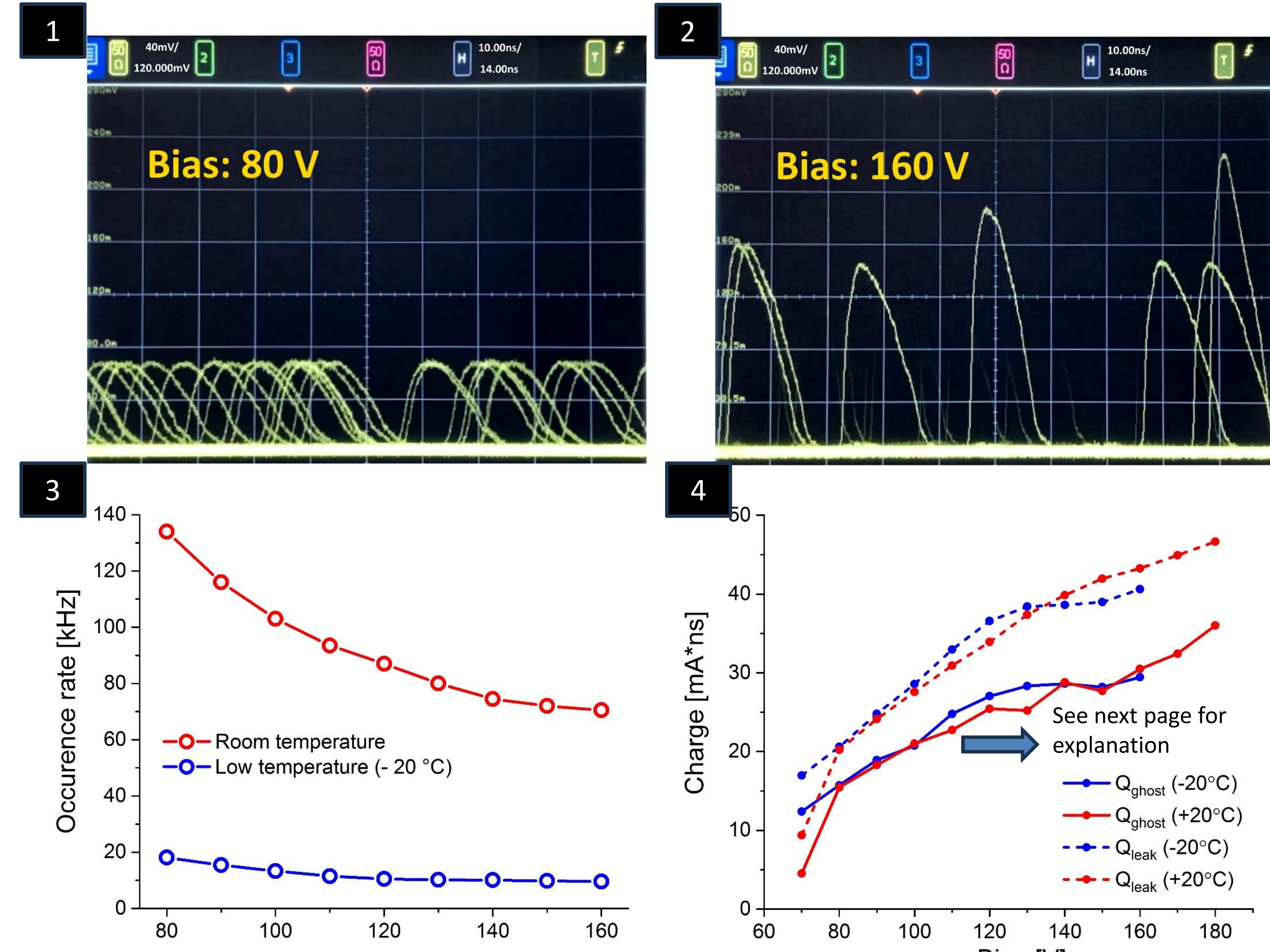


At high bias (140 V) even very weak 0.01 pJ laser pulse induces strong signal. To achieve this regime at 60V pulses with energy about 0.5 pJ are needed.

Ghosts

- We swiched off laser and we kept laser biased



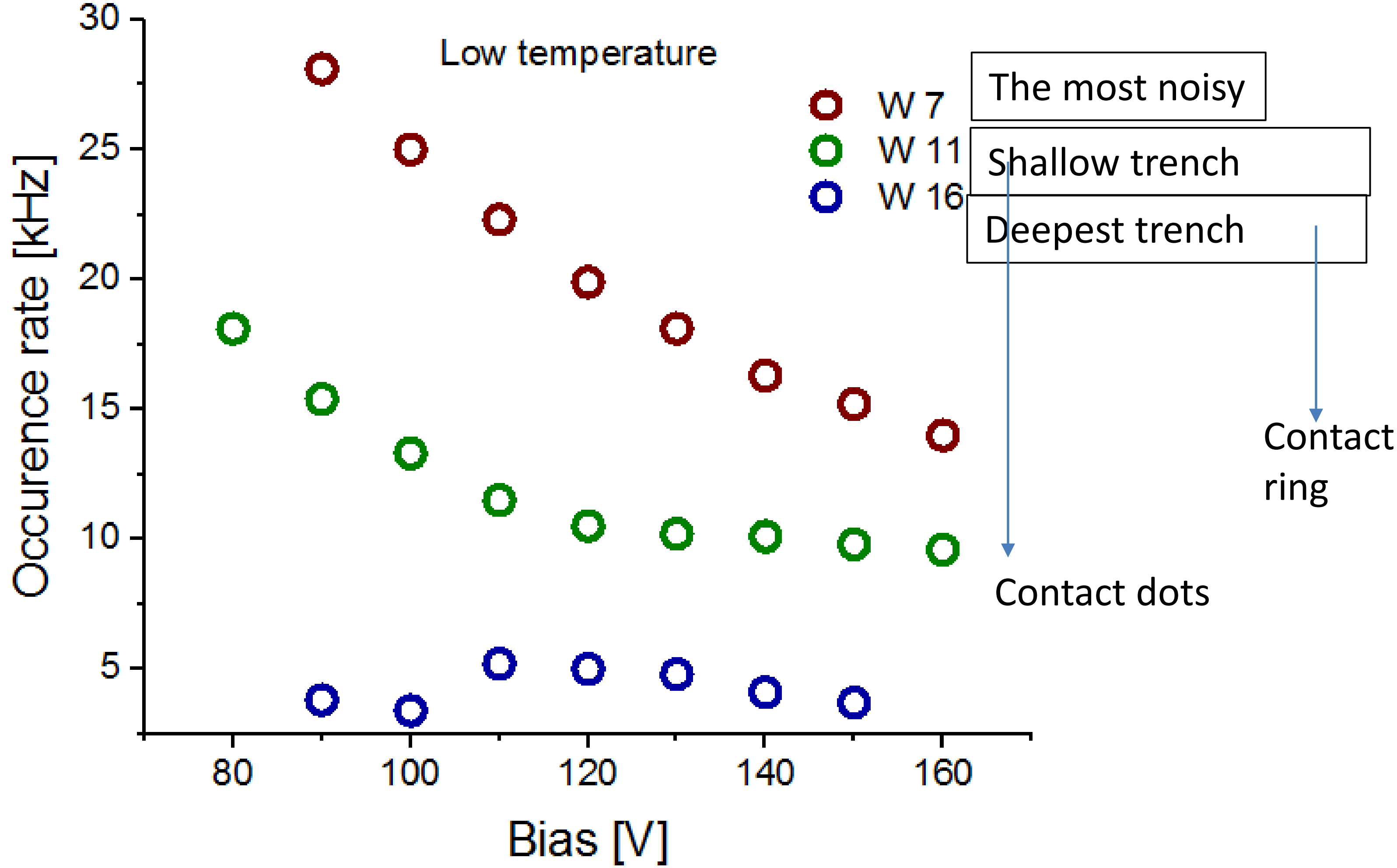


1
40mV/
120.000mV
10.00ns/
14.00ns
Bias: 80 V
2
40mV/
120.000mV
10.00ns/
14.00ns
Bias: 160 V
3
Occurence rate [kHz]
Room temperature
Low temperature (- 20 °C)
0
20
40
60
80
100
120
140
80
100
120
140
160
4
Charge [mA*ns]
See next page for explanation
Q_ghost (-20°C)
Q_ghost (+20°C)
Q_leak (-20°C)
Q_leak (+20°C)
0
10
20
30
40
60
80
100
120
140
160
180

Discussion on Q_Leakage/Q_ghosts

- The ghost charge is the same regardless of the temperature, but the ghost frequency is not. This means that the ghost charge originates from thermal generation of free carriers.
- The leak/ghost_freq scaling seems to works as well; we got sort of a confirmation of the picture that some accumulation due to leakage current and later discharge is responsible.
- If however, we now compare the Q_leakage and Q_ghosrts plot we note that they are of similar order (30-40 mA ns) although the trench to total surface was not considered. The difference in surface ratio means that Q_leakage plot should show less charge if there was no multiplication.
- The fact that Q_leakage and Q_ghost show compatible charge means that in order to get consistent hypotheses about charge multiplication the charge collected in trenches should multiply by roughly the S_total/S_trench. We would say the gain is G(180 V)/G(70 V) ~ 3 and this should be compared to surface ratio (order of magnitude).
- So, the picture of charge accumulation in the trench region due to leakage current and further discharge works, but requires some gain for that charge

Ghost occurace rate for different sensors



Differences are much higher at room temperature

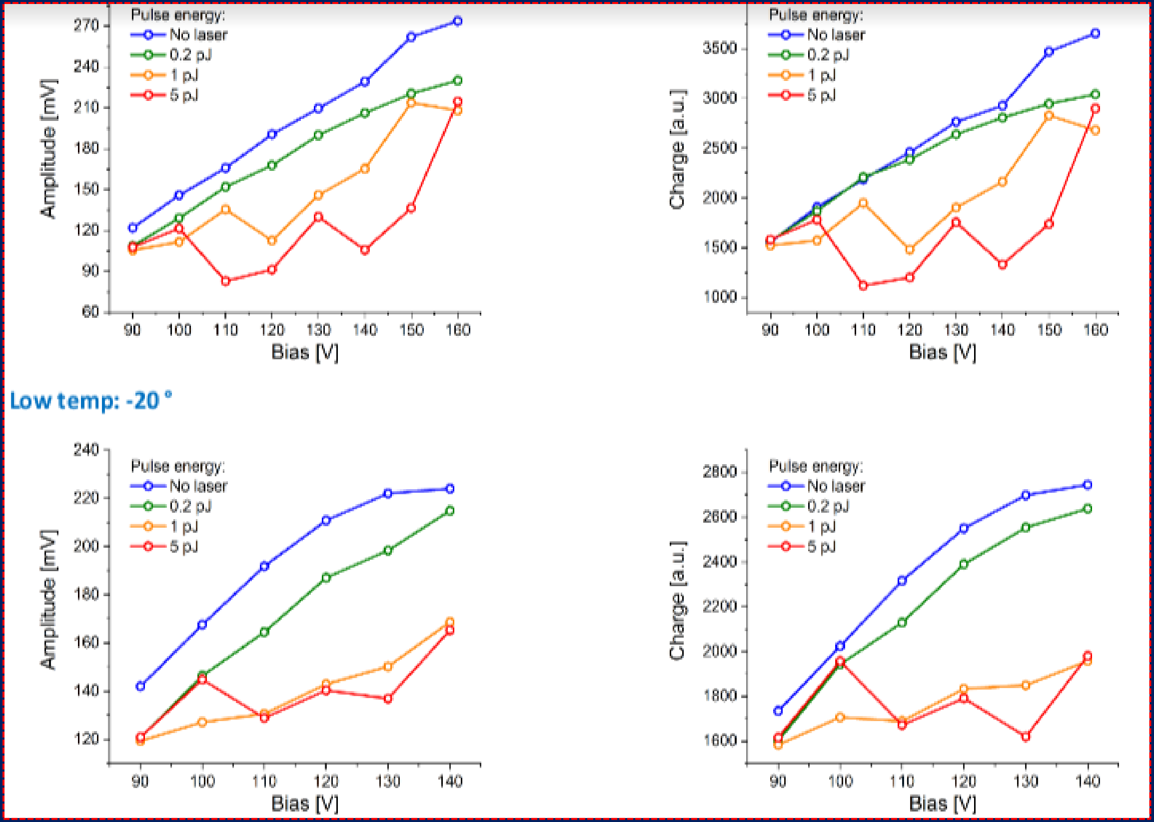
Bias threshold dependence on ghost signal

Sensor	Threshold of "ghosts" generation and occurrence rate	
	Low temperature: T = -20 °C	Room temperature: T = 20 °C
W7: C2-V3-2TR-GRT2	87 V / 28.1 kHz	75 V / 227 kHz
W11: C1-V2-2TR	70 V / 22.9 kHz	67 V / 283 kHz
W16: C1-V4-2TR and C2-V2-2TR	90 V / 3.8 kHz	68 V / 43 kHz

Space charge effects

W16: C1-V4-2TR

- By increasing the bias voltage, the amplitude of the transient current signal increased in all cases, nevertheless whether LGAD was illuminated by fs-laser or laser was not used.
- Signal amplitude decreased with increasing the laser power (more charge is generated more gain was suppressed)

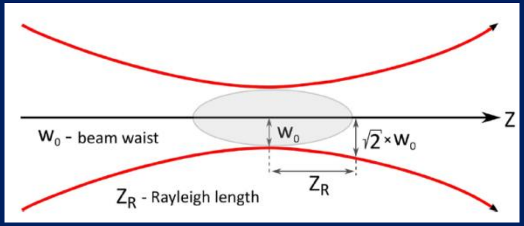


- Noticeably, in all studied cases, the measured IP signal was lower when LGAD IP region was illuminated by laser.

Probing of ghost and strong signals using TPA-TCT

- TPA Z-scans were performed across pad and IP at different laser power and bias
- Presented Z-scans are already rescaled to the real depth (taking n_{Si} = 3.4757 at 1550 nm)
- 3 different laser pulse energies were used: low power (0.25 nJ), medium power (0.6 nJ) and high power (1.4 nJ). These values were selected for easier comparison with SPA data. They correspond (in terms of generated charge) to 0.2 pJ, 1 pJ and 5 pJ in SPA studies
- Applied bias was 100 V and 160 V
- All measurements at room temperature

reminder



Beam parameters		
Wavelength	800 nm	1550 nm
Mode	SPA	TPA
Waist	0.85 µm	1.52 µm
Rayleigh length	3.31 µm	7.74 µm
Pulse duration	~ 50 fs	~ 150 fs

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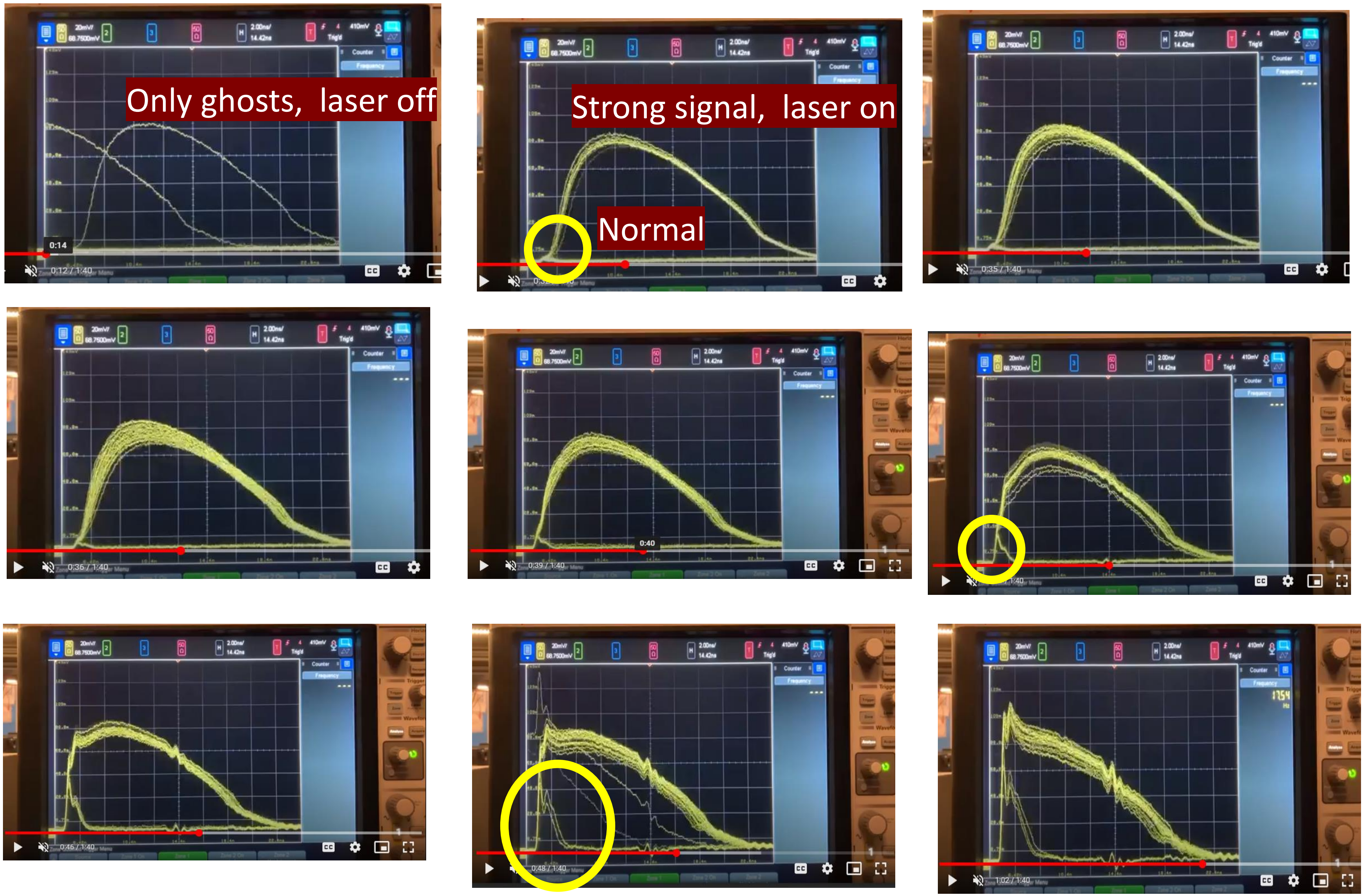
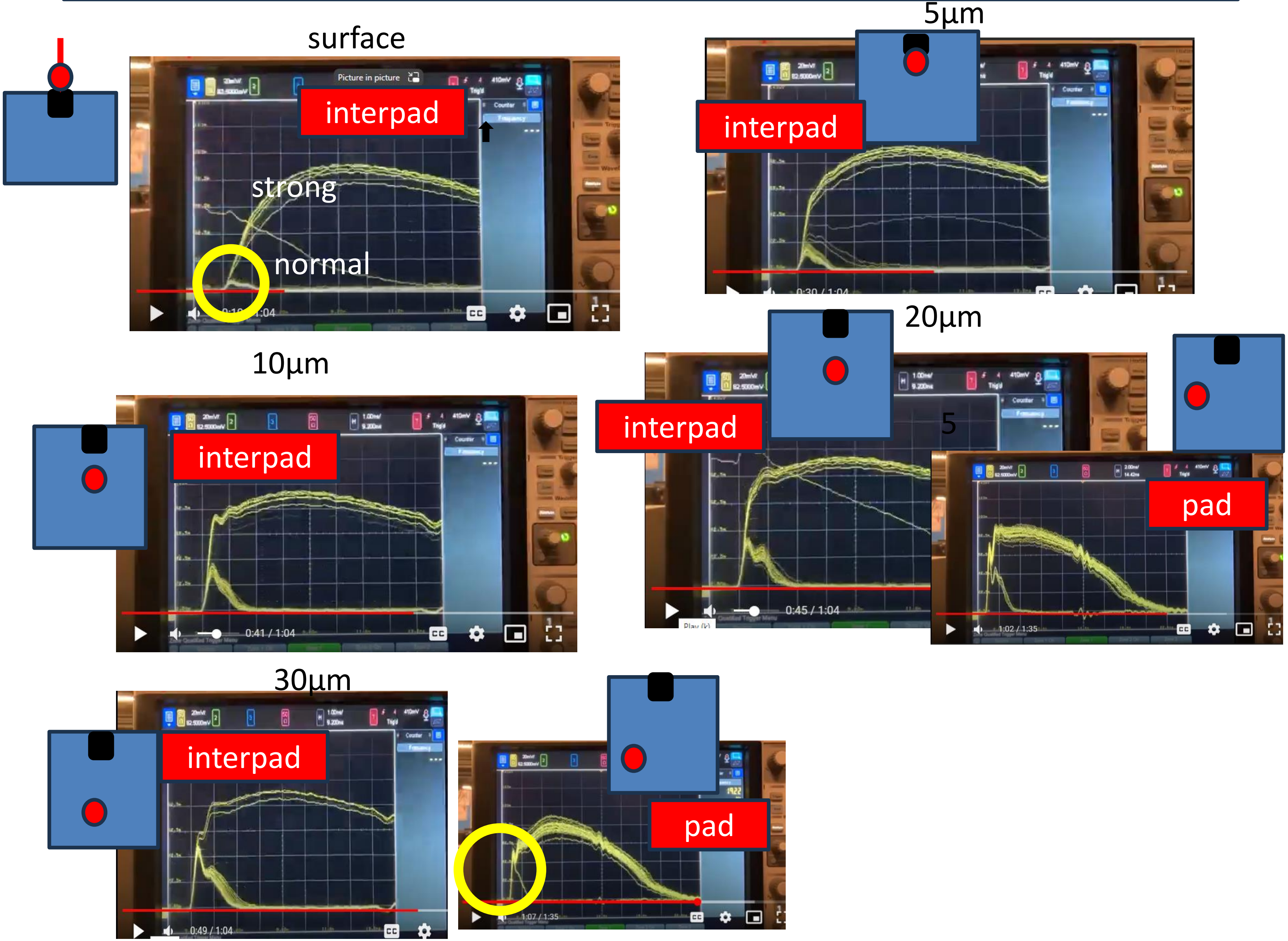
Measured sensor: W11: C1-V2-2TR

TPA depth:20 microns at the center of interpad; then we increased the laser power and observed the changes

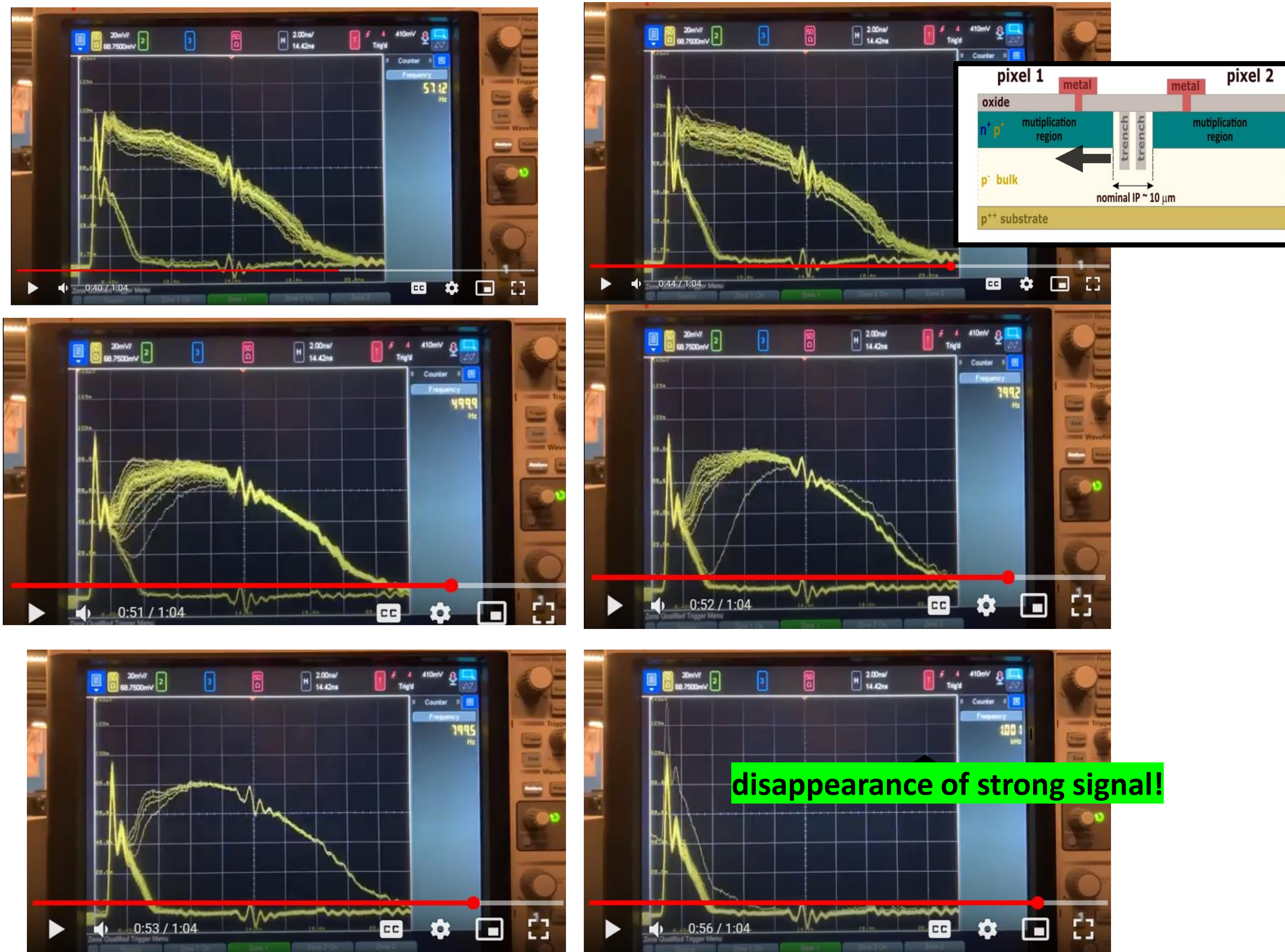


Images captured from videos during data taking

Depth Scanning



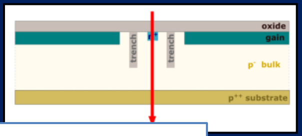
Scanning ocwe pixel peripherr and region towards the center of pixel, at 20 µm depth

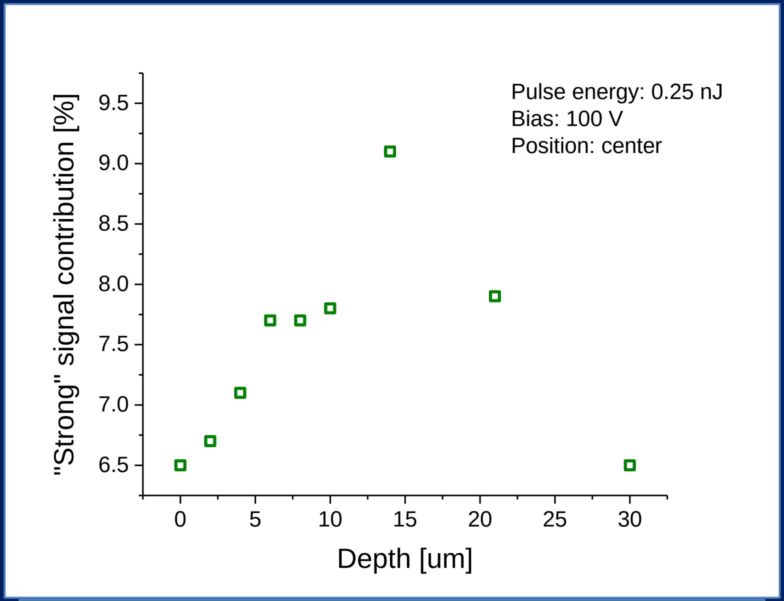


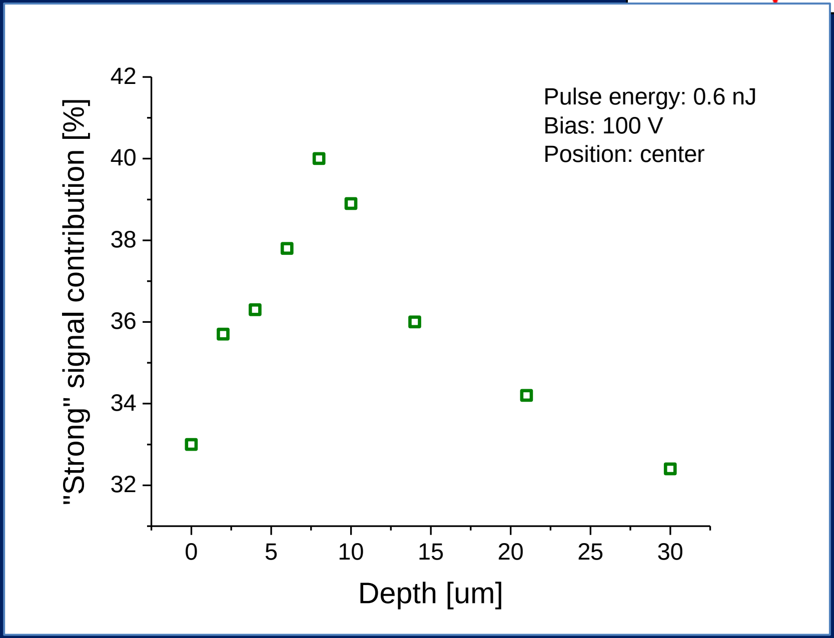
Contribution of “strong” signal probed by TPA

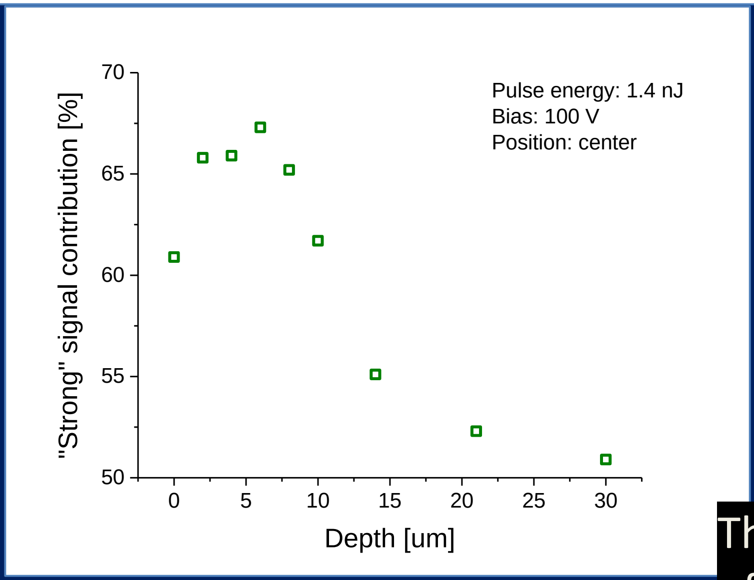
- Contribution of “strong” signal was tested by TPA (how many percent per 10000 laser shots result in “strong” signal
- Laser was focused in different depth and different positions around IP
- 3 different laser pulse energies were used: low power (0.25 nJ), medium power (0.6 nJ) and high power (1.4 nJ). These values were selected for easier comparison with SPA data. They correspond (in terms of generated charge) to 0.2 pJ, 1 pJ and 5 pJ in SPA studies
- Applied bias was 100 V

Different depths at center at different power





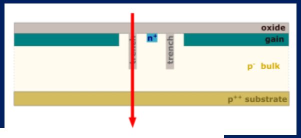


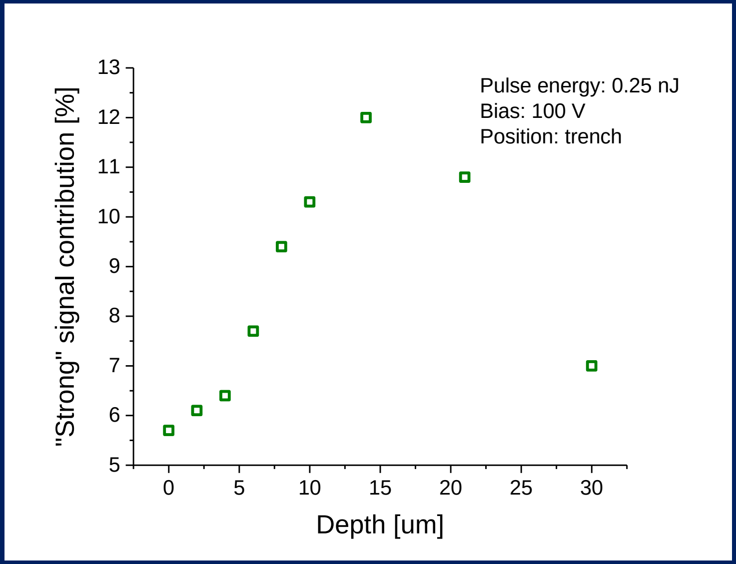


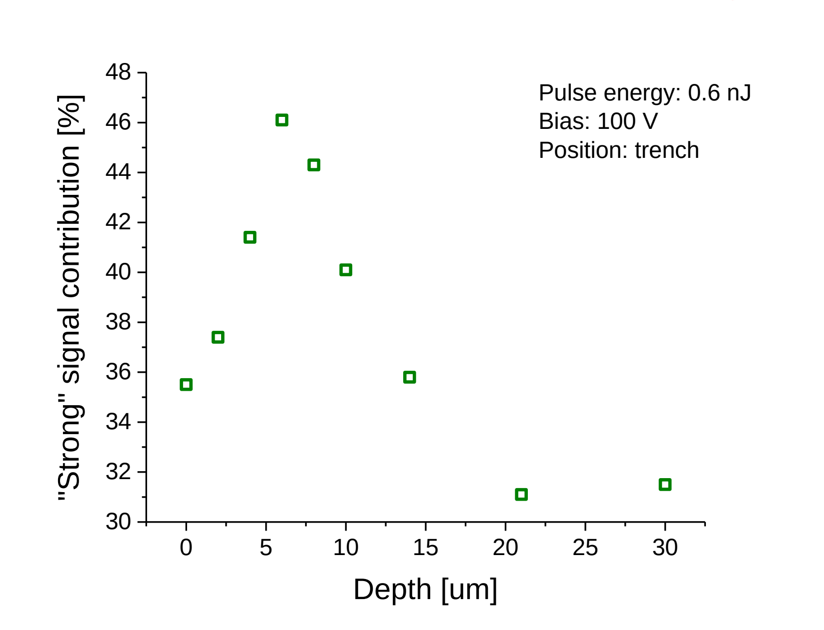
- In general, “strong” signal contribution increases with laser power.
  - At low power maximum “strong” shots contribution is about 14 um.
  - At medium power this maximum is shifted to shorter depth about 8 um.
  - At high power maximum contribution is about 6 um.

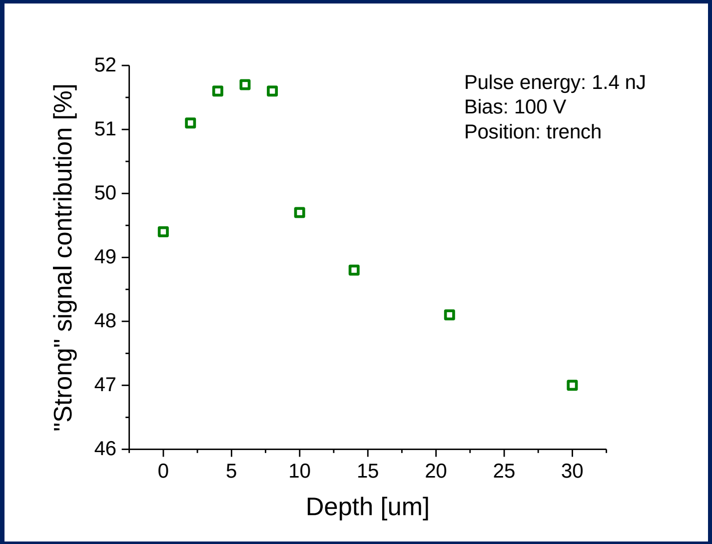
The stronger the laser was the higher contribution of stronger signal was at shorter depth.

Different depths at trench position at different power









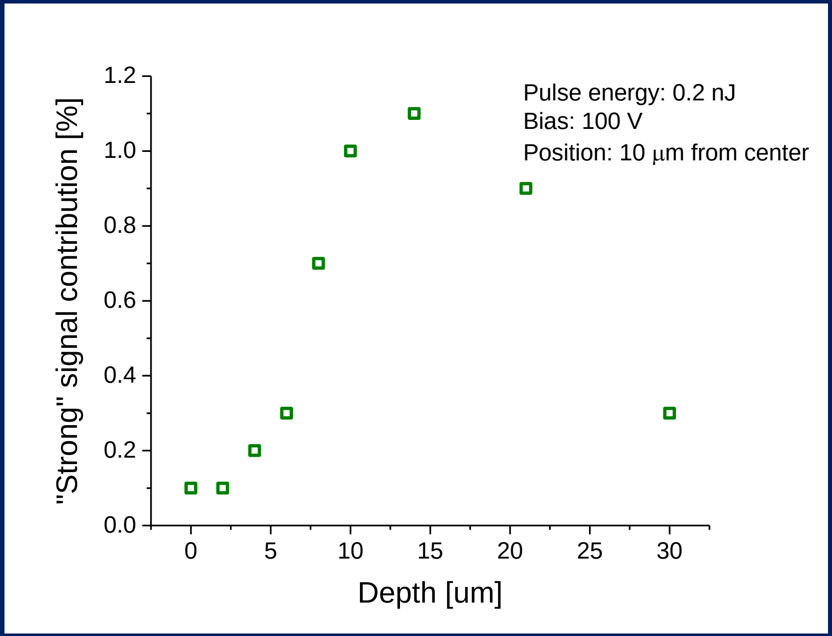
The results are similar to those obtained at central position.

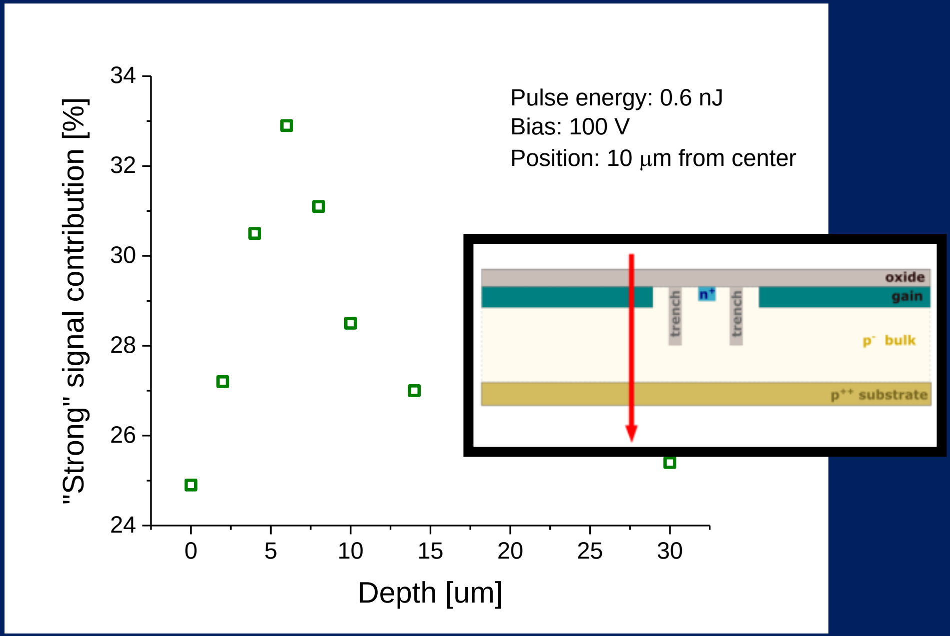
- At low and medium power contribution is a bit higher in comparison to the center.

However, at high power contribution is lower.

Surface charge recombination must have larger effect at a lower depth while diffusion plays more significant role at deeper depth.

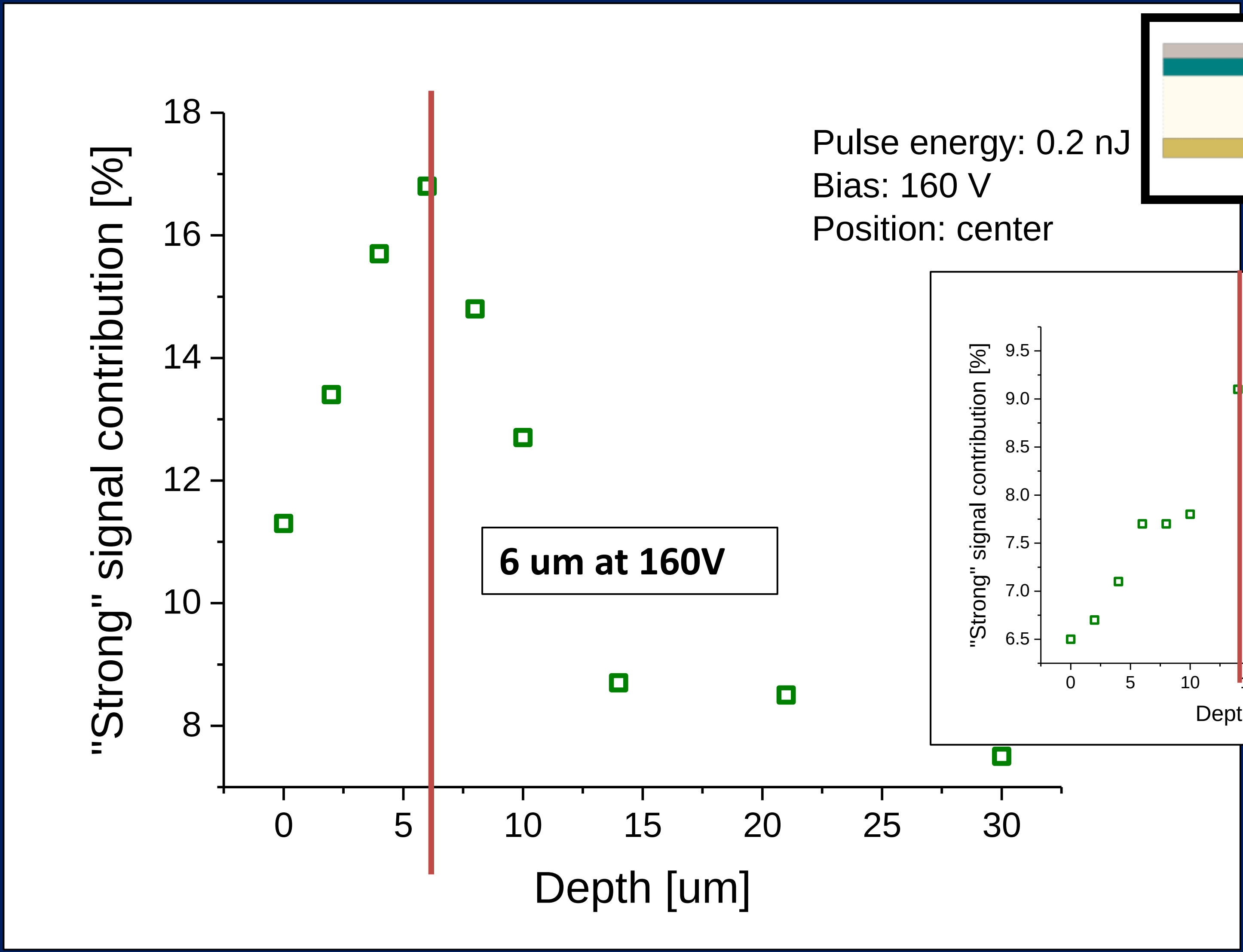
Different depths at position 10 um from the center at different power

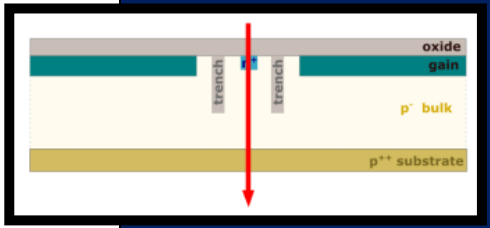


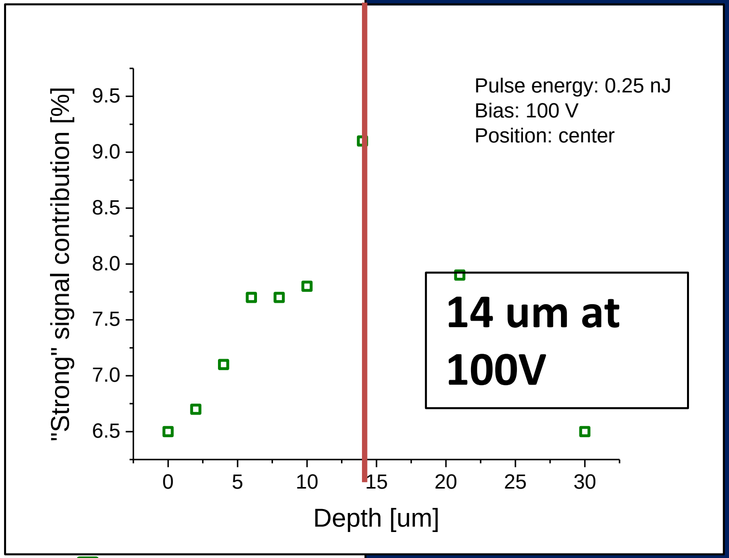


- Position 10 um from the center is already in the pad area.
- However, at this position some strong signal is still observed.
  - Maximal contribution depth corresponds to central and trench positions (14 um at low power and 6-8 um at higher power)

Different depths at the center of IP, at different bias

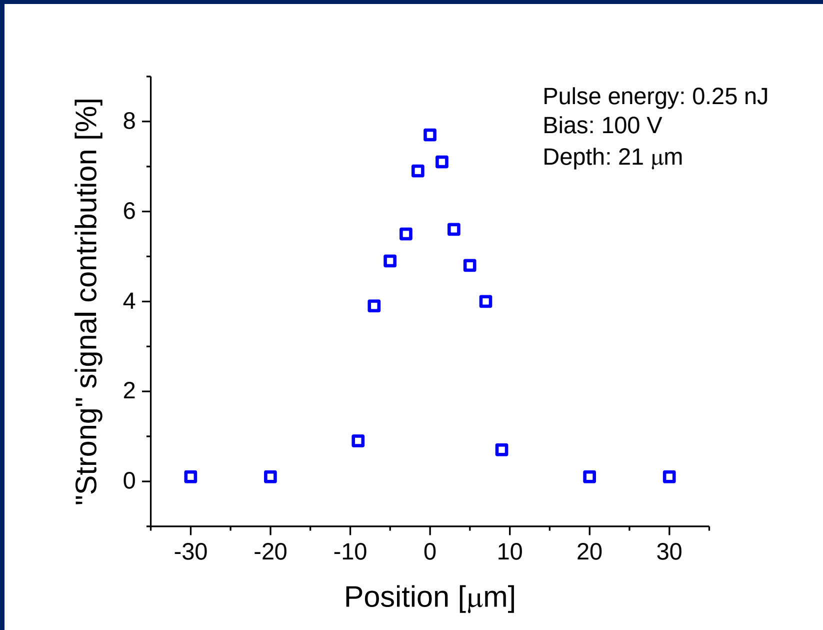


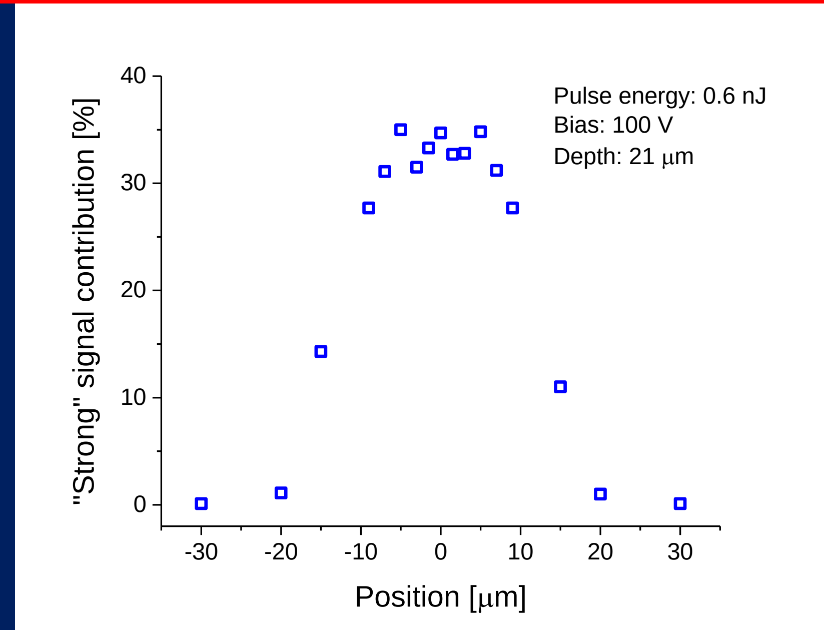


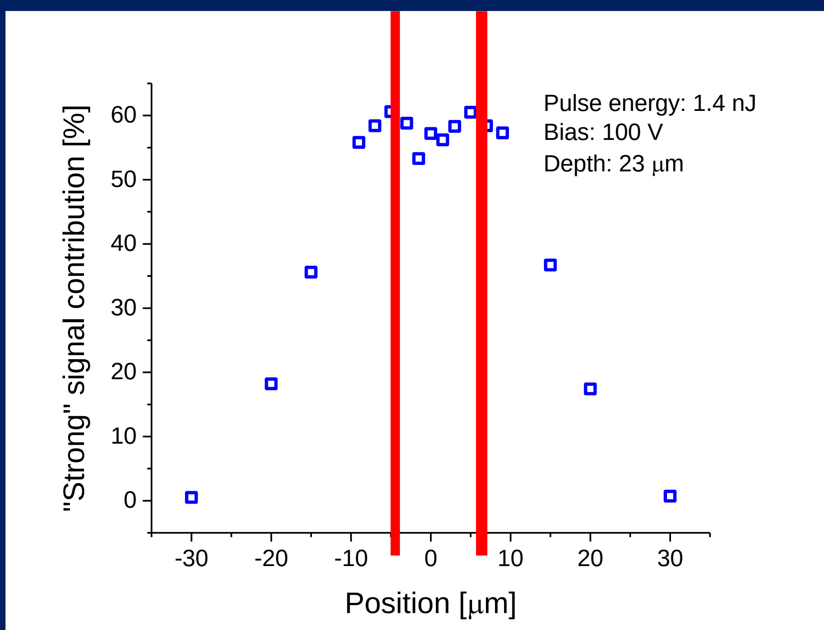


Full bias dependence was not studied yet. However, one example at low power was tested. Interestingly, increasing bias has similar effect to increasing power. Maximal contribution at 14 um at 100V is shifted to 6 um at 160 V

Different positions inside sensor (depth 21 um) at different laser power

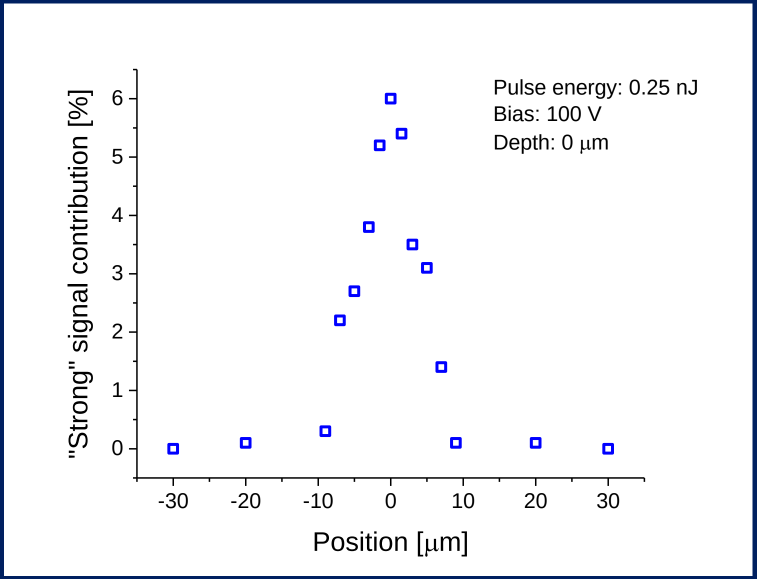


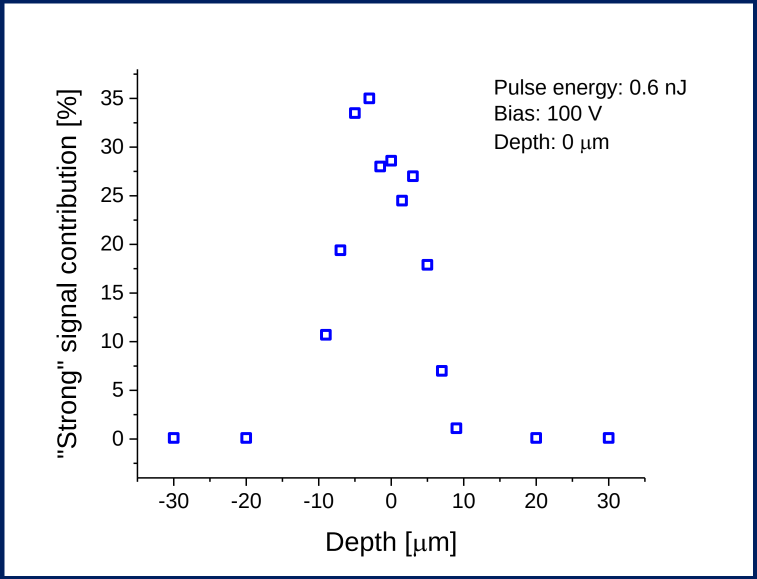


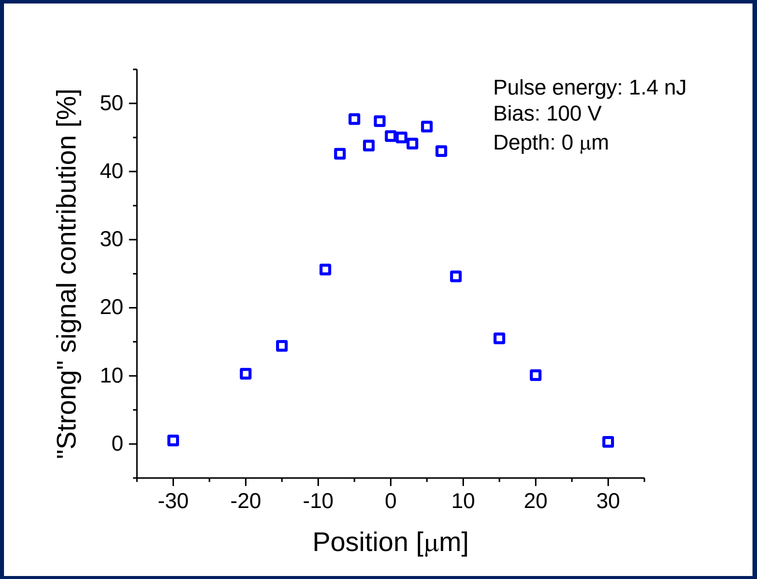


- The range of “strong” signal occurrence is clearly dependent on the laser power.
  - For low power it is more or les +/- 10 um with maximal contribution at the center.
  - For higher power this range is wider and even 20 um from the center the “strong” signal contribution is not negligible. Moreover,- it seems that maximal contribution occurs at the position around 5 um from the center (between trench and gain)

Different positions on the surface (depth 0 um) at different laser pulse energy







For comparison, the study with laser focused on the surface was performed.

- We can assume that in this case we generate charge only close to the surface.
- The contribution of "strong" signal is here a bit lower but the profiles look similar.

Z-Scans and corresponding waveforms

s

- The waveforms shown in this part are normal ones. They correspond to the signal presented in Z-scans (for few selected depths). Pad has only normal signal (measure 50 microns away from IP center) . For IP we have both normal and strong but here (to construct Z profile) only normal signals were used (many shots were recorded for a given depth but only the normal ones were chosen for Z-profile.

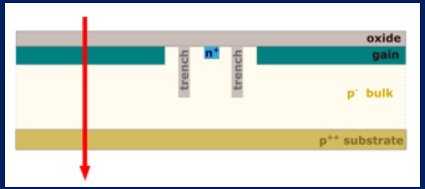
- Just 10 um from the center we are already in pad area but we see still some strong signals. Therefore, every data that are named "pad" were recorded safety far from the center.

- In TPA study the shape of waveforms (normal) evolves vs depth and this dual character with fast and slow component is much better visible than in SPA.

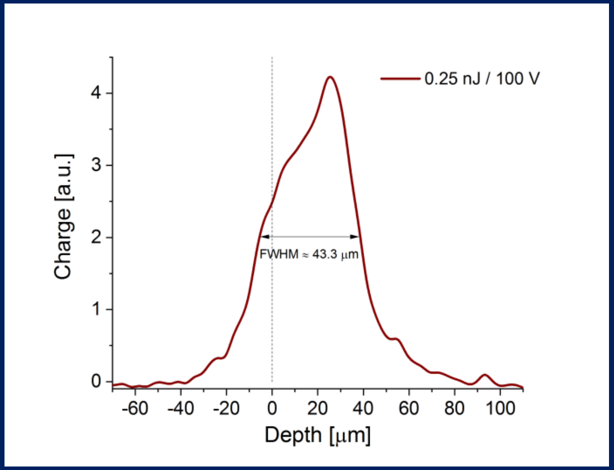
- SPA waveforms corresponds only TPA waveforms recorded close to the surface and actually they are quite similar: dominant maximum (fast component) with a shoulder on the falling edge (slow component).

Z-scans

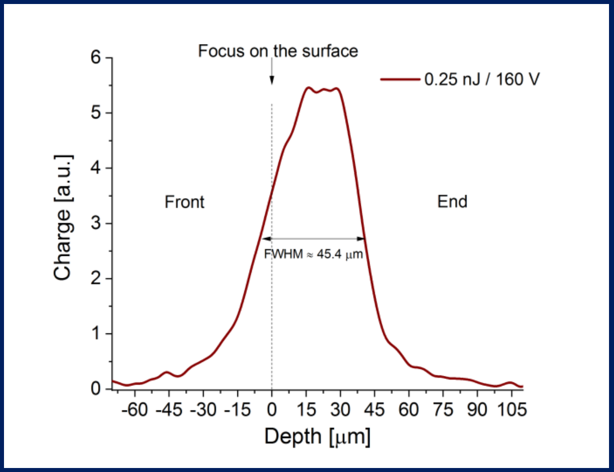
Pad



low power / low bias

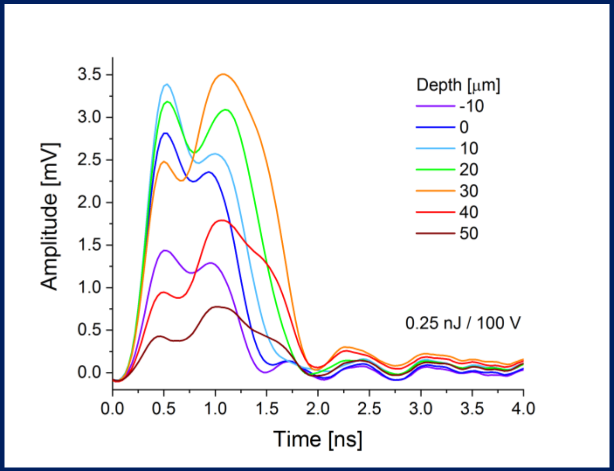


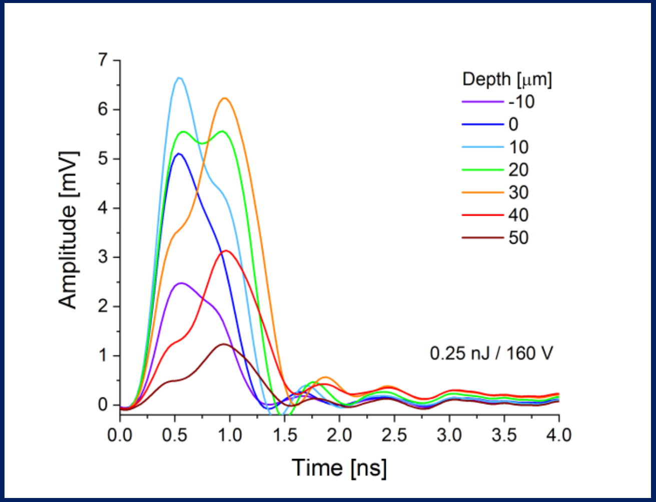
low power / high bias



FWHM of our depth profiles in pad corresponds very well to nominal thickness of the sensor (45 μm)
Depth 0 um (dash line) corresponds to the situation when laser is focused on the surface.

Waveforms

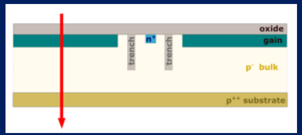




Waveforms are composed of two components: fast and slow. Fast component dominates at small depth. Both components are equal about 20 um and for bigger depths the slow component becomes

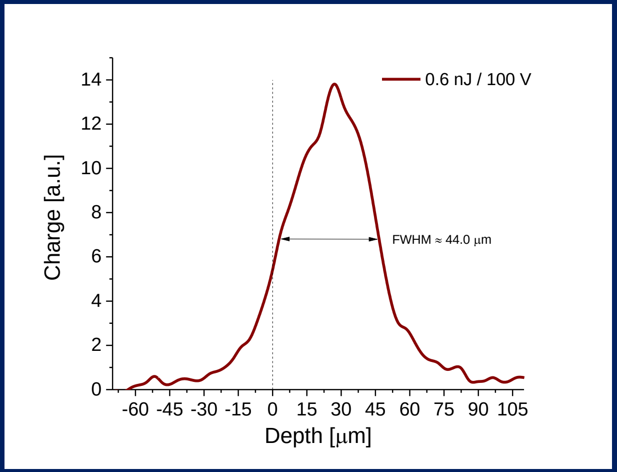
Z-scans

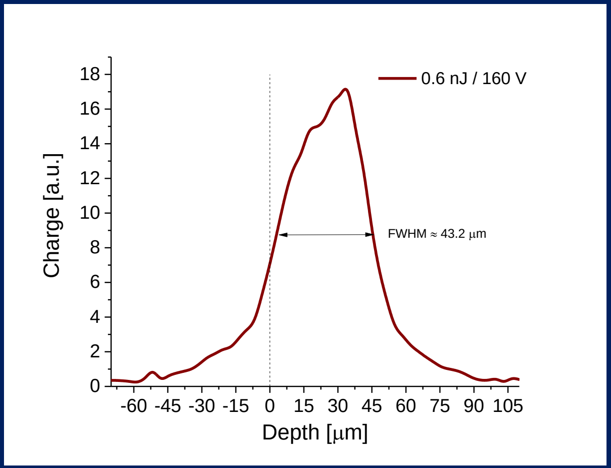
Pad



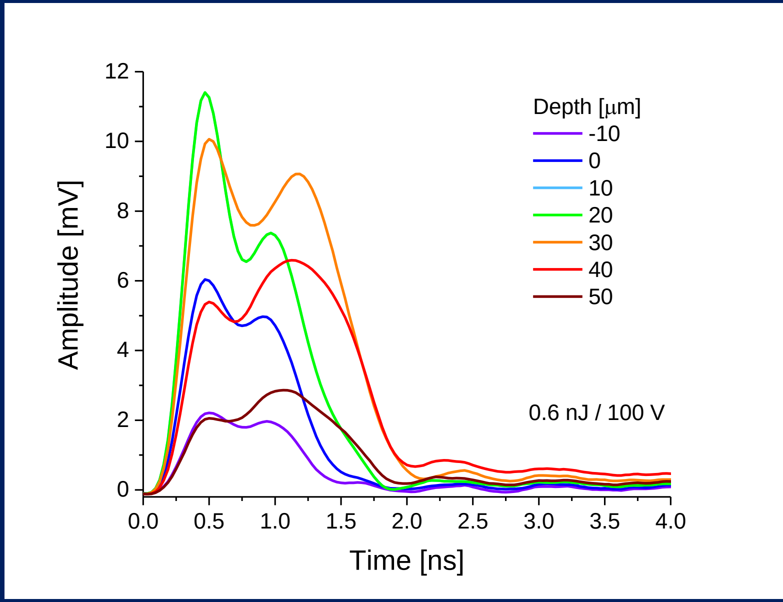
medium power / low bias

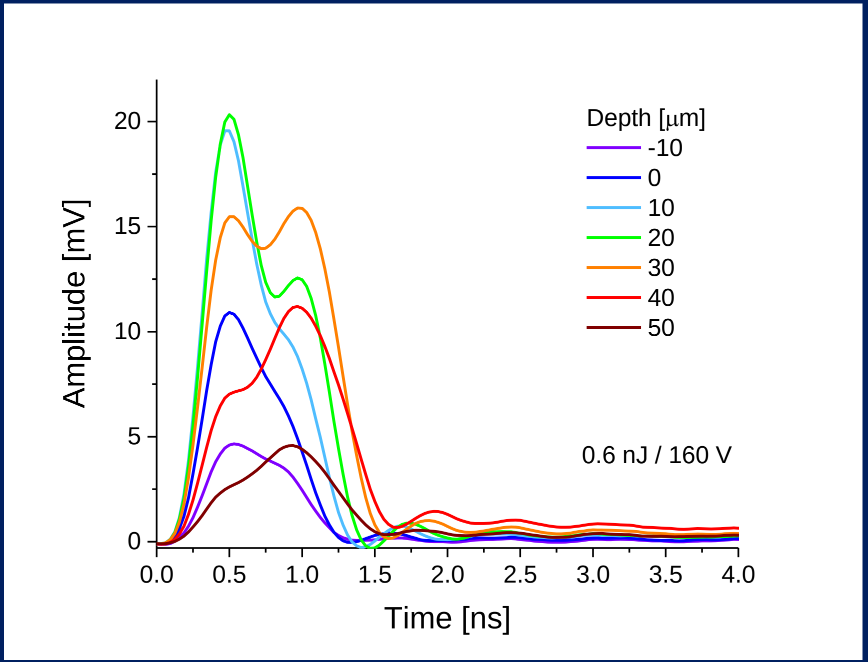
medium power / high bias



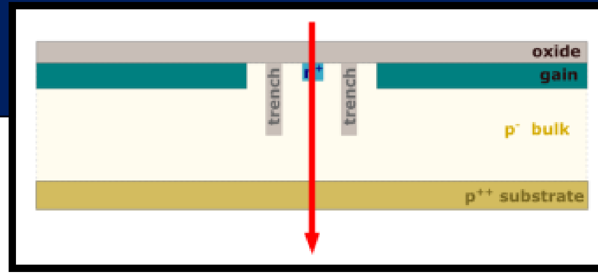


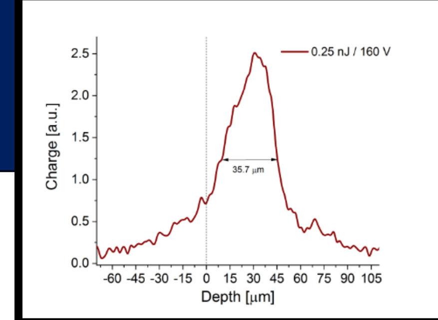
Waveforms

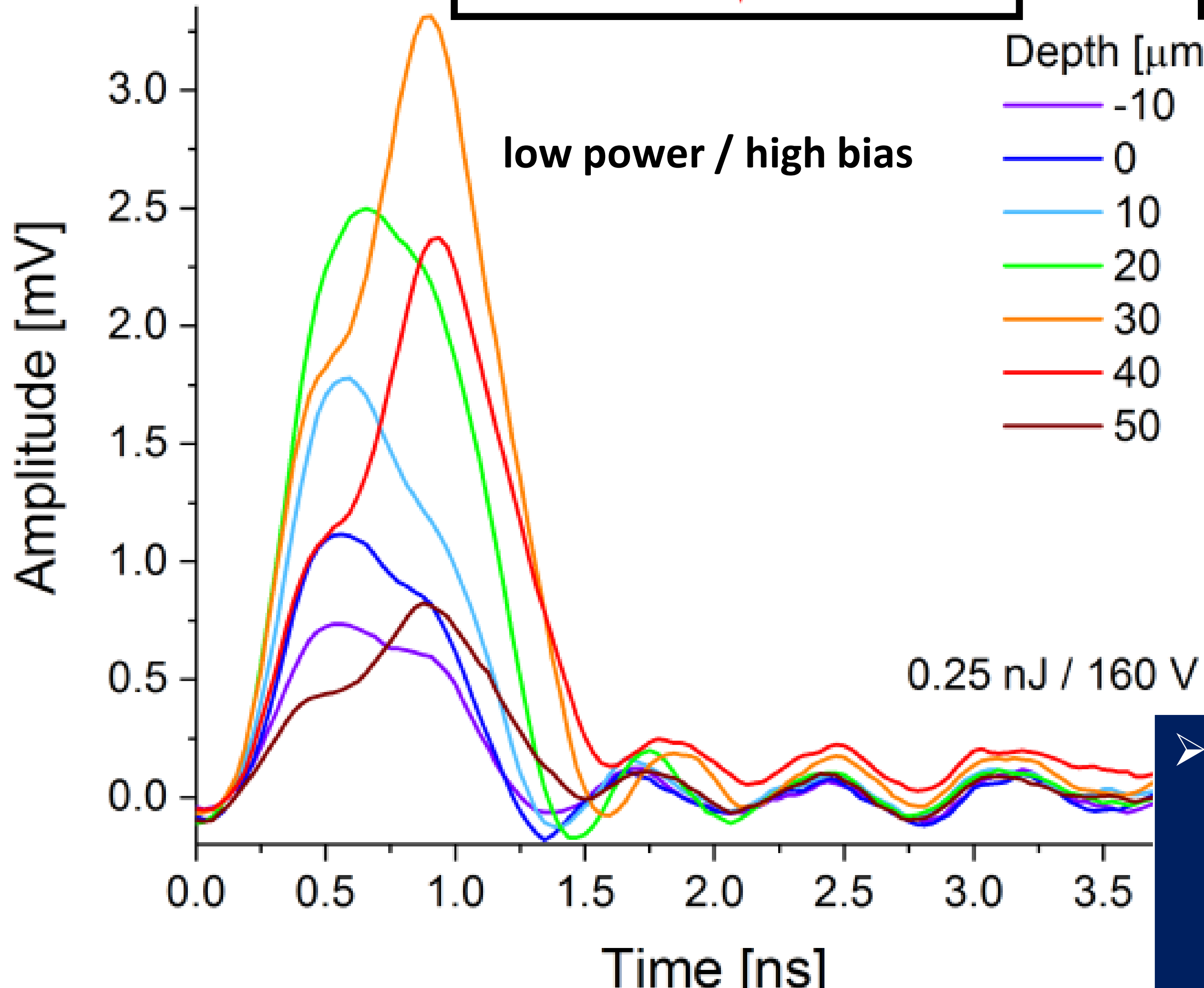




IP center







In IP we have both normal and strong signal but for Z-profiles only normal signal was taken into account.

- Z profiles in IP are clearly narrower than in pad.

- Waveforms are smaller than in pad but they seem to be similar with fast and slow components.

Summary

- The 2 Tr Ti-LGAD samples, produced from different wafers W7, W11 and W16, are studied.
- We found that the examined 2Tr sample showed different induced current signals in the IP and periphery region compared to the previously studied sensors with different isolation structures.
- We identified two types of laser pulse induced signals in the IP region: “normal” signal, and “strong” signal represented by significantly broader waveforms with several times higher amplitude.
- In addition, randomly occurring “ghost” signal appearing in biased but not laser-illuminated sensors were identified. Strong and ghost signal have similar shape.
- All three types of signals were explored in terms of the influence of bias voltage and laser power at different temperatures.
- Bias and charge density threshold is identified for both, ghosts and strong signals

- Occurrence rate of ghosts is temperature dependant.
- Ghosts and strong signal have the same mechanism behind them just external sources are different.
- Strong signal doesn't evolve vs X; it's shape or amplitude don't change. Only one thing changing vs X is its occurrence rate. It shows what is X range of strong signal existence;.
- Strong signal doesn't evolve vs depth; only their occurrence rate is changed

- **There must be a mechanism of discharge and quenching or something similar to a punch-through that produces a transient current that stops when an equilibrium is reached.**

- The disappearance of both sensor self-induced and strong IP signals (laser linked) signals, after irradiation, is observed.

THANK YOU.