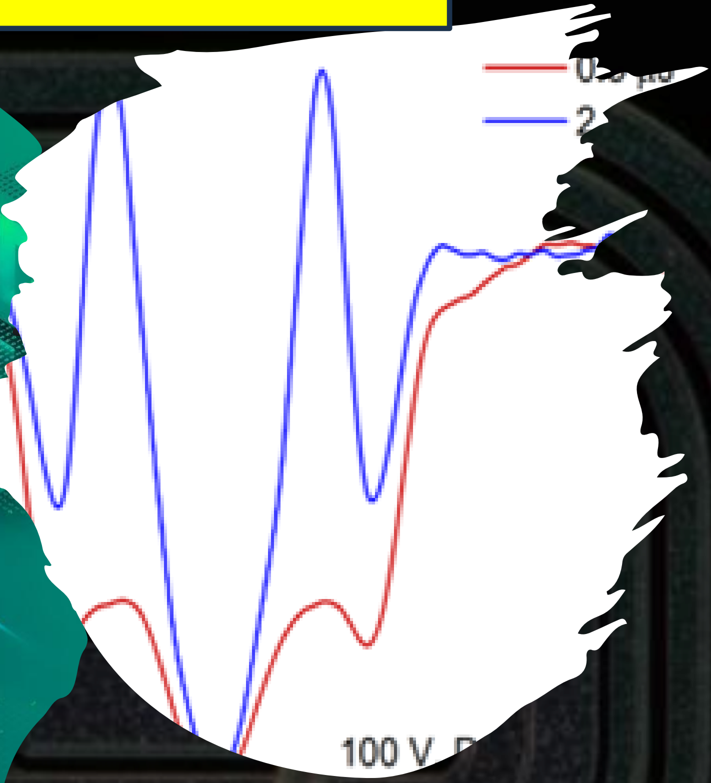
DRD3 Meeting, 17-21 June, 2024, CERN



PUZZLING GHOSTS DOUBLE TRENH ISOLATED LGAD

Gordana Lastovicka-Medin[1], Danijela Mrkic[1], Vuk Baletic[1], Vanja Backovic[1], Jiri Kroll[2],
Gregor Kramberger[3], Mateusz Rebarz[4]

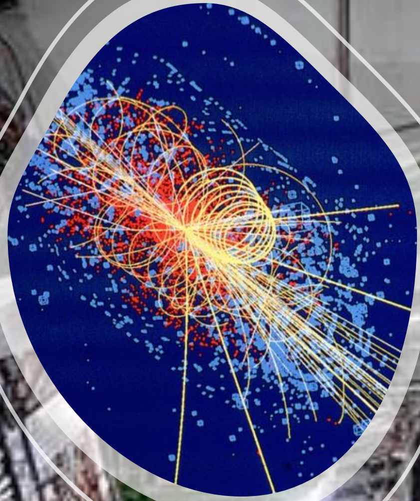
[1]University of Montenegro in Podgorica, [2] Institute for Physics at the Czech Academy of Science, [4]ELI ERIC, ELI Beamline Facility in Prague
[3]Jozef Stefan Institute in Ljubljana

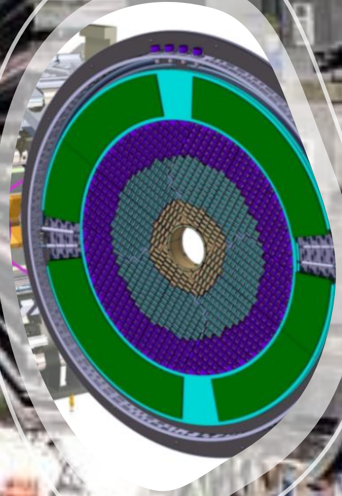
OUTLINE

- ❑Introduction /Motivation
- ❑Problem Defined
- ❑Materials and Methods
- ❑Experimental Results/Interpretation
- ❑Summary

Quest for Timing Detectors at Accelerators

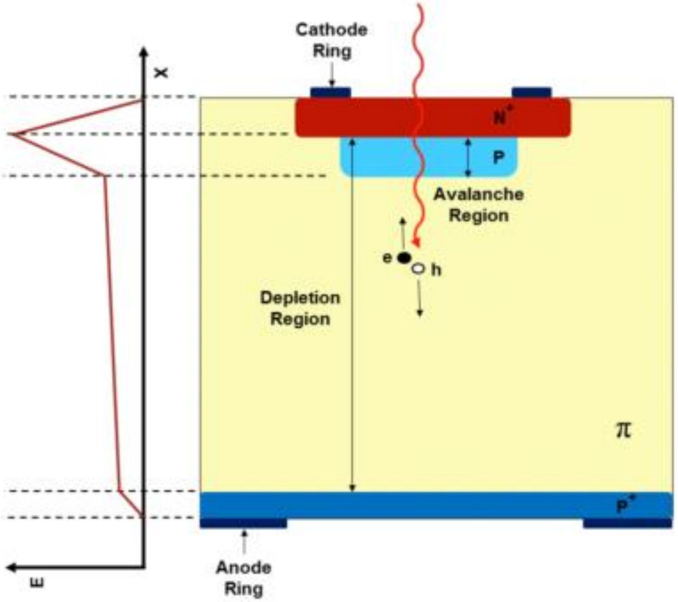
Why do we need a timing detector at the HL-LH and Future colliders?

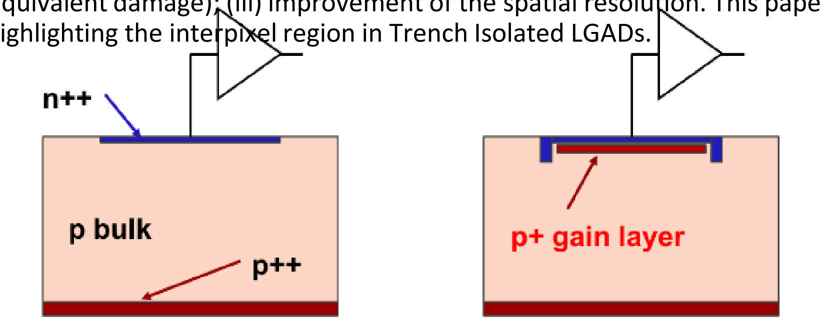




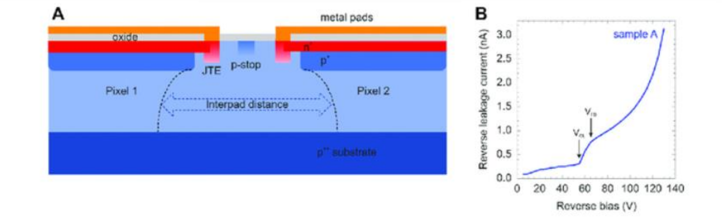
Low Gain Avalanche Diode LGAD

- Low Gain Avalanche Diodes (LGADs) are silicon sensors based on p–n junctions and provided with an internal signal amplification mechanism (gain).
- The internal structure is similar to that of silicon Avalanche Photodiodes (APDs), but the gain is much lower ($O(10)$ with respect to $O(1000)$ of APD).
- The combination of low gain and thin active silicon substrates already made LGADs: sensor technology detectors for High Energy Physics (HEP) experiments (CMS and ATLAS).
- The possibility to arrange the single diodes in large-area segmented sensors (pixel arrays or strips), which can provide information on both the time and position of the interactions between the detected particles.
- The latter aspect is a key enabling feature for the so-called “4-dimensional (4D) tracking”
- However, additional development has to be done to meet the requests of the next generation of HEP experiments and those of other applications, such as x-ray imaging or ion tracking in devices for medical applications (hadron therapy).
- The current R&D activities on LGADs are focused on three different goals, interconnected with each other: (i) improvement of the time resolution; (ii) increase of the radiation hardness beyond 10^{15} n_{eq}/cm2 (where neq stands for 1-MeV-neutron-equivalent damage); (iii) improvement of the spatial resolution. This paper is focused on the latter task, highlighting the interpixel region in Trench Isolated LGADs.





Traditional silicon diode **Low Gain Avalanche Diode**



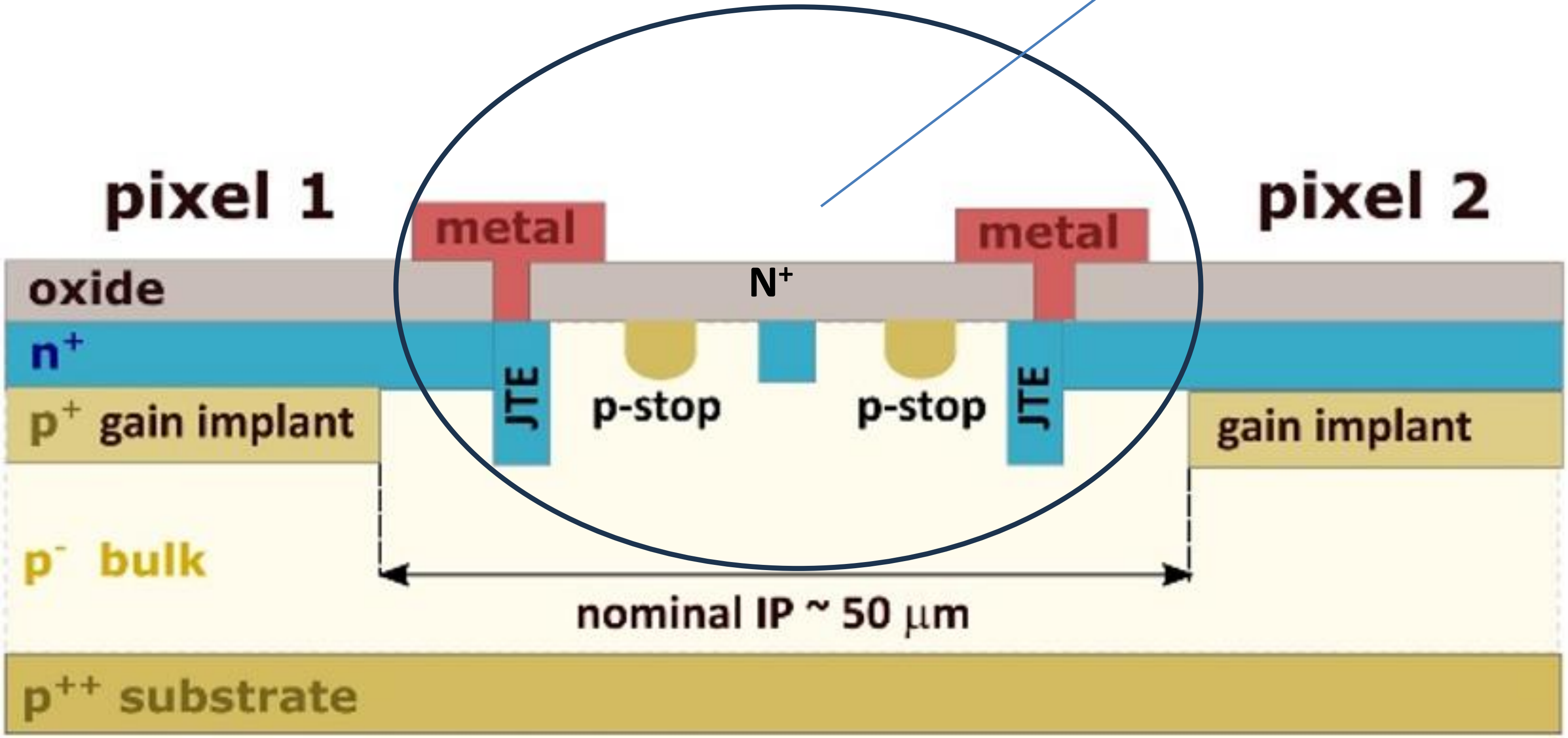
Problem

- Low fill factor
- Radiation hardness
- Gain Suppression
- SEB (set limits on the applied bias in irradiated LGAD)

In this presentation, our focus is on the sensor segmentation.

Standard segmented LGAD

Inter-pixel/interpad region



Low fill factor

JTE: Junction Termination extension

Solution

Reduction of the Inter-Pixel (Inter-Pad) distance

Abbreviation:

IP: Inter-Pixel

Problem

Reduction in inter-pixel distance requires higher doping of p-stops; Also the distance between p-stop and JTE becomes shorter, and as a consequence, the electric field becomes so high and sufficient enough for the impact ionisation to occur where we do not want it (where a pixel has to be isolated!).

Example

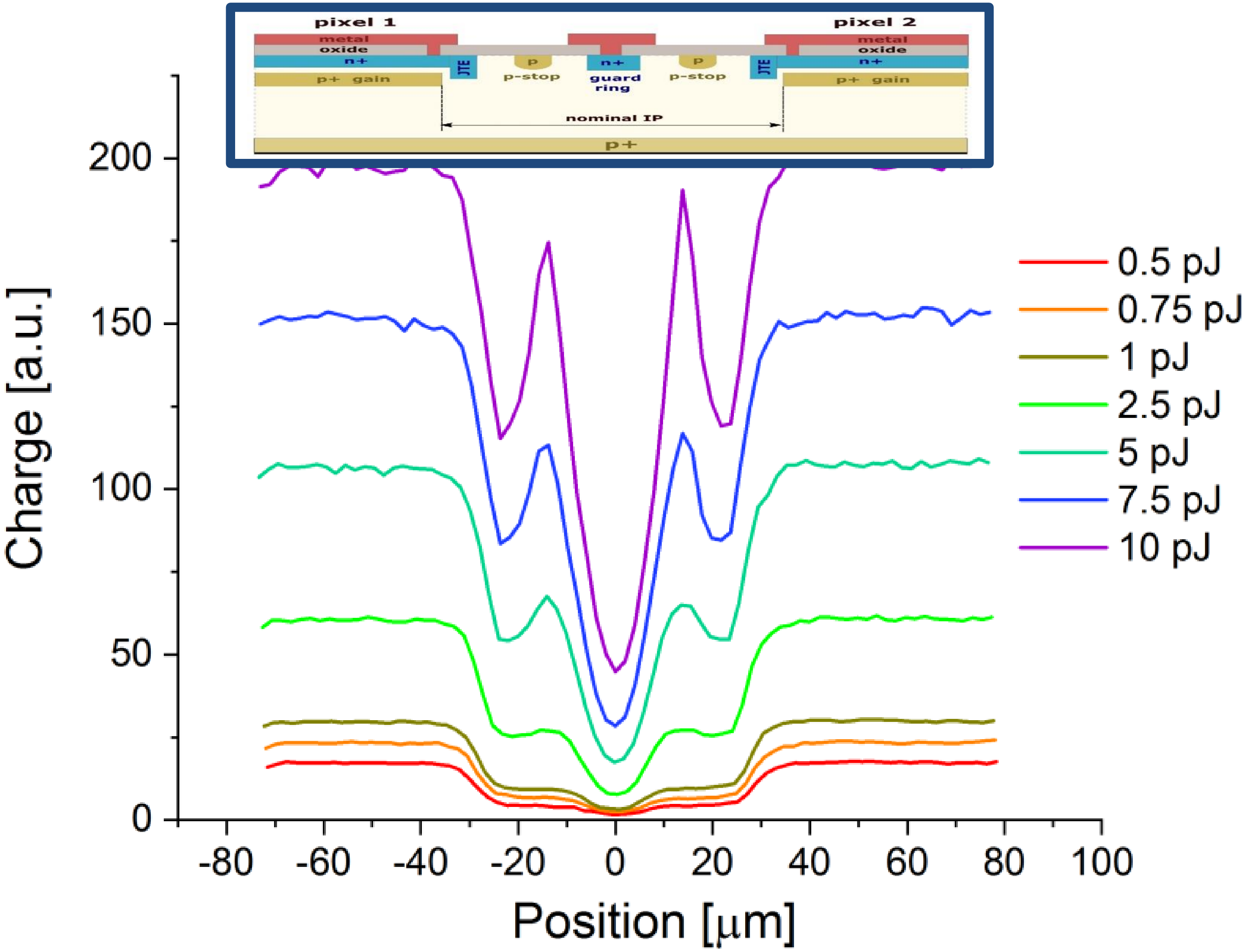
2 p-stops and bias ring in the IP region

An extremely enhanced charge multiplication has been observed in the no-gain region of the LGAD with 2 p-stops and bias in the IP region (interpixel) although this region has no gain and its purpose is to isolate pixels.

☐ Spikes observed in the space charge profile in the no-gain region;

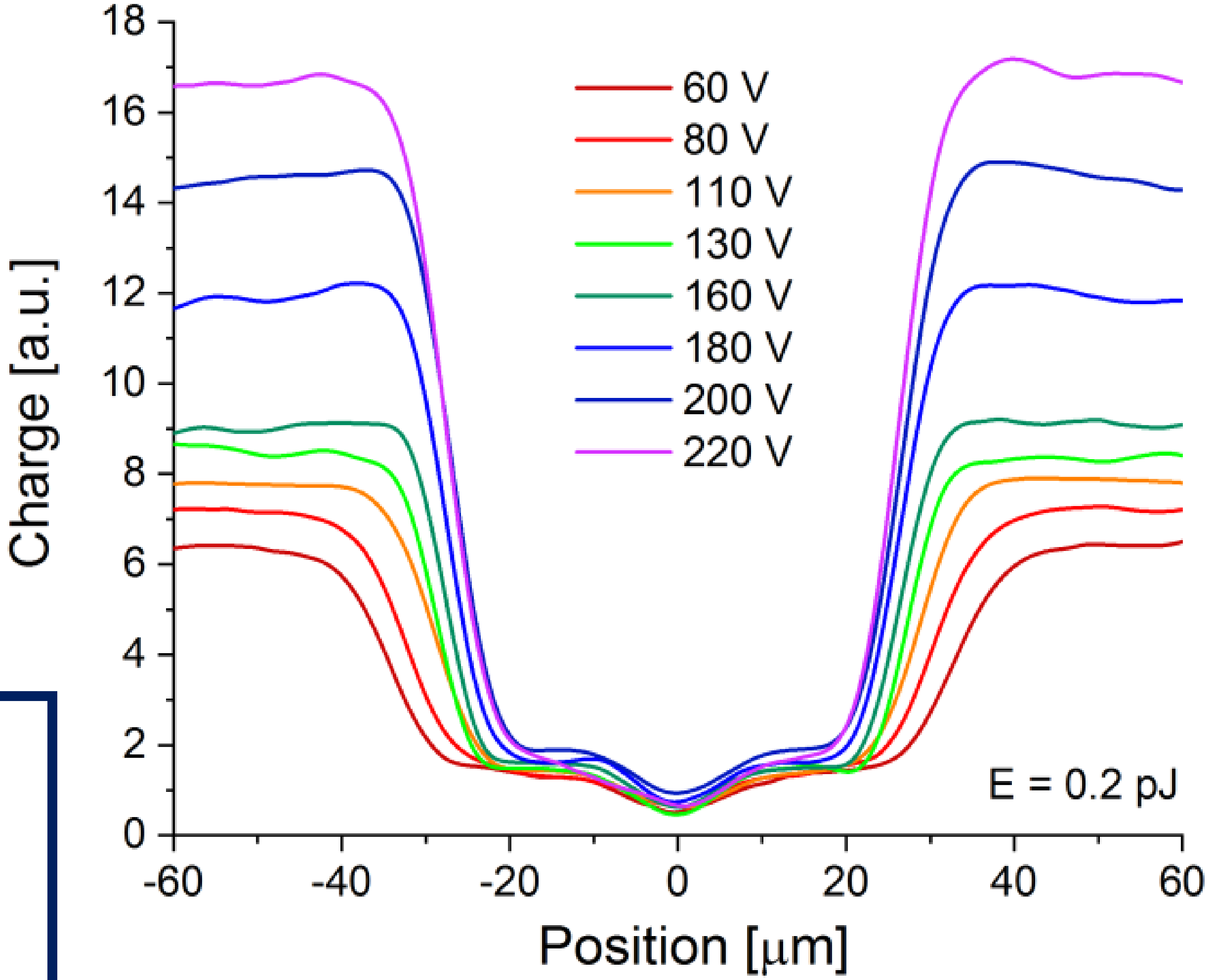
☐ enhanced with increased laser power.

☐ They appear on the sides of the central hollow (more or less at +/- 15 µm).

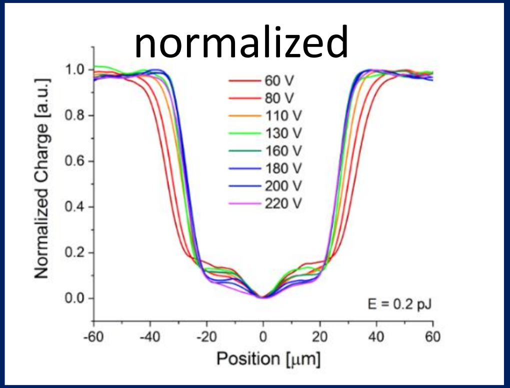


Space-charge profile vs laser pulse energy)

at low laser power

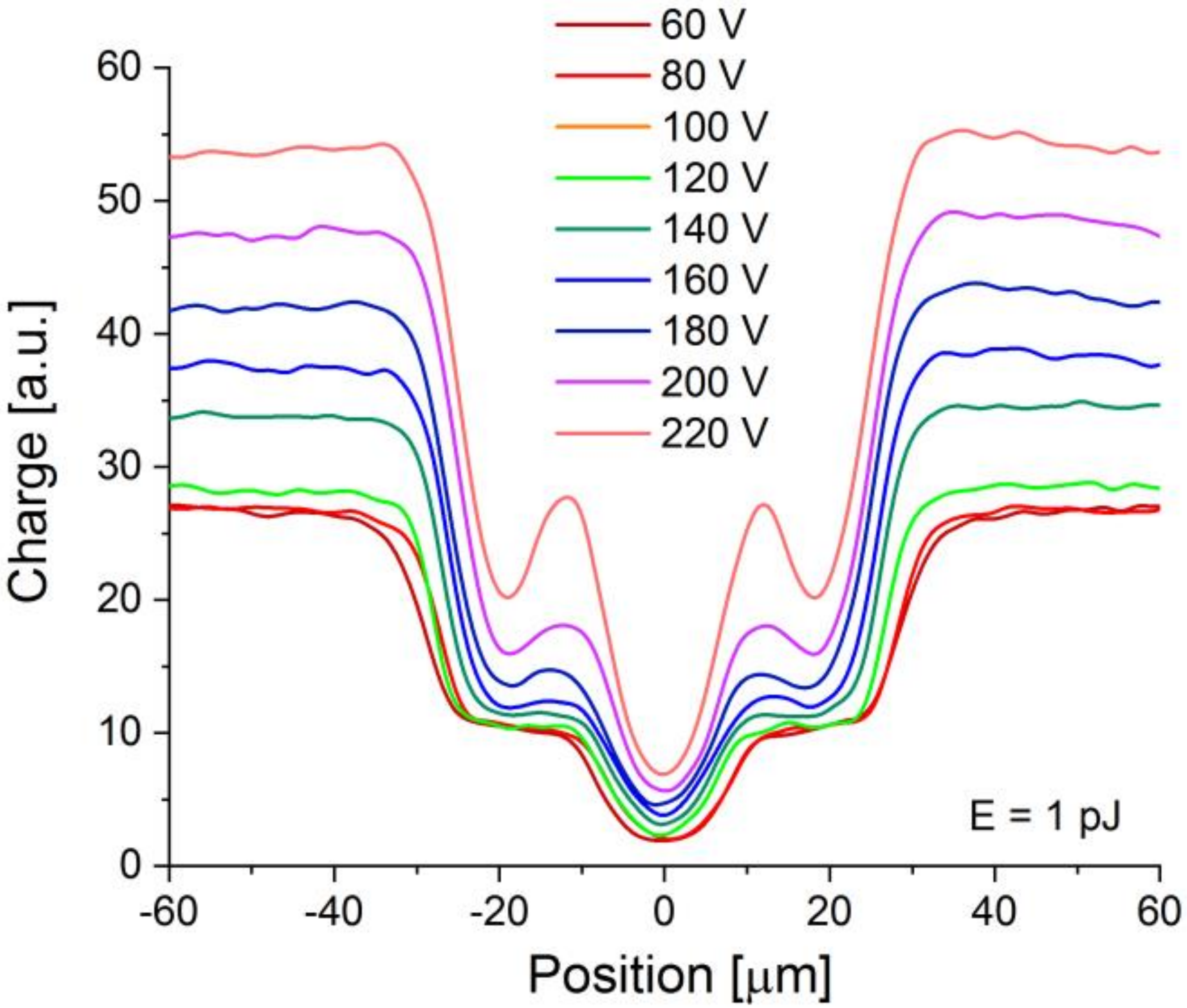


Same data as above but normalized for better comparison



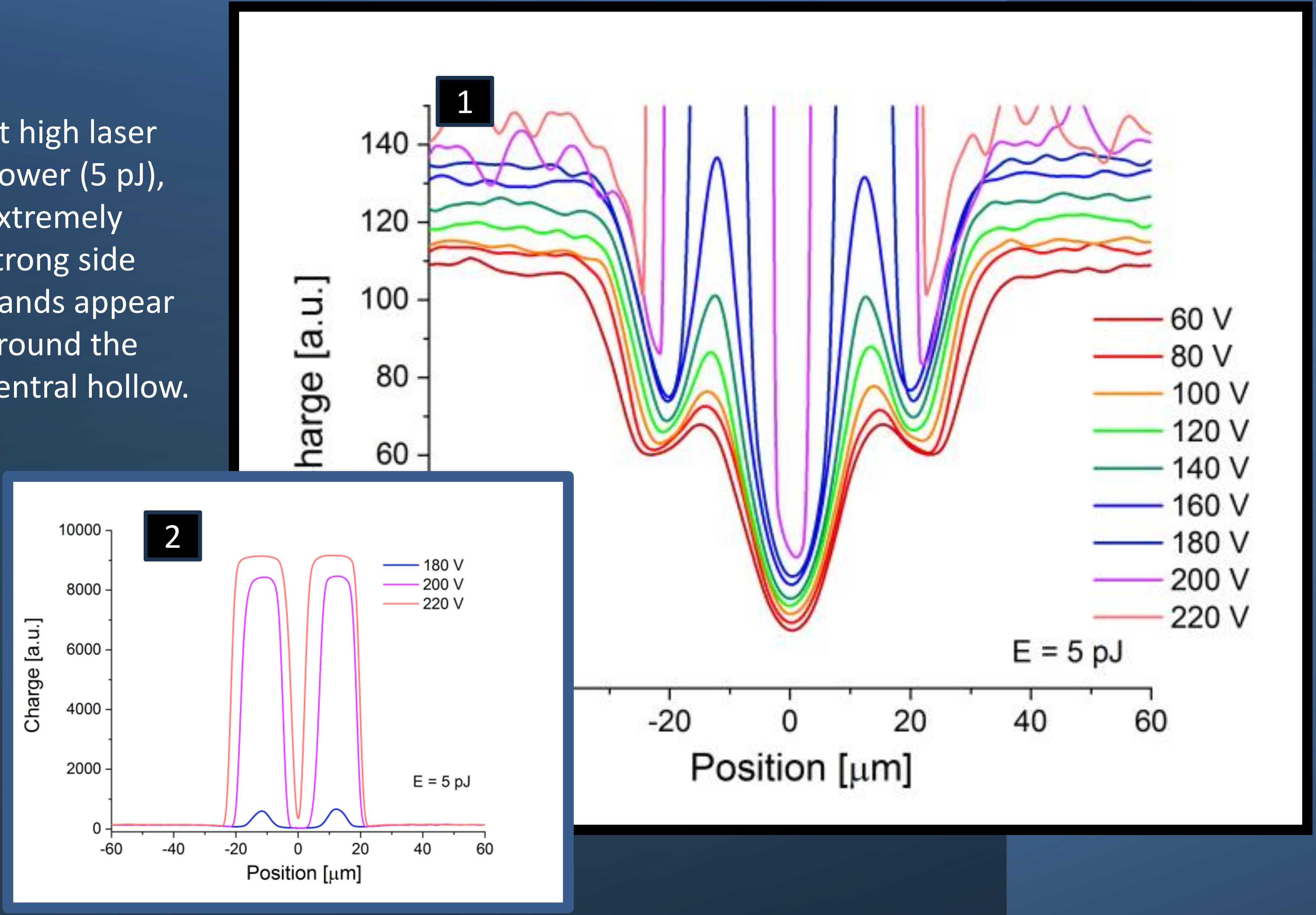
IP distance decreases with increasing bias.

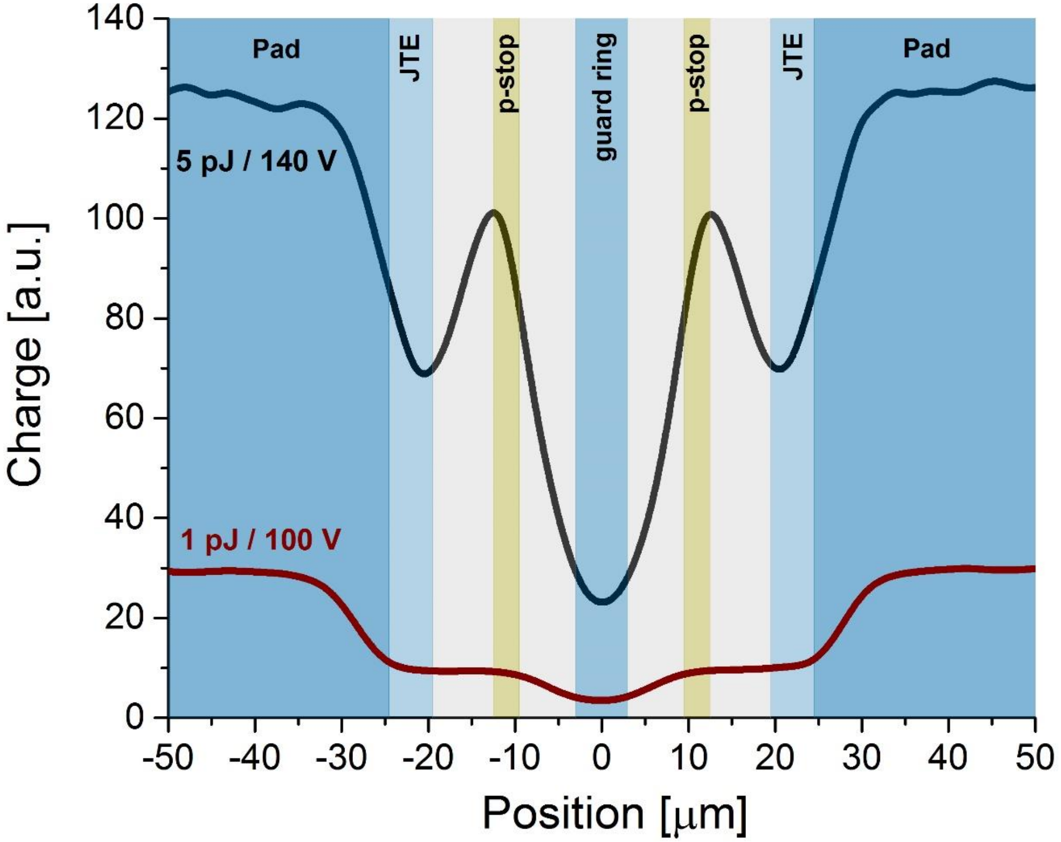
at medium laser power



at high laser power

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



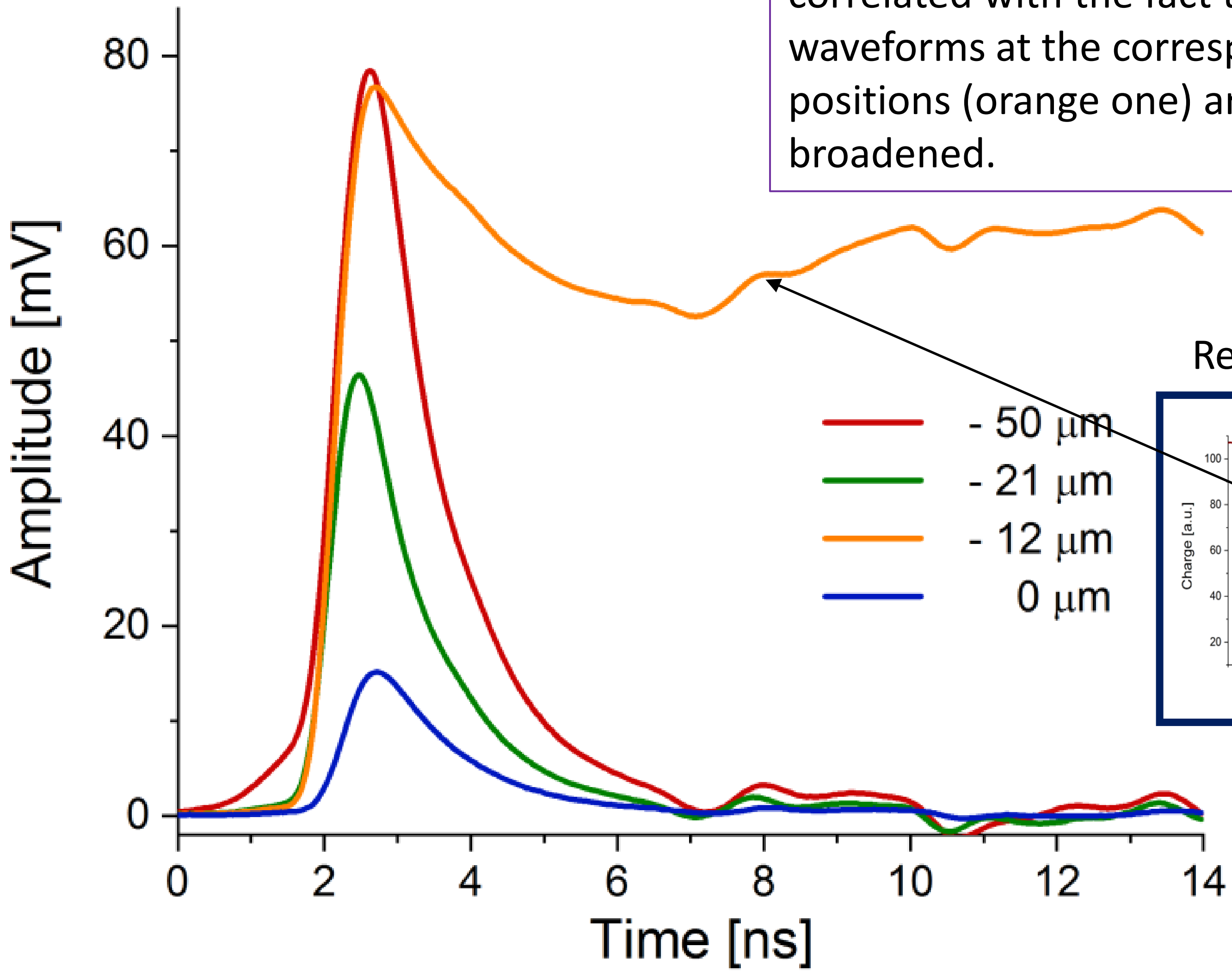


Published in Sensor:

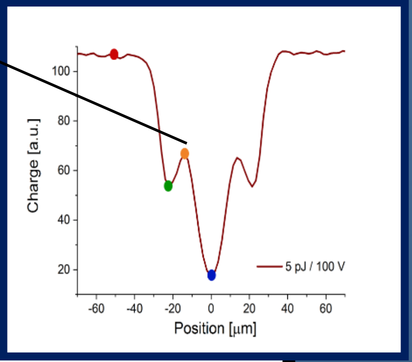
Laštovička-Medin et al., Exploring the Interpad Gap Region in Ultra-Fast Silicon Detectors: Insights into Isolation Structure and Electric Field Effects on Charge Multiplication, Sensors 23, No. 15 (2023) 6746

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

From the waveforms it is visible that the very strong side bands seem to be correlated with the fact that the waveforms at the corresponding positions (orange one) are extremely broadened.



Reminder:



Another Solution

Replacement of JTE and p-stop with SiO_2 trenches : Ti-LGAD

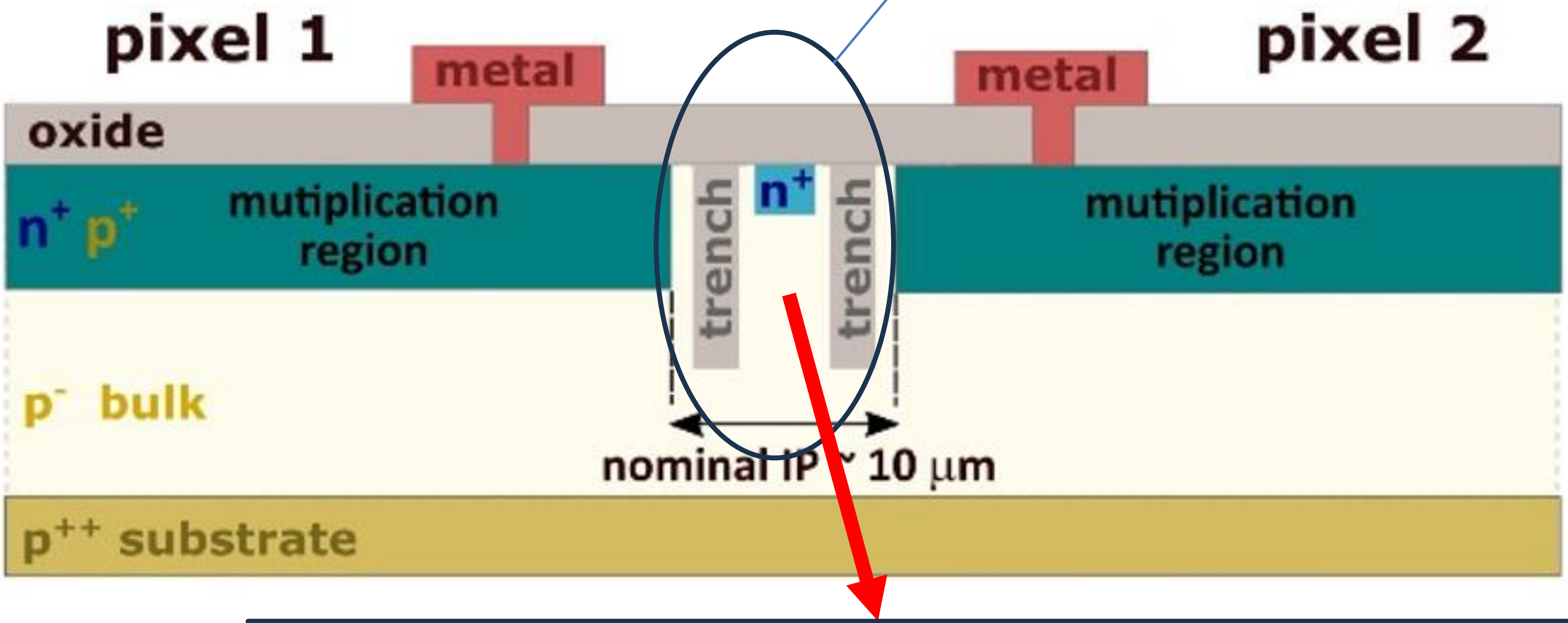
Does it work?

Single trench seems to be ok (61 µm reduced to 10 µm)

Two trenches do not seem to be the solution.

Problem with TWO Trenches in IP region

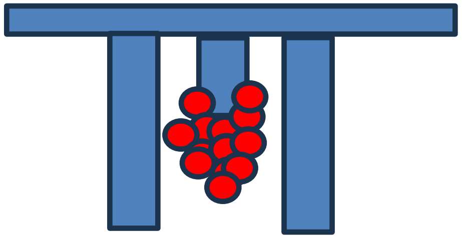
JTE and p-stop replaced by SiO2 trenches

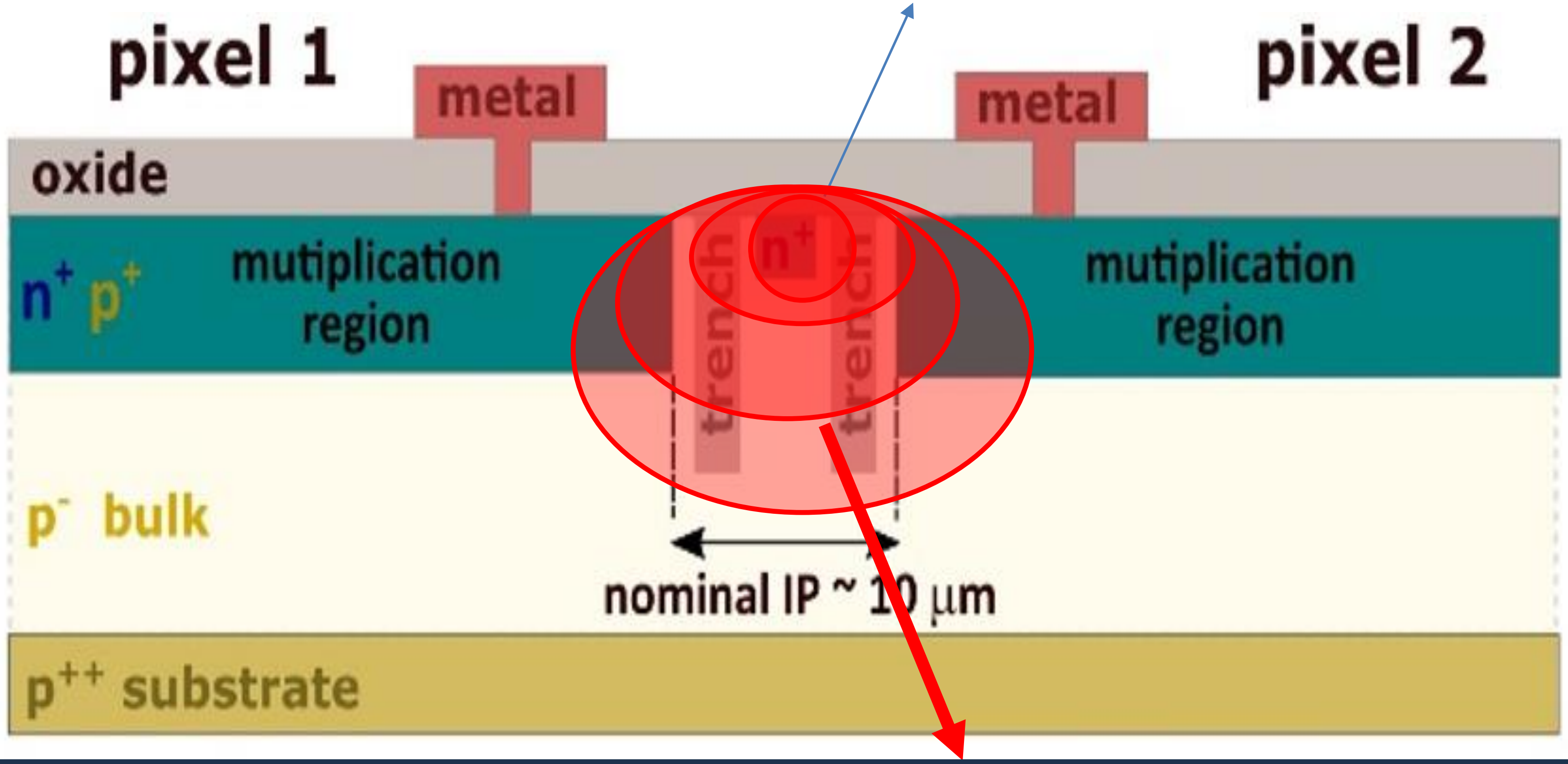


Width of trenches: 1 μm

Depth: 1 - 2 μm

Distance between the trenches: 2 μm





JTE and p-stop replaced by SiO2 trenches

- If a large charge is injected in the region between the trenches, it is quickly confined, creating plasma, and when the threshold is reached then the cloud of dense charge discharges (with avalanche multiplication in the gain region).

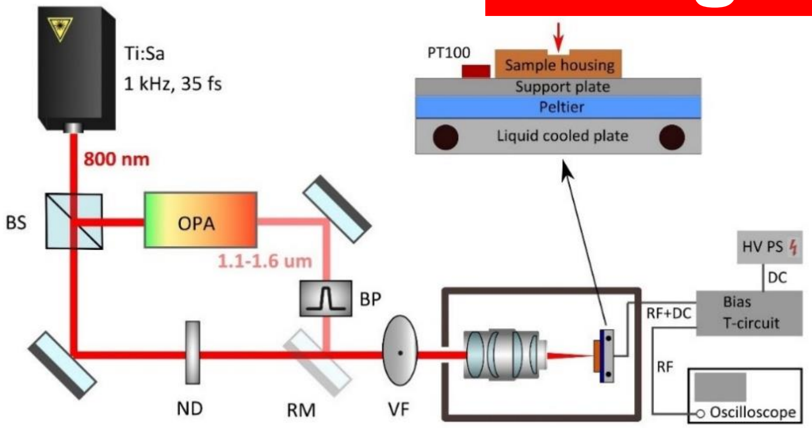
Consequence:

Self-induced (GHOSTS) signals in IP

Here is the story of how we chased ghosts ☹

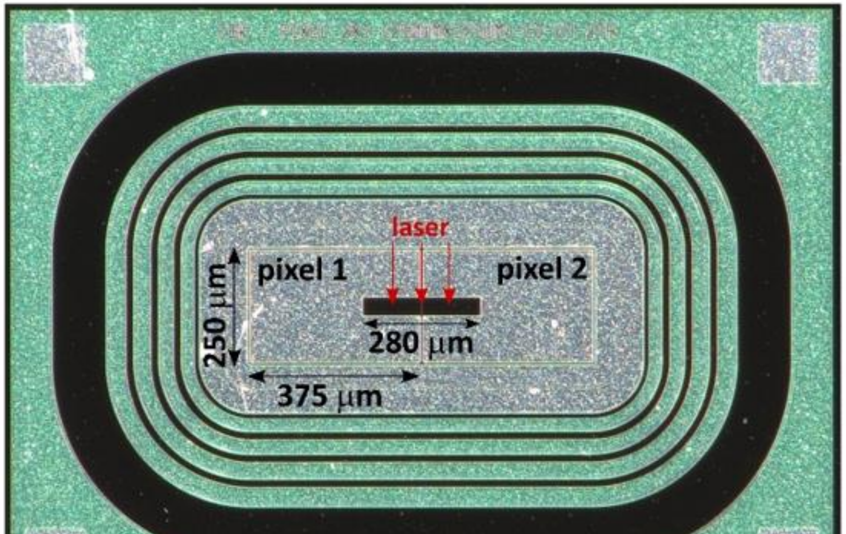
Chasing GHOSTS:

Using fs-laser based TCT at ELI



1x2 segmented sensor

FBK-PIXEL-2X1-(250UMX375UM)-C1-V2-2TR



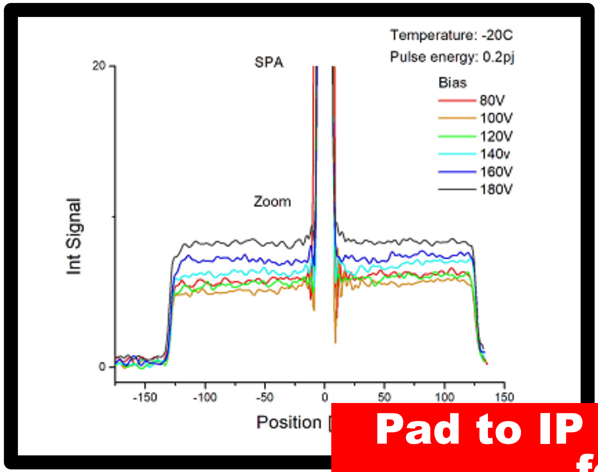
Place	ELI Beamlines
Operational modes	Single and two photon absorption (SPA and TPA)
Pulse energy on sample	Variable by ND filters (accuracy: 0.2 pJ)
Wavelength	800 nm (SPA), 1550 nm (TPA)
Pulse width in sensor	1550 nm, ~ 150 fs 800 nm, ~ 50 fs
Focus waist radius	0.85 µm (SPA), 1.5 µm (TPA)
Rayleigh 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)

Puzzle 1:

The extraordinarily large and long signal was stimulated with a laser in the Inter-Trench area in the Inter-pixel region

Exceptionally large signal in X-profile (Q vs x-position of laser illumination)

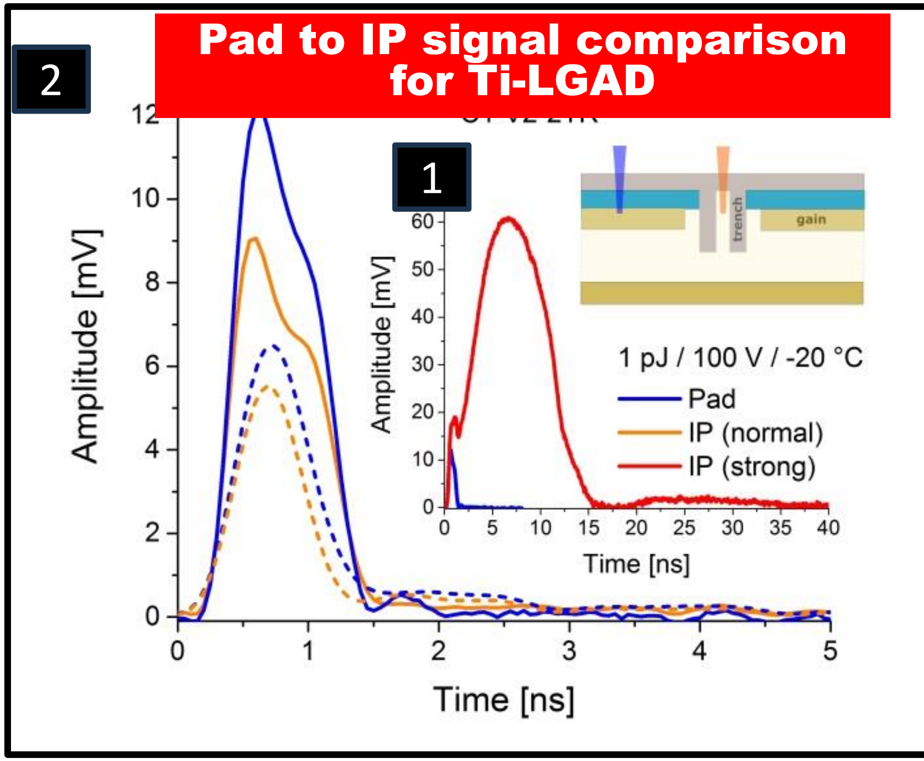
1



2

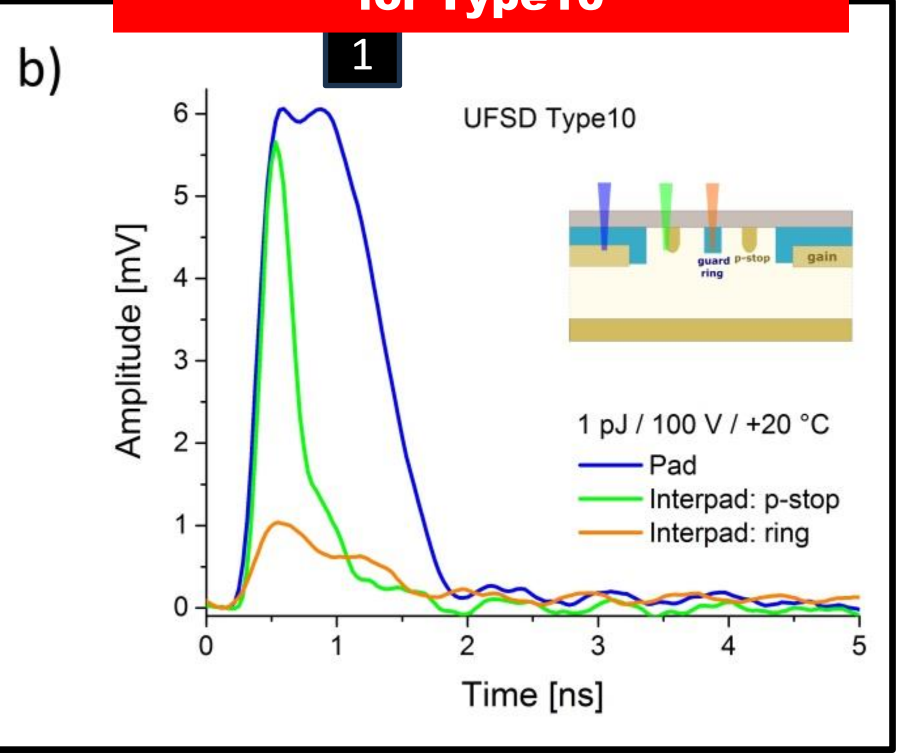
Pad to IP signal comparison for Ti-LGAD

1



Pad to IP signal comparison for Type10

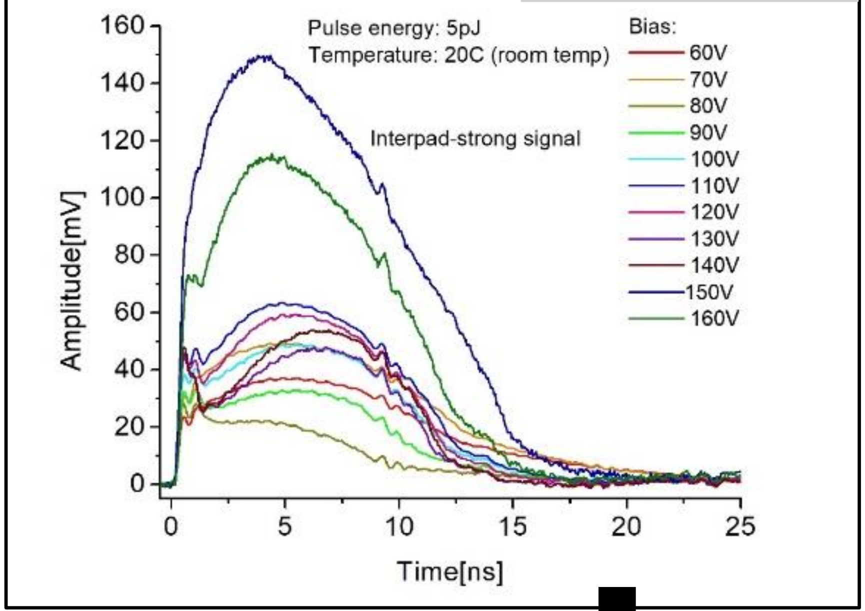
1



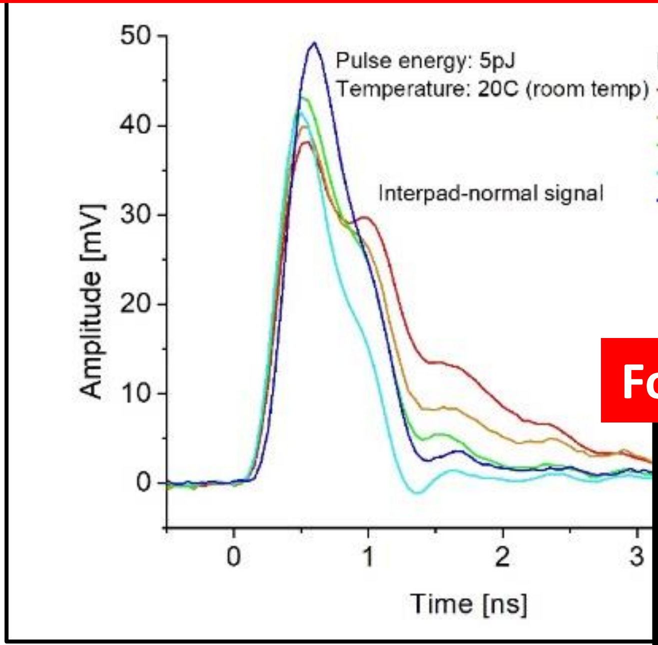
Many type of signals in IP region

T=20^0C

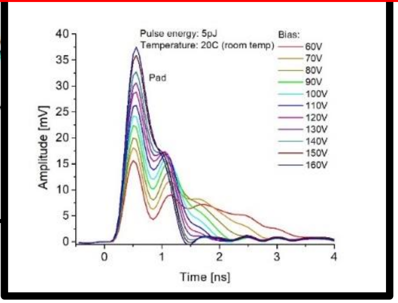
“Strong” IP

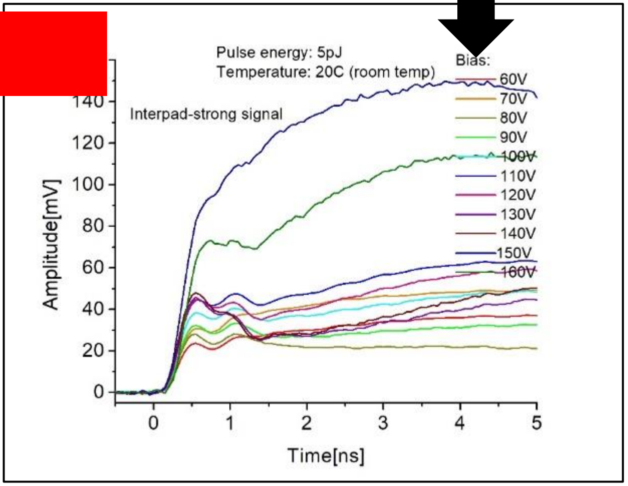


“Expected”(normal) IP signal similar in shape to the pad signal



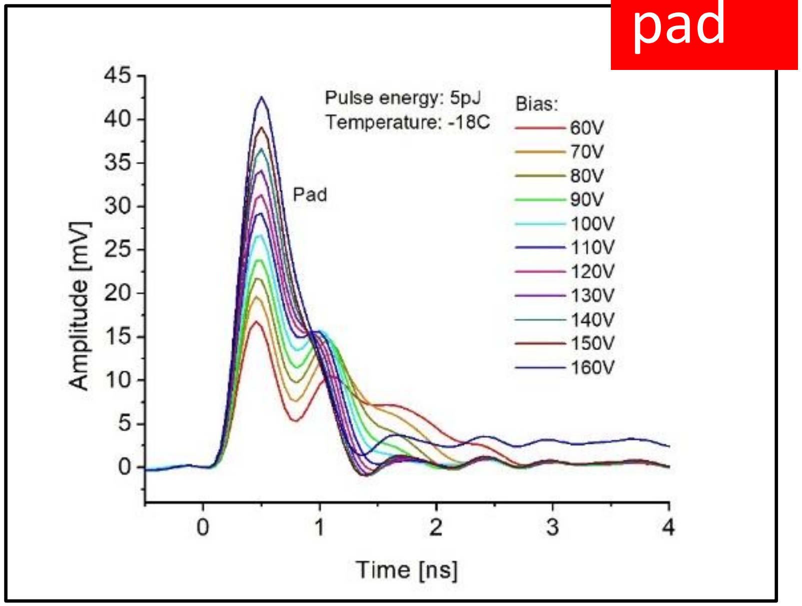
For comparison: Pad



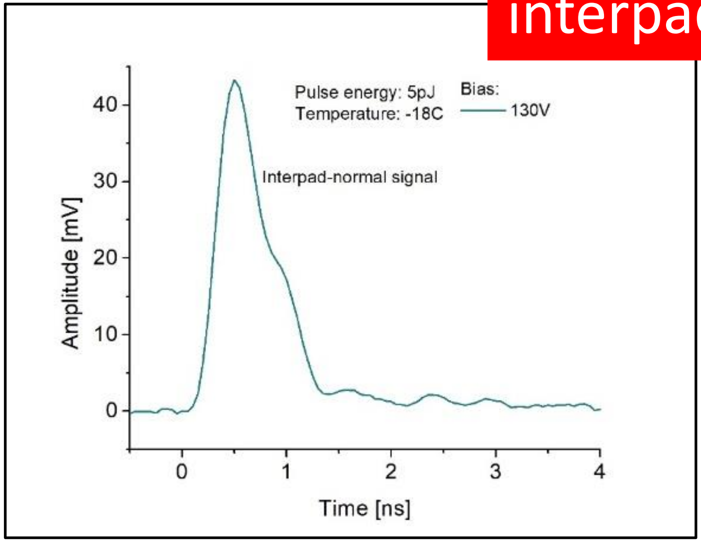


T=-20^{0}C

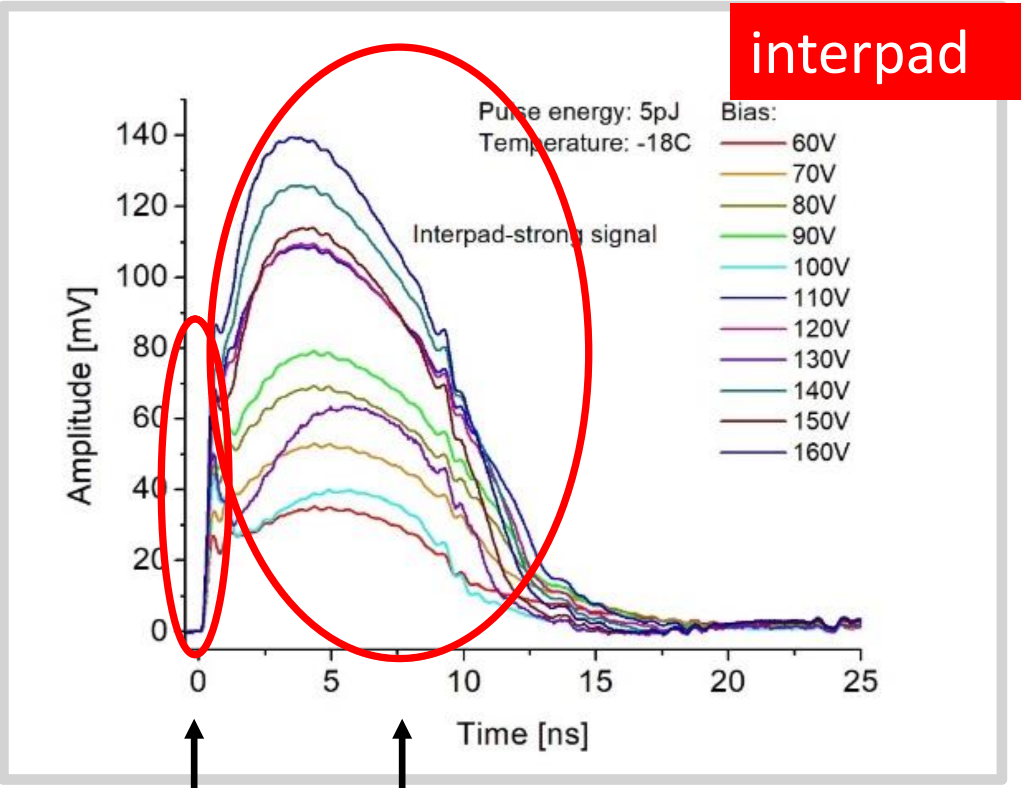
pad



interpad



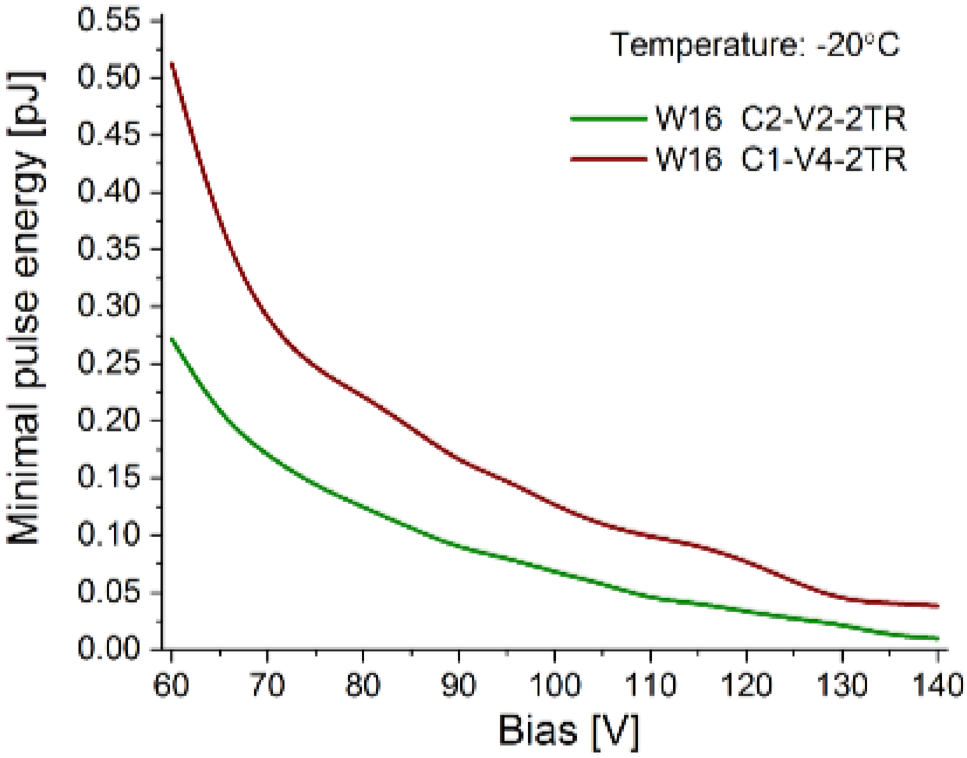
interpad



Fast, narrow component

Slow component

Threshold dependence



1st Observation: Temperature dependence

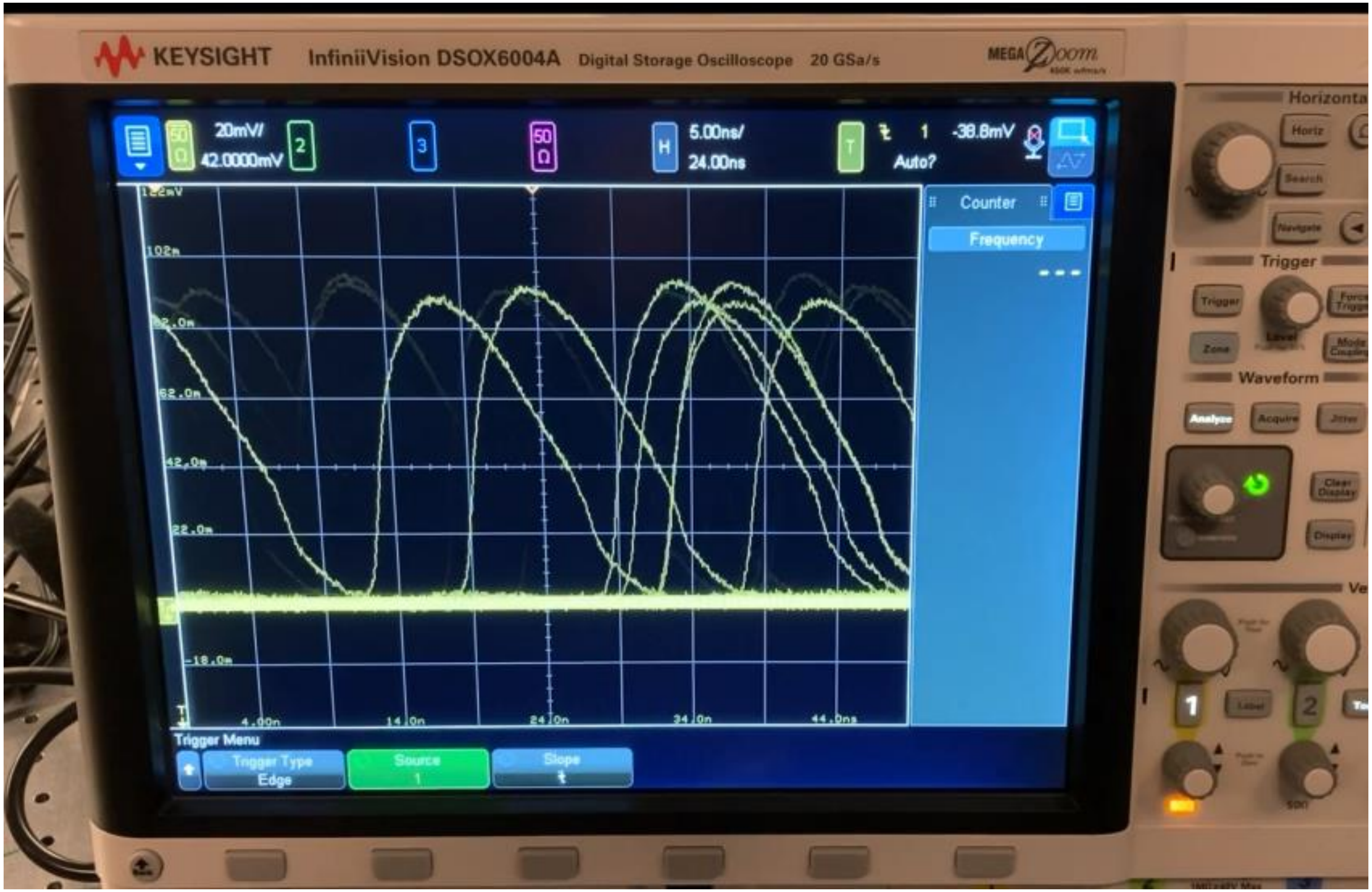
- ➢ At high bias (140 V) even a very weak 0.01 pJ laser pulse induces a strong signal.
- ➢ To achieve this regime at 60V, pulses with energy of about 0.5 pJ are needed.

We decided to switch off the fs-laser and only bias the sensor

Puzzle 2:

Exceptionally large auto-triggered signals were registered, we named them "GHOSTS"

Ghosts


KEYSIGHT
InfiniiVision DSOX6004A Digital Storage Oscilloscope 20 GSa/s
MEGA Zoom
20mV/
42.0000mV
5.00ns/
24.00ns
1 -38.8mV
Auto?
Counter
Frequency
122mV
102m
82.0m
62.0m
42.0m
22.0m
-18.0m
4.00n
14.0n
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34.0n
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Trigger Menu
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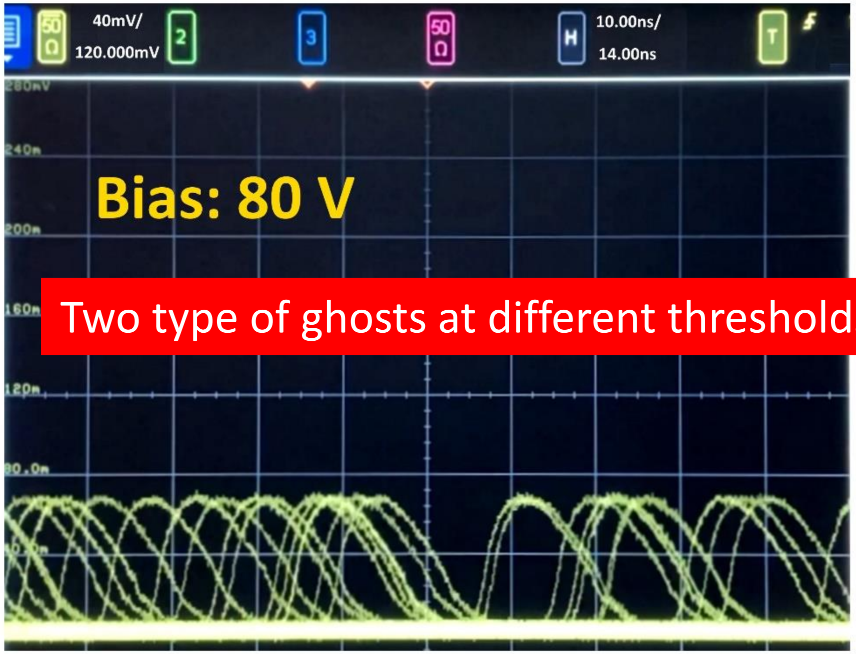
Acquire
Jitter
Clear Display
Display
Label

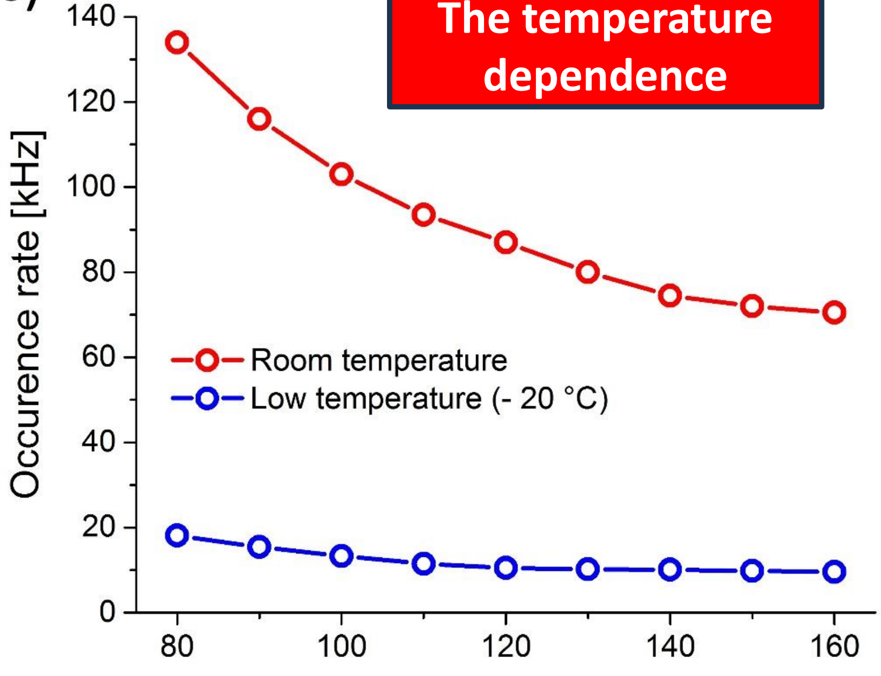
a)



Two type of ghosts at different thresholds.

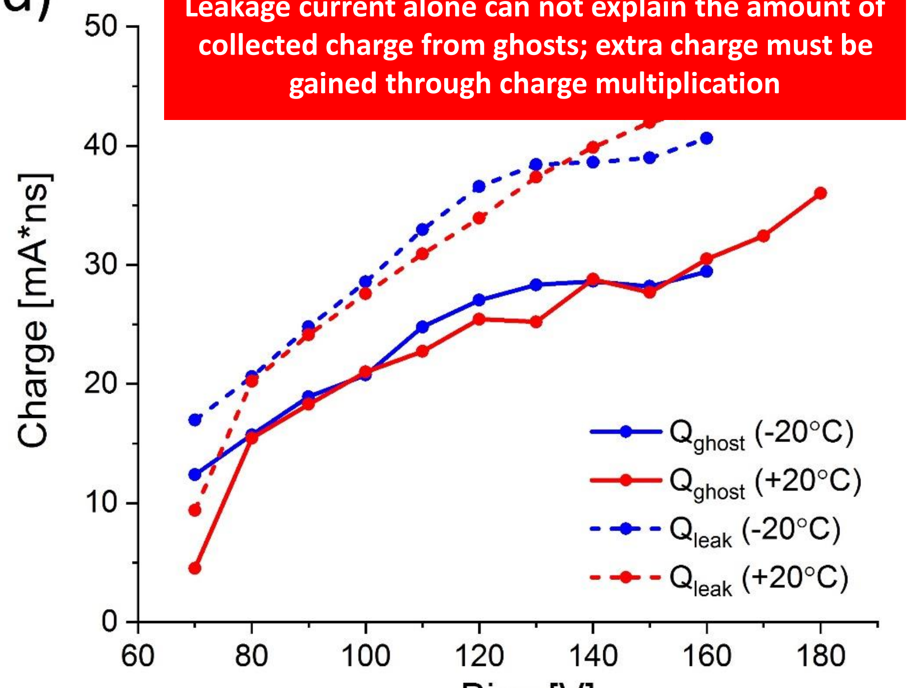
b)

c)



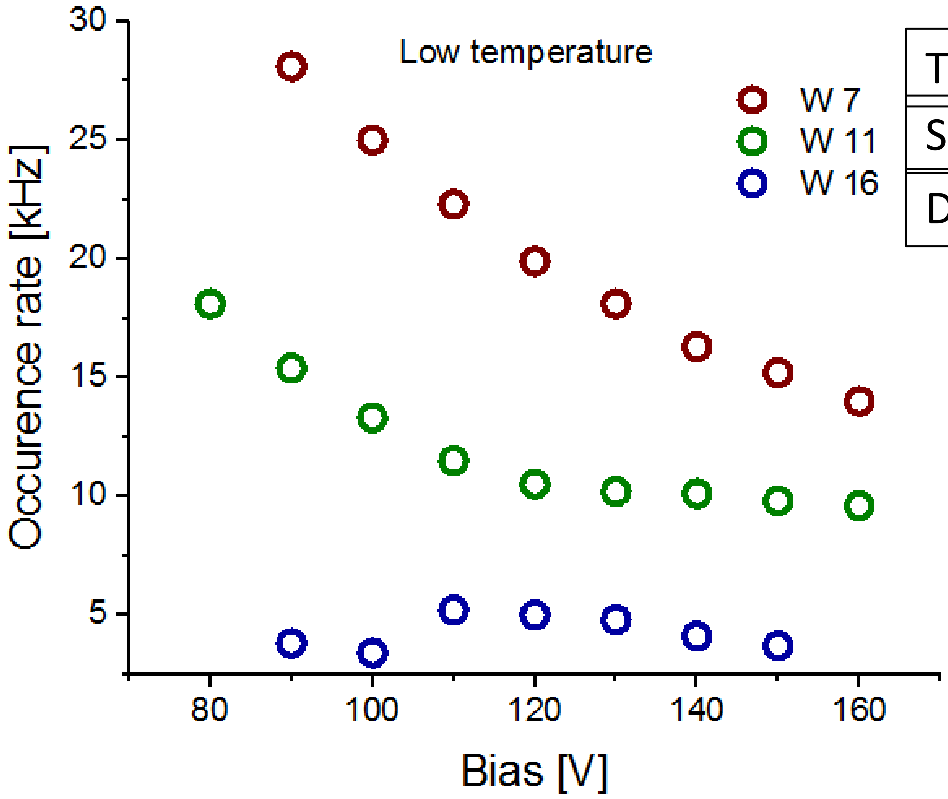
The temperature dependence

d)



Leakage current alone can not explain the amount of collected charge from ghosts; extra charge must be gained through charge multiplication

Ghost occurrence rate dependence on trench depth



The most noisy

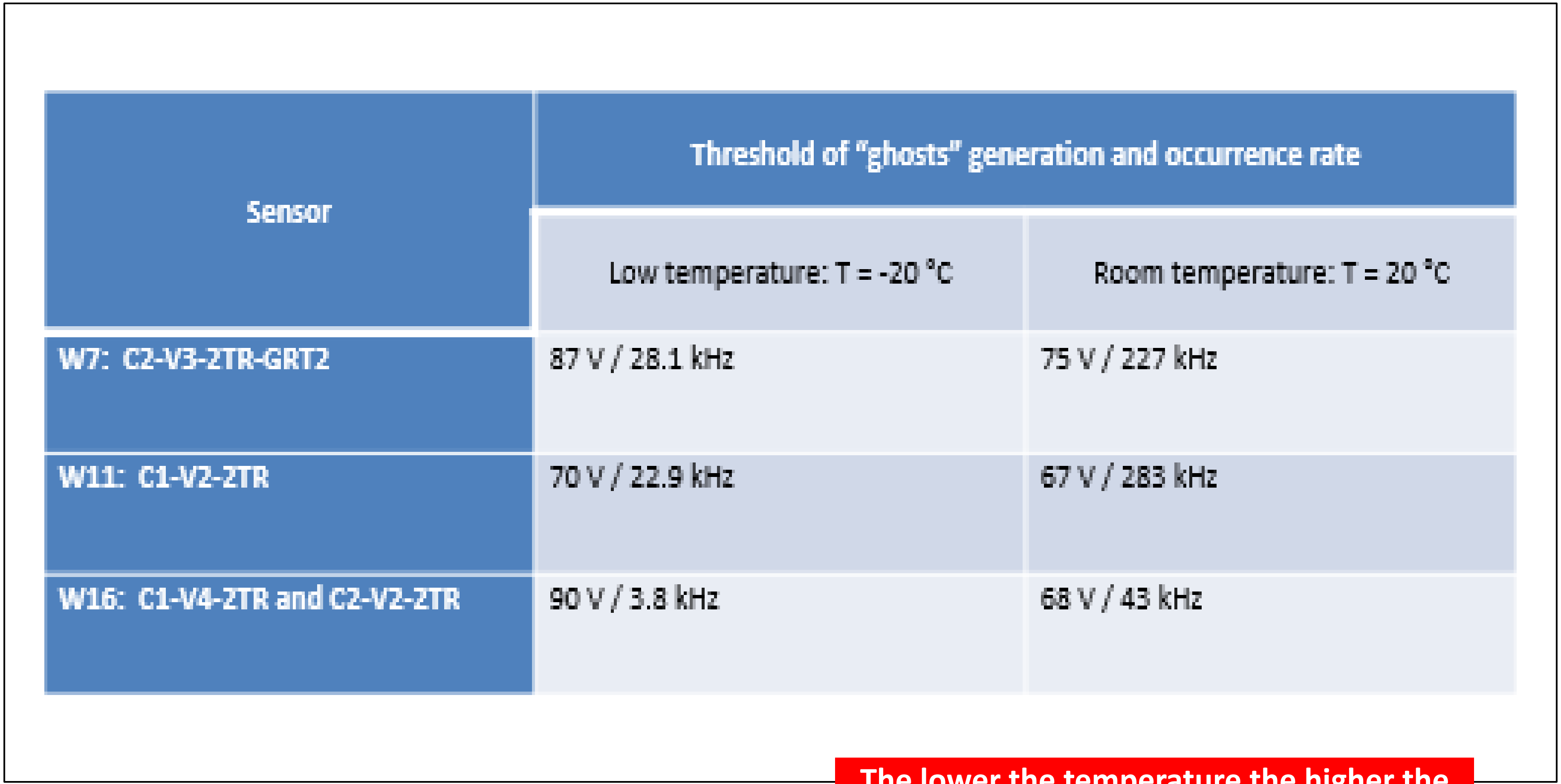
Shallow trench

Deepest trench

2nd observation: The frequency of the ghosts' occurrence decreases with bias! This puzzled us but it was related to the presence of an n^+ structure between trenches**.**

Differences are much higher at room temperature

Bias threshold dependence on temperature



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

The lower the temperature the higher the bias threshold was

We wanted to see whether a similar effect will be seen in the Ti-PIN with two trenches in the IP region

Puzzle 3:
NO GHOST in PINs

Was there insufficient charge accumulation between the trenches?

What happens if we add charge by laser?

Should we reach the critical threshold for discharge by injecting additional energy (charge) in inter-trench region?

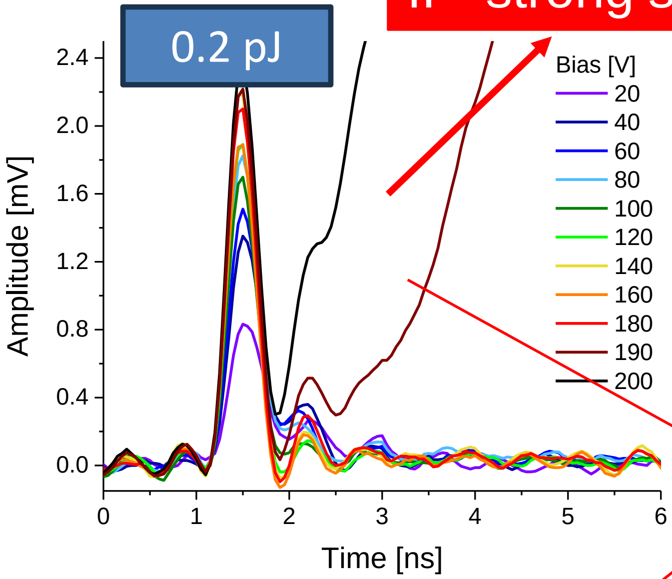
Puzzle 4

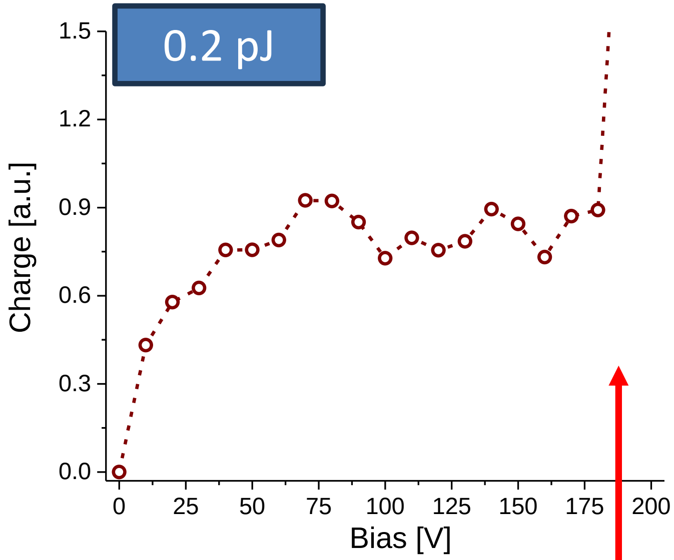
Although no ghosts were registered in IP region od Ti-PIN we managed to stimulate a strong signals akin to those seen in the inter-trench region in LGADs where GHOSTs are present.

The example is shown on the next page.

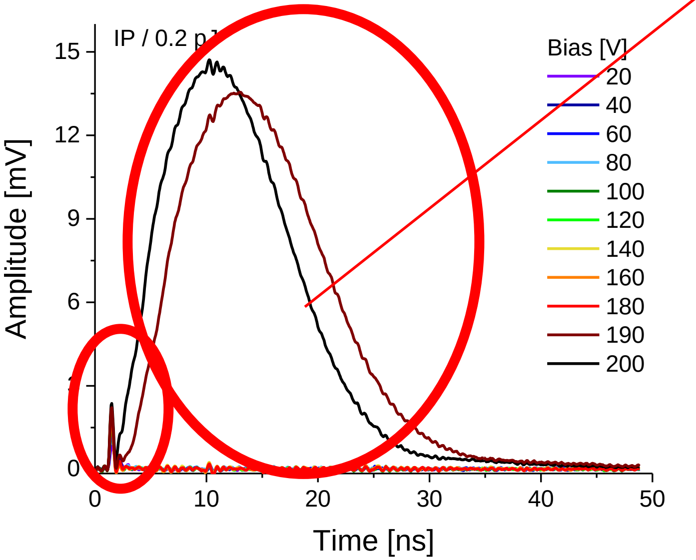
Interpad

IP strong signal





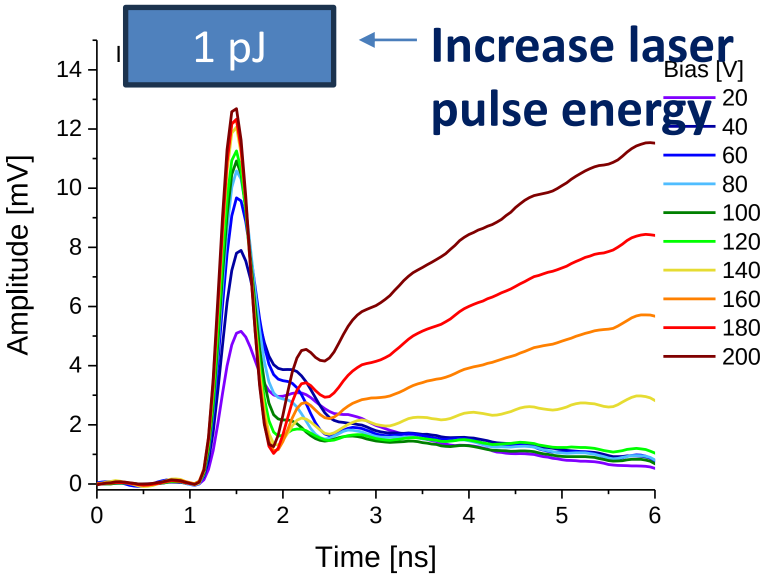
Discharging!



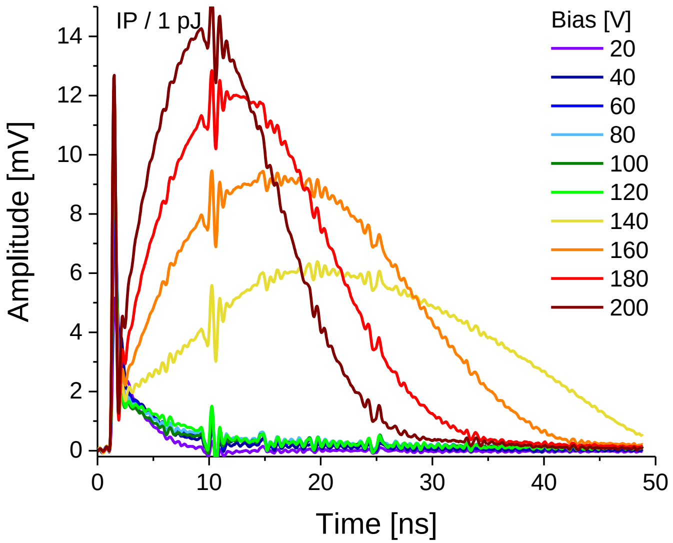
IP strong signal is generated at the highest bias (190 and 200V)

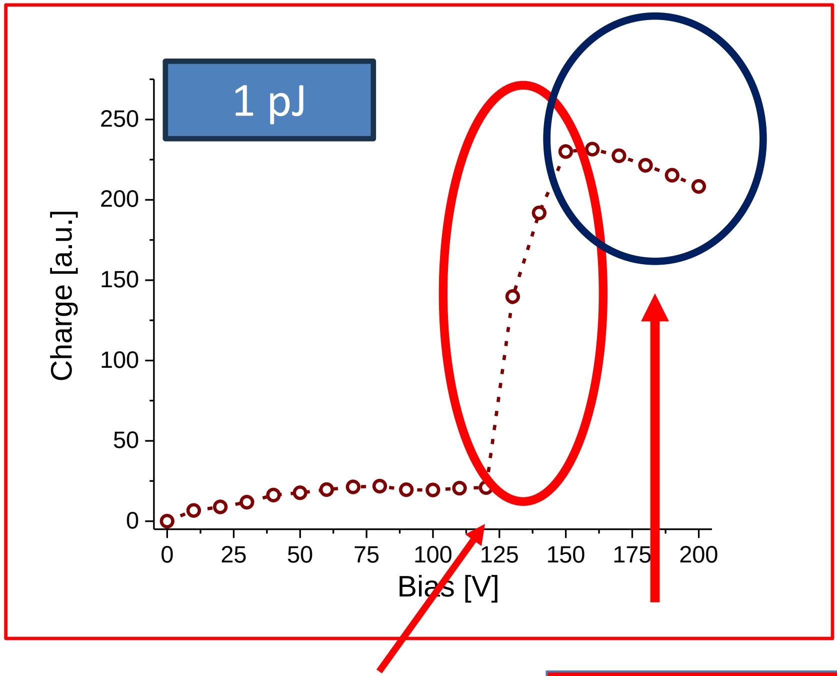
Interpad

RD50 PIN



Increase laser pulse energy





Charge multiplication

Saturation/ Surpression

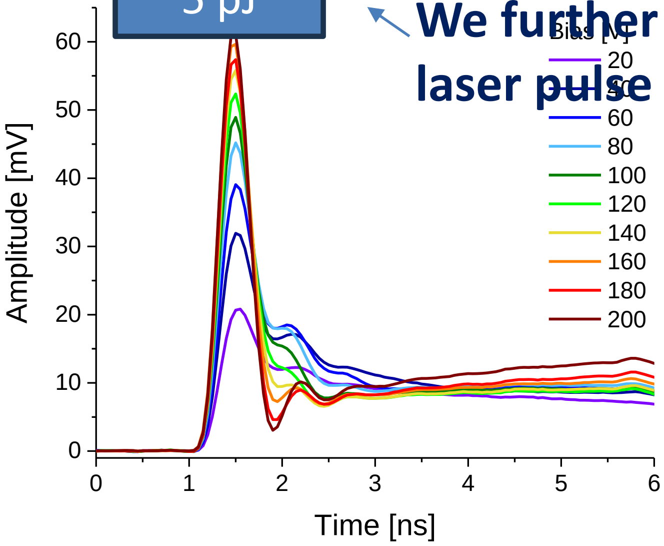
At 1 pJ much lower bias (130 V) is enough to generate strong signal

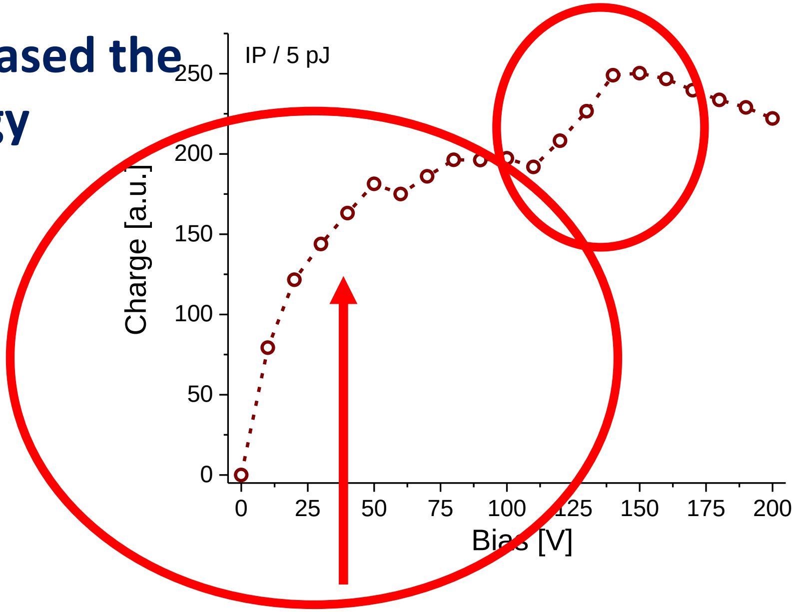
Interpad

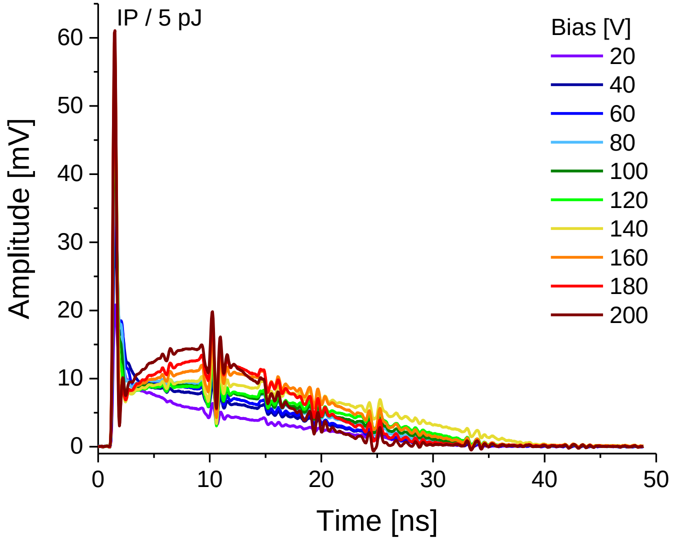
RD50 PIN

5 pJ

We further increased the laser pulse energy

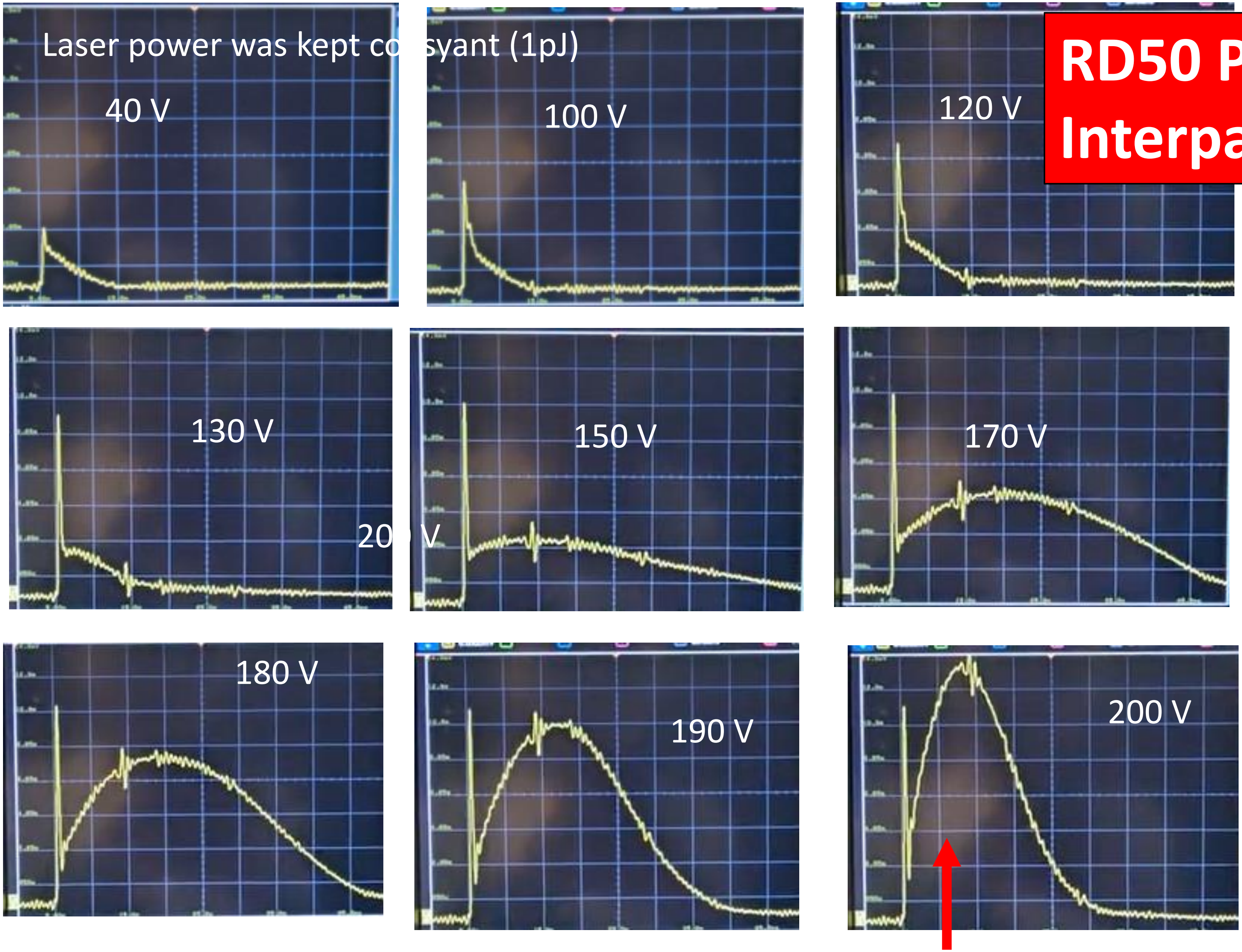






At 5 pJ, even at a low bias, we see a strong signal.

RD50 PIN Interpad



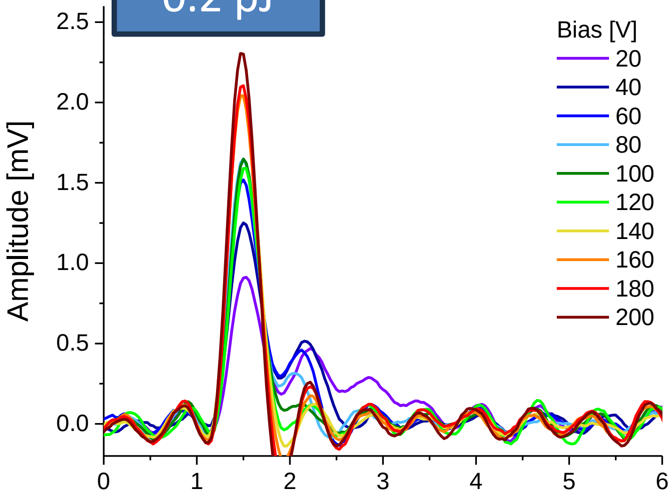
Laser power was kept co syant (1pJ)

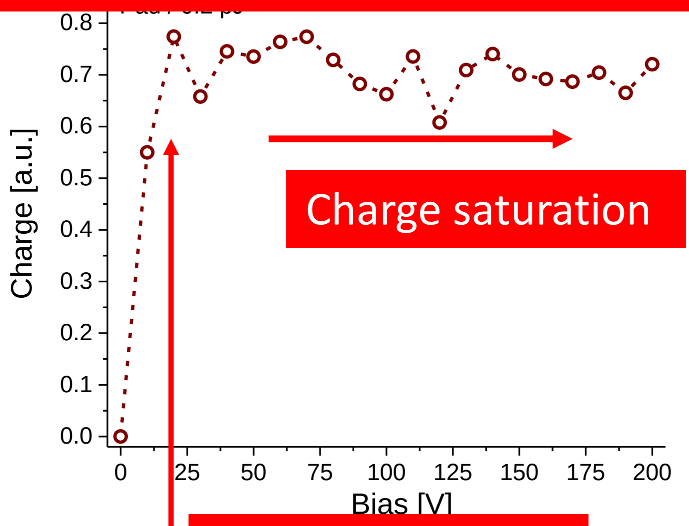
Evolution of stronf signas vs. HV bias.

Pad

Cross-check with Pad; Pad behaves as expected; No amplification

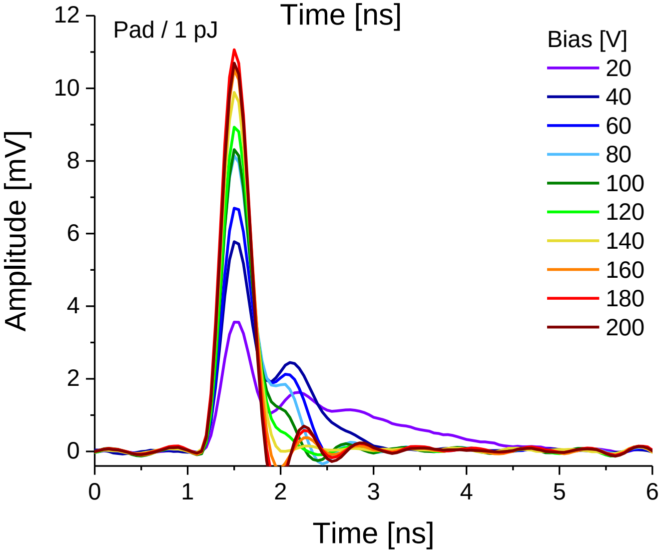
0.2 pJ

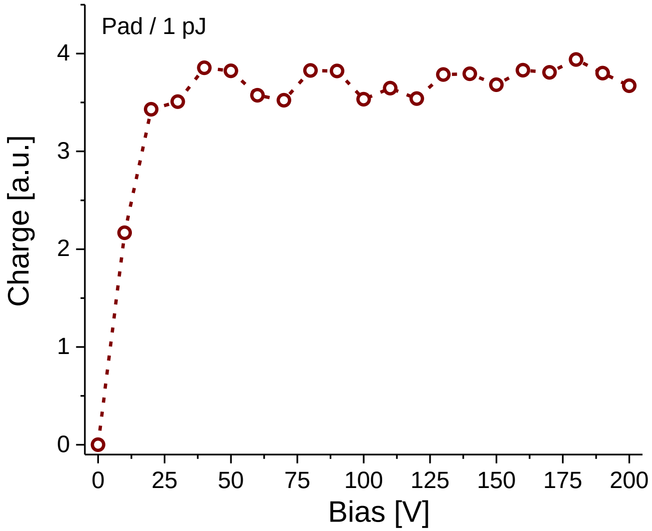




Charge saturation

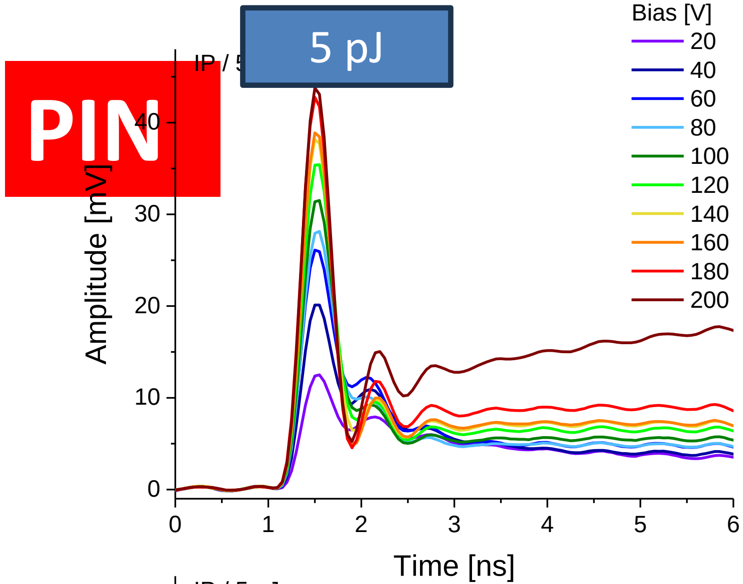
Full bias Depletion



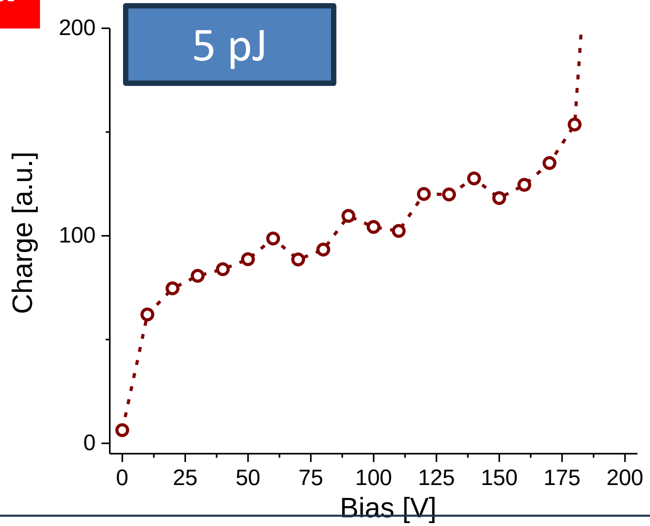


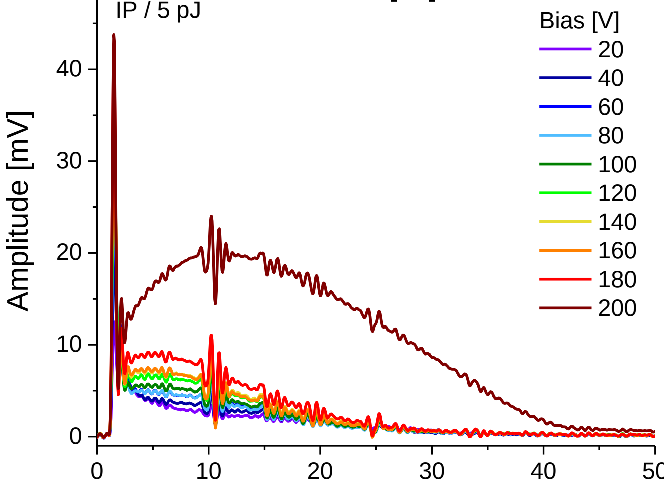
Cross-check with PINs from the latest Ti-LGAD production

AIDAInnova



Interpad





For the AIDA PIN, we induced a strong signal only at the highest bias. **At 200 V we need a minimum of 0.4 pJ and at 190 V, a minimum of 0.6 pJ**. Below 190V we don’t generate strong signals at a reasonable laser power < 10 pJ.

LGADs from AIDAInnova are Co-Carbonized (to reduce the acceptor removal)

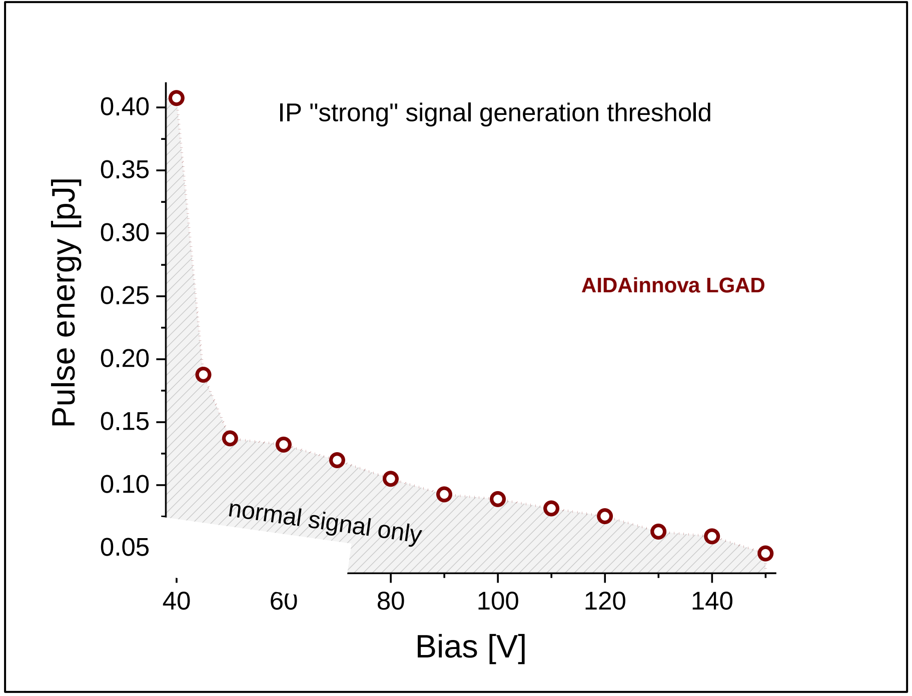
In irradiated Co-Carbonized LGAD, gain is larger then in LGAD without carbon co-implementation, however we tested non-irradiated PIN, therefore something else should play the role; not clear yet.

Interpad

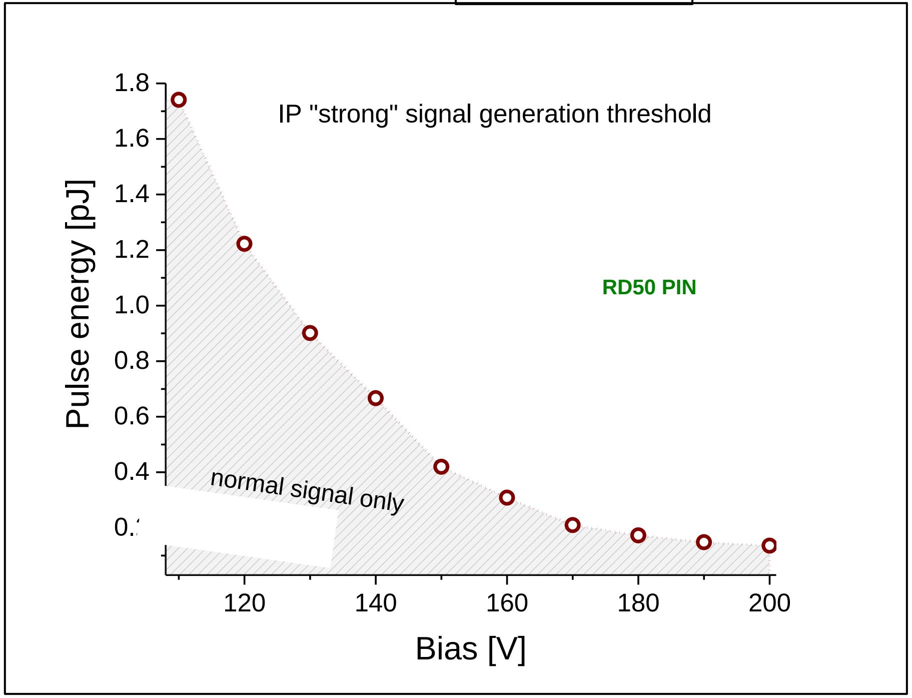
AIDA LGAD & RD50

Pulse energy vs bias for production of strong signal in inter-pad region.

LGAD



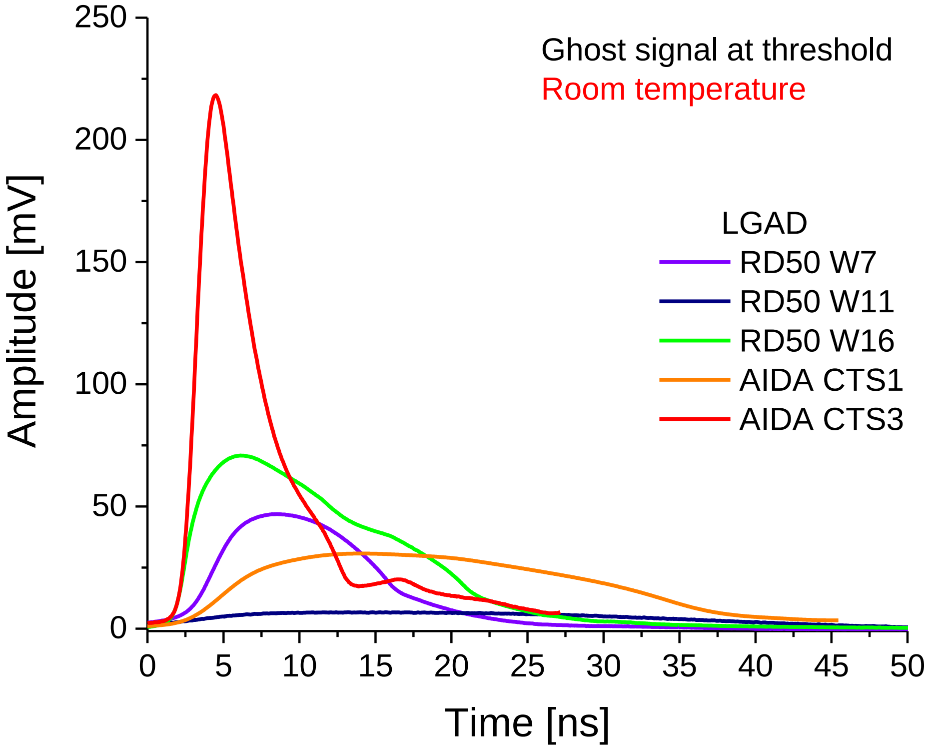
PIN

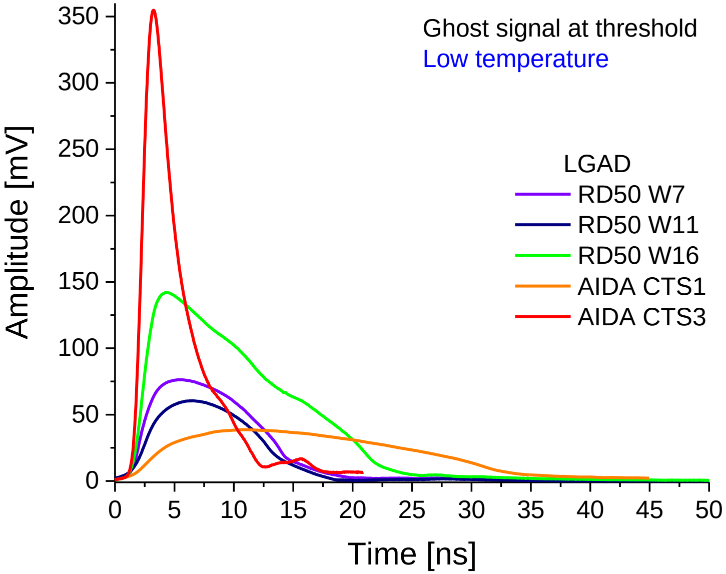


Ghost signals for all studied 2TR sensors

RD50: W7, W11, W16

AIDA (Carbon Co-implemented): CTS1 and CTS3 (Nond)





Conclusion: Trench processing, wafer doping and design parameters affect the ghosts

Puzzle 3 (an ongoing story :)

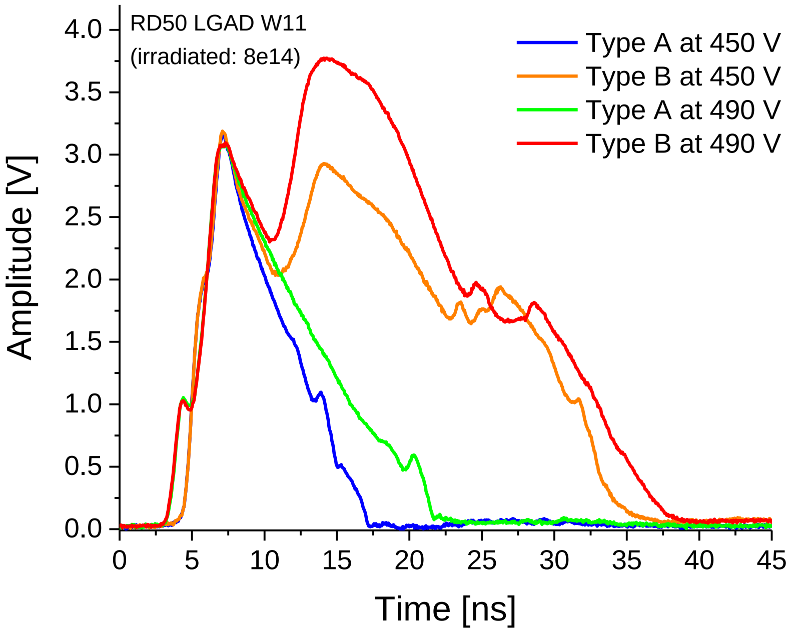
Irradiated LGAD

The “GHOSTS” with 12 x larger amplitude appear in the irradiated sensor BUT we could not stimulate a strong signal

Irradiated: 8e14 n_{eq}/cm^2

RD50 LGAD

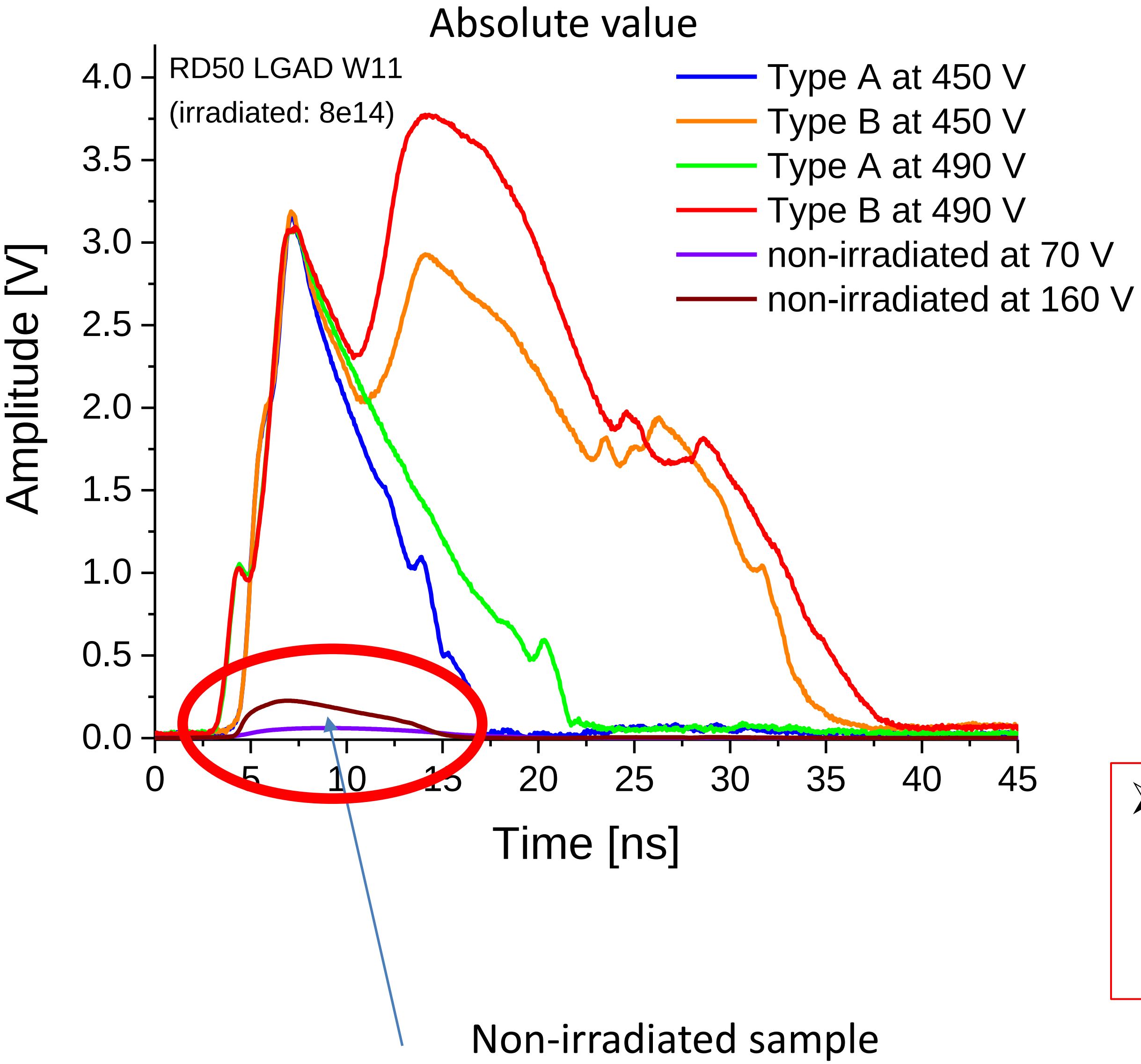
- When we decreased the bias, the signal was still present even at as low as 450 V (disappeared at lower bias) but to restore it we had to again increase it up to 490 V (this behavior was reproducible).
- Two types of signal exist, Type A (narrower) and Type B (broader)
- When we increased bias the sensor broke down at around 530-540V



Observed ghosts have some important differences in comparison to the previously observed ghosts for non-irradiated 2TR LGAD

- They are much stronger than previous ghosts (amplitude of 3-4 V vs 0.2-0.3 V in non-irradiated W11 LGAD
- Frequency is much lower (about 30 Hz vs tens of kHz previously)
- They appear at a very high bias which is close to the damage threshold (previous ghosts appear at quite a low bias, ~50V, quite far from the damage limit)
- This signal does not appear as laser synchronized "strong" signal. We illuminated the IP region (always scanning a bit over it) with different laser powers at different biases up to 490 V and no laser-synchronized strong signal was observed.

Comparison with non-irradiated



Non-irradiated sample

- The ghost signal is much larger in irradiated samples.

Ti-LGAD irradiated at 0.8x10^{15} n_{eq}/cm^2 , and biased at the HV = 490 V, has gain as non-irradiated Ti-LGAD!

BUT

The total charge induced by ghosts is significantly larger for the case of irradiated Ti-LGAD!

Therefore

The radiation defects seems to have an enormous effect on the modification of the electric field, enhancing the charge amplification which sustain until the charge equilibrium is reached and the dischargung is quenched.

From other side it is possible that the regime of plasma in inter-trench region in irradiated Ti-LFAD is not known to us, and that some conductive paths whose formation mechanisms are not known to us are enabling such enormous discharge as we saw in irradiated Ti-LGAD → play with ghosts continuos although ghost suprizes us every time ☺

Summary

- In our presentation, we delve into the investigation of the interpad (IP) region within double trench isolated LGADs (2Tr TI-LGADs), focusing on the double-trenched PINs from both the RD50 and Aida Innova production runs.
- Our previous research revealed that exceptionally large signals, with prolonged duration, manifest in the IP region alongside the standard IP signals recorded in conventional LGADs with 2JET and 2 p-stops.
- We have identified a correlation between strong signals and ghost signals persisting in the IP region even when the laser is deactivated.
- Recently, we replicated a study using double-trenched PINs (without the gain layer in the pads) and observed no ghost signals.
- However, under specific laser power and bias threshold conditions, we recorded remarkably high signals in the IP region between trenches, with prolonged duration, akin to observations in double-trenched LGADs where ghost signals were present.
- A new puzzle came after we found ghosts also in irradiated 2Tr LGAD (0.8×10^{15} n_{eq}/cm^2) although we could stimulate a strong signal in the IP region with a laser. Observed ghosts in irradiated samples have some important differences in comparison to previously observed ghosts for the non-irradiated 2TR LGAD.

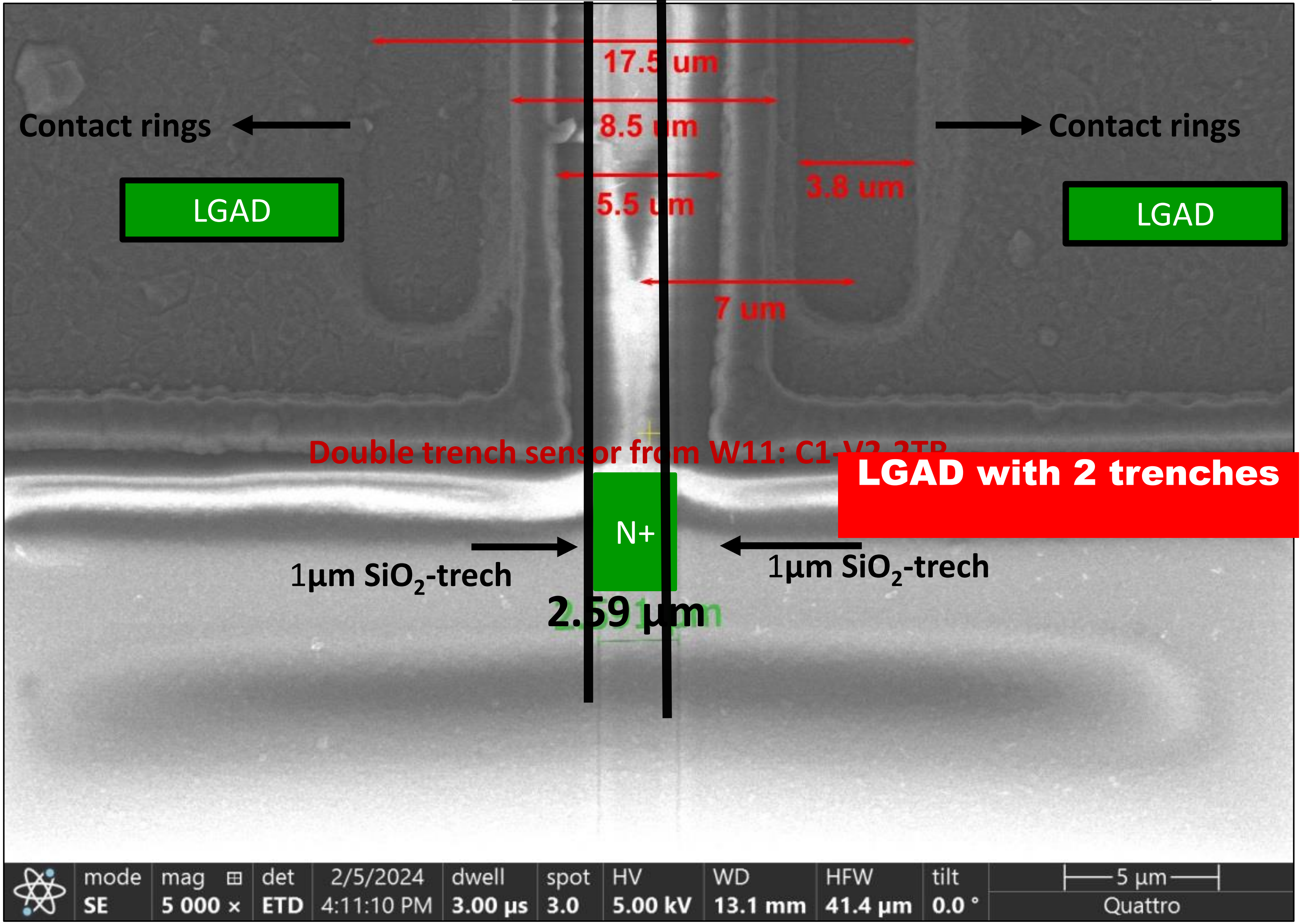
- Those ghosts (seen in the irradiated sample) are much stronger than previous ghosts (amplitude of 3-4 V vs 0.2-0.3 V in non-irradiated W11 LGAD). The frequency of occurrence is much lower (about 30 Hz vs tens of kHz previously). They appear at a very high bias which is close to the damage threshold (previous ghosts appear at quite a low bias, ~50V, quite far from the damage limit). This signal does not appear as a laser-synchronized "strong" signal

The messages to be taken to home:

- Reduction of interpixel distance requires an optimization of the design parameters.
- Scaling down interpixel distance is a challenging task.
- Auto-triggering signals sets the limits on the design of interpixel layouts;
- Multi-tranch isolation design seems to struggle from the auto-triggered events.
- Ghosts known to us, seen typically in pads (originating from the leakage current and enhanced at the breaking HV) are very different from the ghosts we observed in inter-trench region (isolated part of LGAD).
- WE recommend single trencj layout for Ti-LGAD sensor technology.

THANK YOU ☺.

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



LGAD with 2 trenches