Mortality study on irradiated HPK-P2 W36 LGADs and PINs (I part): TCT-SPA

Gordana Lastovicka-Medin
University of Montenegro

Gregor Kramberger
Jozef Stefan Institute

Mateusz Rebarz, Jakob Andreasson, Kamil Kropielniczki
ELI Beamlines

Jiří Kroll, Michal Tomášek, Tomáš Laštovička
Institute of Physics, Academy of Sciences, CZ

Valentina Sola, Nicolo Cartiglia
INFN Torino

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Outline

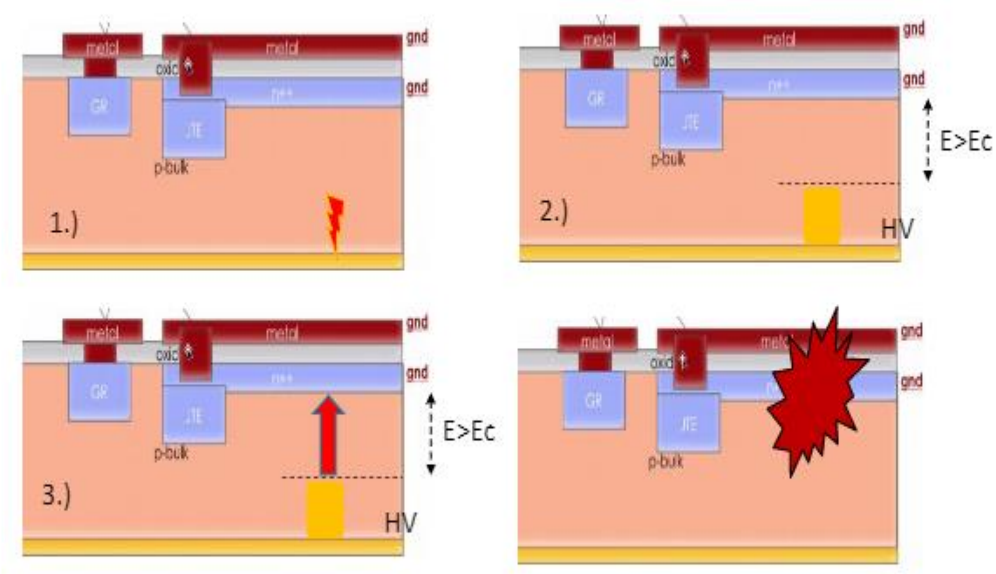
- ❑ Motivation and Mortality Hypotheses
- ❑ Brief overview of outcomes from the 1st ELI Mortality Campaign on LGADs (result shown at the TREDI 2021)
- ❑ Outcomes of the most recent, 2nd ELI Mortality Campaign (successfully completed last week)
- ❑ Conclusions

Quick introduction: LGADs breaking down at high V_{bias}

- ☐ Destructive breakdowns appear mostly in the test beams (TB) – much less in the laboratory setups (Sr90, probe stations)
- ☐ HPK-P2 sensors seem to be robust in the laboratory conditions.
- ☐ Destructive breakdowns (fatalities) appear at bias voltages that are significantly (50 -100V) lower than those in the lab.
- ☐ They appear suddenly without a clear warning (increase of leakage current, instability in leakage current, changes in gain; this also seen in ELI tests)
- ☐ There are indications that fatalities are beam related and not linked to the environmental conditions; When exposed to a high-energy particle beam they continue to behave normally for a while during particle bombardment; but then abnormal events, is probably triggered by rare but highly ionizing nuclear collision events;
- ☐ The tested reasons/hypotheses for these breakdowns:
  - ☐ Is it the high electrics field in highly irradiated sensors that is the problem?
  - ☐ Is it the gain of the devices that plays a role?
  - ☐ Is it the irradiations that are the reason, or they merely facilitate the conditions where high bias voltages can be applied?
- ☐ The main difference between lab (Sr-90 with E_{max}=2.3 MeV) and TB (up to several tens MeV deposits – CMS paper) is the energy of the particles:

  Can huge amount of charge in a single collision cause a conditions that lead to a destructive breakdown?

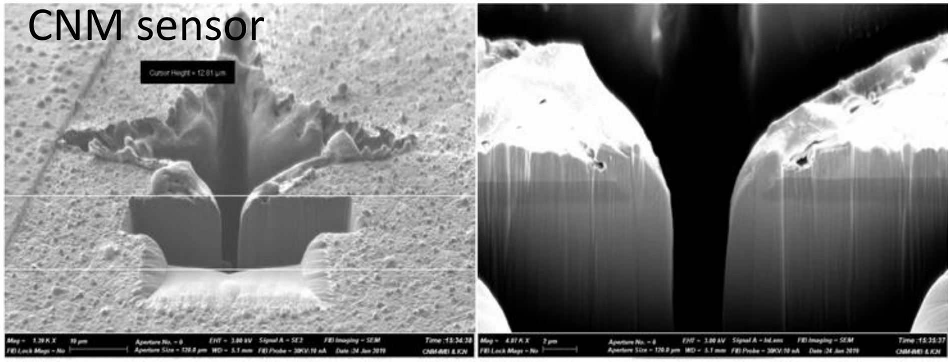
A possible explanation



1.) larger deposition of the charge (fragments producing deposition in few um as large as 1000 mips- CMS tracker paper) in few um (not possible with lab sources)

2.)larger density of carriers leading to collapse of the field (screening prevents the carriers from being swept away)

3.) once the field collapses the HV is brought closer to the pad which leads to very high field strength leading to avalanche breakdown and full discharge of sensors and bias capacitor


CNM sensor

“courtesy of CNM (ATLAS TB sensor)”

10478
W4S1017

Thanks to CNM for providing the photos of such fatality.

Hypotheses: If the speed of deposition is similar to Mip then the laser test with extremely high energy per pulse in 50 fs should lead to fatalities

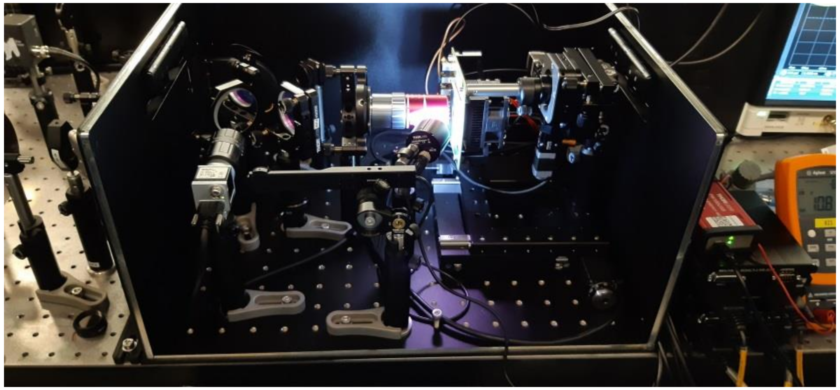
ELI Beamlines becomes fs-beam test facility for LGAD

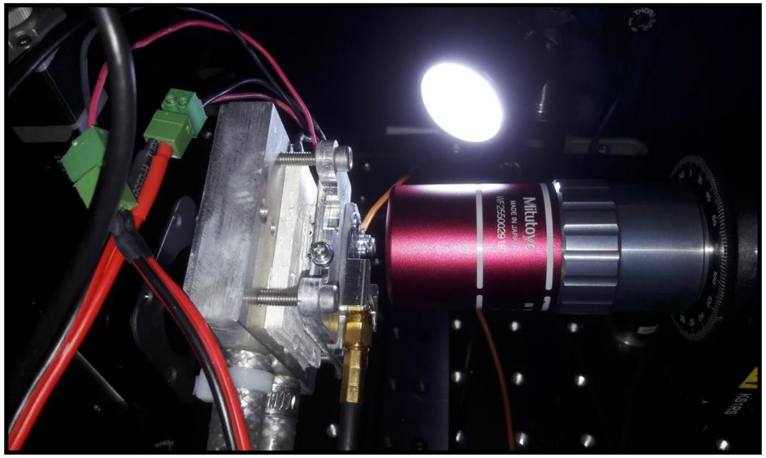
- ❑ A suitable method to measure the damage is to monitor its leakage current; when the device is destroyed the effect is dramatic
- ❑ The leakage current presents “discharge” character

ELI Beamlines, SPA/TPA-TCT setup & Mortality Campaigns

Czech Republic
Dolní Břežany (on the outskirts of Prague)

Experimental hall E1
Research program: Bio and Material Applications





Project supported by: Advanced research using high intensity laser produced photons and particles (ADONIS) Reg. n.: CZ.02.1.01/0.0/0.0/16_019/0000789

ELI findings from the first fatality fs-laser based tests (February 2021)

(results shown at the TREDI2021)

- We managed to set up extremely useful facility to study TCT with 50 fs laser of very high energies.
- Tests uses 800 nm (27 μm penetration) of 50 fs pulses with pulse of up to a 1 mJ. Pulses are focused to dimensions similar that of mip deposition (1-2 μm cone)
- The full setup can be operated cooled at ~-30°C and flushed with nitrogen.
- GADs and PINS from the latest HPK-P2 run irradiated to several different fluences 4,8,15,25e14 cm^{-2}.
- We focused our studies to establishing the conditions where sensors destructively break down:
  - Sensors seem to be quite robust up to bias voltages of around 400-500V, where pulse energies of several tens of nJ are required to trigger destructive breakdown – far larger than that experienced during operation at LHC
  - Both PINs and LGADs seem to be destroyed under this conditions – **breakdown likely field related**
  - At high bias voltages the required pulse energy for destruction of the device decreases rapidly – at 680 V only 3pJ is enough to destroy the sensors
  - Highest irradiated sensors can operate at 1pJ at 720 V – a much finer scan is needed to establish conditions

16th (Virtual) "Trento" Workshop on Advanced Silicon Radiation Detectors.
16-18 February 2021 FBK,

Femtosecond studies of single event effects in thin LGADs at ELI Beamline

Gordana Lastovicka-Medin
University of Montenegro

Gregor Kramberger
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Institute of Physics, Academy of Sciences, CZ

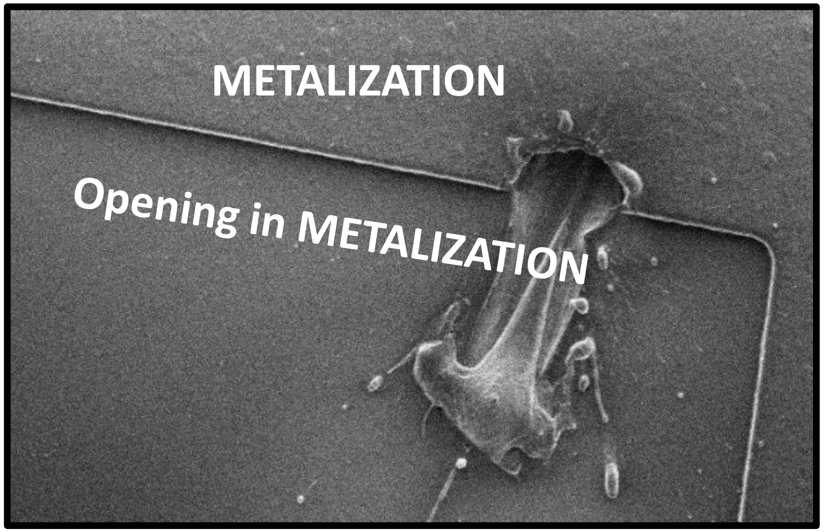
Valentina Sola Nicolo Cartiglia
INFN Torino

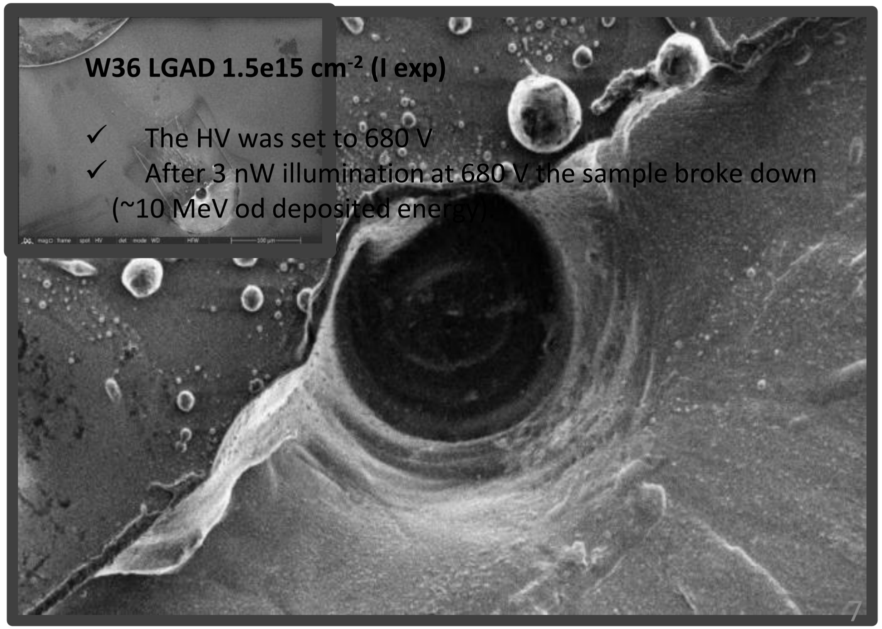
It was clear that at high voltages detectors become sensitive to single highly energetic events, which can lead to destructive breakdown.

Interpreted in relation to proton beam tests: Rare, highly-ionizing proton interactions can lead to single-event burnout.

The added piece to the puzzle

- It seems that all the fatalities occur at the metallization-opening interface!
- **The “avalanche” seems to be triggered in the centre of opening where the laser hits the sensor, but the damage occurs at the point metal-Si interface**, as there is a resistive path at metal-si interface which causes the heating and melting away the silicon. At lower bias voltages these sensors can take huge abuse with highly energetic laser pulses and that doesn’t hurt them. So it must be field related.
- No crater fatality signature seen as it was the case in test-beams; this is the most probable because in ELI tests we did not used 10 nF capacitor (set on timing board) so damage happen later. There is no discharge through sensor, and thus no crater rupture.




W36 LGAD 1.5e15 cm^{-2} (I exp)

- ✓ The HV was set to 680 V
- ✓ After 3 nW illumination at 680 V the sample broke down (~10 MeV od deposited energy)

So from here there are still some very important points open:

- ☐ What is the “threshold for charge deposition” at given HV bias that leads to destruction of the sensor?

- ☐ Does the position of deposition inside LGAD matter? It can be that it is not the same if large amount of charge is released on top or on the bottom of the active layer (a clear case for TPA study, see the next talk)

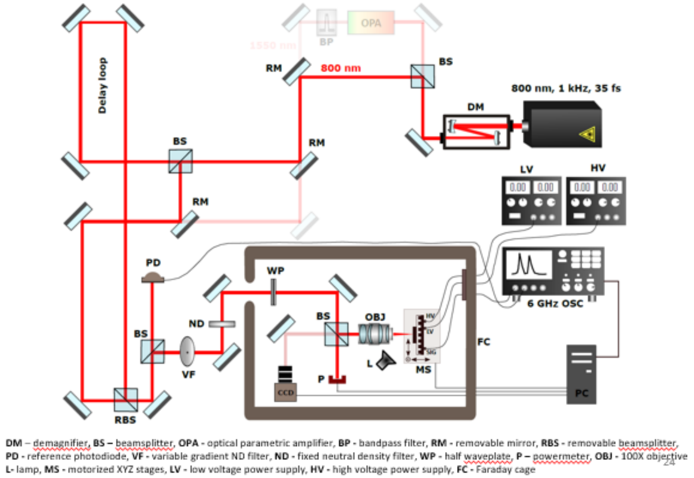
- ☐ What about the potential mitigation strategies? What would be the proper operational mitigation and how sensor mortality can be avoided with minimal impact on the performance of the CMS and ATLAS for LHC-HL? Risk mitigation by reducing the HV bias for 2.5e15 n_{eq}/cm^2?

Still some unknown.

Answers given in the 2nd ELI LGAD Mortality Campaign (May/June 2021)

With focus on finding the HV bias thresholds for stable, unstable and irreversible breakdown of LGAD and covering fs-laser power (charge deposition threshold) that is of the interest for the LGAD fatality study.

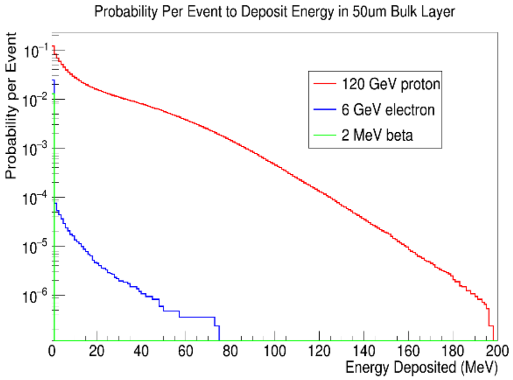
Mortality study procedures



DM – demagnifier, **BS –** beamsplitter, **OPA** - optical parametric amplifier, **BP** - bandpass filter, **RM** - removable mirror, **RBS** - removable beamsplitter, **PD** - reference photodiode, **VF** - variable gradient ND filter, **ND** - fixed neutral density filter, **WP** - half waveplate, **P –** powermeter, **OBJ** - 100X objective **L**- lamp, **MS** - motorized XYZ stages, **LV** - low voltage power supply, **HV** - high voltage power supply, **FC** - Faraday cage

Laser conditions:
λ = 800 nm (beam focused in the center of pad)
Beam diameter: d = 1.7 μm
Temperature: -25 °C
Laser power/energy range 1-50 nW = 1-50 pJ;

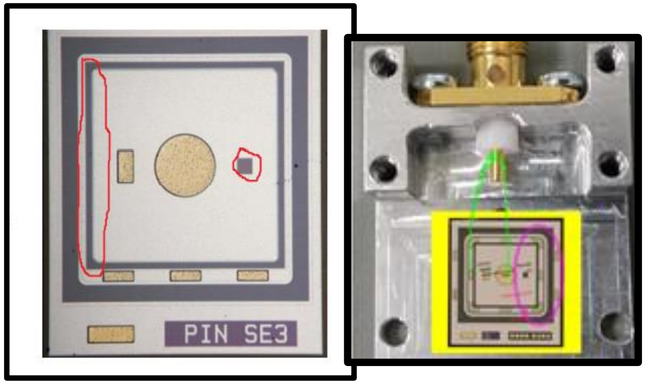
- ❑ Starting with low pulse energy **1 pJ** the bias was increasing from **100 V to 650 V** (later this limit was extended to 670 V) whereas the signal was observed on the oscilloscope (waveforms were recorded) and the leak current was monitored.
- ❑ This procedure was repeated for increasing pulse energies with **5 pJ step until 50 pJ;** 5 pJ would correspond to 5 M e-h pairs
  - ❑ We know **protons can deposit energy up to 200 MeV** in the bulk while **electrons only up to 60 MeV**. We also know that 10pJ of laser power corresponds to 30 MeV od deposited energy.

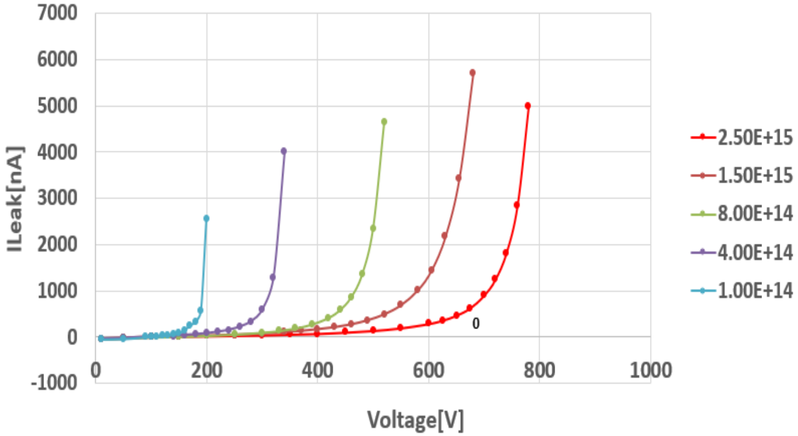


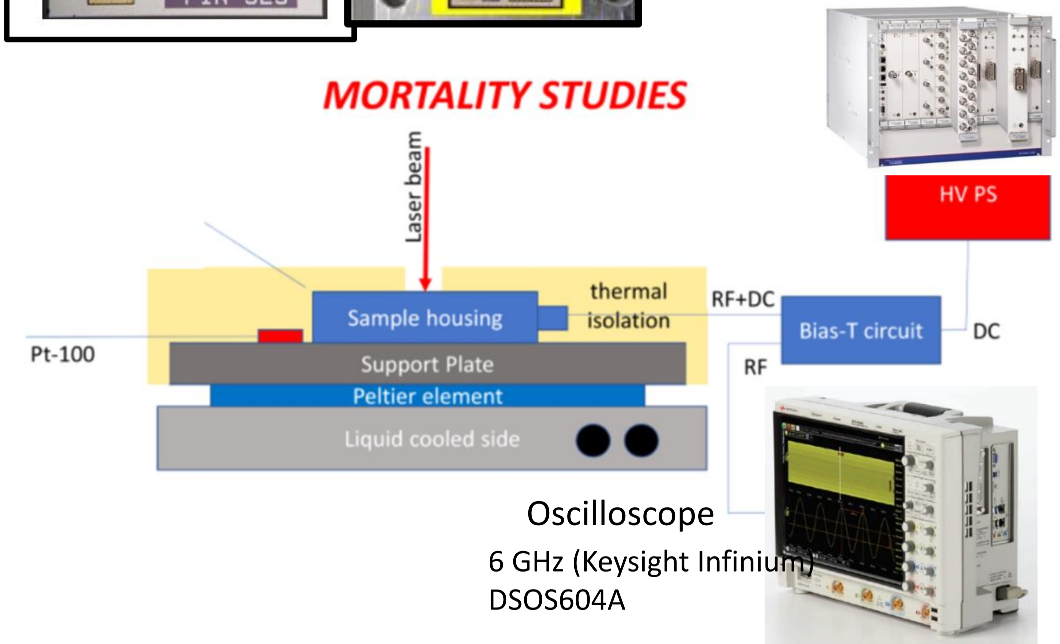
- ❑ For every scan we searched for the first symptoms of instability in the signal. When the signal started slightly “jumping”, we noted the values of energy and bias as "stability threshold“
- ❑ **After reaching the threshold the bias was further increased (to 670 V) to explore "unstable region"** as long as the signal can be safely measured by the scope
- ❑ When the signal was high and significantly deformed the scope was disconnected and only leak current was observed with increasing bias.
- ❑ **In the end the energy was set at 50 pJ** and **the bias was increased until the breakdown of the sensor.**

Samples and readout

- ❑ The samples are from HPK-P2 run, the latest ATLAS/CMS LGAD fabrication (shown in many talk in the workshop)
  - ❑ W36 (Vgl~51.5 V, Vbd~220 V)
  - ❑ fluences covered are the ones of interest for ATLAS & CMS: 1.5e15, 2.5e15 cm^{-2}







Oscilloscope

6 GHz (Keysight Infinium)
DSOS604A

- ➢ Closed circuit chiller T=-25C
- ➢ N2 flushed to avoid condensation.
- ➢ No active amplifier used-we want large signals.
- ➢ Bias-T used to prevent discharge into oscilloscope
- ➢ No other bias filtering used
  - ✓ HV power supply: EB1200305040000200 (Iseg)

Samples

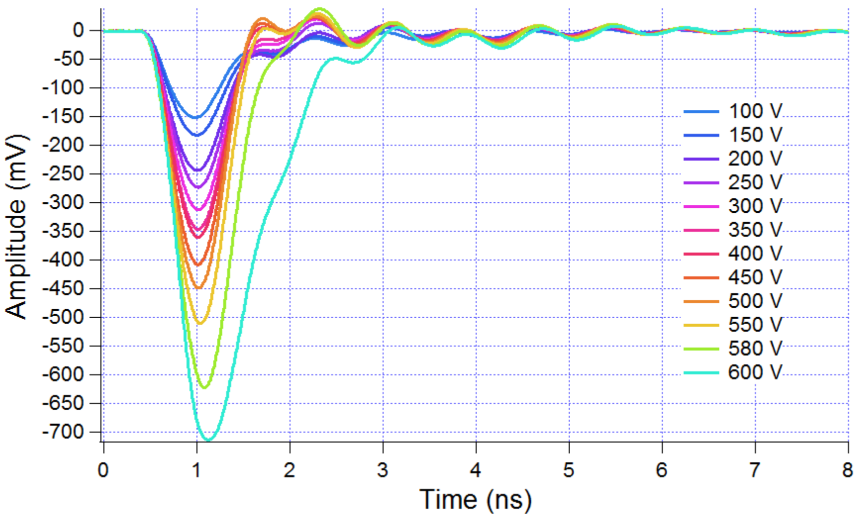
Two sets of samples were used in the study.
The first set of bonded sensors was sent by Gregor directly to ELI. The second one was bonded by Jiri in Prague.

Gregor bonding		Jiri bonding	
W36 LGAD 1.5e15	Damaged by TPA	W36 LGAD 1.5e15	Damaged by SPA
W36 LGAD 2.5e15	Damaged by SPA	W36 LGAD 2.5e15	Damaged by SPA
W36 PIN 1.5e15	Not working	W36 PIN 1.5e15	Damaged by SPA
W36 PIN 2.5e15	Damaged by SPA	W36 PIN 2.5e15	Not working

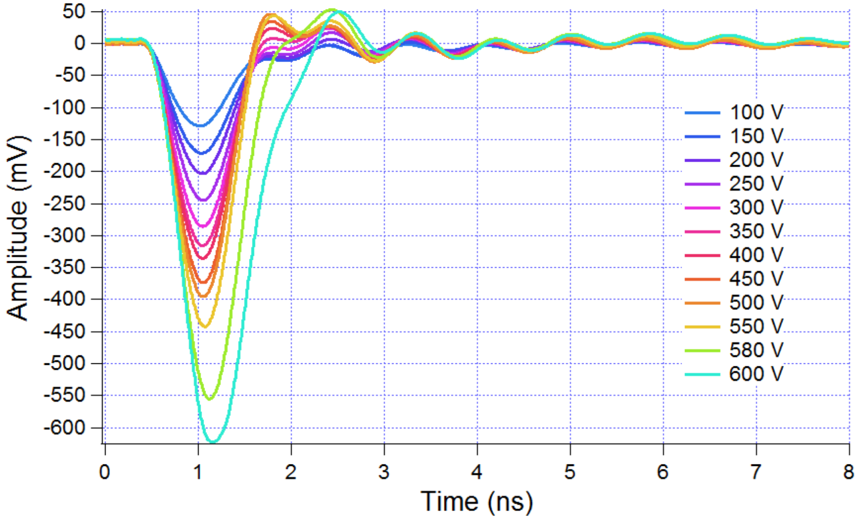
Unfortunately, two samples were not usable:
PIN 1.5e15 from JSI didn't hold any bias voltage
PIN 2.5e15 from Jiri could hold the voltage but it didn't give any measurable signal

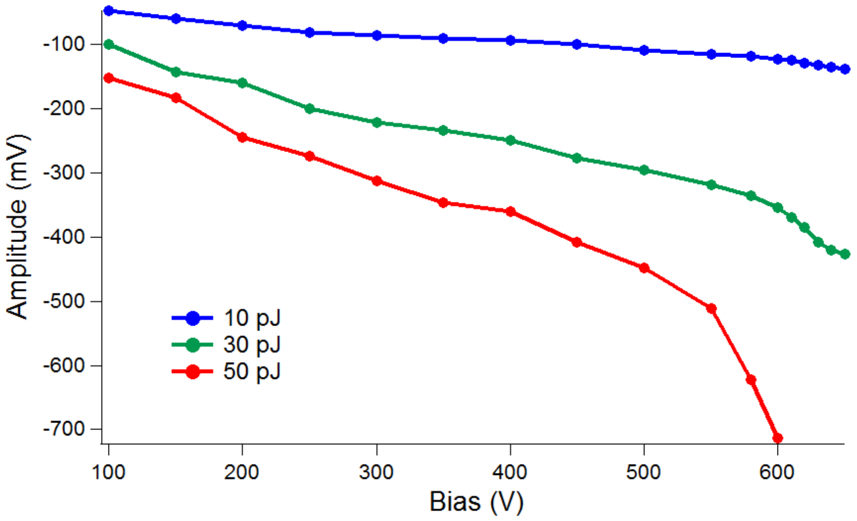
Example waveforms

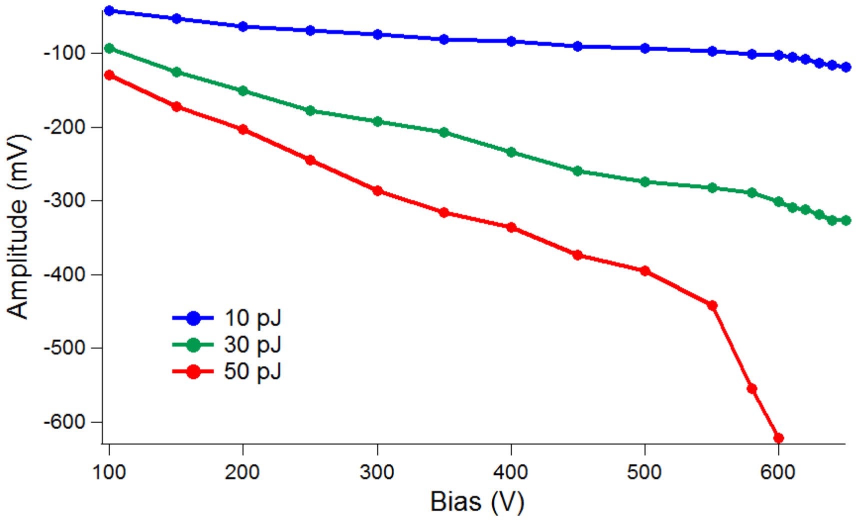
LGAD 2.5e15 at 50 pJ



PIN 2.5e15 at 50 pJ



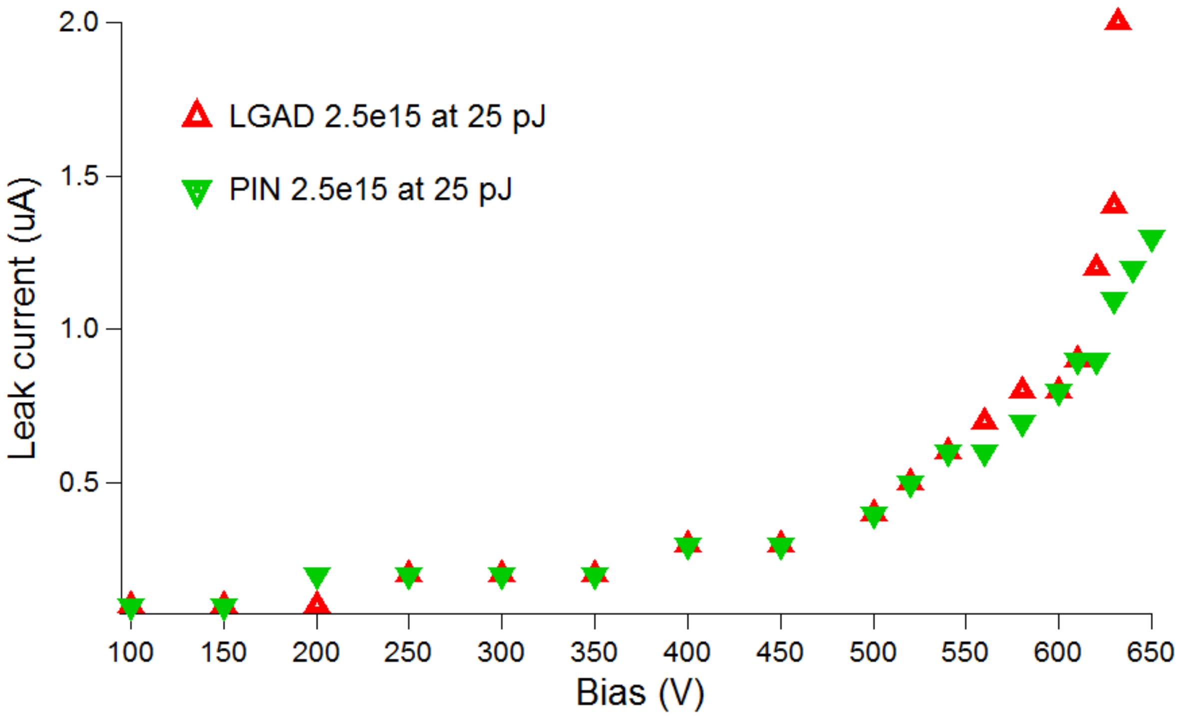




Remarks: The waveforms were recorded for all studied range (not only around stability threshold).
No significant different was observed between irradiated LGADs and PINs. Typically, the signal for LGAD is always slightly bigger than for corresponding PIN but the difference is several percent only. This time we were careful to keep the same measurements conditions.

Leak current

- ☐ The leak current was recorded for different bias values.
- ☐ Nearly identical dependency was observed for all the samples at low illumination level. The small differences between LGADs and PINs appears only for higher laser power (see example below).
- ☐ Above stability threshold the current is jumpy and it's not possible to define the value.

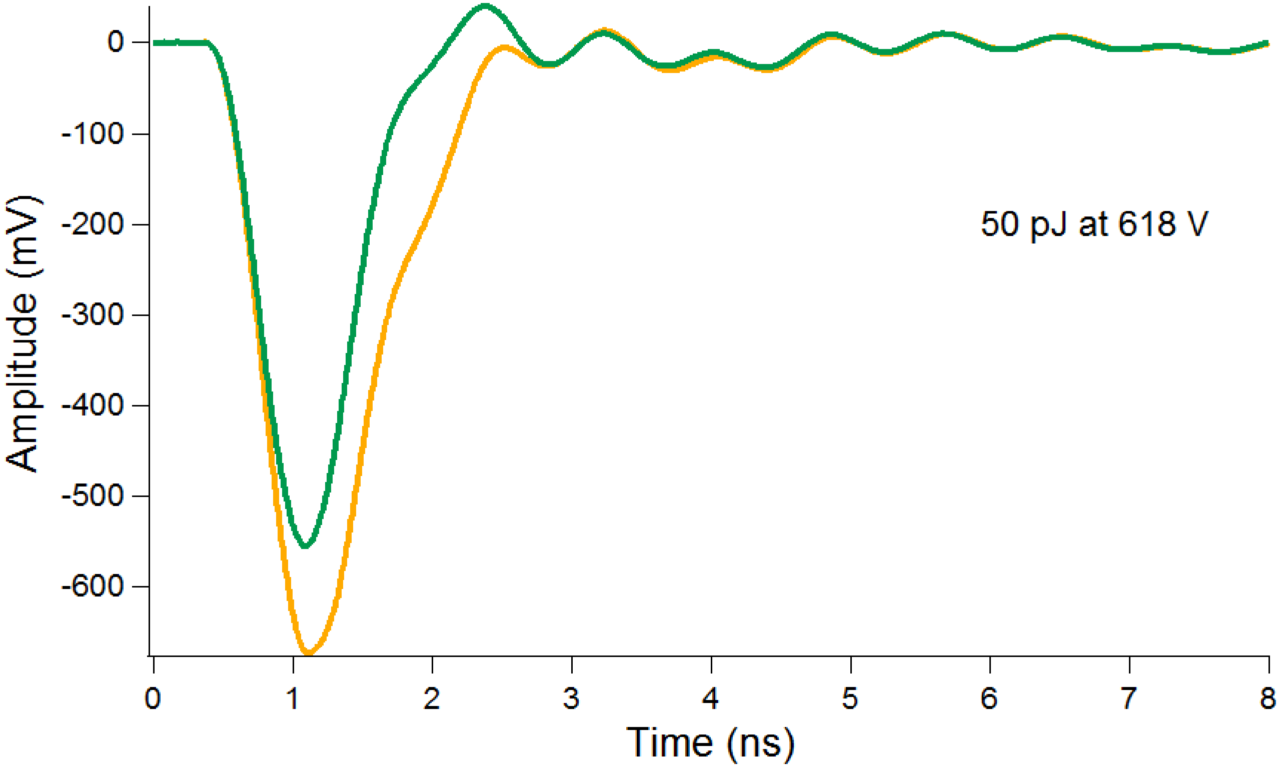


Stability threshold

Stability threshold was found <u>**as pulse energy/bias conditions**</u> when **the signal started slightly jumping at the constant laser power.**
In spite of clear instabilities in the signal, the leak current was stable at the same time (at least with our 0.1 µA accuracy).

LGAD 1.5e15n_{eq}/cm^2

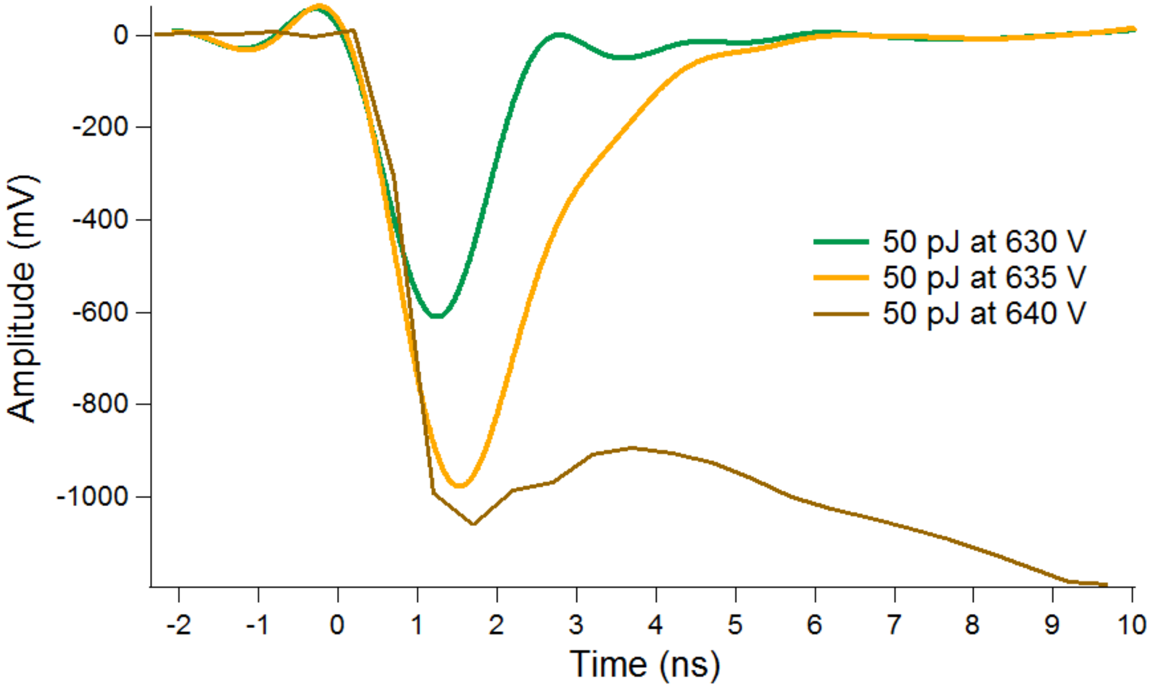
Example of two waveforms measured at the constant laser power and constant bias at two different moments (amplitude and width vary)



Unstable region

Several volts above stability threshold the signal starts varying significantly.
At the same time also small instabilities in the leak current are observed.

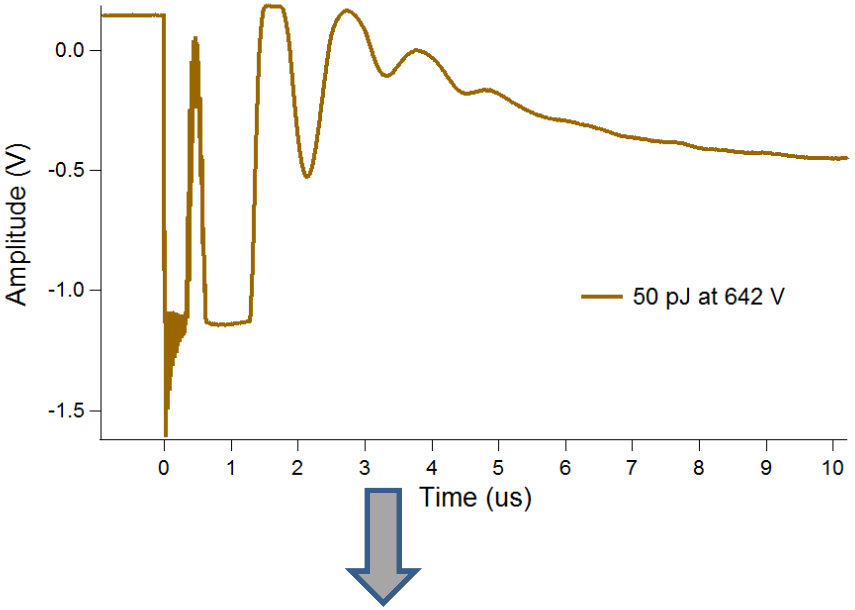
Example of waveforms corresponding to unstable region for LGAD 1.5e15n$_{eq}$/cm^2

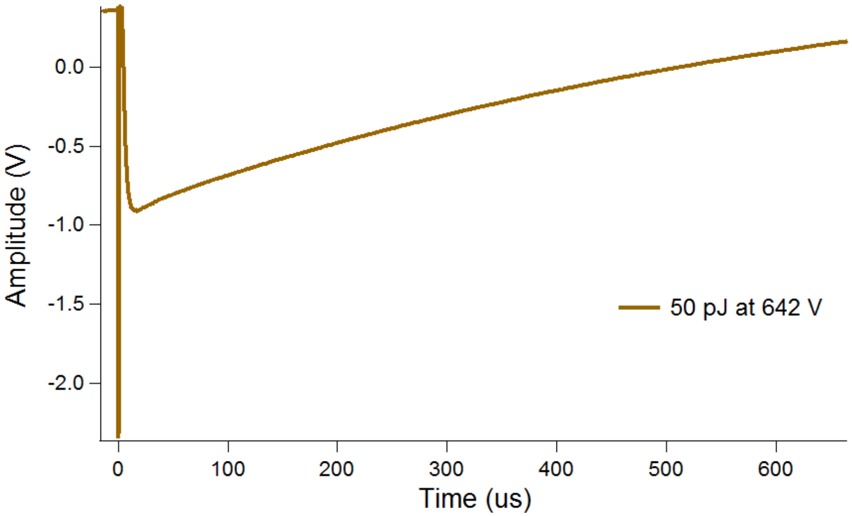


Very unstable region

Further increase of bias results in completely deformed **signal waveforms extending to hundredths of microseconds**. The leak current jumps very rapidly and it shows that we are close to damage threshold.

Example of waveforms corresponding to very unstable region for LGAD 1.5e15 n_{eq}/cm^2
(it's not the one where LGAD went into irreversible breakdown)





- ☐ Sensor not yet irreversible damaged, but next to it
- ☐ Instability is not yet destructive, still reversable
- ☐ Energy imported by laser and el field is such that sensor become unstable but not destroyed yet
- ☐ If HV bias is reduced, for instance by 5V, the sensor would be stable again (tested experimentally and confirmed)

Q: When the sensors died, were they shorted – what is the current drawn?

- ☐ The waveforms recorded at 642V and 50 pJ represent the **signal just before irreversible breakdown** occurred. They are the last waveforms recorded for this sensor. The amplitude and shape of the waveform is very unstable in such condition. The current is also very jumpy and varies between 10 and 70 µA. Since we know from experience that such signal means that we are close to breakdown and amplitude jumps to several Volts we disconnected the scope (for safety) and increased the bias by 1 V observing the current only. At 645V the system broke down.

- ☐ Thus, it's hard to say what was exactly current drawn at that moment. This is very rapid increase and we don't have yet any solution how to record exact value. One thing we can say is that the current drawn is in region 10s of µA when the sensor is close to damage threshold. Of course this conclusion is valid at temperature -25 C.

Remark: **when instability occurs and LGAD experiences sequence of reversable breakdowns, if the HV bias is reduced by a few Volts It is possible to bring LGAD back to the fully operational and stable conditions (experimentally confirmed). Such control over instability (switching from the reverse breakdown to the working LGAD conditions or accelerating the irreversible breakdown by increasing the HV bias by a few Volts) is advantage of fs-laser beam tests.**

Summery: Stability and damage thresholds for 1.5e15 and 2.5e15 samples

E (pJ)	W36 LGAD 1.5e15		W36 LGAD 2.5e15		W36 PIN 1.5e15		W36 PIN 2.5e15	
	Stability threshold (V)	Damage threshold (V)	Stability threshold (V)	Damage threshold (V)	Stability threshold (V)	Damage threshold (V)	Stability threshold (V)	Damage threshold (V)
1	> 670		> 670		> 670		> 670	
5	> 670		> 670		> 670		> 670	
10	> 670		> 670	**750**	> 670		> 670	
15	> 670		> 670		> 670		> 670	
20	> 670		> 670		> 670		> 670	
25	> 670		> 670		> 670		> 670	
30	650		644		652		645	
35	643		635		645		639	
40	635		628		640		629	
45	625		617		631		621	
50	618	**645**	608	**697**	622	**671**	610	**730**

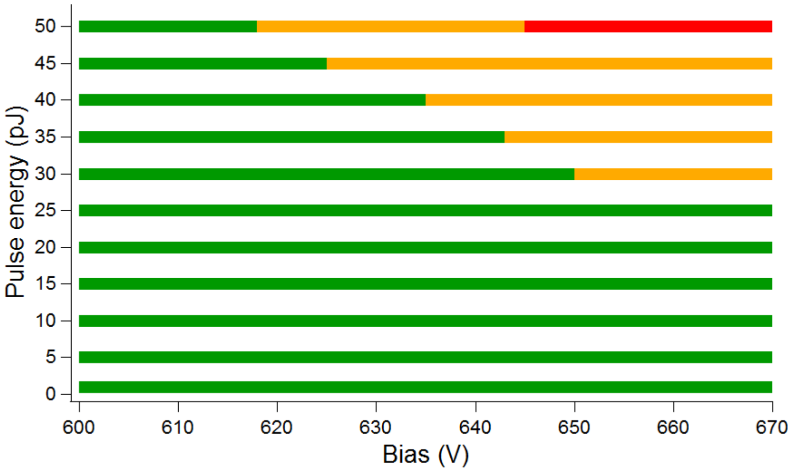
In case of stability threshold, the value is a bit arbitrary (it's a bit subjective feeling if the signal is already unstable) and the uncertainty of this value could be estimated as +/- 5V.

In case of damage threshold, the situation seems to be more defined because we have breakdown at the certain conditions. However, it seems that it depends on the bias ramp up rate so I would also estimate uncertainty as +/- 5 V

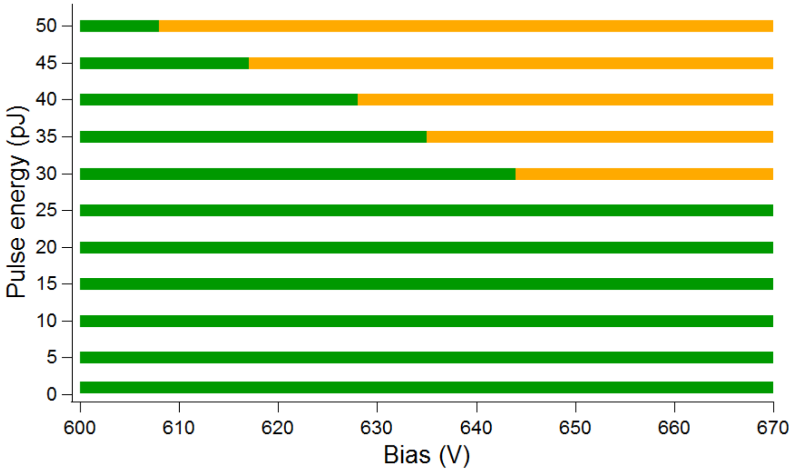
Extra damage for LGAD 2.5e15 at 10 nW was unintentionally caused by mistake. However, this is also extra point on our map.

Summery: Pulse energy - Bias plots presenting "safe operation“ region below 50 pJ and 670 V

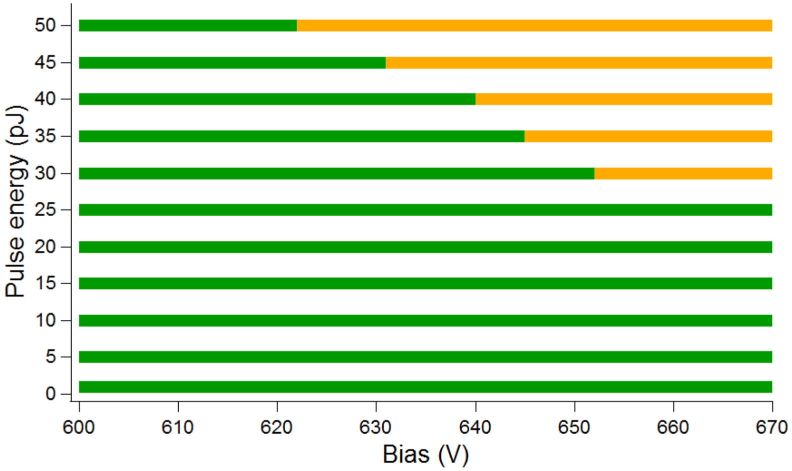
LGAD 1.5e15



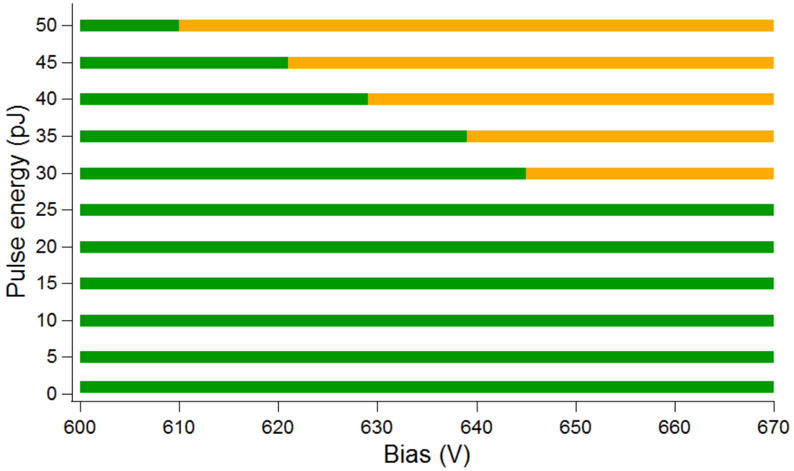
LGAD 2.5e15



PIN 1.5e15

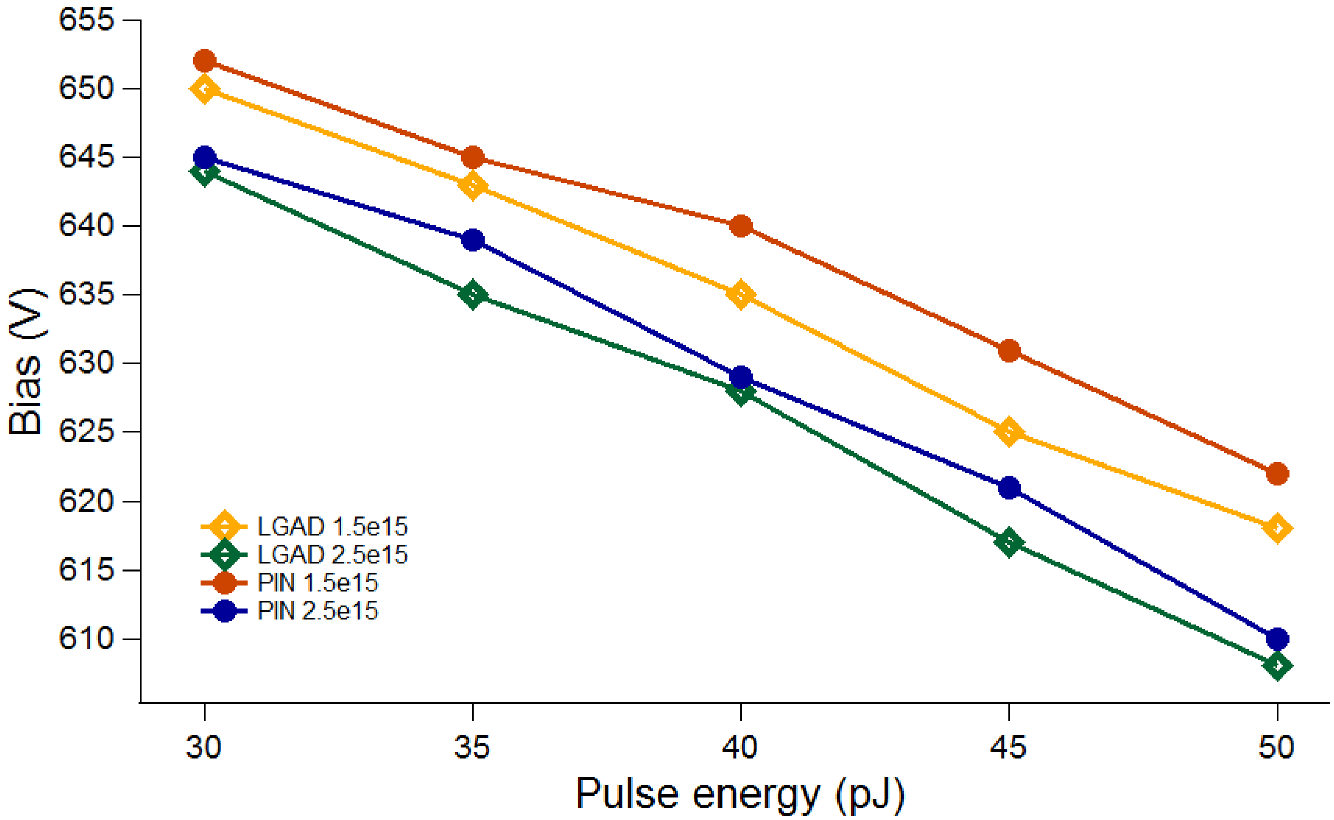


PIN 2.5e15



🟩 Stable region
🟧 Unstable region
🟥 Damage region

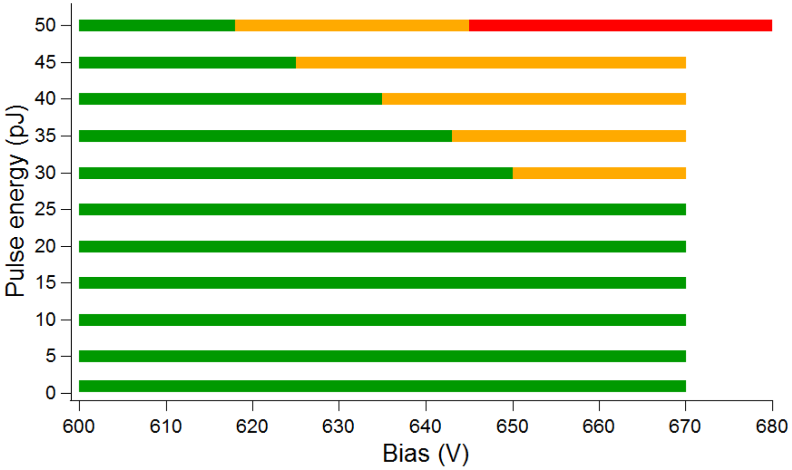
Summery: Stability threshold vs pulse energy



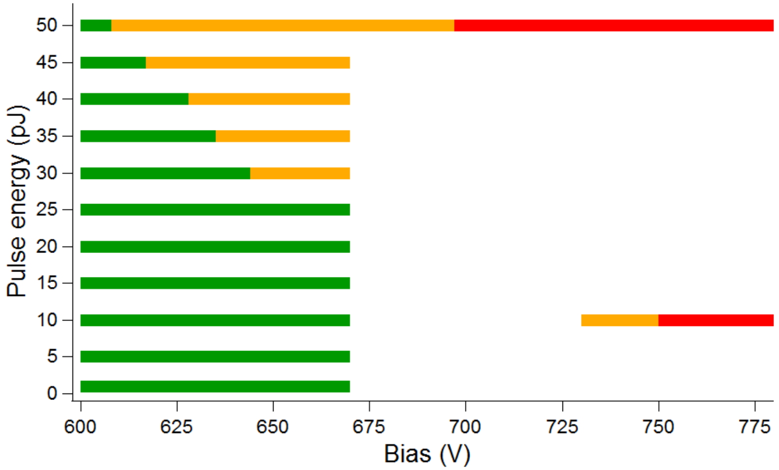
The stability/instability boarder seems to be very similar for all the samples.

Extended version with damage thresholds

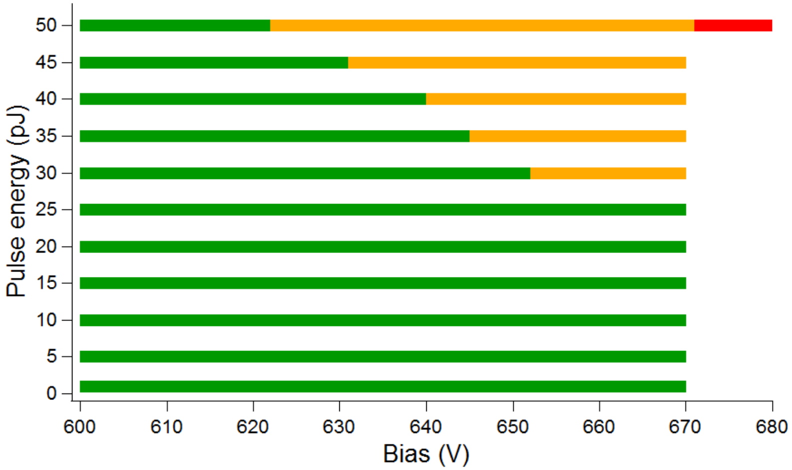
LGAD 1.5e15



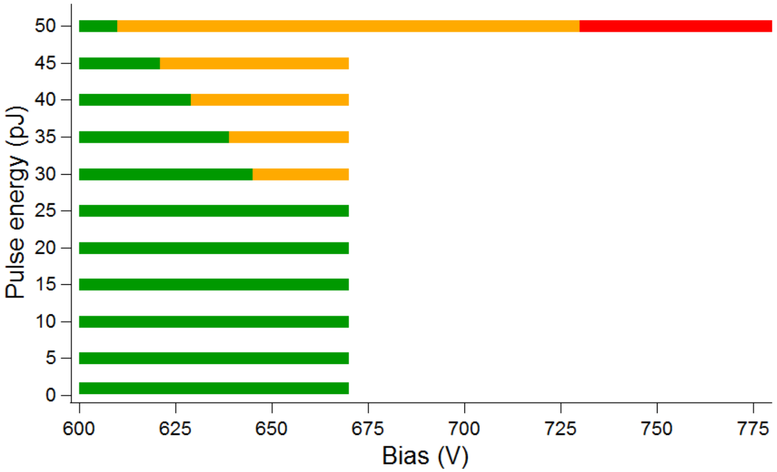
LGAD 2.5e15



PIN 1.5e15



PIN 2.5e15



No mitigation needed for 1.5e15 neq/cm2

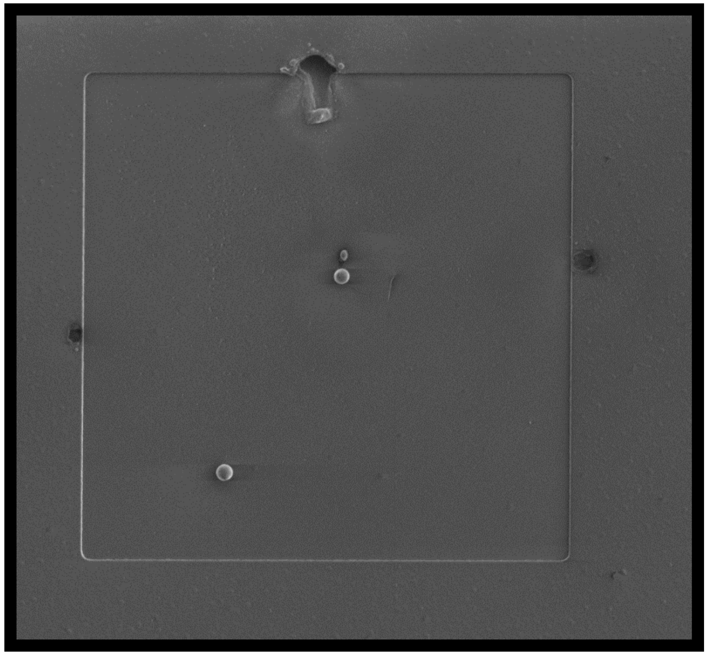
🟩 Stable region
🟧 Unstable region
🟥 Damage region

Risk mitigation for 2.5e15 neq/cm2

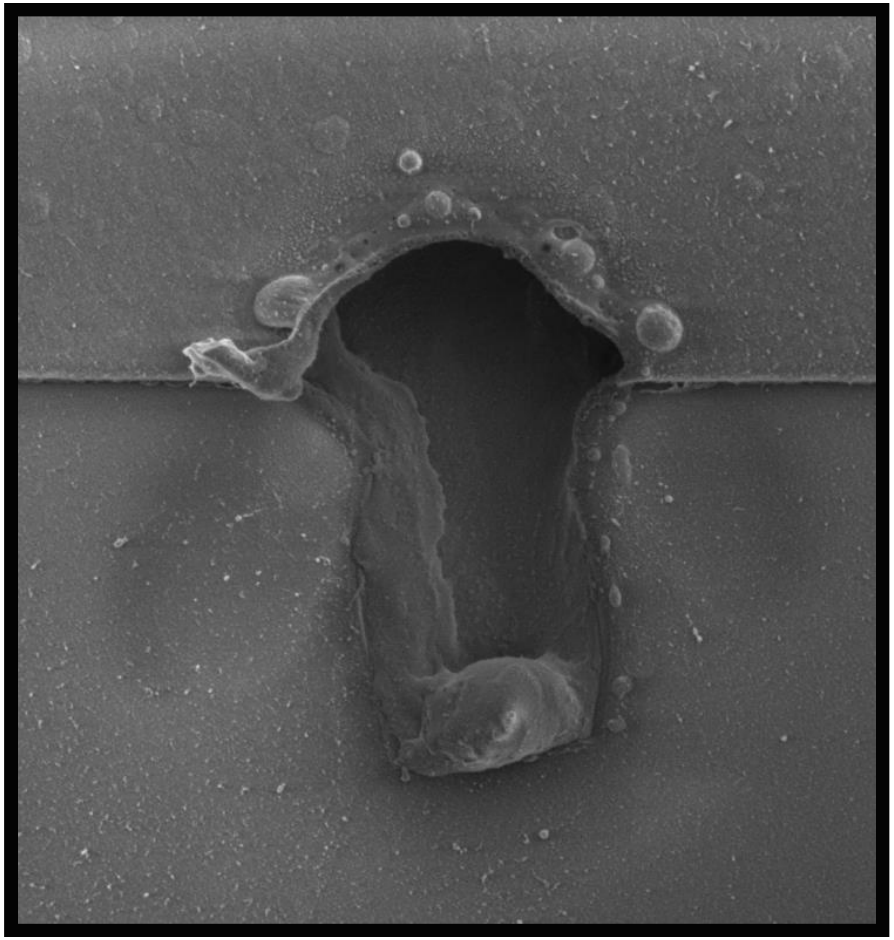
Implication for proton beams: one proton can cause such huge deposition that breakdown sensor irreversibly.

Mortality study: electron microscope images

LGAD 2.5e15



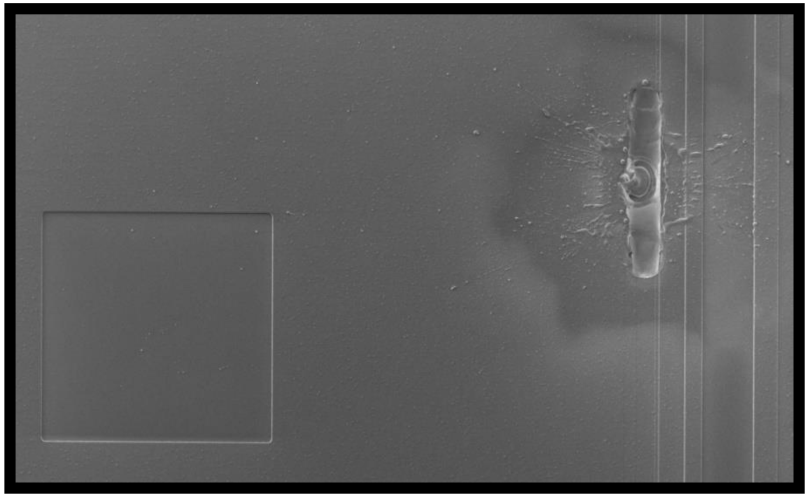
Damaged by SPA: 50 pJ, 692 V

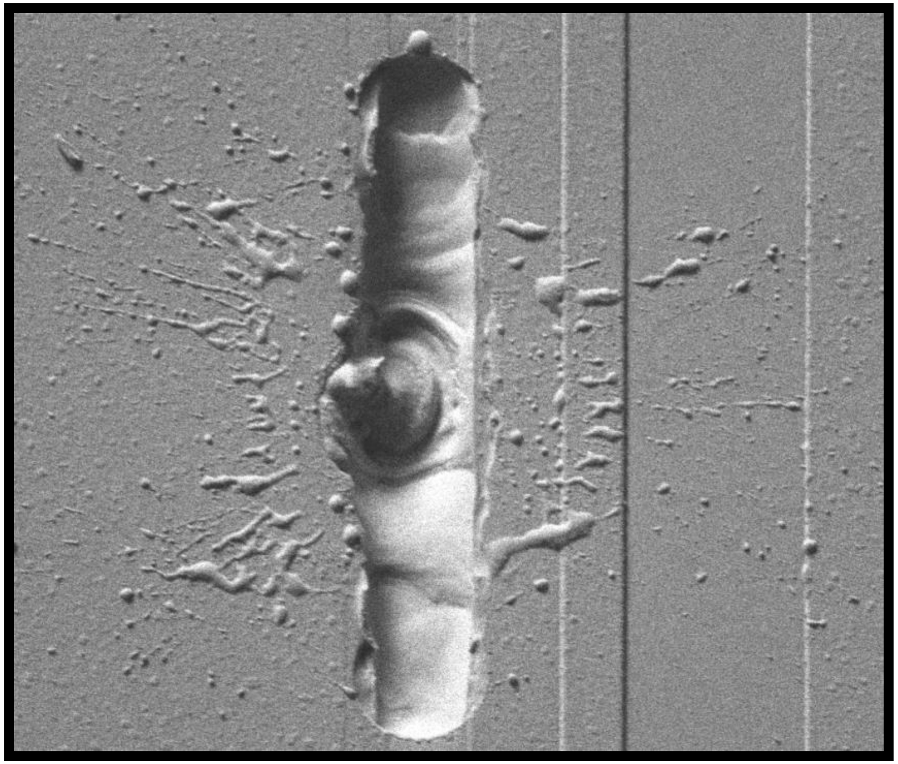


Mortality study: electron microscope images

LGAD 2.5e15

Damaged by SPA: 10 pJ, 750 V



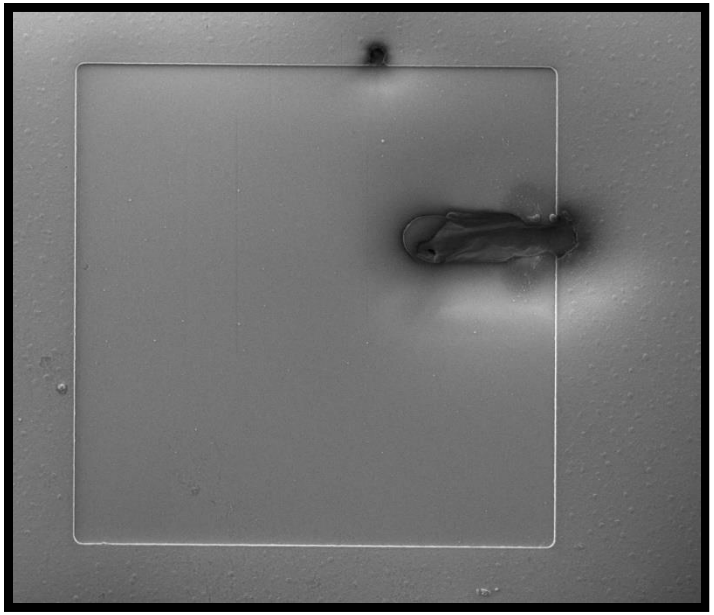


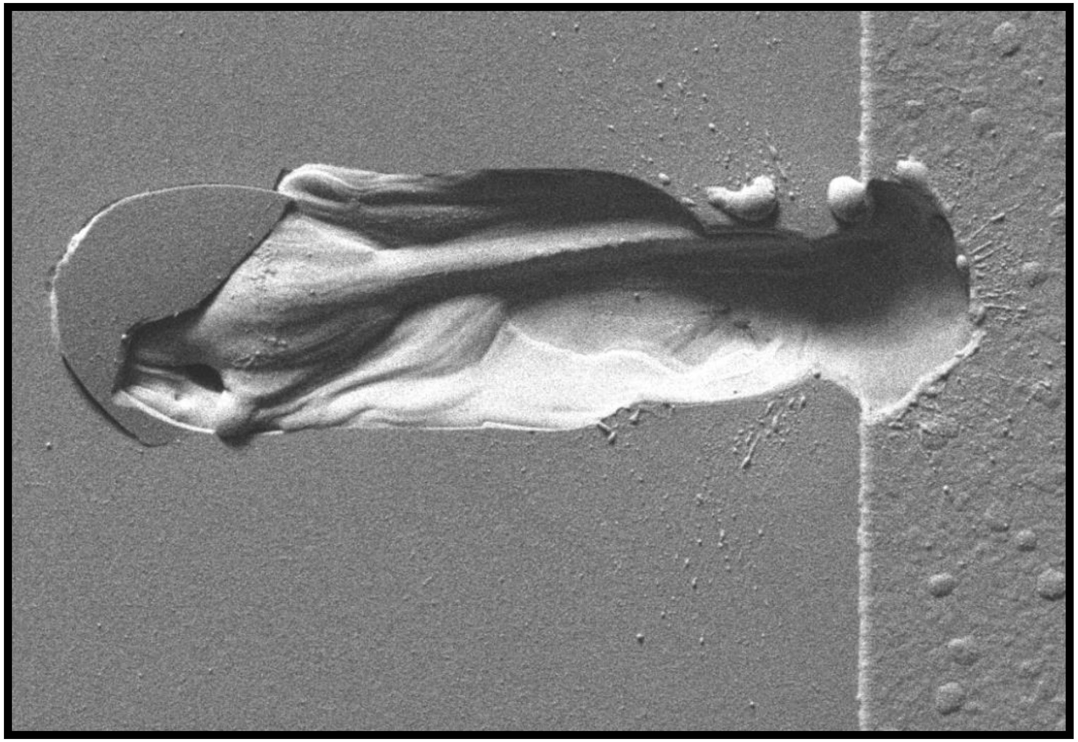
This damage was unintentional. High voltage was applid by mistake. However it resulted in new type of damage. In other cases we observe mostly damage on the pad boarder. Here it happened completely out of the pad.

Mortality study: electron microscope images

LGAD 1.5e15

Damaged by SPA: 50 pJ, 625 V

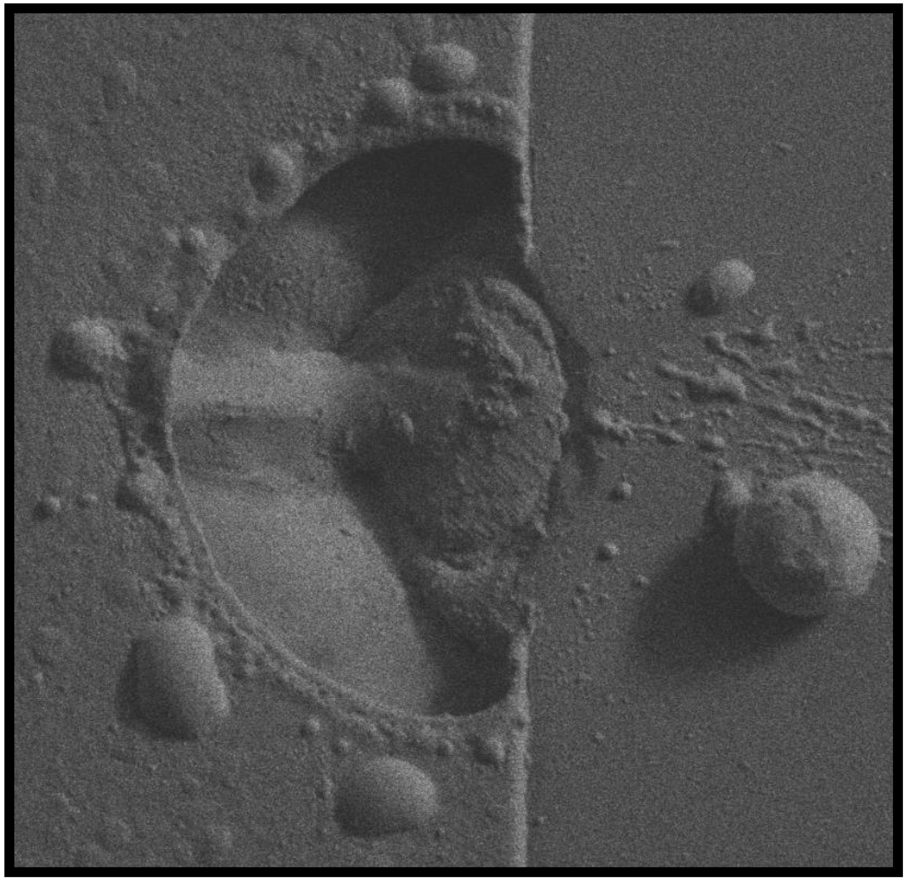


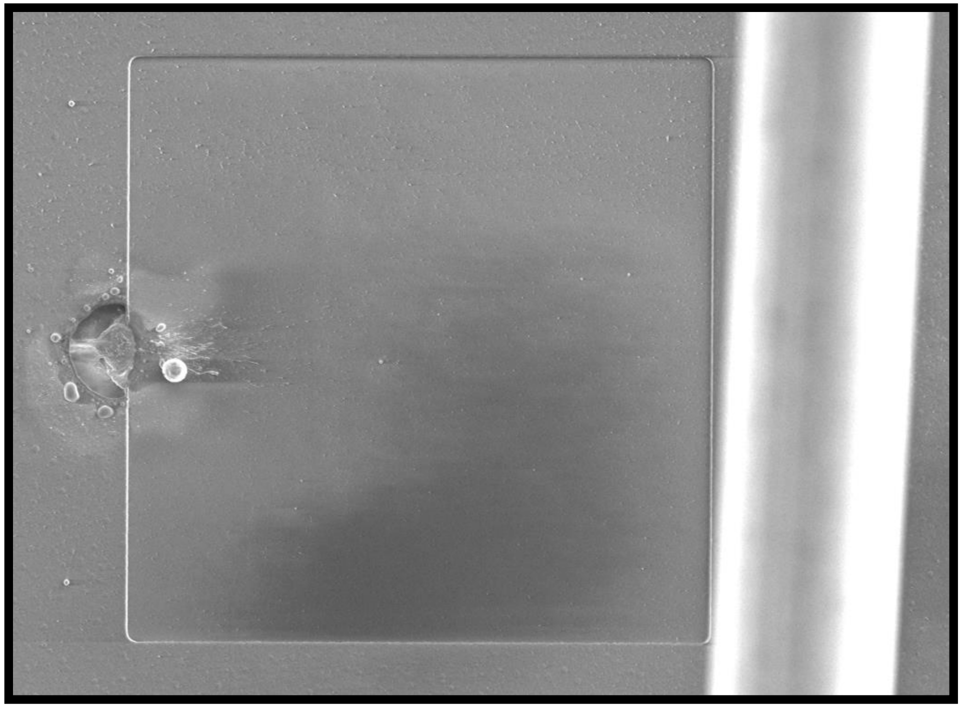


Mortality study: electron microscope images (IV)

PIN 2.5e15

Damaged by SPA: 50 pJ, 730 V





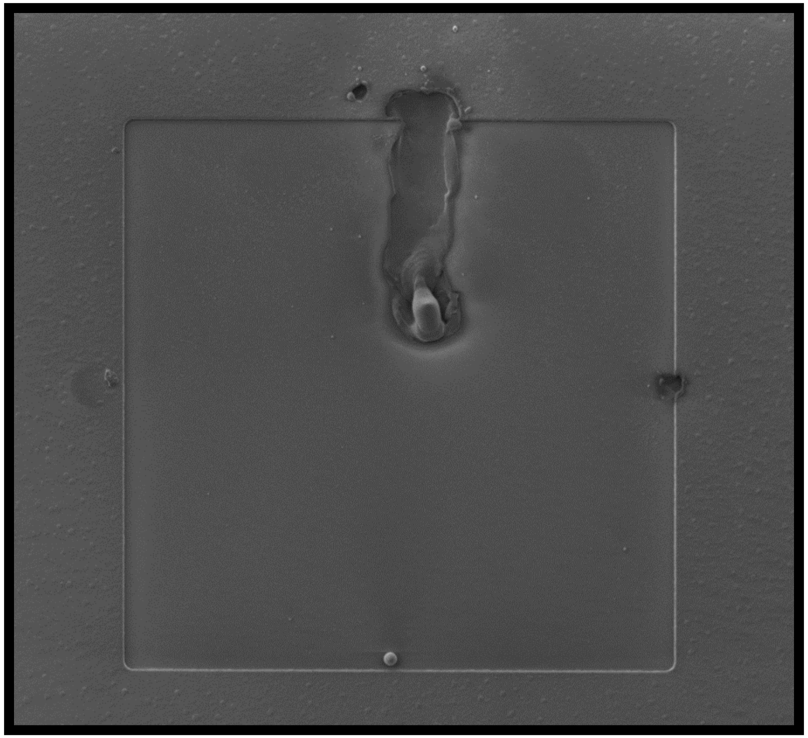
Edge effect: metal-semiconductor

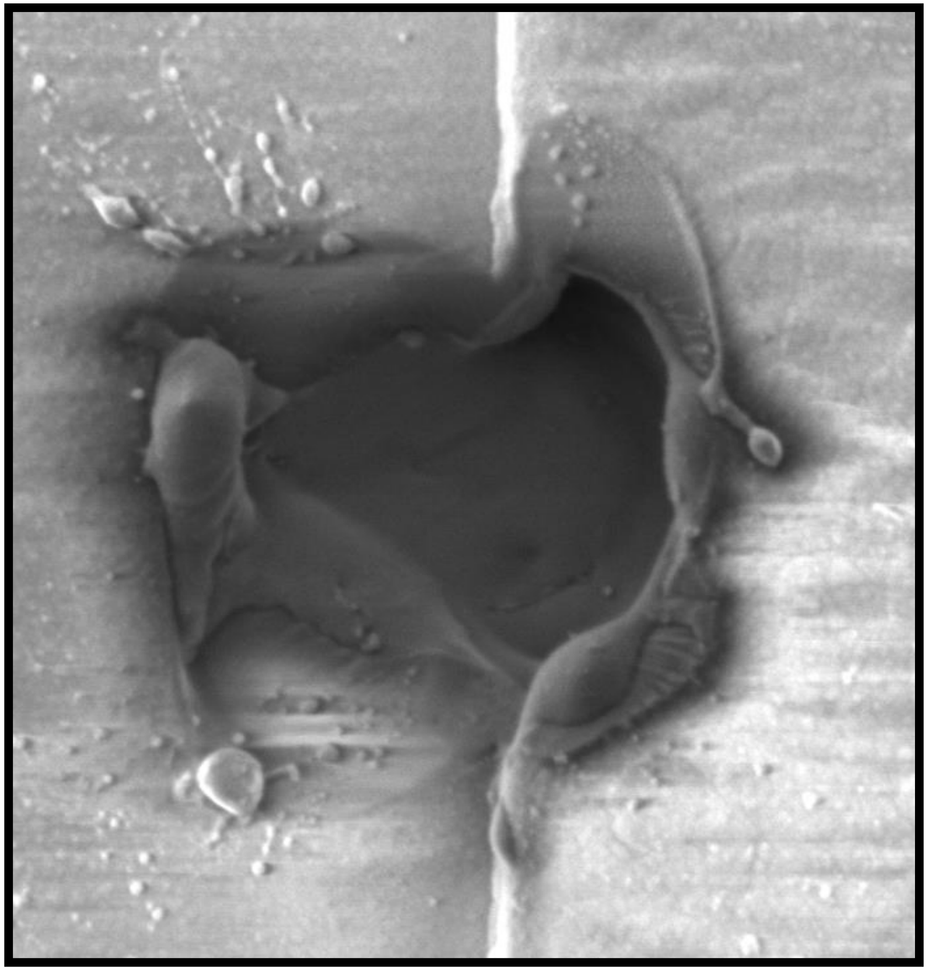
The energy for the crater (seen in proton-beam tests) comes from the filtering capacitors.

Mortality study: electron microscope images (V)

PIN 1.5e15

Damaged by SPA: 50 pJ, 671 V





Conclusion

- The second successful test beam campaign finished last week at ELI (Czech) (May 15 – June 10)
- Focused on mortality of highly irradiated sensors at high voltage
- Lack of HV capacitance deaccelerates death and decreases severity of death events (no crater rupture observed)
- Damage appearance preference: at pad edge
- Both ELI Mortality campaigns significantly improved understanding of LGAD’s death mechanism
  - Irreversible breakdowns are unrelated to gain; LGADs and PINs suffer the same.
  - Irreversible breakdowns are also radiation damage unrelated and not fluency dependent; there is HV and laser power dependance.
  - link to the fluences is only because irradiations enables sensors to be biased at higher HV; (HV >580 V); this leads to the higher el field that LGAD can not sustain.
  - the reason for fatalities is the high field (voltage)
  - In DESY studies death was exacerbated by energy stored in HV capacitance
  - Crater signature not observed in ELI mortality study since capacitor was not mounted to sensors' household (housings provided by IJS).
- Further, we manage successfully to define the stability and damage thresholds for 1.5e15 and 2.5e15n_{eq}/cm^2 HPK (WF36) samples;
- Safe operating voltage regime is also established for HPK-P2 WF36 and “threshold charge” at given voltage that leads to destruction of the sensor was defined too.
- Bottom line: 50-micron HPK-WF35 sensors seem quite safe with HV bias < 600 V.
- **We show that fs-laser based study has advantages over the proton beam tests, since it is possible to monitor the sensor’s instability. The sensor’s instability perhaps presents the reversable breakdowns. This can not be done with proton beam tests.**
- LGAD with a C-enriched gain layer would be an interested option to be further investigated.
- …

Electric field must be kept below critical point
LGAD 2.5e15neq/cm2 must be underbiased

Thank you ☺

Femtosecond studies of single event effects in thin LGADs at ELI Beamline
16th (Virtual) "**Trento**" **Workshop** on Advanced Silicon Radiation Detectors. 16-18 February 2021 FBK
https//indico.cern.ch/event/1010494/contributions/4240495/attachments/2193680/3708234/Mortality%20study%20W36%20LGADs_GordanaMedin.pdf

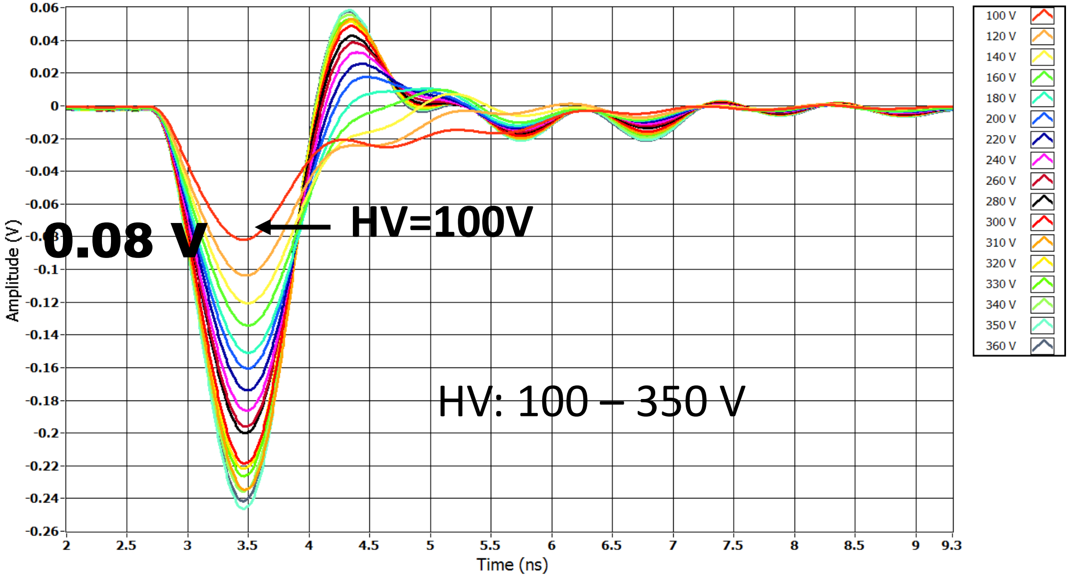
An update report on the upgrade of the TCT - TPA/SPA experimental station at the ELI Beamlines facility
36th RD50 Workshop, Nov 18-20,2020
https//indico.cern.ch/event/896954/contributions/4106493/attachments/2146181/3621008/TCT%20setup%20at%20ELI%20Beamlines-GM.pdf

Special thanks to Mateusz Rebraz from ELI Beamlines.

BACKUP SLIDES

Reminder: TCT signals (shown on the 37th RD50 workshop)

LGAD WF36, 4e14 n_{eq}/cm^2
P_{laser}=10 nW (10pJ)



0.08 V ← **HV=100V**

HV: 100 – 350 V

Generated Ne-h

1. Calculation from signal recorded on the diode at 10 nW

$$N_{e-h} = \frac{1}{e_0 R}\int_0^{5\ ns} V_{sig}(t)dt$$
$$N_{e-h} \sim \frac{1}{1.6e-19\ As\ 50\Omega} 0.08\ V\ \cdot 1ns \sim 10^7\ e-h$$

2. Calculation from the beam parameters at 10 nW

$$E_{pulse} = \frac{P}{\nu}$$
$$N_{e-h} = \frac{E_{pulse}}{e_0} \cdot Q_E\ \cdot R_{e-h}$$
$$N_{e-h} = \frac{10nW}{1000s} \cdot 0.5\ \cdot 1\ \cdot \frac{R_{e-h}}{1.6e-19\ As} = R_{e-h}\ \cdot 6.2\ \cdot 10^7\ e-h$$

3. A factor of 6 difference implies to large recombination possible. Recombination rate R is very much affected by the irradiation on. In order of both calculations to agree R has to be 1/6

4. The equivalent lost charge in the silicon to produce the same signal: $\boxed{\Delta E = N_{e-h}\ 3.62eV = \ \sim 30\ MeV}$

This is of the same order as seen in CMS paper

Ref/CMS paper: Mika Huhtinen, Highly ionising events in silicon detectors, CMS Note, March 2002,