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Critical Electric Field as a Crucial Parameter for Irreversible LGAD Fatalities

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beamlines eli

IJS

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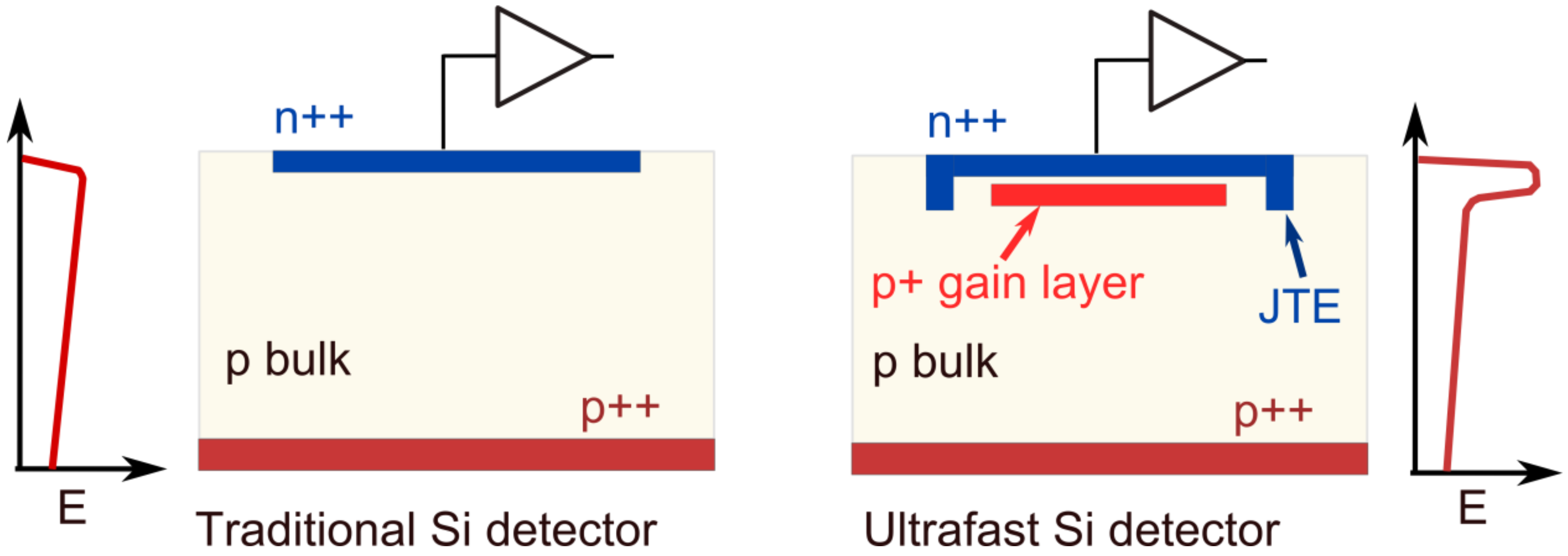
RD50

Outline

- ❑ LGAD
- ❑ Defined problem
- ❑ Hypotheses
- ❑ The way we tested it
- ❑ Experimental setup
- ❑ Results
- ❑ Conclusion

What is LGAD?



Advantages:

- ❑ Excellent timing and spatial resolution
- ❑ Relatively easy to fabricate

Disadvantages:

- ❑ Challenging to operate under stable conditions
- ❑ Gain lost due to acceptor removal mechanism
- ❑ Gain Suppression (dense charge->screening charge effect-> polarisation; beam angle dependence)
- ❑ SEB event (topic of this talk)

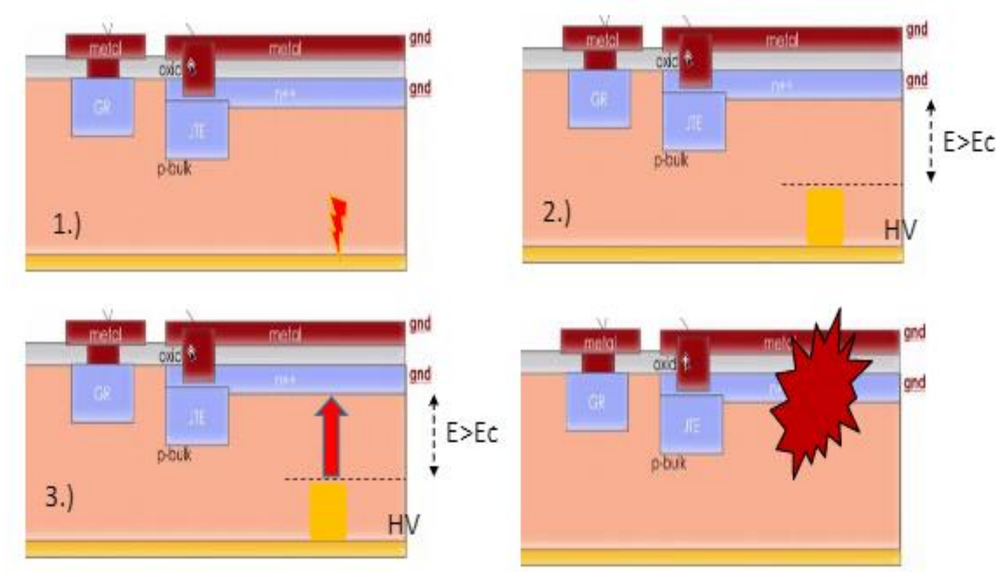
Problem defined: LGAD's Breaking down at high V_{bias}

- Destructive breakdowns appeared mostly in the test beams (TB) – much less in the laboratory setups (Sr90, probe stations)
- Destructive breakdowns (fatalities) appeared at bias voltages that are significantly (50 -100V) lower than those in the lab.
- They appeared suddenly without a clear warning (increase of leakage current, instability in leakage current, changes in gain)
- There are indications that fatalities are beam related and not linked to the environmental conditions
- The assumed reasons for these breakdown:
  - 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?

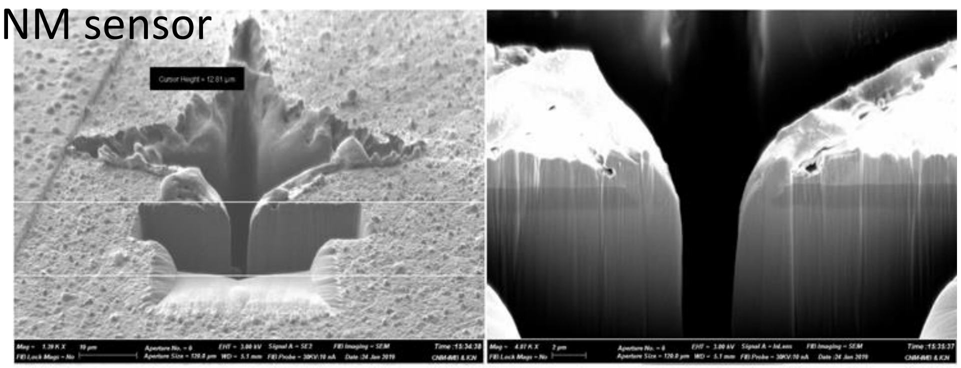
- The main difference between lab (Sr-90 with E_{max}=2.3 MeV) and TB (up to several tens MeV deposits – CMS paper) is the energy of the particles:

The question was can huge amount of charge in a single collision cause a conditions that lead to a destructive breakdown?

A possible explanation



CNM sensor



“courtesy of CNM (ATLAS TB sensor)”

Thanks to CNM for providing the photos of such fatality.

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

The way to test it

➢ Using ultrashort femtosecond, highly intensive and highly repetitive, very focused laser pulses

Justification

- ❑ If the speed of deposition by laser is similar to MIP then the laser test with extremely high energy per pulse in 50 fs should lead to fatalities

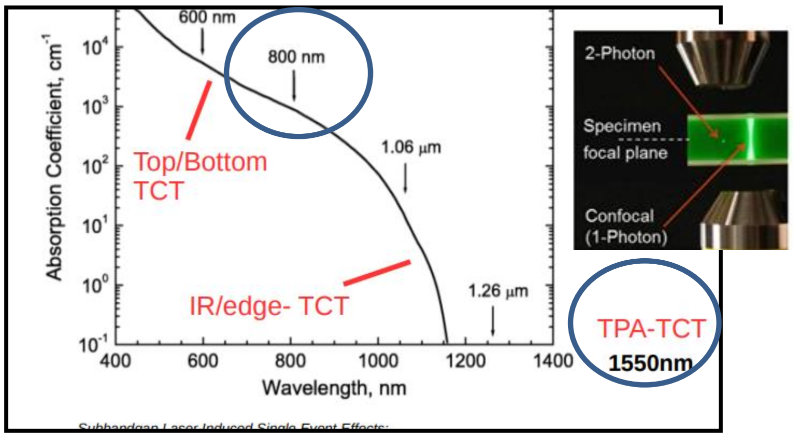
- ❑ If we use

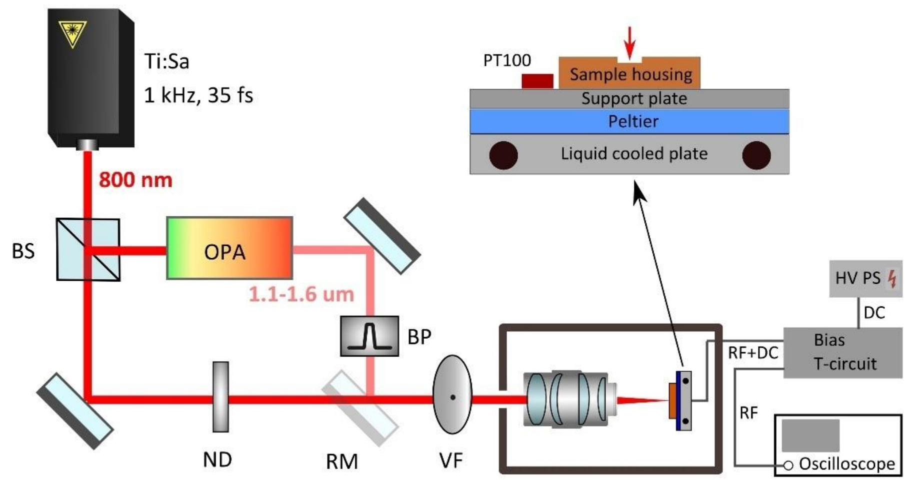
  - ✓ 50 fs laser pulses of 800 nm of wavelength (27 μm of penetration depth);
  - ✓ and of pulse energy up to a 1 mJ.
  - ✓ and if pulses are focused to dimensions similar that of mip deposition (1-2 μm cone)

we might be able to simulate SEB and destroy LGAD!

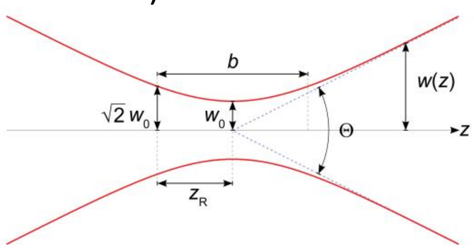
Fs-Laser beam Experimental SETUP

- 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 – beamsplitter, OPA – optical parametric amplifier, BP – bandpass filter, ND – neutral density filter, RM – removable mirror, VF – variable filter).



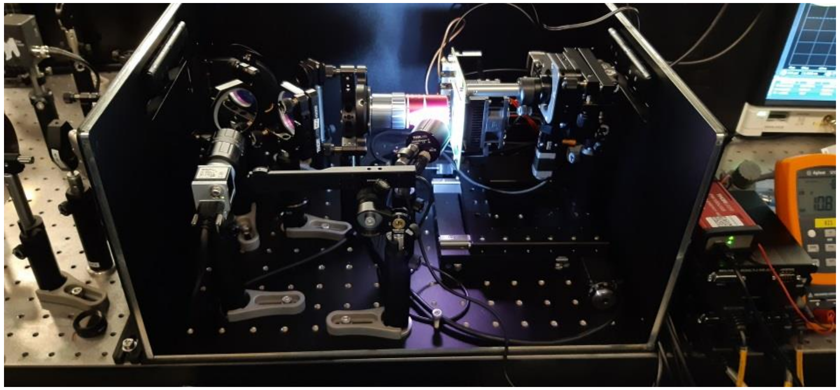
SPA:
$w_0 = 0.85m$
$Z_R = 3.31\mu m$

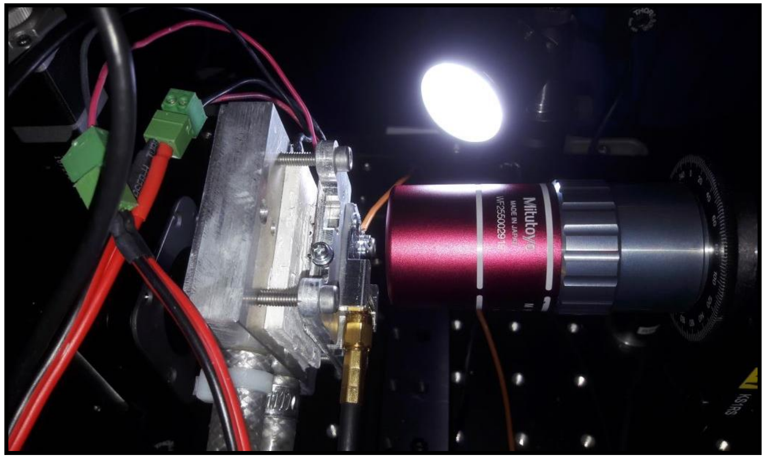
TPA:
$w_0 = 1.52\ \mu m$
$Z_R = 7.74\ \mu m$

ELI Beamlines

Czech Republic
Dolní Břežany (on the outskirts of Prague)

Experimental hall E1
Research program: Bio and Material Applications



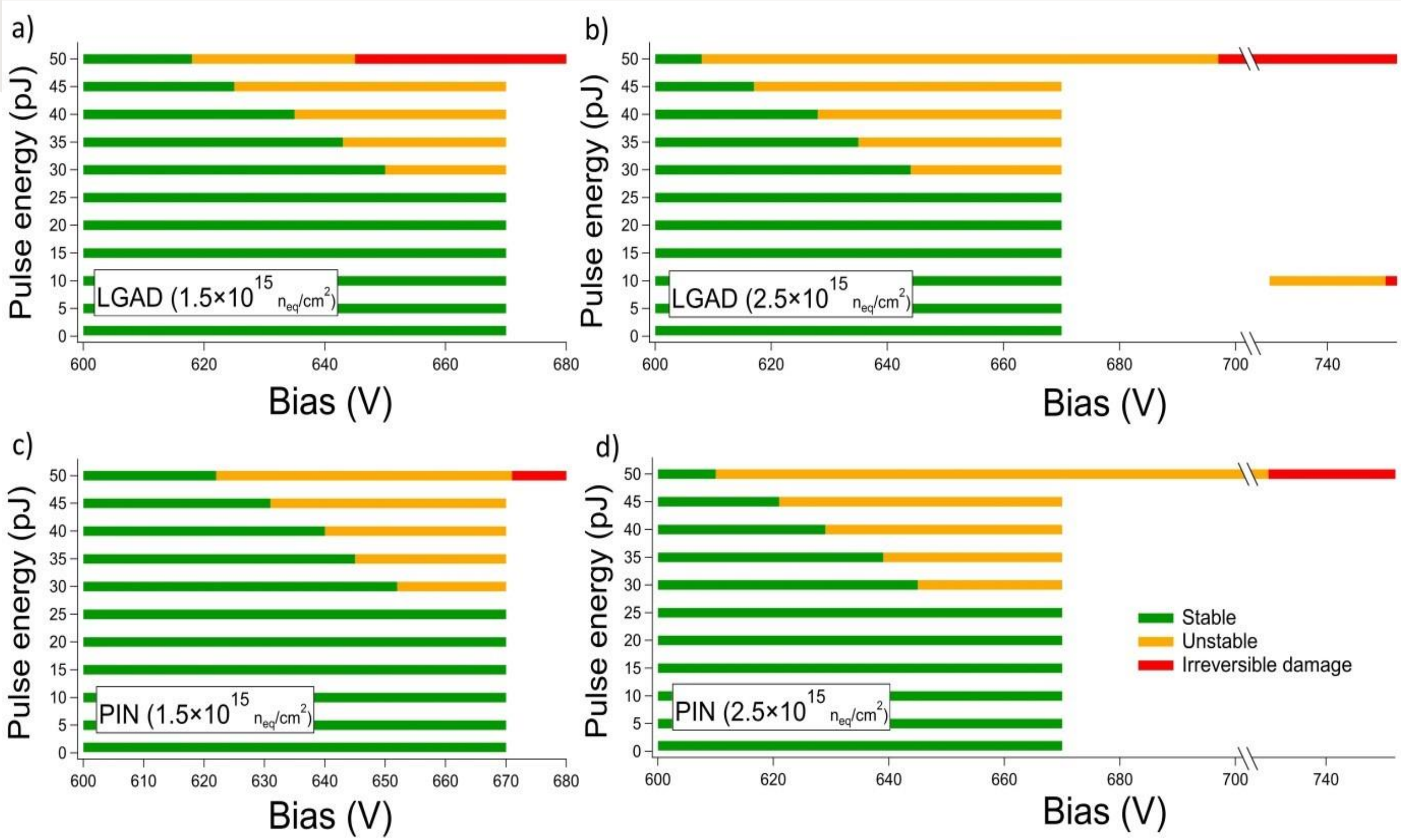


Project supported by: Advanced research using high intensity laser produced photons and particles (ADONIS) Reg. n.: CZ.02.1.01/0.0/0.0/16_019/0000789

RESULTS

Mapping of the Safe, instable and irreversible parameters

Only HPK LGADs W36

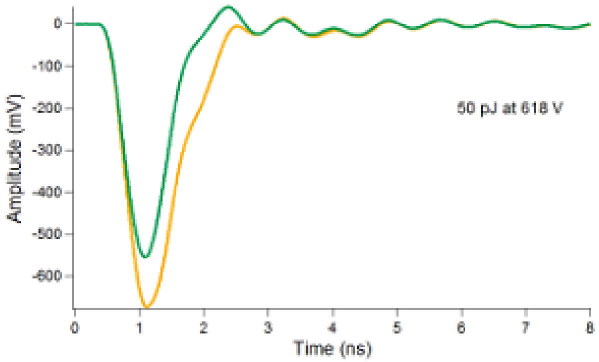


Starting with a low pulse energy of 1 pJ, the bias voltage was slowly increased from 100 V to 670 V (this value was considered safe for the studied sensors based on the experience from the first campaign). The signal waveform was observed and recorded on an oscilloscope. In addition, the leakage current was constantly monitored with an accuracy of 0.1 µA. This procedure was repeated while increasing the laser pulse energy in steps of 5 pJ until reaching 50 pJ.

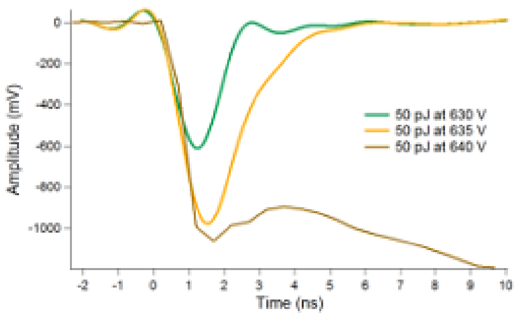
Monitoring the waveform and leakage current

- We managed to set up extremely useful facility to study TCT with 50 fs laser of very high energies.
- HPK-3.2 samples

Stable regime

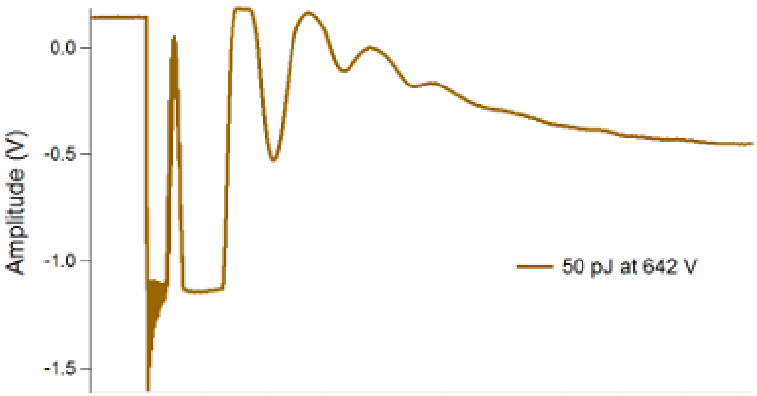


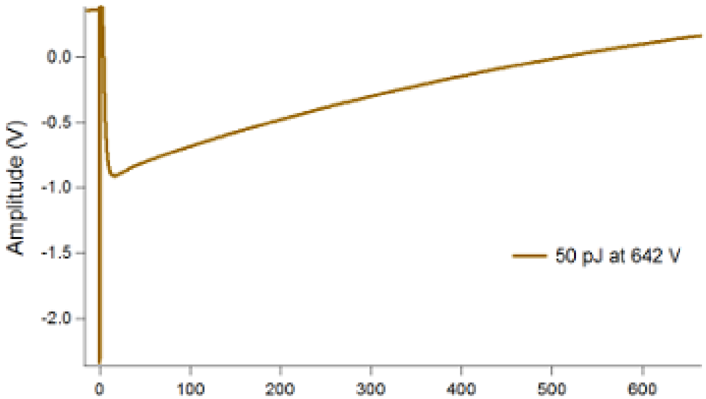
Unstable regime



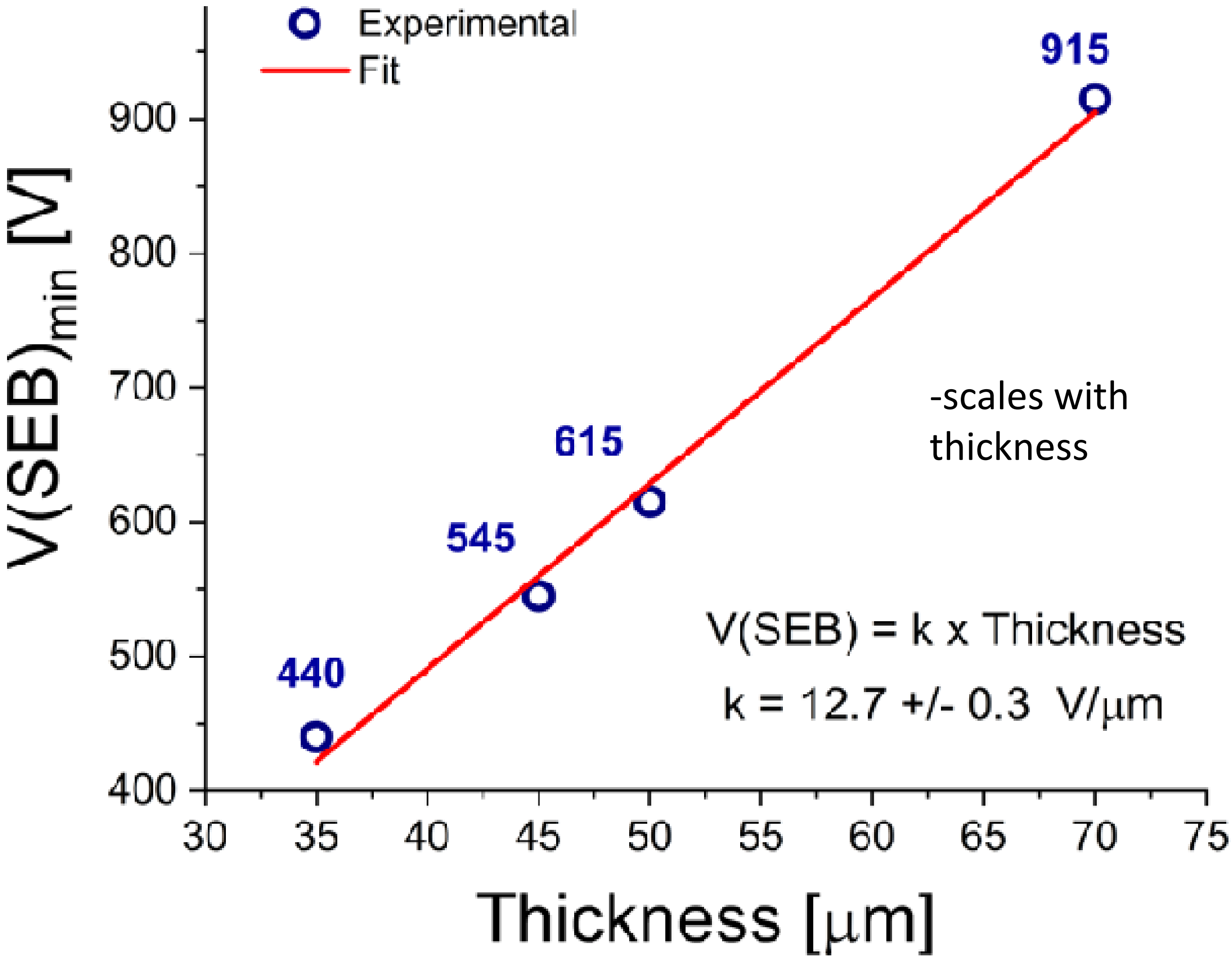
Delicate monitoring: Advantage of tests with laser in comparison to tests with protons

Just before LGAD is permanently broken





Thickness dependence of the SEB bias threshold



LGADs from different vendors (HPK, CNM, FBK) are included

-scales with thickness

WHAT WE KNOW?

WE KNOW HOW TO AVOID SEB
AND WE KNOW HOW LGAD IS RESPONDING TO THE PERPENDICULAR BEAMS ($E_{CRITICAL}$,V(SEB)/DEPTH)

WHAT WE STILL DO NOT KNOW?

THE FULL CHARGE TRANSPORT DYNAMIC MECHANISM UNDER HIGH INJECTION LEVEL & DYNAMICS OF CHARGE COLLECTION EVOLUTION (FROM SEB SEEDING TO LGAD'S MELTING)

Effect of Drift propagation
(only perpendicular illumination was studied)
Effect of diffusion

(I will come back to this slide in outlook)

Trapping
Plasma effect
Space charge modification
Double junction
Increase of gai in bulk
Thermal excitation

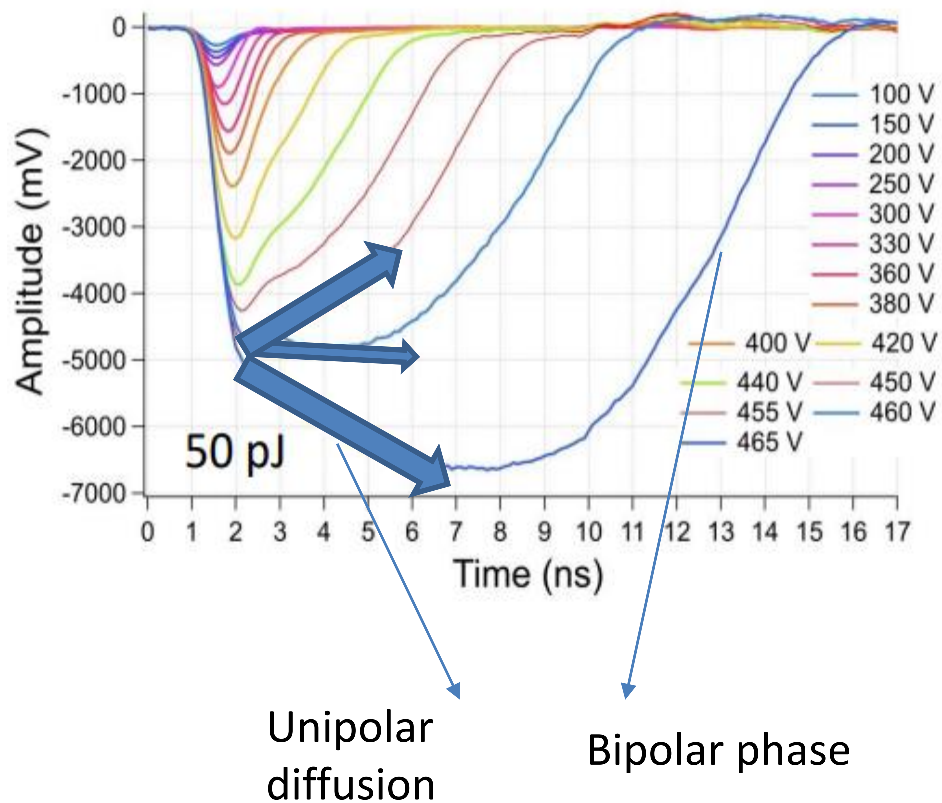
Some insight in next slide

All those phenomena may
-compete or
-collaborate

- A comprehensive explanation has not yet been found due to the complexity of the various phenomena at play.
- Very complex to build the model

Change of gain, plasma effect, modified space charge;

- Here we see the gain rise and the increase of the rise time.
- If the high density of carriers affects the shape of the signal the tails of normalized curves to the highest point should increase with gain.
- The tails should be longer for higher gain and shorter if there is no plasma effect screening of the field in the bulk (plasma).
- These are irradiated samples and an effect of modified space charge due to trapped holes can be seen.
- This seems to be case since the slope of the hole drift are not similar.
- Pulses are very energetic and gain layer screening plays a role as well.

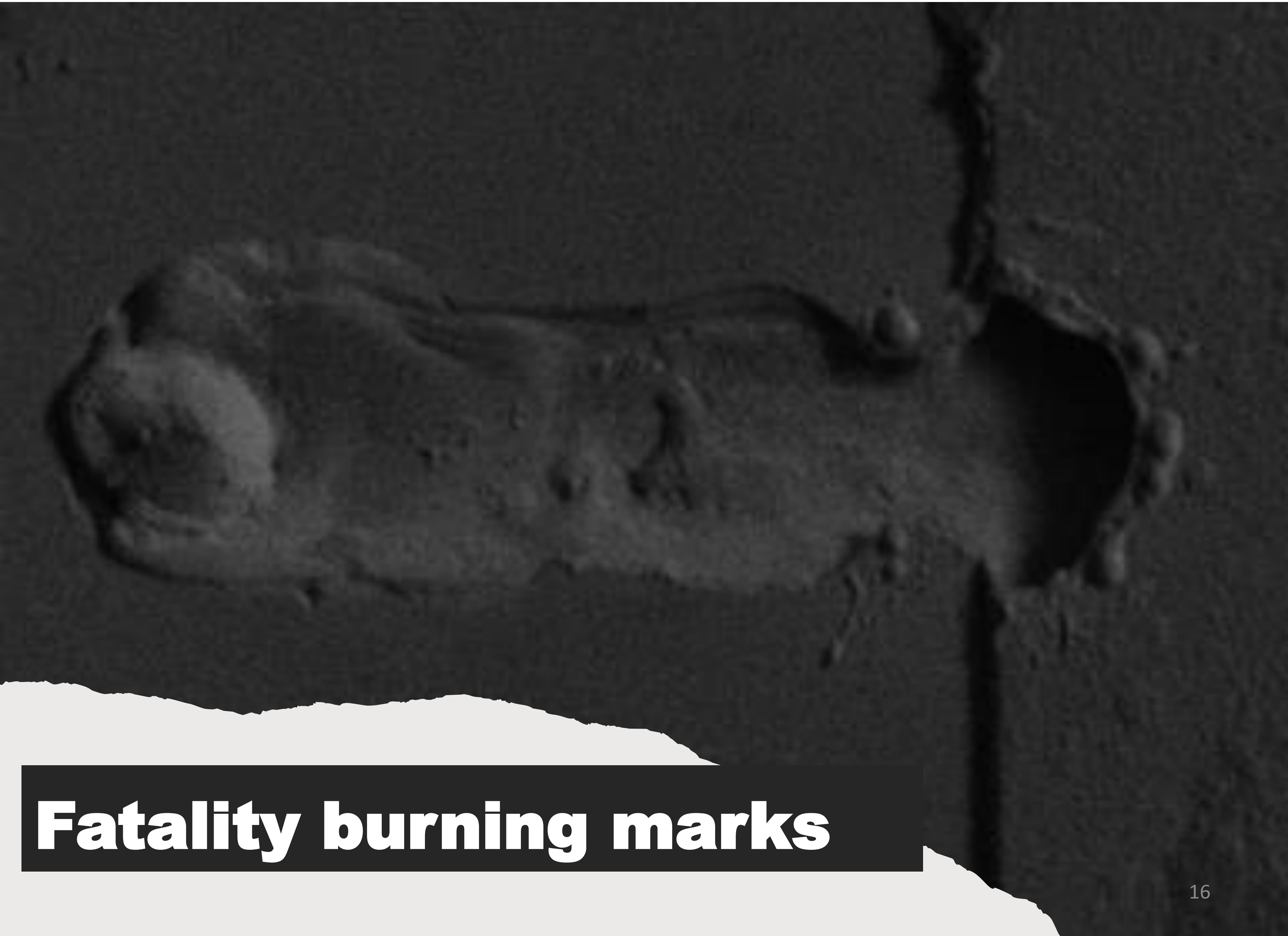


- **All the above mentioned phenomena: change of gain, plasma effect, modified space charge, seen when HV is increased above some turning point and close to irreversible breakdown.**

Double junction effect?

The double junction is a question that it is difficult to answer.

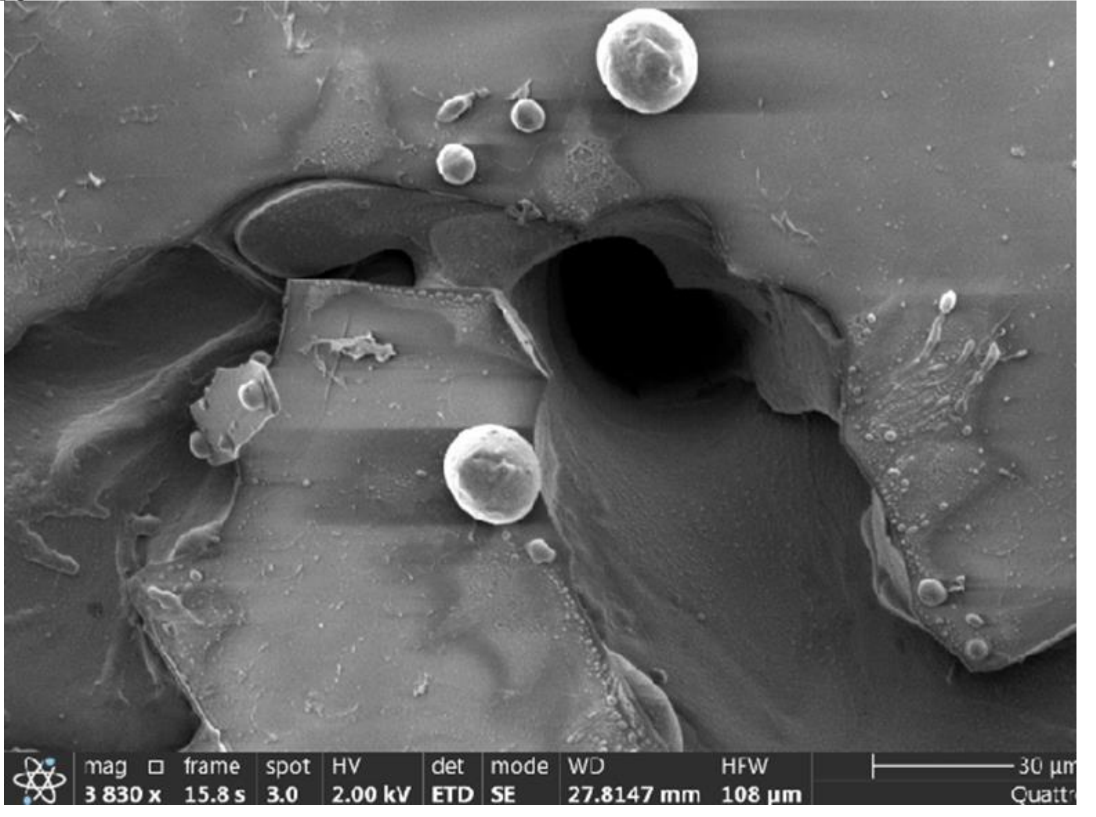
- The steady state hole concertation due to gain is present so there can be some polarization. However it can be extremely large during the drift of the carriers generated by particle.
- The first e-h pairs see different field than the last.
- So, we work now to use laser to simulate all those effects and develop the model.



Fatality burning marks

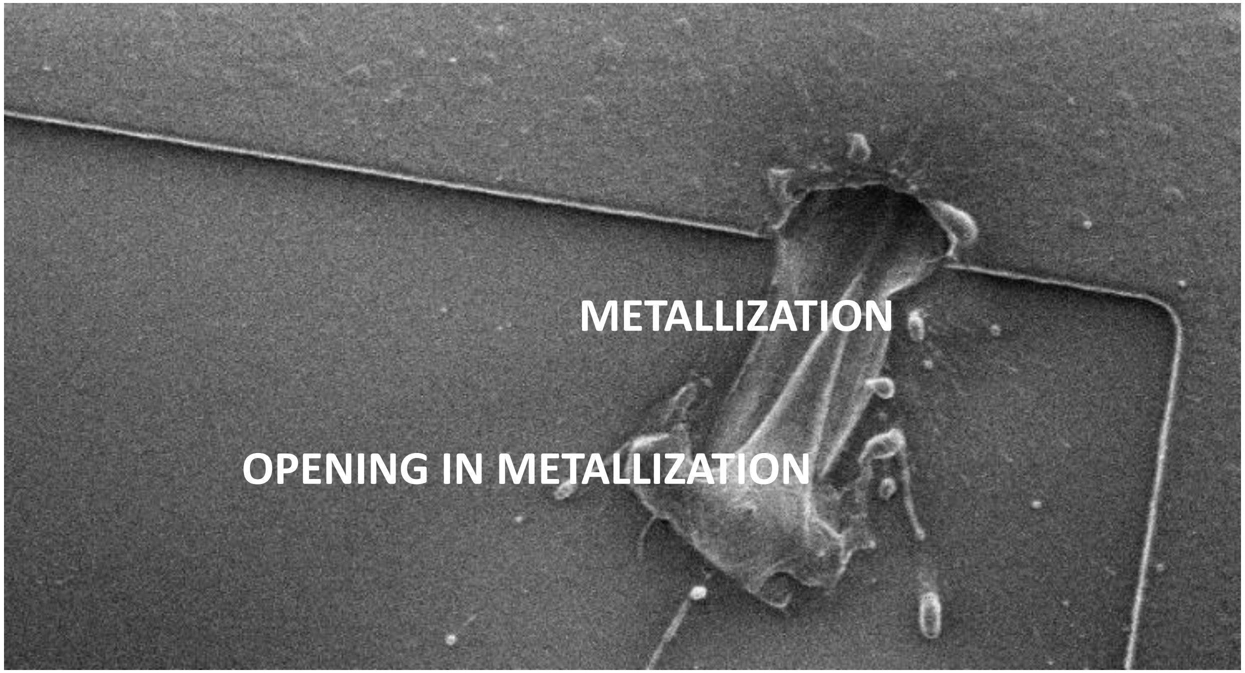
Hamamatsu -HPK

W36 PIN ,2.5e15 cm^{-2}

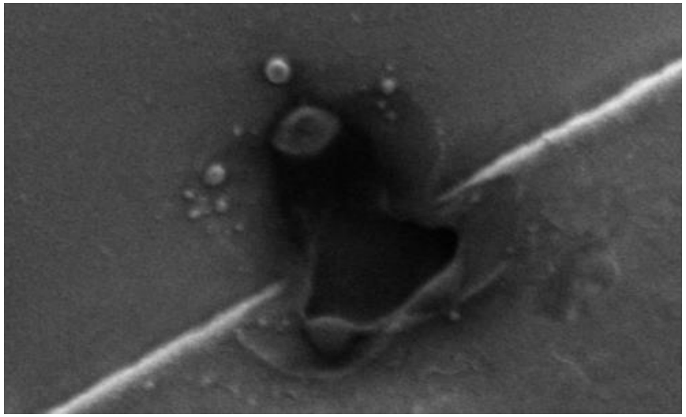


- All sensors exhibit clear crater-like features with a size of a few micrometres;

W36 LGAD, 8e14 cm^{-2}



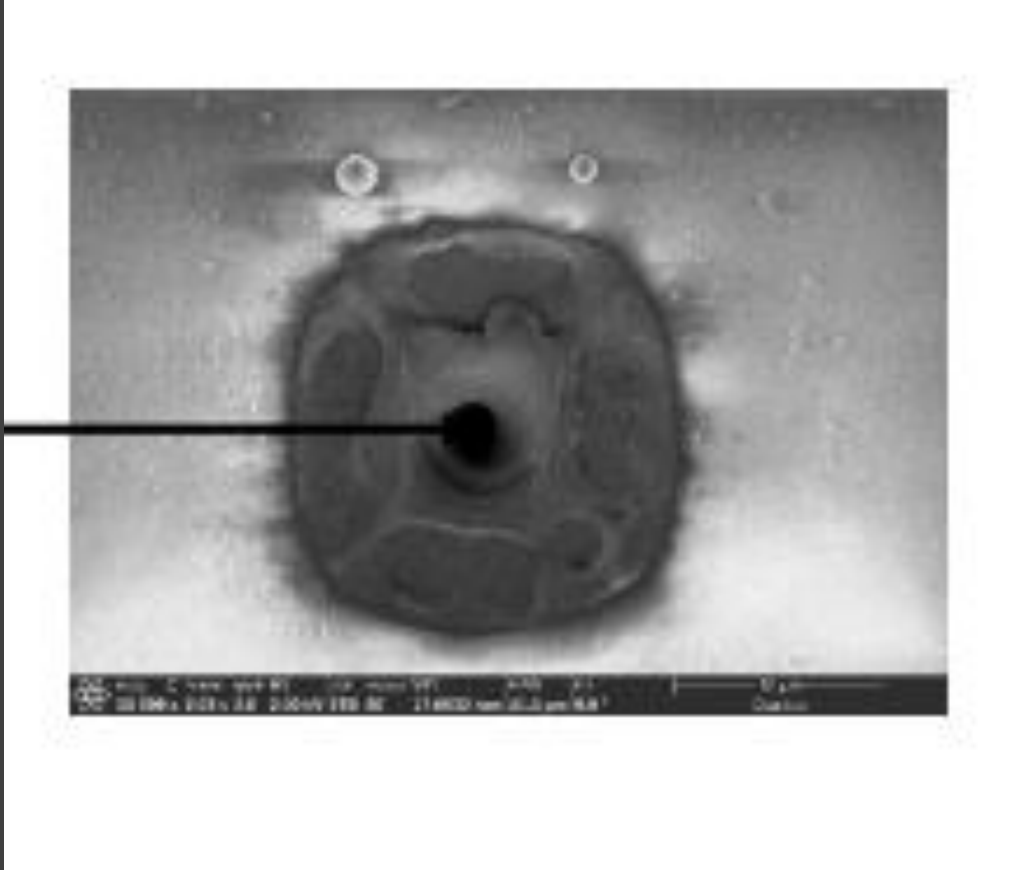
WF36 LGAD 2.5e15 cm^{-2}



- Typically for HPK at the border between metal and semiconductor (although illumination was at the center of the pad)
- A complete understanding of the detailed mechanisms explaining the character and location of the sensor's breakdown require further investigation.

CNM sensor 70 microns

Typical feature for CNM sensors



Can we compare burning mark from the beam test to what is seen in laser tests?

- THE MECHANISM OF DAMAGE TO THE CRYSTAL IS LINKED TO THE CONDUCTIVE PATH FORMED AFTER LASER OR PARTICLE DEPOSITION AND THE CONSEQUENT HEAT RELEASE IN THE DISCHARGE.

- LASER DEPOSITION IS POSSIBLE ONLY IN THE OPTICAL WINDOW WHILE PARTICLES HIT THE DETECTORS UNIFORMLY ACROSS THE SENSOR SURFACE, MOSTLY IN THE METALIZED PART.

- HENCE A DIRECT COMPARISON BETWEEN THE DAMAGES INDUCED BY THE DIFFERENT METHODS IS NOT STRAIGHTFORWARD.

Conclusion

- SEB destructive breakdown has been simulated in LGADs
- In this respect, we do not observe any significant difference between PINs and LGADs, indicating that the irreversible breakdown in LGADs is not gain-related.
- The irreversible breakdowns are independent of the neutron fluence at which the sensors were irradiated prior to the laser measurements. The tests performed on LGADs irradiated at fluences of 1.5×10^{15} and 2.5×10^{15} n_{eq}/cm^2 show the same outcomes. This indicates that the link to the radiation fluences is merely that the radiation damage enables sensors to be biased at high enough voltage.
- There are three clearly distinguishable regions identified in the laser tests: stable – unstable irreversibly damaged.
- Safety regime is set.

Main message

Problem	Consequence	Mitigation technique	Future Prospect
radiation hardness (removal of active acceptors in the gain layer)	limited to 3e15 n_{eq}/cm^2 or less for charged hadrons	✓ Increase of bias voltage up to the point of SEB ✓ Critical el field (threshold mapping) ✓ Introduction of carbon as an impurity in the gain layer	With C implantation and thickness optimization the lifetime of the sensors can be extended. Other gain layer dopants are investigated.

E<12.7 V/µm should be safe operational mode

Outlook

- Some interesting CNM samples with different geometry and arrangement of opening windows are sent to JSI, irradiated and now annealed→ so they will be soon tested.
- To study SEB –angular dependence in LGAD on larger sample of pixeled LGAD
    - ✓ with inclined laser illumination (including effect of charge sharing)
    - ✓ not easy to set experiment due to needs for LGAD's cooling but some mechanics is already built towards this experiment
- To test TI-LGAD (at this moment we are running one campaign on interpad distance study using the same Laser set up at ELI)

ACKNOWLEDGMENT

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- Ministry of Science in Montenegro within the project “Improving research infrastructure and measuring techniques for testing of fast ”state-of-the-art” LHC-HL time detectors,” Contract No. 03/1- 062/20-500/3.
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THANK YOU