IBIC for LGAD Characterization: Fabrication Insights and Carbon Doping Effects

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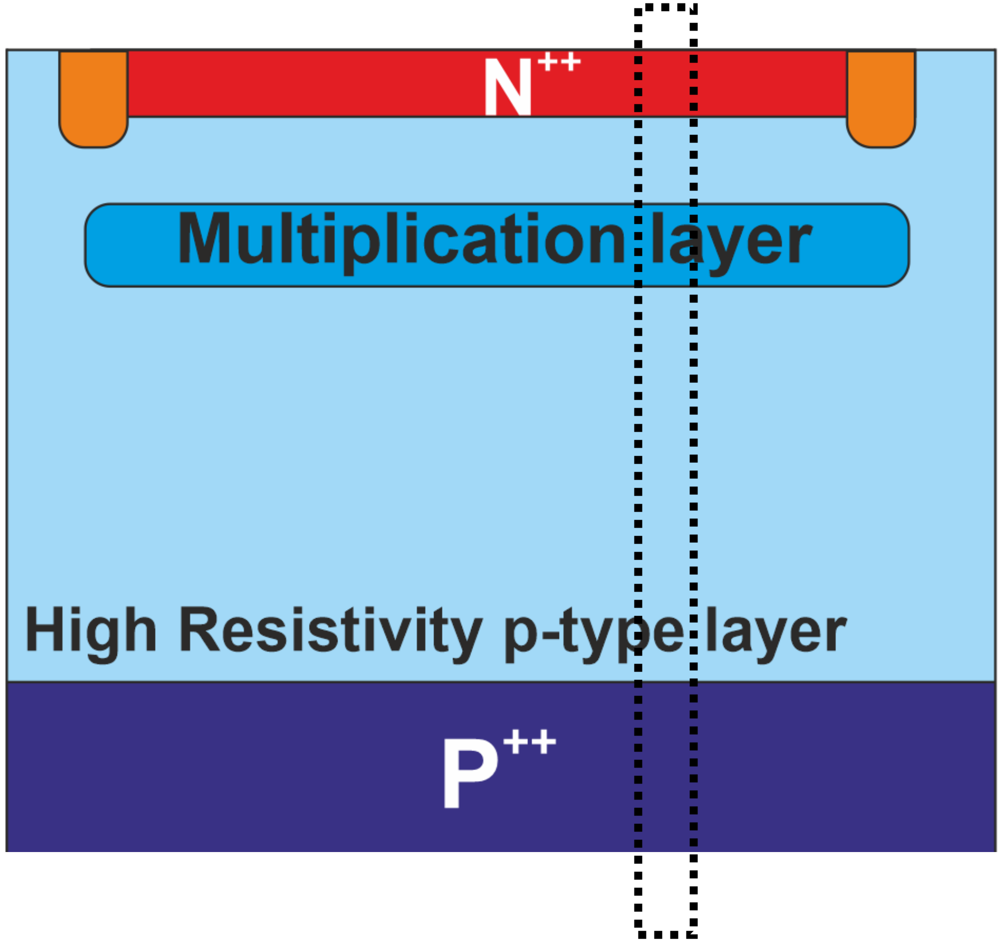
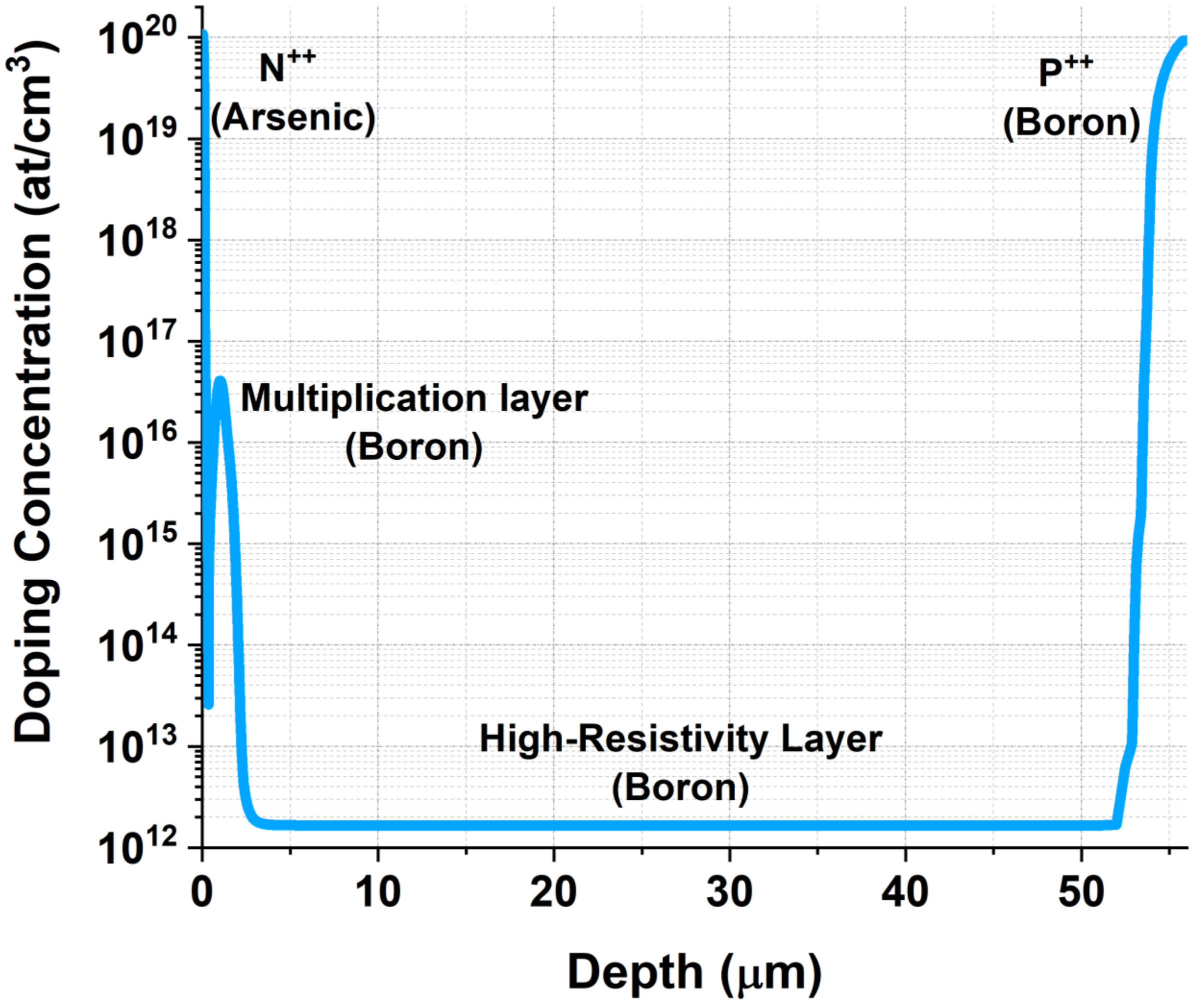
Outline

- Low Gain Avalanche Detector (LGAD) concept
- LGAD Design and Fabrication at IMB-CNM
- Ion Beam Induced Current (IBIC) technique with the Microprobe Line at CNA
  - ➢ Overview
  - ➢ Characterization of LGAD elements via IBIC
  - ➢ Complementary characterization techniques
- Summary

Low Gain Avalanche Detector (LGAD) concept

- In contrast to a standard silicon detector (PiN), an LGAD has a moderately doped **multiplication layer** diffused close to the detector surface.





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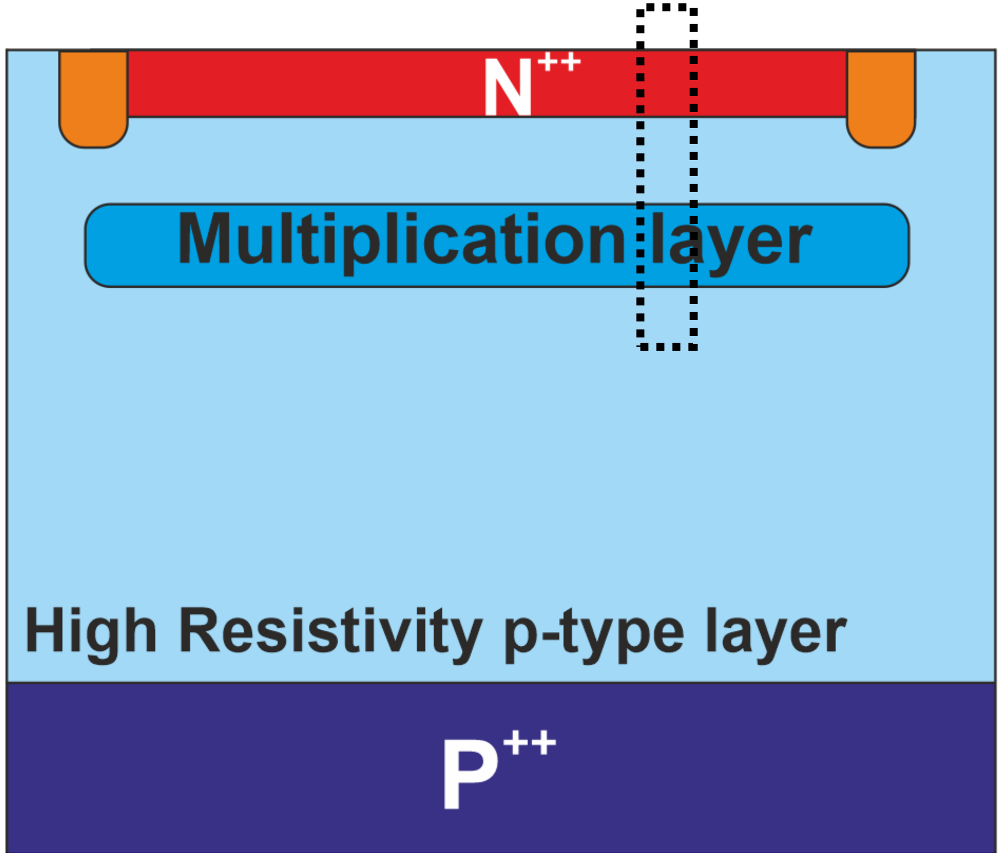
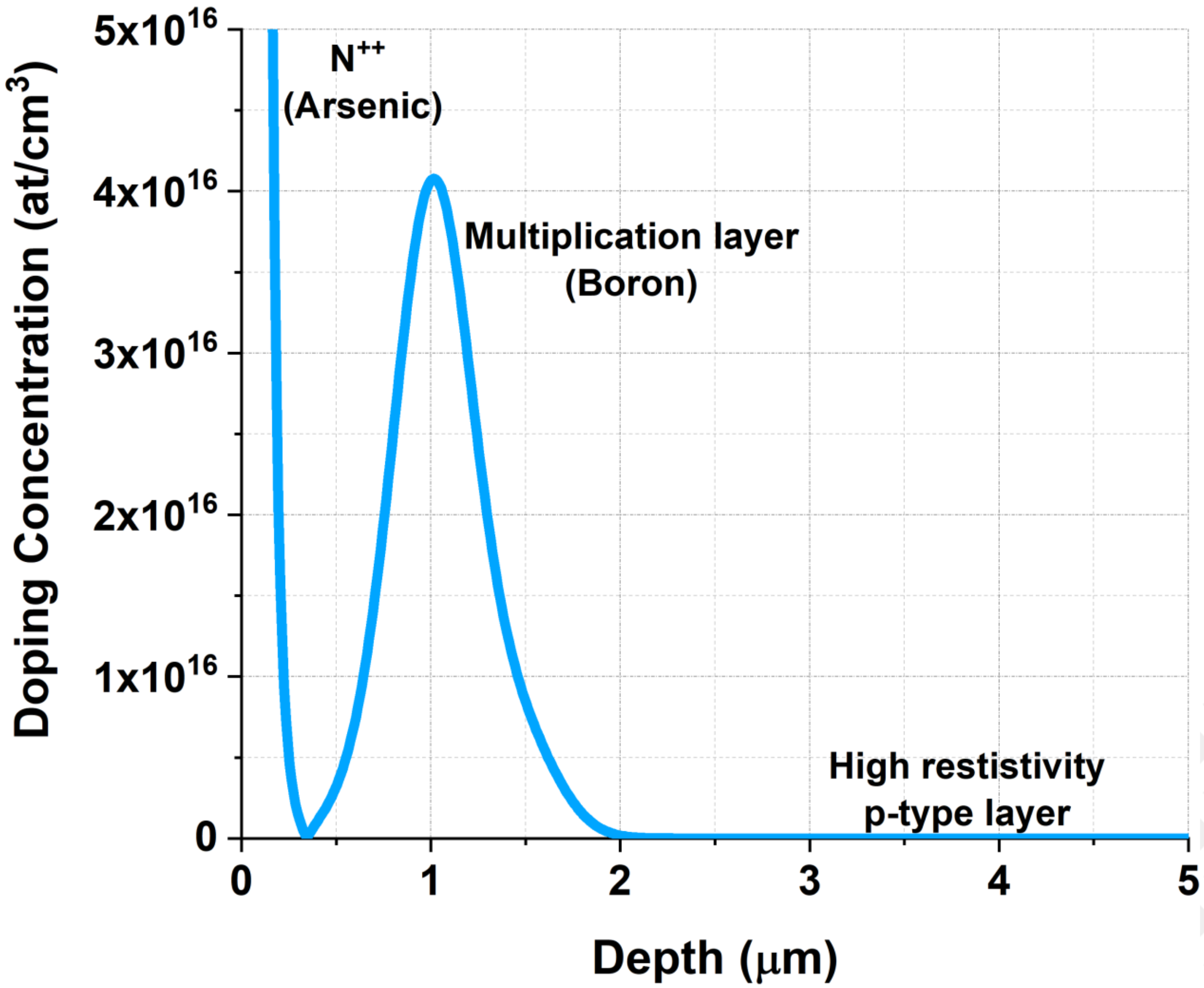
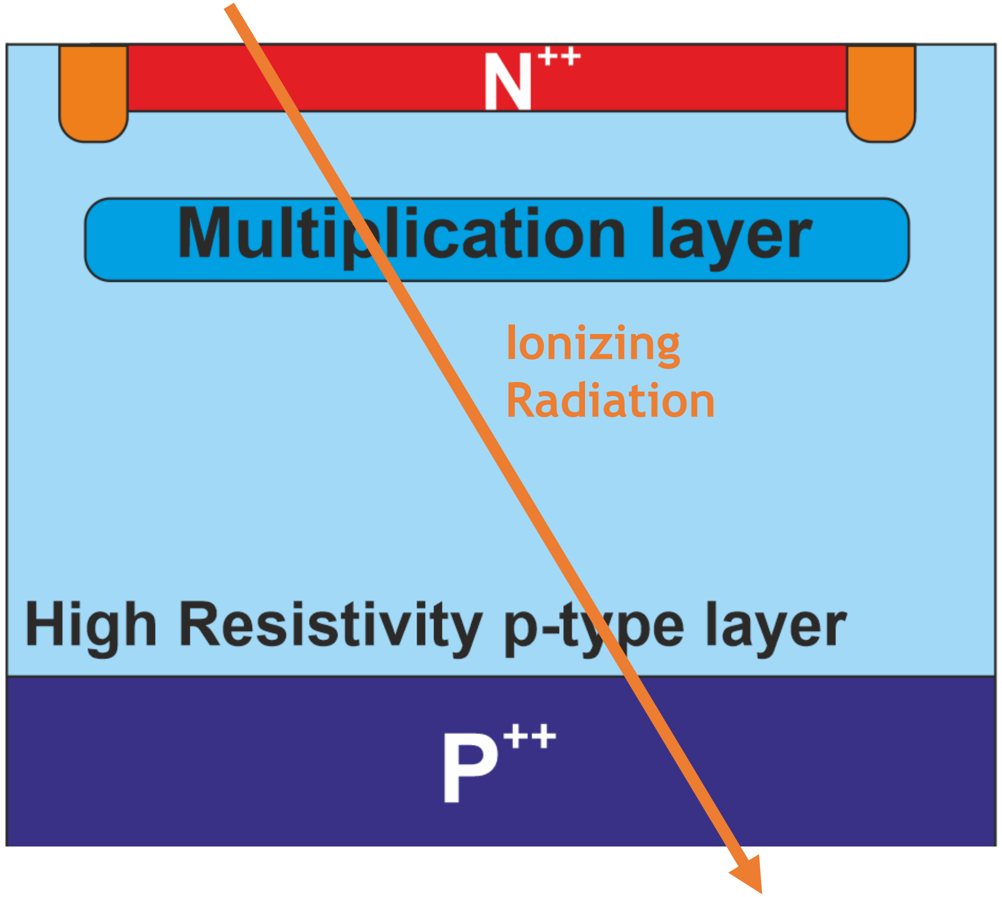
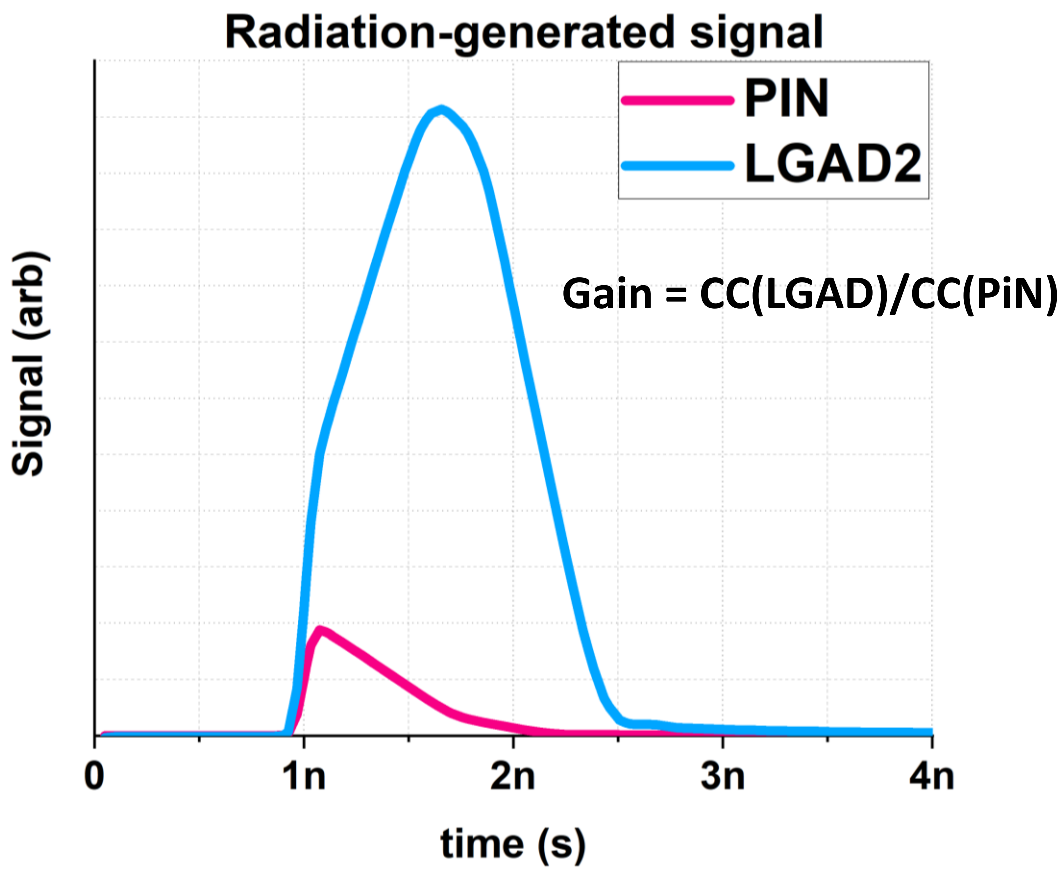




Low Gain Avalanche Detector (LGAD) concept

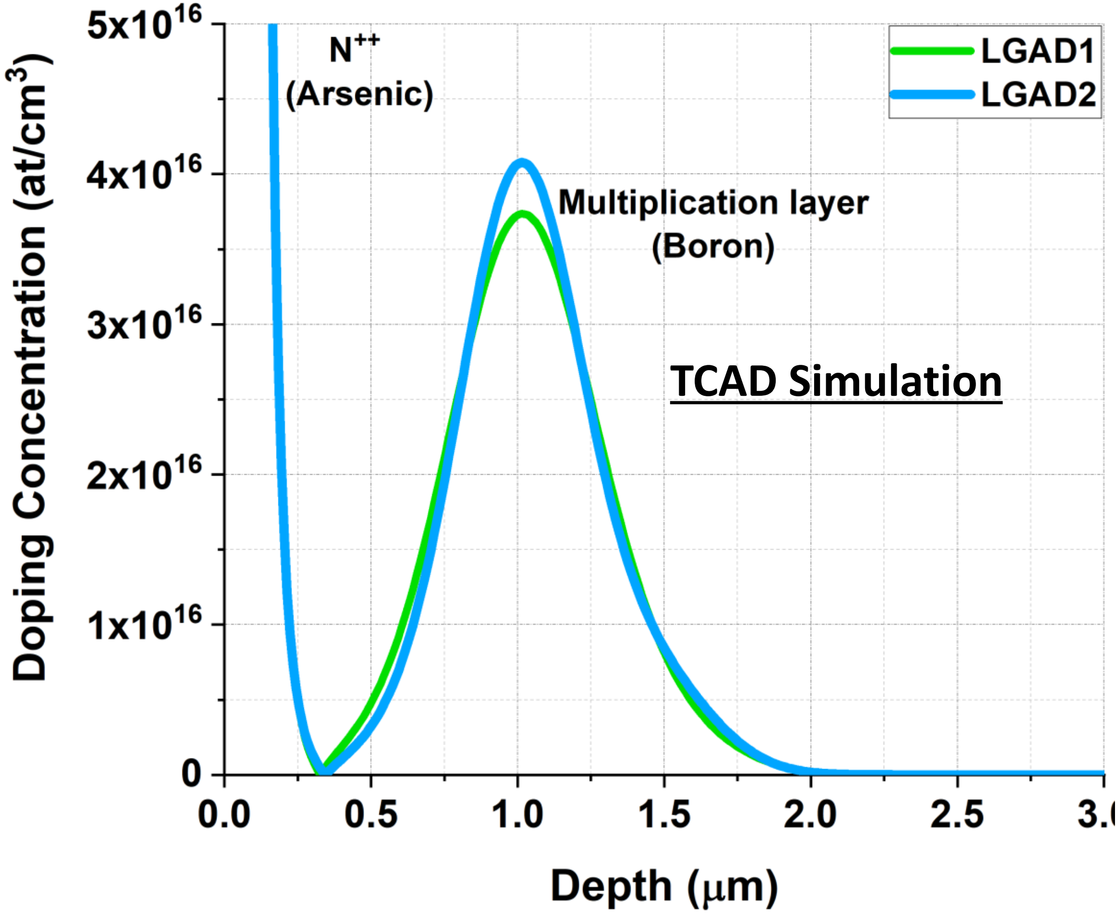
- The presence of such layer **enhances the electric field** close to the PN junction when the detector is reverse biased, in turn **amplifying** the **radiation-generated signal** by an impinging particle.

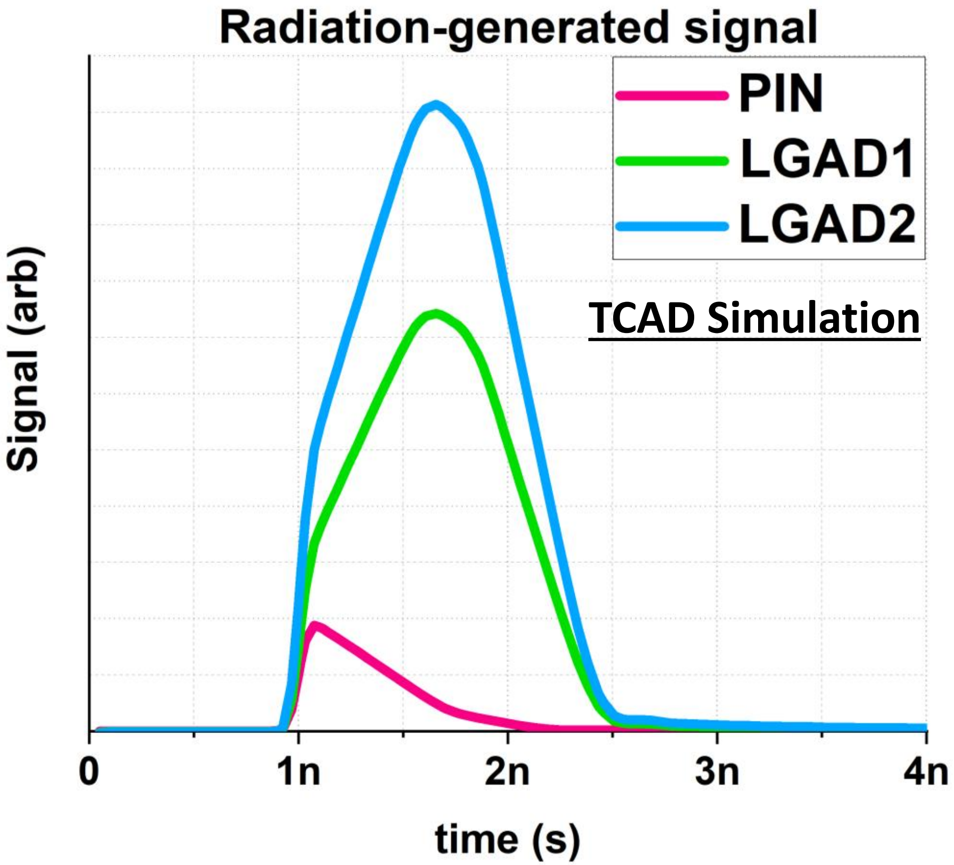




Low Gain Avalanche Detector (LGAD) concept

- The signal is further amplified as the doping peak of the multiplication layer increases.
- These doping profiles are predicted via **TCAD Sentaurus Simulations** before the fabrication starts





LGAD Design and fabrication at IMB-CNM

We start from a raw wafer

- Ion Implantation
- Thermal processes
- Oxidation
- Metalization
- Etching
- Photolitography

...

Commercial Raw Wafer

LGAD Design and fabrication at IMB-CNM

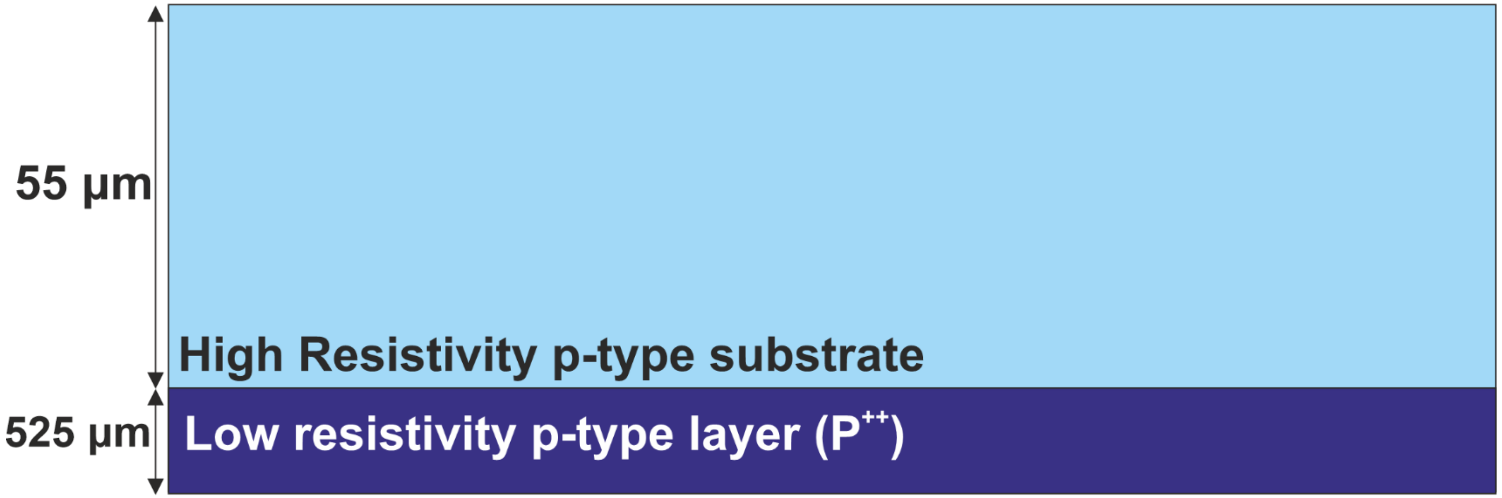
We start from a raw wafer

- Ion Implantation
- Thermal processes
- Oxidation
- Metalization
- Etching
- Photolitography*

...

Few months of engineering processes

* J Villegas. **Development of Low Gain Avalanche Detectors (LGAD) for high- and low-penetrating particles in silicon:** https://repository.cern/records/7deh4-nxz32



Raw Wafer- Cross Section

LGAD Design and fabrication at IMB-CNM

We start from a raw wafer

- Ion Implantation
- Thermal processes
- Oxidation
- Metalization
- Etching
- Photolitography*

We ended up with a fabricated LGAD*

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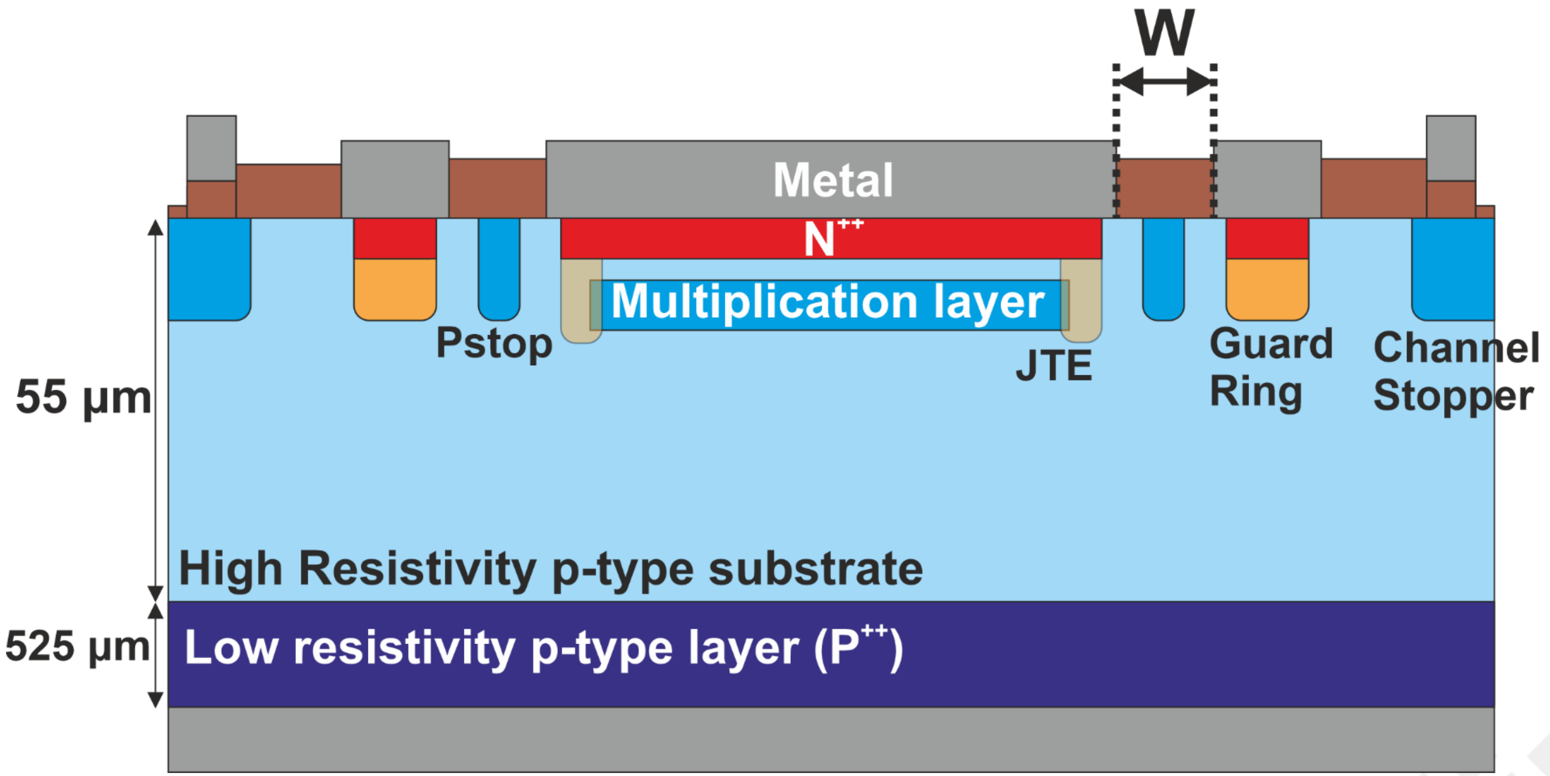
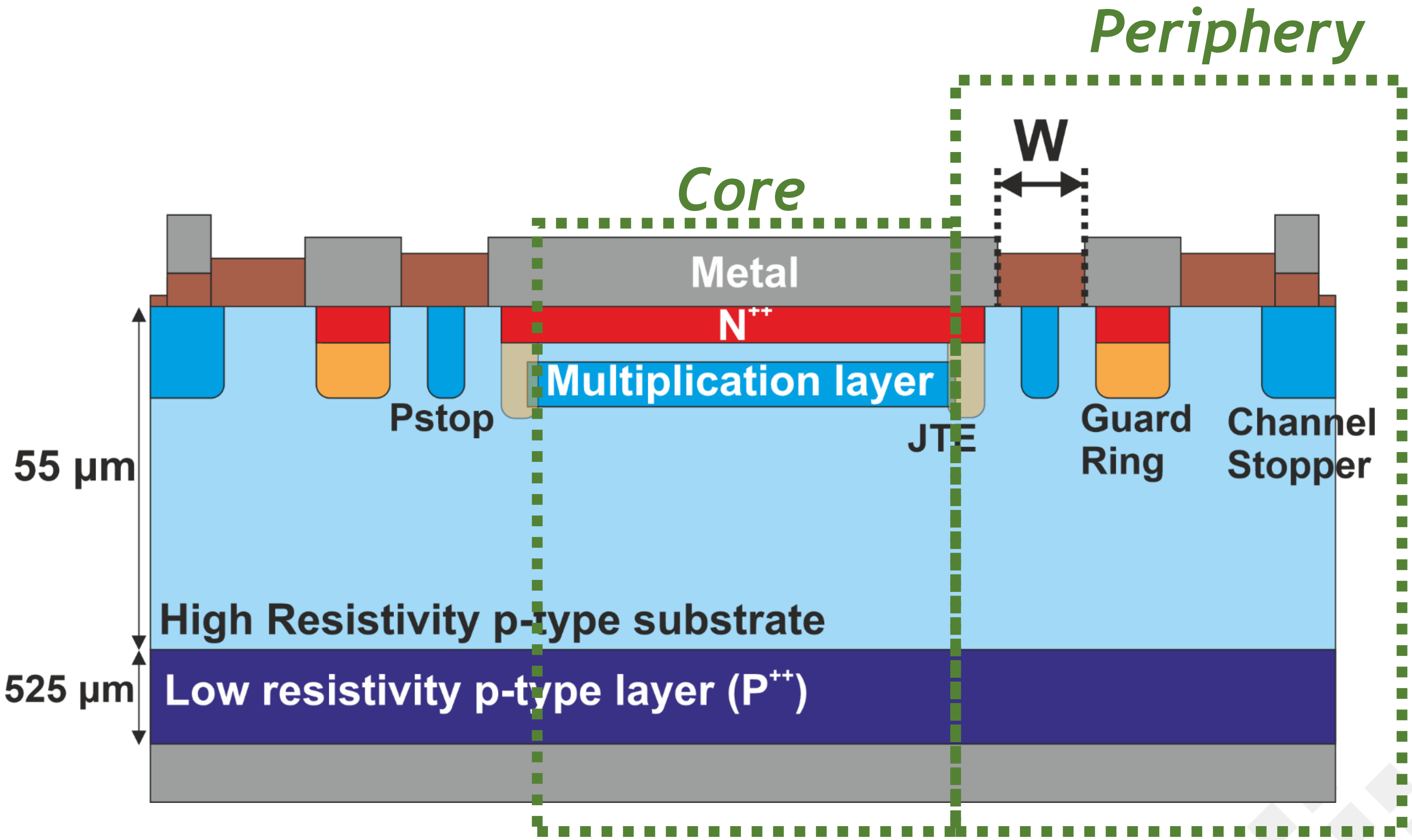


Fabricated LGAD - Cross Section

LGAD Design and fabrication at IMB-CNM

We can differenciate two parts:

- **Core** → Region where the ionizing radiation interacts with the silicon to generate the signal
- **Periphery** → Termination region responsible for ensuring the correct electrical operation and stability of the device.



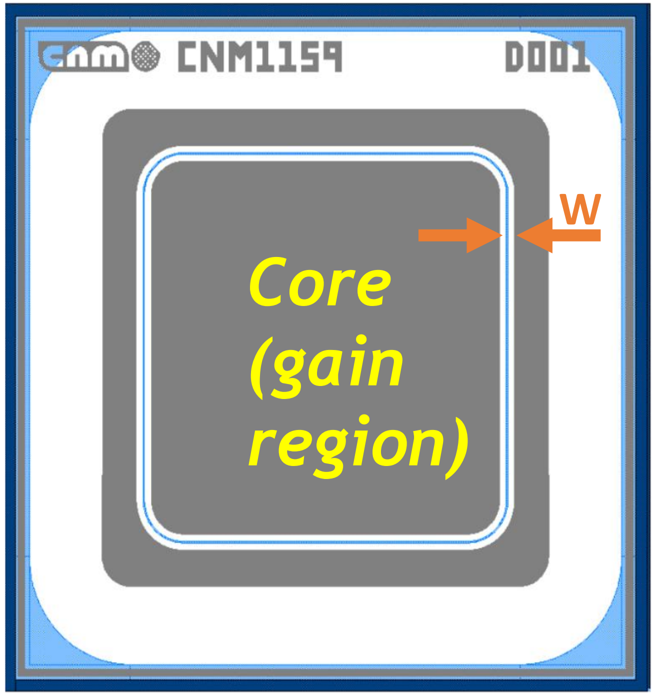
Fabricated LGAD - Cross Section

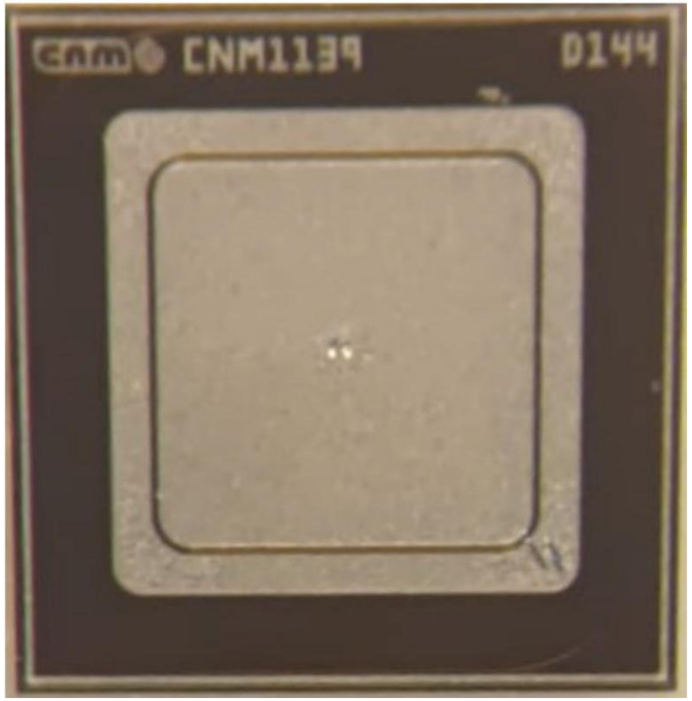
LGAD Design and fabrication at IMB-CNM

We can differenciate two parts:

- **Core → Multiplication layer**: Responsible for amplifying the signal
- **Periphery → Core-ring width (W)**: Specifically designed with a width of about 60 µm. Lower noise levels are observed after irradiation when W > 40 µm*.

Front view





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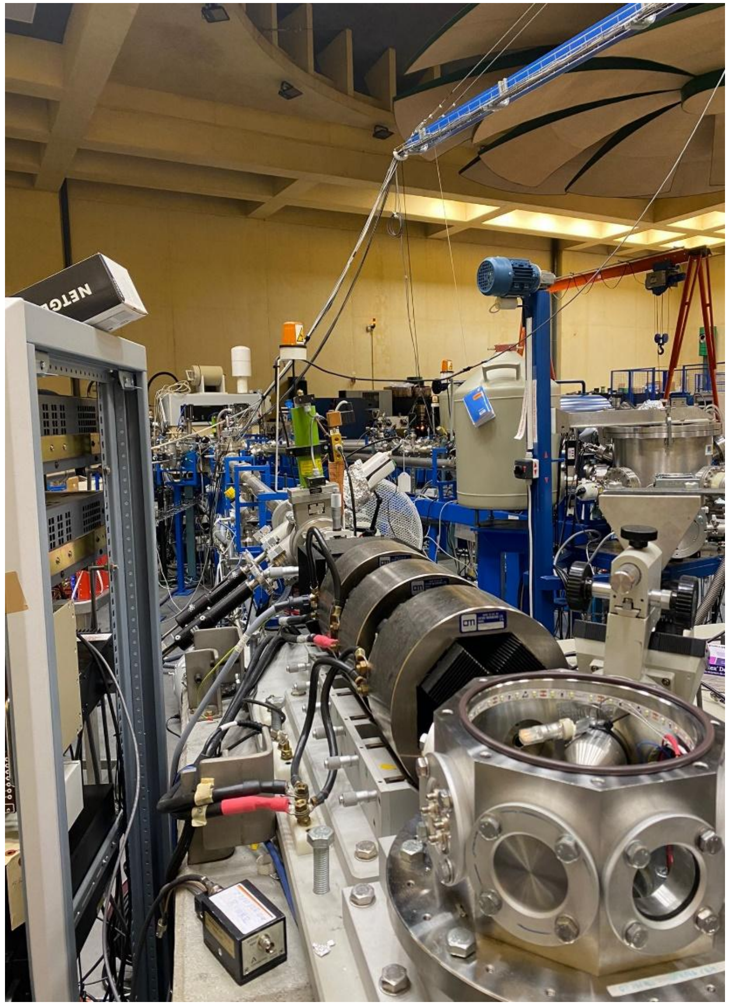
The Microprobe Line at CNA



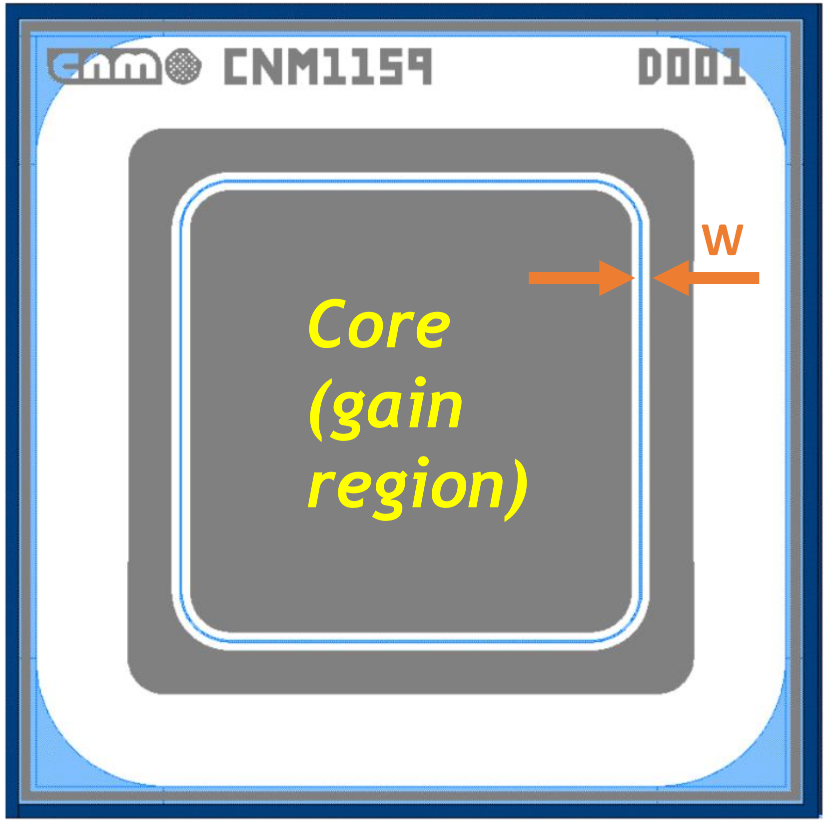
Nuclear Microprobe line

Tandem room

- **High spatial resolution** for 2D mapping of the collected charge (CC) response.
- **Low particle rate** (≈ 100 Hz) to avoid sensor damage.
- Tuning of particle energy within the MeV range (**2.3 MeV protons** used in this work).

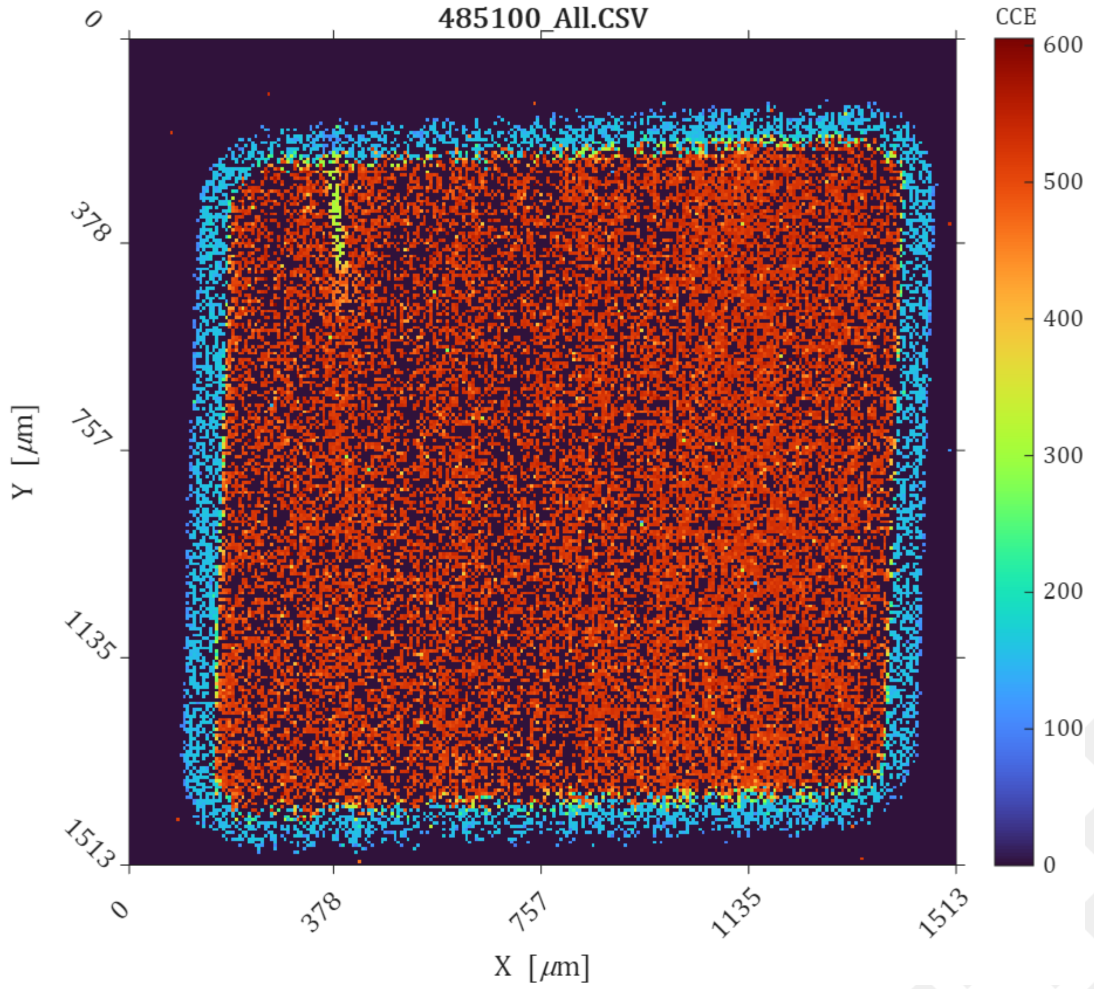
Characterization of LGAD elements via IBIC

- 2D mapping of the collected charge (CC) response to 2.3 MeV protons: Both the core and the W region are clearly observed

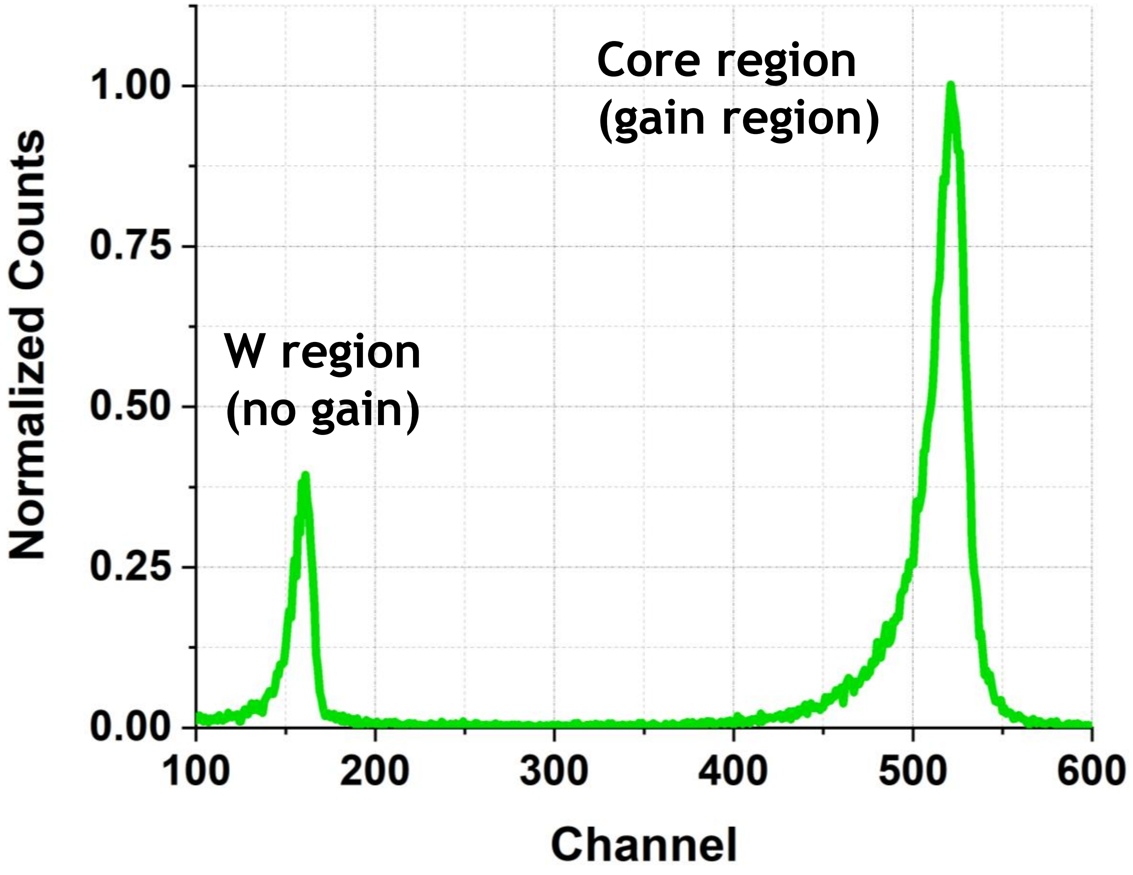


IBIC 2D Map output for a given bias

Room temperature (20ºC)
250 V reverse bias

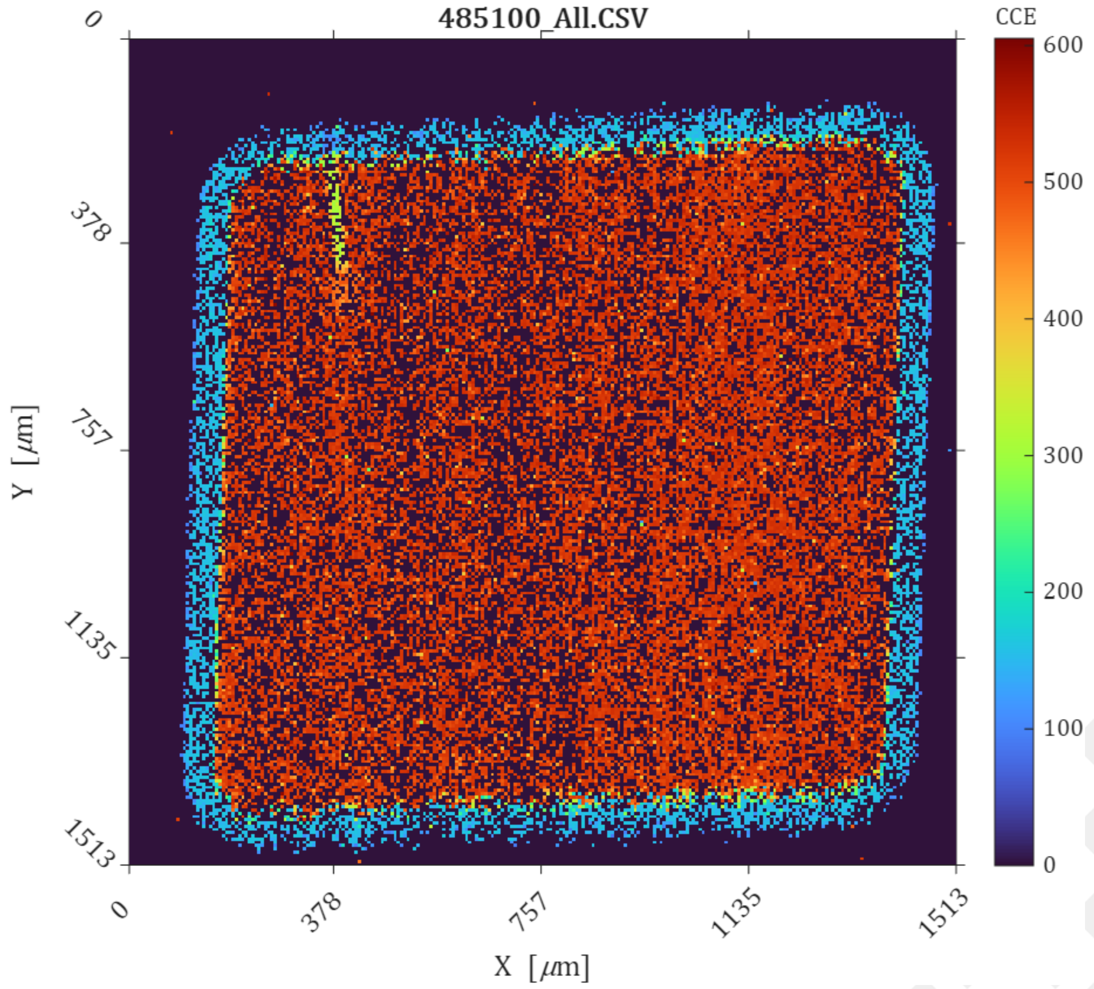


Characterization of LGAD elements via IBIC



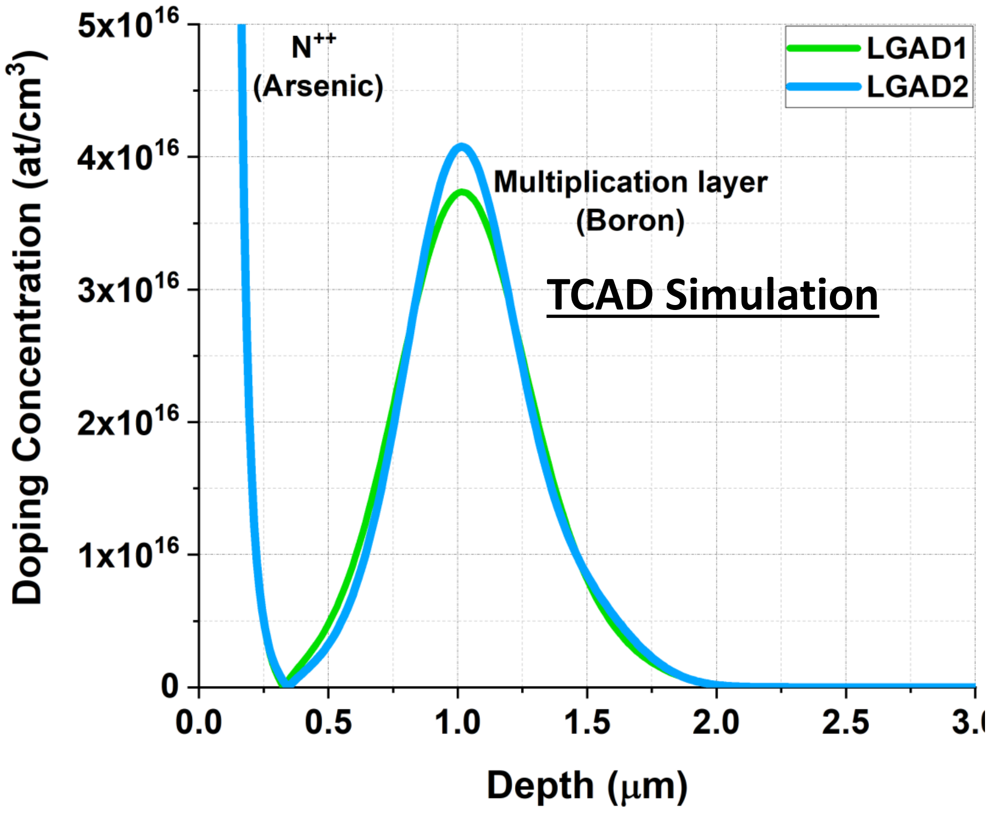
Turning 2D map into spectra

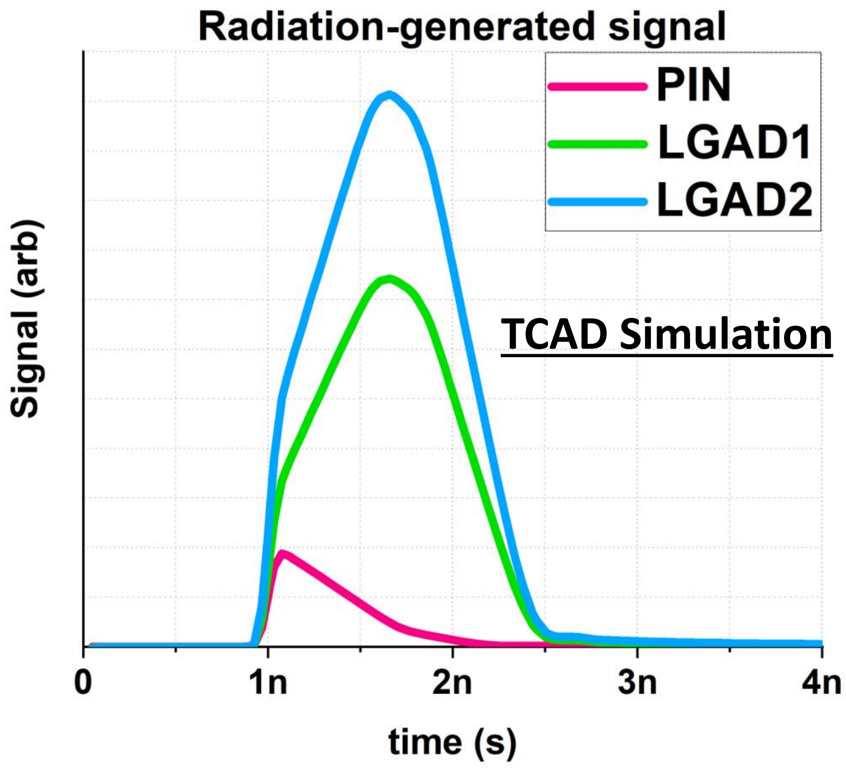
Room temperature (20ºC)
250 V reverse bias



Characterization of LGAD elements via IBIC

- The signal is further amplified as the doping peak of the multiplication layer increases.
- Tested devices: with (LGAD1) and without (LGAD2) carbon co-implantation
- The LGAD design via TCAD Simulations predicts that carbonated LGADs will have a lower signal amplification (gain)*

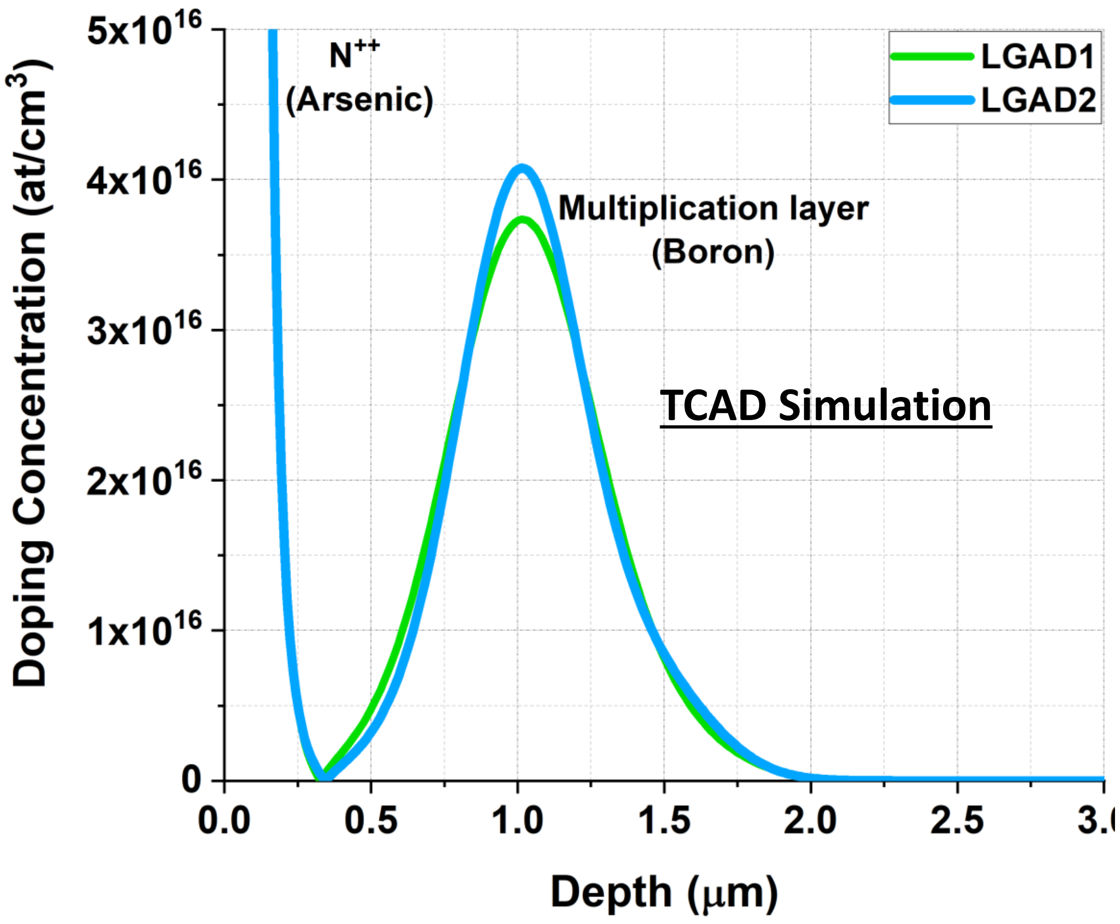


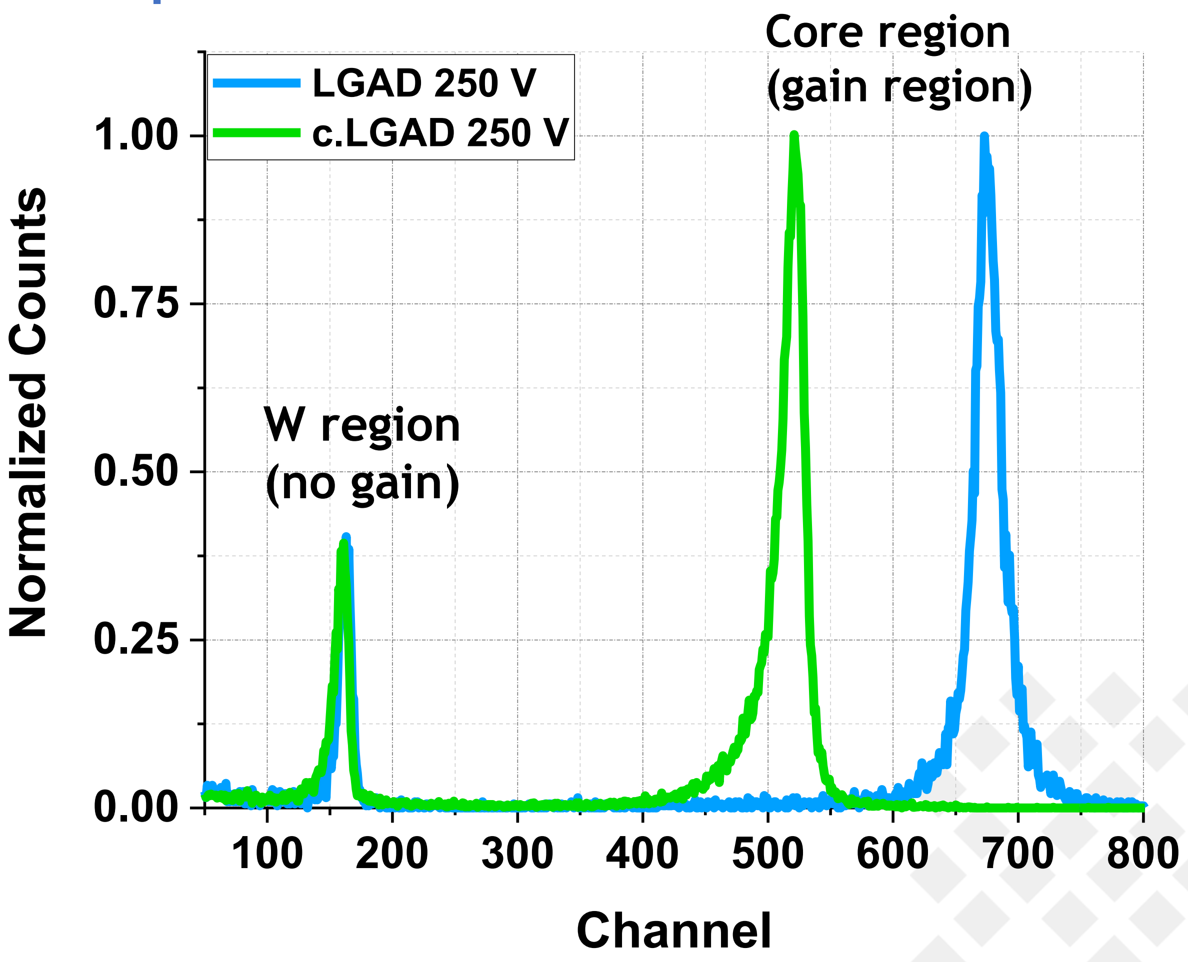


* J. Villegas et al. The Effects of High-Energy Carbon Co-Doping on IMB-CNM LGAD Fabrication and Performance: https://doi.org/10.3390/s25175571

Characterization of LGAD elements via IBIC

- The LGAD design via TCAD Simulations predicts that **carbonated LGADs (cLGADs) will have a lower** signal amplification (**gain**)
- IBIC measurements serve to **prove the simulation prediction**





Characterization of LGAD elements via IBIC

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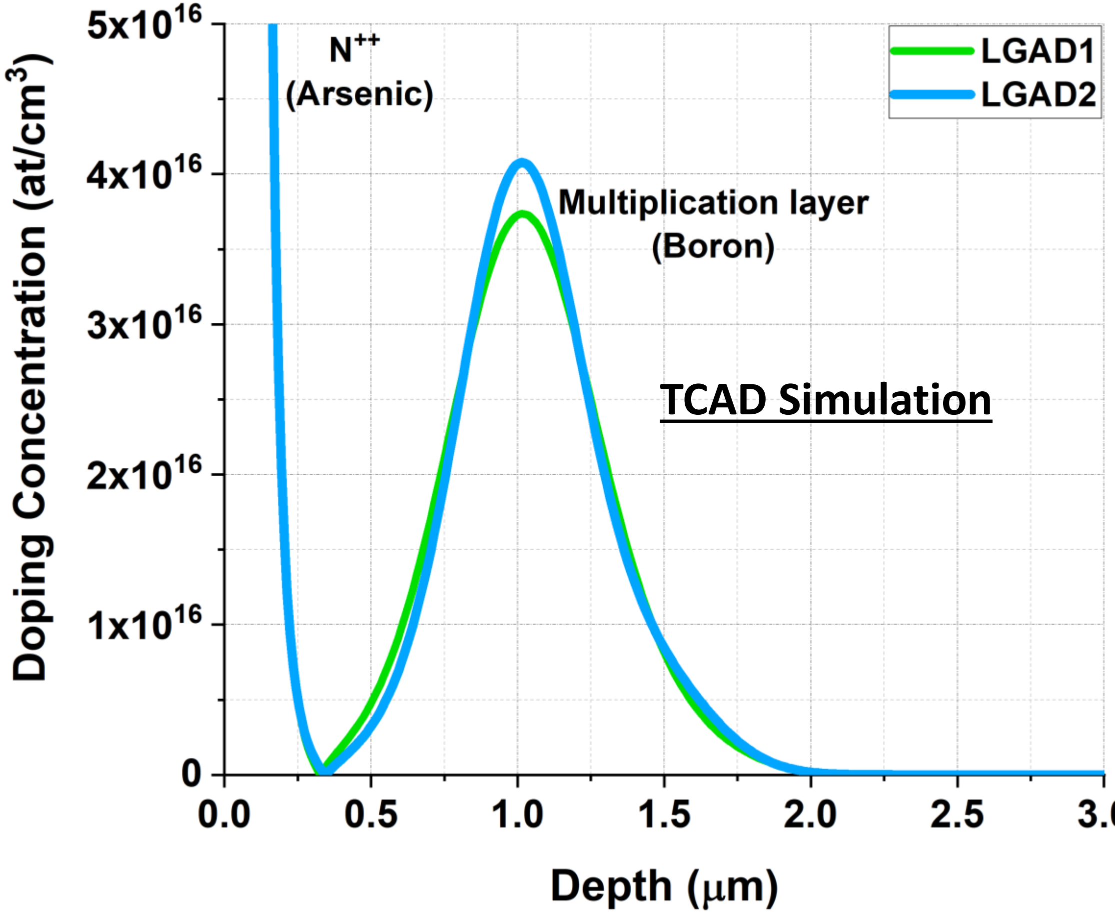
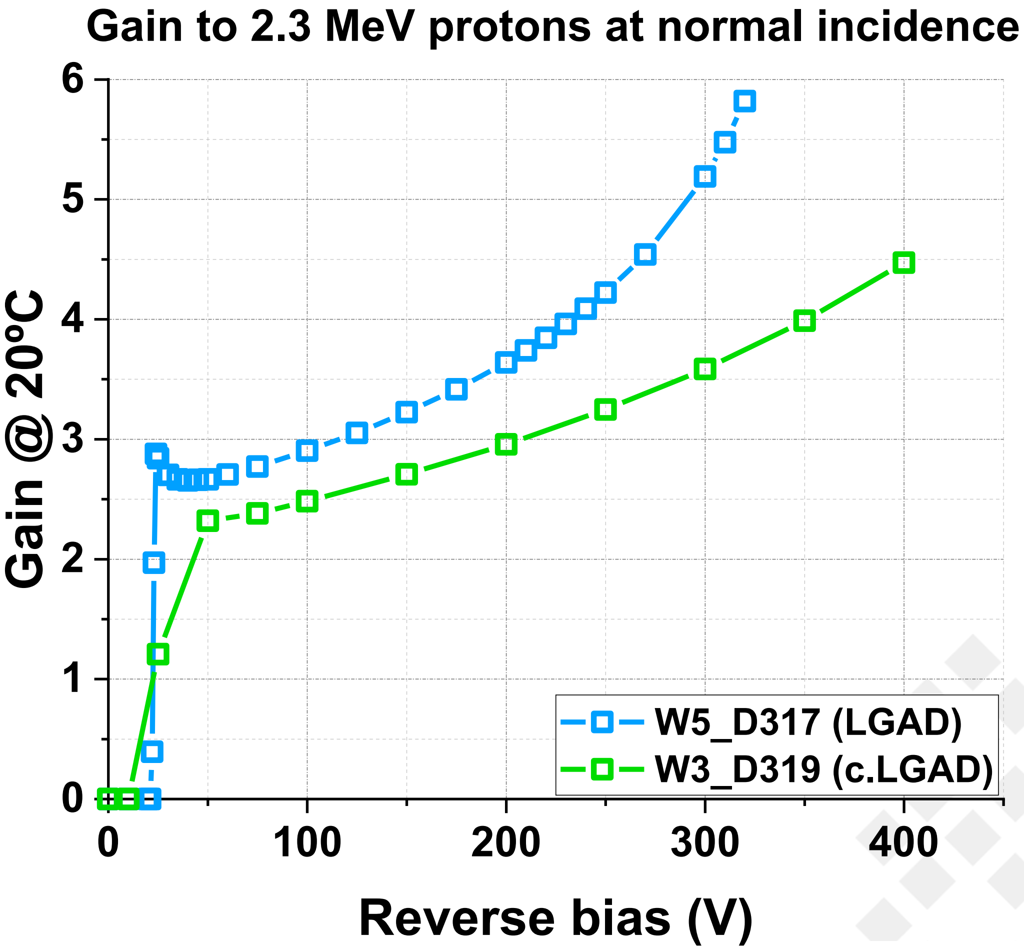
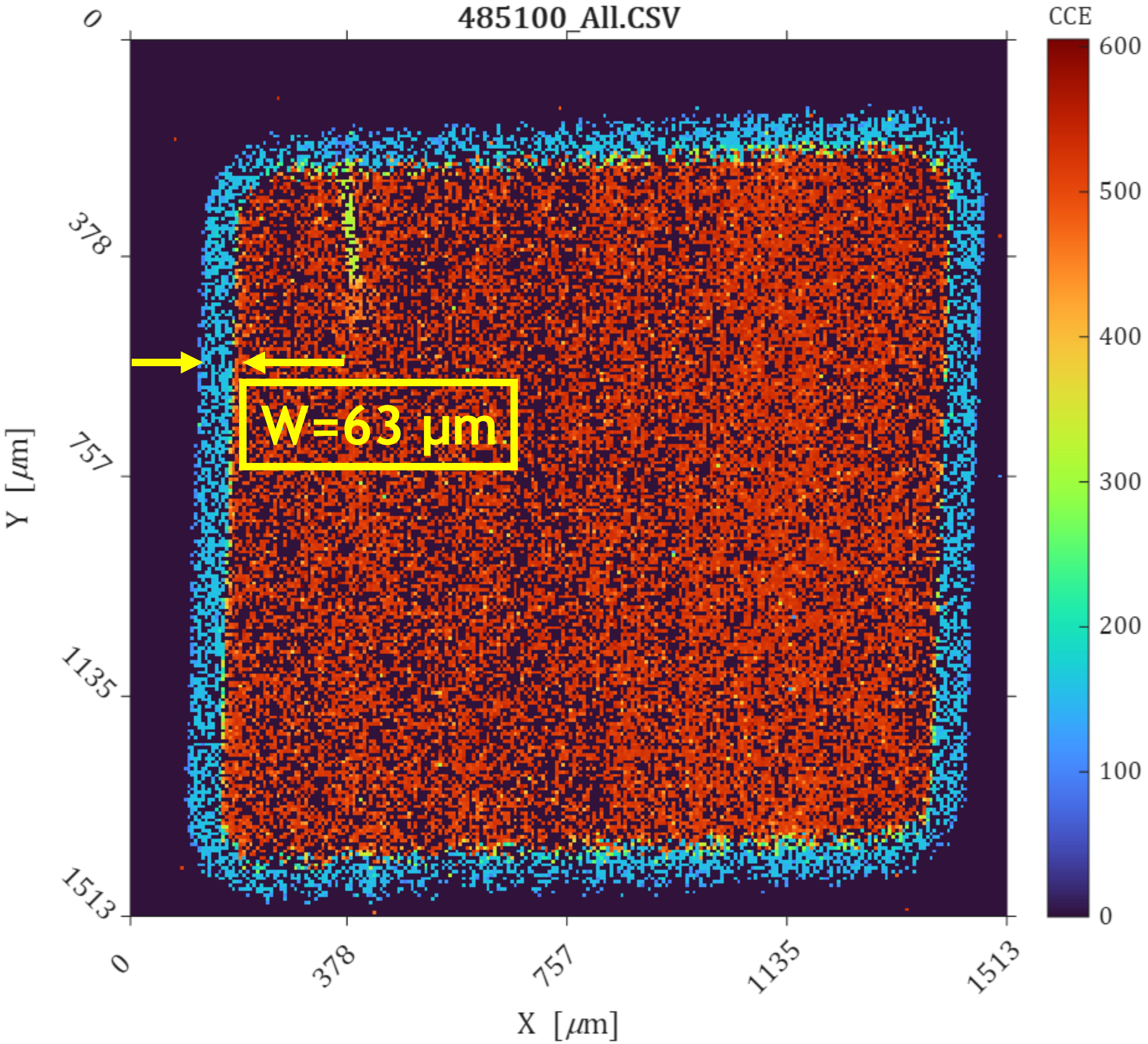


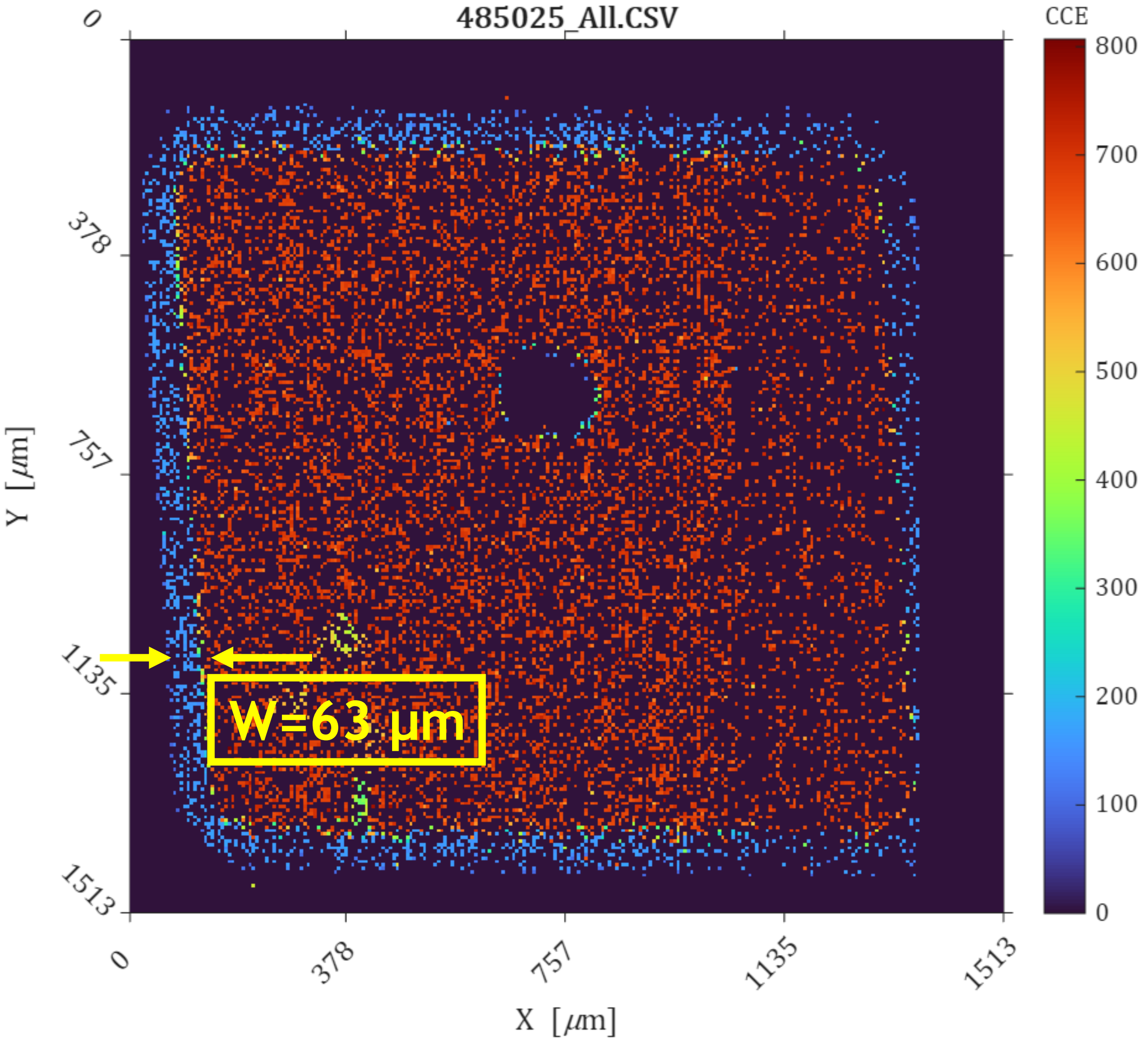


Characterization of LGAD elements via IBIC

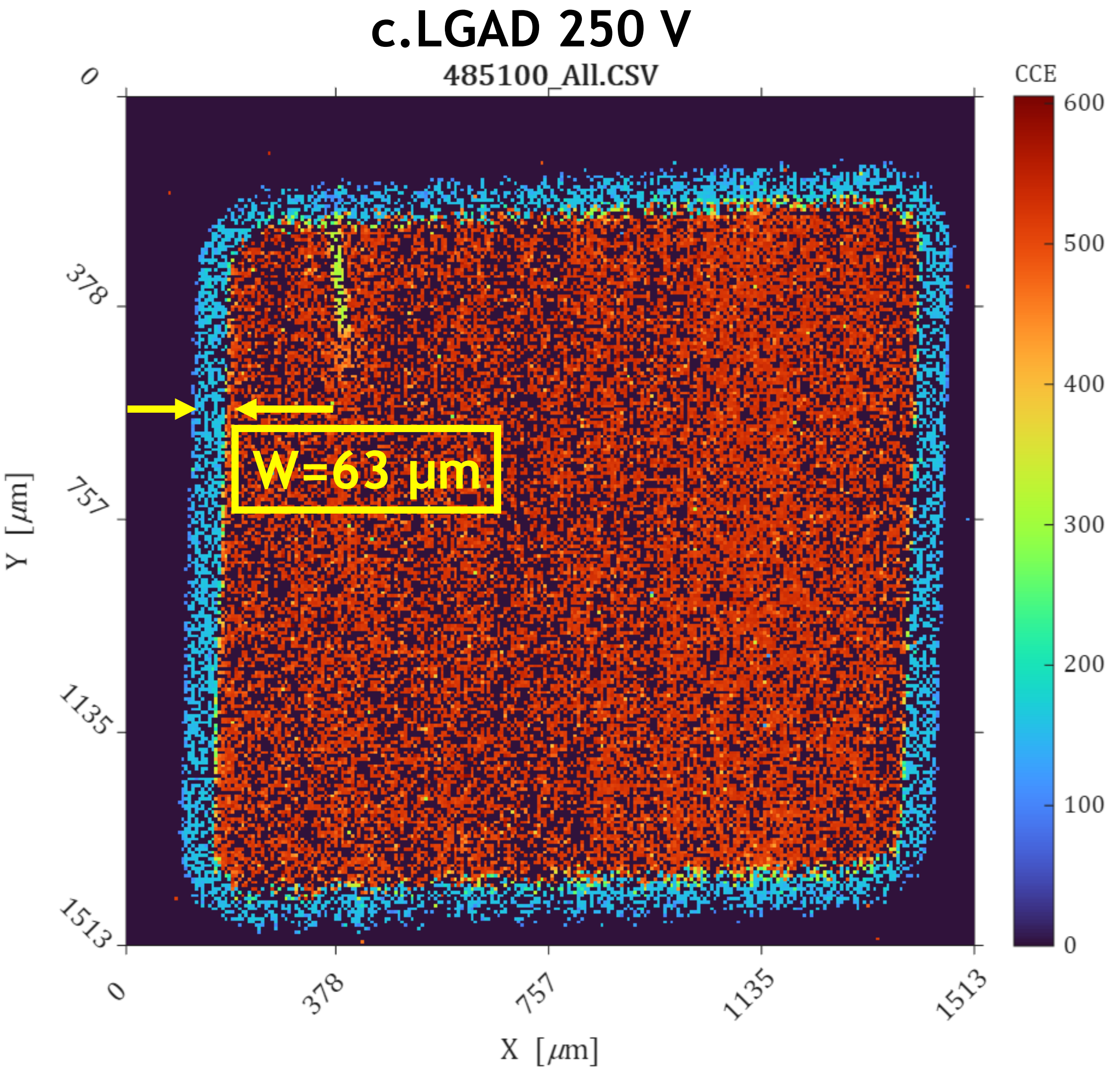
c.LGAD 250 V

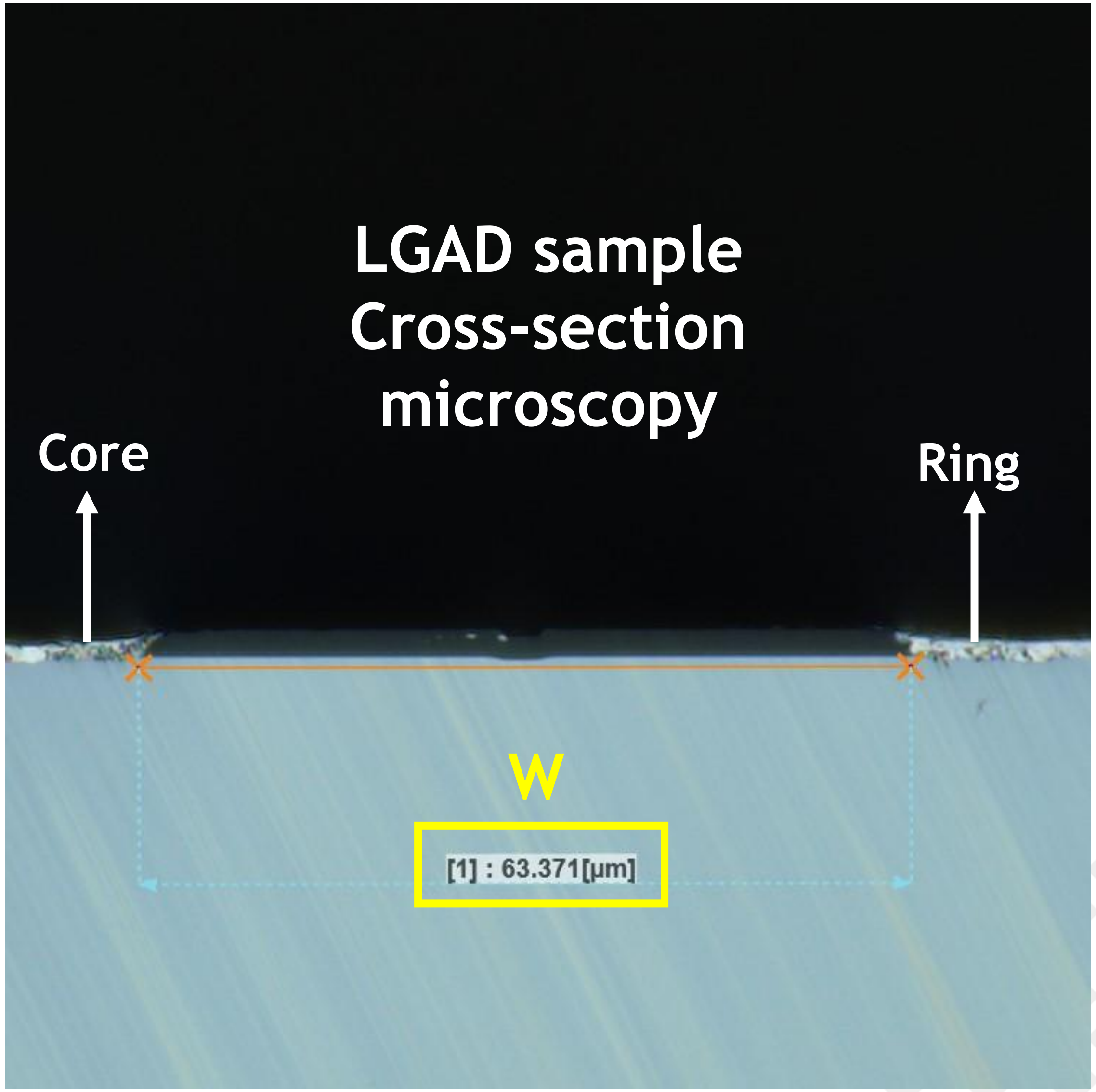


LGAD 250 V



Complementary characterization techniques





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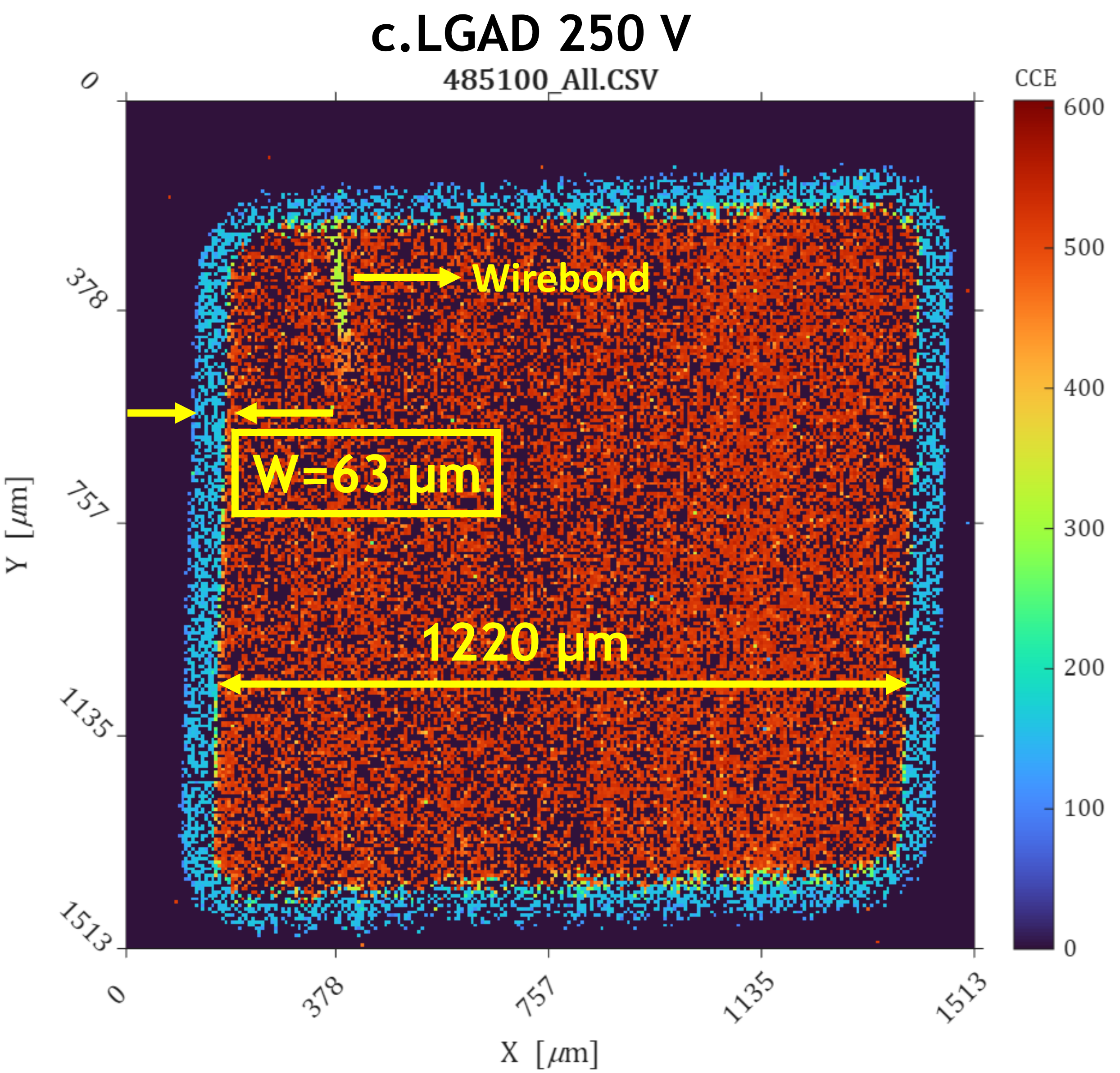
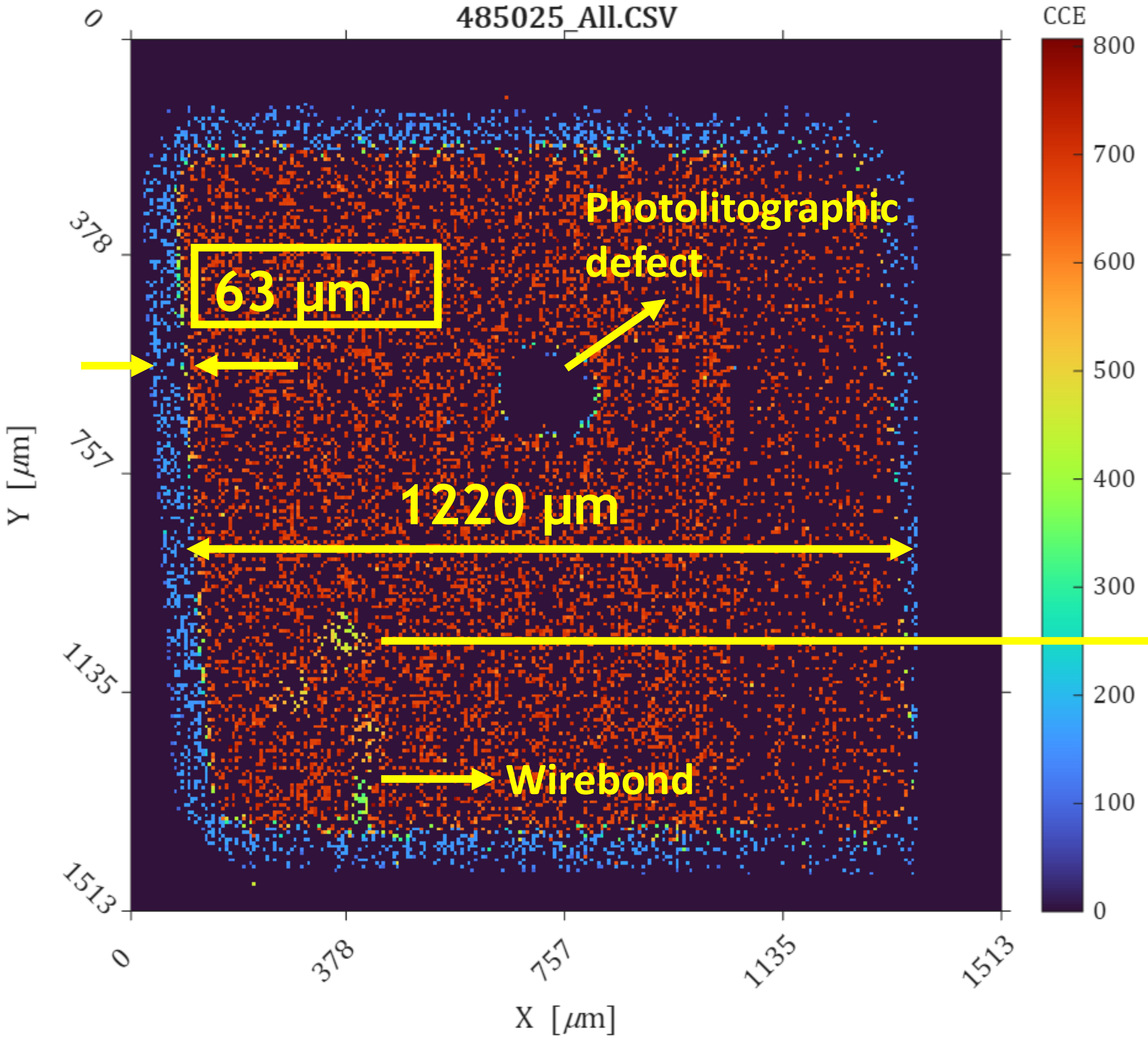


Carbonated LGAD (cLGAD)

- **Uniform response** observed in the device core (gain region) and in the W region (no-gain region).
- Only the wire bond (metallic wire used to bias the device) disrupts the uniformity of the response.

Complementary characterization techniques

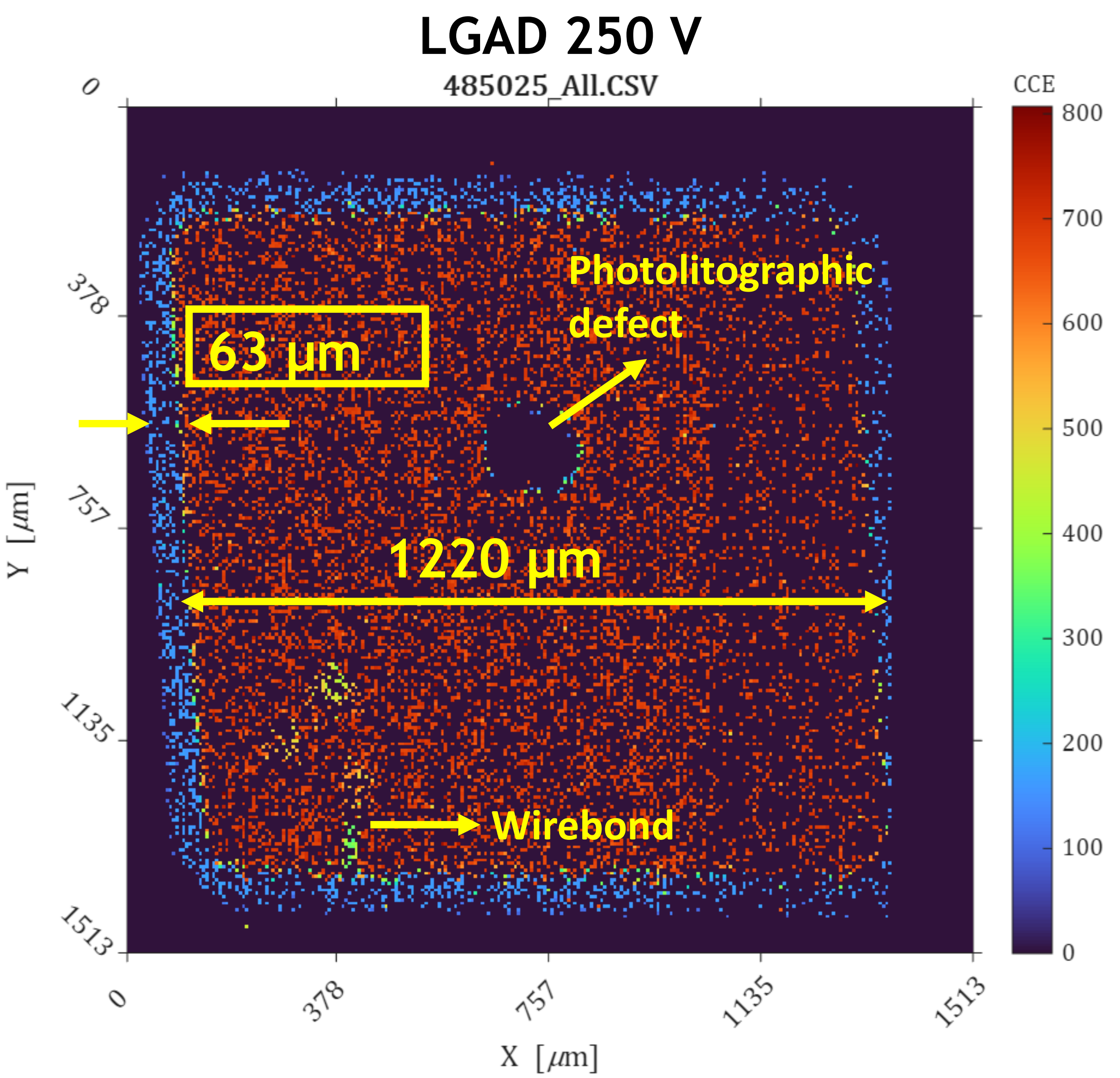
LGAD 250 V



Non carbonated LGAD:

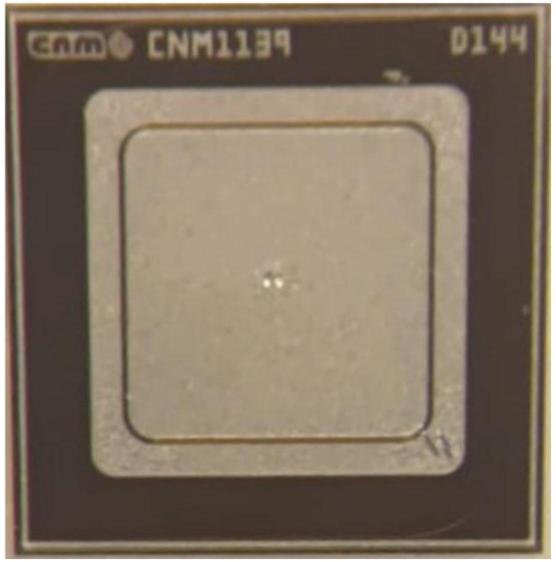
- Uniform response observed in the device core (gain region) and in the W region (no-gain region), but also
- Silver lacquer droplets from wire-bonding

Complementary characterization techniques

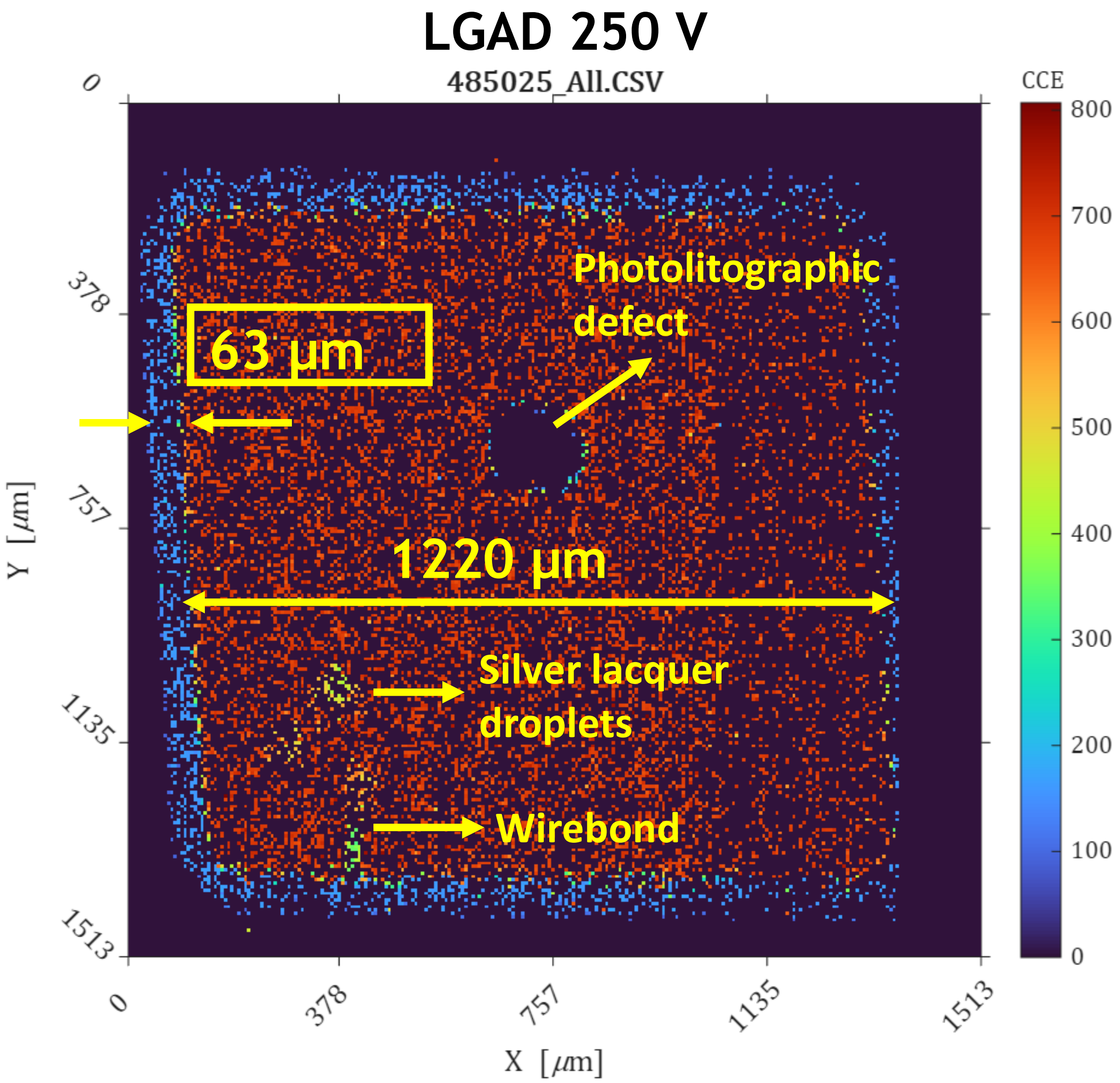


Non carbonated LGAD:

- A **photolithographic defect** (a "hole" where the device shows no response) is also observed. Such defects are difficult to detect with standard microscopic characterization (due to the metal layer on top), which highlights the usefulness of **IBIC for fabrication characterization**.



Summary



- The IBIC technique using the Microprobe Line at CNA can be employed to characterize LGADs and to get insight into:
- Carbon co-doping effects on the gain response of the devices.
- Accurate evaluation of microstructures (e.g., the W region), providing a complement to other techniques such as cross-section microscopy.
- Cross-checking the response uniformity of the devices.
- Detecting small defects introduced during encapsulation (e.g., silver lacquer droplets) and larger defects, such as photolithographic defects, which cannot be detected by microscopy

Acknowledgments

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Thanks for your attention!

Please do not hesitate to contact me for any questions: jvillegas@us.es

Low Gain Avalanche Detector (LGAD) applications

Ongoing and Potential applications:

- High Energy Physics
  - 4D-tracking detectors (high time and space resolution of events)
  - Pile-up mitigation in high luminosity colliders (HL-LHC at CERN)
  - Beam monitoring in accelerators experiments
- Medical and Biological Imaging
  - Time-of-Flight PET
  - Proton therapy monitoring
  - Fast radiation dosimetry
- Neutron detection (with converters)
- Photon science
  - X-ray detection in Synchrotron facilities
  - UV detection for photolithography engineering processes
  - Optical photon timing
- Space Applications: Comic rays of x-rays detection is space-based detectors