Inverse LGAD for X-Ray Applications

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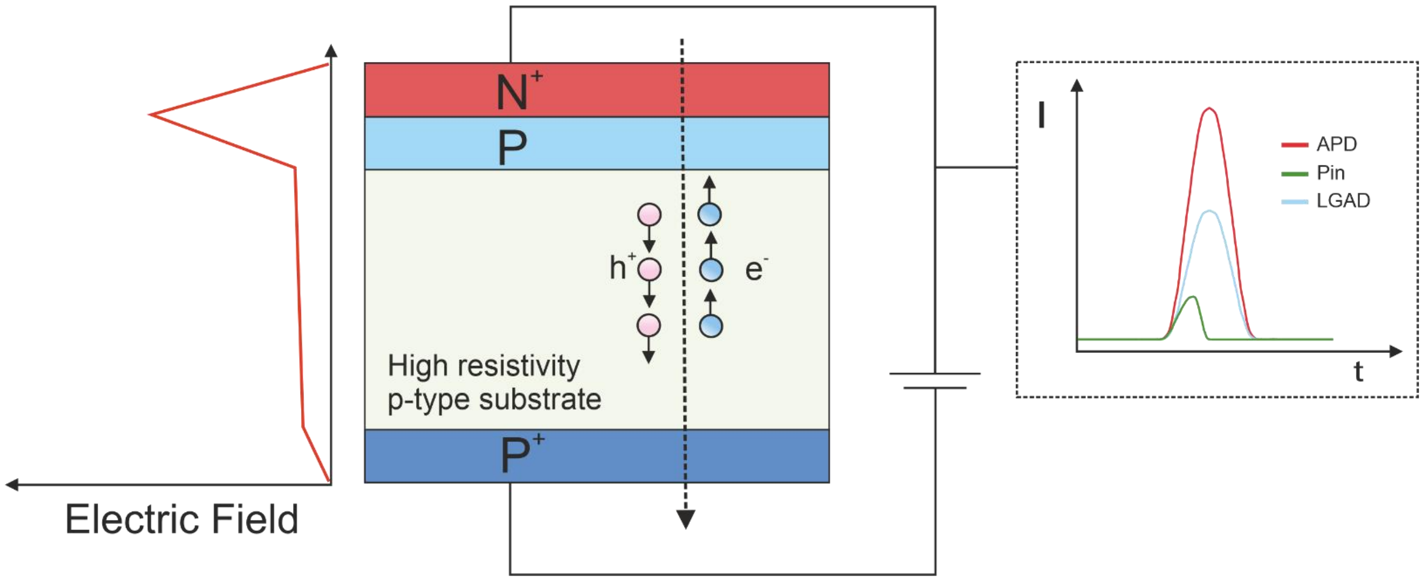
Introduction: Low Gain Avalanche Detector (LGAD) Technology

- **LGAD** technology is based on the APD concept.
- Multiplication layer less doped to reach a **linear** and **moderate gain** (10-30) in a high operating voltage regime.
- **Low** signal to noise ratio **(S/N)**.
- **LGAD** is the baseline technology of the endcap MIP timing detector for the high-luminosity upgrade of the **ATLAS** and **CMS** experiments.



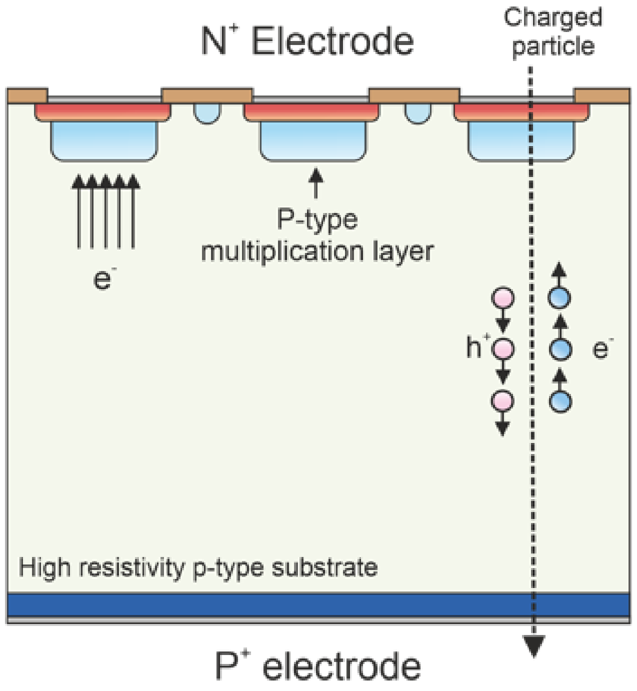
- **Main challenges:**
  - Radiation **tolerance to neutrons and protons.**
  - Technology **long-term reliability (Safe operating voltage).**
  - Large scale **manufacturing yield.**
  - Improve **fill-factor.** → **Motivation for the iLGAD**

Inverse LGAD as 4D Tracking Sensor

- Inverse Low Gain Avalanche Detector (iLGAD) is based on the LGAD technology.
- The main motivation for the iLGAD technology is **increase the fill factor** to a 100%.

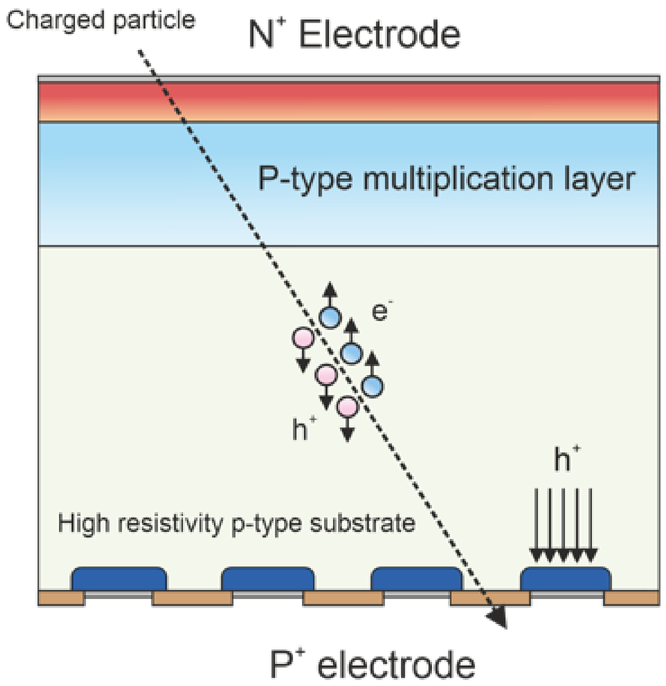
LGAD TECHNOLOGY

- Segmentation of the multiplication.
- Electron collection
- Single side process



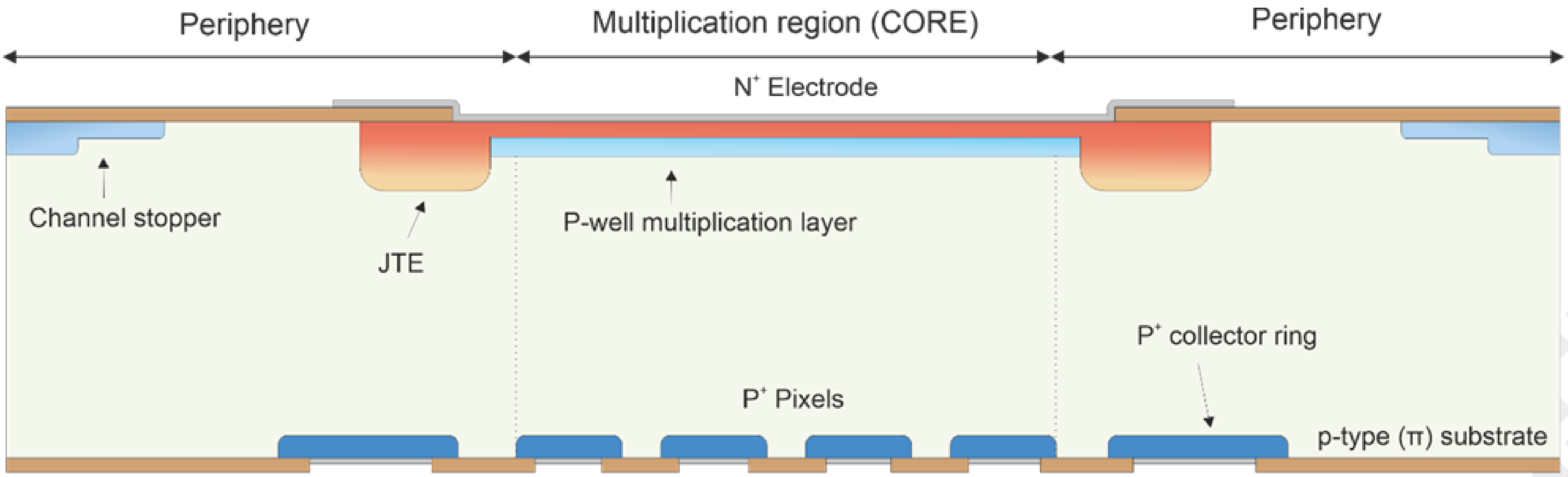
iLGAD TECHNOLOGY (iLG1)

- Multiplication extended over the electrode.
- Hole collection
- Complex double side process



iLGAD First Generation (iLG1)

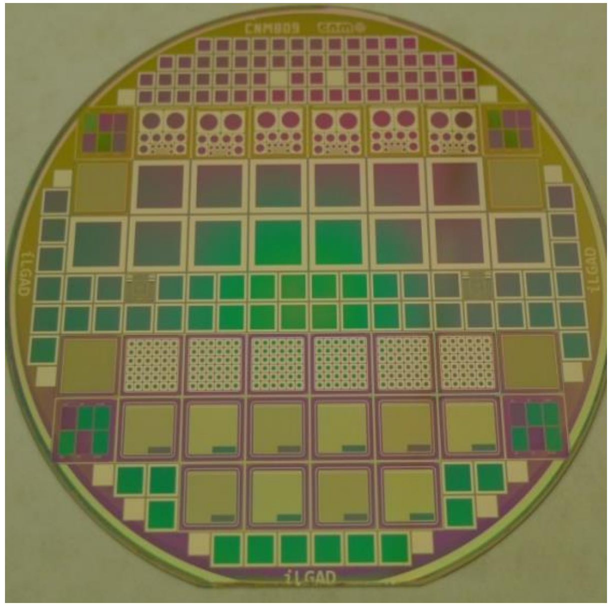
- Segmentation at the **ohmic contact**: strip and pixels.
- **Multiplication** extended over all the **CORE**.
- **P-type collector ring** at the ohmic side to extract leakage current.
- **JTE** to protect the n+/p curvature and **channel stopper** to avoid the depletion reaches the end of the detector.
- Readout is made by the strips/pixels: holes collection.



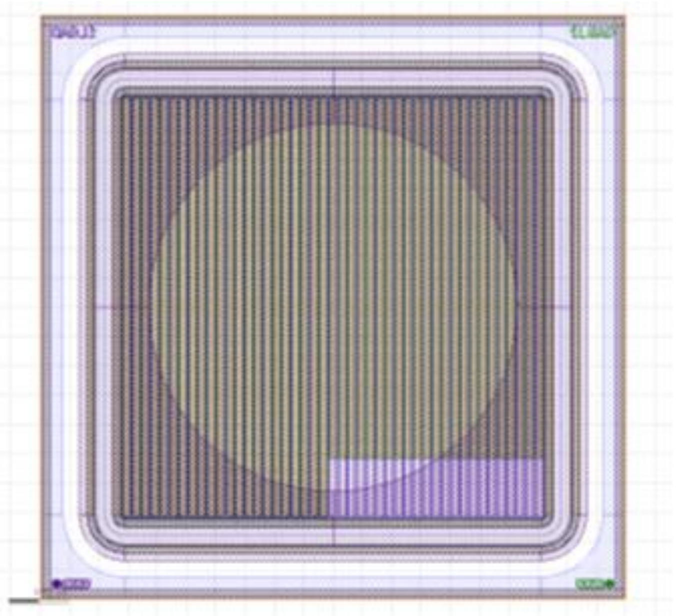
iLGAD First Generation (iLG1)

- 4-inch 285 µm p-type high resistivity wafers.
- More than **100** fabrication steps.
- **11 photolithographic steps**: double side fabrication process.
- **Pad-like**, **strip** and **pixelated** detectors.

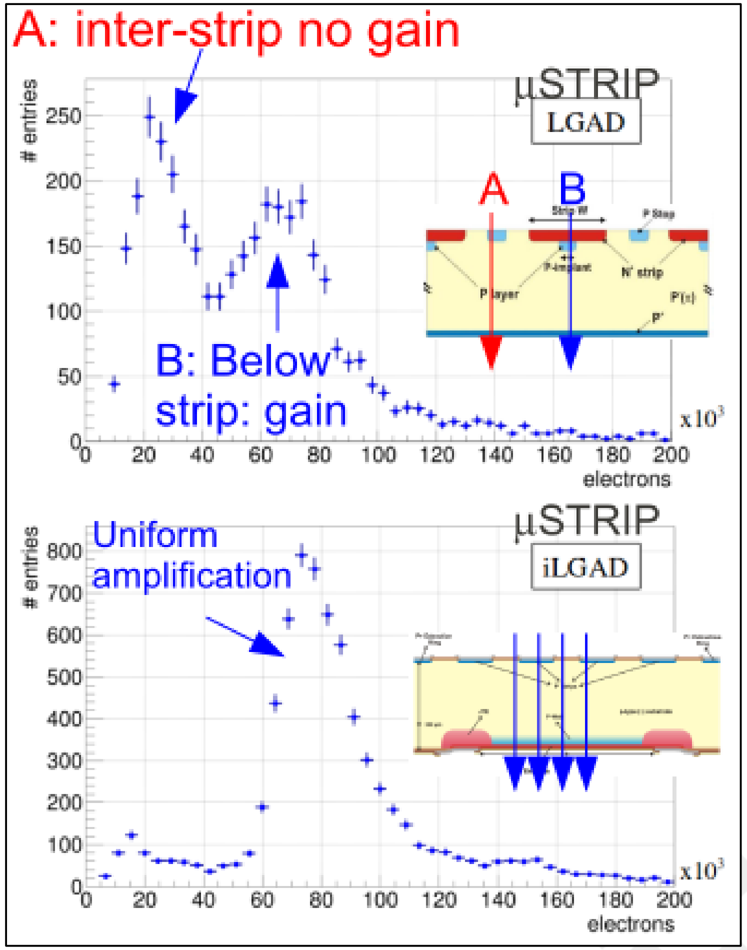
Mask design



µStrip iLGAD



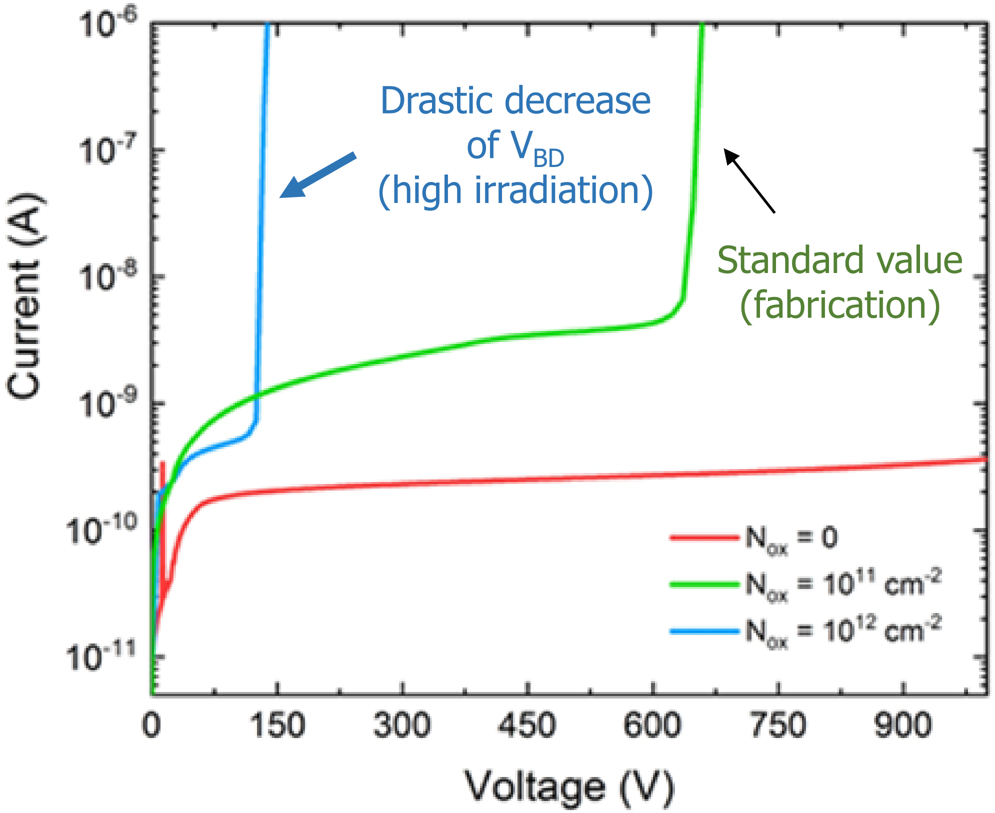
Test Beam Irradiation

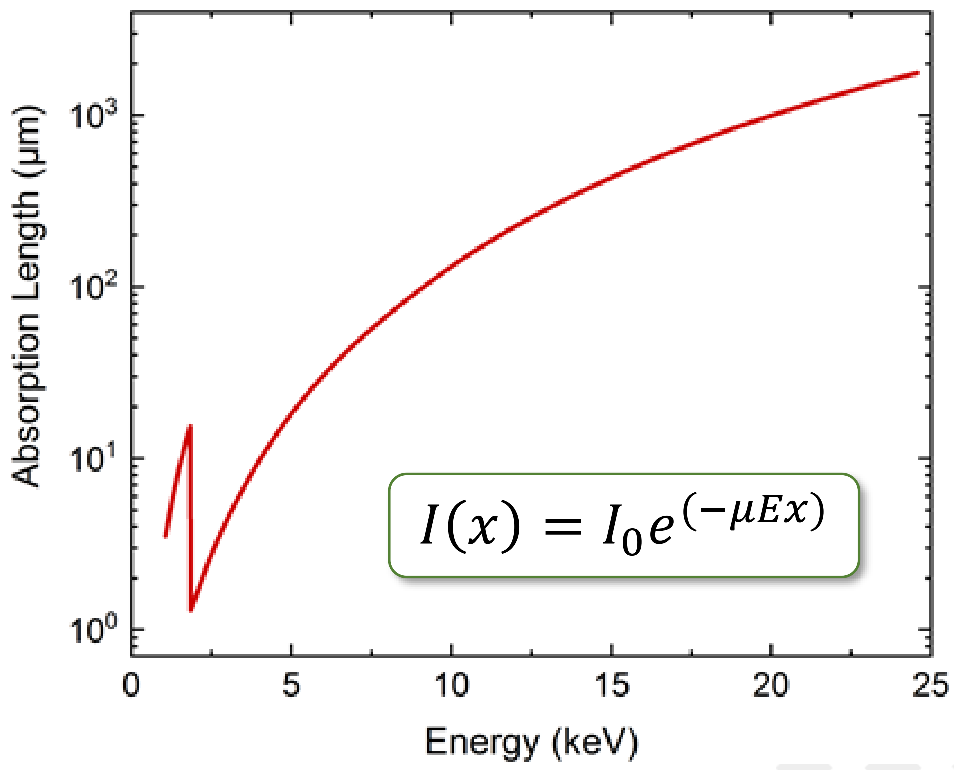


Currás, Esteban, et al. "Inverse Low Gain Avalanche Detectors (iLGADs) for precise tracking and timing applications." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 958 (2020): 162545.

Optimization for X-Ray irradiations

- We have carried out **TCAD simulations** to optimize the periphery of the iLGAD to cope with X-Ray irradiations.
- These sensors are expected to work at 10-15 keV. We need thick substrates (> 200 μm).
- Only **surface damage** is expected for this irradiation energy.
- Fixed charges (N_{ox}) at Si-SiO2 interface.



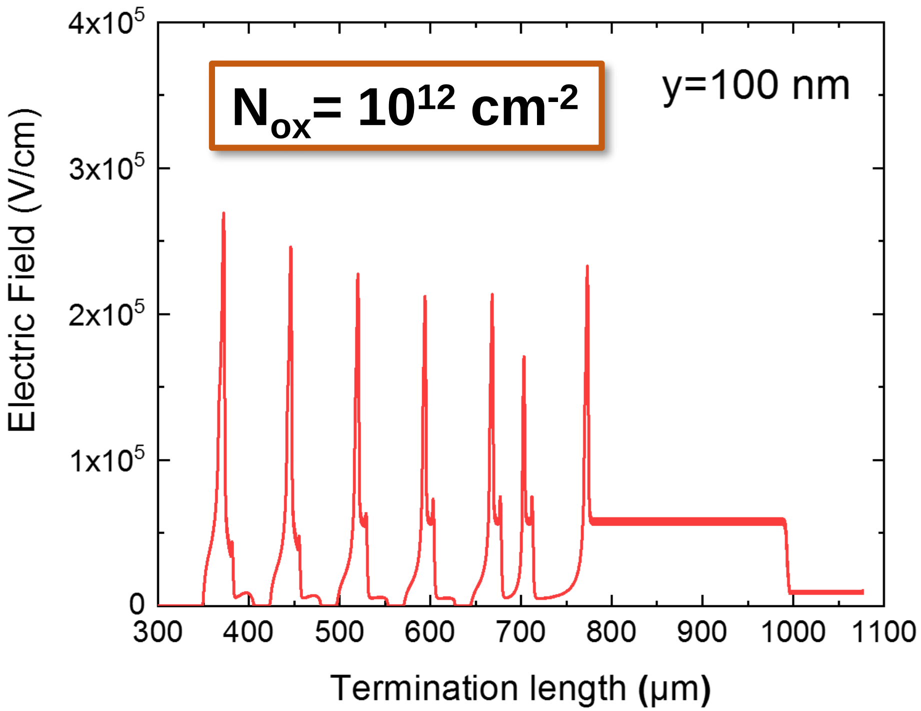


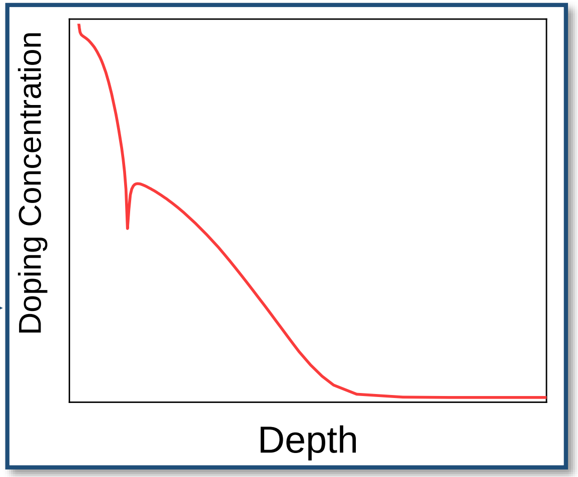
Data taken from: https://physics.nist.gov/PhysRefData/FFast/html/form.html

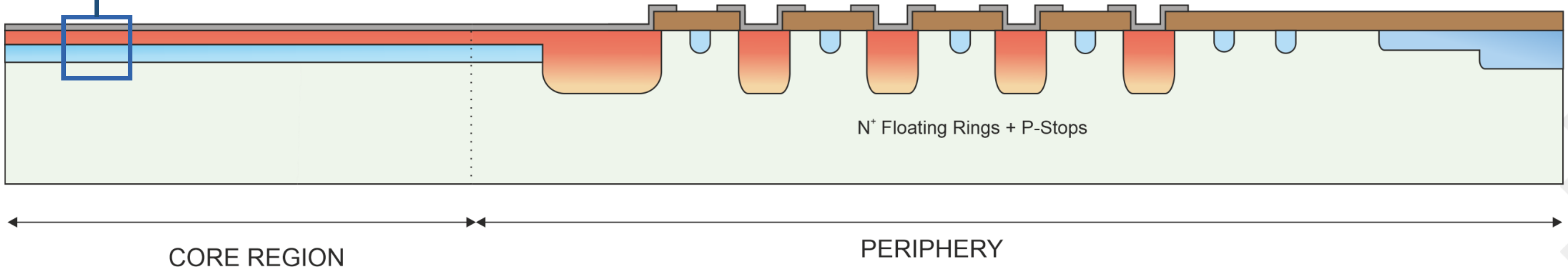
Optimization for X-Ray irradiations

Multiplication side

- We have optimized the multiplication side using n+ floating rings.
- Multiplication region (CORE) is already optimized with standard LGAD runs.





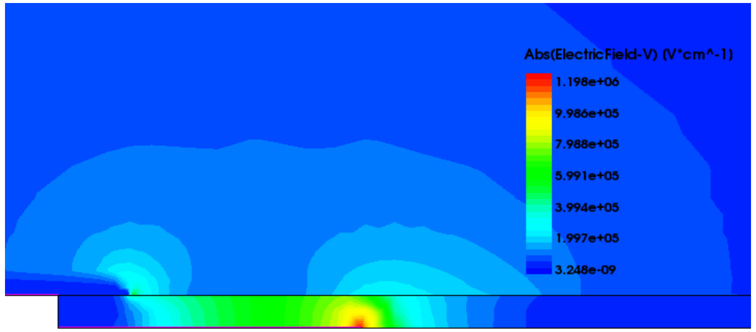


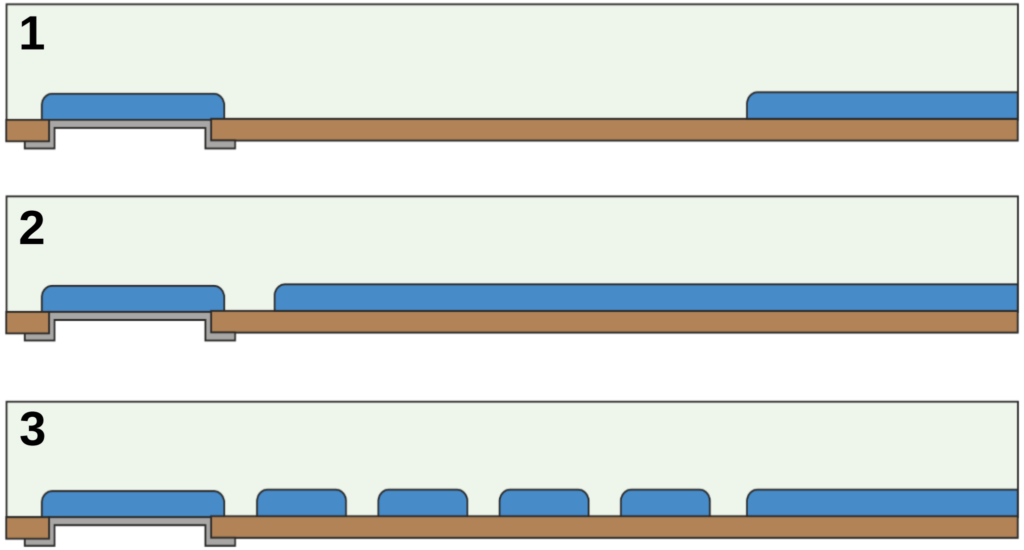
Optimization for X-Ray irradiations

Ohmic (pixels) side

$N_{ox} = 10^{12}\ cm^{-2}$

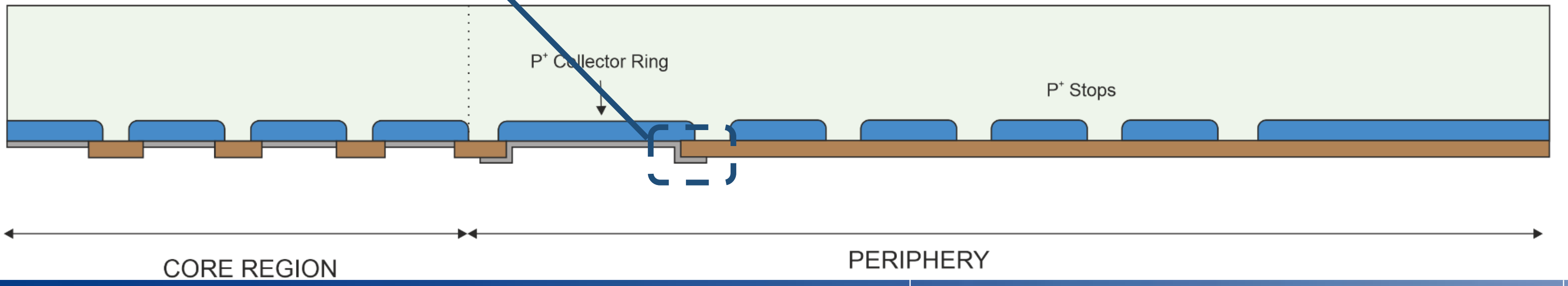
- We have optimized the ohmic side using p+ floating rings.
- Breakdown voltage is increased by using rings and a field-plate contact at the collector ring.





Structure	V_{BD} (V)
1	350
2	400
3	500

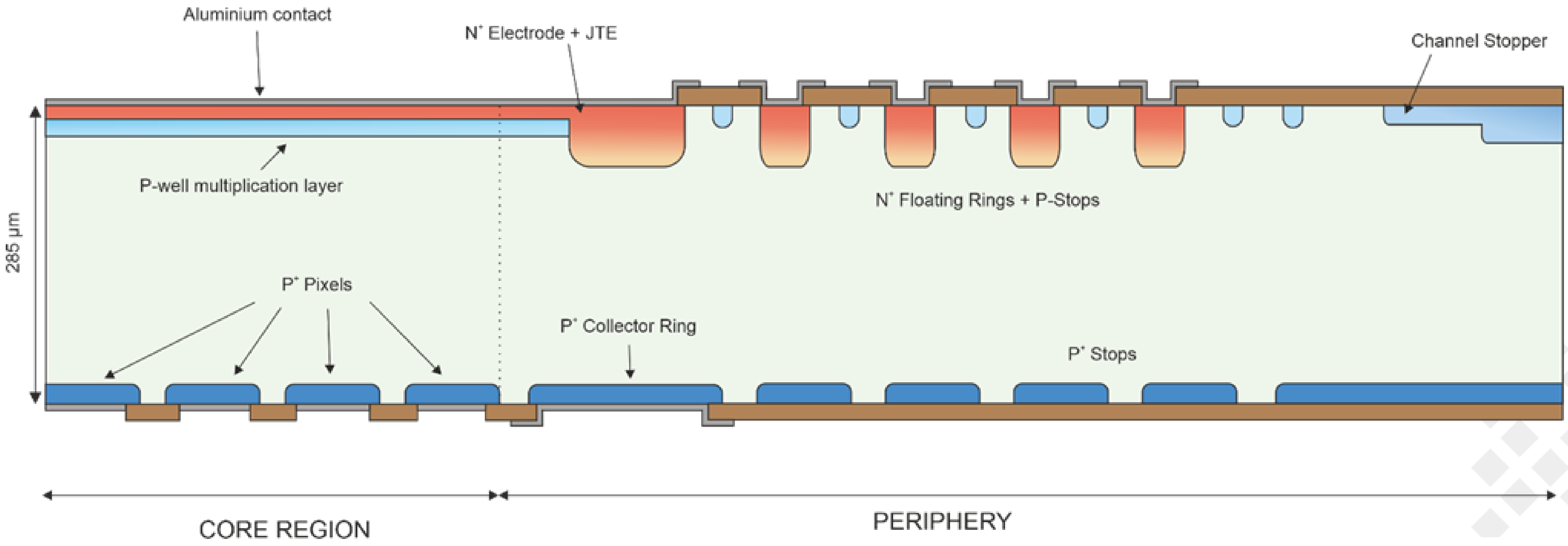
High electric field peaks at the edges of the p+ diffusions due to the conductive layer



Optimization for X-Ray irradiations

Final design

- We have fabricated a mask according with this simulations.
- The final design is able to support up to 500 V in a harsh radiation environment.



Optimization for X-Ray irradiations

Final design

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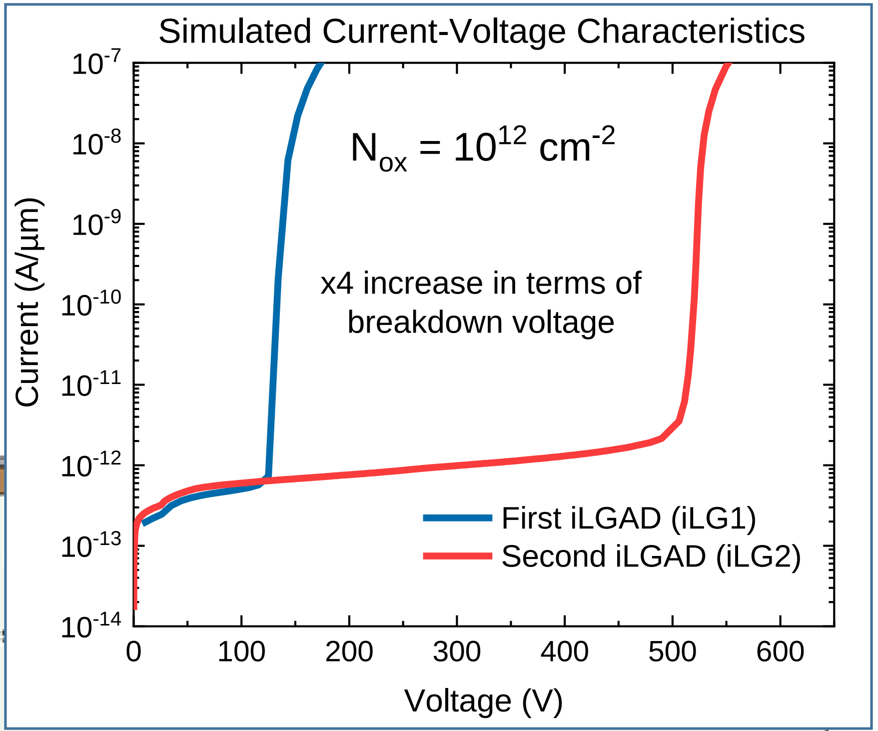
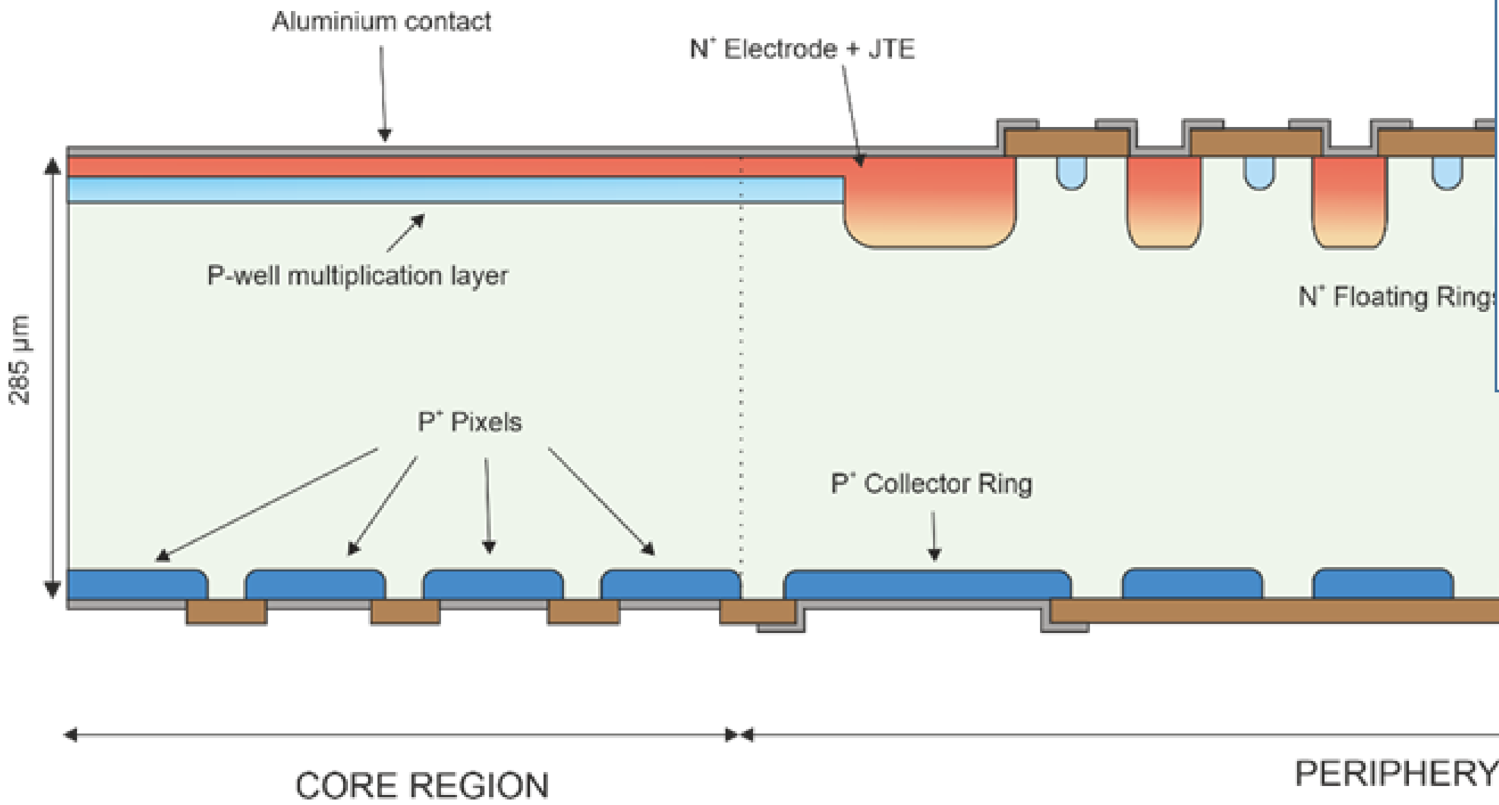
- **The final design is able to support up to 500 V in a harsh radiation environment.**

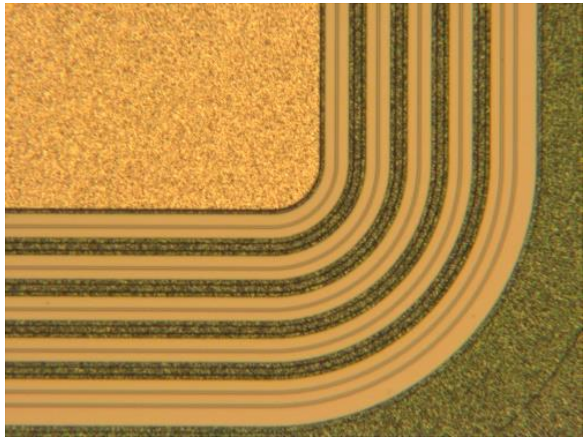




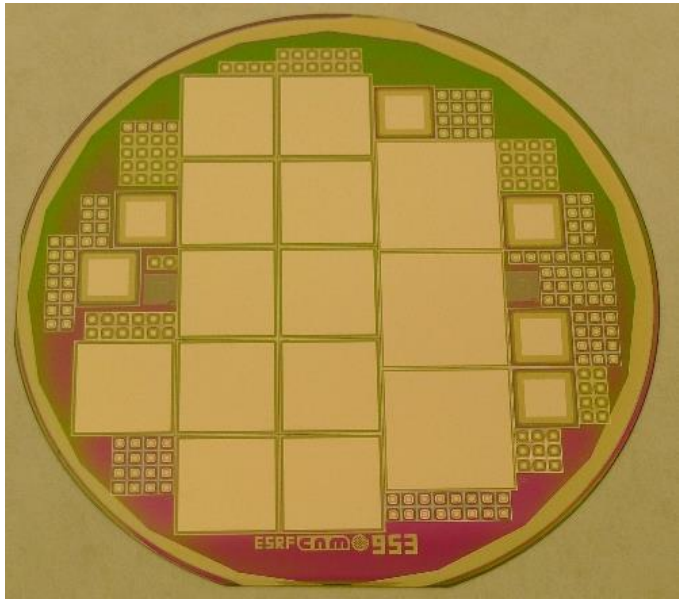
iLGAD Second Generation (iLG2): Run information

- We fabricated the second generation of iLGADs at IMB-CNM. In this case, the iLGAD is optimized for X-Ray applications.
- We have used p-type high resistivity (>10 kΩ·cm) 285 μm wafers.
- Same technological parameters as LGADs runs (AIDA2020 v2).
- 11 photolithographic steps and a total 105 steps.
- Double-side process. Pad, pixelated and strip detectors.

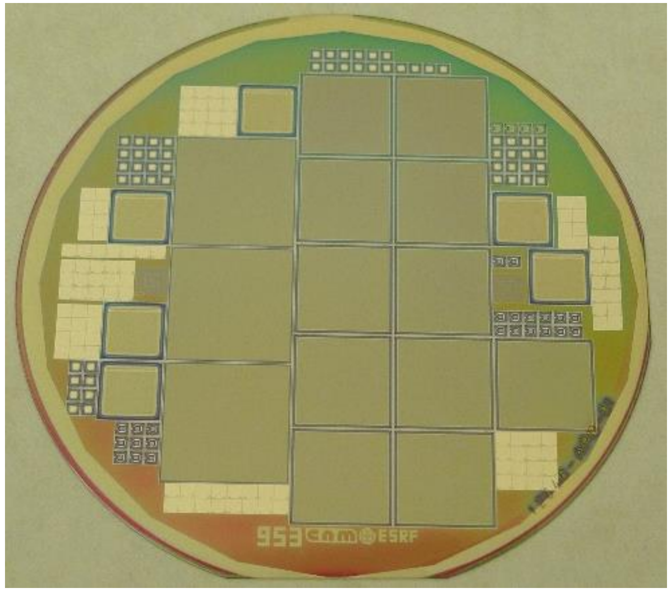
Guard Rings



Multiplication side



Ohmic side



This work has been partially supported by European Synchrotron Radiation Facility (ESRF)

iLGAD Second Generation (iLG2): IV/CV Measurements

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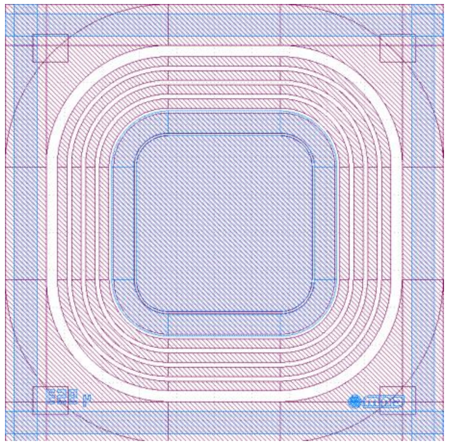
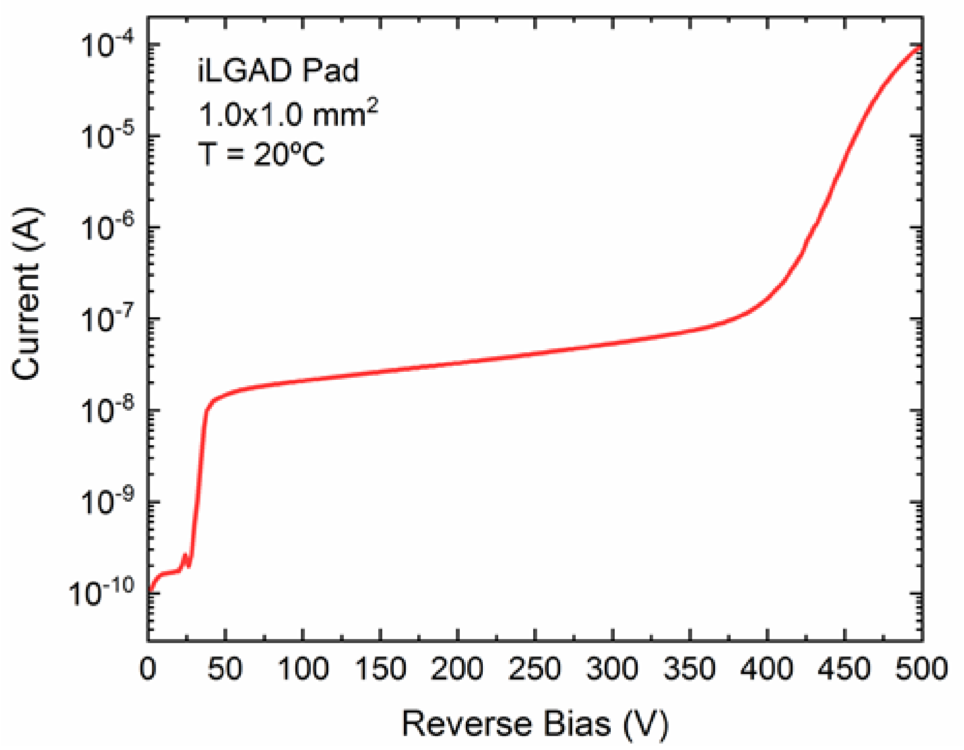
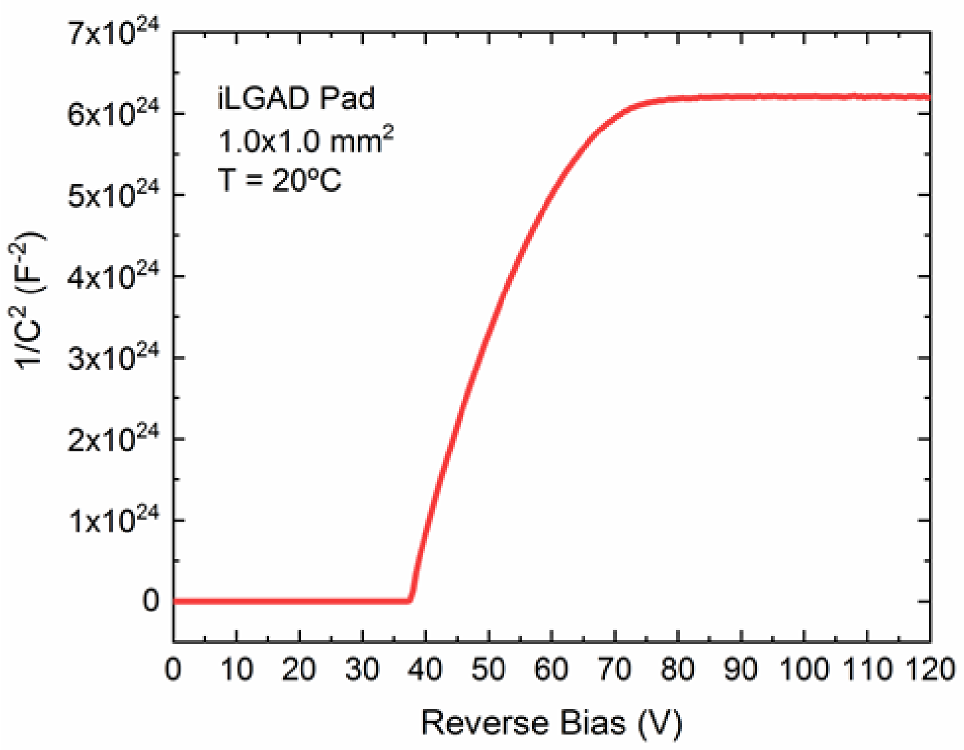
iLGAD Pad (1x1 mm²)

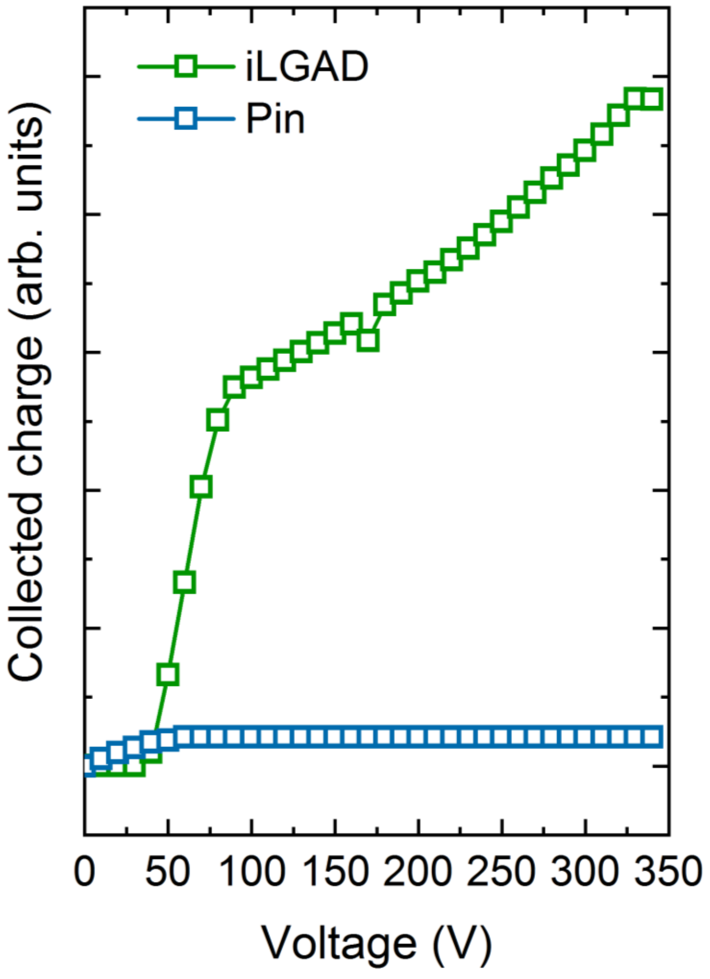


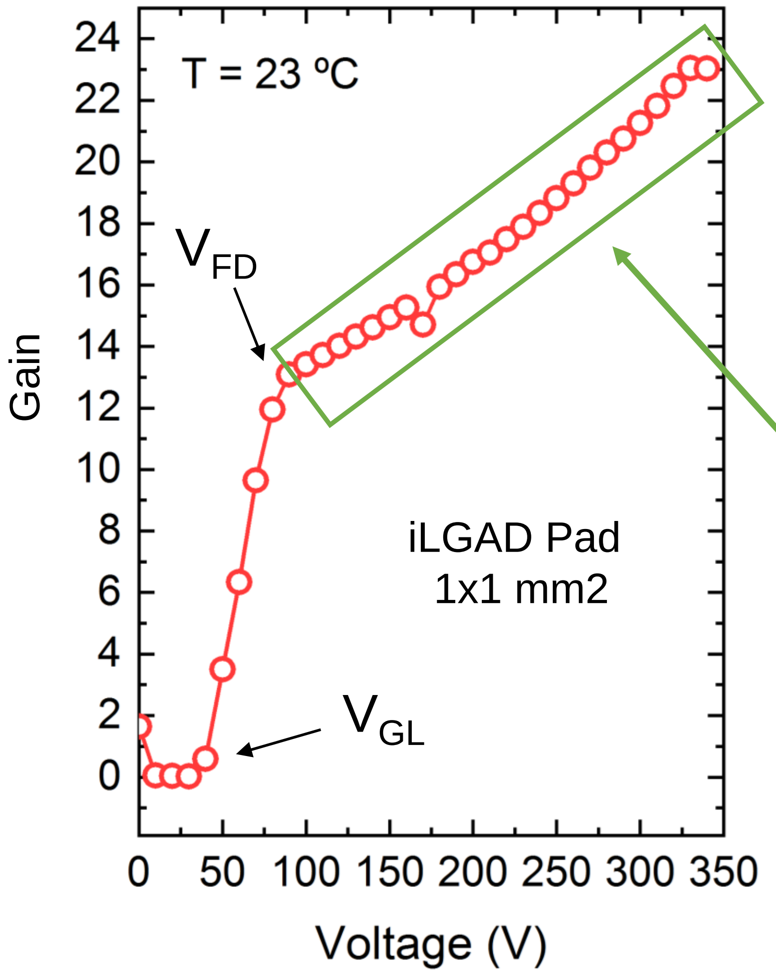




iLGAD Second Generation (iLG2): TCT Measurements

Collected charge and Gain





IR Laser (1064 nm)

V_{GL} = 38 V

V_{FD} = 70 V

V_{BD} = 400 V

Amplifier saturation at 360 V

Auto-triggering > 400 V

Linear gain of 12-24 between 70-350 V

iLGAD Second Generation (iLG2): MOS Capacitor C-V

Theoretical Flat-Band Voltage ($Q_{ox} = 0$)

$$V_{FB} = \phi_M - \phi_S = 4.25 - \left(4.15 - \frac{1.12}{2} - \phi_B\right)$$

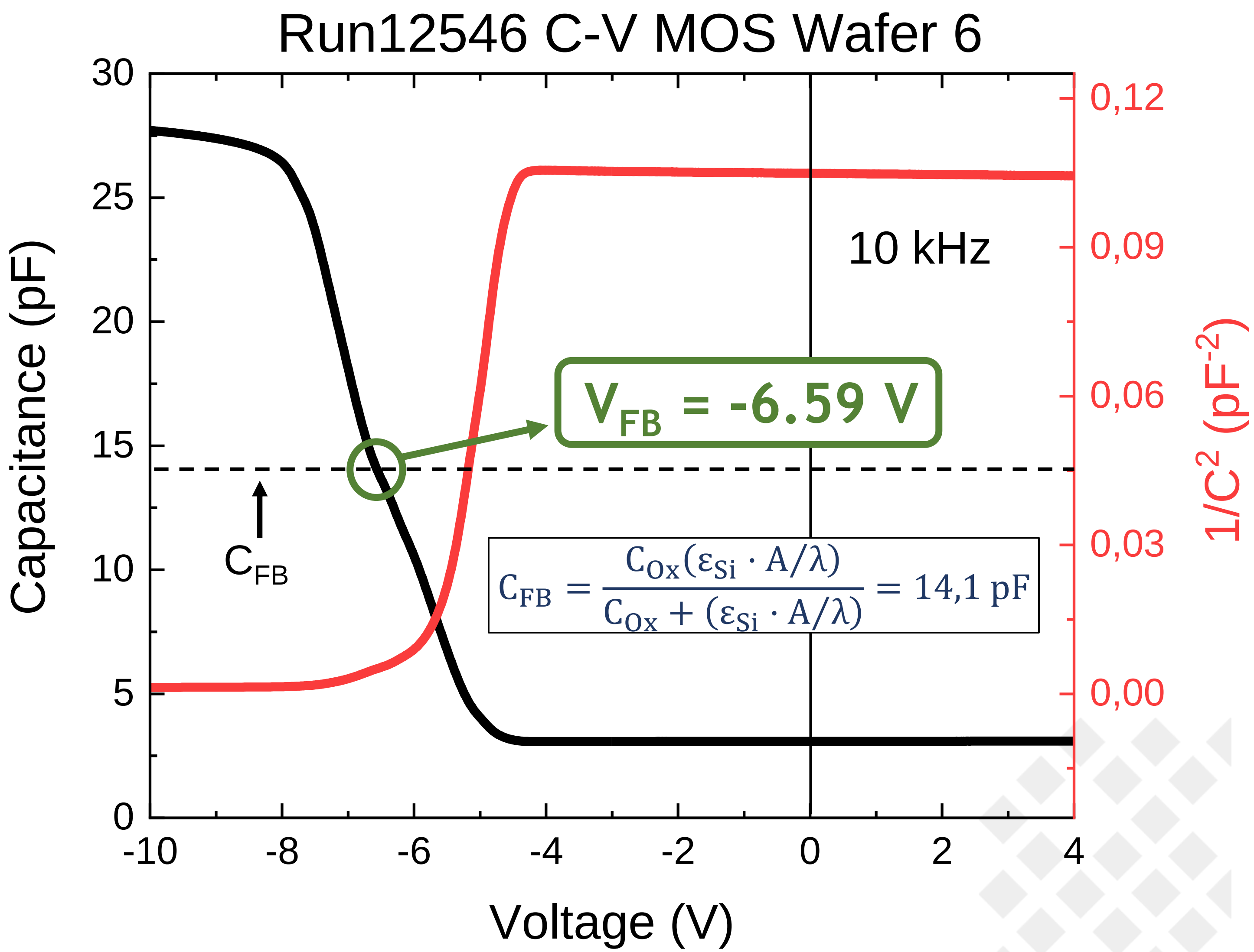
$$= \boxed{-0.58\ \mathrm{V}}$$

$$\phi_B = \frac{k_B T}{q} \ln\left(\frac{N_{bulk}}{N_i}\right)$$

$$Q_{ox} = \frac{C_{ox}(\phi_{MS} - V_{FB})}{q}$$

$Q_{ox} \approx 10^{11}\ \mathrm{cm}^{-2}$

Dieter K. Schroder "Semiconductor Material and Device Characterization" Third Edition (2006)



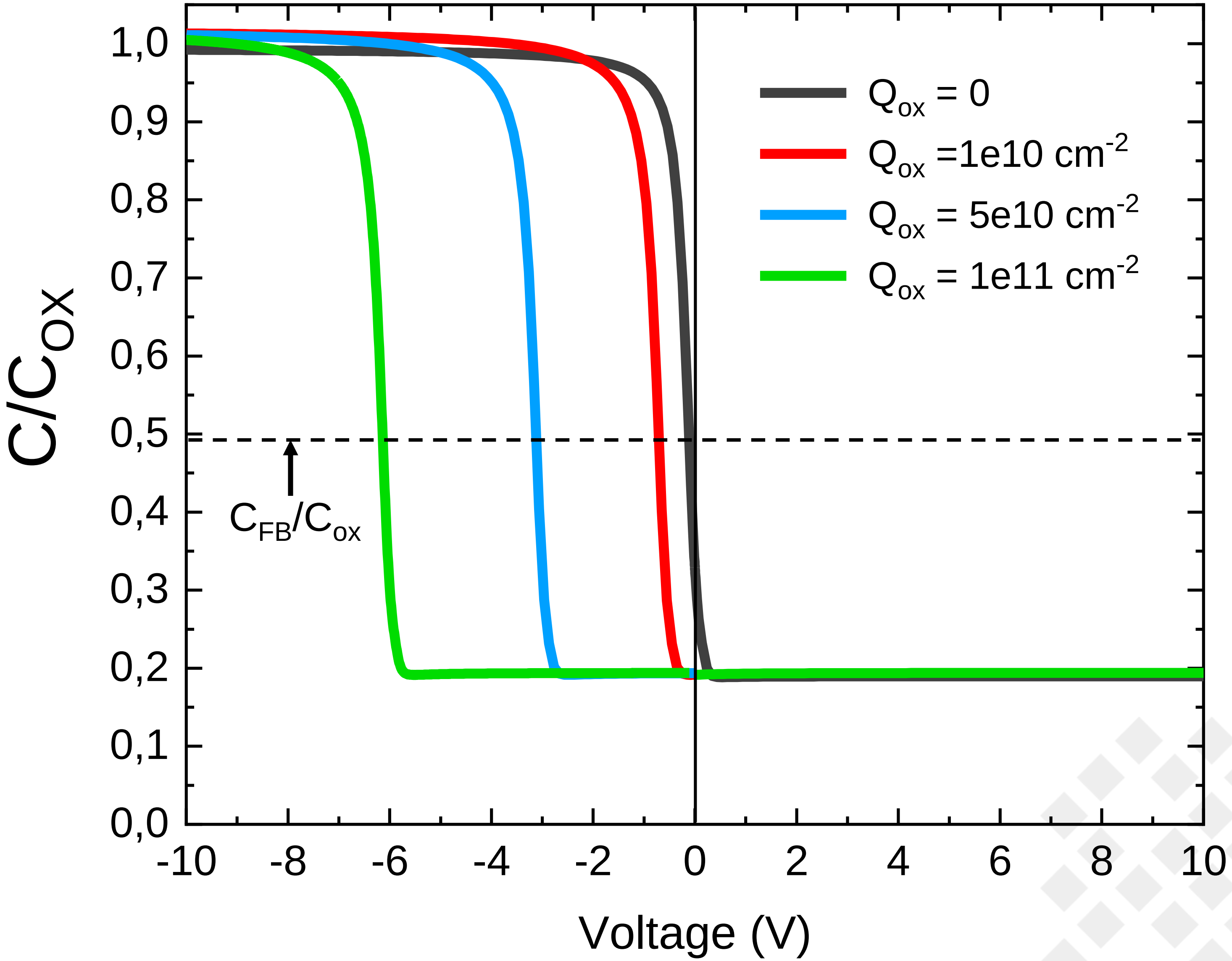
TCAD Simulation of the MOS C-V Measurement

Simulated Flat-Band Voltage

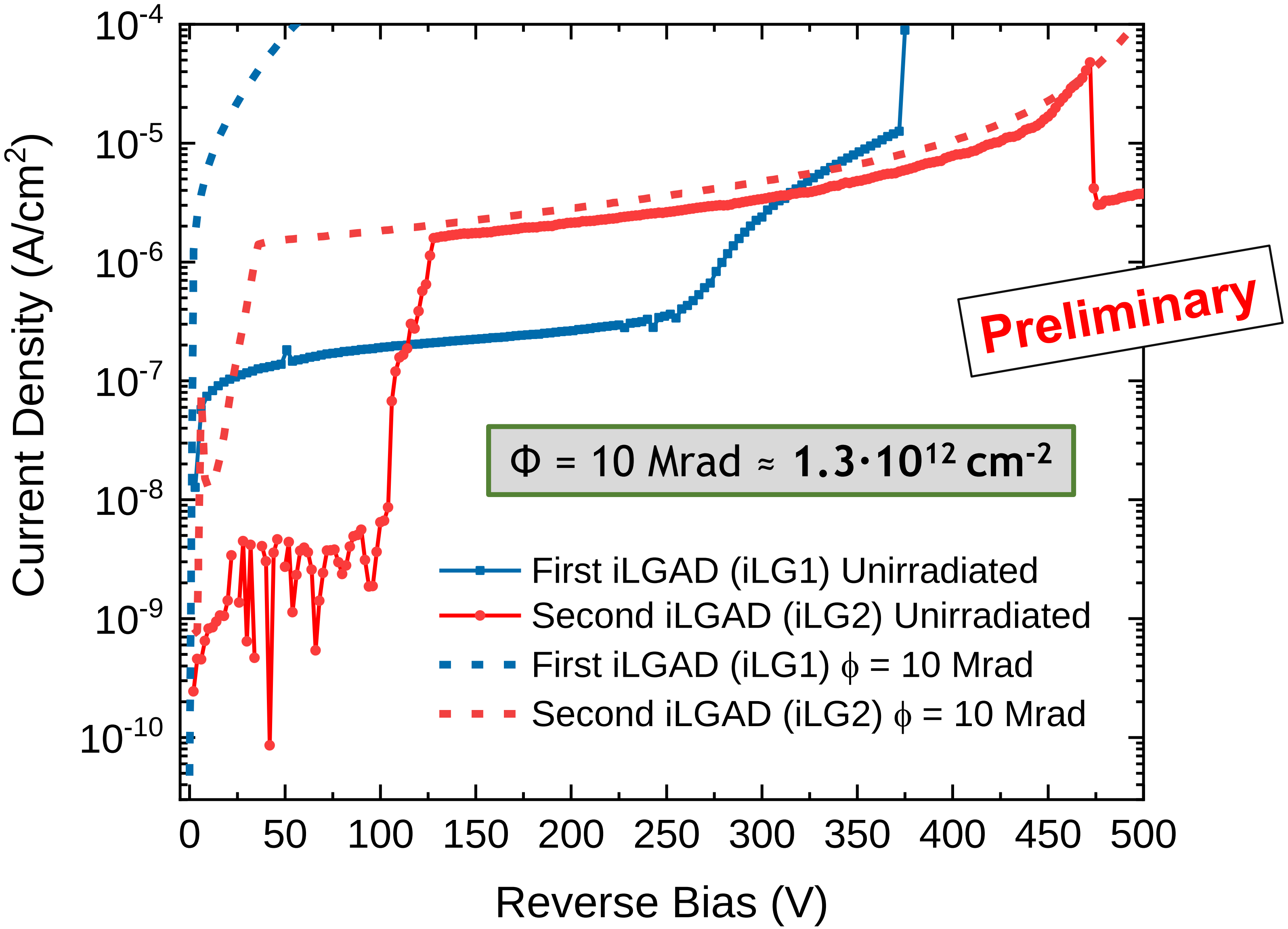
$$\frac{C_{FB}}{C_{OX}} = \frac{(\varepsilon_{Si} \cdot A/\lambda)}{1 + (\varepsilon_{Si} \cdot A/\lambda)} = 0,49$$

Q_{ox} (cm^{-2})	V_{FB} (V)
0	0.07
$1 \cdot 10^{10}$	-0.7
$5 \cdot 10^{10}$	-3
$1 \cdot 10^{11}$	-6.1

Similar result between experimental C-V and simulated



X-Ray Irradiations at Glasgow University

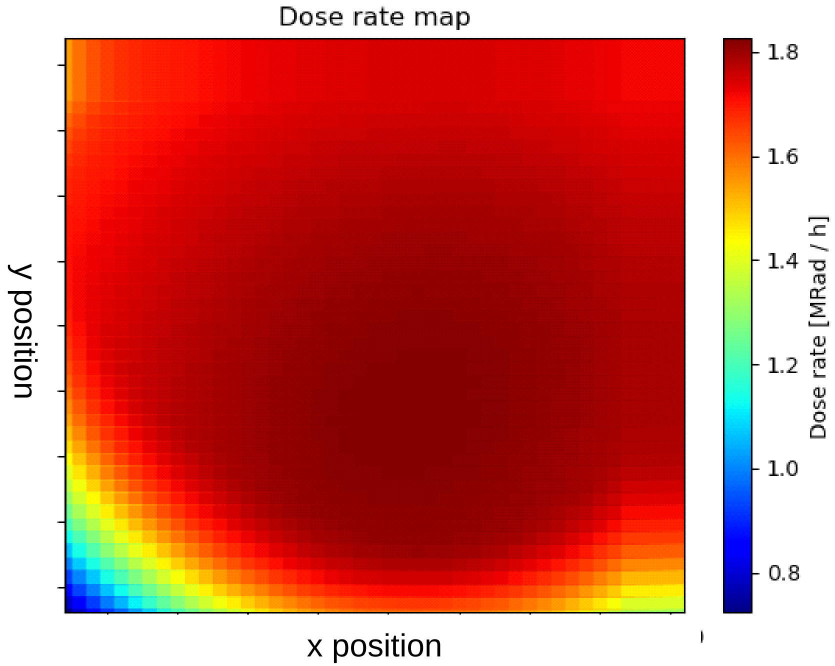


Irradiation conditions

Dose rate = 1.8 Mrad/h

$V_{applied}$ = 50 kV

I = 60 mA



Irradiations performed at University of Glasgow (D. Maneuski)

Conclusions and future work

- We have designed a new periphery for the iLGAD to be used for X-Ray applications.
- Multiplication and ohmic side have been optimized by means of TCAD simulations.
- A new mask has been fabricated with this new design. The sensors have been produced at the IMB-CNM clean room.
- Pad diodes have been characterized showing the expected gain.
- MOS capacitors are measured to obtain the value of the charge in the oxide. A value of 10^{11} cm^{-2} has been found, which is the expected during a fabrication (and checked with the simulation).
- First results in a X-Ray irradiation show that the iLGAD with the new design is able to support more voltage than the first generation.

Future work:

- Comprehensive characterization of irradiated (X-Ray) iLGADs with a dose of 100 Mrad.
- Tests in other X-Ray laboratories.

Thank you for your attention