# Characterization of the last CNM fabrication of carbonated LGADs

## Last 43rd RD50 Workshop

CERN

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Radiation Detectors Group

Centro Nacional de Microelectrónica CSIC

CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

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# Outline

- Challenges in the production of LGADs for ATLAS & CMS
- Review of CNM LGAD Runs
- Run 15973
  - Characterization of LGADs (single-pad diodes) before irradiation
  - Yield of pixelated LGADs from CNM Run 15973 (IVs with temporary metal)
  - Characterization of irradiated LGADs (single pad diodes)
- Upcoming work

# Challenges in the production of LGADs for ATLAS & CMS

## Main challenges:

I. Technology long-term reliability
   - Trade-off between $V_{BD}$, $V_{FD}$ and gain **before irradiation**
   - Trade-off between gain and operation voltage (< 11 V/µm) **after irradiation**

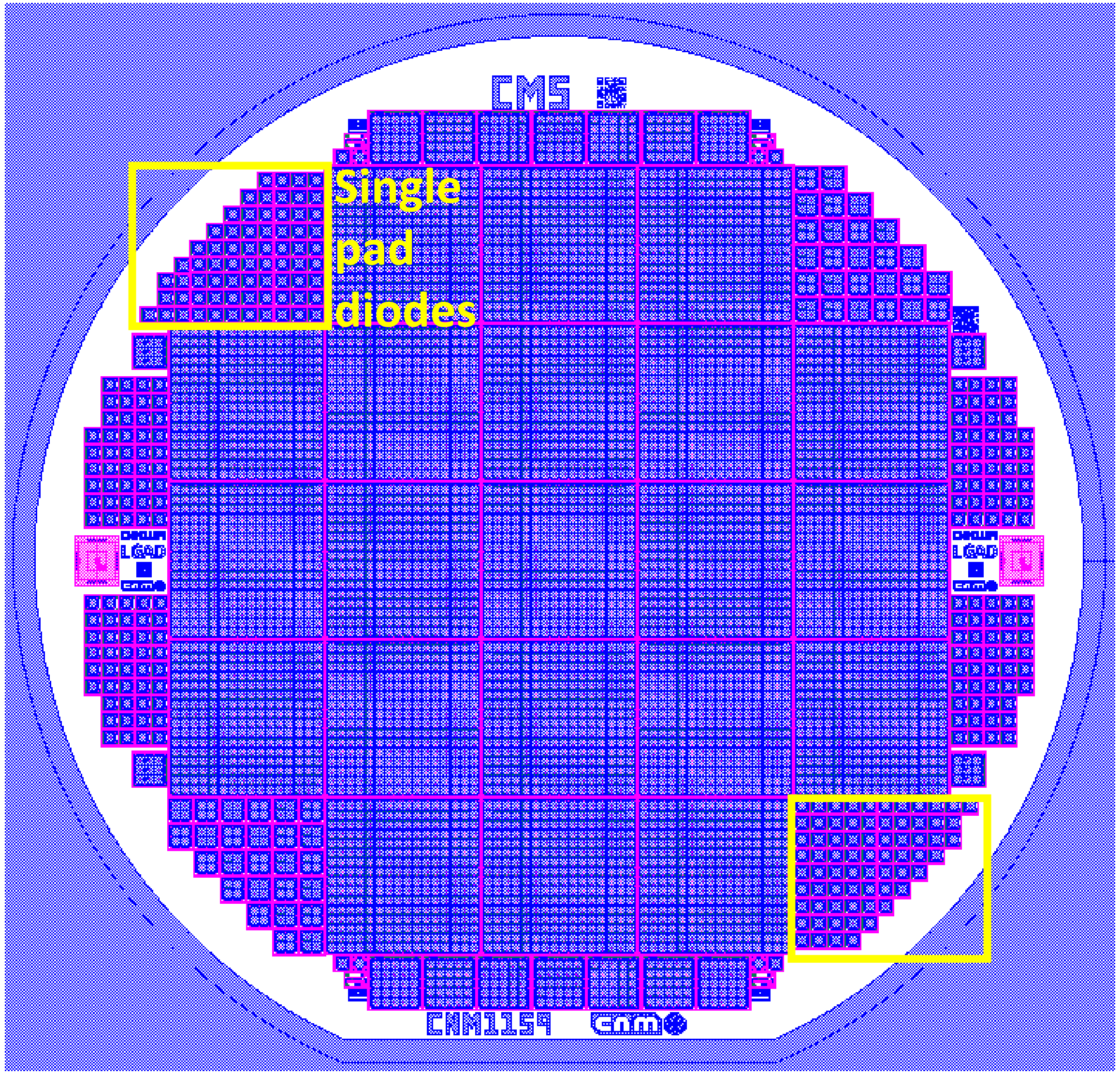
II. Large scale manufacturing yield
   - Pixelated sensors of **15x15** pixels of 50 µm x 1.3x1.3 mm$^2$ (**ATLAS**)
   - Pixelated sensors of **16x16** pixels of 50 µm x 1.3x1.3 mm$^2$ (**CMS**)

III. Radiation tolerance to neutrons and protons
   - **Carbonation** of devices
   - **4 fC** @ V < 11 V/µm @ **2.5e15** $1MeV\ n_{eq}/cm^2$ @ **-30ºC** (**ATLAS**)
   - **8 fC** @ V < 11 V/µm @ **1.5e15** $1MeV\ n_{eq}/cm^2$ @ **-25ºC** (**CMS**)

IV. Improve fill-factor
   - **IP = 47 µm** for pixelated devices of big area (**ATLAS**)
   - **IP = 80 µm** for pixelated devices of big area **(CMS)**

# Review of CNM LGAD Runs

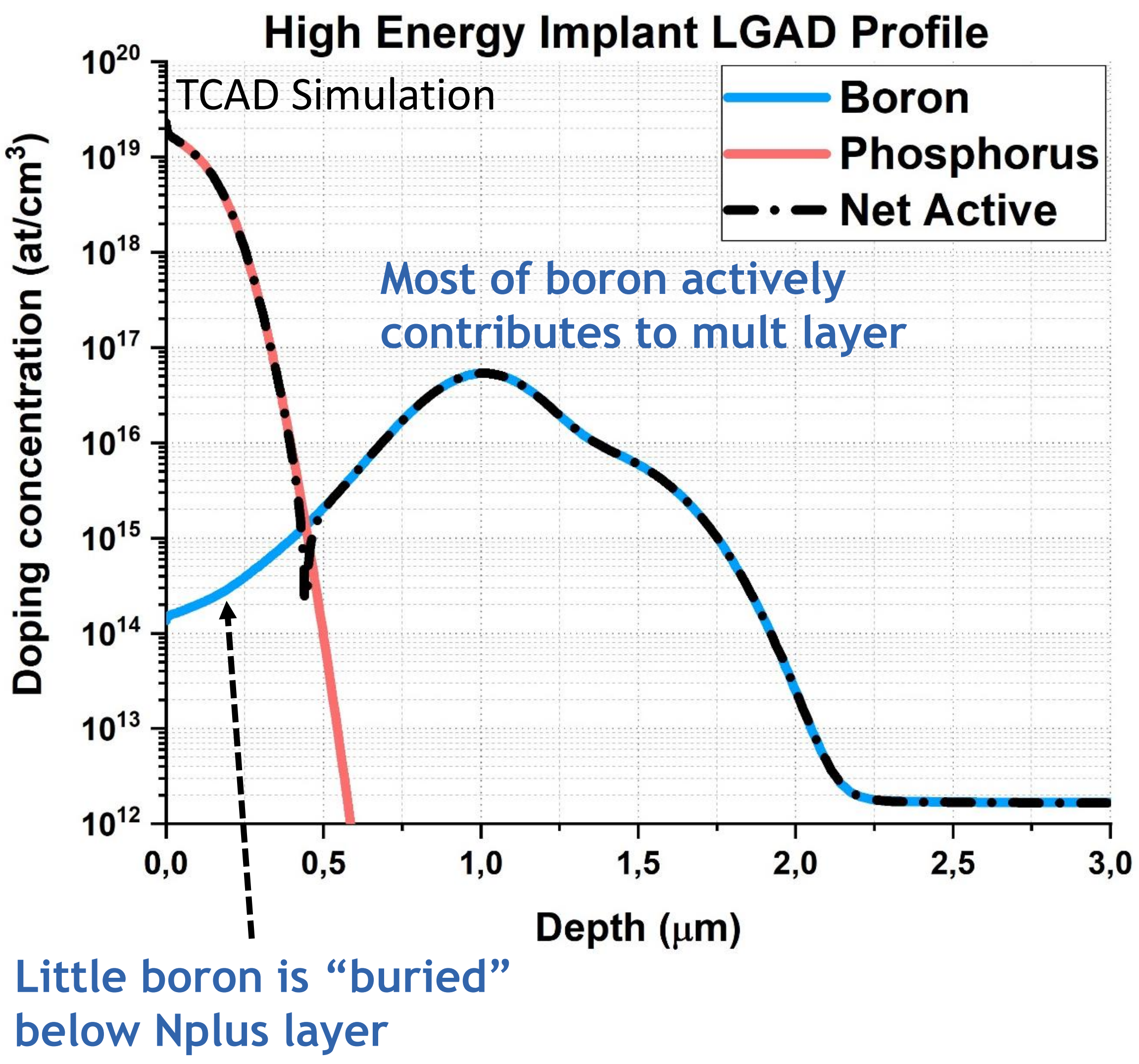
# CNM Run16602 (ongoing) : Overview




| Wafer | Boron dose/ Boron Energy | Carbon dose/Energy |
|---|---|---|
| 1 | 2.5e12/cm² / 480keV | 5e13/cm² / 480keV |
| 2 | 2.6e12/cm² / 480keV | |
| 3 | 2.7e12/cm² / 480keV | |

- CMS Mask: 21 Pixelated sensors of 16x16 pixels of 50 μm x 1.3x1.3 mm², IP = 80 μm and high-energy implant profiles
- 3 boron doses and 1 carbon dose
- 6LG2 technology (LGADs on 6" Si-Si wafers and 350 μm of handle wafer) but with CNM clean-room new equipment
- Status : Metallization (85%)
- To be finished within 1 month
- 6 extra wafers on hold before carbon and multiplication layer implantation

# CNM Run16602 (ongoing) : High Energy Implant profiles

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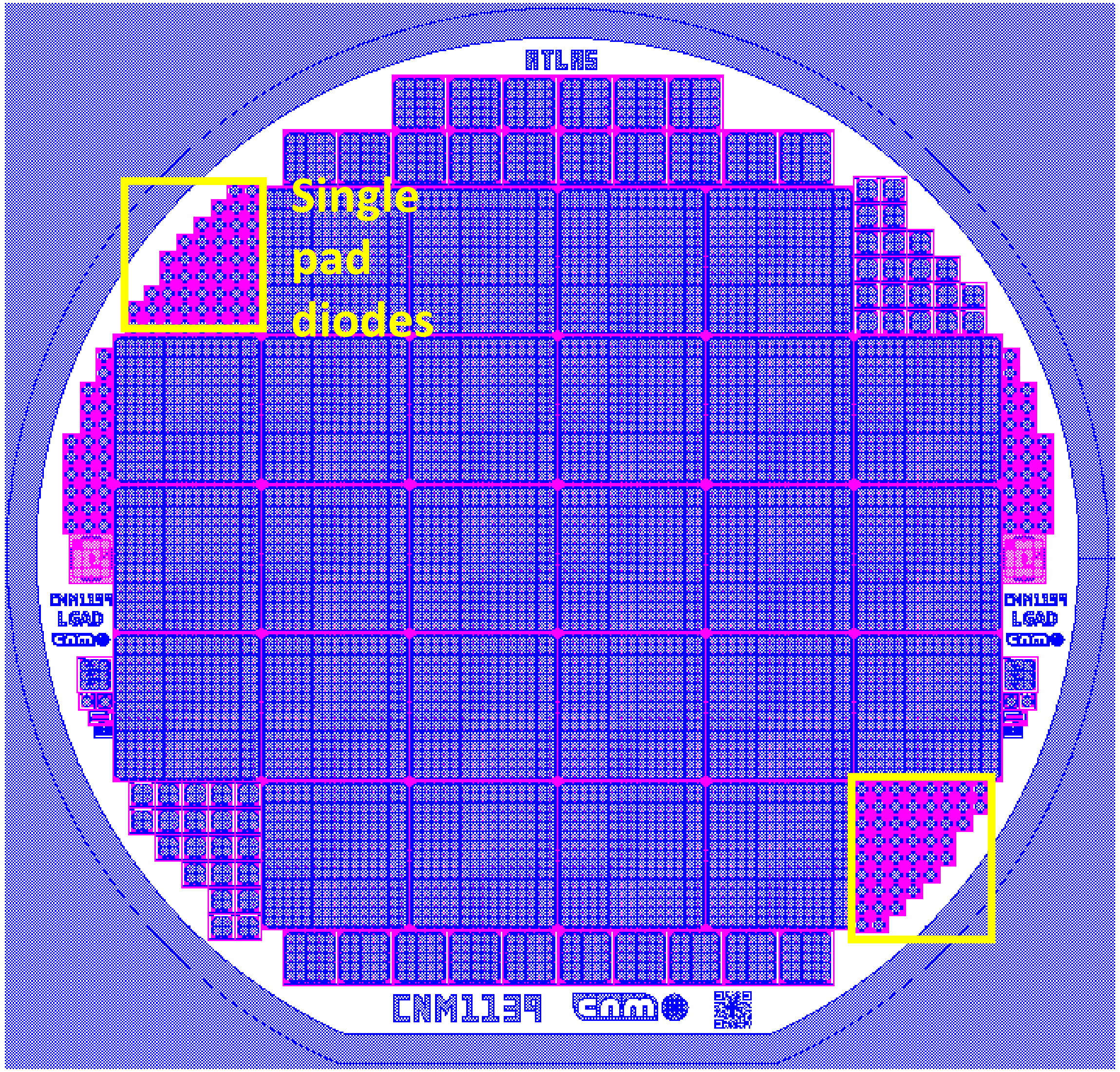
- **CMS Mask**: 21 Pixelated sensors of **16x16** pixels of 50 µm x 1.3x1.3 mm², **IP = 80 µm** and **high-energy implant** profiles
- 3 boron doses and 1 carbon dose
- **6LG2** technology (LGADs on 6'' Si-Si wafers and 350 µm of handle wafer) but with **CNM** clean-room **new equipment**
- Status : **Metallization (85%)**
- To be finished within 1-2 months
- **6 extra wafers** on hold before carbon and multiplication layer implantation

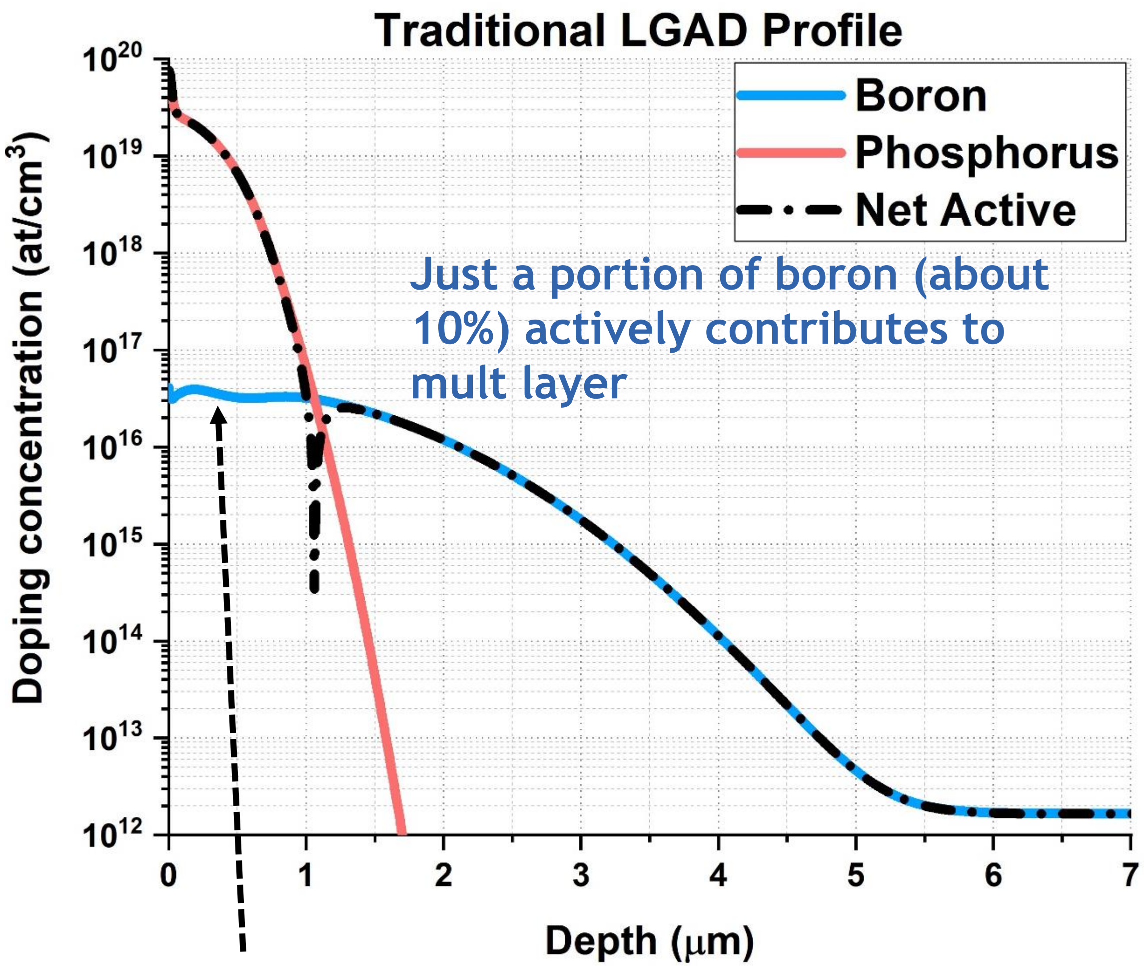
# CNM Run15973 : Overview




| Wafer | Boron dose (1e13/cm²) / Energy (keV) | Carbon dose (1e14/cm²) / Energy (keV) |
|---|---|---|
| 1 | 1.9 / 100 | - |
| 2 | | 1 / 150 |
| 3 | | 2 / 150 |
| 4 | | 3 / 150 |
| 5 | | 6 / 150 |
| 6 | | 9 / 150 |
| 7 | | 3 / 150 |
| 8 | | 6 / 150 |

- **ATLAS Mask**: 26 Pixelated sensors of **15x15** pixels of 50 μm x 1.3x1.3 mm² and **IP = 47 μm** and **traditional LGAD profiles**
- **6LG2** technology (LGADs on 6'' Si-Si wafers and 350 μm of handle wafer) but with **CNM** clean-room **new equipment**
- Single pad devices from wafers 1-6 were used for evaluation of radiation tolerance and electrical parameters trade-off
- Pixelated devices of wafer 7 were measured with temporary metal for yield evaluation

# CNM Run15973 : Traditional LGAD profiles




Most of boron is "buried" below Phosphorus (Nplus)

| Wafer | Boron dose / Energy | Carbon dose (1e14/cm²) / Energy (keV) |
|---|---|---|
| 1 | 1.9e13 / 100 keV | - |
| 2 | | 1 / 150 |
| 3 | | 2 / 150 |
| 4 | | 3 / 150 |
| 5 | | 6 / 150 |
| 6 | | 9 / 150 |
| 7 | | 3 / 150 |
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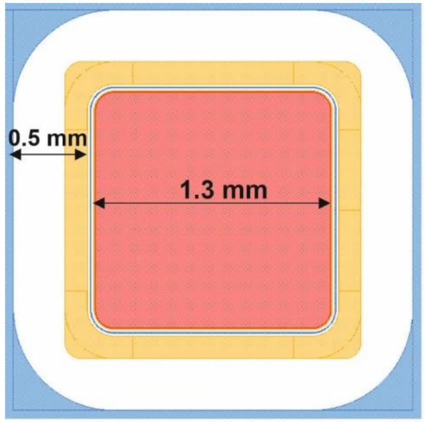
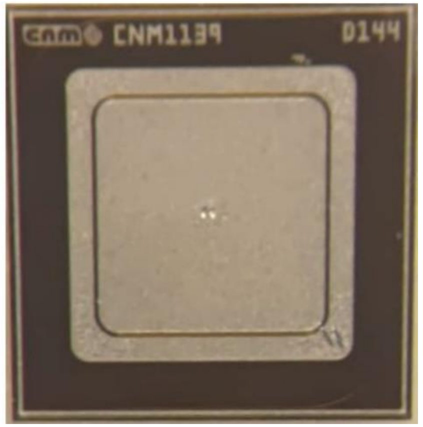
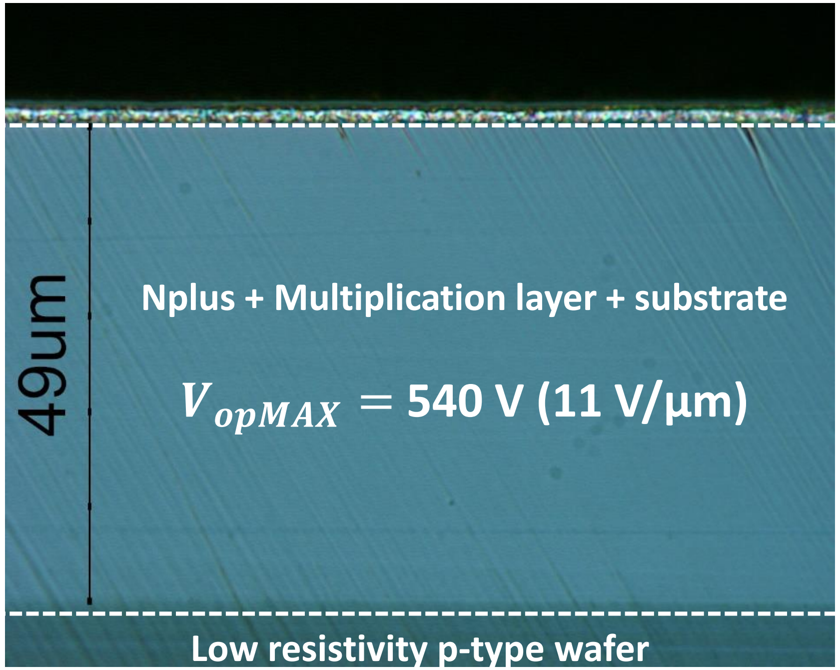
# CNM Run15973 : Microsection of a single-pad diode




| Wafer | Boron dose (1e13/cm²) / Energy (keV) | Carbon dose (1e14/cm²) / Energy (keV) |
|---|---|---|
| 1 | 1.9 / 100 | - |
| 2 | | 1 / 150 |
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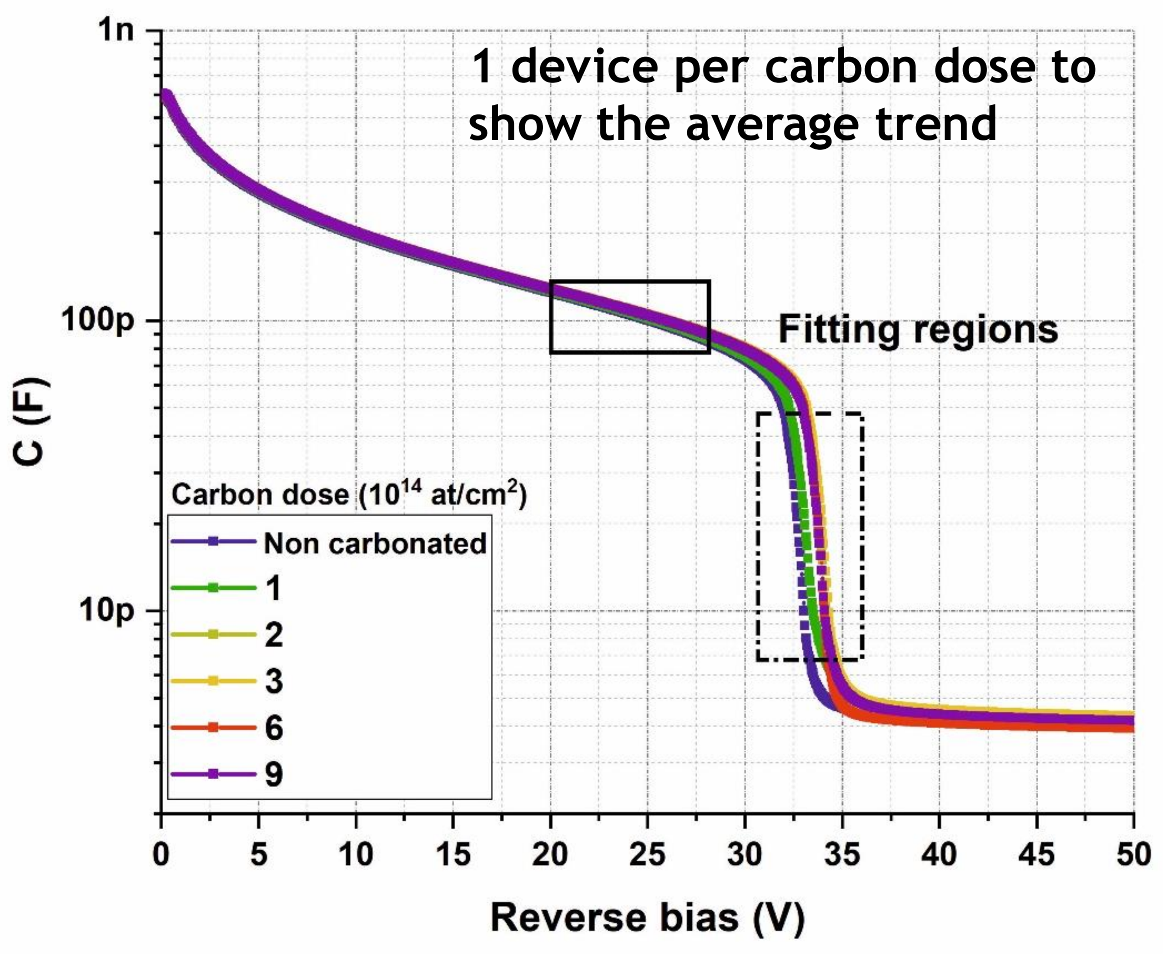
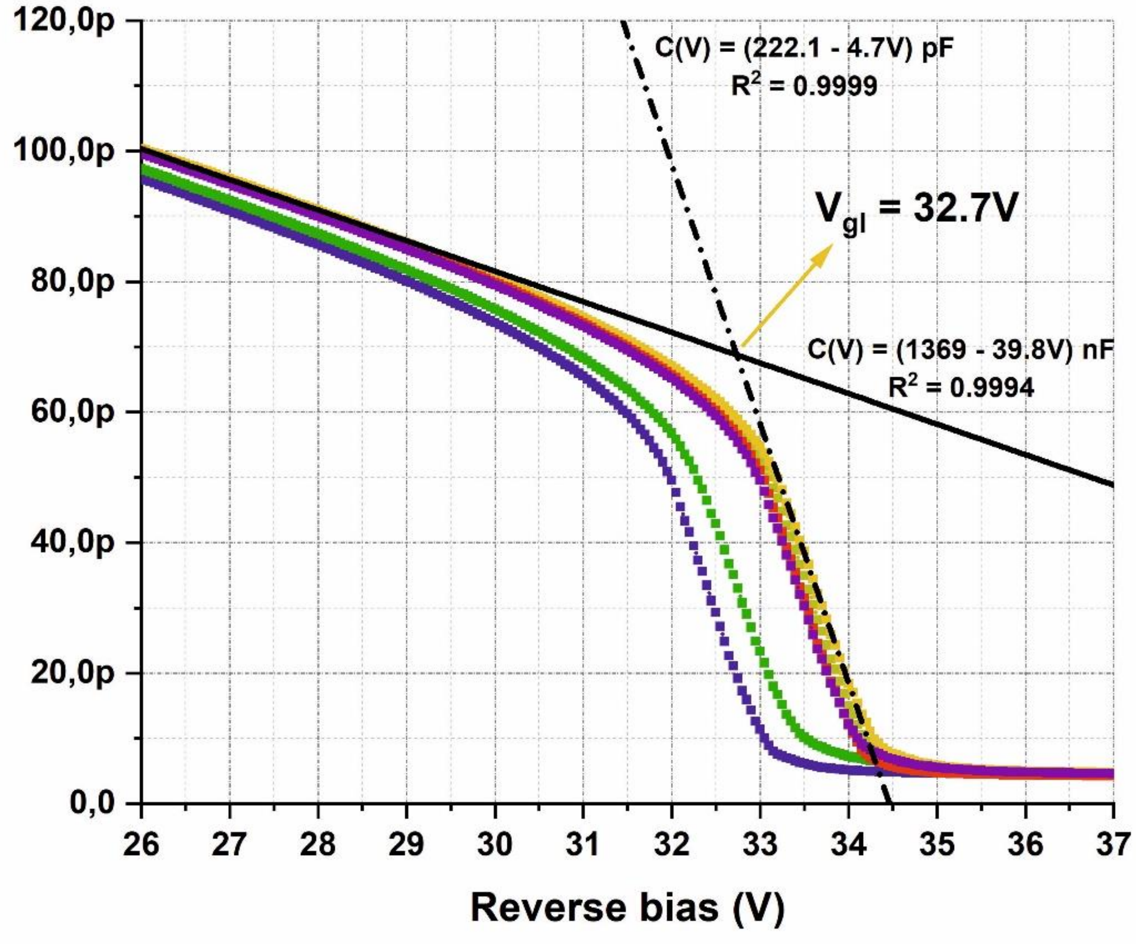
- ATLAS Mask: 26 Pixelated sensors of 15x15 pixels of 50 µm x 1.3x1.3 mm² and IP = 47 µm and traditional LGAD profiles
- 6LG2 technology (LGADs on 6'' Si-Si wafers and 350 µm of handle wafer) but with CNM clean-room new equipment
- Single pad devices from wafers 1-6 were used for evaluation of radiation tolerance and electrical parameters trade-off
- Pixelated devices of wafer 7 were measured with temporary metal for yield evaluation

# Characterization of single-pad diodes from CNM Run 15973 before irradiation

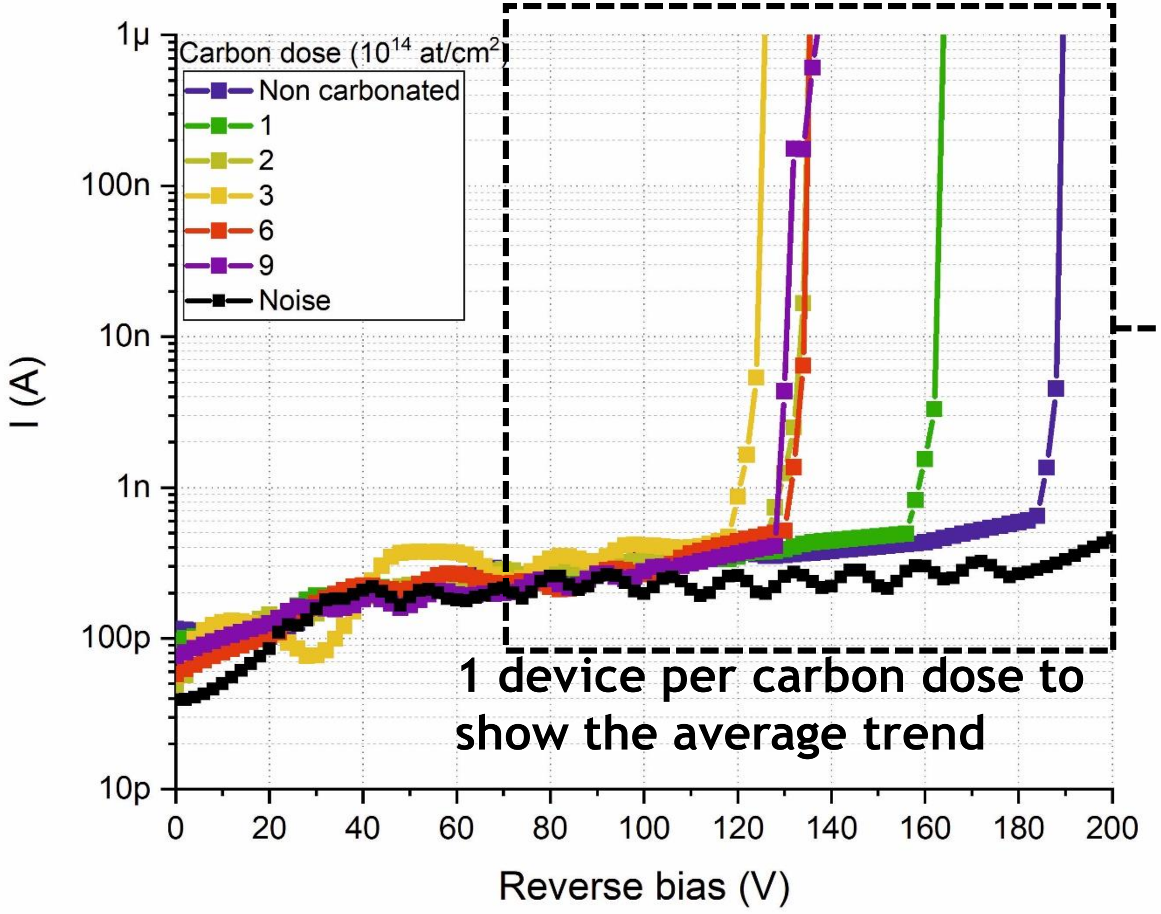
# Determination of $V_{gl}$ for non-irradiated devices

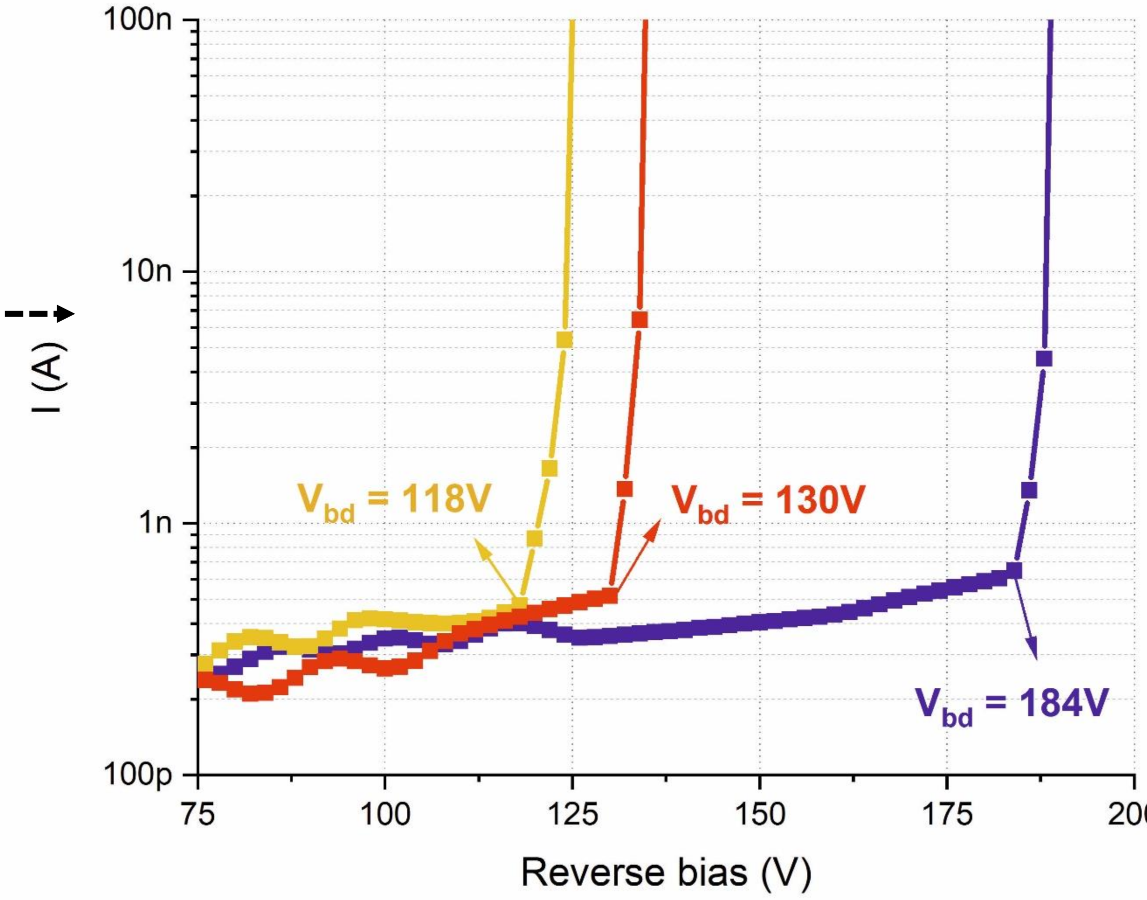
## CV measurements at 20ºC, 10kHz and 500 mV AC



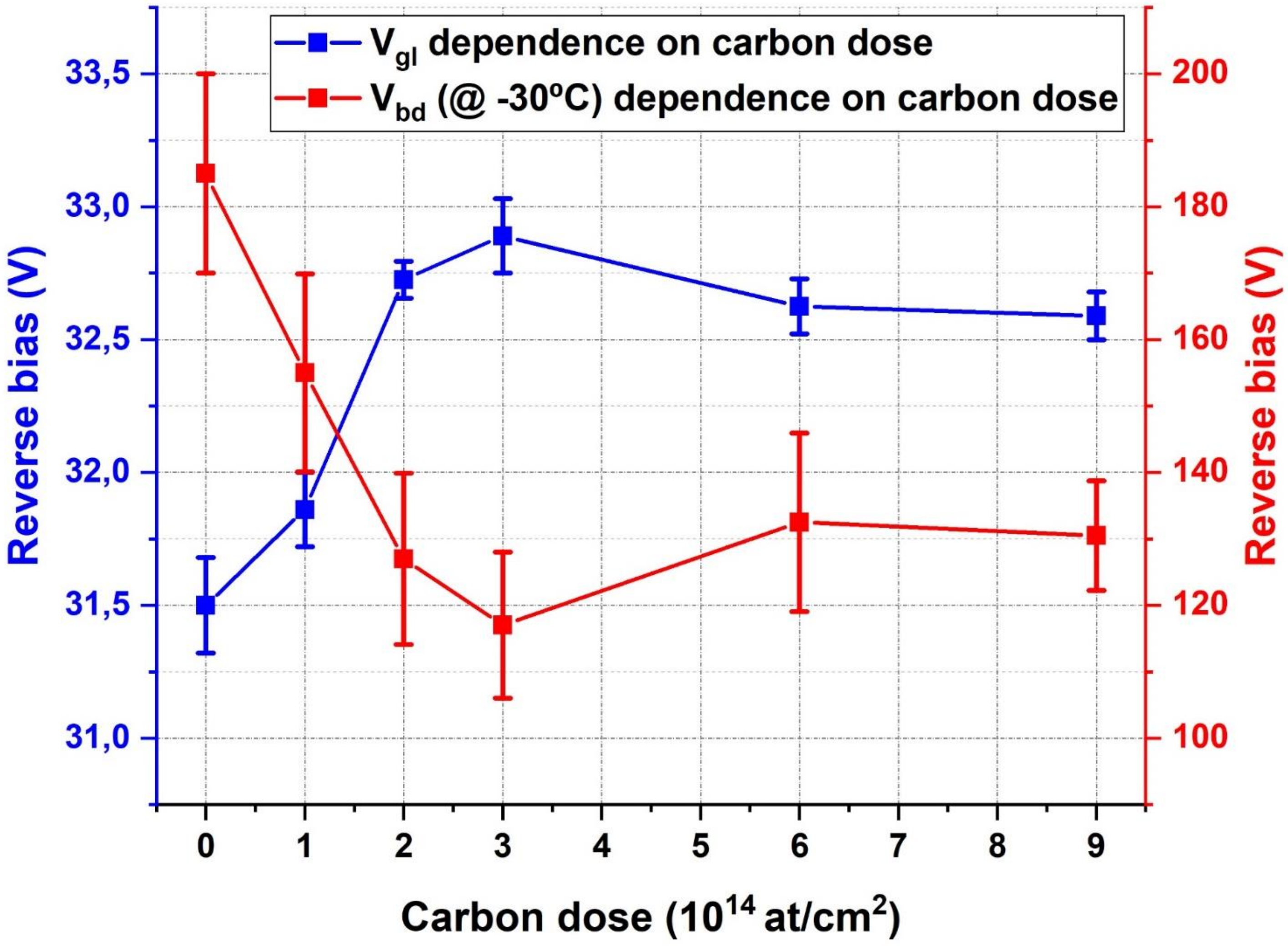
# IV measurements at -30ºC, voltage step = 2 V



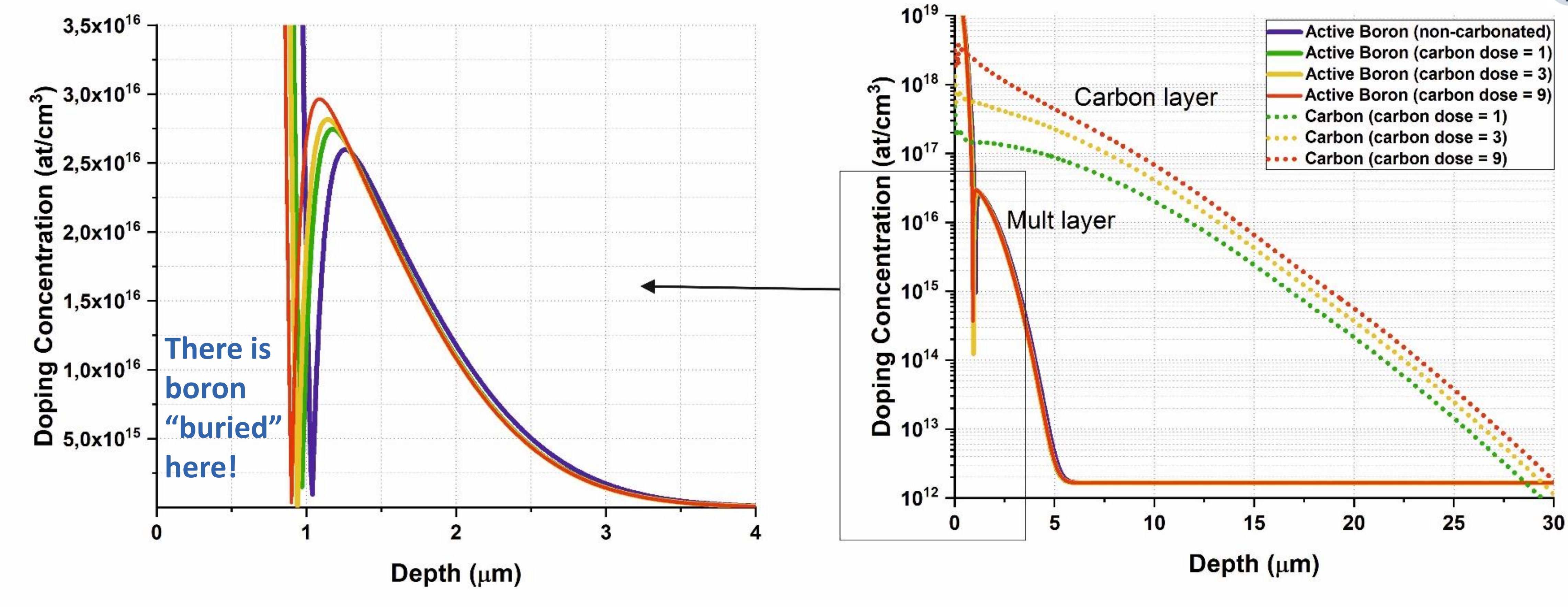



# CNM Run15973 : $V_{gl}$ and $V_{BD}$ @ $-30^oC$ (non-irradiated)

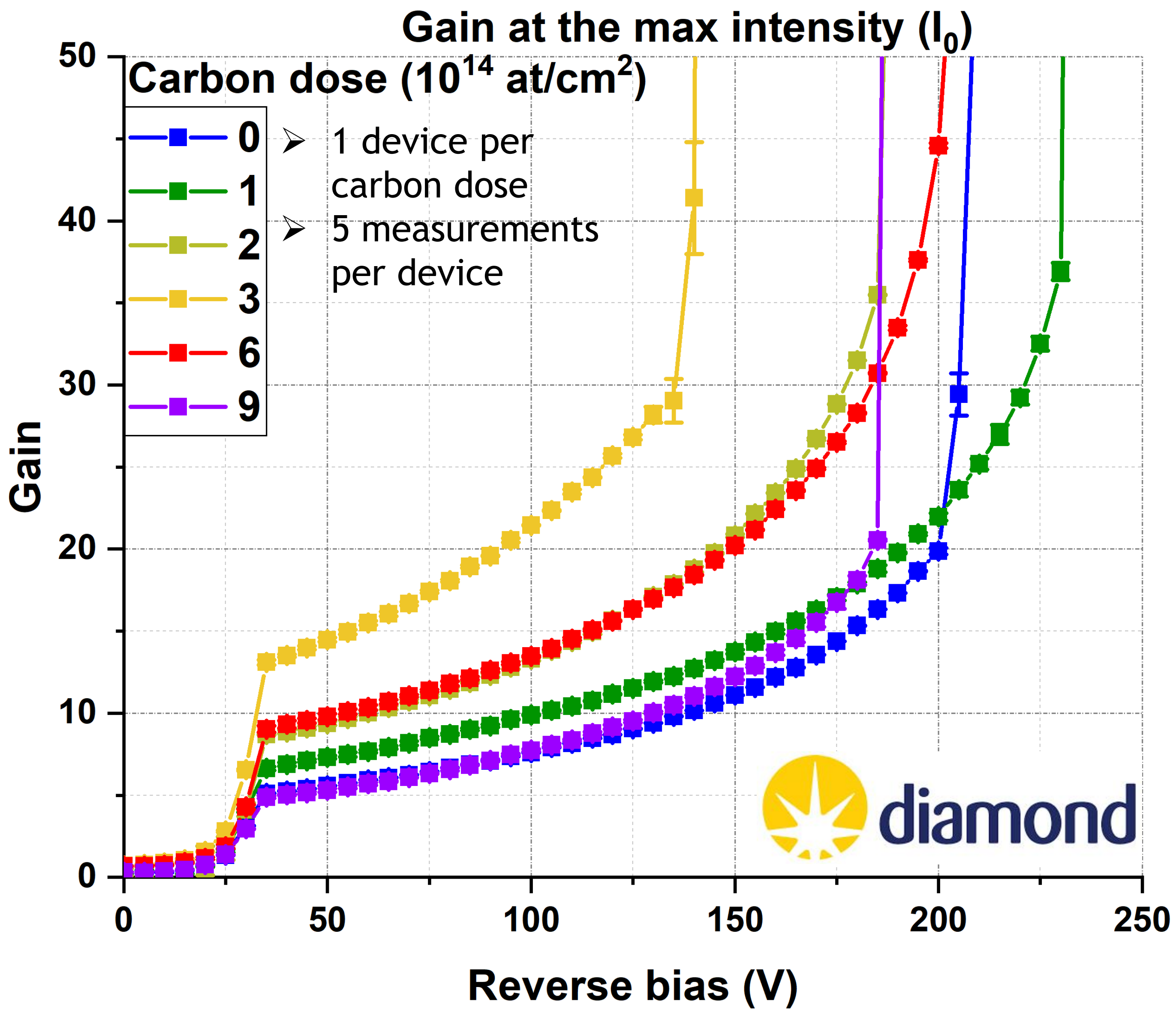
- $V_{gl}$ **increases with carbon** dose up to 3e14/cm² (> 15 CV measurements per carbon dose)
- $V_{BD}@-30^oC$ **decreases with carbon** dose up to 3e14/cm² (> 20 IV measurements per carbon dose)
- **Gain seems to increase with carbon dose** up to a certain carbonation amount.
- Why? **Diffusion of Boron of Phosphorus is supressed in the presence of carbon:**
    - https://doi.org/10.1063/1.113204
    - https://doi.org/10.1063/1.2234315
    - https://doi.org/10.1116/1.2198858
    - https://doi.org/10.1049/el:20052999
    - https://doi.org/10.1063/1.122244



# CNM Run15973 : TCAD-Simulated doping profiles



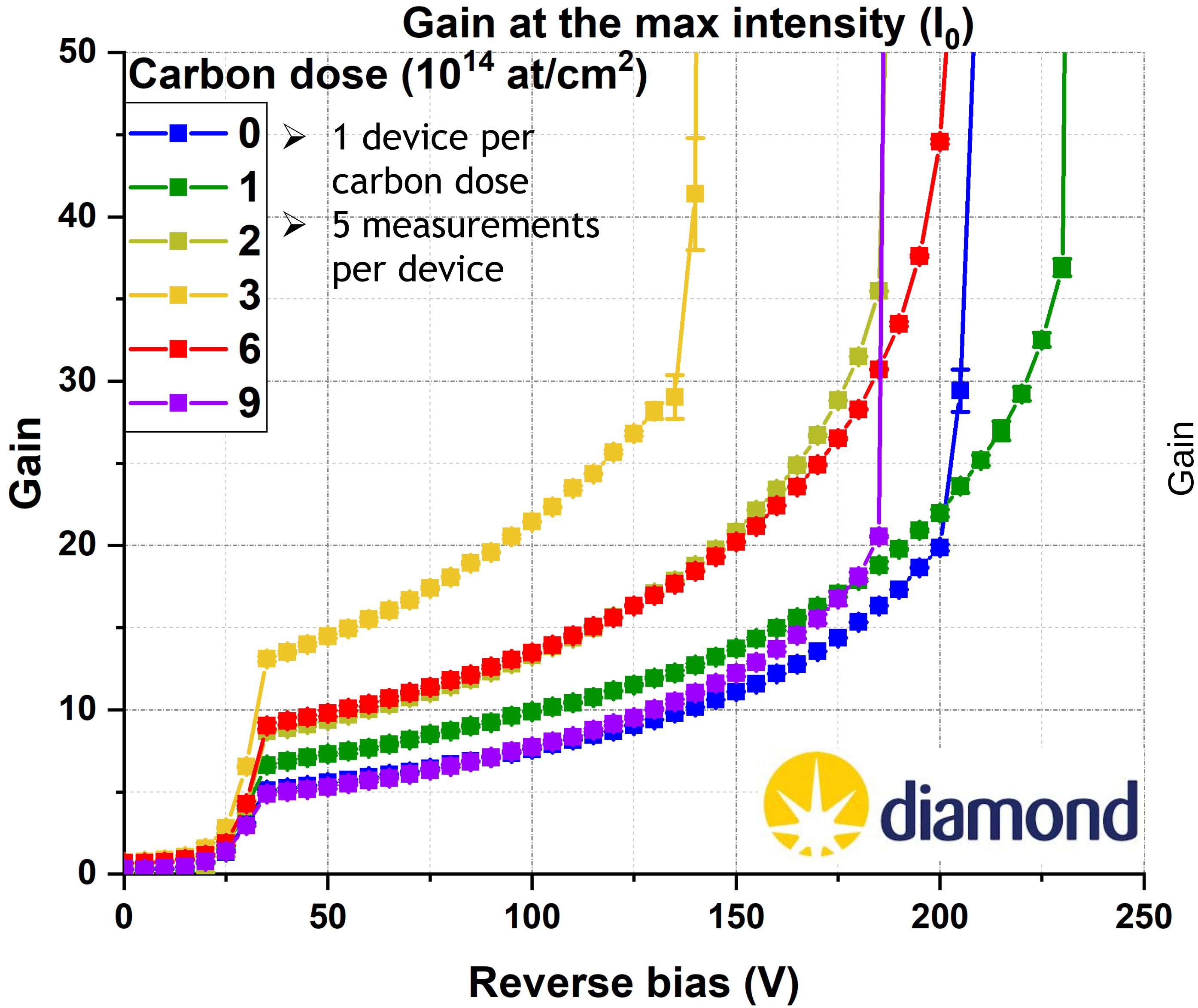

- TCAD simulation predicts this effect
- However, it does not predict the turning point at carbon doses > 3e14/cm$^2$

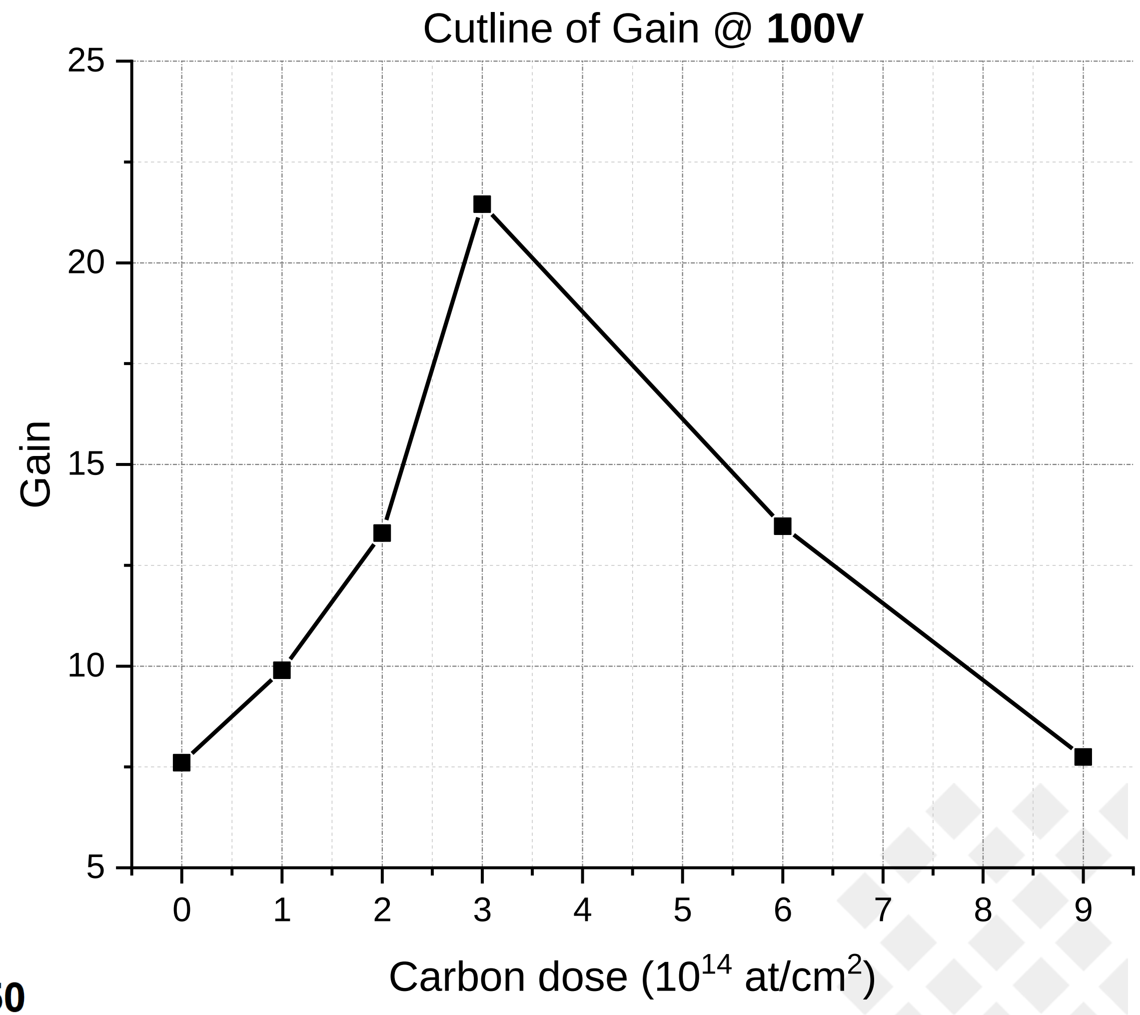



- Room temperature (20ºC)
- 15 keV X-rays (absorption depth of ≈ 1mm (just as near-IR 1064 nm TCT light)
- Beam size of 2.7x1.9 µm² focused on the center of the devices
- At the maximum intensity of the x-ray beam ($I_0$) the gain suppression is also maximum
- **Measurements confirm that a carbon dose of 3e14/cm² offer the highest gain (given a reverse bias)**

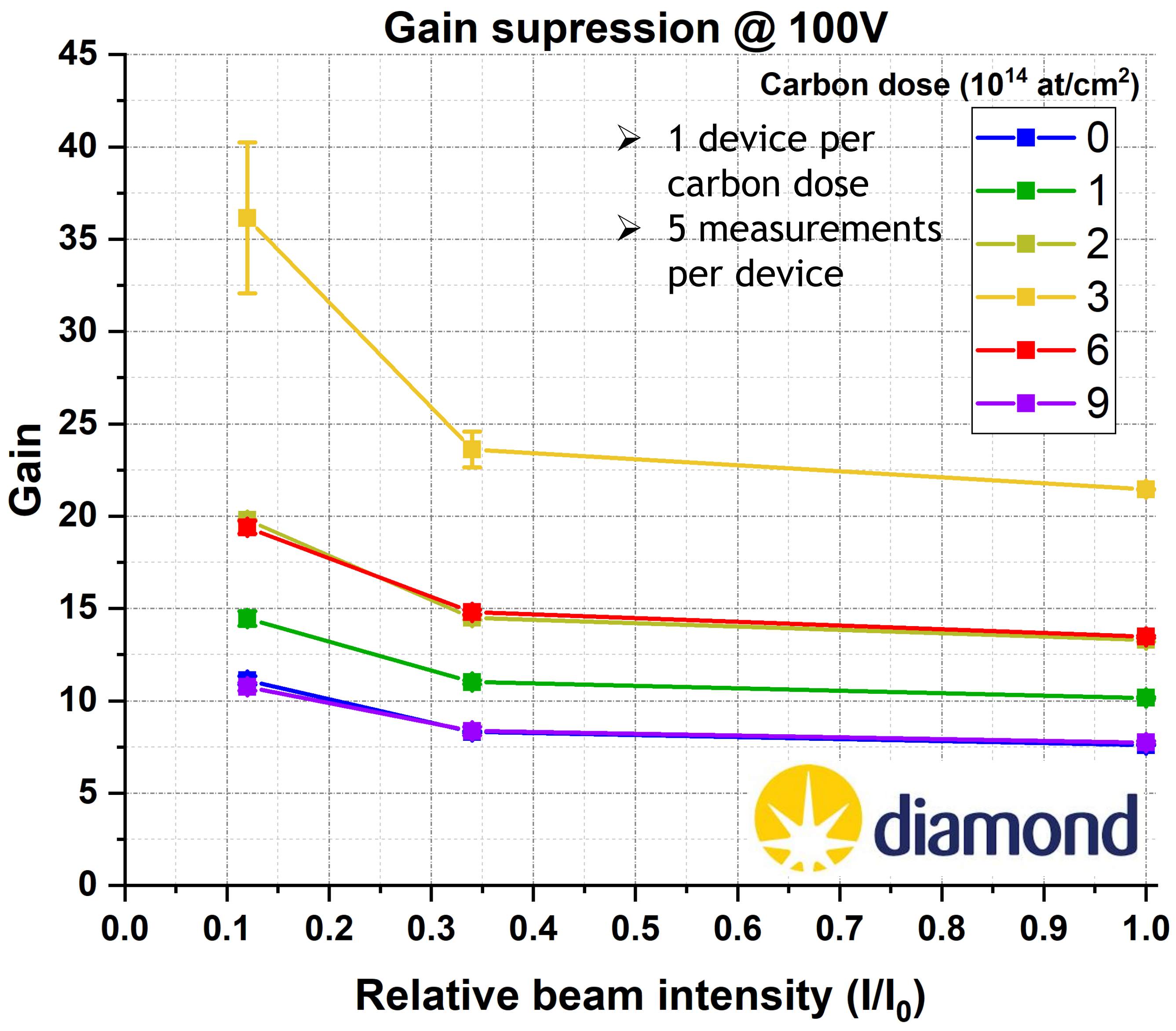
$$Gain = \frac{I_{BeamOn}^{LGAD} - I_{leakage}^{LGAD}}{I_{BeamOn}^{PiN} - I_{leakage}^{PiN}} = \frac{Photocurrent_{LGAD}}{Photocurrent_{PiN}}$$

# CNM Run15973 : Gain measurements with 15 keV x-rays at Diamond LightSource



# CNM Run15973 : Gain measurements with 15 keV x-rays at Diamond LightSource



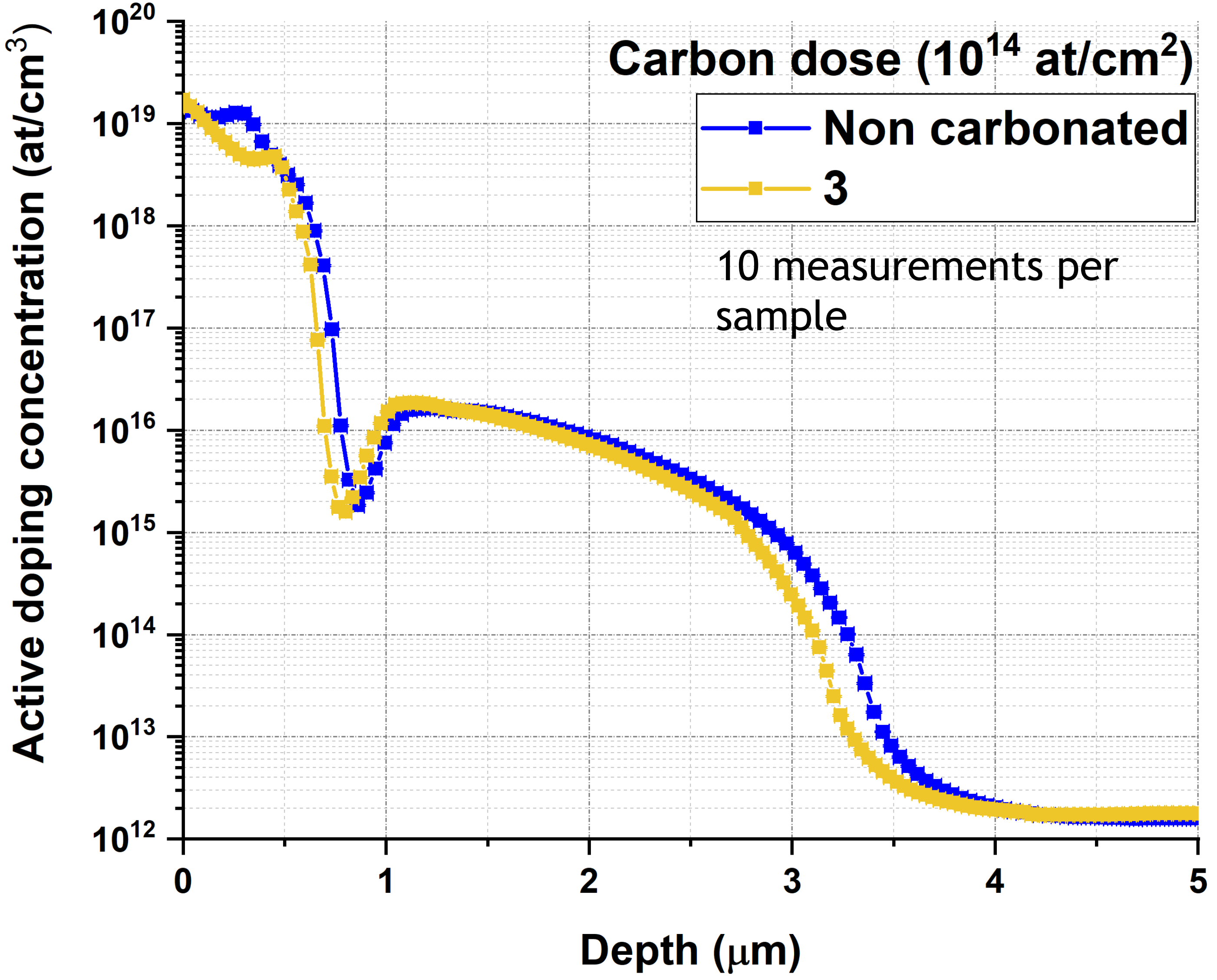

## Gain suppression was also observed.

**Aluminum attenuators for the X-ray beam**

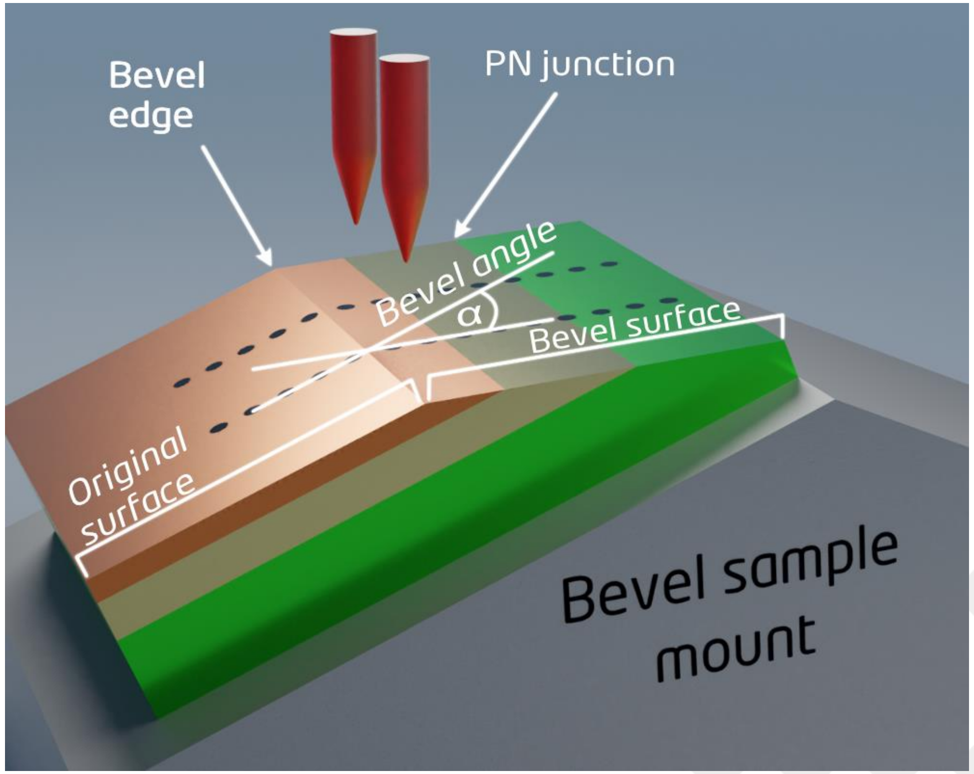
0.5 mm Al → attenuates **66%** of the beam
1.0 mm Al → attenuates **88%** of the beam
1.5 mm Al → attenuates **96%** of the beam
...
5.0 mm Al → attenuates **99.9993%** of the beam

For >1.5mm Al → Photocurrent falls below leakage current for the reference PiN diode.

# CNM Run15973 : SRP-extracted doping profiles




**Resistance** is measured between two probes. Then **resistivity** and **active doping concentration** is extracted from it



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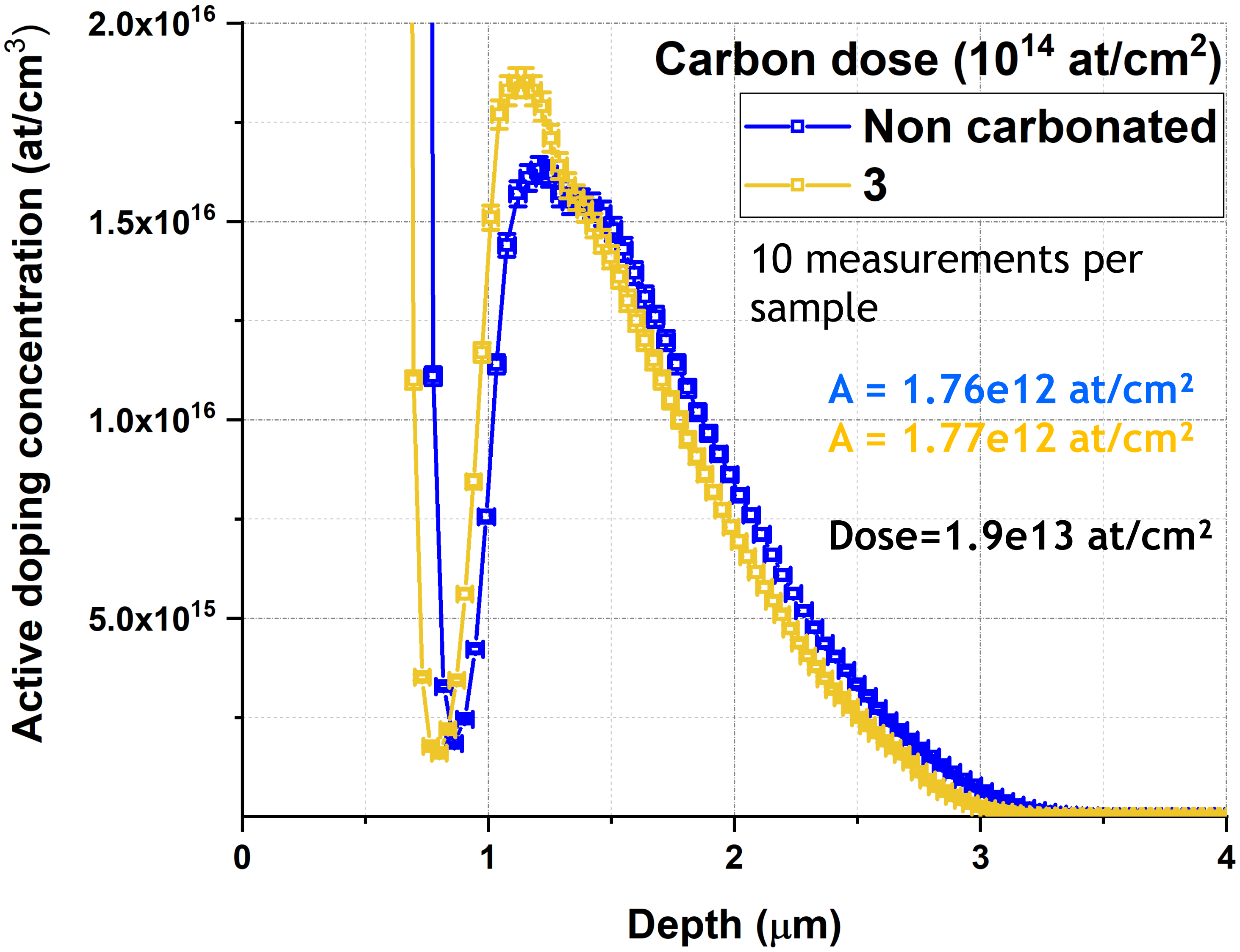


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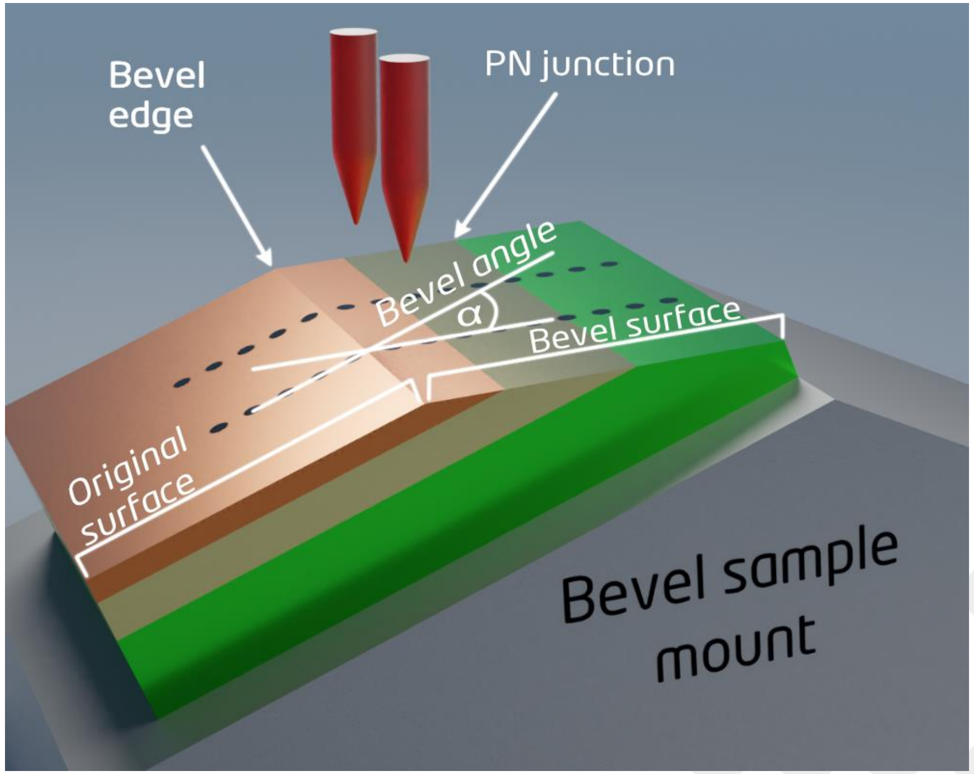

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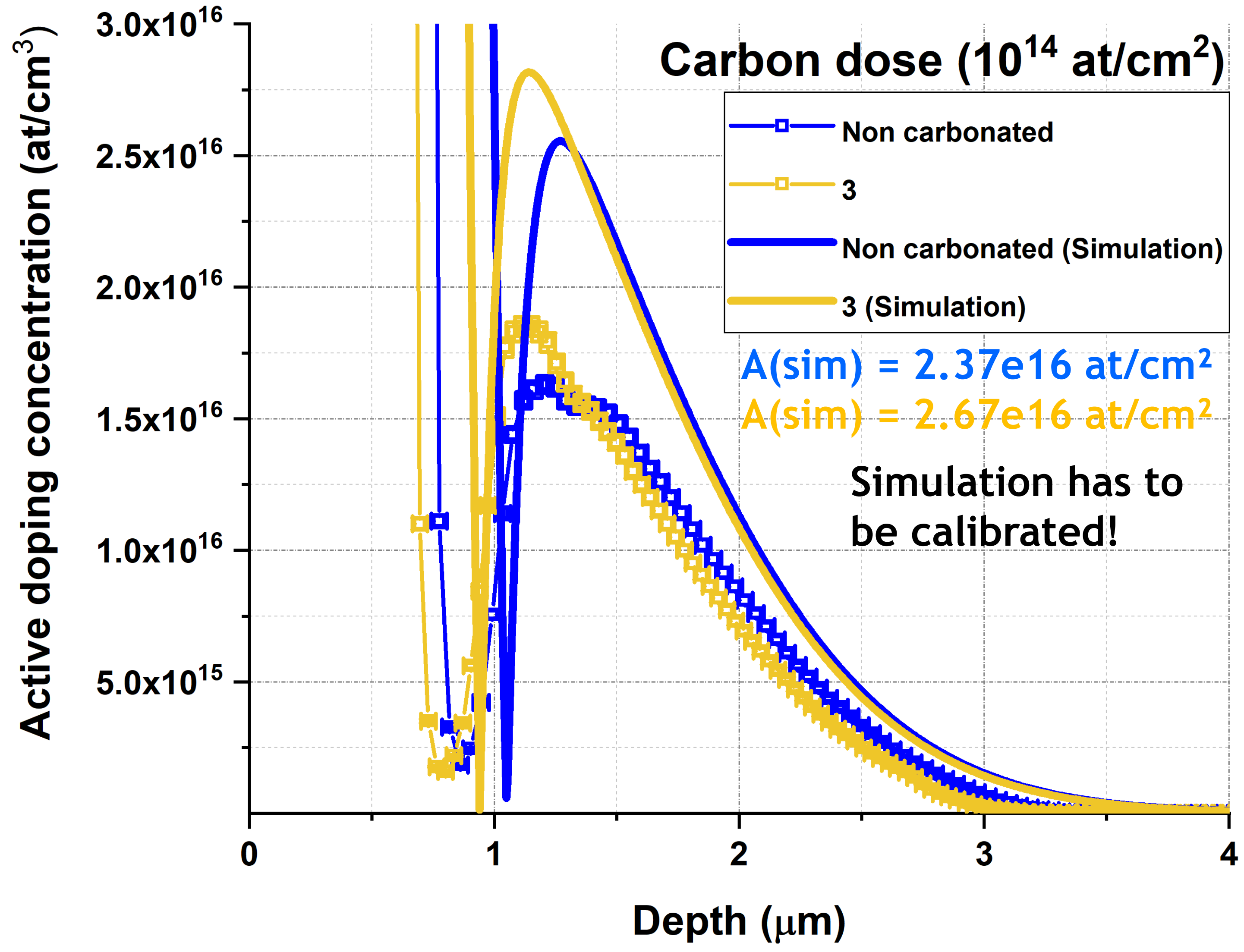


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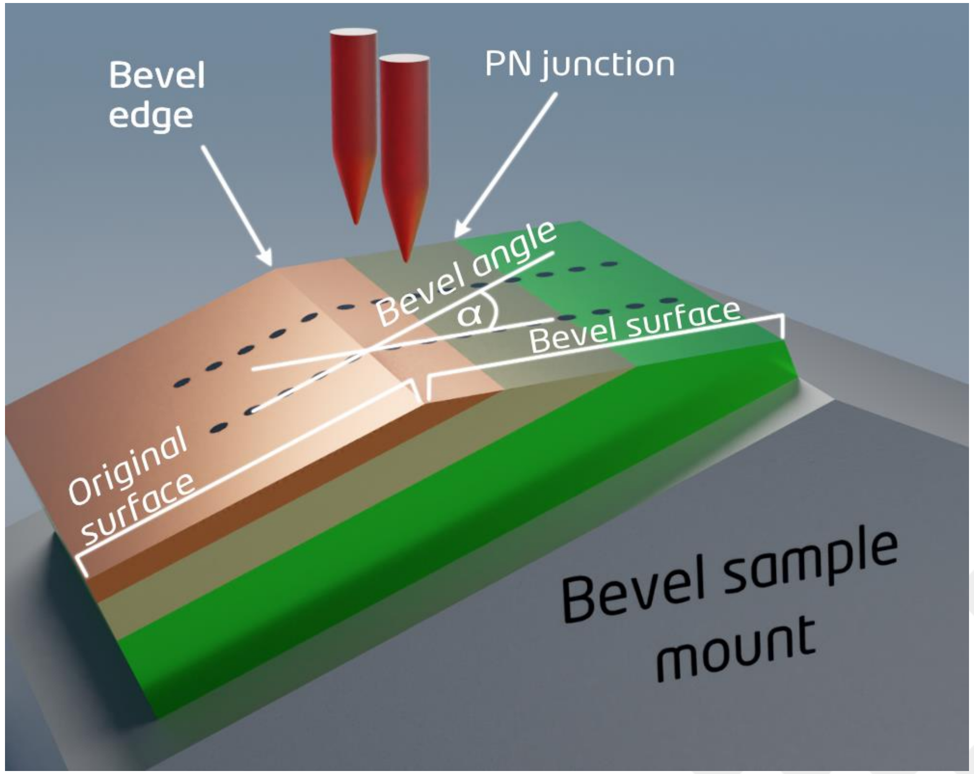


# Non-irradiated devices : Results overview

RDG Radiation Detectors Group

## Characterization of the CNM Run15973 Single-pad diodes

- Good results in terms of leakage current
- Specifications before irradiation are achieved for both CMS and ATLAS (**data in table for carbon dose = 3e14/cm²**)

**CMS**

| Un-irradiated @ -25ºC | |
|---|---|
| $V_{GL}$ | 32 V |
| $V_{FD}$ | 35 V |
| $V_{BD}$ | 122 V |
| $I_{leak}$ | < 0.06 µA/cm2 |
| V (8 fC) | < 100 V* |
| σ at V(CC > 8 fC) | < 50 ps* |

**ATLAS**

| Un-irradiated @ -30ºC | |
|---|---|
| $V_{GL}$ | 32 V |
| $V_{FD}$ | 35 V |
| $V_{BD}$ | 117 V |
| $I_{leak}$ | < 0.06 µA/cm2 |
| V (4 fC) | < 80 V* |
| σ at V(CC > 4 fC) | < 50 ps* |

IFCA

IFAE Institut de Física d'Altes Energies

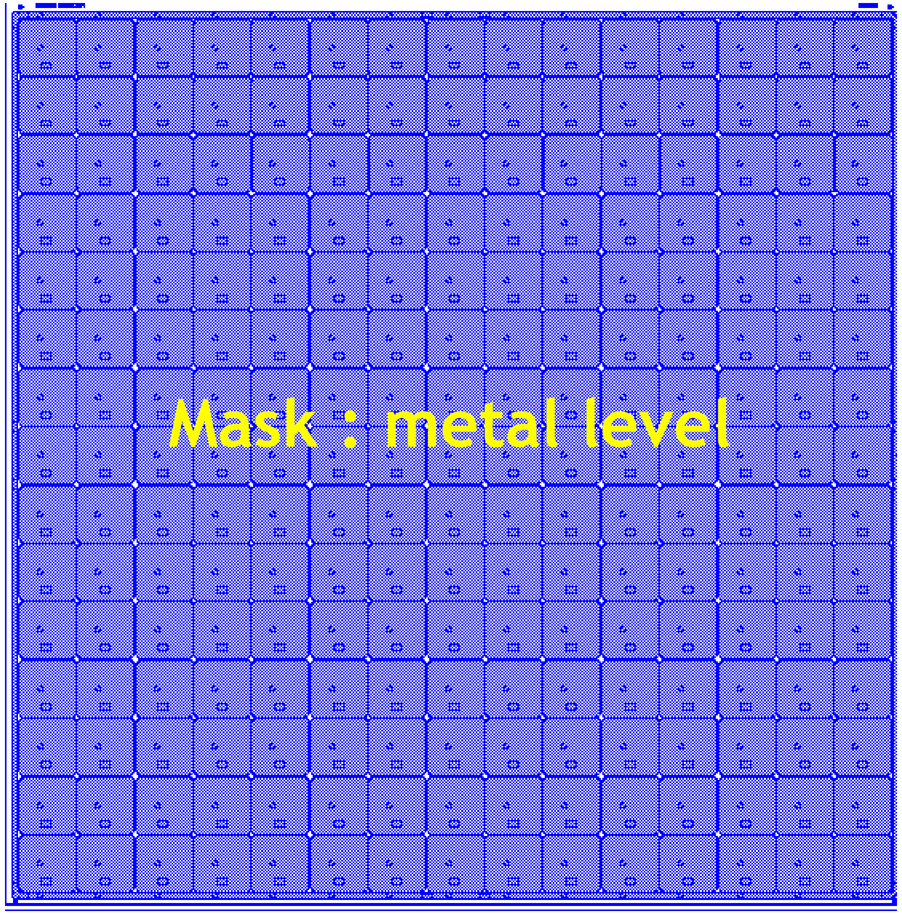
* See Efren's talk tomorrow

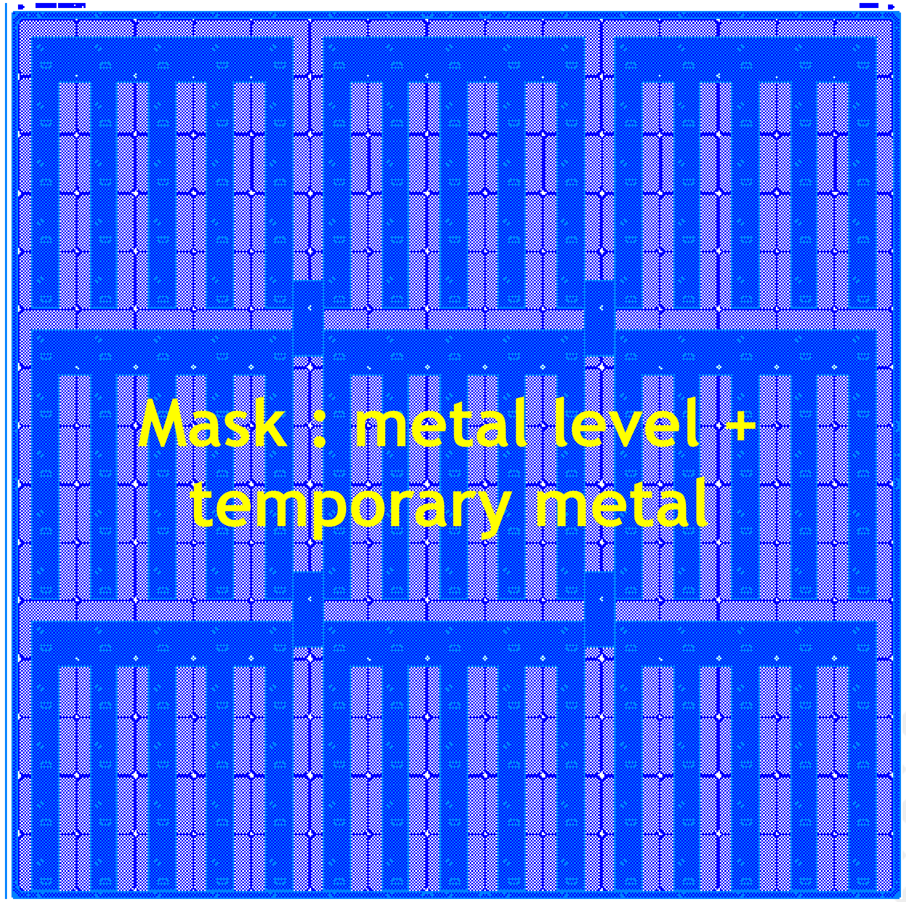
* Viveka's presentation at : https://indico.cern.ch/event/1335539/

# Yield of pixelated LGADs : IVs with temporary metal

# CNM Run15973 : 15x15 pixelated LGADs - IVs with temporary metal

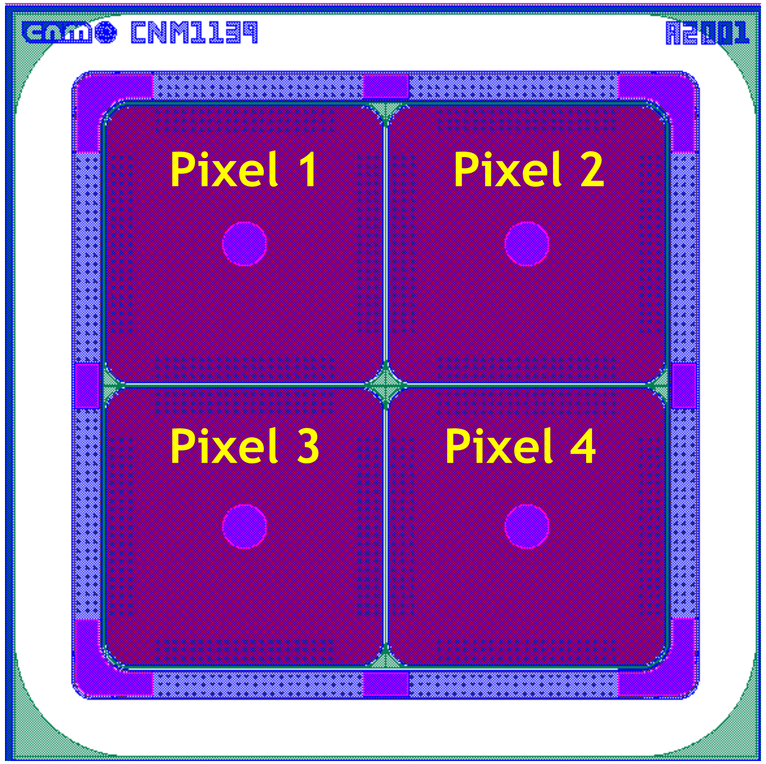
- Temporary metal is deposited to connect all pixels

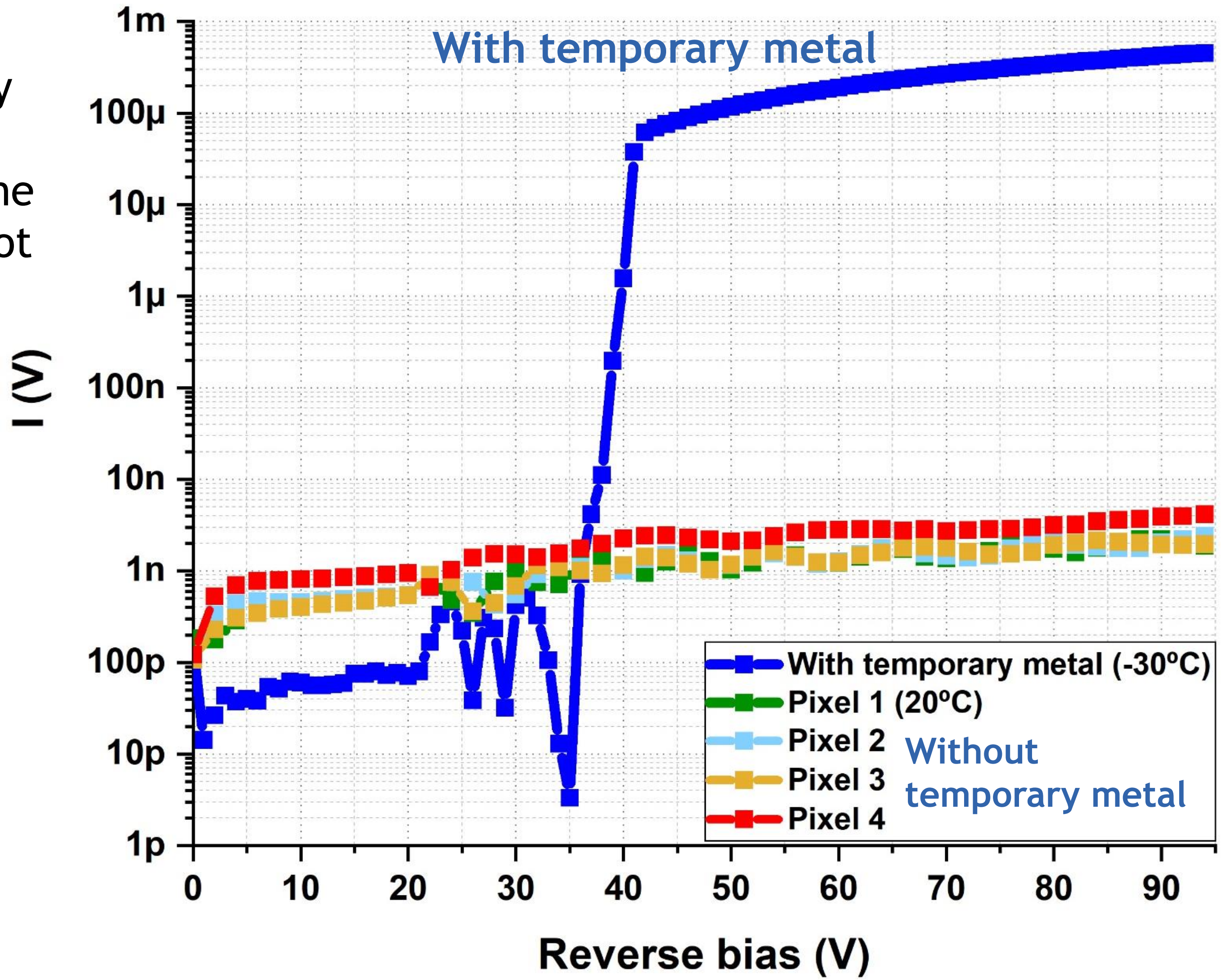


# CNM Run15973 : 15x15 pixelated LGADs - IVs with temporary metal

- Temporary metal is deposited to connect all pixels
- Leakage current is altered when the temporary metal is deposited
- These IVs measurement serve **only** to determine whether there is **shortcut** between pixels or not



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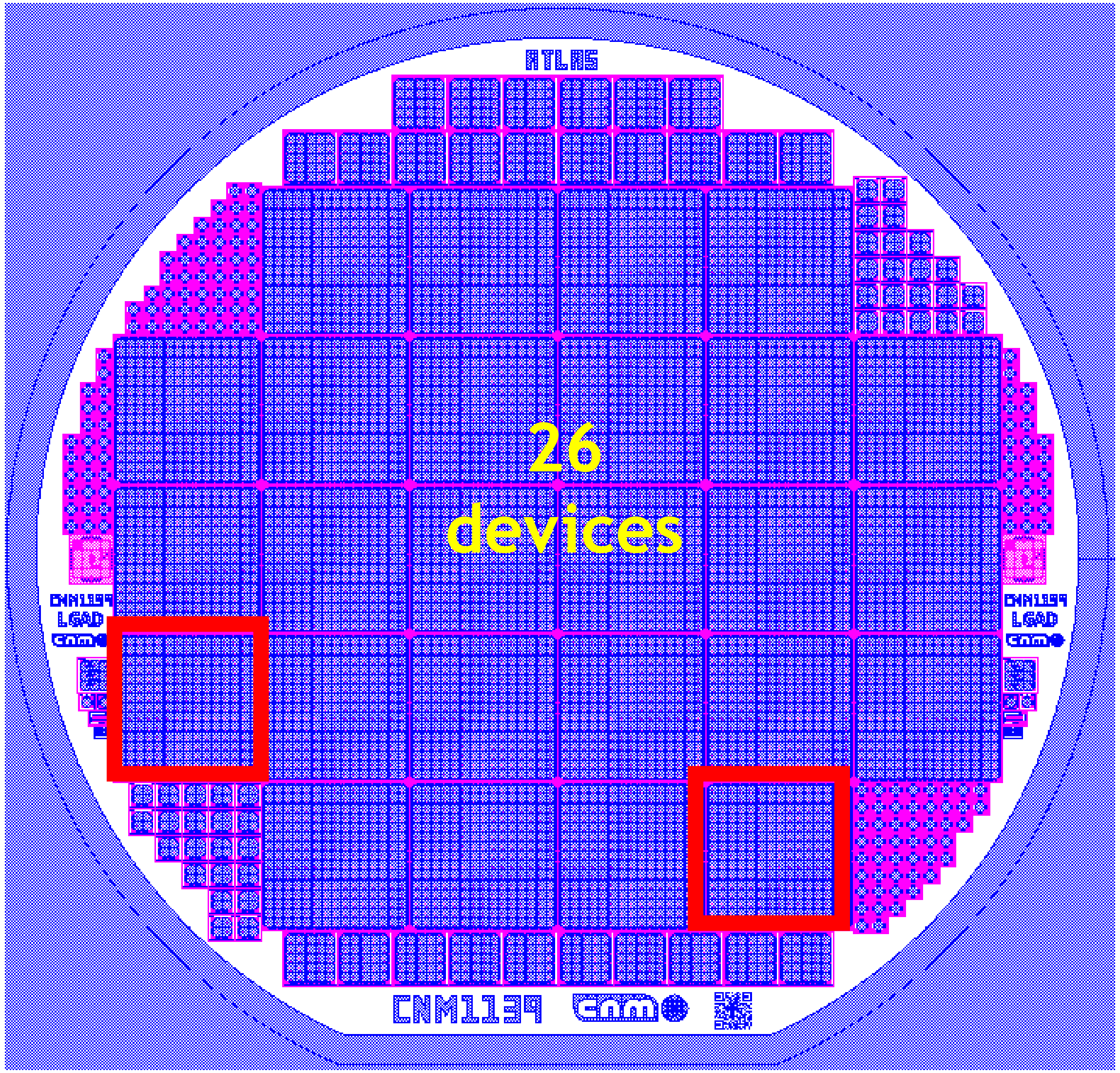
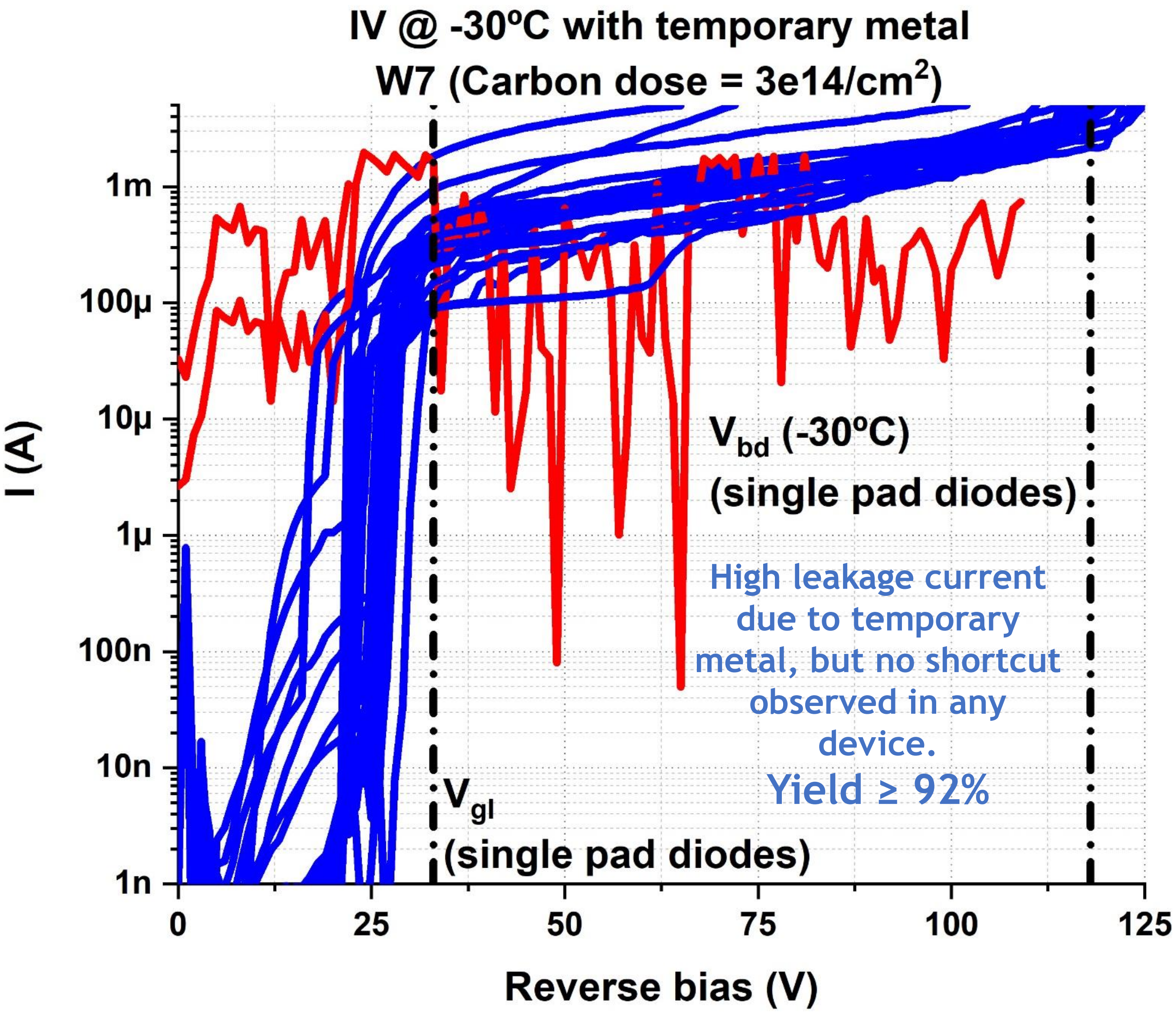
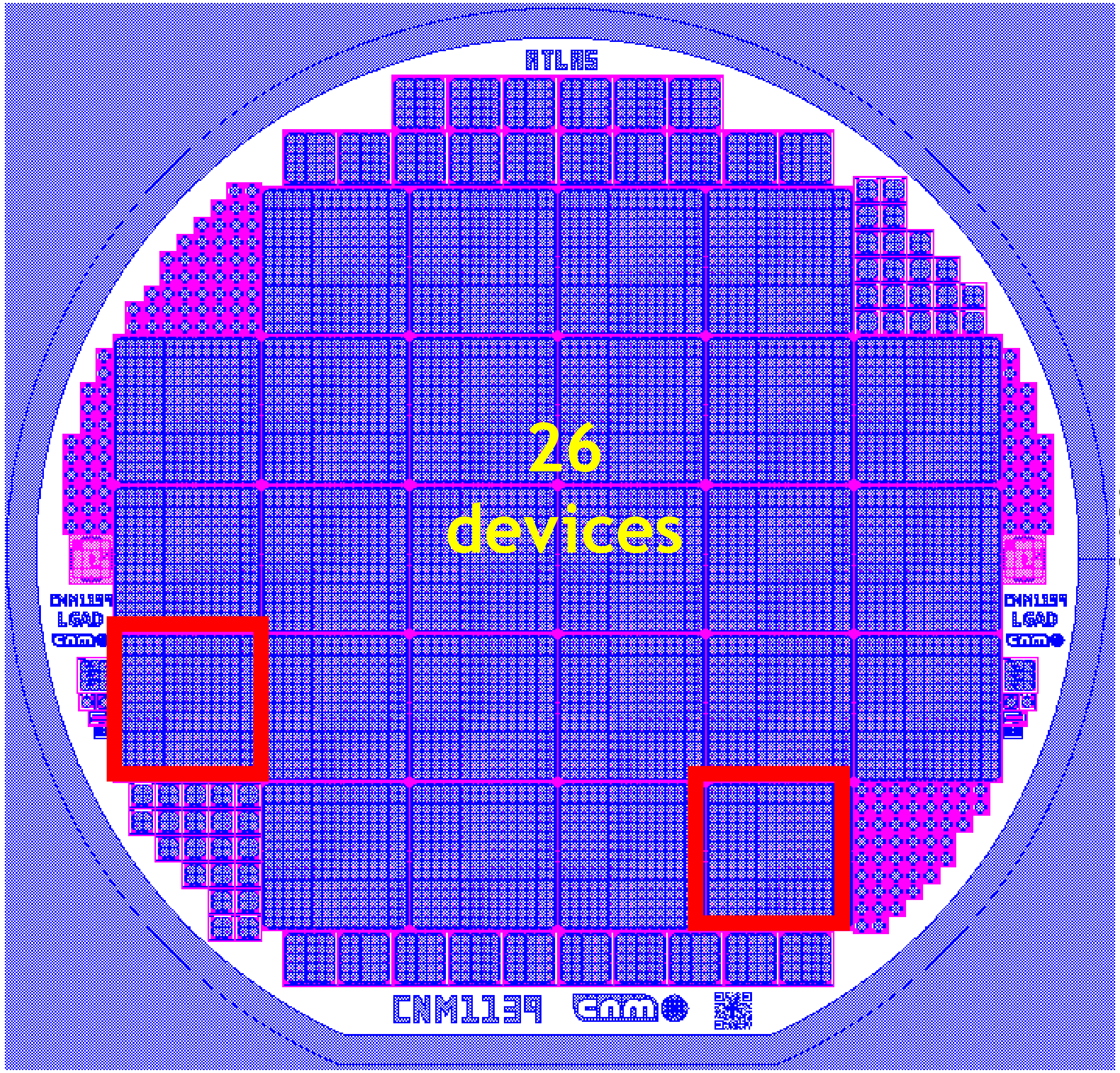


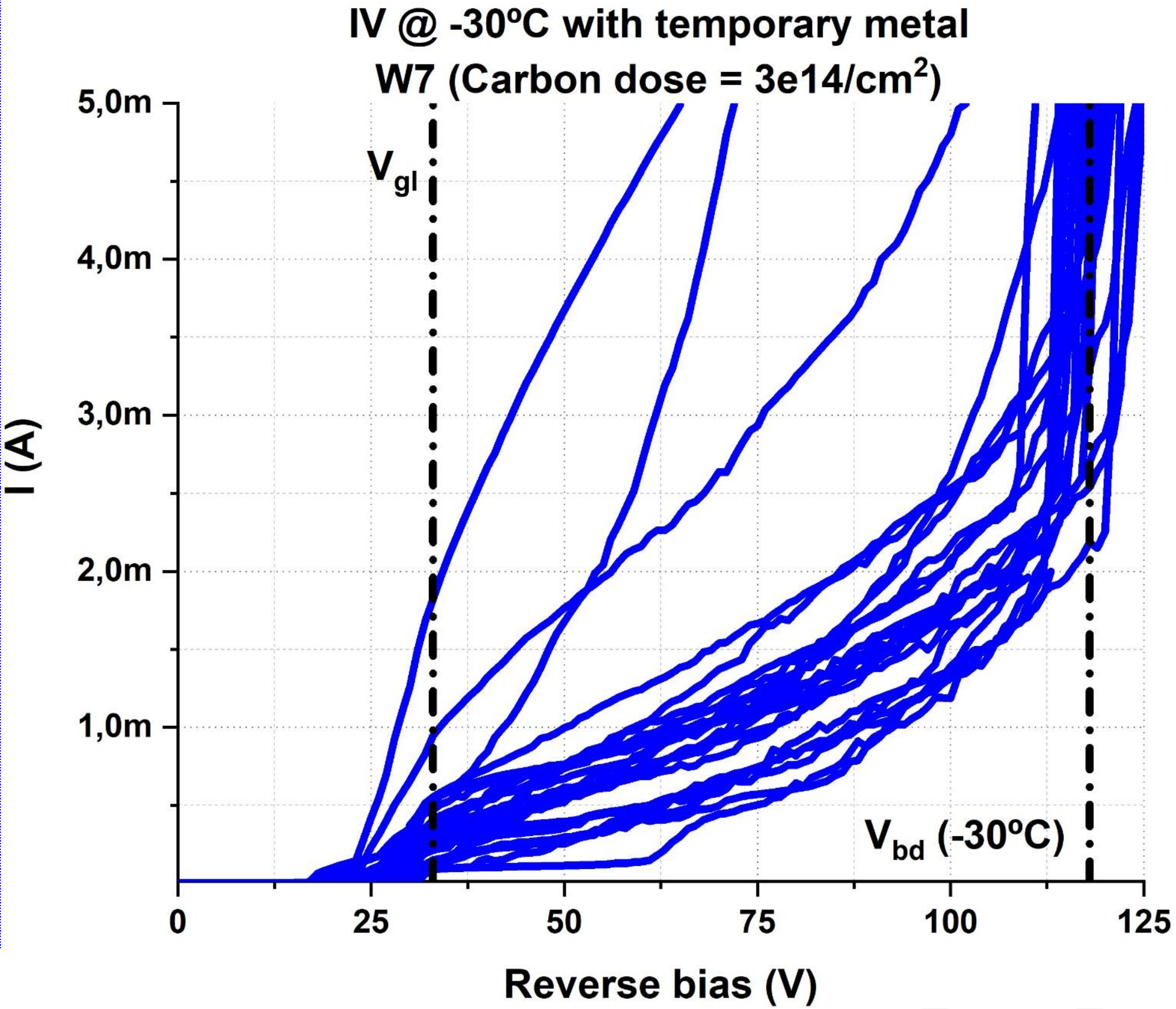




High leakage current due to temporary metal, but no shortcut observed in any device.

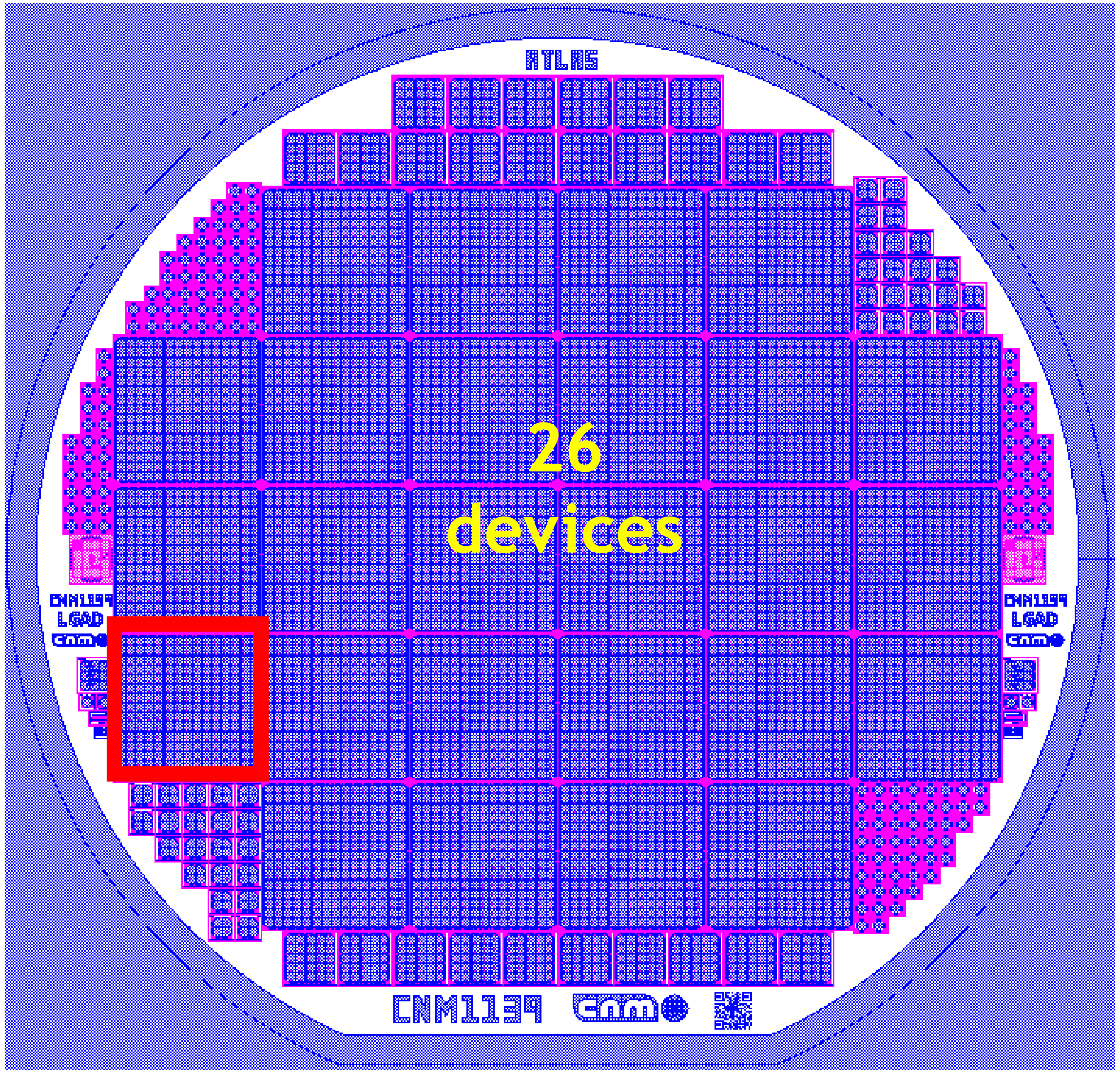
Yield ≥ 92%

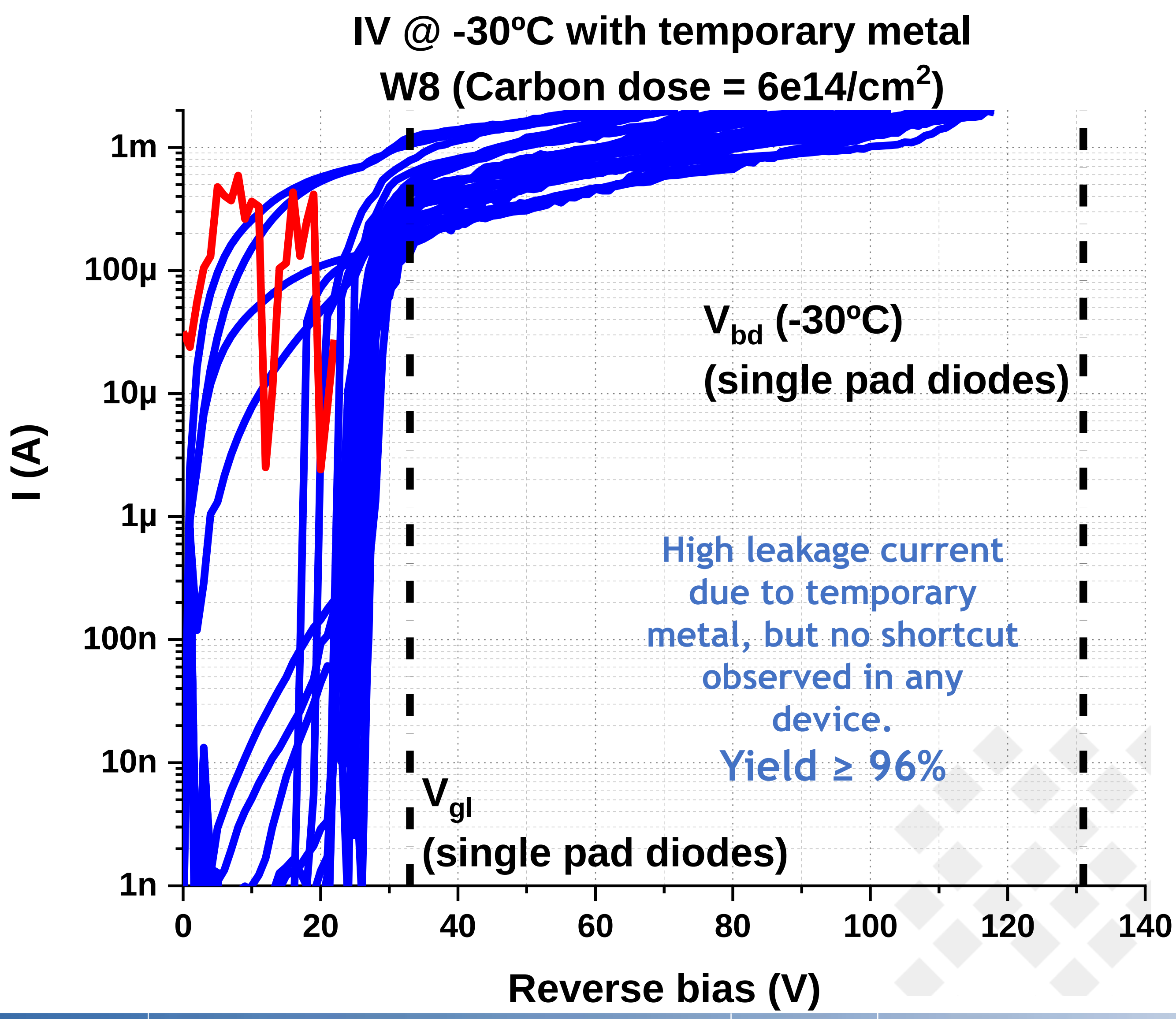
# CNM Run15973 : 15x15 pixelated LGADs - IVs with temporary metal



# CNM Run15973 : 15x15 pixelated LGADs - IVs with temporary metal




High leakage current due to temporary metal, but no shortcut observed in any device.

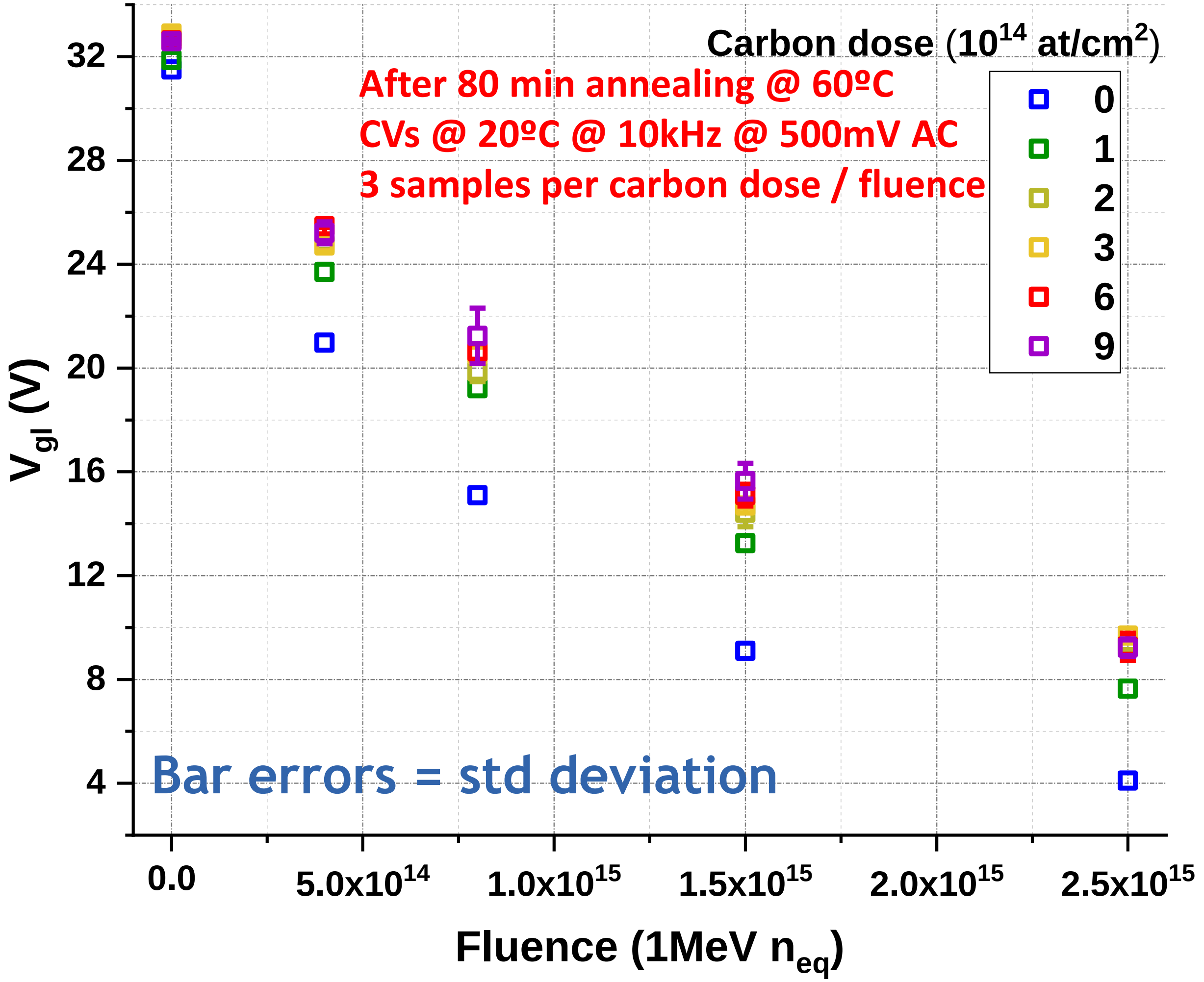
Yield ≥ 96%

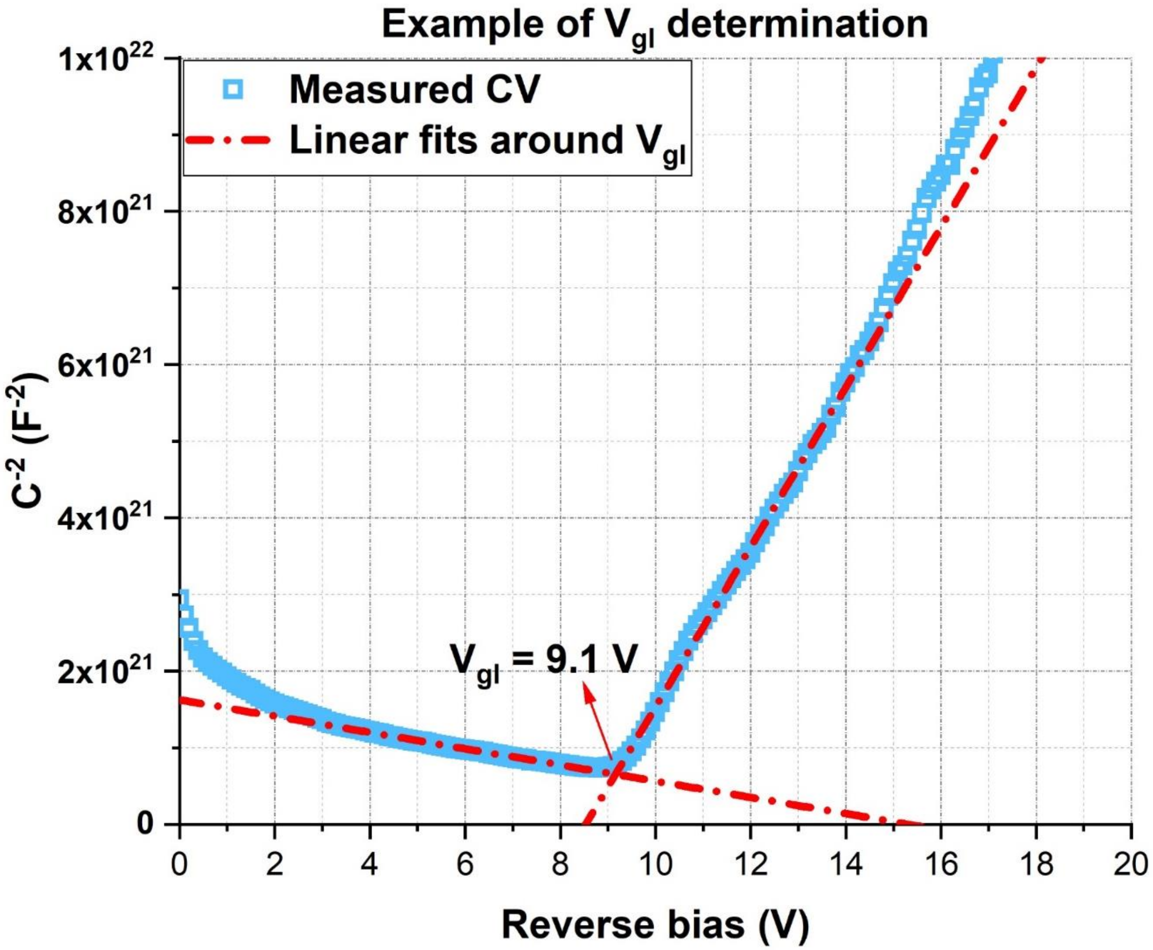
# Characterization of irradiated LGADs (single pad diodes)

# CNM Run15973 : Acceptor removal for irradiated single pad devices

## Single pad devices irradiated with neutrons at JSI for fluences 4, 8, 15 and 25e14 1MeV $n_{eq}$

Jožef Stefan Institute



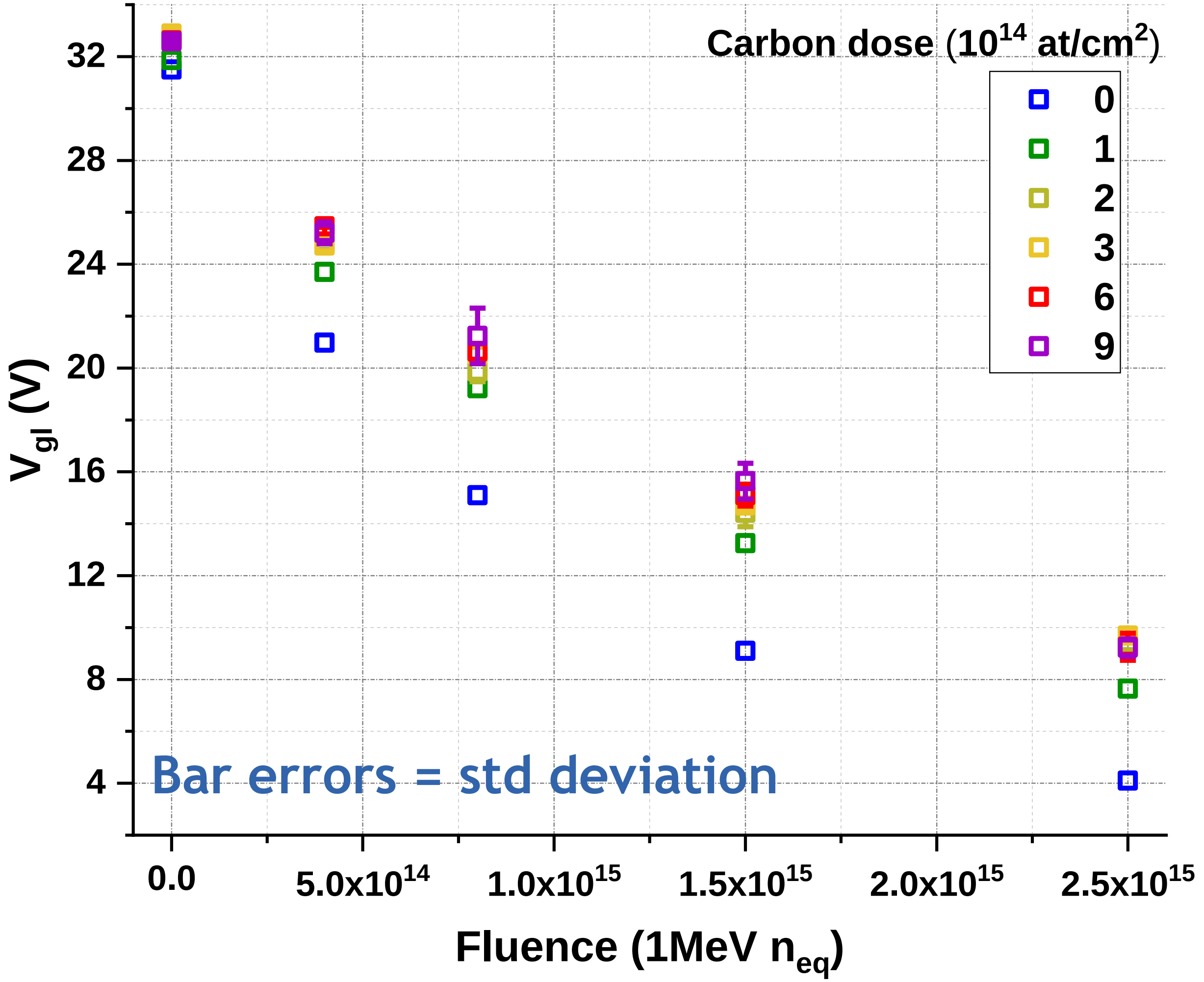



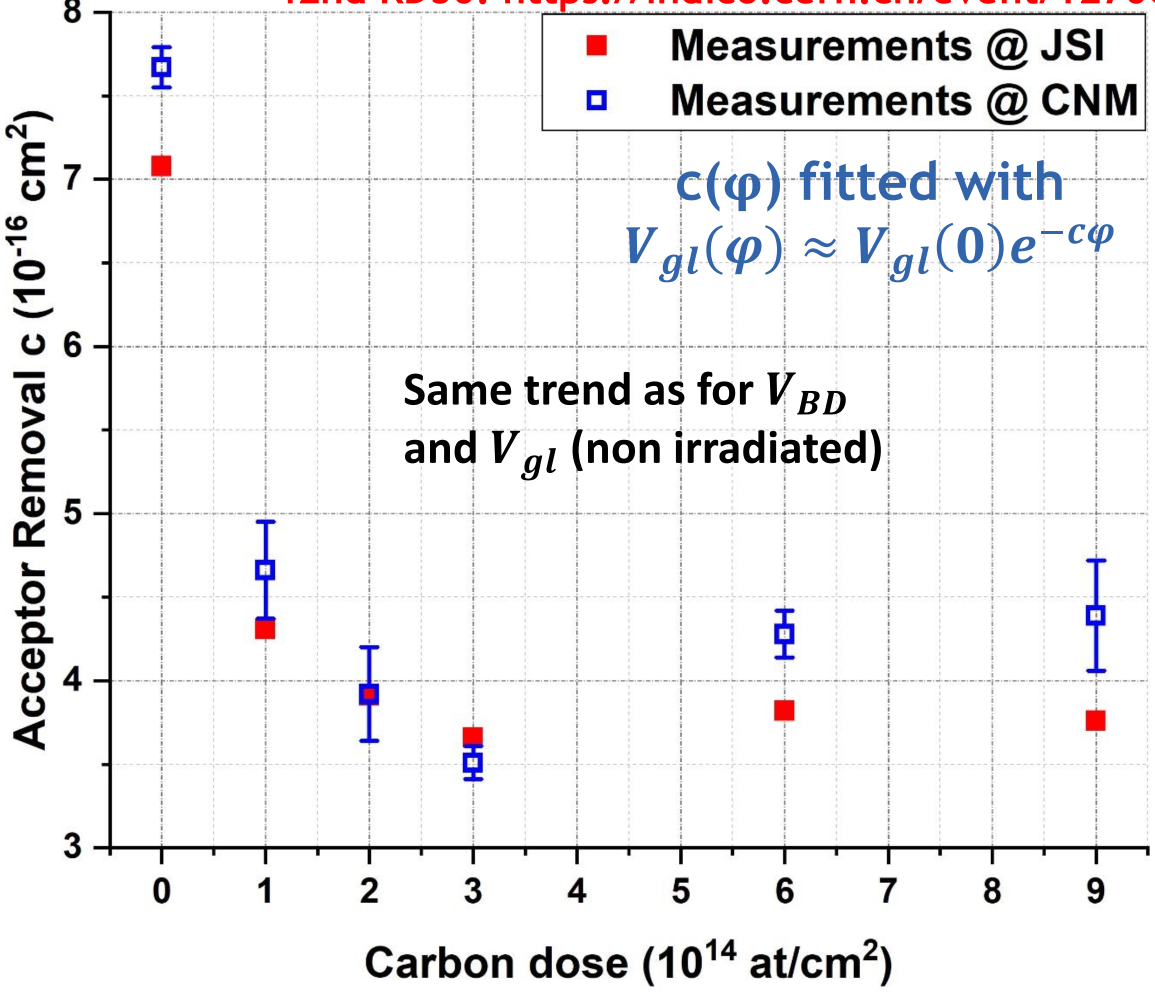
# CNM Run15973 : Acceptor removal for irradiated single pad devices

**Single pad devices irradiated with neutrons at JSI for fluences 4, 8, 15 and 25e14 1MeV $n_{eq}$**

Jožef Stefan Institute

42nd RD50: https://indico.cern.ch/event/1270076/)



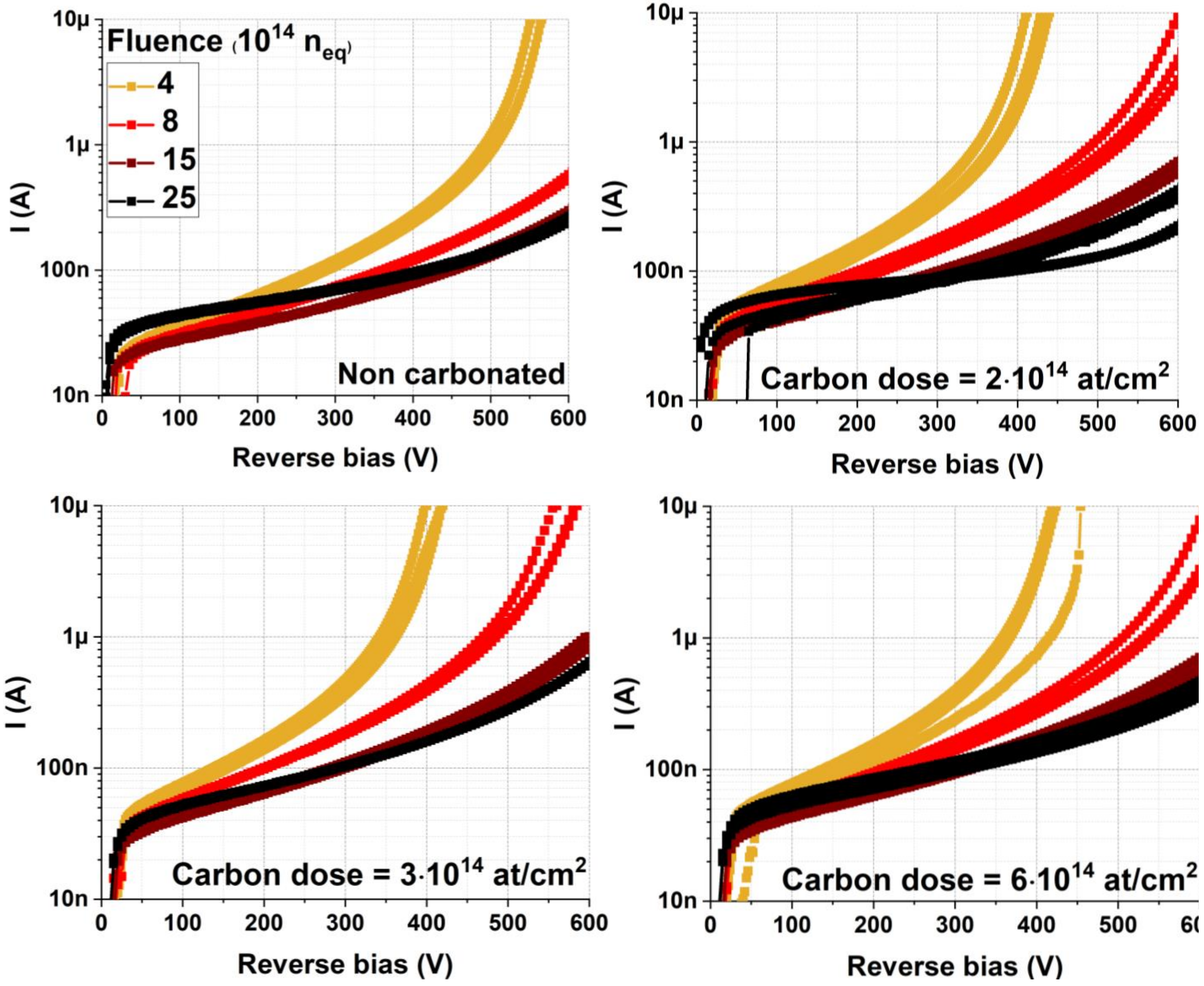

c(φ) fitted with

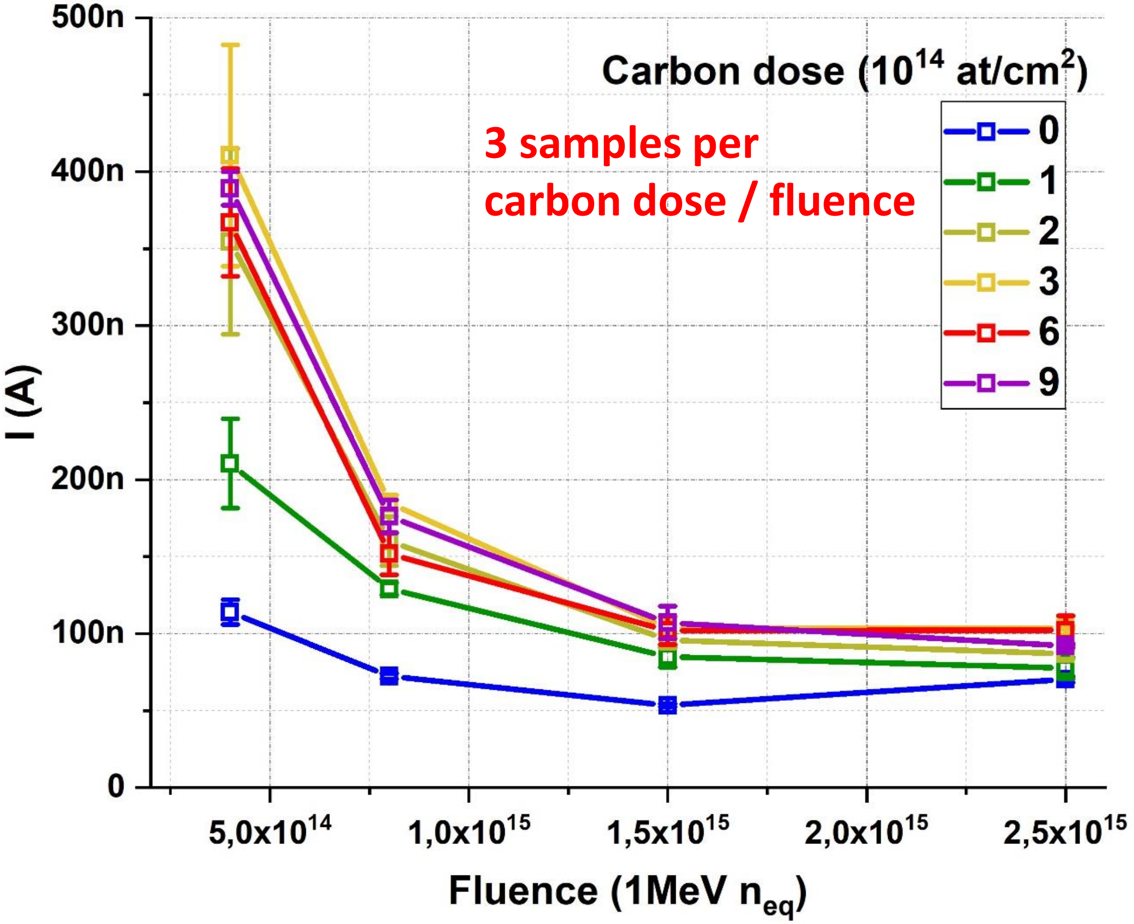
$$V_{gl}(\varphi) \approx V_{gl}(0)e^{-c\varphi}$$

Same trend as for $V_{BD}$ and $V_{gl}$ (non irradiated)

# CNM Run15973 : Leakage current vs irradiation fluence @ -30ºC

The loss of gain counterbalances the increase in leakage current, up to a fluence



# CNM Run15973 : challenges for irradiated LGADs

- CMS → Data in table for carbon dose = 9e14/cm²
- ATLAS → Data in table for carbon dose = 3e14/cm².

* See Efren's talk tomorrow (high spurious pulse levels beyond operation voltage)

* Viveka's presentation at : https://indico.cern.ch/event/1335539/

**CMS***

iFCA

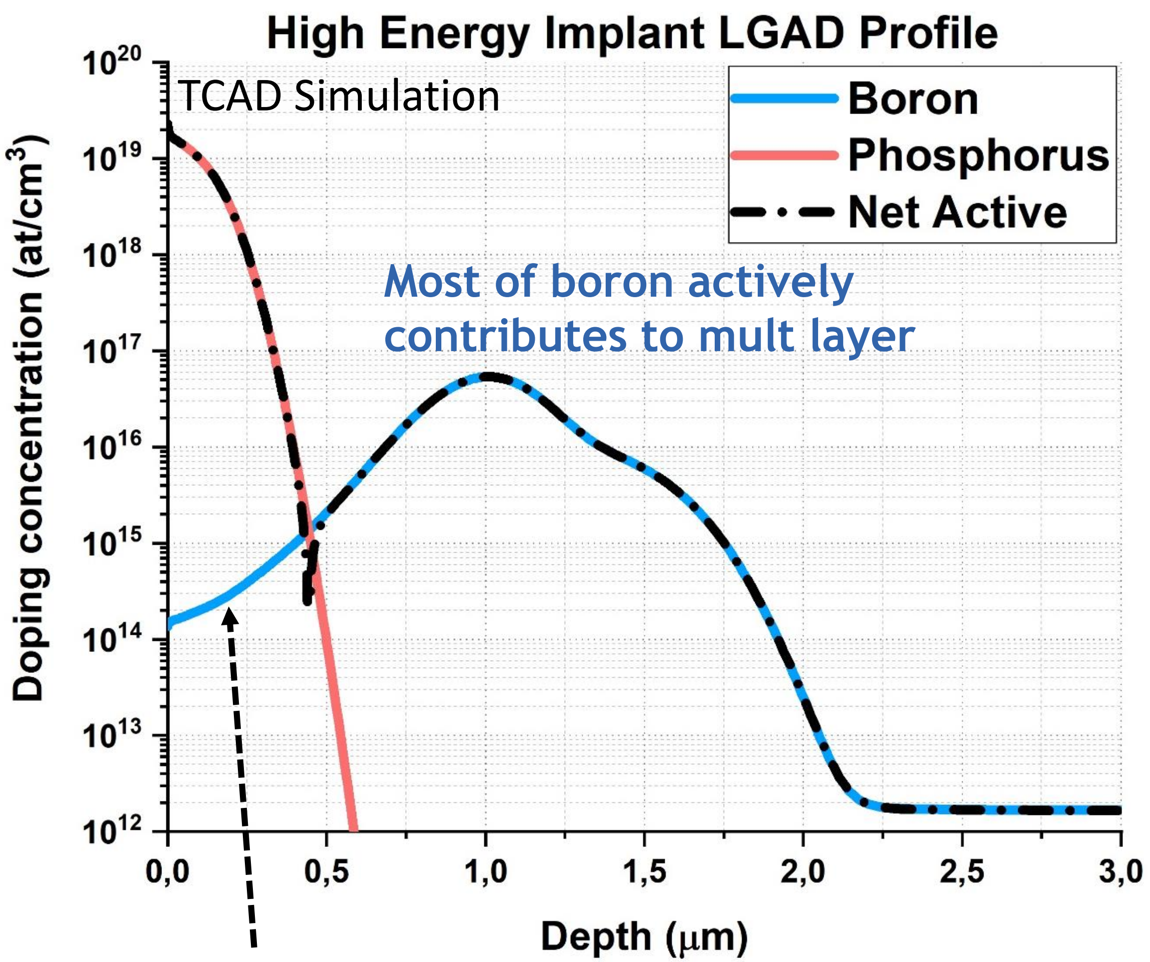
| Un-irradiated @ -25ºC | | Irradiated (1e15 $n_{eq}/cm^2$) @ -25ºC | |
|---|---|---|---|
| $V_{GL}$ | 32 V | $V_{GL}$ | 14 V |
| $V_{FD}$ | 35 V | $V_{opMAX}$ | 540 V ( = 11 V/µm) |
| $V_{BD}$ | 122 V | $V_{BD}$ | > 600 V |
| $I_{leak}$ | < 0.06 µA/cm2 | $I_{leak}$ | 33 µA/cm2 |
| V (8 fC) | < 100 V* | $V_{op}$ (8 fC) | 540 V ( = 11 V/µm) |
| σ at V(CC > 8 fC) | < 50 ps* | σ at $V_{op}$ (8 fC) | < 60 ps |

**ATLAS***

IFAE Institut de Física d'Altes Energies

| Un-irradiated @ -30ºC | | Irradiated (2.5e15 $n_{eq}/cm^2$) @ -30ºC | |
|---|---|---|---|
| $V_{GL}$ | 32 V | $V_{GL}$ | 10 V |
| $V_{FD}$ | 35 V | $V_{opMAX}$ | 540 V |
| $V_{BD}$ | 117 V | $V_{BD}$ | > 600 V |
| $I_{leak}$ | < 0.06 µA/cm2 | $I_{leak}$ | 33 µA/cm2 |
| V (4 fC) | < 80 V* | CC (540 - 600 V) | 2-3 fC |
| σ at V(CC > 4 fC) | < 50 ps* | σ (540 - 600 V) | < 40 ps |

# Upcoming work : CNM Run 16602




Little boron is "buried" below Nplus layer

| Wafer | Boron dose/ Boron Energy | Carbon dose/Energy |
|---|---|---|
| 1 | 2.5e12/cm² / 480 keV | 5e13/cm² / 480 keV |
| 2 | 2.6e12/cm² / 480 keV | |
| 3 | 2.7e12/cm² / 480 keV | |

- **CMS Mask**: 21 Pixelated sensors of **16x16** pixels of 50 µm x 1.3x1.3 mm², **IP = 80 µm** and **high-energy implant** profiles
- **No diffusion supression expected** (Activation via RTA)
- **Lower noise** due to larger IP
- Once a boron dose is well set (expected breakdown between 50 – 300 V), 6 carbon doses will be used for the **remaining 6 wafers**

# Acknowledgments

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Jožef Stefan Institute

Institut de Física d'Altes Energies

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**Thank you for your attention!**

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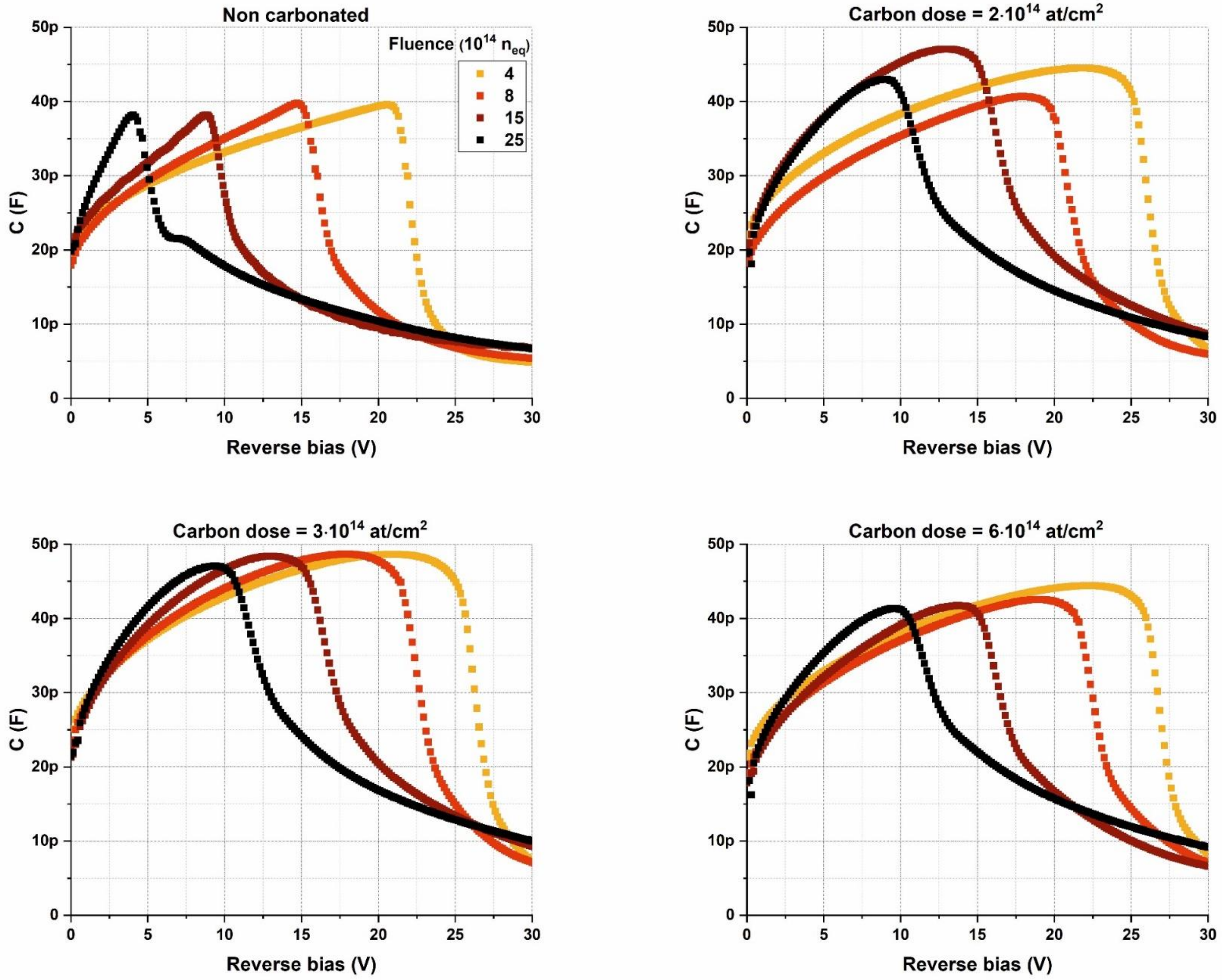
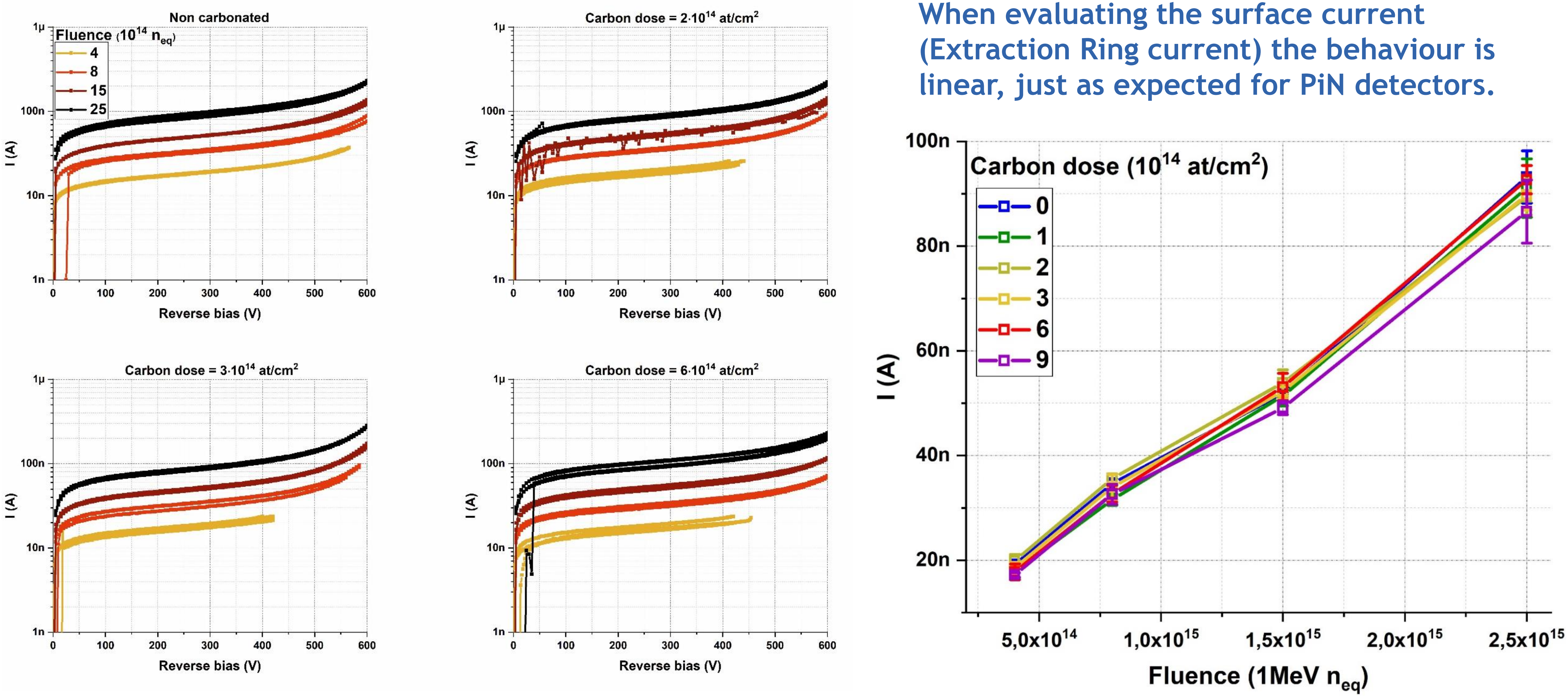
# CVs for irradiated devices




20ºC
10 kHz
500 mV AC

# CNM Run15973 : surface current vs irradiation fluence @ -30ºC




When evaluating the surface current (Extraction Ring current) the behaviour is linear, just as expected for PiN detectors.