Characterization of the last CNM fabrication of carbonated LGADs

Last 43rd RD50 Workshop
CERN
November 30th 2023

Jairo Villegas, Salvador Hidalgo, Milos Manojlovic, Neil Moffat, Guilio Pellegrini
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 $15\times15$ pixels of 50 µm x 1.3x1.3 mm² (ATLAS)
   - Pixelated sensors of $16\times16$ pixels of 50 µm x 1.3x1.3 mm² (CMS)

III. Radiation tolerance to neutrons and protons
   - Carbonation of devices
     - 4 fC @ V < 11 V/µm @ 2.5e15 1MeV $n_{eq}/cm²$ @ -30°C (ATLAS)
     - 8 fC @ V < 11 V/µm @ 1.5e15 1MeV $n_{eq}/cm²$ @ -25°C (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

<table>
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<tr>
<th>Wafer</th>
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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 month
- 6 extra wafers on hold before carbon and multiplication layer implantation
CNM Run16602 (ongoing) : High Energy Implant profiles

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- 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

![High Energy Implant LGAD Profile](image)

TCAD Simulation

Most of boron actively contributes to mult layer

Little boron is “buried” below Nplus layer
**CNM Run15973 : Overview**

- **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

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</tr>
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**CNM Run15973: Traditional LGAD profiles**

### Traditional LGAD Profile

- **Boron**
- **Phosphorus**
- **Net Active**

Just a portion of boron (about 10%) actively contributes to multilayer.

Most of boron is “buried” below Phosphorus (Nplus).

### Wafer Comparison

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</tr>
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- **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: Microsection of a single-pad diode

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Characterization of single-pad diodes from CNM Run 15973 before irradiation
Determination of $V_{gl}$ for non-irradiated devices

CV measurements at 20°C, 10kHz and 500 mV AC

1 device per carbon dose to show the average trend

Reverse bias (V)

Fitting regions

Reverse bias (V)

$C(V) = (222.1 - 4.7V) \text{ pF}$
$R^2 = 0.9999$

$V_{gl} = 32.7V$

$C(V) = (1369 - 39.8V) \text{ nF}$
$R^2 = 0.9994$
Determination of $V_{BD}$ for non-irradiated devices

IV measurements at -30°C, voltage step = 2 V

1 device per carbon dose to show the average trend

$V_{bd} = 118$ V
$V_{bd} = 130$ V
$V_{bd} = 184$ V
CNM Run15973 : $V_{gl}$ and $V_{BD}$ @ −30°C (non-irradiated)

- $V_{gl}$ increases with carbon dose up to 3e14/cm² (>15 CV measurements per carbon dose)
- $V_{BD}$ 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 suppressed 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
• TCAD simulation predicts this effect
• However, it does not predict the turning point at carbon doses > 3e14/cm²
CNM Run15973 : Gain measurements with 15 keV x-rays at Diamond LightSource

- Room temperature (20°C)
- 15 keV X-rays (absorption depth of \(\approx 1\) mm (just as near-IR 1064 nm TCT light))
- Beam size of 2.7x1.9 \(\mu\)m\(^2\) 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 \(3\times10^{14}/\text{cm}^2\) offer the highest gain (given a reverse bias)

\[
\text{Gain} = \frac{I_{\text{BeamOn}}^{\text{LGAD}} - I_{\text{leakage}}^{\text{LGAD}}}{I_{\text{BeamOn}}^{\text{PIN}} - I_{\text{leakage}}^{\text{PIN}}} = \frac{\text{Photocurrent}_{\text{LGAD}}^{\text{PIN}}}{\text{Photocurrent}_{\text{PIN}}^{\text{PIN}}}
\]
Instituto de Microelectrónica de Barcelona (IMB-CNMC)

J. Villegas, 43rd RD50 Workshop

**CNM Run15973**: Gain measurements with 15 keV x-rays at Diamond Light Source

- **Gain at the max intensity ($I_0$)**

  - Carbon dose ($10^{14}$ at/cm²)
    - 0
    - 1
    - 2
    - 3
    - 4
    - 5
    - 6
    - 7
    - 8
    - 9

  - 1 device per carbon dose
  - 5 measurements per device

- **Cutline of Gain @ 100V**

- **Reverse bias (V)**
  - 0
  - 50
  - 100
  - 150
  - 200
  - 250

- **Gain**
  - 0
  - 5
  - 10
  - 15
  - 20
  - 25
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.
Resistance is measured between two probes. Then resistivity and active doping concentration is extracted from it.
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Resistance is measured between two probes. Then **resistivity** and **active doping concentration** is extracted from it.

Simulation has to be calibrated!

**Carbon dose** (10^{14} \text{ at/cm}^2)

- Non carbonated
- 3
- Non carbonated (Simulation)
- 3 (Simulation)

\[ A(\text{sim}) = 2.37\times10^{16} \text{ at/cm}^2 \]
\[ A(\text{sim}) = 2.67\times10^{16} \text{ at/cm}^2 \]
Non-irradiated devices: Results overview

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

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<tbody>
<tr>
<td>( V_{GL} )</td>
<td>32 V</td>
</tr>
<tr>
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<td>V (8 fC)</td>
<td>&lt; 100 V*</td>
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### ATLAS

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<tr>
<td>V (4 fC)</td>
<td>&lt; 80 V*</td>
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<td>( \sigma ) at V(CC &gt; 4 fC)</td>
<td>&lt; 50 ps*</td>
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* 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

Mask : metal level

Mask : metal level + 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
CNM Run15973: 15x15 pixelated LGADs - IVs with temporary metal

IV @ -30°C with temporary metal
W7 (Carbon dose = 3e14/cm²)

- 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

IV @ -30°C with temporary metal

W7 (Carbon dose = 3e14/cm²)

26 devices

Reverse bias (V)

I (A)

V_{bd} (-30°C)
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)
Single pad devices irradiated with neutrons at JSI for fluences 4, 8, 15 and 25\texttimes{}10^{14} 1\text{MeV} n_{eq}

**After 80 min annealing @ 60ºC**

CVs @ 20ºC @ 10kHz @ 500mV AC

3 samples per carbon dose / fluence

**Example of V_{gl} determination**

- **V_{gl} = 9.1 V**

**Carbon dose (10^{14} \text{ at/cm}^2)**

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

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

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

42nd RD50: https://indico.cern.ch/event/1270076/
The loss of gain counterbalances the increase in leakage current, up to a fluence point and depending on the carbon dose.

Carbon dose (10^{14} at/cm^{2})

3 samples per carbon dose / 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/](https://indico.cern.ch/event/1335539/)

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<td>V_{op} (8 fC)</td>
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Upcoming work: CNM Run 16602

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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
- **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

**TCAD Simulation**

- Little boron is “buried” below Nplus layer
- Most of boron actively contributes to mult layer
Acknowledgments

• Thanks to:
  ➢ Gregor Kramberger and the JSI team for the irradiation of samples
  ➢ Viveka Gautam and the IFAE team for Sr-90 measurements
  ➢ Ivan Vila, Efren Navarrete and the IFCA team for Sr-90 measurements
  ➢ Vishal Dhamgaye and the Diamond Lightsource team for their help at the Synchrotron facilities

Thank you for your attention!

This work has also been funded by the Spanish Ministry of Science and Innovation (MCIN/AEI/10.13039/501100011033/) and by the European Union’s ERDF program “A way of making Europe”. Grant Reference: PID2020-113705RB-C32
CVs for irradiated devices

20°C
10 kHz
500 mV AC
When evaluating the surface current (Extraction Ring current) the behaviour is linear, just as expected for PiN detectors.