TCT MEASUREMENTS AND ANALYSES OF PROTON IRRADIATED LGADS

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With CNM-Barcelona and RD50 LGAD Teams

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WAFTER CHARACTERISTICS
CNM RUN 7859

- Multiplication layer dose: $1.8 \times 10^{13} \text{ cm}^{-2}$
  - Wafers 1 and 2.
  - Only one LGAD without JTE.
  - PIN diodes also available.

- Multiplication layer dose: $2.0 \times 10^{13} \text{ cm}^{-2}$
  - Wafers 3 and 4.
  - PIN diodes also available.
IRRADIATION CAMPAIGN

- Irradiation performed at the PS facility
  - 24-GeV protons
- Sets of 4 sensors, formed by
  - 1 PIN + 1 LGAD from W1 or W2
  - 1 PIN + 1 LGAD from W3 or W4
- Fluences:
  - $10^{12}$ 1 MeV n$_{eq}$/cm$^2$
  - $10^{13}$ 1 MeV n$_{eq}$/cm$^2$
  - $10^{14}$ 1 MeV n$_{eq}$/cm$^2$
  - $10^{15}$ 1 MeV n$_{eq}$/cm$^2$
- Annealing: 80 min at 60°C

References

Hardness factor: $\kappa = 0.56$

Multiplication layer dose:
- W1 and W2: $1.8 \times 10^{13}$ cm$^{-2}$
- W3 and W4: $2.0 \times 10^{13}$ cm$^{-2}$
TCT MEASUREMENTS

- Picosecond-pulsed LASER (200 ps)
- Red front and back (660 nm, 47.4 μW)
- IR front and back (1064 nm, 29.5 μW)
HOMOGENEITY ANALYSIS
Sample: LGAD_7859_2.0_4_W4_I3-1

Fluence $10^{12}$ n$_{eq}$/cm$^2$

Mult. layer $2.0 \times 10^{13}$cm$^{-2}$

**TCT - Red front @ -20°C, 100V**

Max. spread $\approx 6$ pC

Before irradiation

After irradiation

**TCT - Red back @ -20°C, 100V**

Max. spread $\approx 8$ pC

Before irradiation

Max. spread $\approx 4$ pC

After irradiation

Max. spread $\approx 5$ pC

07/06/2016  S. Otero Ugobono, TCT Measurements and Analyses of Proton Irradiated LGADs, 28th RD50 Workshop, Torino, Italy
Sample: LGAD_7859_1.8_4_W2_E3-1

Fluence $10^{12}$ n$_{eq}$/cm$^2$

TCT - Red front @ -20°C, 100V

Max. spread $\approx$ 7.5 pC

Before irradiation  

After irradiation

TCT - Red back @ -20°C, 100V

Max. spread $\approx$ 2 pC  

Max. spread $\approx$ 1 pC

Before irradiation  

After irradiation

Mult. layer $1.8 \times 10^{13}$ cm$^{-2}$
Sample: LGAD_7859_2.0_7_W3_C2-3

TCT - Red front @ -20ºC, 100V

Max. spread ≈ 8 pC

Before irradiation

Max. spread ≈ 0.3 pC

After irradiation

TCT - Red back @ -20ºC, 100V

Max. spread ≈ 2.5 pC

Before irradiation

Max. spread ≈ 1 pC

After irradiation

Fluence $10^{14}$ n$_{eq}$/cm$^2$

Mult. layer $2.0 \times 10^{13}$ cm$^{-2}$

07/06/2016
S. Otero Ugobono, TCT Measurements and Analyses of Proton Irradiated LGADs, 28th RD50 Workshop, Torino, Italy
Sample: LGAD_7859_1.8_9_W1_F10-3

**TCT - Red front @ -20°C, 100V**

Before irradiation

Max. spread $\approx 14 \text{ pC}$

After irradiation

Max. spread $\approx 0.23 \text{ pC}$

**TCT - Red back @ -20°C, 100V**

Before irradiation

Max. spread $\approx 1.4 \text{ pC}$

After irradiation

Max. spread $\approx 0.3 \text{ pC}$

Fluence $10^{15} \text{n}_{eq}/\text{cm}^2$

Mult. layer $1.8 \times 10^{13} \text{cm}^{-2}$

07/06/2016 S. Otero Ugobono, TCT Measurements and Analyses of Proton Irradiated LGADs, 28th RD50 Workshop, Torino, Italy
VOLTAGE SCANS
Charge collection with voltage

LGAD - TCT - Red front @ -20°C

Before irradiation

After irradiation

PIN - TCT - Red front @ -20°C

Before irradiation

After irradiation

Gain 3 - 6

\[\phi(n_{eq}/cm^2)\] Gain
\[10^{12}\] 2.9-5.6
\[10^{13}\] 3.0-5.9
\[10^{14}\] 1.8-2.7

Mult. layer 1.8x10^{13}cm^{-2}

\documentclass{article}
\usepackage{graphicx}
\begin{document}
\begin{figure}
\centering
\includegraphics[width=\textwidth]{charge_collection.png}
\caption[Charge collection with voltage]{Charge collection with voltage for LGADs and PINs.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{pin_collection.png}
\caption[Charge collection with voltage]{Charge collection with voltage for PINs.}
\end{figure}

\end{document}
Charge collection with voltage

LGAD - TCT - Red back @ -20°C

Before irradiation

After irradiation

PIN - TCT - Red back @ -20°C

Before irradiation

After irradiation

Mult. layer 1.8x10^{13} cm^{-2}
Charge collection with voltage

LGAD - TCT - IR back @ -20°C

Before irradiation

Gain 3.7 - 8.4

PIN - TCT - IR back @ -20°C

Before irradiation

Gain 3.7 - 8.4

After irradiation

PIN - TCT - IR back @ -20°C

Gain 3.7 - 8.4

After irradiation

PIN - TCT - IR back @ -20°C

Gain 3.7 - 8.4

After irradiation

Mult. layer 1.8x10^{13} cm^{-2}
Charge collection with voltage

LGAD - TCT - Red front @ -20°C

- LGAD_4_W4_D7-1
- LGAD_4_W4_I3-1
- LGAD_4_W3_E8-1
- LGAD_7_W3_C2-3
- LGAD_7_W3_D1-4

- LGAD_4_W4_I3-1 ($\phi = 10^{12}$ cm$^{-2}$)
- LGAD_4_W3_E8-1 ($\phi = 10^{13}$ cm$^{-2}$)
- LGAD_7_W3_C2-3 ($\phi = 10^{14}$ cm$^{-2}$)
- LGAD_7_W3_D1-4 ($\phi = 10^{15}$ cm$^{-2}$)

PIN - TCT - Red front @ -20°C

- PIN_4_W3_H9-1
- PIN_5_W4_A6-4
- PIN_4_W3_I8-1
- PIN_4_W4_A6-3

- PIN_4_W3_H9-1 ($\phi = 10^{12}$ cm$^{-2}$)
- PIN_5_W4_A6-4 ($\phi = 10^{13}$ cm$^{-2}$)
- PIN_4_W3_I8-1 ($\phi = 10^{14}$ cm$^{-2}$)
- PIN_4_W4_A6-3 ($\phi = 10^{15}$ cm$^{-2}$)

Gain 5 - 14

Before irradiation

After irradiation

Mult. layer

2.0x10^{13}$cm$^{-2}$
**Charge collection with voltage**

**LGAD - TCT - Red back @ -20°C**

**Gain** 10 - 28

**Before irradiation**

**After irradiation**

**PIN - TCT - Red back @ -20°C**

**Before irradiation**

**After irradiation**

**Mult. layer**

2.0\(\times10^{13}\) cm\(^{-2}\)
Charge collection with voltage

LGAD - TCT - IR back @ -20°C

Gain 8.3 - 44

Before irradiation

After irradiation

PIN - TCT - IR back @ -20°C

Before irradiation

After irradiation

Mult. layer 2.0x10^{13} cm^{-2}

ϕ (n_{eq}/cm^{2}) Gain
10^{12} 9.2–33
10^{13} 8.9–35
10^{14} 2.9–8.5
GAIN VALUES

“Type-1 Gain”:

- Ratio between the charge collected, after full depletion, in the LGAD and its respective PIN diode.

- This ratio should be obtained between sensors from identical wafers.

- If the samples were irradiated, in order to calculate the gain, the LGAD and the PIN must have been exposed to the same fluence.
**Type-I gain values at 700 V**

<table>
<thead>
<tr>
<th>Multiplication layer doping</th>
<th>IR back</th>
<th>Red back</th>
<th>Red front</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.8x10^{13} cm^{-2}</td>
<td>5.7</td>
<td>1.8x10^{13} cm^{-2}</td>
<td>6.6</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>1.8x10^{13} cm^{-2}</td>
<td>5.3</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>1.8x10^{13} cm^{-2}</td>
<td>3.1</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>1.8x10^{13} cm^{-2}</td>
<td>1.1</td>
</tr>
<tr>
<td>2.0x10^{13} cm^{-2}</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>W3 = 31.9</td>
<td>10^{12}</td>
<td>31.5</td>
<td>10^{12}</td>
</tr>
<tr>
<td>W4 = 25.7</td>
<td>10^{13}</td>
<td>24.6</td>
<td>10^{13}</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>10^{14}</td>
<td>7.7</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>10^{15}</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
<td>10^{15}</td>
<td>0.97</td>
</tr>
</tbody>
</table>

*The gain values before irradiation correspond to the mean between the type-I gain values at 700 V of all the corresponding sensors.*
GAIN VALUES

- “Type-2 Gain”:
  - Ratio between the electrons injected and the holes created in the multiplication layer.
  - Obtained by integration of the waveform.
### Type-2 gain values at 700 V

<table>
<thead>
<tr>
<th>Multiplication layer doping</th>
<th>Before Irradiation*</th>
<th>After Irradiation - $\phi$ ($n_{eq}/cm^2$)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$10^{12}$</td>
<td>$10^{13}$</td>
<td>$10^{14}$</td>
<td>$10^{15}$</td>
<td></td>
</tr>
<tr>
<td>$1.8 \times 10^{13}$ cm$^{-2}$</td>
<td>7.4</td>
<td>7.7</td>
<td>6.9</td>
<td>3.0</td>
<td>Not possible to calculate</td>
<td></td>
</tr>
<tr>
<td>$2.0 \times 10^{13}$ cm$^{-2}$</td>
<td>29.6</td>
<td>33.2</td>
<td>26.3</td>
<td>7.3</td>
<td>Not possible to calculate</td>
<td></td>
</tr>
</tbody>
</table>

### Type-1 gain values with red back TCT at 700 V

<table>
<thead>
<tr>
<th>Multiplication layer doping</th>
<th>Before Irradiation*</th>
<th>After Irradiation - $\phi$ ($n_{eq}/cm^2$)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$10^{12}$</td>
<td>$10^{13}$</td>
<td>$10^{14}$</td>
<td>$10^{15}$</td>
<td></td>
</tr>
<tr>
<td>$1.8 \times 10^{13}$ cm$^{-2}$</td>
<td>6.2</td>
<td>6.0</td>
<td>5.7</td>
<td>2.8</td>
<td>0.9</td>
<td></td>
</tr>
<tr>
<td>$2.0 \times 10^{13}$ cm$^{-2}$</td>
<td>21.4</td>
<td>23.1</td>
<td>18.9</td>
<td>7.7</td>
<td>0.97</td>
<td></td>
</tr>
</tbody>
</table>

*The gain values before irradiation correspond to the mean between the gain values at 700 V of all the corresponding sensors.*
THRESHOLD VOLTAGE
To actually have gain the multiplication layer must be depleted.

The threshold voltage indicates as from which voltage the multiplication layer is depleted.

The threshold voltage can be determined by red front TCT.
According to Gregor’s results* the threshold voltage decreases with fluence.

The opposite effect was observed in the LGADs from CNM run 7859.

Most plausible explanation: double junction effect due to hole trapping.

DOUBLE JUNCTION EFFECT
HOLE TRAPPING

- Before irradiation there are no deep traps => the depletion region grows from the front.

- After irradiation trapping is significant.

- Excess holes + multiplication holes can get trapped and thus change the space charge.

- Because of the occupation probability of traps, the process is highly dependent on temperature
  - The lower the temperature, the longer charges remain trapped.
Fluence $10^{14} \text{neq/cm}^2$

**TCT - Red back**

**LGAD_4_W2_I3-1**

- **20°C**
- **0°C**
- **-20°C**

**PIN_7_W1_C9-3**

- **20°C**
- **0°C**
- **-20°C**

Mult. layer $1.8 \times 10^{13} \text{cm}^{-2}$
Fluence $10^{14}$ n$_{eq}$/cm$^2$

TCT - Red front

LGAD_4_W2_I3-1

20°C

PIN_7_W1_C9-3

20°C

0°C

-20°C

0°C

-20°C
Fluence $10^{14}$ n$_{eq}$/cm$^2$

Mult. layer $2.0 \times 10^{13}$cm$^{-2}$
Fluence $10^{14}$ n$_{eq}$/cm$^2$

**LGAD 7_W3_C2-3**

**PIN 4_W3_I8-1**

20ºC

0ºC

-20ºC

20ºC

0ºC

-20ºC

Mult. layer 2.0x$10^{13}$cm$^{-2}$
CONCLUSIONS

- Homogeneous charge collection before and after irradiation.

- Charge collection and gain decrease after irradiation.
  - At a fluence of $10^{14} \text{n}_{\text{eq}}/\text{cm}^2$ the gain is
    - $\approx 2$ times smaller than before irradiation, for W1 and W2,
    - $\approx 4$ times smaller than before irradiation, for W3 and W4.
  - At $10^{15} \text{n}_{\text{eq}}/\text{cm}^2$ there is no difference in charge collection between PIN diodes and LGADs.

- The voltage required to deplete the multiplication layer increases with fluence, when the irradiation is with protons.
  - This is a direct consequence of the double junction effect caused by hole trapping.
THANK YOU
Fluence $10^{14}$ n$_{eq}$/cm$^2$

TCT - Red back

LGAD_4_W2_I3-I

PIN_7_W1_C9-3

-20°C

Fluence $10^{14}$ n$_{eq}$/cm$^2$
TCT - Red front

Fluence $10^{14} \text{n}_{\text{eq}}/\text{cm}^2$

Mult. layer $1.8 \times 10^{13} \text{cm}^{-2}$

LGAD_4_W2_I3-1

PIN_7_W1_C9-3

-20°C

-20°C

07/06/2016 S. Otero Ugobono, TCT Measurements and Analyses of Proton Irradiated LGADs, 28th RD50 Workshop, Torino, Italy
Fluence $10^{14}$ n$_{eq}$/cm$^2$

TCT - Red back

LGAD_7_W3_C2-3

PIN_4_W3_I8-I

Mult. layer $2.0 \times 10^{13}$ cm$^{-2}$
Fluence $10^{14} \text{neq/cm}^2$

TCT - Red front

LGAD_7_W3_C2-3

PIN_4_W3_I8-1

Mult. layer $2.0 \times 10^{13} \text{cm}^{-2}$
Fluence $10^{14} \text{n}_{\text{eq}}/\text{cm}^2$

Mult. layer $1.8 \times 10^{13} \text{cm}^{-2}$

Voltage range: 10V to 1000V, 10V steps
Fluence \(10^{14}\) n\(_{eq}/cm^2\)

TCT - Red front

Voltage range: 10 V to 1000 V, 10 V steps

LGAD_4_W2_I3-1

Voltage at:
- 0°C
- 20°C
- -20°C

Fluence: \(10^{14}\) n\(_{eq}/cm^2\)

Mult. layer: \(1.8\times10^{13}\) cm\(^{-2}\)
Fluence $10^{14} \text{n}_{eq}/\text{cm}^2$

PIN_7_W1_C9-3

Voltage range: 10V to 1000V, 10V steps
Fluence \(10^{14} \text{n}_{eq}/\text{cm}^2\)

TCT - Red front

**PIN_7_W1_C9-3**

Voltage range: 10V to 1000V, 10V steps
Fluence $10^{14} \, \text{n}_{\text{eq}}/\text{cm}^2$

**TCT - Red back**

**LGAD_7_W3_C2-3**

Voltage range: 10V to 1000V, 10V steps

**0°C**

**20°C**

**-20°C**
Fluence $10^{14}$ $n_{eq}/cm^2$

TCT - Red front

LGAD_7_W3_C2-3

Voltage range: 10V to 1000V, 10V steps

0ºC

20ºC

-20ºC
Fluence $10^{14}$ n$_{eq}$/cm$^2$

PIN_4_W3_I8-1

Voltage range: 10V to 1000V, 10V steps

$0^\circ$C

$20^\circ$C

$-20^\circ$C
Fluence $10^{14}\text{ n}_{\text{eq}}/\text{cm}^2$

TCT - Red front

**Voltage range:**

10V to 1000V, 10V steps

PIN_4_W3_I8-1

0°C

20°C

-20°C