Multiplication onset and electric field properties of proton irradiated LGADs

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HL-LHC: Challenging Technology

HL-LHC Upgrade:

- Increase in luminosity.
- Radiation levels up to $1.6 \times 10^{16}$ cm$^{-2}$.
  - 10 times the current fluence.
- Higher event pile-up.
  - Better timing resolution needed (≈20 ps).
- Maintain spatial accuracy.

Possible solution:

Detectors with intrinsic gain.
Detectors with Intrinsic Gain

- Internal multiplication of charge: increase in signal.
  - Better signal-to-noise ratio, even after irradiation.
  - Better timing capabilities.
- One possible technology:
  - Low Gain Avalanche Detectors (LGAD).
Low Gain Avalanche Detectors

- Planar silicon sensors ($n^+/p/p^-$).
- $n^+$ implant, $\pi$ substrate.
- $p$-type multiplication layer.

High electric field region in the multiplication layer.

- Charges undergo impact ionisation.
- Gain depends on:
  - multiplication layer doping,
  - bias voltage,
  - temperature.

Low gain (~10 to 30)

- Signal increase & low noise.
- Low risk of breakdown.
Irradiation Campaign

- LGADs from CNM Run 7859.
  - Wafers 1 and 2.
    - Multiplication layer dose: $1.8 \times 10^{13} \text{ cm}^{-2}$.
  - Wafers 3 and 4.
    - Multiplication layer dose: $2.0 \times 10^{13} \text{ cm}^{-2}$.

- Irradiated at the CERN IRRAD facility with 24-GeV/c protons.

- 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.
Measurements Performed

Transient Current Technique (TCT)

- Picosecond-pulsed LASER (200 ps).
- Laser-induced charge injection.
- Red front and back illumination.
- ~3 μm absorption length in Si.
- Charge injection close to the surface.
Red front illumination TCT - Mult. Layer 1.8E13 cm\(^2\) at -20\(^\circ\)C

- Non-irradiated (4_W2_I3-1)
- \(\phi = 10^{12} \text{ cm}^{-2}\) (4_W2_E3-1)
- \(\phi = 10^{13} \text{ cm}^{-2}\) (4_W2_D8-2)
- \(\phi = 10^{14} \text{ cm}^{-2}\) (4_W2_I3-1)
- \(\phi = 10^{15} \text{ cm}^{-2}\) (9_W1_F10-3)

Red front illumination TCT - Mult. Layer 2.0E13 cm\(^2\) at -20\(^\circ\)C

- Non-irradiated (7_W3_C2-3)
- \(\phi = 10^{12} \text{ cm}^{-2}\) (4_W4_I3-1)
- \(\phi = 10^{13} \text{ cm}^{-2}\) (4_W3_E8-1)
- \(\phi = 10^{14} \text{ cm}^{-2}\) (7_W3_C2-3)
- \(\phi = 10^{15} \text{ cm}^{-2}\) (7_W3_D1-4)
Depletion Region

Before Irradiation

After Irradiation
Double junction effect
Charge Collection vs. Bias

- Non-irradiated

\( \phi = 10^{12} \text{ cm}^{-2} \) (4_W2_E3-1)

\( \phi = 10^{13} \text{ cm}^{-2} \) (4_W2_D8-2)

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- $\phi=10^{15}$ cm$^{-2}$ (7_W3_D1-4)
To actually have gain the multiplication layer must be depleted.

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

The multiplication onset voltage can be determined by red front TCT.

Observed as a *foot* in the charge collection vs. bias voltage curves.
According to G. Kramberger’s results* (CNM run 6474), the mult. onset voltage decreases with fluence in LGADs with low leakage current (≤ 1 μA at V_{fd}, 20°C).

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

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

The device is depleted from the back.

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Before irradiation, there are no deep traps => the depletion region grows from the front (multiplication layer).

After irradiation, trapping is significant.

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 the charges remain trapped.
Further analyses of the two LGADs irradiated up to $10^{14} \text{n}_{\text{eq}}/\text{cm}^2$

The apparent double junction effect is most noticeable at this fluence.
Both sensors qualify as low current devices according to the classification employed by G. Kramberger*:

leakage current ≤ 1 μA at V_{fd}, 20°C

*G. Kramberger, Effects of irradiation on LGAD devices with high excess current, 25th RD50 Workshop, CERN, November 2014
IV Curves at 20°C (before irradiation)

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TCT voltage scans performed on:
- One unirradiated LGAD used as reference (mult. layer $2.0 \times 10^{13} \text{ cm}^{-2}$).
- Both LGADs irradiated up to $10^{14} \text{n}_{\text{eq}}/\text{cm}^2$.

Conditions:
- Two temperatures: 20ºC and -20ºC.
  - To see the effects of temperature on the multiplication onset (double junction effect).
- The measurements were performed
  - with the guard ring (GR) floating (usual procedure),
  - with the GR connected to ground (to assess any possible differences).

The scans were compared to those measured in 2016 and presented at the 28th RD50 Workshop.
The GR connection scheme causes no significant changes.

The multiplication onset does not depend on temperature.
At -20°C the GR shifts the onset of multiplication.

The multiplication-onset voltage is lower at high temperatures.

The multiplication-onset voltage decreased with time.

Recovery of gain with time. ➔ Possible cause: annealing.
Irradiated LGAD - Mult. Layer: $2.0 \times 10^{13}$ cm$^{-2}$

The GR connection causes no significant changes.

The multiplication onset does not change significantly with temperature now.

Significantly large shift in the multiplication-onset voltage with respect to 2016.

Recovery of gain with time/annealing.

Onset voltage before irradiation: $\sim 32$ V
Gain before irradiation at 400V and -20°C: $\sim 6.83$

Gain at 400 V, -20°C. Calculated w.r.t a PiN. Normalised by laser power.
Results from Irradiated LGADs

- Device with a multiplication layer dose of $1.8 \times 10^{13} \text{ cm}^{-2}$.
  - Multiplication onset dependant on temperature.
  - Consistent with double junction effect.

- Device with a multiplication layer dose of $2.0 \times 10^{13} \text{ cm}^{-2}$.
  - In 2016 this sample presented clear signs of double junction effect.
  - In 2017 the multiplication onset ceased to be affected by temperature.
  - Just as before irradiation.
Double Junction Effect?

- How does the electric field evolve with voltage?
- How does the electric field change with temperature?
Measurements Performed

Edge Transient Current Technique (eTCT)

- IR edge illumination.
- ~1 mm absorption length in Si.
- Probing of the electric field profile.

Diagram:

- Field Plate + JTE
- N+ Cathode
- P+ Anode
- IR laser eTCT
- eTCT Diagram
Two Photon Absorption TCT (TPA)

- The energy of each individual photon is smaller than the bandgap.
- Sum of energies from 2 photons \( \geq \) bandgap.
- If the \( \Delta t \) between photons is smaller than \( \sim 0.1 \) fs, both photons are absorbed.

\[
\tau \approx \frac{\hbar}{E_{gap}/2} \approx 0.1 \text{ fs}
\]

- Transition via an intermediate virtual state.
- An e-h pair is produced.
- Femtosecond pulsed mode-locked laser required.
- Beam spot volume: ellipsoid of \( \sim 1 \) \( \mu \text{m} \) section and \( \sim 10 \) \( \mu \text{m} \) length.
Edge TCT and TPA

- TPA-TCT was performed on one sample (mult. dose: $1.8 \times 10^{13} \text{cm}^{-2}$).
- eTCT scans were performed on both irradiated samples.
- The objective is to better comprehend the distribution of the electric field inside the devices.

**Conditions:**
- Temperatures: 20°C, -20°C, and 0°C (only for TPA).
- Several voltages.
- The edge was polished.
The electric field grows from the back of the device.

The electric field begins to increase in the front side at:
- ~96 V for -20°C,
- ~45 V for 0°C.

Consistent with double junction effect.
- The lower the temperature the more noticeable the effect.
Temperature does not seem to affect dramatically the profile of the electric field (unirradiated-like).

At 20ºC the electric field on the back of the device is higher than at -20ºC.
Conclusions

- Good quality samples
  - i.e. low leakage current before irradiation < 1 µA at $V_{fd}$, and 20°C.
- Devices irradiated up to $10^{14}$ 1 MeV n$_{eq}$/cm$^2$.
- Double junction effect observed in TCT measurements (TCT, eTCT and TPA-TCT).
  - The electric field starts growing from the back of the device.

Open question: why are our results different from previous measurements on similar devices?
Conclusions

- Devices irradiated up to $10^{14}$ 1 MeV $n_{eq}/cm^2$.
- Measurements show that with annealing
  - the multiplication-onset voltage decreases,
  - the gain is recovered to 60-70% of the value before irradiation.
- Sample with a multiplication layer dose of $2.0 \times 10^{13} cm^{-2}$: no temperature dependance of the onset voltage (as before irradiation) in 2017.

The double junction effect shows a dependance on the annealing history.

As samples get annealed, they tend towards an unirradiated-like state.

Annealing is playing an important role for LGAD performance and might be exploitable for LGAD long term operation.
Further Studies

- Perform an annealing study on the devices presented today.

- Perform TPA on sample LGAD_7859_7_W3_C2-3 (mult. layer dose: $2.0 \times 10^{13}$ cm$^{-2}$).

- Irradiate to $10^{14}$ 1 MeV n$_{eq}$/cm$^2$ the LGAD kept unirradiated for reference.
  - Perform CV/IV, TCT and eTCT.
  - Do an annealing study on the device.

- Irradiate a new set of LGADs of similar characteristics and compare the results.
  - The devices have already been characterised before irradiation.
  - To be irradiated at the CERN IRRAD facility with 24-GeV/c protons.

- Analyse if the behaviour of the other irradiated devices (fluences between $10^{12}$ and $10^{15}$ 1 MeV n$_{eq}$/cm$^2$) has changed.
Backup Slides
The electric field grows from the back.
20°C:

- The drift velocity is higher on the front of the device.
- At higher voltages the velocity tends to be more homogeneous throughout the device.

-20°C:

- V < 85 V: drift velocity on the back is either higher or comparable to that on the front.
- V > 85 V: drift velocity peaks at the front.
- V >> 85 V: drift velocity tends to be more homogeneous throughout the device.
Irradiated LGAD - Mult. Layer: $1.8 \times 10^{13}$ cm$^{-2}$

Red front TCT - LGAD_7859_4_W2_I3_1 - $1 \times 10^{14}$ n$_{eq}$/cm$^2$

- GR grounded -20°C back bias and front read-out (August 2017)
- GR floating -20°C back bias and front read-out (May 2017)
- GR grounded 20°C back bias and front read-out
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- GR floating -20°C front bias and front read-out (April 2016)
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Irradiated LGAD - Mult. Layer: $2.0 \times 10^{13} \text{ cm}^{-2}$

Red front TCT - LGAD_7859_7_W3_C2_3 - $1 \times 10^{14} \text{n}_{eq}/\text{cm}^2$

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Red front TCT - LGAD_7859_7_W3_C2_3 - $1 \times 10^{14} \text{n}_{eq}/\text{cm}^2$

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Close-up