Annealing and Characterization of Low Gain Avalanche Detectors

Moritz Wiehe\textsuperscript{1,2}, E. Curras Rivera\textsuperscript{3}, M. Fernández García\textsuperscript{1,3}, M. Moll\textsuperscript{1}, S. Otero Ugobono\textsuperscript{1,4}, U. Parzefall\textsuperscript{2}, A. Ventura Barroso\textsuperscript{5}, I. Vila Alvarez\textsuperscript{3}

\textsuperscript{1} CERN
\textsuperscript{2} Albert-Ludwigs Universität Freiburg
\textsuperscript{3} Universidad de Cantabria
\textsuperscript{4} Universidad de Santiago de Compostela
\textsuperscript{5} University of Barcelona

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Outline

- Introduction:
  Samples, setup and previous studies
- Gain after annealing
- Onset voltage for IV/CV and TCT-measurements
- E-Field profile after annealing
- Conclusions
Low Gain Avalanche Detectors

LGADs are based on APDs but have lower gain:
- optimal S/N ratio
- reduced cross-talk among neighboring strips/pixel
- limited collection times

Depletion of p⁺-multiplication layer at ~ 30V
Full depletion of device at ~ 70V - 100V
Radiation Effects

Acceptor Removal

- believed to be originating from dislocated acceptors (boron) forming complex states with oxygen: $\text{Bi}_i\text{O}_i$
→ boron electrically deactivated
→ $N_{\text{eff}}$ decreases

Deterioration of Electric Field

- trapping of charge carriers in bulk material alters electrical properties
- can lead to space charge sign inversion
- creating apparent junction at the back of the detector

S. Otero Ugobono
Previous Studies

Gregor Kramberger, 2015:
Radiation effects in Low Gain Avalanche Detectors after hadron irradiations

Sofía Otero Ugobono, 2018:
Characterisation and Optimisation of Radiation-Tolerant Silicon Sensors with Intrinsic Gain

Acceptor removal in p+ layer
- decreasing onset voltage ($V_{mr}$)
- no temperature dependence

Double junction effect
- increasing onset voltage
- strong temperature dependence

samples annealed at 60°C for 80min before characterization
LGAD Annealing Study - Samples

- Two LGADs from CNM Run 8622, Wafer 5
  - ‘E3_1’, ‘I3_1’
    - Amplification layer: ‘medium dose’
- PIN diode, Run 8622, Wafer 5
  - ‘E3_4’
    - no amplification layer, otherwise identical

- all samples:
  - Thickness: 285\(\mu\)m, active area 3x3mm\(^2\)
  - 24 GeV/c - proton irradiated with \(10^{14}\) \(n_{eq}/cm^2\) at CERN IRRAD facility
  - high resistivity p-FZ wafers

- annealing steps at 60°C: 80, 240, 560, 1200, 2480, 5040 ... minutes
Red Front TCT

- Red Front TCT measurements at -20°C and +20°C
- all measurements normalized by the laser power

devices are biased from the back
signal read-out at the top
guard ring grounded

all samples:
$10^{14} \text{n}_{\text{eq}} \text{ / cm}^2$

PIN W5_E3_4

annealing time

LGAD W5_E3_1

annealing time

RF TCT PIN W5_E3_4

-20°C

+20°C

solid lines: +20°C
dotted lines: -20°C

Charge in 25ns [arb.]

U_{bias} [V]

Charge in 25ns [arb.]

U_{bias} [V]
Gain after Annealing

Gain($U_{bias}$) calculated for each annealing step.
PIN diode (at same annealing state) used as reference (type-1 gain):

$$Gain = Q^{L_{GAD}}_{25ns} / Q^{PIN}_{25ns}$$

Note: Impact ionization coefficient is temperature dependent
→ higher gain for -20°C before and after irradiation

Stable gain after irradiation
→ Annealing does not affect the gain layer.
Charge Collection – Onset Voltage

Red Front TCT measurements at -20°C and +20°C

- all measurements normalized by the laser power
- devices are biased from the back
- signal read-out at the top
- guard ring grounded

Determination of onset voltage by fit:

\[ Q_{25\text{ns}}(U_{bias}) = \sqrt{U_{bias} - U_{onset}} \]

Onset voltage ~ 33V before irradiation
~ 50V after irradiation (80min annealing)

reduces with increasing annealing time

all samples: \(10^{14} n_{eq} / \text{cm}^2\)

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Moritz Wiehe - 14th Trento Workshop, Feb. 2019
Leakage Current – Onset Voltage

- Decrease of leakage current with annealing as expected
- 'Kink' visible for LGADs at ~ 26V, independent of annealing time!

all samples: $10^{14} \text{n}_{\text{eq}} / \text{cm}^2$
IV vs. TCT Onset Voltage

Kink position in IV measurements

80min annealing: 27V
>80min: stable at 26V

TCT - Onset voltage decreases from 50V to ~ 26V with annealing.

RedFront TCT

- E3_1 -20°C
- I3_1 -20°C
- E3_1 +20°C
- I3_1 +20°C

all samples: $10^{14} \text{n}_{eq}/\text{cm}^2$
- after irradiation: kink starting at 26V (same voltage as in IV)

increasing capacitance with annealing, in agreement with lower depletion width (eTCT, next slide) and less signal charge (RF-TCT)
**Edge-TCT**

Drift velocity vs. z-position for 80 and 2480min annealing

Signal after ~500ps used to estimate E-field (simplified!):

\[ I(t \approx 0) \propto v_{drift} \propto \mu(E)E(z) \]

Indication of double junction at ~ 50V after 80min annealing (60°C)

Front/amplification layer

Back

All samples: \(10^{14} n_{eq} / \text{cm}^2\)
Annealing behavior at 55 V

Double junction after 80 minutes of annealing visible at low voltages
→ E-Field at back of sensor
→ increased TCT- onset voltage

Double junction disappears with longer annealing times
→ acceptor removal dominant
→ reduced onset voltage wrt. before irradiation

all samples: $10^{14} n_{eq} / \text{cm}^2$
Edge-TCT at Front Side

Unirradiated:
Onset voltage as expected at around 30V

After irradiation (80min annealing):
Onset voltage expected to be \(~50V\) (from red front measurements)
observed at \(~25V\) in eTCT (most likely due to large charge deposition volume)
Annealing of LGADs - Conclusion

Sensors functional after irradiation with $10^{14}\, n_{eq} / \text{cm}^2$ (24 GeV/c protons)
No recovery of (type-1) gain after annealing

Complex annealing behavior observed
Double junction at short annealing times
→ TCT - onset voltage increased to ~ 50V due to change in E-Field
  but not observed with eTCT measurements (larger charge deposition volume)

→ IV/CV – onset voltage stable at ~26V independent of annealing time

Deterioration of gain layer with irradiation
→ Reduced gain
→ Gain layer is not affected by annealing

Onset voltage measured by (Front-) TCT is not necessarily related to the properties of the gain layer.
TCT - Transient Current Technique

Red Front TCT

IR edge-TCT

![Diagram of TCT](image)

- **electron signal**
- **hole signal**

![Graph of PIN unirradiated](image)

- **PIN unirradiated**
  - $U_{bias} = 100V$, $-20^\circ C$

![Graph of edge TCT](image)

- **edge TCT**
  - PIN unirradiated
  - $U_{bias} = 100V$, $-20^\circ C$
TCT+ setup at CERN

- Samples glued to PCB for electrical connection
- Peltier-based cooling system (~ -25°C)
- Temperature sensor attached to PCB
- 3D stage system to align laser and sample

**Two laser heads:**
- **Red** (top and bottom measurements)
  \( \lambda = 660\text{nm} \)
- **Infrared** (edge + top/bottom)
  \( \lambda = 1064\text{nm} \)

LabView based DAQ and control

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Christian Gallrapp, “The TCT+ setup - a system for TCT, eTCT and timing measurements”, 1st TCT Workshop DESY
Previous Studies

Decreasing onset voltage ($V_{mr}$)
- explained by acceptor removal in p+ layer

No temperature dependence of $V_{mr}$ rules out possible explanation of compensation of effective acceptors by trapped holes

Increasing onset voltage
- explained by double junction effect

Strong temperature dependence of $V_{mr}$ supports explanation by trapped holes, creating double junction
Recap: Gain

Gain reduced after irradiation

From these previous measurements, some recovery after annealing is expected
Onset voltage measured at 200-300V for $10^{14} \text{n}_{\text{eq}}/\text{cm}^2$
Current Related Damage Rate

calculated using physical sensor volume: 285µm x 3x3mm²

No multiplication factor (M=1)

\[ \alpha = \frac{I}{\Phi_{eq}V M} \]

all samples: 10^{14} n_{eq} / cm²
Capacitance - CV

- 'Kink' visible at same voltage as in IV measurement
- Depletion voltage increasing with annealing
Capacitance - CV

- 'Kink' visible at same voltage as in IV measurement

[Graph showing capacitance characteristics]
RF – TCT onset -20/+20
Red Front TCT measurements at -20°C and +20°C all measurements are normalized by the laser power devices are biased from the backside signal read-out at the top guard ring grounded
RF TCT - 50ns

Charge in 50ns [arb.]

RF TCT PIN W5_E3_4
- unirrad
- 80min
- 240min
- 560min
- 1200min
- 2480min
- 5040min

solid lines: +20°C
dotted lines: -20°C

Charge in 50ns [arb.]

RF TCT LGAD W5_E3_1
- unirrad
- 80min
- 240min
- 560min
- 1200min
- 2480min
- 5040min

solid lines: +20°C
dotted lines: -20°C