Annealing and Characterization of Low Gain Avalanche Detectors

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Outline

- Introduction:
  Samples, setup and previous studies
- Gain after annealing
- Onset voltage for IV and TCT measurements
- E-Field profile after annealing
- Conclusions
TCT - Transient Current Technique

Red Front TCT

IR edge-TCT

hole signal

electron signal

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

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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 $\sim 30V$
Full depletion of device at $\sim 70V$ - $100V$
Radiation Effects

Acceptors Removal
- yet to be fully understood
- believed to be originating from dislocated acceptors (boron) forming complex states with oxygen (B\textsubscript{i}O\textsubscript{i})
  → boron electrically deactivated
  → N\textsubscript{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 side of the detector

S. Otero Ugobono
Previous Studies

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

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

G. Kramberger et al 2015 JINST 10 P07006

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

- Double junction effect
  - increasing onset voltage
  - strong temperature dependence

samples annealed at 60°C for 80min before characterization
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)
  λ=660nm
- Infrared (edge + top/bottom)
  λ=1064nm

LabView based DAQ and control

CERN – SSD TCT+ (B186)

Christian Gallrapp, “The TCT+ setup - a system for TCT, eTCT and timing measurements”, 1st TCT Workshop DESY
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: \textbf{285\,\mu m}, active area \textbf{3x3\,mm$^2$}
  \textit{24 GeV/c - proton irradiated with $10^{14}\text{n}_{\text{eq}}/\text{cm}^2$ 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 backside
signal read-out at the top
guard ring grounded

PIN W5_E3_4
annealing time

LGAD W5_E3_1
annealing time

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

Gain/U<sub>bias</sub> calculated for each annealing step. PIN diode (at same annealing state) used as reference (type-1 gain):

\[
Gain = \frac{Q_{LGAD}^{25\text{ns}}}{Q_{PIN}^{25\text{ns}}}
\]

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

11/26/18

Moritz Wiehe - 33rd RD50, CERN Nov. 2018
Stable gain after irradiation
→ Annealing does not affect the gain layer

Note: Impact ionization coefficient is temperature dependent
→ higher gain for -20°C before and after irradiation
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 backside
- signal read-out at the top
- guard ring grounded

Determination of onset voltage by fit:

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

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

reduces with increasing annealing time
no obvious dependence on temperature
Leakage Current – Onset Voltage

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

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

**Graphs:**
- **IV measurements**
  - 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
- E3_1 +20°C
- I3_1 -20°C
- I3_1 +20°C

**Note:**
- All samples: $10^{14} n_{eq}/cm^2$
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)

frontside amplification layer

backside

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

Annealing behavior at 55 V

Double junction after 80 minutes of annealing visible at low voltages
→ affects Charge Collection for TCT measurements
→ increased TCT- onset voltage
Double junction disappears with longer annealing times
→ acceptor removal dominant
→ reduced onset voltage wrt. before irradiation

all samples: $10^{14} \text{n}_{eq} / \text{cm}^2$
Annealing of LGADs - Conclusion

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

Complex annealing behavior observed
  Double junction at short annealing times
    → Charge collection - onset voltage increased to ~ 50V due to change in E-Field

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

Deterioration of gain layer with irradiation
  → Reduced gain
    → Depletion of gain layer already at 26V (~33V before irradiation)
  → Gain layer is not affected by annealing (see IV + gain)

Onset voltage measured by TCT is not directly related to the depletion of the amplification layer
Backup
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

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

\(10^{14} \text{n}_{eq} / \text{cm}^2\)
Capacitance - CV

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

Proton $10^{14} n_{eq} / \text{cm}^2$

LGAD W5_I3_1 -20°C

- 80 min $U_{id} = 142.7 \text{V}$
- 240 min $U_{id} = 172.1 \text{V}$
- 560 min $U_{id} = 196.8 \text{V}$
- 1200 min $U_{id} = 225.1 \text{V}$
- 2480 min $U_{id} = 284.5 \text{V}$

Proton $10^{14} n_{eq} / \text{cm}^2$

Annealing time at 60°C [min]
Red Front TCT

LGAD W5_E3_1

LGAD W5_I3_1

PIN W5_E3_4

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

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