Radiation hardness of thin LGAD detectors

Gregor Kramberger
Jožef Stefan Institute, Ljubljana

on behalf of RD50 project collaborators:
CNM–Barcelona, IFAE – Barcelona, Univ. Of Torino and INFN–Torino, SCIPP–UCSC Santa Cruz, Univ. Ljubljana and Jožef Stefan Institute
Motivation

- ATLAS–High Granularity Timing Detector/CMS Totem–PPS– timing detectors
- Good timing devices require large gain and small thickness for several reasons:
  - “uncorrectable–Landau” time walk, due to energy loss fluctuations becomes a smaller problem
  - an additional advantage is short drift times and consequently trapping effects (e.g. 50 μm thick device and the saturation velocity for holes yields drift time of 600 ps → few $10^{15}$ cm$^{-2}$ the trapping should not influence the performance dramatically
  - slew rate of the signal is proportional to the ratio Gain/Thickness
    (NIM A831(2016) p.18, N. Cartiglia 11th Trento Workshop)
Standard thickness LGADs have problems with effective acceptor removal, which degrades gain fast – almost gone at $5 \times 10^{14}$ cm$^{-2}$ for applicable voltages.

Why can thin sensors be potentially more radiation hard than standard even if the removal is the same:

- With over depletion ($V > V_{fd}$) the electric field in the multiplication layer grows as: $\Delta E = \Delta V/W$

Smaller electric field in the multiplication layer due to smaller $N_{eff}$ can be much easily compensated with higher applied bias voltage.

Properties of the bulk material become more important.
At $r,z=(11\ cm,350\ cm)$ the share of charged hadrons/neutrons contribution to NIEL is $\sim 0.5$ in ATLAS.

Two potential differences wrt to neutron irradiated LGADs:
- Difference in effective acceptor removal (factor 2 observed in standard LGADs of small gain)
- Difference in electric field profile in the bulk (more pronounced in thin sensors)

The key questions are:
- Can we operate e.g. ATLAS HGTD for the entire lifetime – $\Phi_{eq} \sim 4 \cdot 10^{15}\ cm^{-2}$ at adequate performance ($\sim 20\ ke\rightarrow\ 55\ ps\ per\ layer$)?
- Do we have to replace modules? If yes, how to do it?
Devices and experimental technique

- **CNM Run 6827** - (Epitaxial devices, 100 Ωcm, 50 μm thick)
  - LGAD samples of low boron concentration in multiplication layer - gain of 7 reached only at high bias voltages
  - Control PIN samples with no multiplication layer
  - Excellent high voltage tolerance

- **CNM Run 9088** (SOI devices, high-resistivity, 45 μm thick)
  - Three different multiplication layer doping concentrations
    - W3 – Dose=1.8e13 cm\(^{-2}\)
    - W5 and W7 – dose =1.9e13 cm\(^{-2}\) (most studied)
    - W11 – Dose=2.0e13 cm\(^{-2}\)
  - Three different device structures
  - Control PIN diodes produced along the LGAD

Excellent results with these R9088 devices – see: Jörn Lange’s talk and N. Cartiglia’s paper arXiv:1608.08681

- **Images:**
  - HGTD 4x2x2 mm\(^2\)
  - LGB 3x3 mm\(^2\)
  - LGA 1.3x1.3 mm\(^2\)

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G. Kramberger et al.,“Radiation hardness of thin LGAD detectors”, 12th Trento Workshop, Trento
Signal/gain is directly correlated to timing resolution.

Clear influence on implantation dose:
Smaller dose -> higher gain at given voltage, but earlier breakdown
A good agreement with basic simulations
Signal after neutron irradiations (R9088)

- Gain degrades, but follows the expectations
- “Breakdown” voltage of the device is shifting to higher bias with irradiations

1.) at fluences < $1 \times 10^{15}$ cm$^{-2}$ effective acceptor removal in multiplication layer reduces the gain, which appears as soon as the multiplication layer is depleted.

2.) Smaller $N_{\text{eff}}$ in multiplication layer leads to smaller slope of the Q–V dependence.

3.) at fluences of $1 \times 10^{15}$–$2 \times 10^{15}$ cm$^{-2}$ the multiplication is visible only at higher bias voltages – up to few 100 V collected charge similar to pin diode – the difference between LGAD and PIN becomes small.
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LGAD are advantageous for high gain device up to $2 \times 10^{15} \text{ cm}^{-2}$

At high fluences $\Phi_{\text{eq}} > 2 \cdot 10^{15} \text{ cm}^{-2}$ the behavior is the same for all samples:

- regardless of initial doping concentration (to confirmed by more statistics)
- regardless of p$^+$ layer doping (acceptor removal is almost complete)
- regardless of annealing behavior (needs to be verified by several samples – so far PIN only).
- It seems that at high enough fluences the performance doesn’t degrade anymore – in accordance with predictions (see G. Kramberger et al talk at 28th RD 50 Workshop in Torino)

The last point is always taken just before the detector exhibits a “soft break down”:

- Irradiation shifts the breakdown voltage to higher values.
- The rise of the charge is associated with the rise of the current and noise (system dependent) which could be kept under control by cooling and cell size.
- Note, that average $E > 12 \, \text{V/\mu m}$ for voltages above 600 V.
Two factors are important for good timing resolution:

- **Gain**
- **saturated drift velocity** (high gain at low bias voltage is not sufficient)

With irradiations the required bias voltage for gain increases (above $<E>=3\text{ V}/\mu\text{m}$ the velocity is almost saturated) and the gain becomes directly related with time resolution.

Is there a sensor design that allows with all the required geometry constraints operation at extreme voltages?
Comparison of reactor neutrons and 200 MeV pion irradiations

- Shift of required bias voltage to larger values: $\Delta V_{bias}(20 \text{ ke}) \sim 160 \text{ V}$

- Smaller collected charge for $1.5\times10^{15} \text{ cm}^{-2}$ wrt to neutron irradiated samples – the same performance as for pin sample – the beneficial effect of LGAD has gone.

- The effect of initial doping remains visible after low fluence irradiation, while it is gone at the $\Phi_{eq}=1.5\times10^{15} \text{ cm}^{-2}$ pions.

Charged hadrons are more damaging than neutrons!
What is the best initial gain/dose?

- High implantation dose – very high initial gain, but early breakdown
- Low implantation dose – lower initial gain, but high voltages can be applied
- The difference in doping is seen as difference in $V_{bias}(20 \text{ ke})$ up to $\Phi_{eq} \sim 2 \cdot 10^{15} \text{ cm}^{-2}$? Is it worth risking some of the initial performance in timing for lower e.g. $V(20 \text{ ke})$ in the high fluence region? Already at $\Phi_{eq} = 1 \cdot 10^{14} \text{ cm}^{-2}$ high implantation dose devices can be biased to >150V!
What is the best initial gain/dose?

- High implantation dose – very high initial gain, but early breakdown
- Low implantation dose – lower initial gain, but high voltages can be applied
- The difference in doping is seen as difference in $V_{bias}(20ke)$ up to $\Phi_{eq} \sim 2 \cdot 10^{15}$ cm$^{-2}$?

Option of risking some of the initial performance in timing for lower required bias in the high fluence region? In particular as already at $\Phi_{eq} = 1 \cdot 10^{14}$ cm$^{-2}$ high implantation dose devices can be biased to >150V.

**Implantation doses:**

- $D = 1.8 \cdot 10^{13}$ cm$^{-2}$
- $D = 1.9 \cdot 10^{13}$ cm$^{-2}$
- $D = 2.0 \cdot 10^{13}$ cm$^{-2}$
Leakage current

- Leakage current follows the equation: \( I = M_I \cdot I_{gen} \)
- Leakage current affects thermal performance (requires powerful cooling to avoid thermal runaway and keep the noise low)

\[
\frac{S}{N} = \frac{M_Q Q}{\sqrt{ENC_S^2 + k_f F M_I^2 e_0 I_{gen} \tau}}
\]

For S/N to increase in multiplication mode

- \( M_I \sim M_Q \) (for thin) – gain
- \( F = 2 \) for \( M \gg 1 \), \( F = 1 \) for \( M \sim 1 \)
- \( k_f \) - factor depending on shaping
- \( \tau \) – shaping time

\[ ENC_S^2 \gg k_f F M_I^2 e_0 I_{gen} \tau \]

Clear benefits for thin sensors:
- smaller \( I_{gen} \) due to smaller cell size
- Integration time (\( \tau \sim 1 \) ns) can be very small due to short drift, hence small parallel noise contribution
- \( M_Q \sim M_I \)

A drawback is higher capacitance, which however makes is slightly easier to fulfil the above condition
Leakage current measurements are nicely correlated with gain measurements.

Measured leakage currents are higher than expected for factor 2–4

- possibly larger temperature than measured (T is not measured on the sensor)
- leakage current gain can be larger than that for the charge collection
- surface current contribution is not separated in these measurements
- we still don’t understand fully the origin of the dark current before irradiation

**Probably not related to multiplication mechanism as control samples show same behavior**
Ways to improve gain after irradiation

The paradigm has changed from that in the past – we want as high $N_{\text{eff}}$ as possible for peaked fields which result in gain:

- Long term “reverse” annealing has been shown to increase multiplication in standard FZ strip devices (JINST 7 P06007,) – no such effect seen in thin control samples at $\Phi_{\text{eq}}=10^{15}$ cm$^{-2}$.
- See if impurities such as C (carbon enriched Si) help to keep $N_{\text{eff}}$ high:
  - reduces the amount of removed initial acceptors
  - larger introduction of deep acceptors
- Is maybe Ga less prone to effective acceptor removal $\rightarrow$ answer at 13th Trento workshop... first samples coming in few months

![Graph of $N_{\text{eff}}$ vs. Proton fluence (24 GeV/c) [cm$^{-2}$] with data points for different samples and equations $\beta_{\text{C1}}=0.0437$, $\beta_{\text{C2}}=0.0154$, $\beta_{\text{C3}}=0.0044$ and $\beta_{\text{C4}}=0.0053$.](image1)

![Graph of Most Probable Signal [e] vs. Bias Voltage [V] with data points for different annealing times and a note T=-10C, annealed at 60C R6827– pin diode.](image2)
FBK samples – radiation hardness by different gain layer design

FBK Run samples–300 μm, 10 kΩcm,
- 0.5 mm² active region (source of difficulties)
- two different implant doses (W3, W10)
- pin control sample
- A deeper doping profile – is it more than CNM standard one?
- Samples irradiated to equivalent fluences of 0,1,2,5 \times 10^{14} \text{cm}^{-2} – fluence range selected to maximize effects that could be determined by measurements
- annealed for 80min@60°C
Determination of the gain – back ill. TCT

**W3 - wafer**

\[ I_{\text{PIN}} = 0.06 \text{ arb.} \]

\[ I_{\text{LGAD}} = 0.1 \text{ arb.} \]

\[ V_{\text{bias}} = 300 \text{ V} \]

\[ T = 20^\circ \text{C} \]

\[ G_{\text{TCT}} = 3.9 \]

**W10 - wafer**

\[ I_{\text{PIN}} = 0.02 \text{ arb.} \]

\[ I_{\text{LGAD}} = 0.1 \text{ arb.} \]

\[ V_{\text{bias}} = 300 \text{ V} \]

\[ T = 20^\circ \text{C} \]

\[ G_{\text{TCT}} = 14 \]

**Gain > 120**

\[ G = Q_{\text{LGAD}} / Q_{\text{PIN}} \]

PIN diode

LGAD diode

red laser

red laser
Small sample size is a problem as trigger purity is affected:
- Noise peak – events missing the sensor
- Guard ring collection – capacitively transferred charge to the connected electrode
- Active area – multiplication

Huge signals saturate the amplifier for W10 – break down ~500–600V
Impure trigger complicates the analysis; even more at smaller gain (difficult separation of peaks – analysis not possible for W3 at high fluences).

Evaluation of FBK detectors performance in terms of gain after irradiation seems to be comparable to CNM detectors – still ongoing study.
Clear and significant decrease of gain seen in TCT signals – almost gone at 5e14 cm$^{-2}$

Gain somewhat larger than measured in CCE

Some unexplained features in the signal – change of SC for non-irradiated samples
Conclusions

- Thin LGAD sensors perform better than that of standard thickness and retain the beneficial effect on collected charge up to $1-2 \cdot 10^{15}$ cm$^{-2}$.
- At fluences $>2 \cdot 10^{15}$ cm$^{-2}$ the LGAD and control samples performs similarly even at very high $V_{bias}$ where there is gain.
- The Gain($V$) depends on fluence and implant dose – the larger the doping (implant dose) the higher the fluence up to which LGADs perform beneficially.
- Pions are more damaging than neutrons in terms of gain.
- Time resolution is correlated with gain $\rightarrow V(Q)$ can be mapped to $\sigma_t(V)$ once the voltage is high enough to saturate drift velocity.

How to overcome the loss of multiplication layer?

Several approaches of how to mitigate the loss of multiplication layer are under investigation?

- Ga doping (more difficult to displace than B)
- C enrichment (less deactivation of B); both diffusion and implantation
- Prolonged annealing (works on strips, not seen in pads so far)
- Different doping profiles – benefit on different acceptor removal rate for different concentrations (FBK run) – preliminary studies show small effect!