Characterisation of the first Compensated LGADs from FBK before and after irradiation

The acceptor removal mechanism deactivates the $p^+$-doping of the gain layer with irradiation according to

$$p^+(\Phi) = p^+(0) \cdot e^{-c_A \Phi}$$

where $c_A$ is the acceptor removal coefficient. $c_A$ depends on the initial acceptor density, $p^+(0)$, and on the defect engineering of the gain layer atoms.

Is it possible to improve $c_A$ further?

[Images and data from R.S. White, 43rd RD50 Workshop (2023) CERN]
Towards a Radiation Resistant Design

The acceptor removal mechanism deactivates the $p^+$-doping of the gain layer with irradiation according to

$$p^+(\Phi) = p^+(0) \cdot e^{-c_A \Phi}$$

where $c_A$ is the acceptor removal coefficient.

To substantially reduce $c_A$, it is necessary to increase $p^+(0)$, the initial acceptor density.

Lowering $c_A$ can extend the gain layer survival up to $\Phi \geq 10^{17} \text{n}_{\text{eq}}/\text{cm}^2$. 

Higher the acceptor density, lower the removal.
A new Paradigm – Compensation

Doping Profile – Standard LGAD

Irradiation
\( \Phi = 1 \times 10^{16} \text{/cm}^2 \)
A new Paradigm – Compensation

Doping Profile – Standard LGAD

- Boron × 1 \(\Phi = 0\)
- Boron × 1 \(\Phi = 1E16\)

Doping Profile – Compensated LGAD

- Boron × 5 \(\Phi = 0\)
- Phosp × 4 \(\Phi = 0\)
- Comp \(\Phi = 0\)
- Boron × 5 \(\Phi = 1E16\)
- Phosp × 4 \(\Phi = 1E16\)
- Comp \(\Phi = 1E16\)
- Comp \(\Phi = 0\)

Effective doping

Irradiation
\(\Phi = 1x10^{16}/cm^2\)

Doping Density [a.u.]
Depth [a.u.]
A new Paradigm – Compensation

Use the interplay between acceptor and donor removal to keep a constant gain layer active doping density

Many unknowns:
- donor removal coefficient, from \( n^+(\Phi) = n^+(0) \cdot e^{-c_D \Phi} \)
- interplay between donor and acceptor removal \((c_D vs c_A)\)
- effects of substrate impurities on the removal coefficients
Process simulations of Boron ($p^+$) and Phosphorus ($n^+$) implantation and activation reveal the different shape of the two profiles.
Compensation from Simulation

Process simulations of Boron \((p^+\)) and Phosphorus \((n^+\)) implantation and activation reveal the different shape of the two profiles.

→ The simulation of the electrostatic behaviour shows that it is possible to reach similar multiplication for different initial concentrations of \(p^+\) and \(n^+\) dopants.
First Compensated LGADs – EXFLU1

First compensated LGAD sensors have been released by FBK in the framework of the EXFLU1 batch

Other R&D paths pursued by the EXFLU1 batch to extend the radiation tolerance of the LGAD sensors:

▷ new guard ring design
▷ decrease of the acceptor removal – carbon shield
▷ thin substrates (15–45 µm)

Design and preparatory studies have been performed in collaboration with the Perugia group

→ The EXFLU1 wafers exited the FBK clean room at the end of 2022

[V. Sola, TREDI 2023, Trento]
First Compensated LGADs – EXFLU1

6” Wafer

⇒ An extensive testing campaign on compensated LGADs started 1 year ago and is still ongoing
### Compensated Gain Layer Design – Split Table

<table>
<thead>
<tr>
<th>Wafer #</th>
<th>Thickness</th>
<th>p+ dose</th>
<th>n+ dose</th>
<th>C dose</th>
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<td>2</td>
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<tr>
<td>14</td>
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<td>3 c</td>
<td>2</td>
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<tr>
<td>15</td>
<td>30</td>
<td>5 a</td>
<td>4</td>
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</tbody>
</table>

3 different combinations of p⁺ – n⁺ doping: 2 – 1, 3 – 2, 5 – 4
Compensated LGAD – I-V on wafer

Simulation

- Effective Doping
- Arsenic
- Phosphorus × 4
- Boron × 5

Signal Current (A)

Substrate Voltage (V)

V. Sola et al.

Properties of compensated LGAD
Compensated LGAD – I-V on wafer

Simulation

EXFLU1 – Compensated LGAD 2–1 – I-V

EXFLU1 – Compensated LGAD 3–2 – I-V

EXFLU1 – Compensated LGAD 5–4 – I-V

V. Sola et al.

Properties of compensated LGAD
Compensated LGAD – I-V

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<td>15</td>
<td>30</td>
<td>5a</td>
<td>4</td>
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\[2 \text{ – 1 is more doped than standard LGAD}\]
\[3 \text{ – 2 & 5 – 4 exhibit a flat behaviour followed by an abrupt increase of the current}\]
**IR Laser Stimulus on Compensated LGAD 2–1**

**TCT Setup from Particulars**
- Pico-second IR laser at 1064 nm
- Laser spot diameter ~ 10 µm
- Cividec Broadband Amplifier (40dB)
- Oscilloscope LeCroy 640Zi
- Room temperature

Gain = \( \frac{Q_{LGAD}}{<Q_{PIN}>} \)

Laser intensity
\(~ 10 \text{ MIPs} \)

→ Good transient behaviour of 2–1 compensated LGAD sensors
IR Laser Stimulus on Compensated LGAD 3–2 + C

TCT Setup from Particulars
Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
Room temperature

Gain = \frac{Q_{\text{LGAD}}}{Q_{\text{PIN}}}

Laser intensity
~ 80 MIPs

→ Very low gain from 3 – 2 compensated LGAD sensors
Compensated LGAD – 2D Scan with IR Laser

What is the origin of the abrupt rise of the dark current?

Scan surface

Tentative sketch of a compensated LGAD

⚠ NOT TO SCALE ⚠

TCT scan with IR laser
Laser spot ~ 10 µm
Sensor from W12 (3–2)
$V_{\text{bias}} = 81$ V
Very close to BD

$\text{p}^+ \times 2, \text{n}^+ \times 1$
$\text{p}^+ \times 3, \text{n}^+ \times 2$
$\text{p}^+ \times 4, \text{n}^+ \times 3$
$\text{p}^+ \times 5, \text{n}^+ \times 4$

→ Investigate the edges of the compensated gain implant using TCT
Compensated LGAD – 2D Scan with IR Laser

What is the origin of the abrupt rise of the dark current?

Scan surface

Tentative sketch of a compensated LGAD
⚠️ NOT TO SCALE ⚠️

TCT scan with IR laser
Laser spot ~ 10 µm
Sensor from W12 (3–2)
V_{bias} = 81 V
Very close to BD

→ Investigate the edges of the compensated gain implant using TCT
Compensated LGAD – 2D Scan with IR Laser

What is the origin of the abrupt rise of the dark current?

Tentative sketch of a compensated LGAD

Scan surface

TCT scan with IR laser
Laser spot ~ 10 µm
Sensor from W12 (3–2)
V\text{bias} = 81 V
Very close to BD

→ No issues observed at the edge of the compensated gain implants
Compensated LGAD – C-V

→ 3–2 & 5–4 C-V measurements have shapes similar to the one from the PIN diode, measuring a slightly bigger thickness at bias values between 0 and -10 V
Secondary Ion Mass Spectroscopy – W15

Compensated LGAD – W15 5-4
SIMS vs Process Simulation

- Boron peak is shallower than phosphorus
- Boron peak is lower than predicted from simulation
Neutron Irradiation of Compensated LGADs

Compensated LGAD sensors have been irradiated with neutrons at the JSI TRIGA Reactor Irradiation Facility (Ljubljana)

Irradiation fluences from $1 \times 10^{14}$ to $5 \times 10^{15}$ $n_{eq}/cm^2$

Fluence uncertainty ± 5%
I-V from Compensated LGAD – Irradiated

\[ \Phi = n_{eq}/cm^2 \]

\[ T_{F=0} = +20^\circ C \]

\[ T_{IRR} = -20^\circ C \]

W6

\[ 2 - 1 \]

W12

\[ 3 - 2 \]

W13

\[ 3 - 2 + C \]

W15

\[ 5 - 4 \]
C-V from Compensated LGAD – Irradiated

\[ \Phi = \frac{n_{eq}}{cm^2} \]

\[ T = +20^\circ C \]

\[ f = 2k \text{ Hz} \]

\[ W6 \]

\[ 2 - 1 \]

\[ W12 \]

\[ 3 - 2 \]

\[ W13 \]

\[ 3 - 2 + C \]

\[ W15 \]

\[ 5 - 4 \]
$[\Phi] = n_{eq}/\text{cm}^2$

$T = + 20^\circ\text{C}$

$f = 2\text{k Hz}$

$\text{W6}$

$2 - 1$
Doping Profile of Compensated LGAD 2 – 1

\[ \Phi = n_{eq}/cm^2 \]

\[ T = +20^\circ C \]

\[ f = 2k \text{ Hz} \]

W6 2 – 1

Doping density profiling as a function of depth is extracted from the \( 1/C^2-V \) information.
Doping Profile of W6

\[ \Phi = \frac{n_{eq}}{cm^2} \]

\[ T = +20^\circ C \]

\[ f = 2k \text{ Hz} \]

Gain implant profile appears more and more evident as the fluence increases

\[ \rightarrow \text{Is donor removal faster than acceptor removal?} \]
IR Laser Stimulus on Compensated LGAD 3–2

**TCT Setup from Particulars**

Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
\[ T = -10^\circ \text{C} \]

**Gain**

\[
\text{Gain} = \frac{Q_{\text{LGAD}}}{< Q_{\text{PiN}} >}
\]

Laser intensity
~ 4 MIPs
\[ \Phi = 2.5E15 \text{ n}_{eq}/\text{cm}^2 \]

Laser stimulus on a LGAD-PiN structure from \textit{W12 (3 – 2)}

\[ \rightarrow \text{Exceptional gain behaviour at a fluence of } 2.5E15 \text{ n}_{eq}/\text{cm}^2 \]
Compensated LGADs represent the sensor technology for the extreme fluences

First compensated LGAD batch has been released 1 year ago

Characterisation of compensated LGAD sensors is ongoing

An ERC Consolidator Grant will be funded to develop compensated LGAD sensors

Doping Compensation in Thin Silicon Sensors: the pathway to Extreme Radiation Environments CompleX
We acknowledge the following funding agencies and collaborations:

- INFN CSN5
- RD50, CERN
- AIDAinnova, WP13
- Compagnia di San Paolo
- Ministero della Ricerca, Italia, PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- Ministero della Ricerca, Italia, PRIN 2022, progetto 2022RK39RF – ComonSens
- European Union’s Horizon 2020 Research and Innovation programme, Grant Agreements Nos 101004761 (AIDAinnova) and 101057511 (EURO-LABS)
Backup
Saturation

At fluences above $5 \cdot 10^{15} \text{ cm}^{-2} \rightarrow \text{Saturation of radiation effects observed}$

Leakage current saturation
\[ I = \alpha V \Phi \]
\[ \alpha \text{ from linear to logarithmic} \]

Trapping probability saturation
\[ \frac{1}{\tau_{\text{eff}}} = \beta \Phi \]
\[ \beta \text{ from linear to logarithmic} \]

Silicon detectors irradiated at fluences $10^{16} - 10^{17} \text{n}_{\text{eq}}/\text{cm}^2$ do not behave as expected $\rightarrow$ They behave better

Accepting-like defect creation
\[ N_{A,\text{eff}} = g_c \Phi \]
\[ g_c \text{ from linear to logarithmic} \]
Thin Substrates

\[ V_{FD} = e |N_{eff}| d^2 / 2\varepsilon \]

**Saturation**  
**Reduce thickness**

At high fluences, only thin substrates can be fully depleted

**What does it happen to a 25 µm sensor after a fluence of 5 \cdot 10^{16} n_{eq}/cm^2?**

- It can still be depleted
- Trapping is limited (small drift length)
- Dark current is low (small volume)

**However:** charge deposited by a MIP \( \sim 0.25 \) fC

→ This charge is lower than the minimum charge requested by the electronics  
(\( \sim 1 \) fC for tracking, \( \geq 5 \) fC for timing)

→ **Need a gain of at least \( \sim 5 \)** in order to efficiently record a hit

Optimal candidate: LGAD sensors
Thin LGAD for the Extreme Fluences

The idea: use thin sensors (15 – 45 µm) with internal gain

→ **Low-Gain Avalanche Diodes** (LGADs) provide a controlled internal multiplication of signal

Minimum charge requested by the electronics

→ ~ 1 fC for tracking

→ ≥ 5 fC for timing

Charge from a MIP crossing thin sensors

→ ~ 0.1 fC every 10 µm

[S. Meroli et al., doi:10.1088/1748-0221/6/06/P06013]

⇒ **Need a gain of at least 5 – 10**

up to \( \Phi = 10^{17} \text{ n}_{\text{eq}}/\text{cm}^2 \) to efficiently record a hit
The EXFLU1 Layout

6" Wafer Layout

Reticle Layout
Compensated LGAD – C-V

### Effective Doping

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</table>

→ 2 – 1 is more doped than standard LGAD
→ 3–2 & 5–4 exhibit a lower capacitance than PIN

### Capacitance vs. Reverse Bias

**EXFLU1 – Compensated LGAD – C-V**

- Capacitance [F]
- Reverse Bias [V]

**EXFLU1 – Compensated LGAD – 1/C²-V**

- 1/C² [1/F²]
- Reverse Bias [V]
IR Laser Stimulus on Compensated LGAD 5–4

TCT Setup from Particulars
Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope LeCroy 640Zi
Room temperature

Gain = \( \frac{Q_{\text{LGAD}}}{<Q_{\text{PiN}}>} \)

Laser stimulus on a LGAD-PiN structure from W6 (5 – 4)

→ Not easy to operate 5 – 4 compensated LGAD sensors
$[\Phi] = \frac{n_{eq}}{\text{cm}^2}$

$T = + 20^\circ \text{C}$

$f = 2 \text{k Hz}$

W6 2 – 1

W13 3 – 2 + C

W12 3 – 2

W15 5 – 4