Study of the radiation resistance of different LGAD gain layer designs

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(SCIPP, Univ. of California Santa Cruz)
FBK-UFSD2 production

<table>
<thead>
<tr>
<th>Wafer #</th>
<th>Dopant</th>
<th>Gain dose</th>
<th>Carbon</th>
<th>Diffusion</th>
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- 50 micron active area, Si-on-Si wafer
- 5 different gain layer strategies:
  - **Boron** (Low & High diffusion)
  - **Carbonated Boron** (B High diffusion)
  - **Gallium** (Low diffusion)
  - **Carbonated Gallium** (Low diffusion)

Main issue: LGAD gain strongly affected by the irradiation. Gain disappears after $\Phi = 2-3 \times 10^{15}$

Both gain layer and bulk are subject to:
- Initial acceptor removal
- Acceptor-like deep traps creation

see G. Paternoster talk in this workshop
FBK-UFSD2 production

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- **Low Diffusion**: “thinner” gain layer could be more radiation resistant
- **Gallium**: Ga could have a lower probability than B to become interstitial (lower interstitial mobility)
- **“Carbonation”**: Carbon could be trapped by defects faster than B or Ga

see G. Paternoster talk in this workshop
Irradiation campaign

Sensors from B, B-LD, Ga, Ga + C , B+ C wafers have been sent for irradiation

**Neutron irradiation in Ljubljana** (AIDA2020)
Fluence steps: 0.2 0.4 0.8 1.5 3.0 6.0 $\cdot 10^{15}$ n$_{eq}$/cm$^2$

**24 GeV/c Proton irradiation at CERN**
(IRRAD – thanks Joern!)
Fluence steps: 0.1 0.6 1.0 3.0 6.0 9.0 $\cdot 10^{15}$ p/cm$^2$

Irradiated PIN/LGAD tested:
- in the laboratory in Torino and in Santa Cruz (plus some other ATLAS institutes)
- at FNAL beam test, with proton beam @120 GeV (in Jan18 - analysis ongoing)
IV, CV curves, gain measurements with laser, gain/noise/time resolution with $\beta$ source.
Irradiation campaign

Sensors from B, B-LD, Ga, Ga + C, B+C wafers have been sent for irradiation

Evolution of active acceptor density with fluence

\[ N_A(\Phi) = g_{\text{eff}} \Phi + N_A(0) e^{-c(N_A(0)) \Phi/\Phi_0} \]

\( \Phi = \text{fluence} \quad (\Phi_0 \text{ is a constant }) \)

\( N_A(\Phi), N_A(0) = \text{active acceptor density at fluence } \Phi, \text{ or initial } \)

\( g_{\text{eff}} = \text{empirical constant} \quad (~0.02 \text{ cm}^{-1}) \)

The \( c \) coefficients to be determined depends upon the irradiation type, the acceptor type and the initial acceptor density
How do we measure the Acceptor density?

- The foot in the $1/C^2$ - V curves indicates the depletion of the gain layer.

- In UFSD2:
  - Carbon reduces the active doping concentration of gain layer for both B and Ga acceptor types.

$V_{GL} = \text{depletion voltage for gain layer}$

$V_{FD} = \text{full depletion voltage}$

$slope \propto \frac{1}{N_{bulk}}$

$V_{GL}$ is proportional to the amount of active doping in the gain layer.
Gain layer inactivation with neutrons

The reduction of gain layer doping is mitigated by factor $\gtrsim 2$ by Carbon
Measurement of coefficient “c”

\[
\frac{N_A(\Phi)}{N_A(0)} = \frac{V_{GL}(\Phi)}{V_{GL}(0)} = e^{-c(NA(0))\Phi/\Phi_0}
\]

- Each point is the average of two CV curves
- Measurements done at room temperature, \( f = 1 \text{ kHz} \)
Coefficient “c” for FBK, CNM, HPK

\[ \frac{N_A(\Phi)}{N_A(0)} = e^{-c(NA(0))\Phi/\Phi_0} \]

Neutrons

\[ y = 9.9E-01e^{-2.1E-16x} \]
\[ y = 9.7E-01e^{-2.7E-16x} \]
\[ y = 9.8E-01e^{-4.1E-16x} \]
\[ y = 1.0E+00e^{-5.5E-16x} \]
\[ y = 9.5E-01e^{-5.5E-16x} \]
\[ y = 1.0E+00e^{-6.9E-16x} \]
\[ y = 9.6E-01e^{-7.7E-16x} \]
\[ y = 1.0E+00e^{-8.5E-16x} \]
\[ y = 1.0E+00e^{-1.1E-15x} \]

CNM, HPK data points taken from
- 12th Trento Workshop on Advanced Silicon Radiation Detectors [online] (2017).
On the “c” coefficients (at $N_A \sim 10^{16}$)

Acceptor Removal "c" values

- FBK Ga
- CNM Ga
- HKP B 50A
- HKP B 50B
- HKP B 50C
- HKP B 50D
- CNM B
- FBK B
- FBK B LD
- FBK Ga+C
- FBK B+C

Value of the acceptor removal coefficient as a function of implant width

- Smaller c, better resistance
- ➔ Add Carbon

Smaller c, better resistance

- ➔ Make the gain layer thin
Gain measurement on neutron irradiated LGADs

\[ \text{GAIN} = \frac{\text{Signal area LGAD}}{\text{Signal area PiN}} \text{ irradiated at the same fluence} \rightarrow \text{only from gain layer} \]

W14 (Ga)

W15 (Ga + C)

W8 (B)

W6 (B + C)

W1 (B - LD) has a similar behavior to B+C
Proton irradiation: coefficient “c”

\[
\frac{N_A(\Phi)}{N_A(0)} = e^{-c(NA(0))\Phi/\Phi_0}
\]

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<td>W14</td>
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</table>
Preliminary results on time resolution

Time resolution measured with $\beta$ source, at low temperature, for W6 (B+ C) and W8 (B), in Santa Cruz

(see H. Sadrozinski talk in this workshop)
Preliminary results on time resolution

CMS goal for the silicon timing layer (ETL): time resolution between 30 – 35 ps unchanged till the end of lifetime (4000 fb⁻¹ - 1e15 neq/cm²)

![Graph showing time resolution vs bias for UFSD2 W6 (B+C)]
Summary

- The presence of Carbon in the gain layer:
  - decreases by more than a factor of two the initial acceptor removal rate
  - does not degrade the time resolution
  - enable to obtain a better time resolution at equal voltage, or a similar time resolution with lower voltage
- Narrower gain layers (low diffusion) are more radiation resistant
- The concentration of Carbon used in UFSD2 was an “educated guess”. It will be further explored in UFSD3
- The initial acceptor removal rate for proton irradiation is ~ double wrt to that of neutrons
- UFSD2 B+C meets the ETL CMS requirement of a time resolution of 30-35 ps up to 4000 fb^{-1}
Acknowledgements

Thank you for your attention!

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Gain Measurement in LAB – Unirradiated LGADs

- Carbon reduces the gain
- Low Diffusion increase the gain

Laser set-up. Ratio of QV curves on LGAD an associated PiN (reference)
Initial Acceptor Removal

\[ N_A(\Phi) = g_{eff} \Phi + NA(0) e^{-c(N_A(0))} \frac{\Phi}{\Phi_0} \]