Studies of the acceptor removal mechanism in UFSD irradiated with neutrons and protons

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Outline

- Carbonated UFSDs:
  - Effect of Carbon co-implantation on the gain layer in not irradiated sensors
  - Acceptor removal study on UFSDs with four different doses of co-implanted Carbon into gain layer

- Comparison of acceptor removal between UFSDs with and without metallization on the active area

- Comparison of the acceptor removal coefficients obtained with irradiation with neutrons ($c_n$) and protons ($c_p$) at different energies

- Extraction of NIEL factor from acceptor removal measurements and comparison with values in literature
Co-implantation of Carbon, effect on gain layer in FBK UFSDs

In UFSD3, the latest FBK production:
Co-implantation of 4 Carbon doses in the gain layer to minimize the acceptor removal mechanism

The Boron in the gain layer is captured by the Carbon during activation, resulting in a lower gain layer foot

This effect becomes more important for higher Carbon doses.
Carbon effect on gain layer in FBK UFSDs

- Non linear Carbon-Boron capture as a function of the Carbon dose:
  - Mild Boron capture for low Carbon dose (Carbon A)
  - Important Boron capture for high Carbon doses (Carbon B/C/D)

- Linearity of Carbon-Boron capture in Carbon doses range A-C

<table>
<thead>
<tr>
<th>Carbon dose [a.u.]</th>
<th>Fraction of gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0.97</td>
</tr>
<tr>
<td>2</td>
<td>0.83</td>
</tr>
<tr>
<td>3</td>
<td>0.69</td>
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</table>
Irradiation Campaign on FBK and HPK UFSDs

Type of sensors used in the irradiation campaign

<table>
<thead>
<tr>
<th>Vendors</th>
<th>Production</th>
<th>Gain Layer</th>
<th>Irradiation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Neutron</td>
</tr>
<tr>
<td>FBK</td>
<td>UFSD2</td>
<td>B LD</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B HD</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B HD + C_A</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ga</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ga + C_A</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td>UFSD3</td>
<td>B LD</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B LD + C_A</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B LD + C_B,C,D</td>
<td>✓</td>
</tr>
<tr>
<td>HPK</td>
<td>Exx28995</td>
<td>B (3.1)</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B (3.2)</td>
<td>✓</td>
</tr>
</tbody>
</table>
Acceptor removal parametrization

Nicolò Cartiglia’s talk, 32nd RD50 Workshop, DESY, Hamburg
“A naïve parameterization of initial acceptor removal”

Points on this line differ in acceptor removal rate only due to the initial acceptor density

![Graph](image_url)
Acceptor removal parametrization and measurements

Considering the same initial acceptor density:

- Gain layer with Carbon dose A has a different parameterization than Carbon dose B, C, D
- UFSDs with co-implantation of Carbon B, C and D are less radiation hardness than UFSDs with Carbon A
Acceptor removal parametrization and measurements

Considering the same initial acceptor density:

- **Gallium** and **Boron** have the same radiation hardness, they follow the same parametrization. The measured differences are due to the different initial densities.
- The acceptor removal rate doesn’t depend upon the **bulk type** (Epitaxial, Float Zone)
Effect of pad metallization on the acceptor removal mechanism

Results in recent beam tests on irradiated sensors showed a disuniformity of gain in metallized and not metallize active area

What is causing this effect?

Beam test @ FNAL
Post irradiated sensors
CNM W11 LGA35 6E14 $n_{eq}/cm^2$
Effect of pad metallization on the acceptor removal mechanism

The gain layer in non-metallized pad disappears faster than that in metalized pad.
Small systematic different (≈ %) on fraction of gain layer at 1.5E15 n_{eq/cm^2}
Effect of pad metallization on the acceptor removal mechanism

The same effect is visible also in UFSD with EPI substrate

Metallized UFSDs are more radiation hard than not-metallized UFSD
# Proton irradiation facilities

## UFSDs irradiated with Proton at different energies in four facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>Proton Energy [MeV/c]</th>
<th>NIEL\textsubscript{Proton}</th>
</tr>
</thead>
<tbody>
<tr>
<td>KIT, Karlsruher (DE)</td>
<td>23</td>
<td>2</td>
</tr>
<tr>
<td>CYRIC, Japan</td>
<td>70</td>
<td>1.47</td>
</tr>
<tr>
<td>Los Alamos, (USA)</td>
<td>800</td>
<td>0.73</td>
</tr>
<tr>
<td>IRRAD, CERN</td>
<td>24000</td>
<td>0.67</td>
</tr>
</tbody>
</table>

NIEL is a factor introduced to conform the leakage current induced by particles (p\textsuperscript{+}, n, e\textsuperscript{-}). The reference particle is 1MeV Neutron equivalent (n\textsubscript{eq}).

The expected leakage current induced by a Proton with a NIEL factor > 1 (E\textsubscript{p} < 300MeV) is higher than the same one induced by a Neutron equivalent.
Acceptor removal: comparison between neutron and proton irradiation

- Effect of proton energy: low energy protons deactivate the gain layer faster than high energy protons.
- The acceptor removal from protons of tens MeV is faster than that of neutrons.
- Acceptor removal by 24 GeV/c protons and 1 MeV neutrons is very similar.

Measurements on two flavors of gain layer:
- Boron LD + Carbon A
- Boron HD + Carbon A

Graphs showing the fraction of gain layer versus fluence for different irradiation conditions.
Dependence of the acceptor removal coefficient upon the proton energy

The trend of $c_p$ coefficients as a function of the proton energy is very similar to that of the NIEL factor.
NIEL extraction from acceptor removal coefficient ”c”

Initial acceptor removal

\[ N(\varnothing)_A = N(0)_A e^{-c_P \varnothing_P} = N(0)_A e^{-c_{neq} \varnothing_{neq}} \]

\[ \frac{c_P}{c_{neq}} = \text{NIEL} \]

To apply the NIEL to the acceptor removal curve correspond to multiply the axes of fluences

The ratio between the acceptor removal coefficient of proton “c_P” and of neutron “c_n” is the NIEL
The NIEL value as a function of energy calculated using the acceptor removal mechanism is somewhat higher than the value of NIEL reported in literature.

**NIEL at 24 GeV ~ 1**: The damages into gain layer by high energy proton (\(E_p > 24\) GeV) and neutron are similar.
Conclusions

- Co-implantation of Carbon decreases the Boron activation (Carbon-Boron capture);
- The Carbon-Boron capture happens only above a critical carbon density (dose A);
- Carbon-Boron capture mechanism is linear above dose A;
- The radiation hardness improve for all Carbon doses;
- Gain layer with co-implantation of Carbon dose A is the most radiation hard configuration until now;
- Gain layers with Carbon doses B,C and D have the same radiation hardness, lower than Carbon doses A;
- Metallized pads are more radiation hard than not metallized pads: they have a lower acceptor removal coefficient
- Proton irradiation induces more or equal acceptor removal than Neutron;
- Effect of Proton energy: acceptor removal is faster for lower Proton energy;
- Protons of 24 GeV/c are as damaging as 1 MeV Neutron;
- NIEL factor measured by acceptor removal has the same trend but it is higher than NIEL in literature.
Acknowledgements

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- Dipartimenti di Eccellenza, Torino Physics Dep. (ex L. 232/2016, art. 1, cc. 314, 337)
Backup
UFSD3

Wafer layout of UFSD3
CV measurements (laboratory setup)

Keysight
B1505A Power Device Analyzer / Curve Tracer

Modules
- High Voltage SMU: Max Range (±3000V, ±4mA);	Min Range (200V, 1nA);
- CMU Modules: Range In frequency (1khz-1MHz);

Probe station
Bias of the the Cf measurements (10V)

- No Irr
- 4E14 neq/cm²
- 8E14 neq/cm²
- 1,5E15 neq/cm²
- 3E15 neq/cm²

Capacitance vs Frequency for different bias conditions.
Extrapolation of $V_{GL}$

**C-V Measurement parameters:**
- Measurement Model = $C_p - R_p$
- Measurement Frequency = 1 kHz
- Measurement temperature = Room Temperature
- Sensors measured after annealing (80min @ 60°C)

**V$_{GL}$ Extrapolation method**
Using the *cusp on the $R_p$ curve*, in coincidence with the *foot in the $1/C_p^2$ curve*

*This method is precise even for fluences above $10^{15}$ n$_{eq}$/cm$^2$*

Sensor W1_Irr(3E15 n$_{eq}$/cm$^2$)
Carbon-Boron Capture on UFSD gain layer

Gain layer profile extracts from CV measurements

\[ N_A = \frac{2}{A^2 e \varepsilon_{si} \frac{d \left( \frac{1}{C^2} \right)}{dV}} \]

Effect of Carbon-Boron capture on the profile of active Boron density
Acceptor removal in UFSD3

Acceptor removal fits on UFSDs with 4 different Carbon doses co-implantanted in gain layer

\[
\frac{V_{GL}(\phi)}{V_{GL}(0)} = \frac{N_A(\phi)}{N_A(0)} = e^{-c(N_A(0))\phi}
\]

Degradation in radiation resistance at higher Carbon doses

Steeper curves \(\rightarrow\) lower radiation resistant
Acceptor removal coefficient at different Carbon doses

Degradation of radiation hardness

Effect of Carbon-Boron capture on the profile of active Boron density
Remind on parameterization of initial acceptor removal

Nicolò Cartiglia’s talk, 32nd RD50 Workshop, DESY, Hamburg
“A naïve parameterization of initial acceptor removal”

A two steps process

Initial acceptor removal is believed to be a two step process:
1. Irradiation knocks out a silicon atom
2. The interstitial silicon atoms trap the Boron (Gallium) dopant

\[ \Phi_o \times N_{Si} \times \sigma = \left( 1 - \frac{1}{e} \right) \times N(0)_A = N(0)^{rem}_A \]

- **\( \Phi_o \)** = fluence \([\text{cm}^{-2}]\)
- **\( N_{Si} \)** = silicon atom density \(5 \times 10^{22} \text{ cm}^{-3}\)
- **\( \sigma \)** = fit parameter \([\text{cm}^2]\): cross section for the 2 steps process
  1. \( \Phi + Si \rightarrow Si_i \)
  2. \( Si_i + B_s \rightarrow Si_s + B_s \)

\( N(0)_A^{rem} \) = removed initial acceptor after a fluence \( \Phi_o \) \([\text{cm}^{-3}]\)

The fluence needs to have \(1/e\) of the initial acceptor density \(N(0)_A\)
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Initial acceptor density factor

\[
\phi_o \times N_{Si} \times \sigma = N(0)^{rem}_A
\]

Introduction into the parameterization a density factor \((D_n)\) to consider low Boron density cases

At low densities:

- Si-interstitials do not find the Boron
- a higher fluence is needed to remove low density Boron

Density factor: probability of a Si-interstitial to be closed to a Boron substitutional

Limiting behaviors:

\[
\begin{align*}
\lim_{N(0) \to 0} Dn &= 0 \\
\lim_{N(0) \to \infty} Dn &= 1
\end{align*}
\]

\[
D_n = \frac{1}{1 + \left(\frac{N_{Ao}}{N(0)_A}\right)^n}
\]

- \(n = 1\) linear
- \(n = 2\) surface
- \(n = 3\) volume

\[
N_{Ao} = 2.5 \times 10^{16} \text{ [cm}^{-3}\text{]}
\]

Density at which an interstitial has 50% probability of interacting with an acceptor

Fit parameter \(N_{Ao}\)
Remind on parameterization of initial acceptor removal

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\[ \phi_0 = \frac{1}{c} \]

\[ \phi_o = \frac{N(0)^{rem}}{N_{Si} \* \sigma \* Dn} \]

Fit with \( D_2 \)