Studies of the radiation hardness of the FBK UFSD3 production


1INFN, Torino, Italy
2Università di Torino, Torino, Italy
3University of Trento and INFN, Department of Industrial Engineering, Trento, Italy
4Università del Piemonte Orientale, Novara, Italy
5Fondazione Bruno Kessler (FBK), Trento, Italy
Outline

- Comparison between UFSD2 and UFSD3, CV and Gain measurement;
- Effect of different Carbon Doses on gain layer of not-irradiated sensors;
- Acceptor removal comparison between UFSD2 and UFSD3
- Acceptor removal study in UFSD on sensors with co-implantation of 4 splits of Carbon doses into the gain layer
# Irradiation campaign on UFSD3

## UFSD3

<table>
<thead>
<tr>
<th>Wafer #</th>
<th>Dose Pgain</th>
<th>Carbon</th>
<th>Diffusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.98</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>2</td>
<td>0.96</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>3</td>
<td>0.96</td>
<td>A</td>
<td>L</td>
</tr>
<tr>
<td>4</td>
<td>0.96</td>
<td>A</td>
<td>L</td>
</tr>
<tr>
<td>5</td>
<td>0.98</td>
<td>A</td>
<td>L</td>
</tr>
<tr>
<td>6</td>
<td>0.96</td>
<td>B</td>
<td>L</td>
</tr>
<tr>
<td>7</td>
<td>0.98</td>
<td>B</td>
<td>L</td>
</tr>
<tr>
<td>8</td>
<td>0.98</td>
<td>C</td>
<td>L</td>
</tr>
<tr>
<td>9</td>
<td>0.98</td>
<td>C</td>
<td>L</td>
</tr>
<tr>
<td>10</td>
<td>1.00</td>
<td>C</td>
<td>L</td>
</tr>
<tr>
<td>11</td>
<td>1.00</td>
<td>D</td>
<td>L</td>
</tr>
<tr>
<td>12</td>
<td>1.02</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>13</td>
<td>1.00</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>14</td>
<td>1.02</td>
<td>A</td>
<td>H</td>
</tr>
<tr>
<td>15</td>
<td>1.00</td>
<td>A</td>
<td>H</td>
</tr>
<tr>
<td>16</td>
<td>1.02</td>
<td>B</td>
<td>H</td>
</tr>
<tr>
<td>17</td>
<td>1.02</td>
<td>B</td>
<td>H</td>
</tr>
<tr>
<td>18</td>
<td>1.04</td>
<td>B</td>
<td>H</td>
</tr>
<tr>
<td>19</td>
<td>1.04</td>
<td>C</td>
<td>H</td>
</tr>
<tr>
<td>20</td>
<td>1.04</td>
<td>C</td>
<td>H</td>
</tr>
</tbody>
</table>

- **Wafer 1 (Boron Low Diffusion-dose 0.98)** is the reference of the two FBK productions UFSD2 and UFSD3
- **4 splits of Carbon doses** to study the radiation resistance (Carbon A/B/C/D)

## UFSD2

<table>
<thead>
<tr>
<th>Wafer #</th>
<th>Dopant</th>
<th>Gain dose</th>
<th>Carbon</th>
<th>Diffusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Boron</td>
<td>0.98</td>
<td></td>
<td>Low</td>
</tr>
</tbody>
</table>

- **IRRADIATION CAMPAIGN:**
  - (AIDA2020) → thank you GK and friends!
  - Neutron Irradiation in Ljubljana, fluences: \(4 \times 10^{14} / 8 \times 10^{14} / 1.5 \times 10^{15} / 3 \times 10^{15}\) \(n_{eq}/cm^2\)
  - Irradiated wafers: W1/W4/W5/W7/W9/W11

**Irradiated structures**

- Couple LGAD-LGAD
- Couple PiN-LGAD
Pre-irradiation
Comparison between UFSD3 and UFSD2 on Wafer1 (B LD)

Same depletion Voltage ($V_{GL}$) of the gain layer ($\sim 23V$)

Same active acceptor density into gain layer

$V_{GL} = \frac{d^2 qN_A}{2\varepsilon Si}$

Agreement between the two measurements of gain in UFSD2 and UFSD3
Co-implantation of Carbon, effect on gain layer

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

This effect was already seen in UFSD2 for dose A but it becomes more important for higher C doses
Carbon effect on gain layer

- 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>
</tr>
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</table>
Post-irradiation
UFSD3, improvements in radiation hardness

CV measurements at different fluences in B HD + C_A (UFSD2)

Decreasing of acceptor density

CV measurements at different fluences in B LD + C_A (UFSD3)

Decreasing of acceptor density
UFSD3, improvements in radiation hardness

CV measurements at different fluences in B HD + C_A (UFSD2)

\[ V_{GL} = \frac{d^2 qN_A}{2\varepsilon_{Si}} \]

Fraction of active acceptor density

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

Decreasing of acceptor density

Steeper curves \(\rightarrow\) lower radiation resistant

Combination of Boron Low Diffusion and Carbon_A in UFSD3 improves the best result on radiation hardness obtained in UFSD2 (B HD + C_A)

Fraction of active acceptor density

\[ c_{UFSD2} = 2.1 \times 10^{-16} \text{ cm}^2 \]

\[ c_{UFSD3} = 1.6 \times 10^{-16} \text{ cm}^2 \]
UFSD2 – UFSD3 comparison

UFSD3 extends by 50% the radiation resistance of UFSD2

![Graph showing the comparison between UFSD2 and UFSD3 in terms of radiation resistance.](image-url)

- **Best UFSD2**: 80% @ ~1E15
- **Best UFSD3**: 80% @ ~1.5E15

Marco Ferrero, INFN, 33rd RD50 Workshop, CERN 26-28 November 2018
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 coefficients in UFSD3

<table>
<thead>
<tr>
<th>Wafer</th>
<th>Gain type</th>
<th>$c_n$ [$cm^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B LD</td>
<td>3.77E-16</td>
</tr>
<tr>
<td>4 (Epi)</td>
<td>B LD + C_A</td>
<td>1.55E-16</td>
</tr>
<tr>
<td>5</td>
<td>B LD + C_A</td>
<td>1.59E-16</td>
</tr>
<tr>
<td>7</td>
<td>B LD + C_B</td>
<td>2.48E-16</td>
</tr>
<tr>
<td>9</td>
<td>B LD + C_C</td>
<td>2.81E-16</td>
</tr>
<tr>
<td>11</td>
<td>B LD + C_D</td>
<td>3.63E-16</td>
</tr>
</tbody>
</table>

**All Carbon doses (A/B/C/D) improve the gain layer radiation resistance compared to a not carbonated Gain layer**

Best radiation resistance obtained with **Carbon dose A**

Acceptor removal coefficient **get worse** at the increasing of Carbon doses

Same radiation resistance in **Float Zone** and **Epitaxial wafers**
Acceptor removal coefficient at different Carbon doses

Degradation of radiation hardness

Relationship between c coefficients and Carbon doses in UFSD3

Two possible reasons:

- Effect of Carbon on active initial acceptor density into gain layer;
- Dependence of c coefficient on active initial acceptor density due to Carbon-Boron capture
Acceptor removal coefficient at different Carbon doses

The degradation of radiation hardness in high doses carbonated sensors can be only explained by combination of Carbon-Boron Capture and dependence of coefficient on active initial acceptor density?

- Effect of Carbon-Boron capture on the profile of active Boron density
- acceptor density into gain layer;
- Dependence of coefficient on active initial acceptor density due to Carbon-Boron capture
Points on this line differ in acceptor removal rate only due to the initial acceptor density.
Acceptor removal parametrization: zoom on $1\times 10^{16}$-$1\times 10^{17}$ n/cm$^3$ range

**Boron** parameterization:
- **c coefficient** for **Boron Low Diffusion** in UFSD3 in agreement with the UFSD2 parameterization

![Graph showing the initial acceptor removal coefficient c as a function of initial acceptor density.](image-url)
Comparison model-data
Boron + Carbon A parameterization:
• Boron + carbon A have a different parameterization compared to Boron
• Same parameterization for B HD + C_A (UFSD2) and B LD + C_A (UFSD3)

![Graph showing Initial Acceptor Removal coefficient c as a function of initial acceptor density.](image)
**Comparison model-data**

**Boron + Carbon X parameterization**:

- Different parameterization for **Carbon A** and **Carbon X**
- Same parameterization for **Carbon B, C and D**
- At same initial acceptor density UFSDs with co-implantation of **Carbon B, C and D** less radiation hardness than UFSDs with **Carbon A**

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**Initial Acceptor Removal coefficient c as a function of initial acceptor density**

- B: \((N_{Si}\sigma D)/(0.7\rho_A(0))\)
- B + C_x: \((N_{Si}\sigma D)/(1.4\rho_A(0))\)
- B + C_A: \((N_{Si}\sigma D)/(2.2\rho_A(0))\)

- UFSD2
- UFSD2 W6 C_A
- UFSD3 W1
- UFSD3 W4 Epi C_A
- UFSD3 W7 C_B
- UFSD3 W9 C_C
- UFSD3 W11 C_D
Density Corrected “c” values

After correcting for the different initial B density:
- C_A shows the best radiation resistance (both Epi and FZ are the same)
- C_B, C_C, and C_D doses are equally radiation hard

UFSD4: we need to explore around C_A
Summary and considerations

- Co-implantation of Carbon induces a lower activation of the Boron implanted to form the gain layer (Boron-Carbon capture);
- Boron-Carbon capture happens only above a certain critical Carbon density (dose A);
- Boron-Carbon capture mechanism is linear for Carbon doses > A;
- The radiation hardness improves with all Carbon doses;
- Boron Low Diffusion + Carbon A is the most radiation hard configuration of gain layer until now;
- Boron Low Diffusion + Carbon B/C/D have the same radiation hardness, lower B LD + C_A;
- UFSD3 B LD + C_A improves the radiation hardness over UFSD2 B HD + C_A by 50%;
- UFSD3 B LD + C_A retains 80% of the gain layer up to 1.5E15 n/cm2.

Next: UFSD4 will explore the region around Carbon_A to reach the most rad-hard configuration.
Acknowledgements

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- Grant Agreement no. 654168 (AIDA-2020)
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);
Cf measurement on irradiated sensors

Bias of the Cf measurements (10V)

- No Irr
- 4E14 neq/cm²
- 8E14 neq/cm²
- 3E15 neq/cm²
- 1,5E15 neq/cm²
- 3E15 neq/cm²
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 $10^{15} \text{n}_{eq}/\text{cm}^2$

Sensor W1_Irr(3E15 $\text{n}_{eq}/\text{cm}^2$)
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

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

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

- $\Phi_o$ = fluence [cm$^{-2}$]
- $N_{Si}$ = silicon atom density 5*E22 [cm$^{-3}$]
- $\sigma$ = fit parameter [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 $\phi_o$ [cm$^{-3}$]
Remind on parameterization of initial acceptor removal

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**Initial acceptor density factor**

\[ \phi_0 \ast N_{Si} \ast \sigma = N(0)_{A}^{rem} \]

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

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

**Limiting behaviors:**

\[ \lim_{N(0) \to 0} D_n = 0 \]
\[ \lim_{N(0) \to \infty} D_n = 1 \]

\[ D_n = \frac{1}{1 + \left( \frac{N_{Ao}}{N(0)_A} \right)^{n/3}} \]

- \(n = 1\) 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** \(N_{Ao}\)

At low densities:

- Si-interstitials do not find the Boron
- A higher fluence is needed to remove low density Boron
Remind on parameterization of initial acceptor removal

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

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

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

Fit with D₂