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Studies of the radiation hardness of the FBK UFSD3 production

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Outline

- Comparison between UFSD2 and UFSD3, CV and Gain measurement;
- Effect of differet 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

Wafer #	Dose Pgain	Carbon	Diffusion
● 1	0.98		L
2	0.96		L
3	0.96	A	L
● 4	0.96	A	L
● 5	0.98	A	L
6	0.96	B	L
● 7	0.98	B	L
8	0.98	B	L
● 9	0.98	C	L
10	1.00	C	L
● 11	1.00	D	L
12	1.02		H
13	1.00		H
14	1.02	A	H
15	1.00	A	H
16	1.02	B	H
17	1.02	B	H
18	1.04	B	H
19	1.02	C	H
20	1.04	C	H

● *Wafers irradiated with Neutron in Ljubljana*

Reference Wafer

UFSD2

Wafer #	Dopant	Gain dose	Carbon	Diffusion
1	Boron	0.98		Low

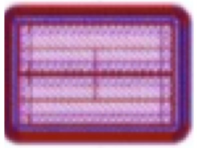
- **Wafer 1 (Boron Low Diffusion-dose0,98)** is the reference of the two FBK productions UFSD2 and UFSD3
- **4 splits of Carbon doses** to study the radiation resistance (**Carbon A/B/C/D**)

IRRADIATION CAMPAIGN:

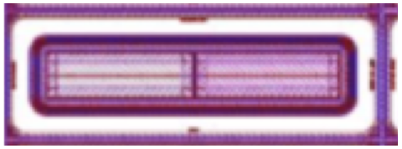
(AIDA2020) ➔ thank you GK and friends!

- Neutron Irradiation in Ljubljana, fluences: **$4*10^{14}$ / $8*10^{14}$ / $1,5*10^{15}$ / $3*10^{15}$** n_{eq}/cm^2
- Irradiated wafers: **W1/W4/W5/W7/W9/W11**

Irradiated structures



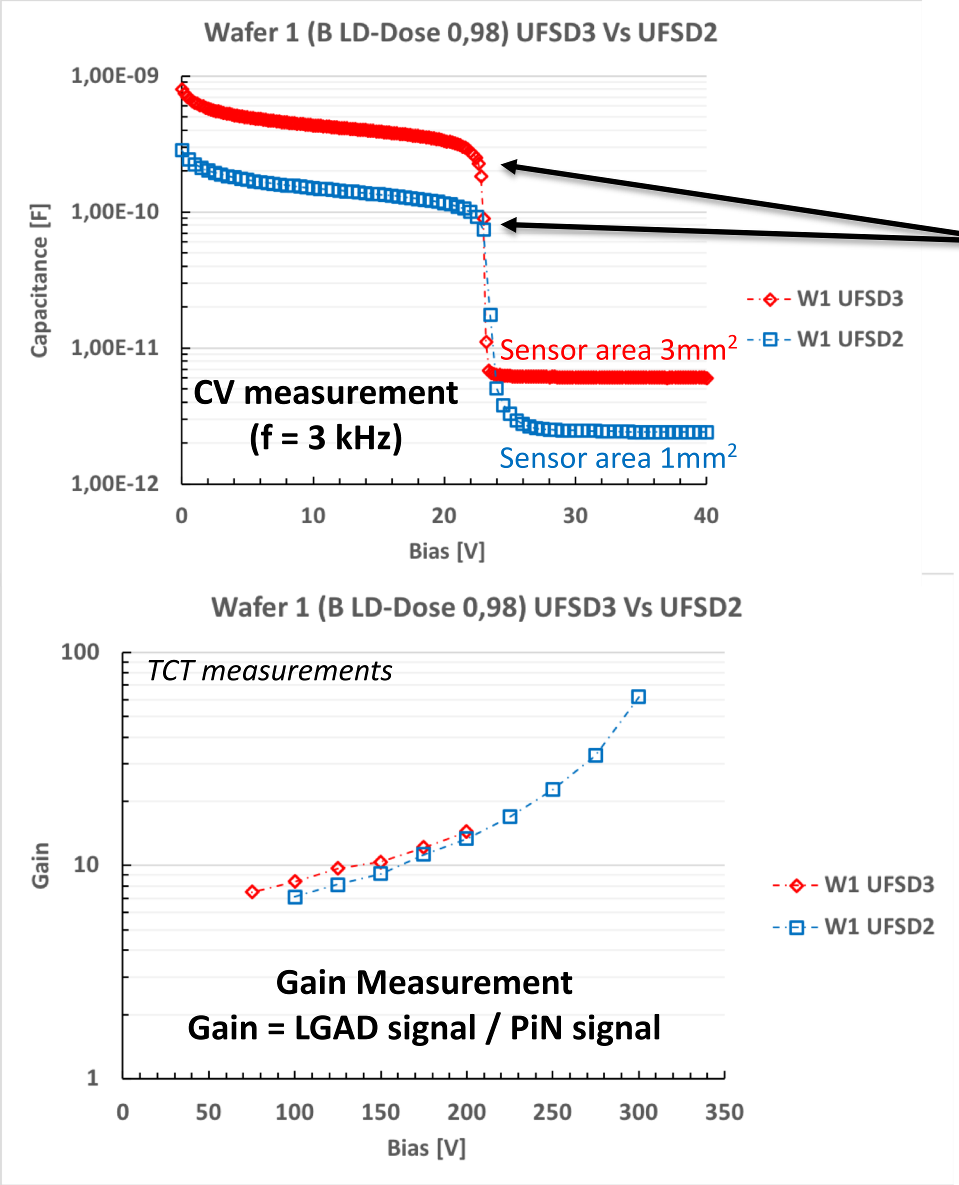
Couple LGAD -LGAD



Couple PiN-LGAD

Pre-irradiation

Comparison between UFSD3 and UFSD2 on Wafer1 (B LD)



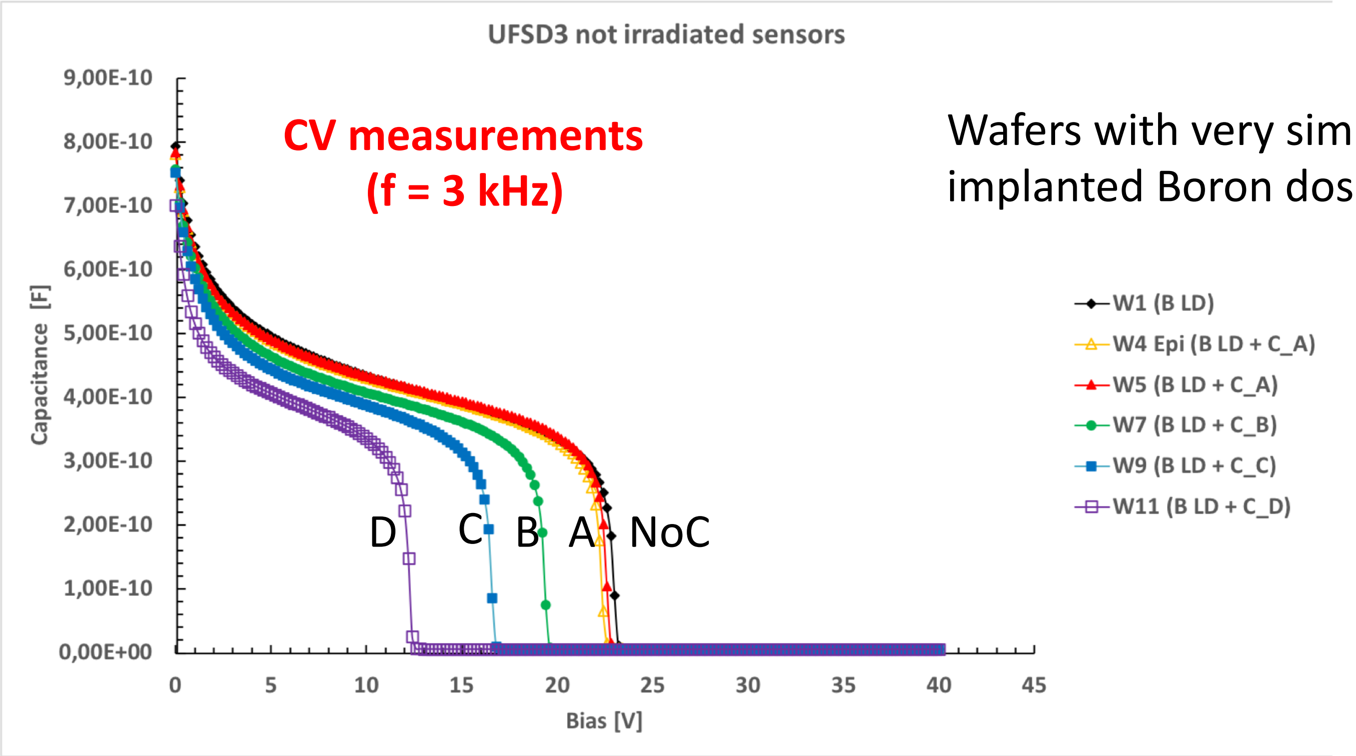
Same depletion Voltage (V_{GL}) of the gain layer (~ 23V)

Same active acceptor density into gain layer

$$V_{GL} = {d^2 q N_A}/{2\varepsilon_{Si}}$$

Agreement between the two measurements of gain in UFSD2 and UFSD3

Co-implantation of Carbon, effect on gain layer



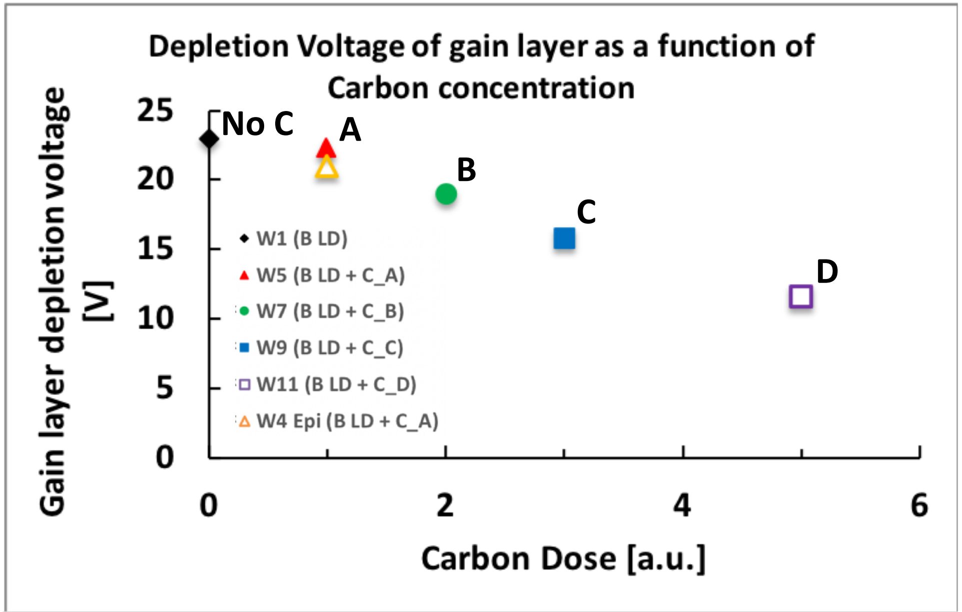
CV measurements
(f = 3 kHz)

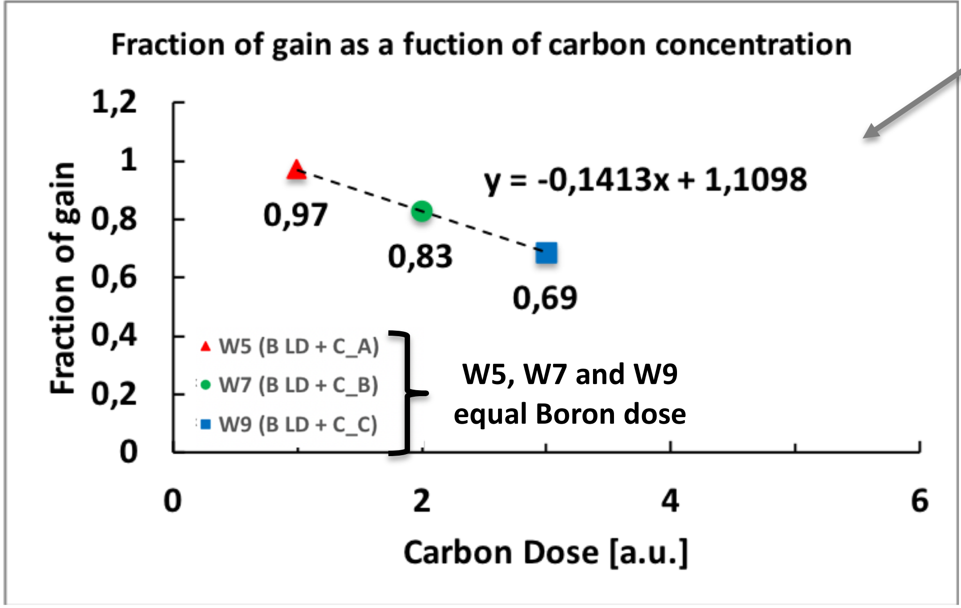
Wafers with very similar implanted Boron dose

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



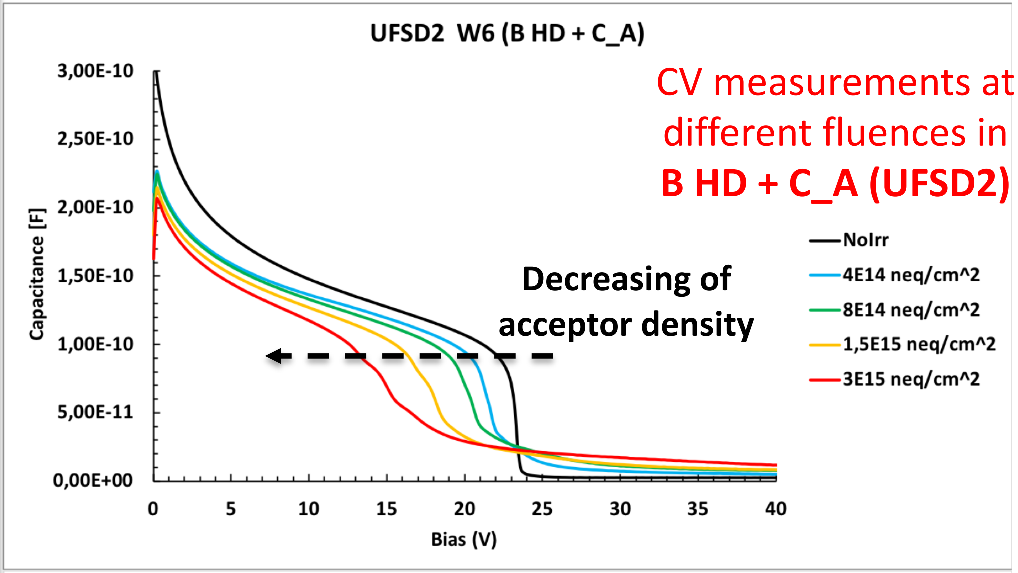


- Non linear Carbon-Boron capture as a function of the Carbon dose:
  - **Mild Boron capture** for low Carbon dose (Carbon A)
  - **Important Boron capture** for high Carbon doses (Carbon B/C/D)
- Linearity of Carbon-Boron capture in Carbon doses range A-C

Carbon dose [a.u.]	Fraction of gain
0	1
1	0,97
2	0,83
3	0,69

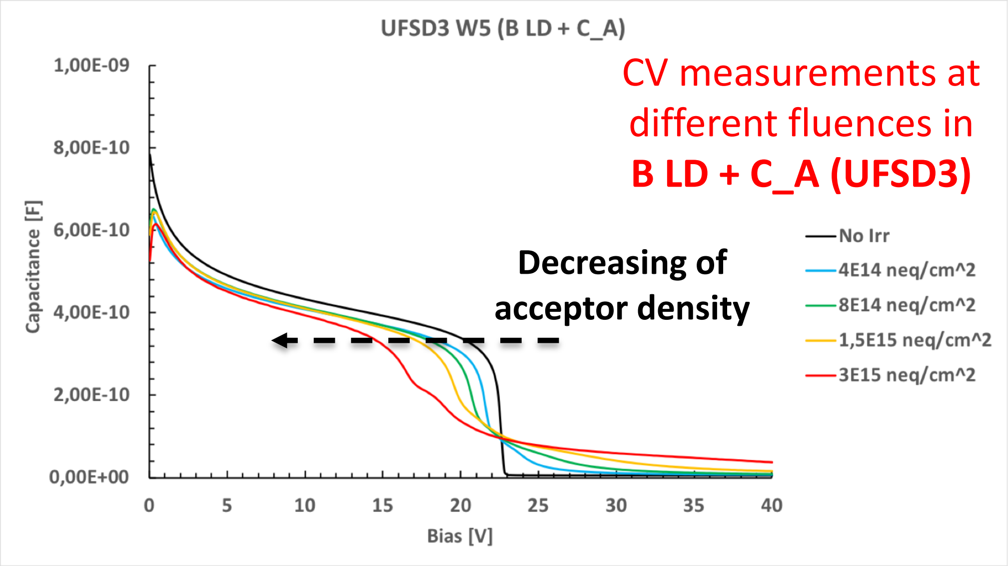
Post-irradiation

UFSD3, improvements in radiation hardness


UFSD2 W6 (B HD + C_A)

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

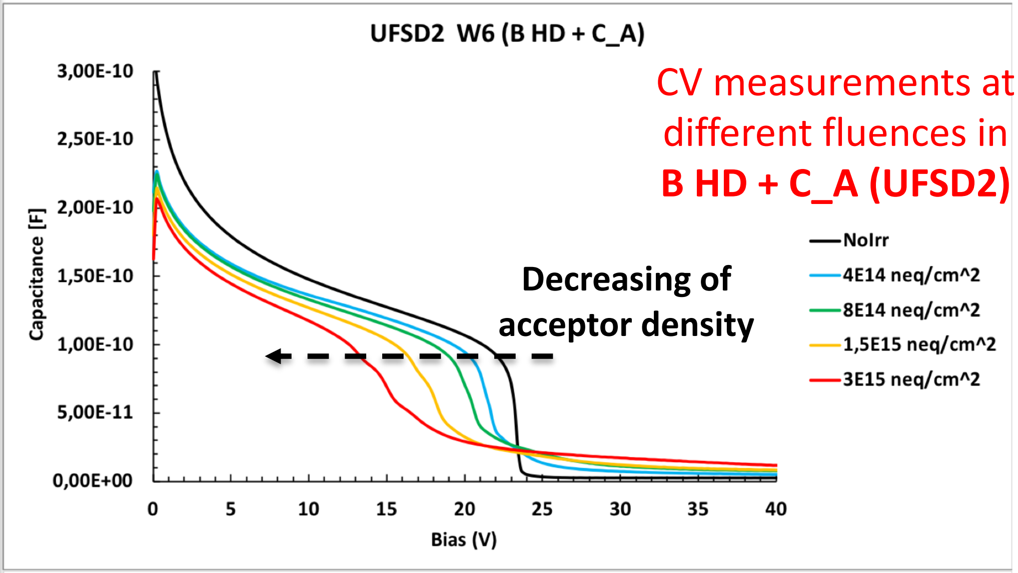
Decreasing of acceptor density


UFSD3 W5 (B LD + C_A)

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

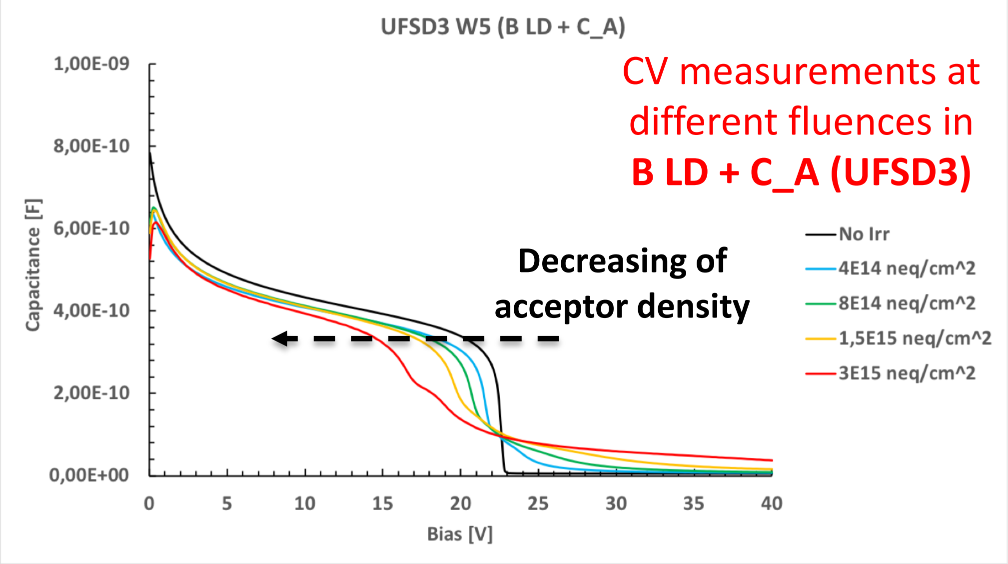
Decreasing of acceptor density

UFSD3, improvements in radiation hardness



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

Decreasing of acceptor density



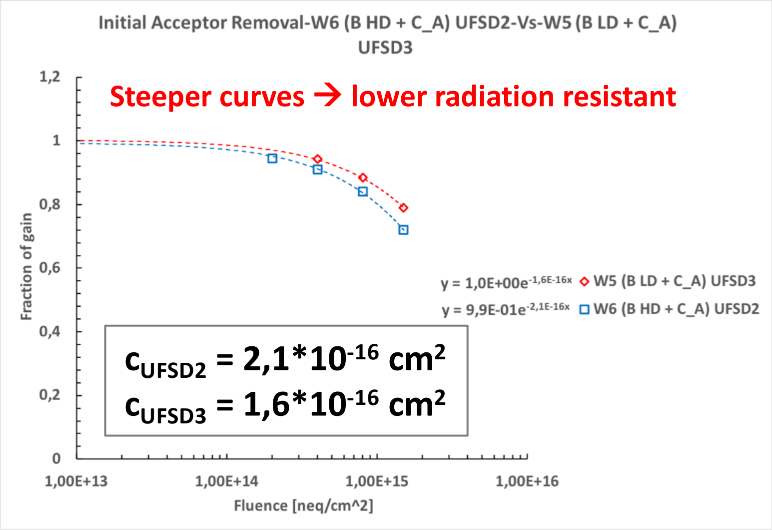
CV measurements at different fluences in **B LD + C_A (UFSD3)**

Decreasing of acceptor density

$$V_{GL} = \frac{d^2 q N_A}{2\varepsilon_{Si}}$$

Fraction of active acceptor density

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



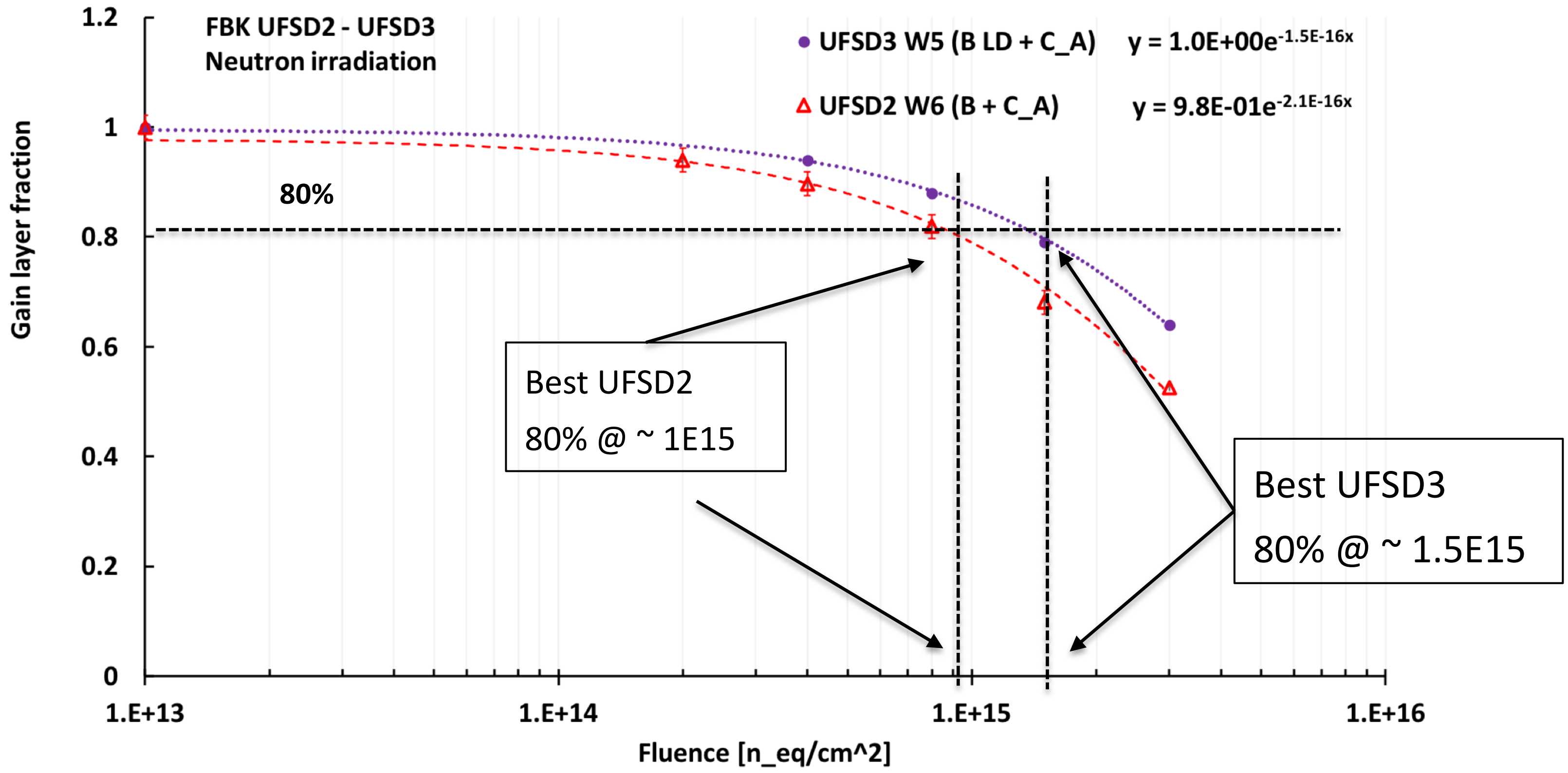
Steeper curves → lower radiation resistant

c_{UFSD2} = 2,1*10^{-16} cm^2
c_{UFSD3} = 1,6*10^{-16} cm^2

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

UFSD2 – UFSD3 comparison

UFSD3 extends by 50% the radiation resistance of UFSD2



Best UFSD2

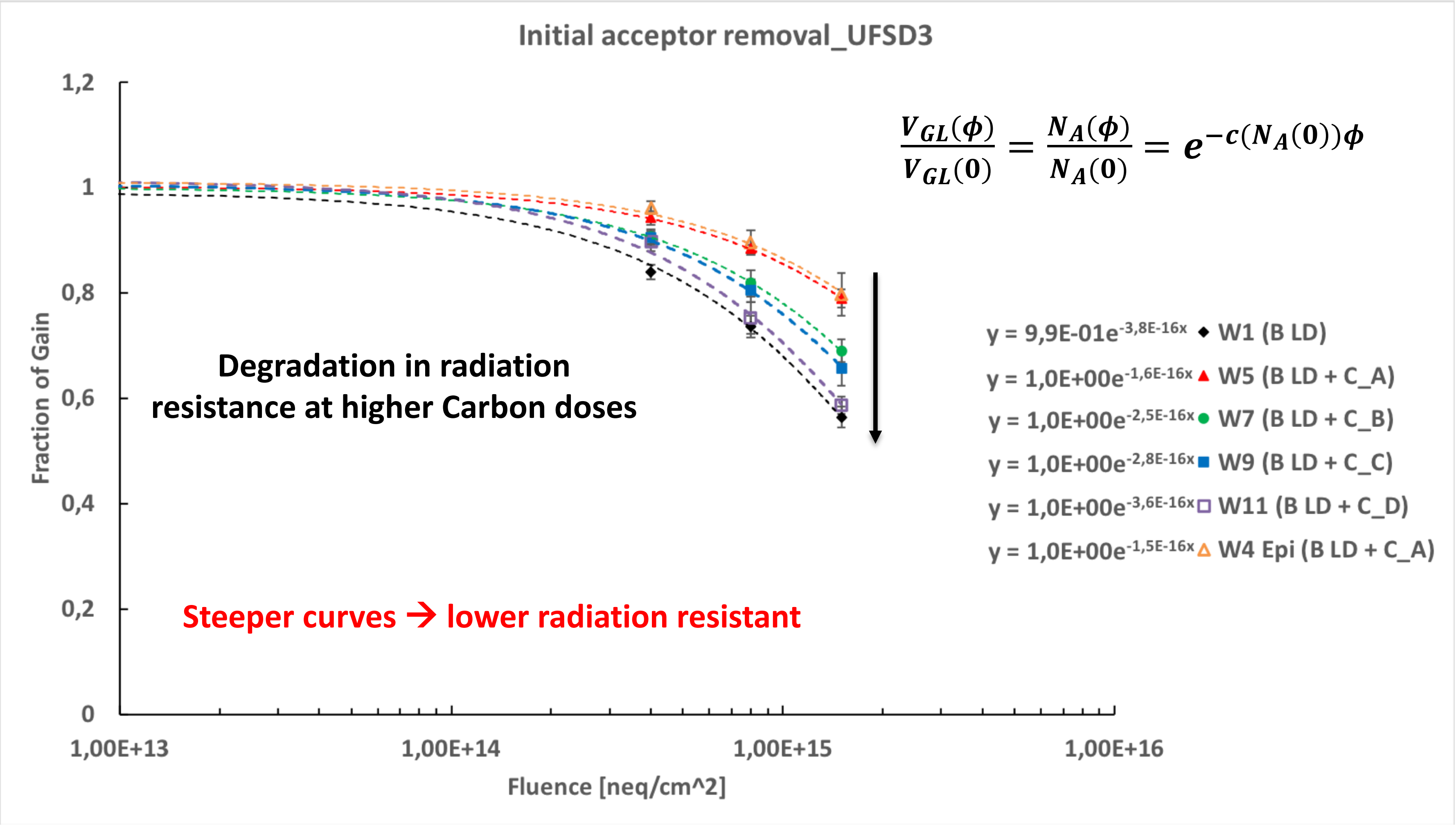
80% @ ~ 1E15

Best UFSD3

80% @ ~ 1.5E15

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 → lower radiation resistant

Acceptor removal coefficients in UFSD3

Wafer	Gain type	c_n [cm^2]
1	B LD	3,77E-16
4 (Epi)	B LD + C_A	1,55E-16
5	B LD + C_A	1,59E-16
7	B LD + C_B	2,48E-16
9	B LD + C_C	2,81E-16
11	B LD + C_D	3,63E-16

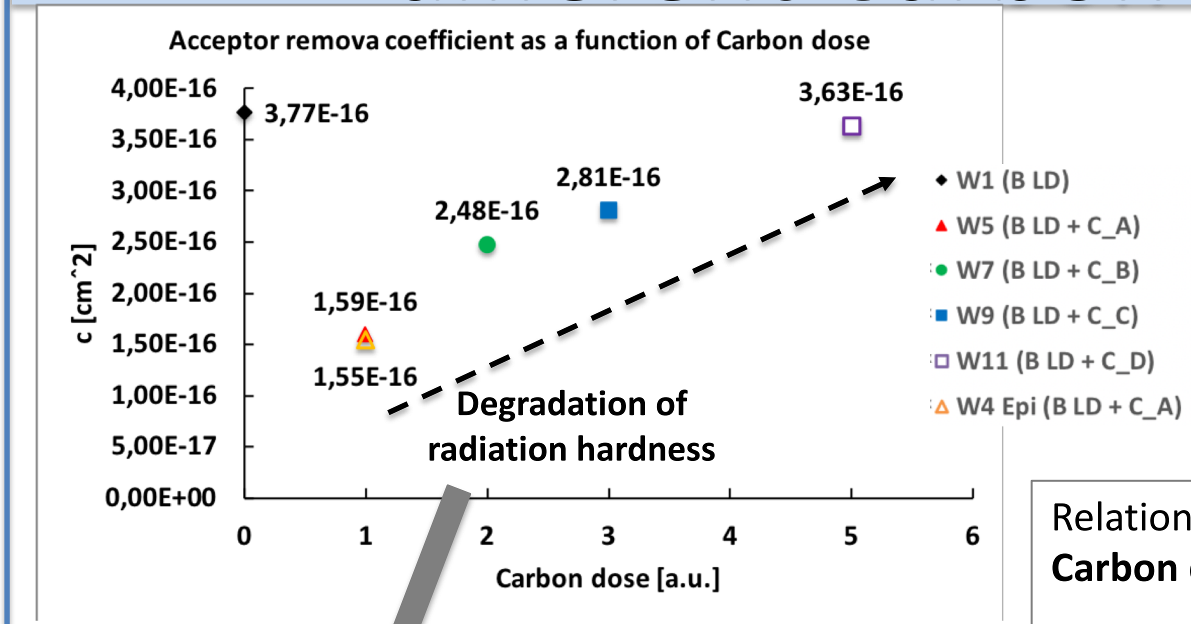
All Carbon doses (A/B/C/D) improve the gain layer radiation resistance compared to a not carbonated Gain layer

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

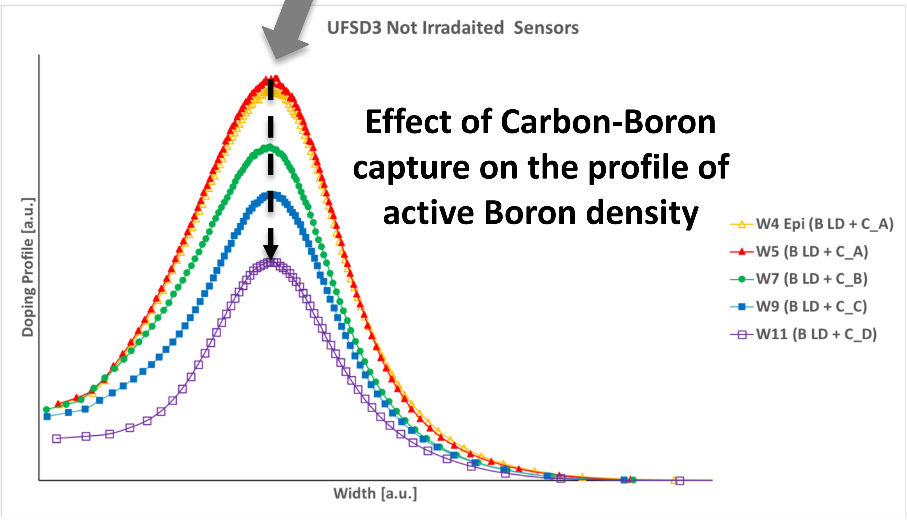
Acceptor removal coefficient **get worse** at the increasing of Carbon doses

Same radiation resistance in **Float Zone** and **Epitaxial wafers**

Acceptor removal coefficient at different Carbon doses



Degradation of radiation hardness



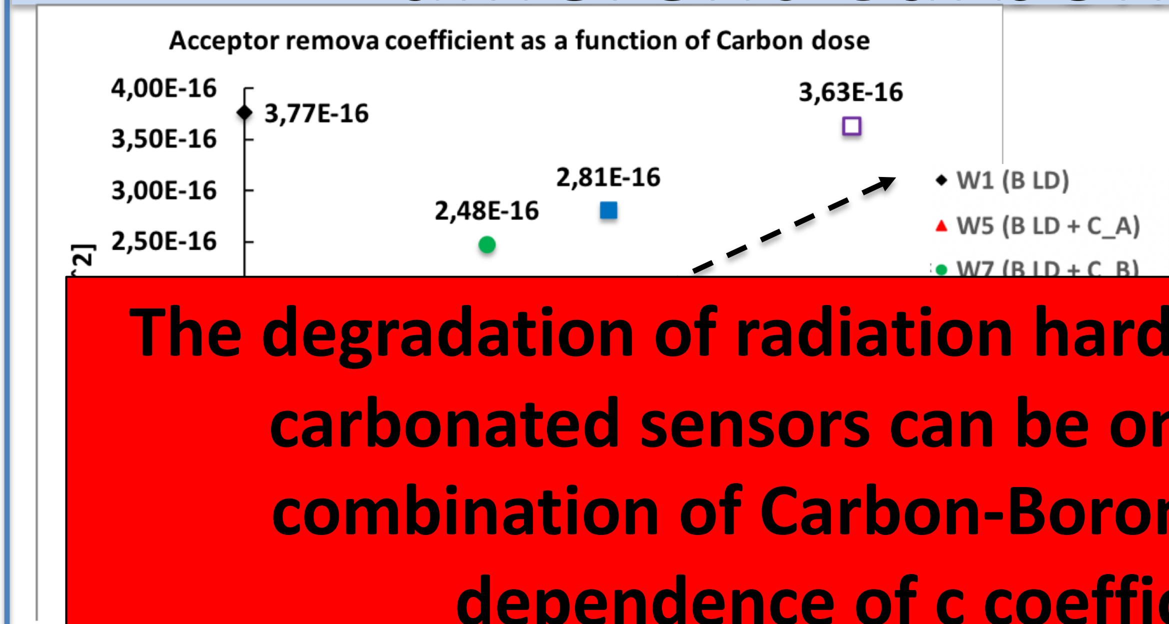
Effect of Carbon-Boron capture on the profile of active Boron density

Relationship between **c coefficients** and **Carbon doses in UFSD3**

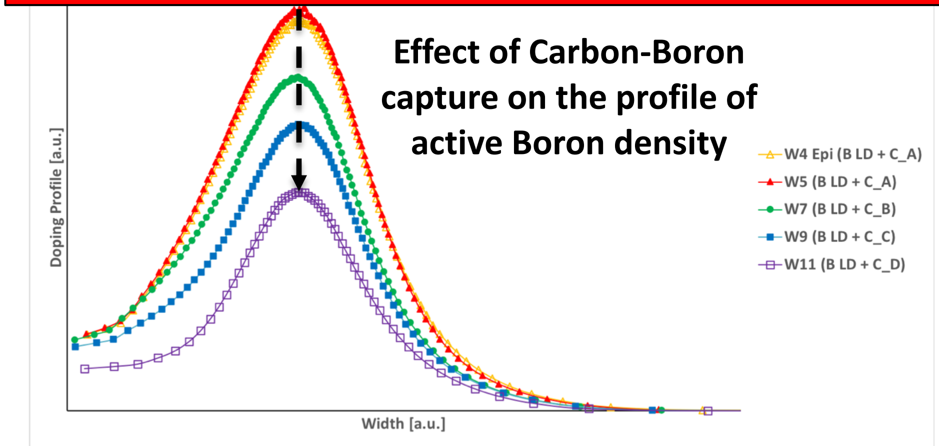
Two possible reasons:

- 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 explain by combination of Carbon-Boron Capture and dependence of c coefficient on active initial acceptor density?

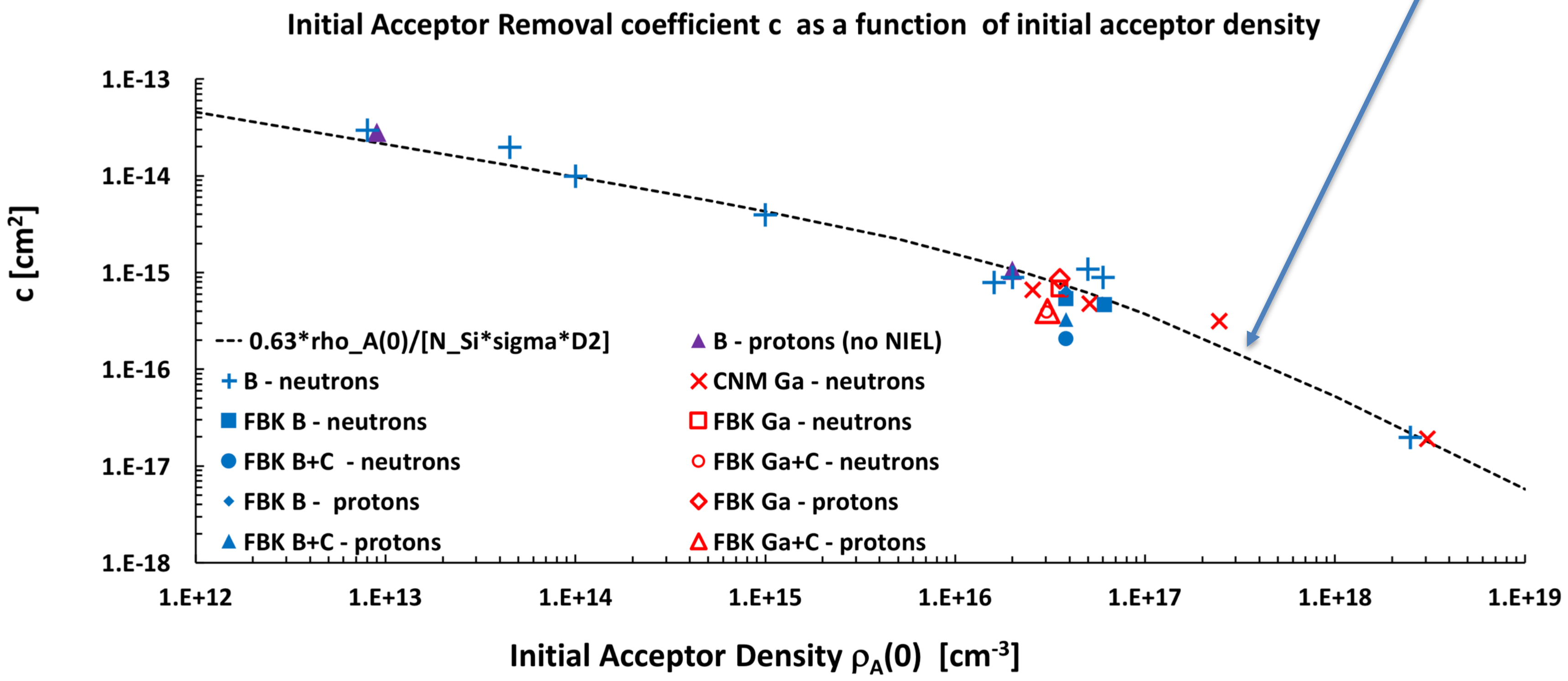

Effect of Carbon-Boron capture on the profile of active Boron density

acceptor density into gain layer;
- Dependence of **c coefficient** on **active initial acceptor density due to Carbon-Boron capture**

Acceptor removal parameterization

Nicolò Cartiglia's talk, 32nd RD50 Workshop, DESY, Hamburg
"A naïve parameterization of initial acceptor removal» "

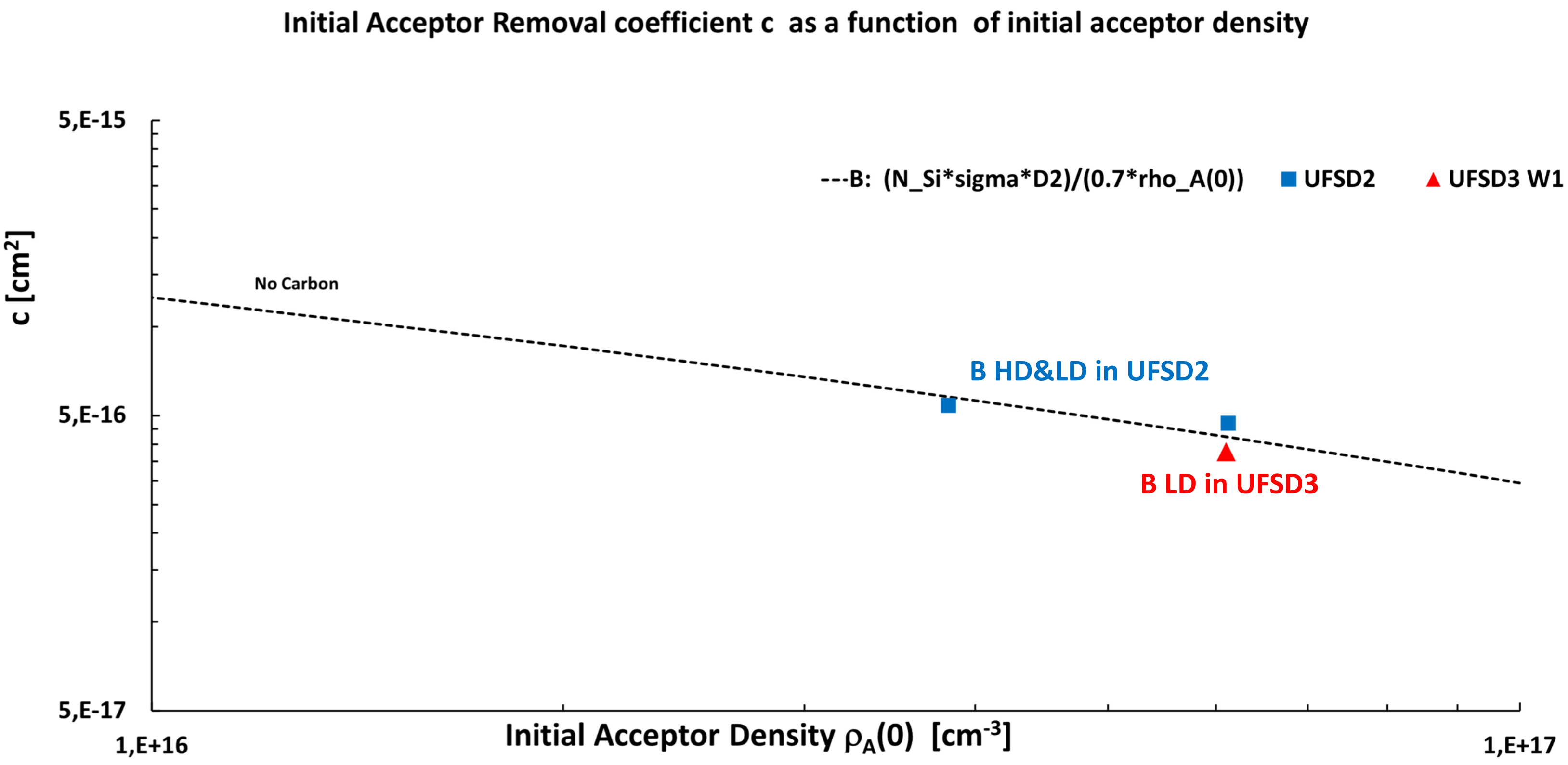
Points on this line differ in acceptor removal rate only due to the initial acceptor density



Acceptor removal parametrization: zoom on 1E16-1E17 n/cm^3 range

Boron parameterization:

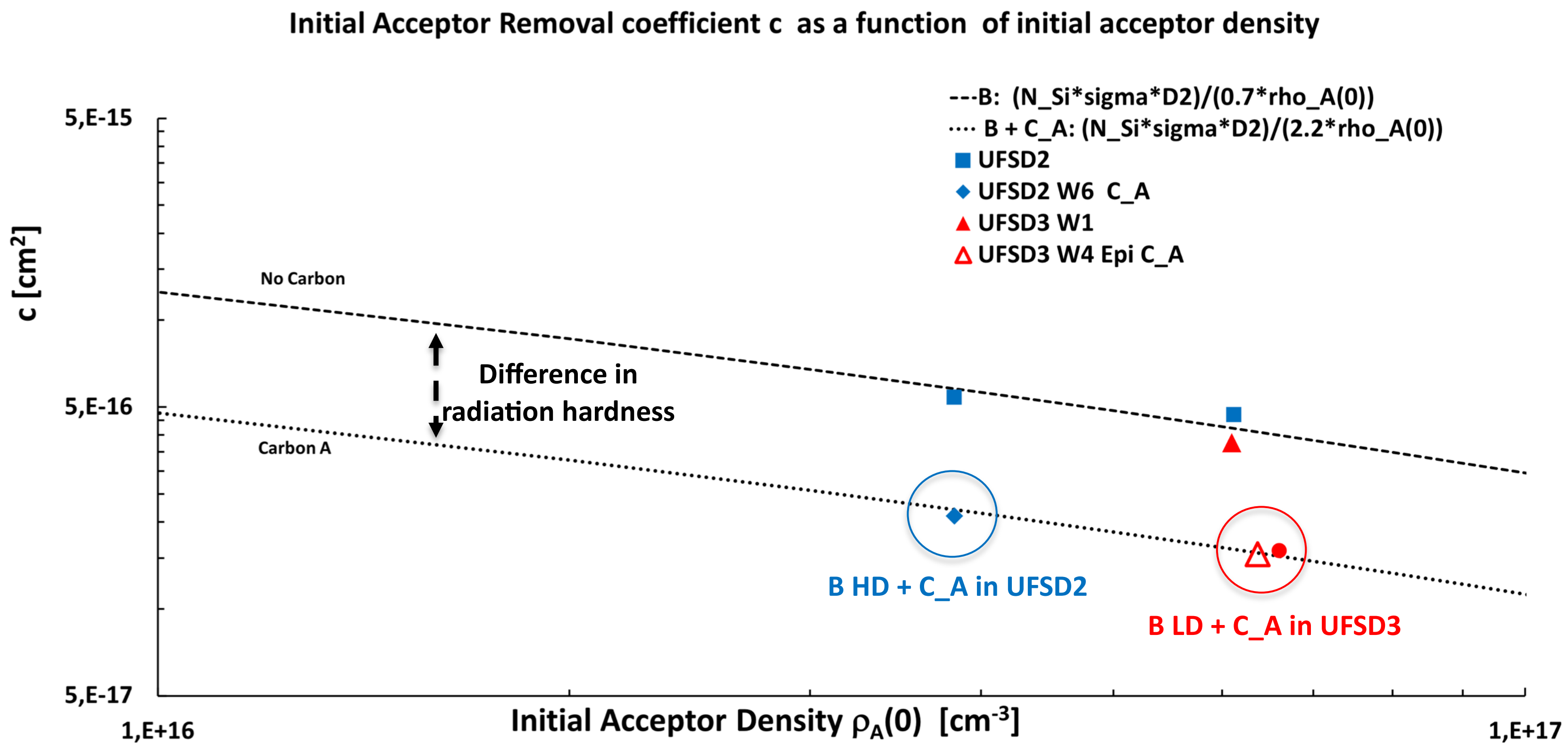
- **c coefficient** for **Boron Low Diffusion** in UFSD3 in agreement with the UFSD2 parameterization



Comparison model-data
Boron + Carbon A parameterization

Boron + Carbon A parameterization:

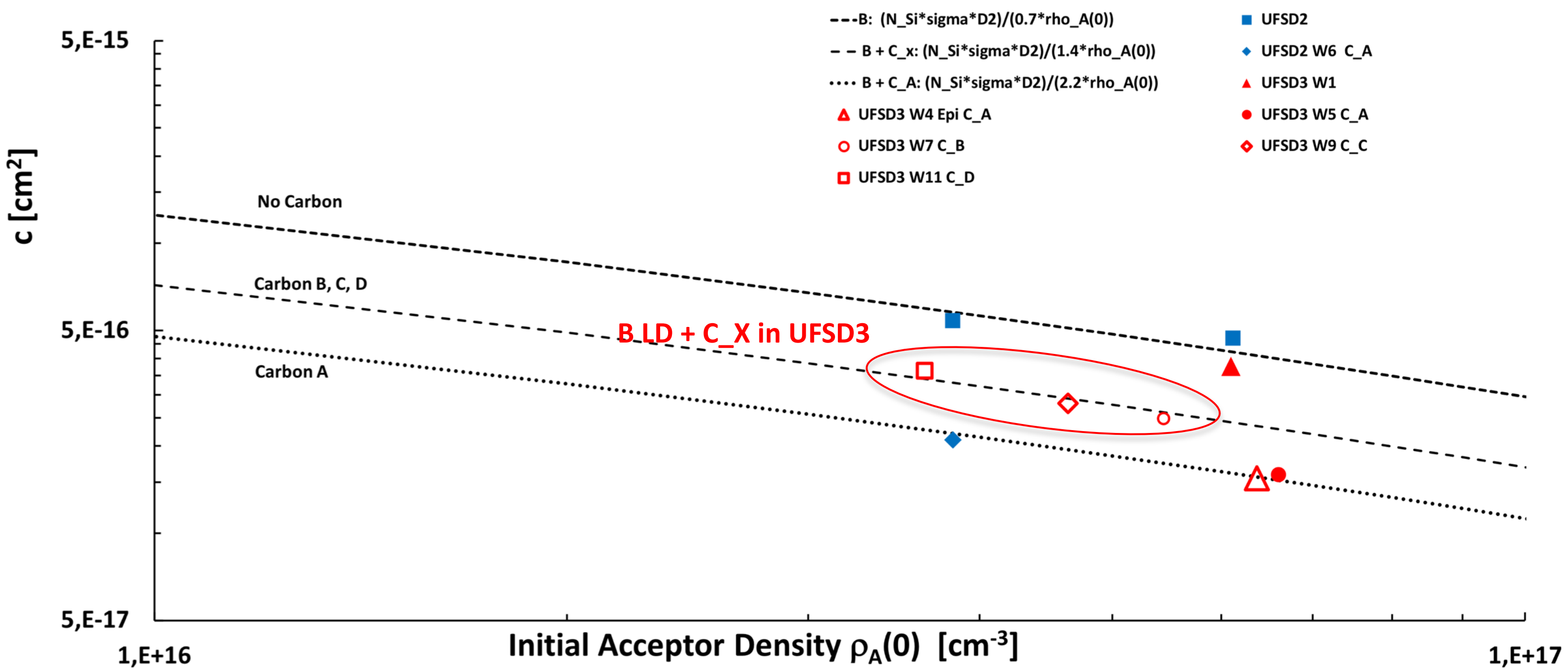
- **Boron + carbon A** have a different parameterization compared to **Boron**
- Same parameterization for B HD + C_A (UFSD2) and B LD + C_A (UFSD3)



Comparison model-data
Boron + Carbon X parameterization

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**

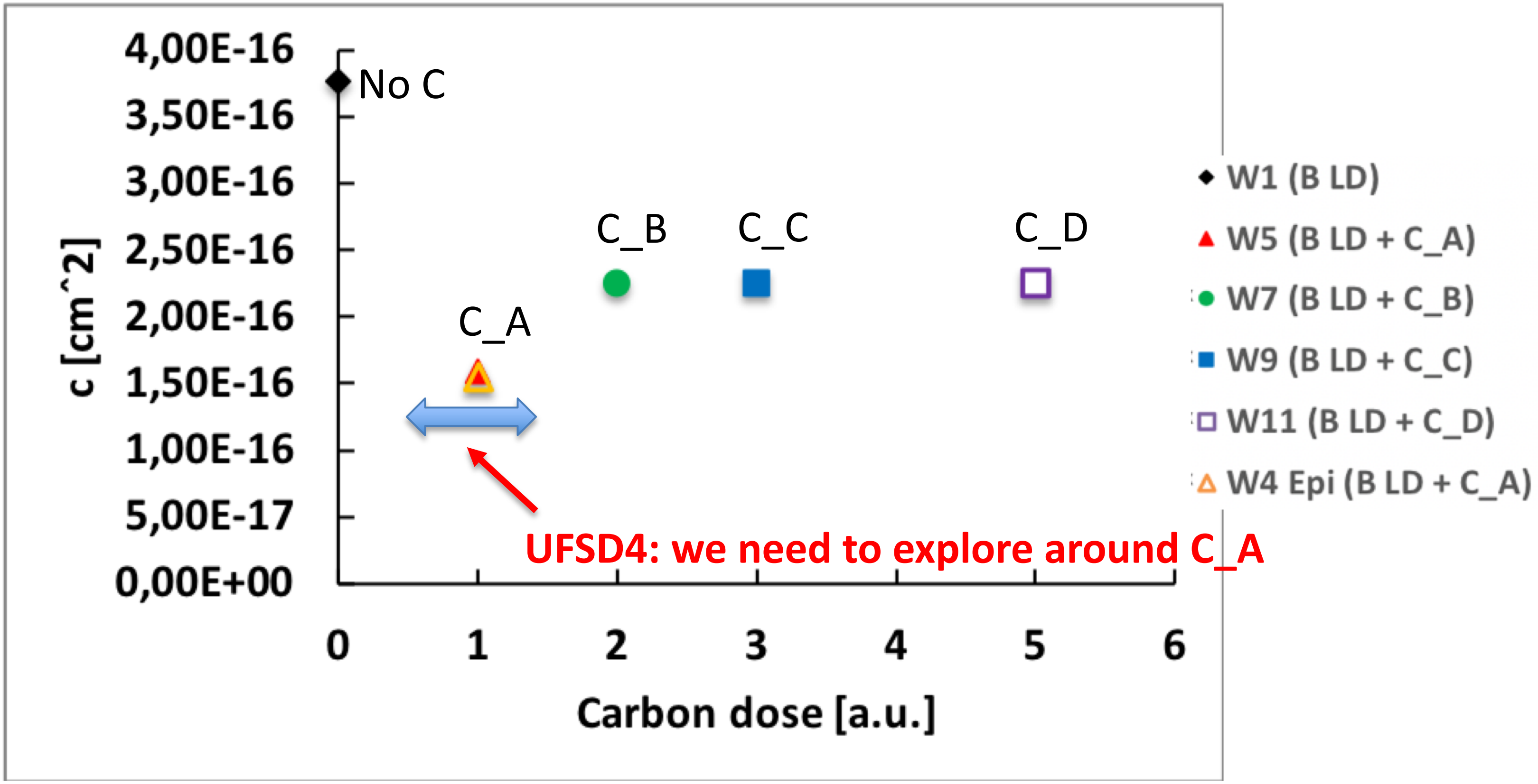


Initial Acceptor Removal coefficient c as a function of initial acceptor density

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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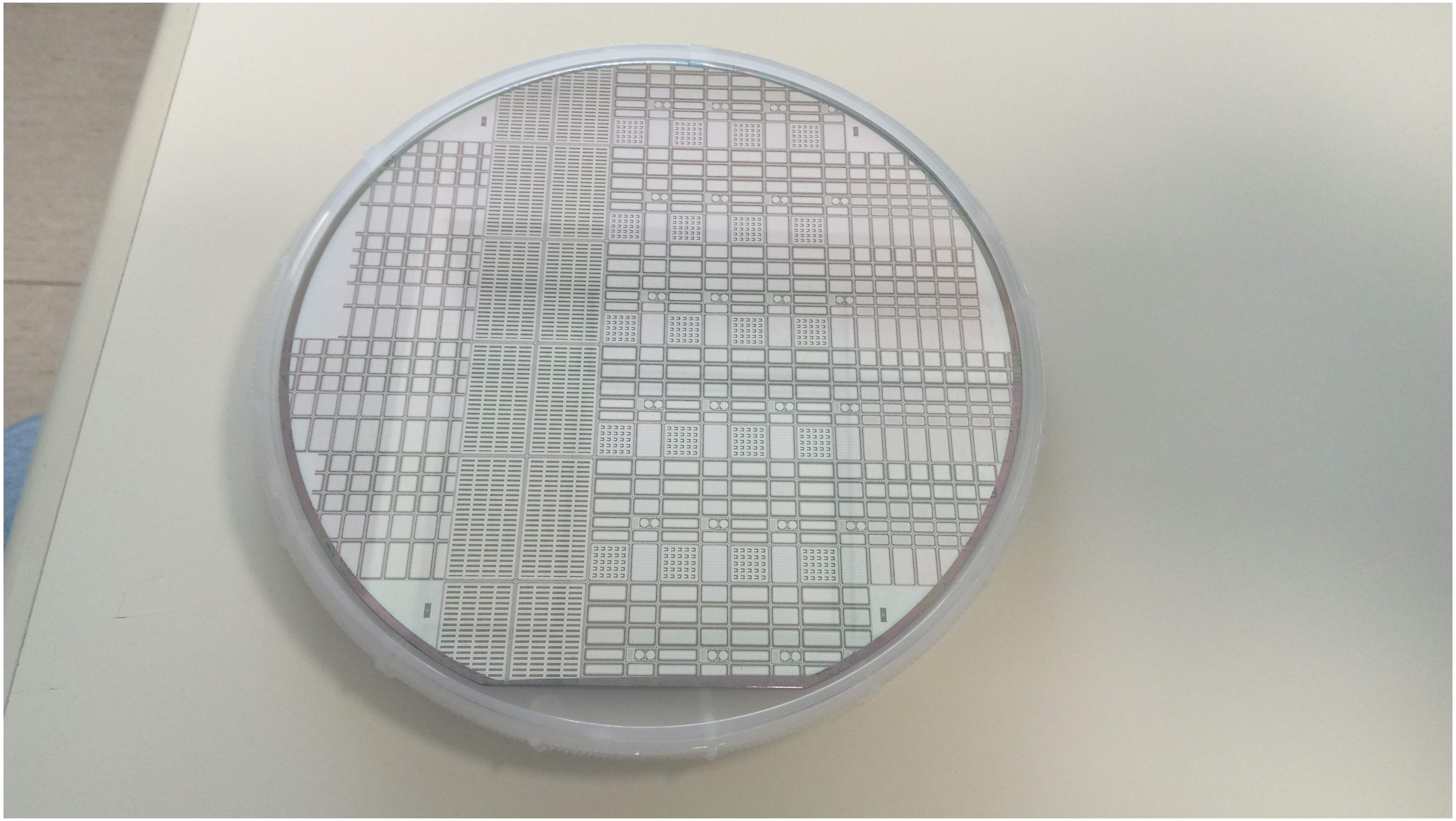
- INFN - Gruppo V
- Horizon 2020, grant UFSD669529
- Horizon 2020, grant INFRAIA
- Ministero degli Affari Esteri, Italy,MAE, “Progetti di Grande Rilevanza Scientifica”
- U.S. Department of Energy grant number DE-SC0010107
- Grant Agreement no. 654168 (AIDA-2020)

Backup

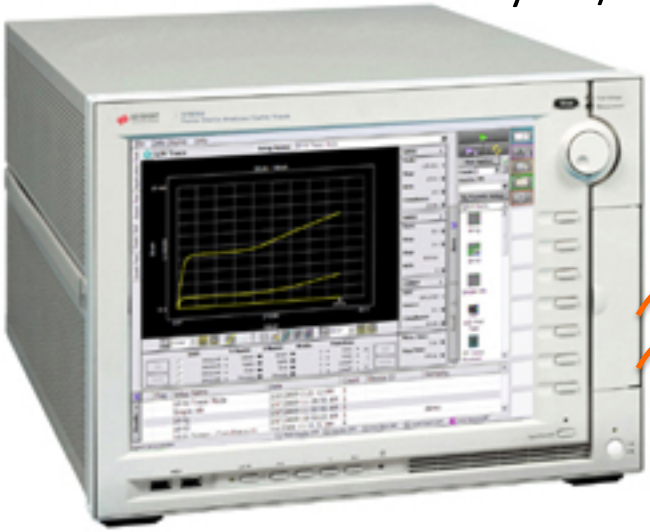
UFSD3



Wafer layout of UFSD3

CV measurements (laboratory setup)

Keysight
B1505A Power Device Analyzer / Curve Tracer

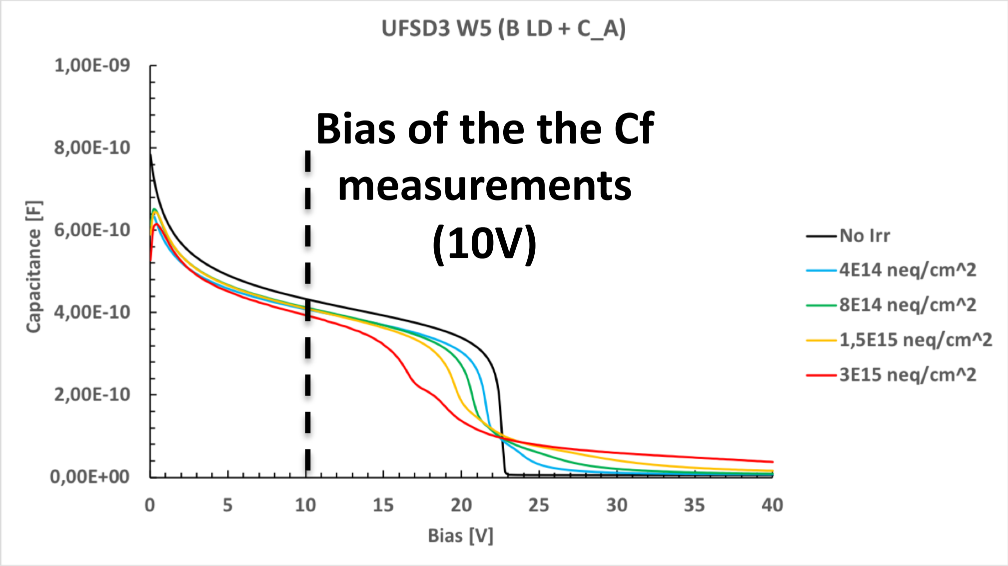


Probe station

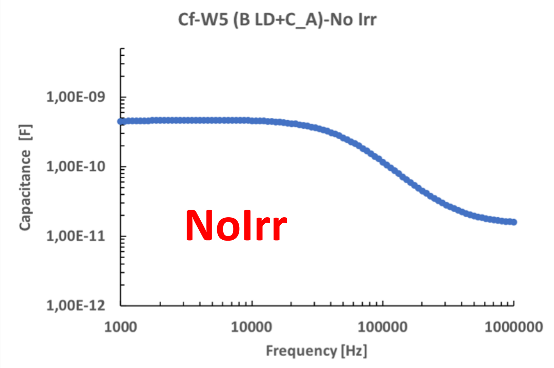
Modules

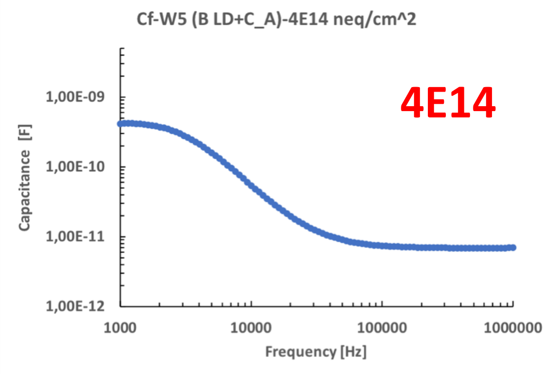
- High Voltage SMU: Max Range (±3000V, ±4mA);
  Min Range (200V, 1nA);
- CMU Modules: Range In frequency (1khz-1MHz);

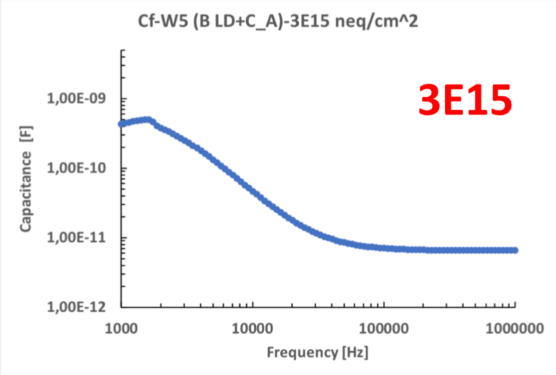
Cf measurement on irradiated sensors

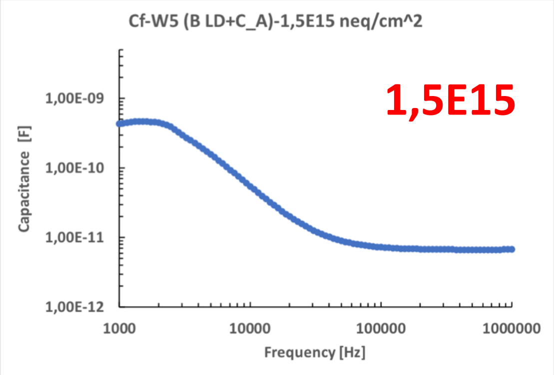


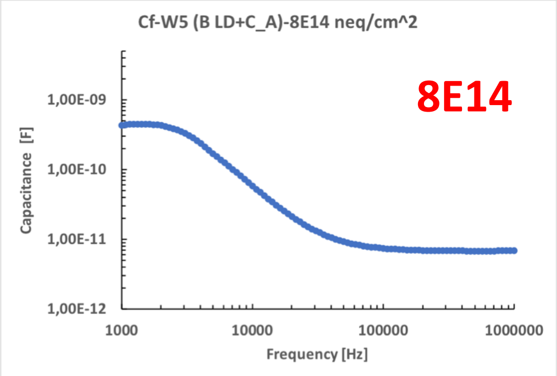
Bias of the the Cf measurements (10V)











Extrapolation of V_{GL}

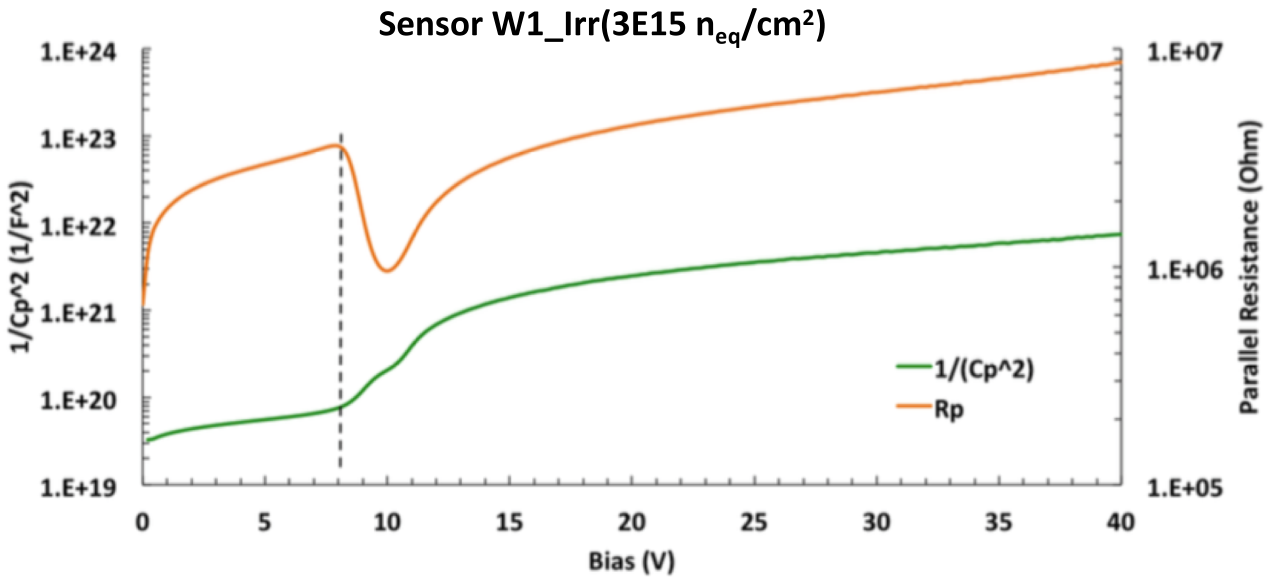
C-V Measurement parameters:

- Measurement Model = $C_p - R_P$
- Measurement Frequency = 1 kHz
- Measurement temperature = Room Temperature
- Sensors measured after annealing (80min @ 60°)

V_{GL} Extrapolation method

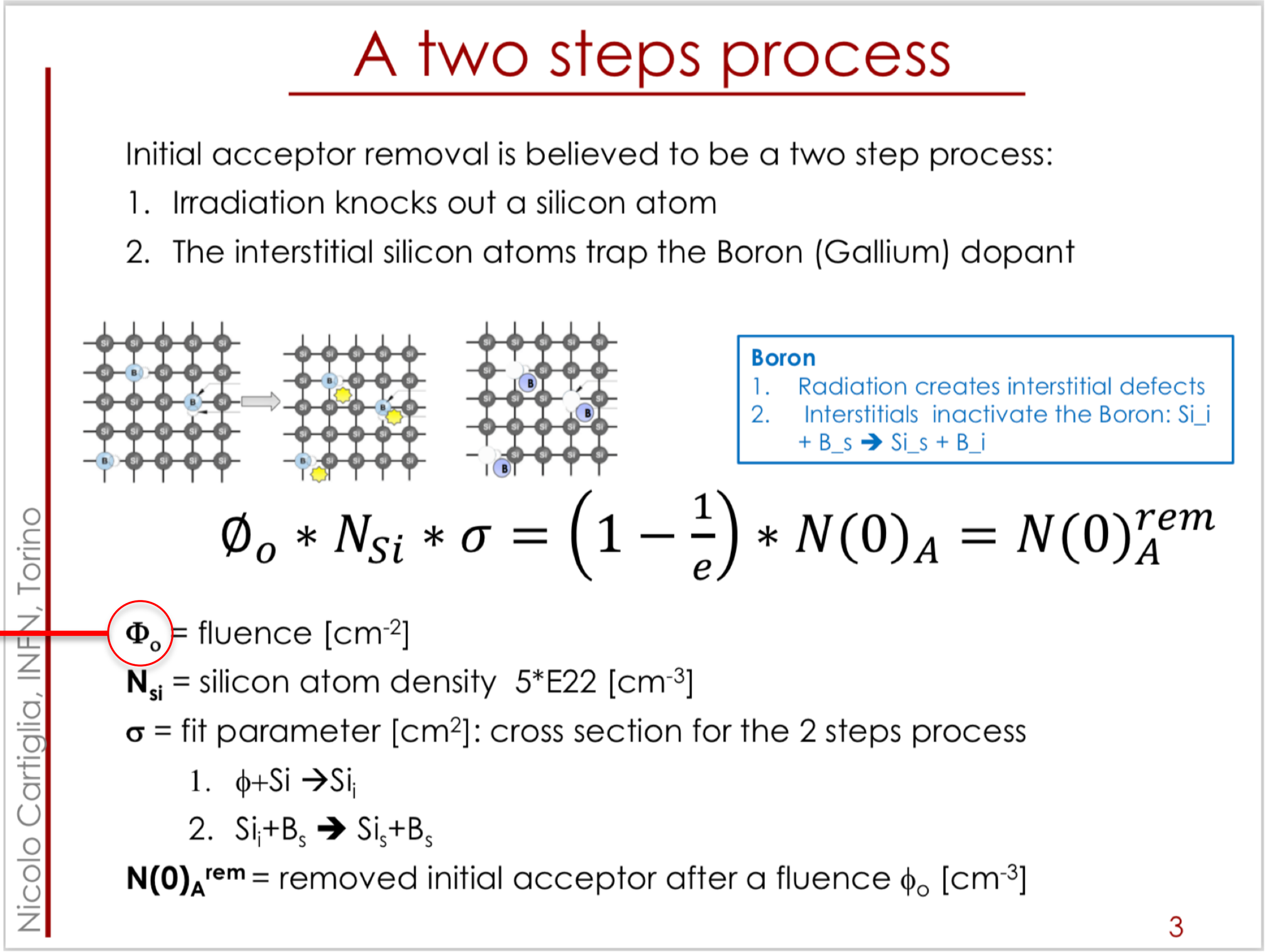
Using the **cusp on the R_p curve**, in coincidence with the **foot in the $1/C_p^2$ curve**

This method is precise even for fluences above 10^{15} n_{eq}/cm^2


Sensor W1_Irr(3E15 n_{eq}/cm^2)

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

Boron
1. Radiation creates interstitial defects
2. Interstitials inactivate the Boron: Si_i + B_s ➔ Si_s + B_i

$$\emptyset_o * N_{Si} * \sigma = \left(1-\frac{1}{e}\right) * N(0)_A = N(0)_A^{rem}$$

Φ_o = fluence [cm^{-2}]

N_{si} = silicon atom density 5*E22 [cm^{-3}]

σ = 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 ϕ_o [cm^{-3}]

Nicolo Cartiglia, INFN, Torino

3

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

Remind on parameterization of initial acceptor removal

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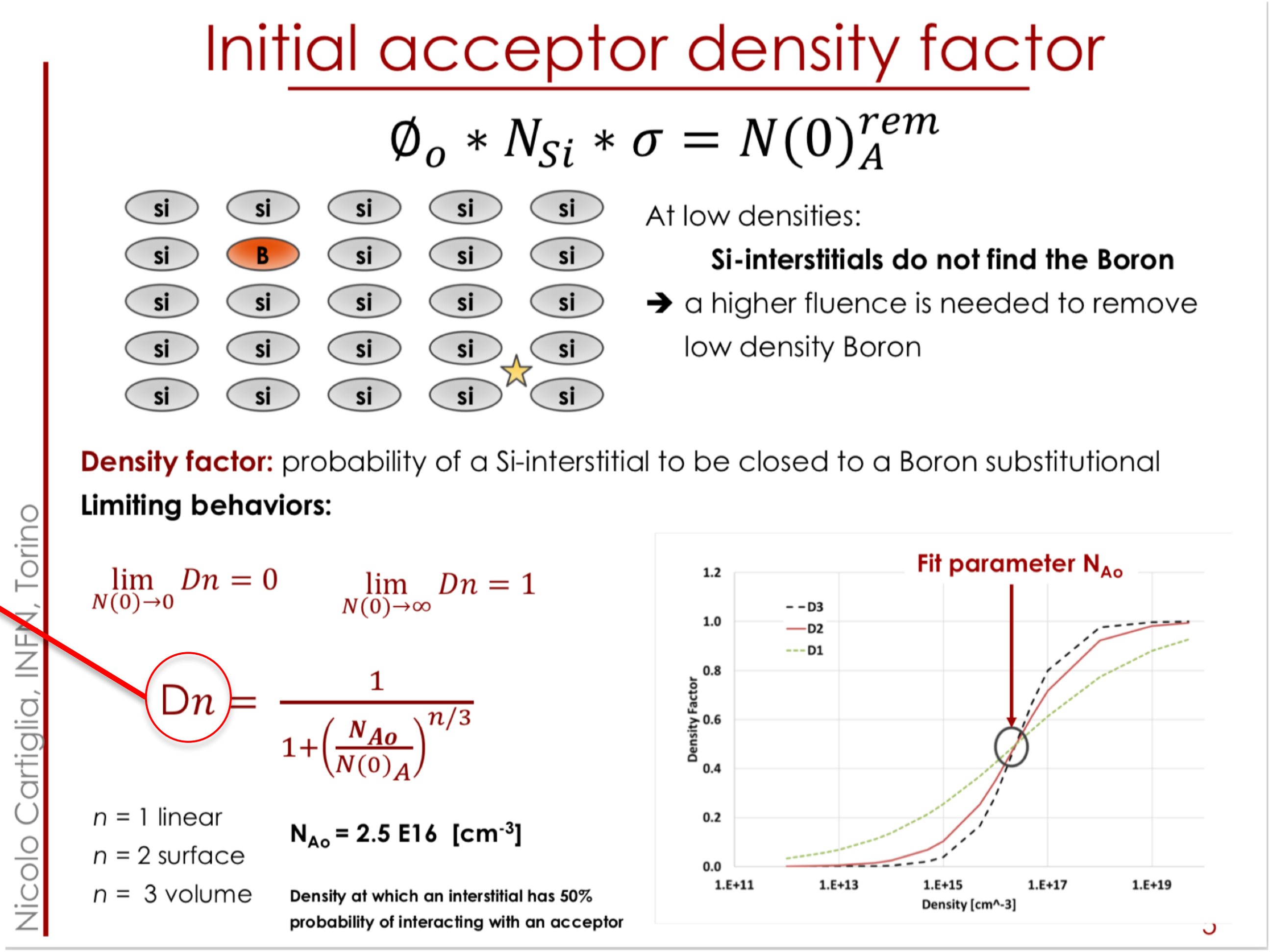
Introduction into the parameterization a density factor (D_n) to consider low Boron density cases



Initial acceptor density factor

$$\emptyset_o * N_{Si} * \sigma = N(0)_A^{rem}$$

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:

$$\lim_{N(0)\to 0} Dn = 0 \qquad \lim_{N(0)\to\infty} Dn = 1$$

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

n = 1 linear
n = 2 surface
n = 3 volume

N_{Ao} = 2.5 E16 [cm^{-3}]

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

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Remind on parameterization of initial acceptor removal

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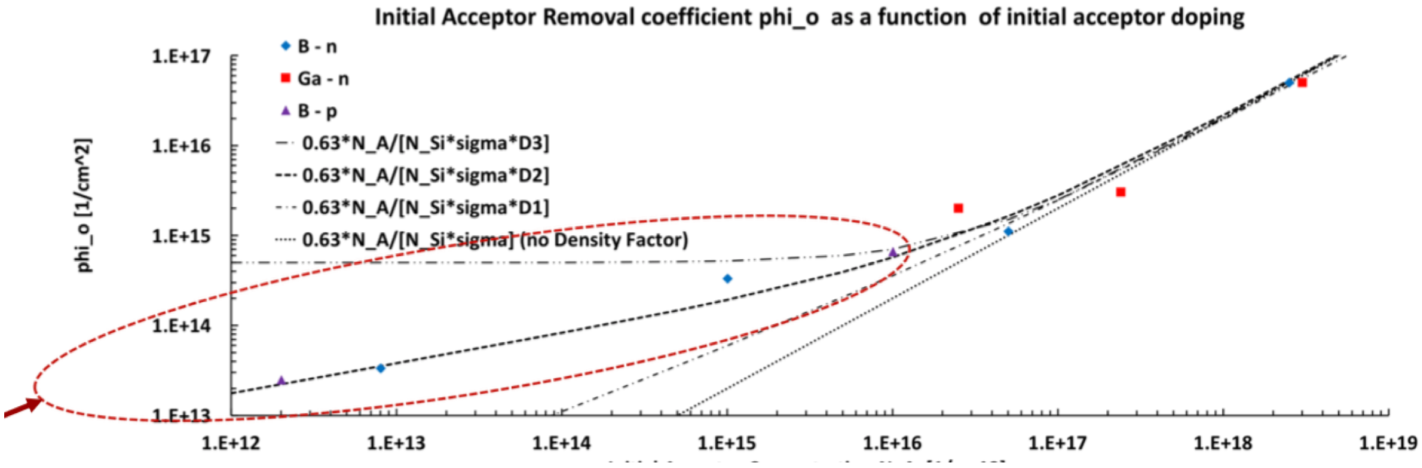
$$\emptyset_0 = \frac{1}{c}$$

$$\emptyset_o = \frac{N(0)_A^{rem}}{N_{Si} * \sigma * Dn}$$



Fit with D_2