37th RD50 Workshop – Zagreb – online Workshop

A summary of the radiation resistance of carbonated gain implants

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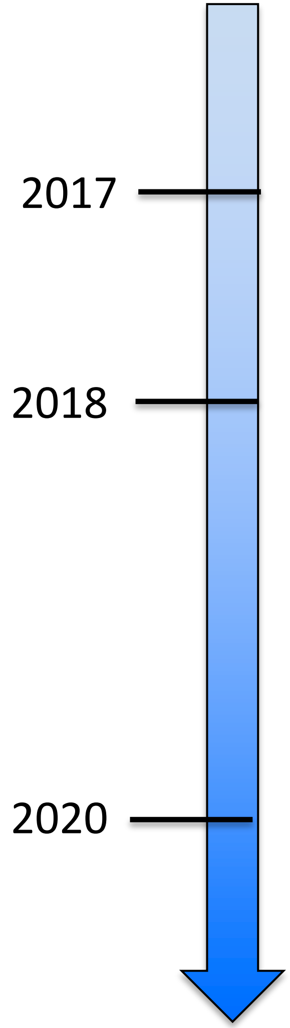
Outline

- Overview on the main features in FBK-UFSD3.2 production, with special focus on the radiation resistance
- New developments in Boron-activation in carbonated gain implants.
  - Question to experts: “Why in carbonated implants, less B is activated?”
- Acceptor removal measurements on UFSD3.2
- Optimization of the carbon dose to maximize the radiation resistance of gain implants
- Discussion on the next steps to improve the radiation resistance of the gain layer

Carbonated gain implants, roadmap at FBK



UFSD2 → Shallow-gain implants enriched with carbon doses 1C and 10C

R. Arcidiacono talk at 13th Trento Workshop on Advanced Silicon Radiation Detectors , Munich, 2018

Carbon improves the radiation resistance of the gain implant

Carbonated gain implants, roadmap at FBK

- **2017** — **UFSD2** → Shallow-gain implants enriched with carbon doses 1C and 10C
- **2018** — **UFSD3** → Shallow-gain implants enriched with carbon doses 1C, 2C, 3C and 5C

M. Ferrero talk at 33rd RD50 Works, CERN, 2018

- **2020**

Carbon-Boron inactivation (CBI): monotonic-growing trend as a function of the carbon dose, in un-irradiated UFSDs

Gain layer radiation resistance: no improvement increasing the carbon dose

Carbonated gain implants, roadmap at FBK

2017 — **UFSD2** → Shallow-gain implants enriched with carbon doses 1C and 10C

2018 — **UFSD3** → Shallow-gain implants enriched with carbon doses 1C, 2C, 3C and 5C

2020 — **UFSD3.2** → Shallow and deep-gain implants enriched with carbon doses 0.4C, 0.6C, 0.8C and 1C

FBK UFSD3.2 production

Wafer #	thickness	GL DEPTH	Dose Pgain	Carbon	Diffusion
1	45	shallow	0.98	1*A	CHBL
2	45			1*A - Spray	L
3	45			0.8*A	L
4	45			0.4*A	L
5	25		0.94	1*A	L
6	35			1*A	L
7	55		0.98	1*A	L
8	45	deep	0.70	1*A	CBL
9	55			1*A	L
10	45			0.6*A	L
11	45				L
12	45		0.74	1*A	L
13	45			0.6*A	L
14	45			1*A	CBH
15	55			1*A	H
16	45			0.6*A	H
17	45				H
18	45		0.78	1*A	H
19	45			0.6*A	H

UFSD3.2 production-GL designs

Shallow-carbonated gain implant (standard gain layer design implemented in UFSD2 and UFSD3)

Deep-Carbonated gain implant, **new design implemented in UFSD3.2:**

FBK UFSD3.2 production

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UFSD3.2 production-GL designs

Gain implants enriched with **four carbon doses**

Carbon dose	Shallow G-implant	Deep G-implant
0.4C	X	
0.6C		X
0.8C	X	
1C*	X	X

** Reference dose in UFSD2 and UFSD3*

FBK UFSD3.2 production

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UFSD3.2 production-GL designs

Diversification of the implantation-diffusion process of the gain implant

Carbon High Boron Low (CHBL)

Carbon implantation (external company)

↓

Diffusion process at **high thermal load** (in FBK)

↓

Boron Implantation (in FBK)

↓

Diffusion process at **low thermal load** (in FBK)

FBK UFSD3.2 production

Wafer #	thickness	GL DEPTH	Dose Pgain	Carbon	Diffusion
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UFSD3.2 production-GL designs

Diversification of the implantation-diffusion process of the gain implant

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Diffusion process at **low thermal load** (in FBK)

FBK UFSD3.2 production

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UFSD3.2 production-GL designs

Diversification of the implantation-diffusion process of the gain implant

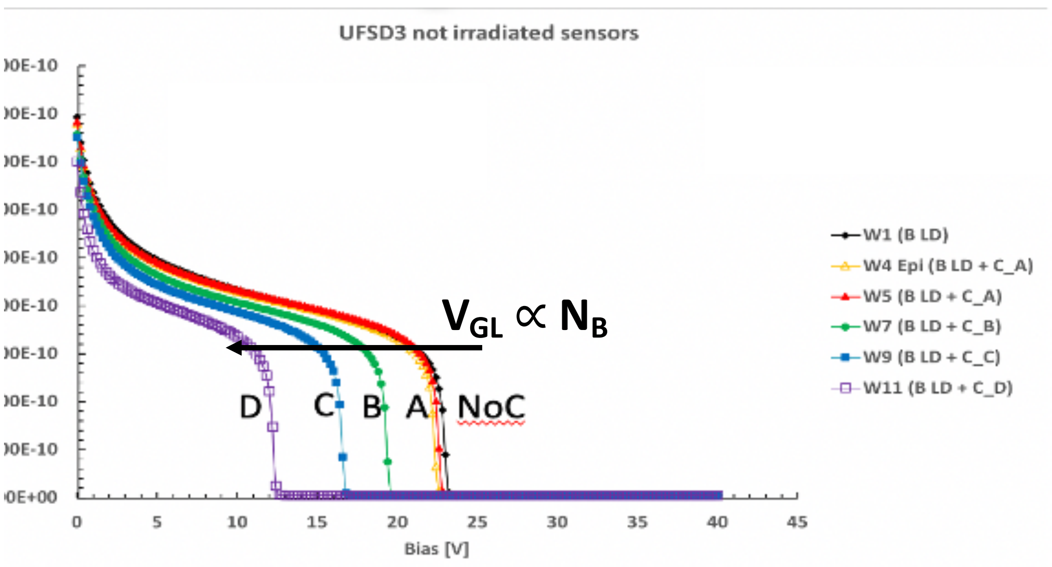
Carbon Boron High (CBH)

Carbon implantation (external company)

Boron Implantation (external company)

Diffusion process at **high thermal load** (in FBK)

Carbon-Boron inactivation (CBI) in un-irradiated UFSD



M. Ferrero talk at 33rd RD50 Works, CERN, 2018

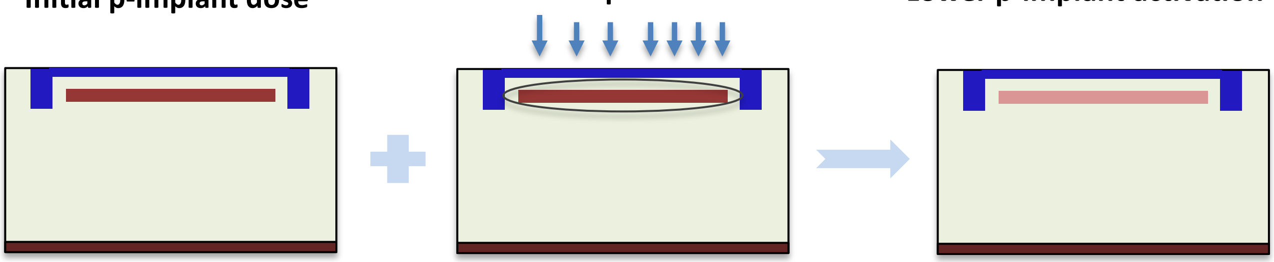
Carbon-Born inactivation observed for the first time in UFSD2 and UFSD3 productions

Carbon-boron capture is not an understood mechanism

Initial p-implant dose

carbon implantation

Lower p-implant activation



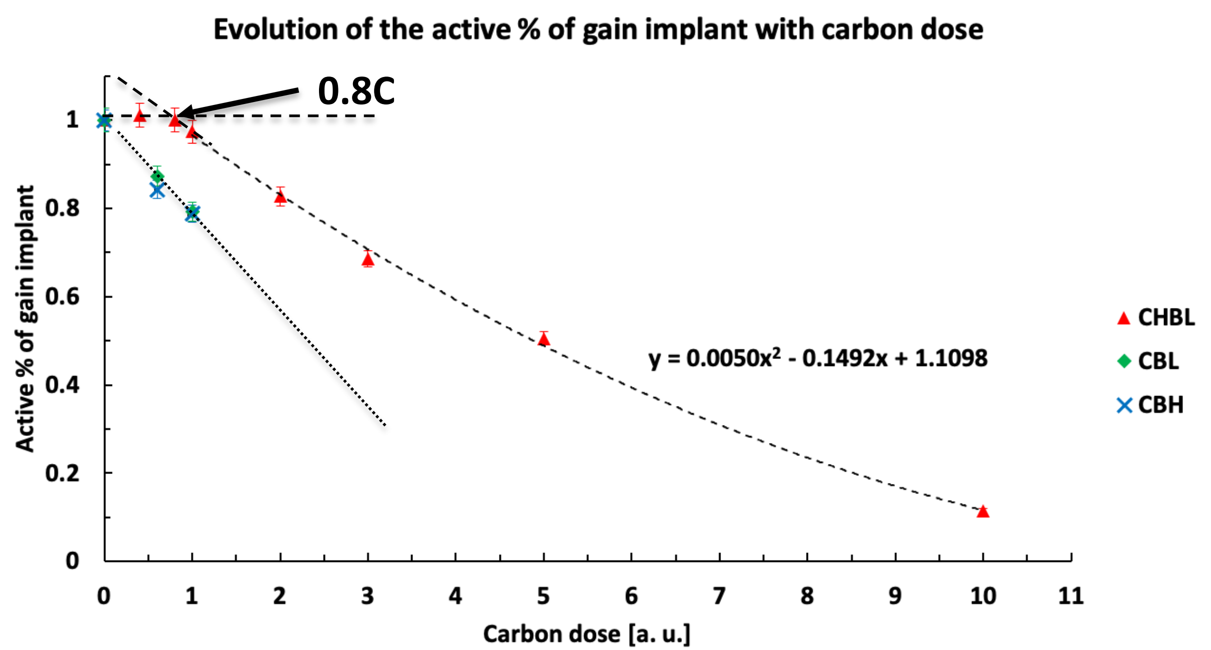
Is carbon-born capture or a competition between carbon and boron to become substitutional?

Carbon-Boron inactivation (CBI) in un-irradiated UFSD

$$\textit{\%-active } \rho_A = \frac{\rho_A(GL\ carbonted)}{\rho_A(GL\ not\ carbonated)} = \frac{V_{GL}(GL\ carbonated)}{V_{GL}(GL\ not\ carbonated)}$$

$$V_{GL} \propto \rho_A$$

V_{GL} extracted from CV measurements



Data from UFSD2, UFSD3 and UFSD3.2 productions

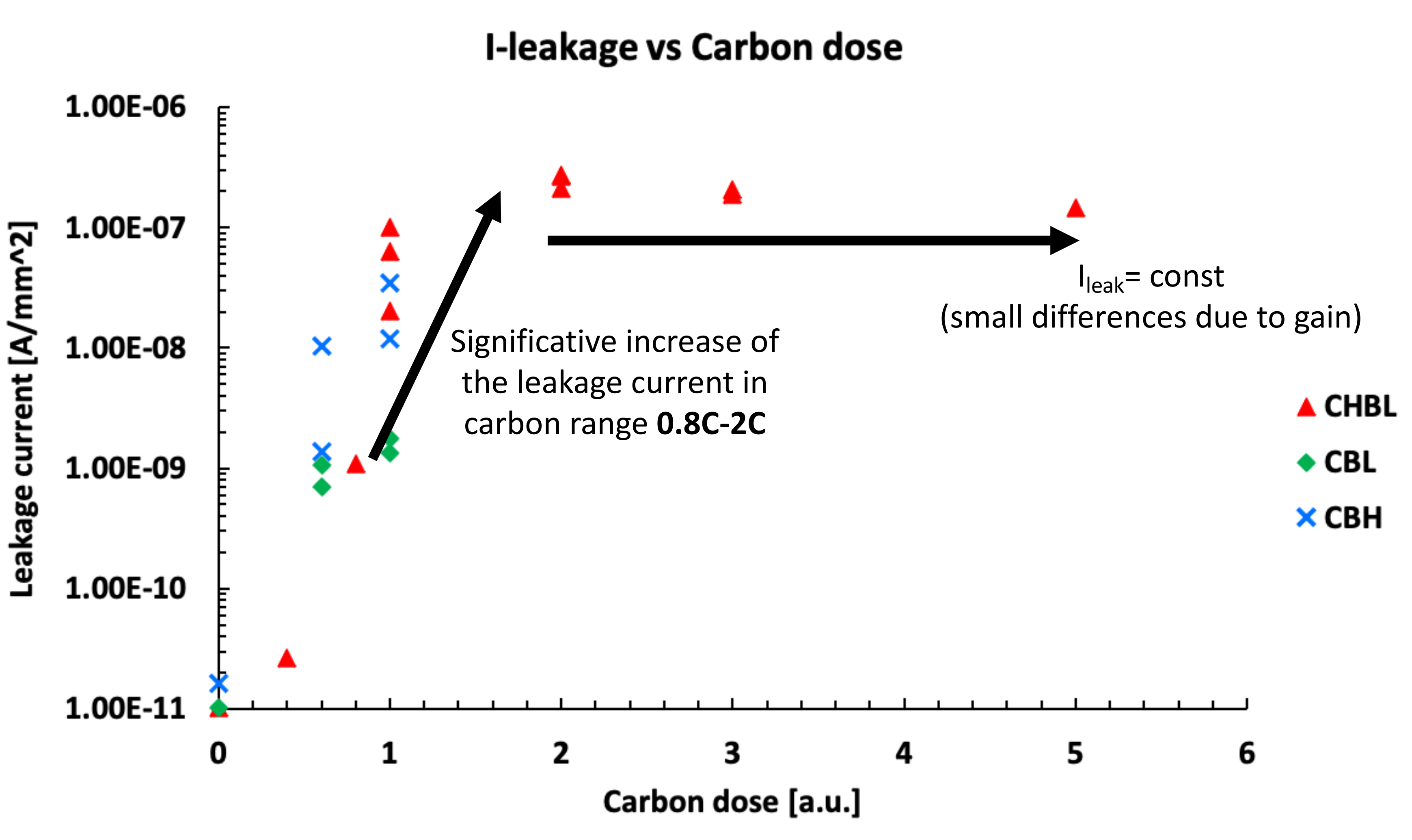
Carbon-Boron (C-B) capture depends by diffusion process

For **CHBL** process:

- C-B capture is a threshold mechanism
- C_{th} = 0.76C (from fit extrapolation)
- Saturation at high carbon doses

C-B capture for **CBL/H** processes is stronger than **CHBL** process

Leakage current in un-irradiated carbonated UFSDs



Irradiation campaign

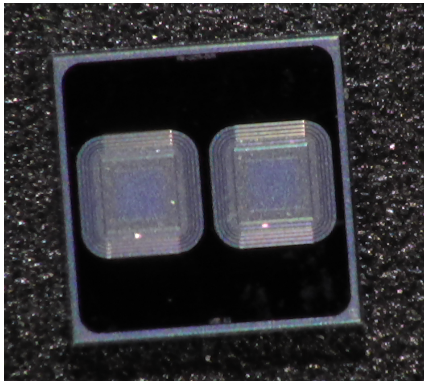
Irradiation campaign with **neutrons** at TRIGA reactor in Ljubjana, **up to fluence 2.5E15 n_{eq}/cm^2**

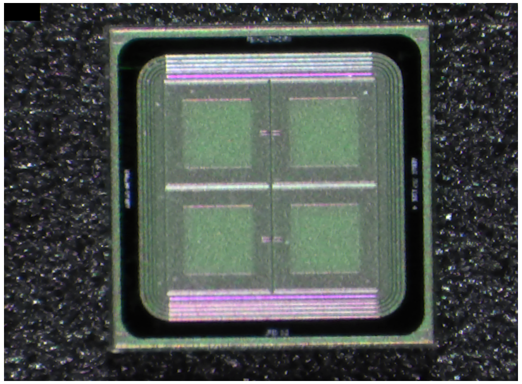
Wafer irradiated:

- 3/4/7 (shallow GL-CHBL);
- 8/10/12/13 (deep GL-CBL);
- 14/18/19 (deep GL-CBH);

Irradiated structures:

- 1 mm^2 single pad (LGAD-PIN couple);
- Array 2x2 (pad size = 1.3x1.3 mm^2)



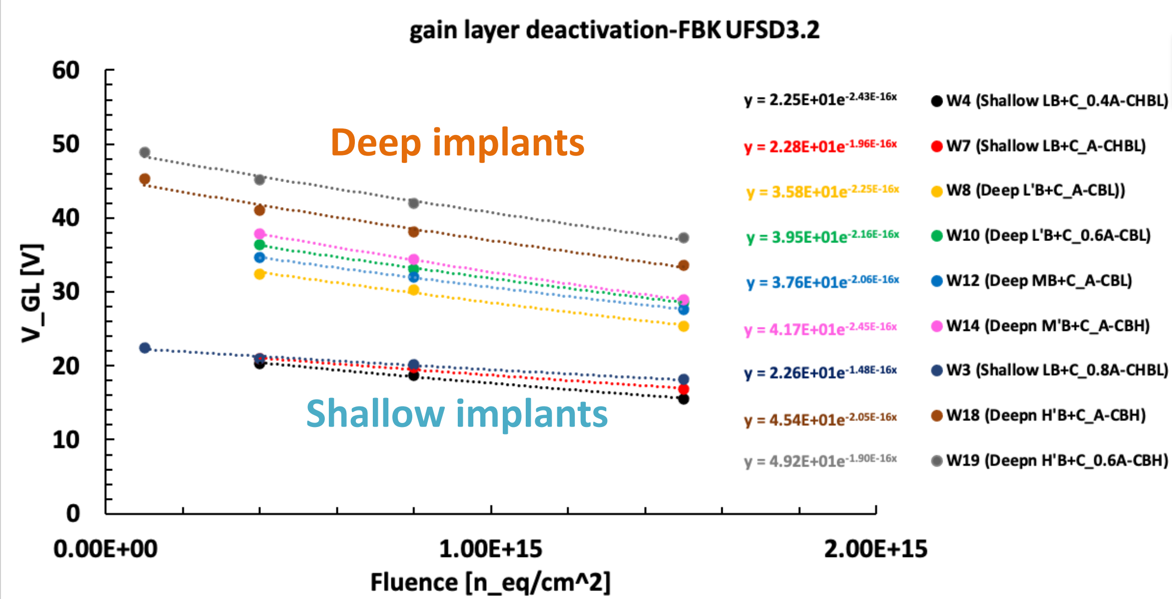


Acceptor removal coefficients in UFSD3.2

Acceptor removal's law

$$V_{GL}(\emptyset) \propto N_B(\emptyset) = N_B(0)e^{-c(N_B)\emptyset} = N_B(0)e^{-\emptyset/\emptyset_0}$$

$^1/_c = \emptyset_0$ = **fluence to which the gain implant concentration is reduced by 1/e**



Wafer	c [10^{-16} cm^2]	$\emptyset_0$ [n_{eq}/cm^2]
3	1.48	$6.76\cdot10^{15}$
4	2.43	$4.12\cdot10^{15}$
7	1.96	$5.10\cdot10^{15}$
8	2.25	$4.44\cdot10^{15}$
10	2.16	$4.63\cdot10^{15}$
12	2.06	$4.85\cdot10^{15}$
13	1.63	$4.13\cdot10^{15}$
14	2.45	$4.08\cdot10^{15}$
18	2.05	$4.88\cdot10^{15}$
19	1.90	$5.26\cdot10^{15}$

More radiation resistant gain implant design

~15% error estimated on c and $\emptyset_0$

UFSD3.2 acceptor removal coefficients in the range **1.5-2.5·10^{-16} cm^2**

Radiation resistance of **Deep-carbonated GL comparable to that of Shallow-carbonated GL;**

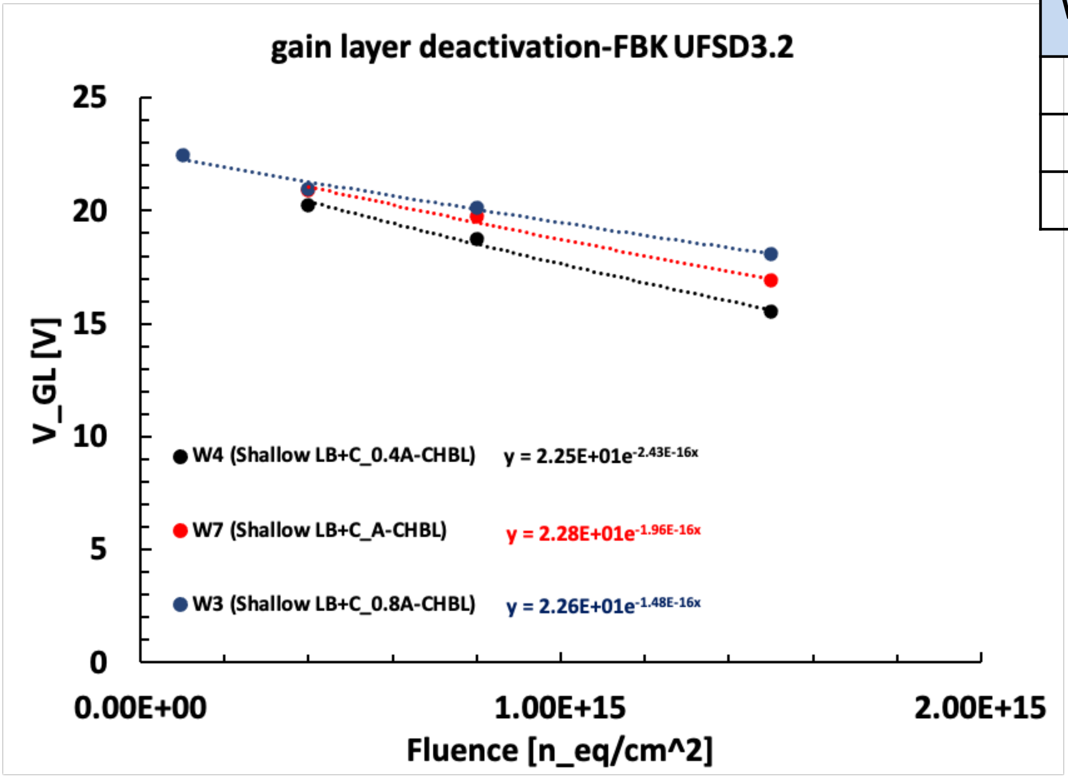
Deep gain implants successfully enriched with carbon

Relationship between C-dose and $c(N_B)$

Acceptor removal's law

$$V_{GL}(\emptyset) \propto N_B(\emptyset) = N_B(0)e^{-c(N_B)\emptyset} = N_B(0)e^{-\emptyset/\emptyset_0}$$

$1/c = \emptyset_0$ **= fluence to which the gain implant concentration is reduced by 1/e**



Wafer	Carbon [a.u.]	c [10^{-16} cm^2]	$\emptyset_0$ [n_{eq}/cm^2]
3	**0.8**	1.48	$6.76\cdot10^{15}$
4	**0.4**	2.43	$4.12\cdot10^{15}$
7	**1**	1.96	$5.10\cdot10^{15}$

~15% error estimated on c and $\emptyset_0$

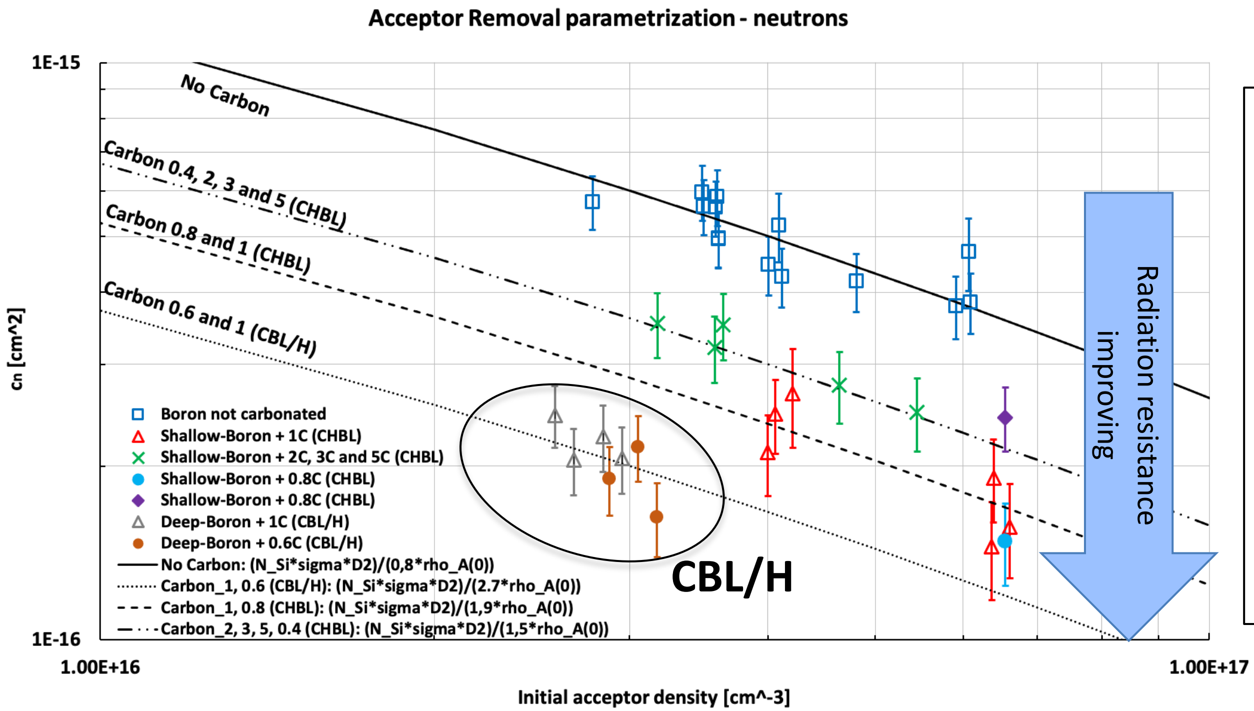
Shallow B + 0.8C more radiation resistance compared to **B + 0.4C/1C**. (Similar result in Deep B + 0.6 and B + 1C)

Is this difference due to carbon-boron capture?

Acceptor removal parametrization

$$c(N_B) = \frac{N_{Si} * \sigma_{Si} * D_2}{k_{param.} * N_B(0)} \qquad D_2 = \frac{k_{cap} * N_{Int}}{1 + \left(\frac{2.5 \cdot 10^{16}}{N_B(0)}\right)^{2/3}}$$

Moving along a parametrization → same intrinsic radiation resistance, acceptor removal differs due to different initial acceptor density
Moving through parametrizations → different intrinsic radiation resistance

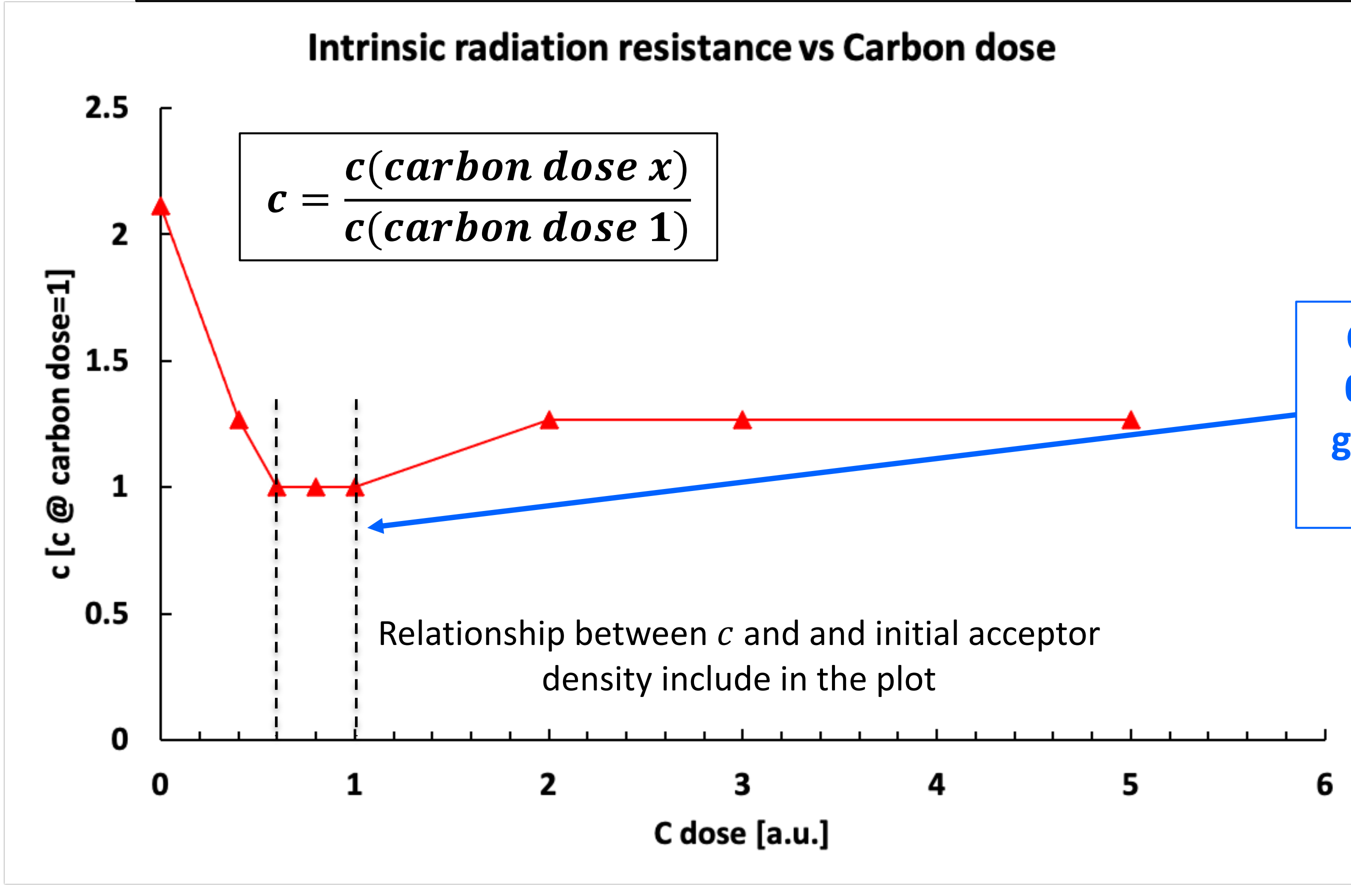


CBL gain implants have a higher intrinsic radiation resistance compared to CHBL ones

Differences in radiation resistance of gain implants carbonated 0.6C, 0.8C and 1C are only due to carbon-boron capture

Relationship between C-dose and $c(N_B)$

Hypothesis:
- **Gain implant B + 0.4C** same intrinsic radiation resistance than **B + 2C/3C/5C**
- **Gain implant B + 0.8C/0.6C** same intrinsic radiation resistance than **B + 1C**

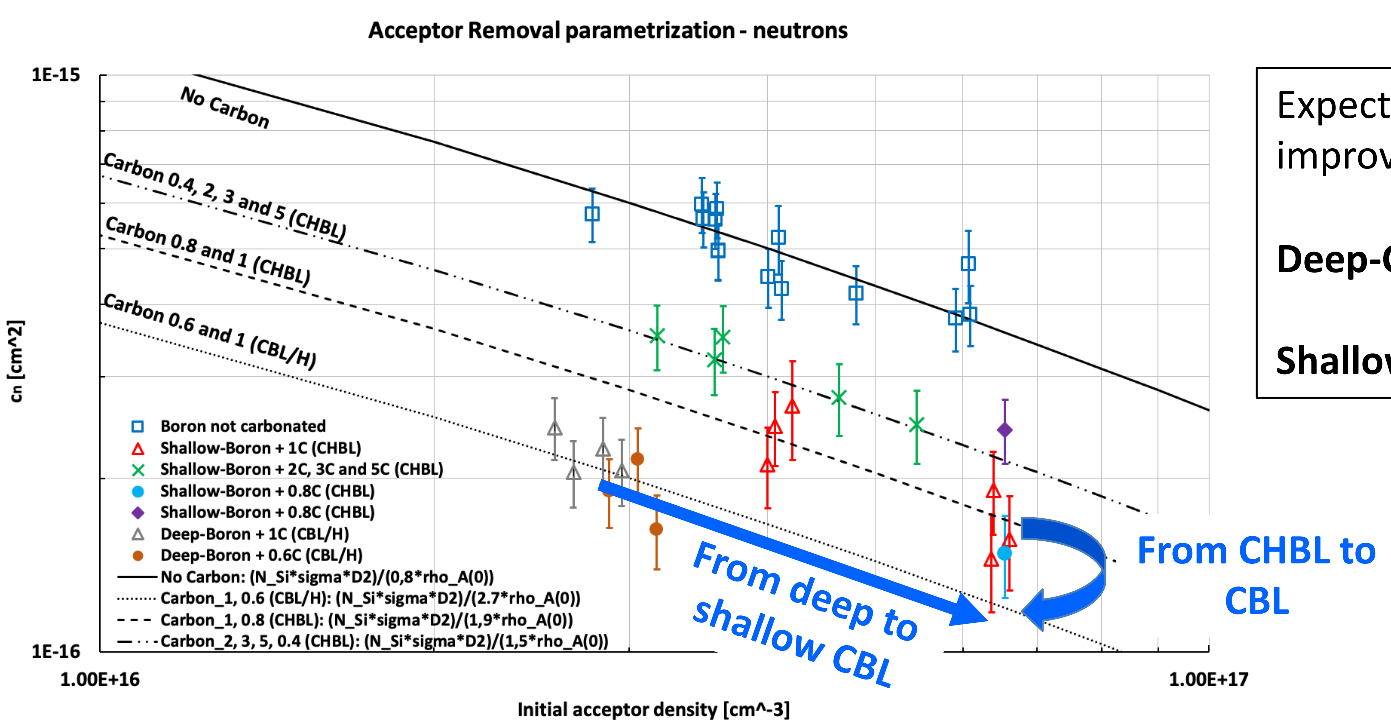


C-dose into the range 0.6C-1C maximize the gain implants radiation resistance

Data from UFSD2, UFSD3 and UFSD3.2 productions

Shallow-CBL gain implant
Next step in radiation resistance improvement

$$c(N_B) = \frac{N_{Si} * \sigma_{Si} * D_2}{k_{param.} * N_B(0)} \qquad D_2 = \frac{k_{cap} * N_{Int}}{1 + \left(\frac{2.5 \cdot 10^{16}}{N_B(0)}\right)^{2/3}}$$



Expected radiation resistance improvement:

Deep-CBL –> Shallow-CBL

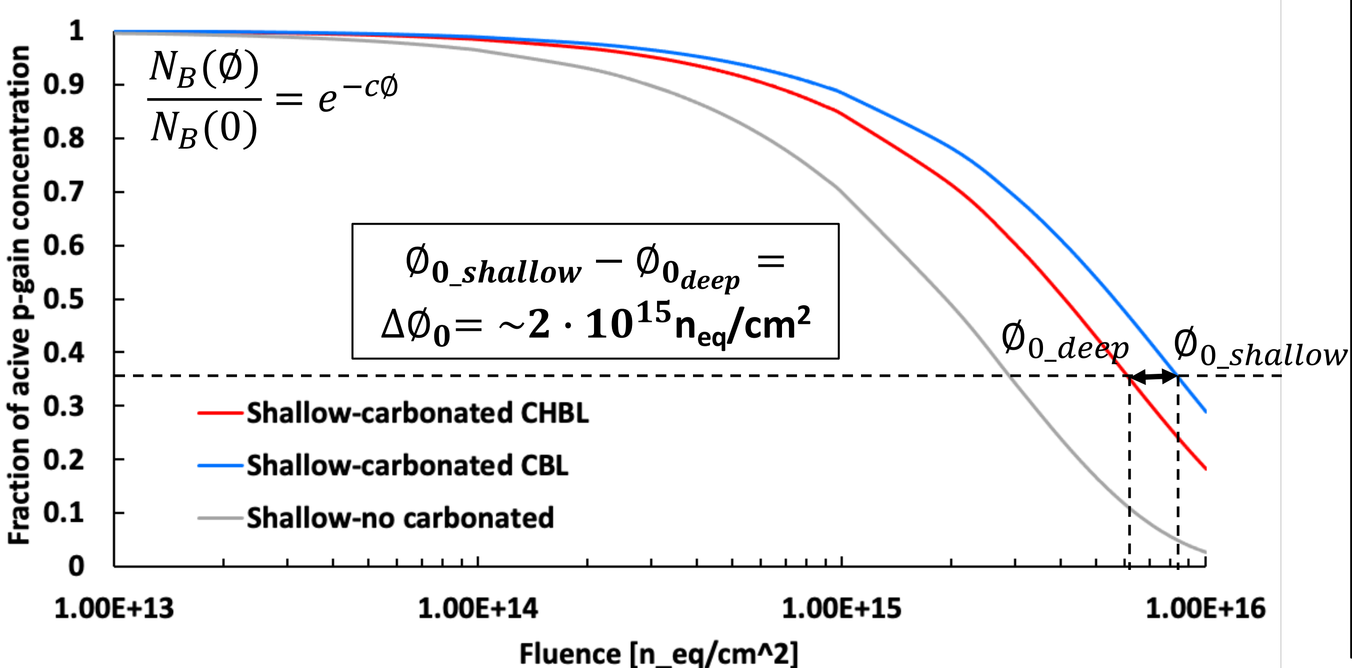
Shallow-CHBL –> Shallow-CBL

Shallow-CBL gain implant
Next step in radiation resistance improvement

Advantages in radiation resistance of a Shallow-CBL gain layer:

- **Higher initial acceptor concentration and narrower gain implant compared to deep implants**
- **Higher intrinsic radiation hardness given by CBL process compared to CHBL process**

Expected acceptor remova difference between Shallow CHBL and CBL gain implants



From Shallow-CHBL to CBL gain implant

$\emptyset_0$ increasing of $\sim 2 \cdot 10^{15} n_{eq}/cm^2$

CBL process should **improves of ~1/3** the acceptor removal coefficient compared to CHBL process

Summary

- Carbon-enrichment of deep implants for the first time
- Acceptor removal coefficients of deep-carbonated gain implants comparable with shallow-carbonated ones; **c in range 1.5-2.5·10^{-16} cm^2**
- **Carbon dose in range 0.6C-1C** maximize the radiation resistance of the gain implants
- Gain layer's radiation resistance depends upon the diffusion process on the gain implant: the intrinsic radiation resistance of CBL/H gain implants is better than CHBL ones
- **Shallow-CBL** is expected to be a factor **1/3 more radiation resistance** than Shallow-CHBL gain layer design,

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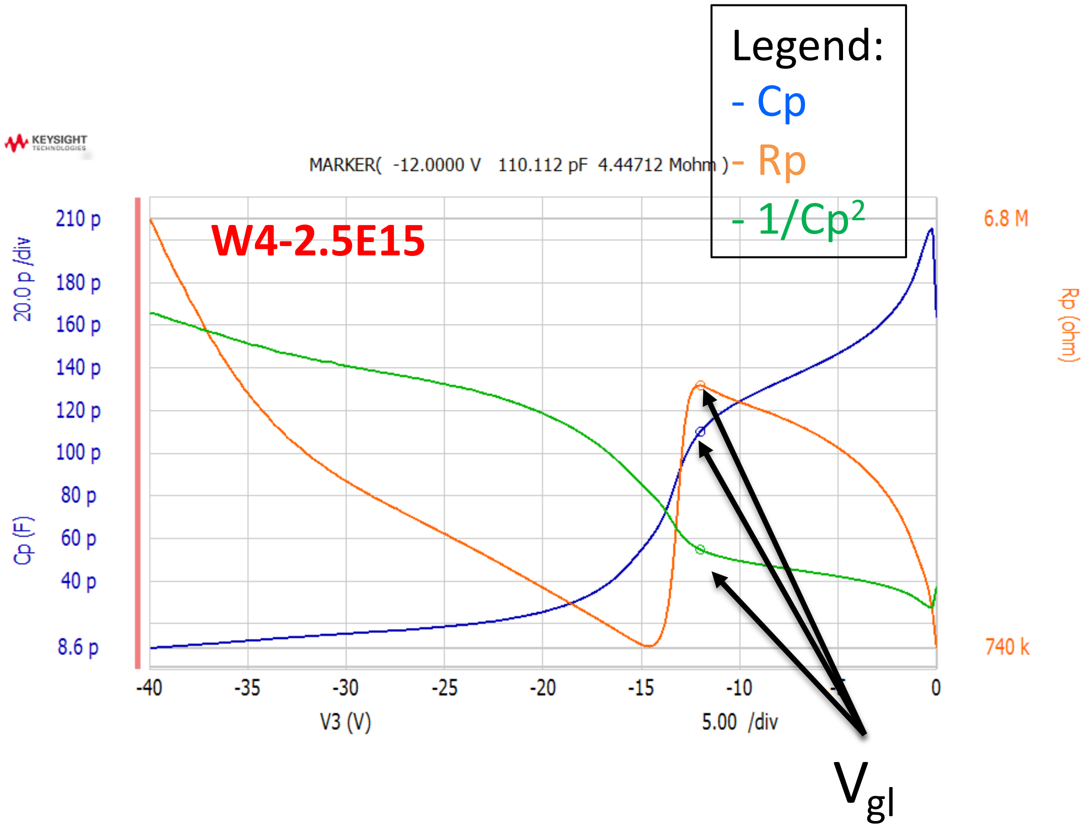
- Progetto FARE, MIUR, R165xr8frt_fare
- Dipartimenti di Eccellenza, Torino Physics Dep. (ex L. 232/2016, art. 1, cc. 314, 337)

Backup

V_GL extraction method



Measurements parameters:

- Cp-Rp model (equivalent to Cs-Rs)
- V-step of 0.2V
- AC signal ~50mV
- Measurements at room Temperature
- Sensors annealed 80min @ 60°
- AC signal frequency from Capacitance-frequency measurements

Good correspondence between the cusp in Rp curve and the slope variation in Cp and 1/Cp curves

Acceptor removal parametrization

$$D_2 = \frac{k_{cap} * N_{Int}}{1 + \left(\frac{2.5 \cdot 10^{16}}{N_B(0)}\right)^{2/3}}$$

$$c(N_B) = \frac{N_{Si} * \sigma_{Si} * D_2}{k_{param.} * N_B(0)}$$

N_{Si} → Silicon density
σ_{Si} → Cross section
k_{cap} → capture coefficient
N_{Int} → Number of defect created
D_2 → density function