16th (Virtual) “Trento” Workshop on Advanced Silicon Radiation Detectors

A summary of the radiation resistance of carbonated gain implants

M. Ferrero, R. Arcidiacono, G. Borghi, M. Boscardin, N. Cartiglia, M. Centis Vignali, M. Costa, G. F. Dalla Betta, F. Ficorella, O. Hammad Ali, M. Mandurrino, L. Menzio, M. Milanesio, L. Pancheri, G. Paternoster, F. Siviero, V. Sola, M. Tornago

Outline

- Overview on carbonated wafers in FBK-UFSD productions (UFSD2, UFSD3 and UFSD3.2)
  Focus on wafer with Deep-carbonated gain implant in UFSD3.2;

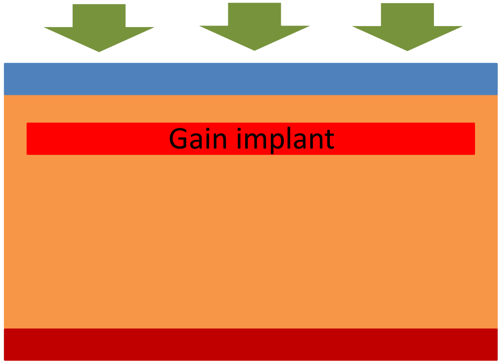
- Carbon effects on un-irradiated UFSDs:
  - Carbon-Boron Inactivation
    Question to expert: "Why in carbonated implant less Boron is activated?";
  - Increase of leakage current:
  - Reduction of the gain implant profile diffusion;

- Comparison between acceptor removal measurements on Shallow- and Deep-carbonated gain implants;

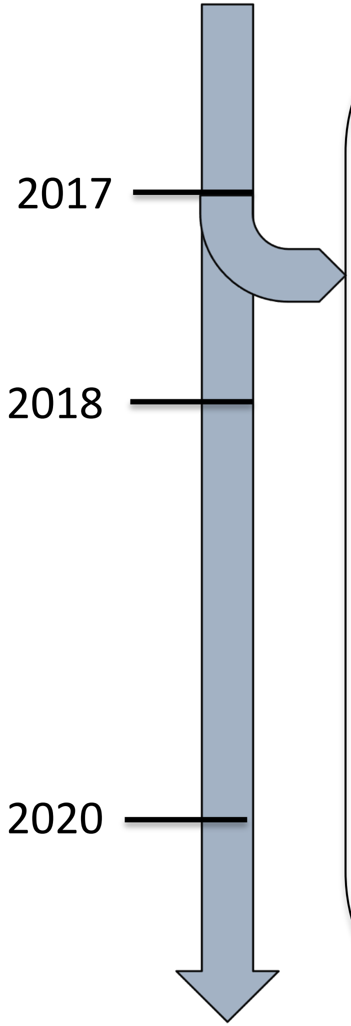
- Optimization of the carbon dose to maximize the radiation resistant of the gain implant;

- Discussion on the more intrinsic radiation resistant gain implant design;

Carbon Implantation



Carbonated gain implants, roadmap at FBK



UFSD2

Shallow-gain implants enriched with **carbon** for the **first time**

Wafer #	Dopant	Gain dose	Carbon	Diffusion
1	Boron	0.98		Low
2	Boron	1.00		Low
3	Boron	1.00		HIGH
4	Boron	1.00	Low	HIGH
5	Boron	1.00	HIGH	HIGH
6	Boron	1.02	Low	HIGH
7	Boron	1.02	HIGH	HIGH
8	Boron	1.02		HIGH
9	Boron	1.02		HIGH
10	Boron	1.04		HIGH
11	Gallium	1.00		Low
12	Gallium	1.00		
13	Gallium	1.04		Low
14	Gallium	1.04		
15	Gallium	1.04	Low	Low
16	Gallium	1.04	HIGH	Low
17	Gallium	1.08		Low
18	Gallium	1.08		

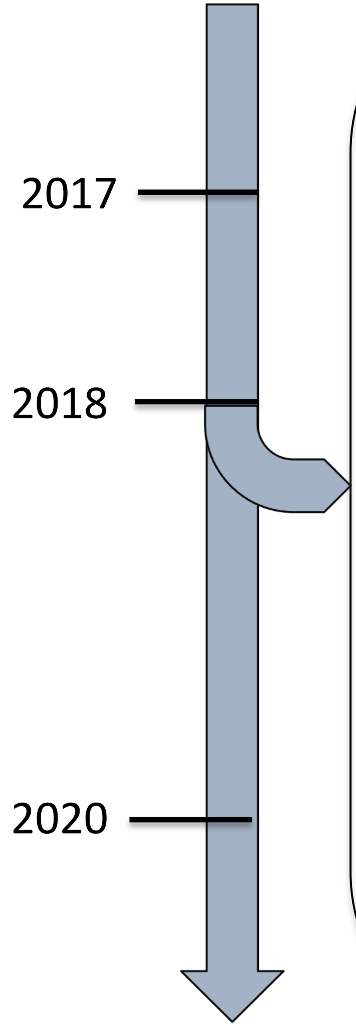
Two carbon doses:

- Low = dose 1 a.u. (reference)
- High = dose 10 a.u.

Production as demonstrator of increased radiation resistant of carbonated gain implants

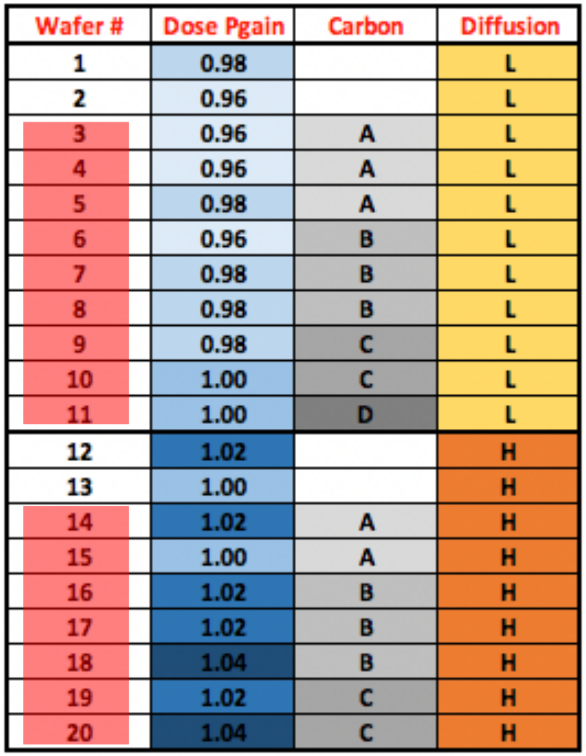
R. Arcidiacono talk at 13th Trento Workshop on Advanced Silicon Radiation Detectors , Munich, 2018

Carbonated gain implants, roadmap at FBK



UFSD3

Shallow-gain implants enriched with four different **carbon doses**



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

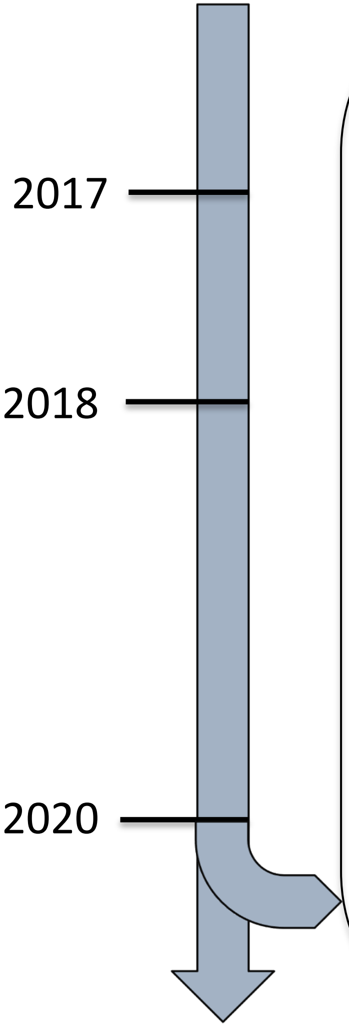
Four carbon doses:

- A = dose 1 a.u. (reference)
- B = dose 2 a.u.
- C = dose 3 a.u.
- D = dose 5 a.u.

Exploration of the effect of different carbon doses on the gain implant radiation resistance

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

Carbonated gain implants, roadmap at FBK



UFSD3.2

Wafer #	thickness	GL DEPTH	Dose Pgain	Carbon	Diffusion
1	45		L	1*A	CHBL
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
3	45	Shallow	L	0.8*A	L
4	45		L	0.4*A	L
[redacted]	[redacted]	[redacted]	[redacted]	[redacted]	[redacted]
7	55		L	1*A	L
8	45	Deep	L’	1*A	CBL
9	55		L’	1*A	L
10	45		L’	0.6*A	L
11	45		L’		L
12	45		M’	1*A	L
13	45		M’	0.6*A	L
14	45		M’	1*A	CBH
15	55		M’	1*A	H
16	45		M’	0.6*A	H
17	45		M’		H
18	45		H’	1*A	H
19	45		H’	0.6*A	H

Gain recovery capability of V_{bias} is stronger in deep implant than in shallow one

Two gain layer designs:

- Shallow-carbonated (standard)
- Deep-carbonated (**carbon infusion in deep implant for the first time)**

Four carbon doses:

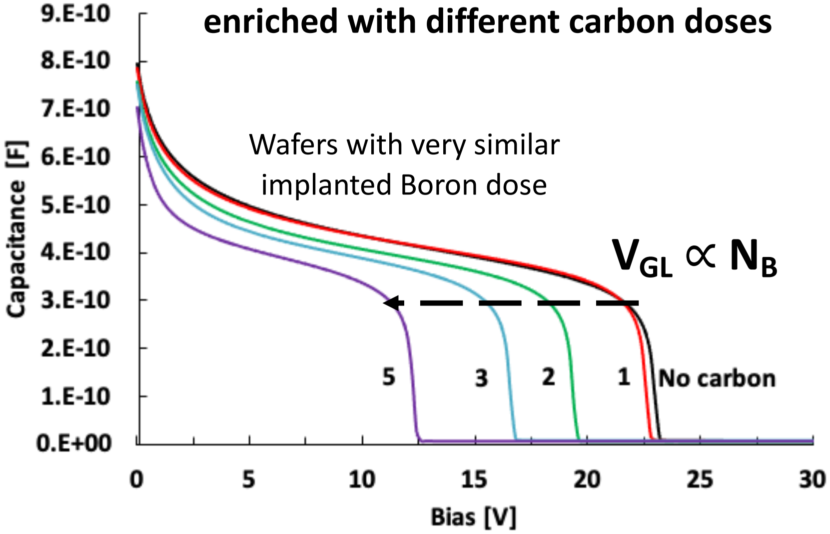
- **0.4, 0.8** and **1** a.u. co-implanted in shallow implant;
- Dose **0.6** and **1** a.u. co-implanted in deep implant

Two different Carbon-Boron implantation and diffusion schemes:

- **CHBL** = Carbon Implantation and diffusion + Boron implantation and diffusion (shallow Implants)
- **CBL/CBH =** Carbon and Boron Implantation and diffusion (deep implants)

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

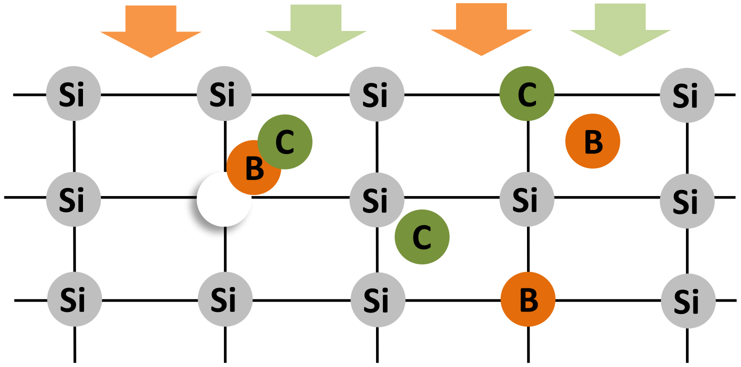
C(V) of un-irradiated UFSD3 sensors, enriched with different carbon doses



Depletion voltage of the gain layer (V_{GL}) used as parameter to show the inactivation of the active boron concentration (N_B)

Carbon-Born inactivation observed in UFSD2, UFSD3 and UFSD3.2 productions

Carbon and Boron implantation



Two possible mechanisms cause Carbon-Boron Inactivation

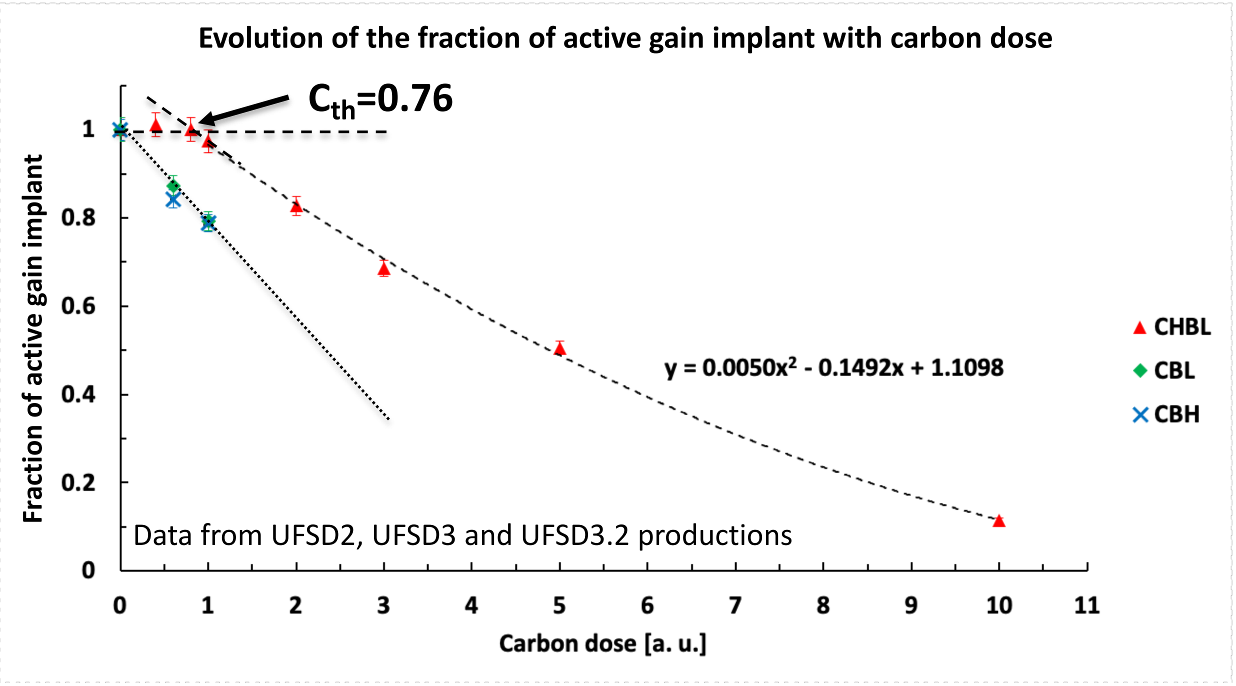
$$\begin{tikzcd} & SiC_s + B_i \\ Si + B + C \arrow[ur] \arrow[dr] & \\ & Si + B_iC_i \end{tikzcd}$$

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

$$\textit{Fraction of active } N_B = \frac{N_B(GL\ carbonted)}{N_B(GL\ not\ carbonated)} = \frac{V_{GL}(GL\ carbonated)}{V_{GL}(GL\ not\ carbonated)}$$

$$V_{GL} \propto N_B$$

V_{GL} extracted from C(V) measurements


Evolution of the fraction of active gain implant with carbon dose

C_{th}=0.76

y = 0.0050x² - 0.1492x + 1.1098

Data from UFSD2, UFSD3 and UFSD3.2 productions

Carbon-Boron Inactivation depends by diffusion process

CHBL process:

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

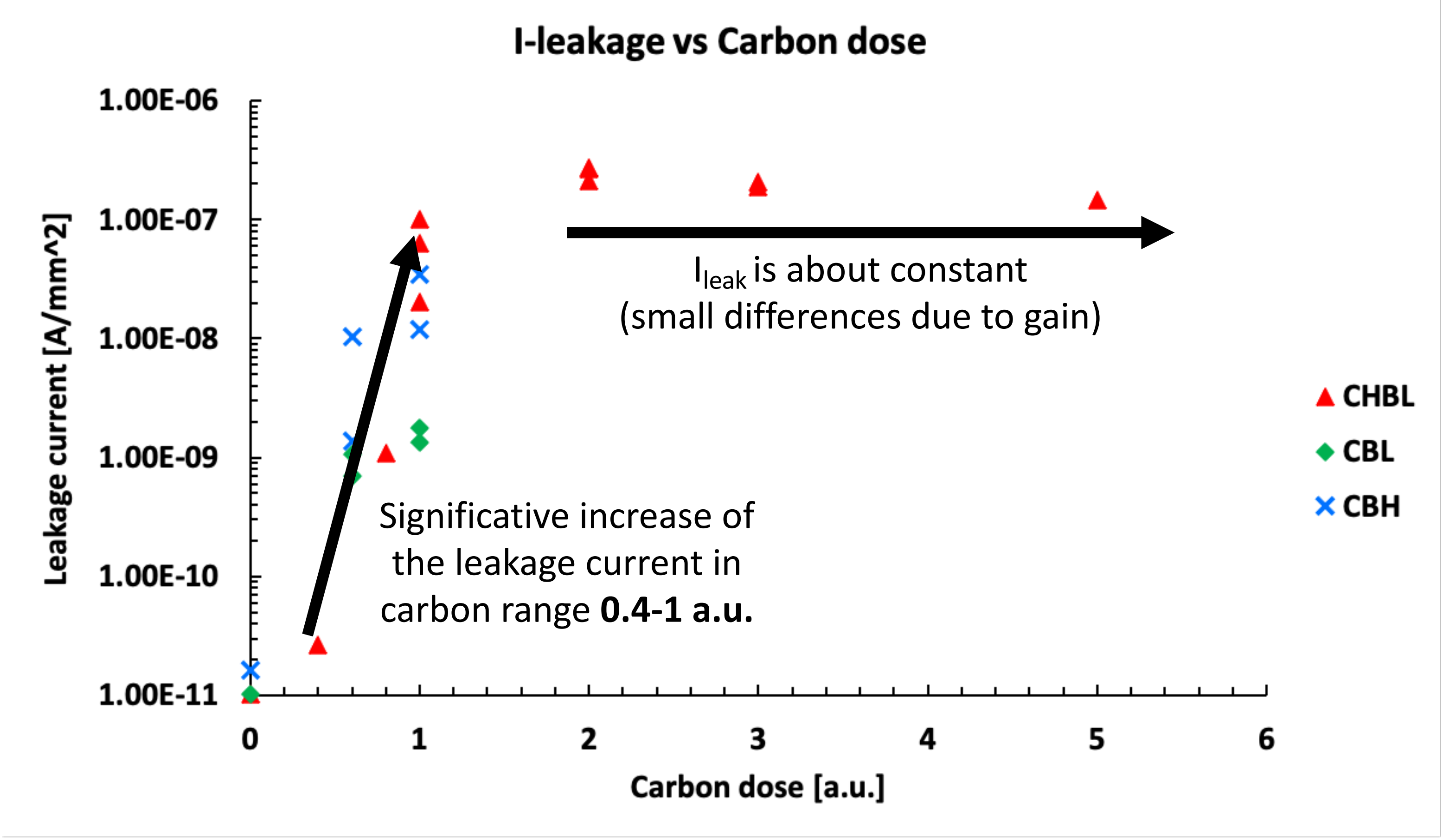
CBL/H processes:

- CBI for **CBL/H** processes is stronger than **CHBL** process
- CBI seems not to be a threshold mechanism

Carbon-Boron Inactivation determines the sensor working bias

Δp-dose of 1% is equivalent to **$\Delta V_{working}$~12V**

Leakage current in un-irradiated carbonated UFSDs



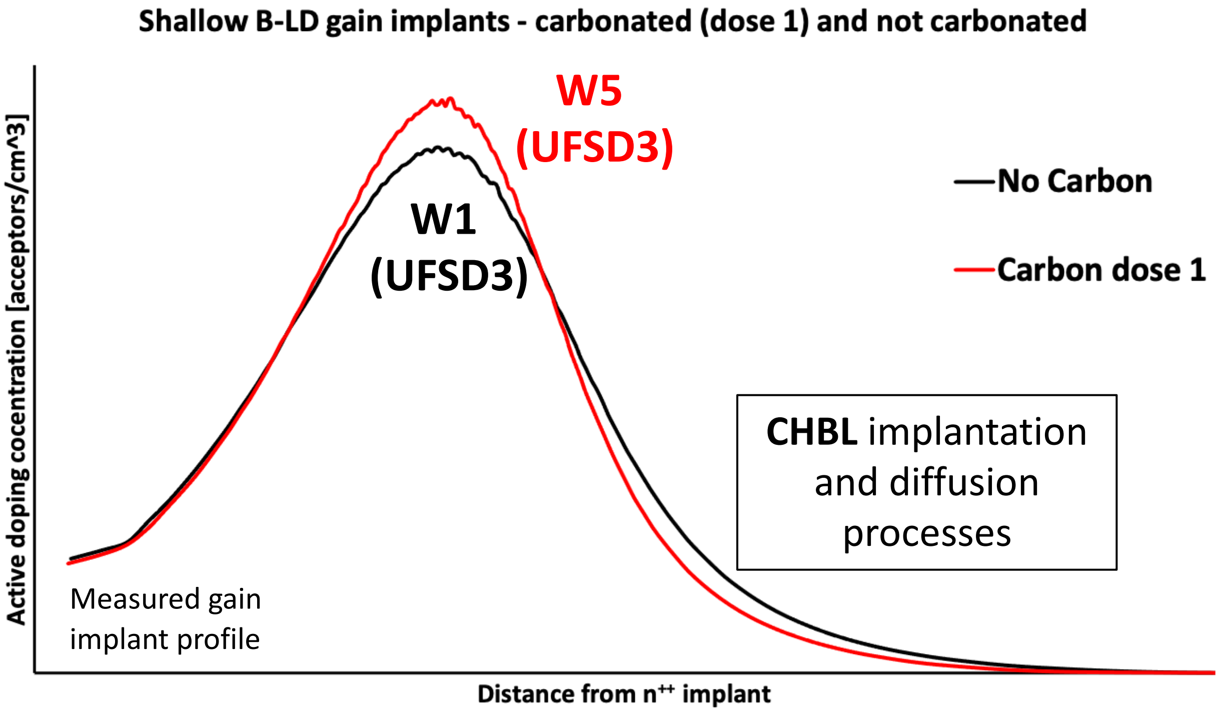
I_{leak} is about constant
(small differences due to gain)

Significative increase of
the leakage current in
carbon range **0.4-1 a.u.**

Higher leakage current in carbonated UFSD does not affect the temporal performances

See F. Siviero's talk,

Gain implant profile - carbonated vs not carbonated



Shallow B-LD gain implants - carbonated (dose 1) and not carbonated

CHBL implantation and diffusion processes

Measured gain implant profile

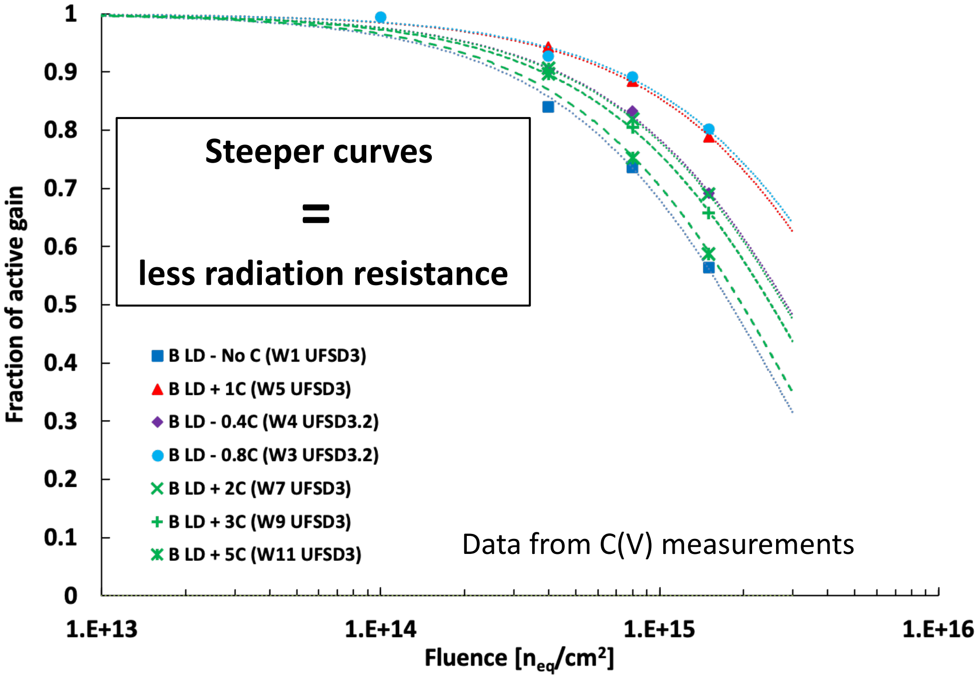
Co-implantation of carbon decreases the diffusion of the gain implant profile

Low-diffused carbonated profile is ~**10% higher** and **narrower** than not carbonated

Acceptor removal coefficients of shallow-carbonated gain implants

Acceptor removal measurements on ∼40 gain layer designs, of which 20 carbonated: (*i*) Shallow and deep gain implant; (*ii*) carbonated and not carbonated; (*iii*) High and low activation thermal load; (*iv*) Different p-dose

Shallow Low Diffused gain implants
CHBL activation scheme



Steeper curves

=

less radiation resistance

Data from C(V) measurements

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-dose [a.u.]	c [10^{-16} cm^2]	$\emptyset_0$ [$10^{15} n_{eq}/cm^2$]
1 (UFSD3)	0	3.9±0.5	2.6±0.2
4 (UFSD3.2)	0.4	2.4±0.3	4.1±0.3
3 (UFSD3.2)	0.8	1.5±0.2	6.8±0.4
5 (UFSD3)	1	1.6±0.3	6.4±0.4
7 (UFSD3)	2	2.5±0.4	4.0±0.3
9 (UFDS3)	3	2.8±0.4	3.6±0.3
11 (UFSD3)	5	3.5±0.5	2.9±0.2

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

Acceptor removal coefficients of shallow-carbonated gain implants

Acceptor removal measurements on ~40 gain layer designs, of which 20 carbonated: (*i*) Shallow and deep gain implant; (*ii*) carbonated and not carbonated; (*iii*) High and low activation thermal load; (*iv*) Different p-dose

Shallow Low Diffused gain implants
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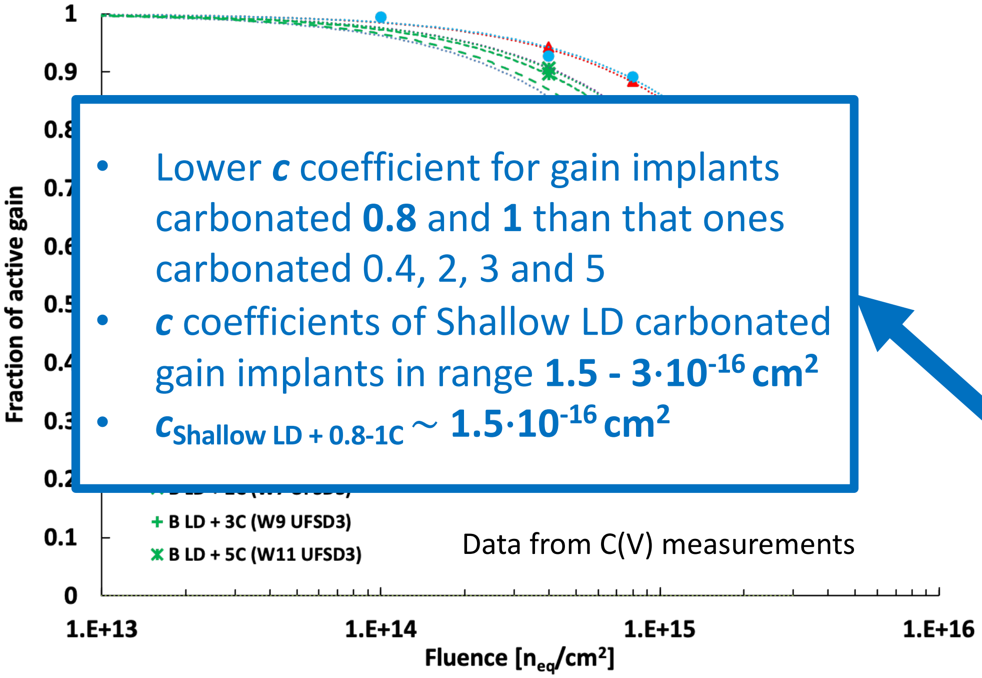

Data from C(V) measurements

- Lower ***c*** coefficient for gain implants carbonated **0.8** and **1** than that ones carbonated 0.4, 2, 3 and 5
- ***c*** coefficients of Shallow LD carbonated gain implants in range **1.5 - 3·10^{-16} cm^2**
- $c_{\text{Shallow LD + 0.8-1C}}$ ~ **1.5·10^{-16} cm^2**

Acceptor removal's law

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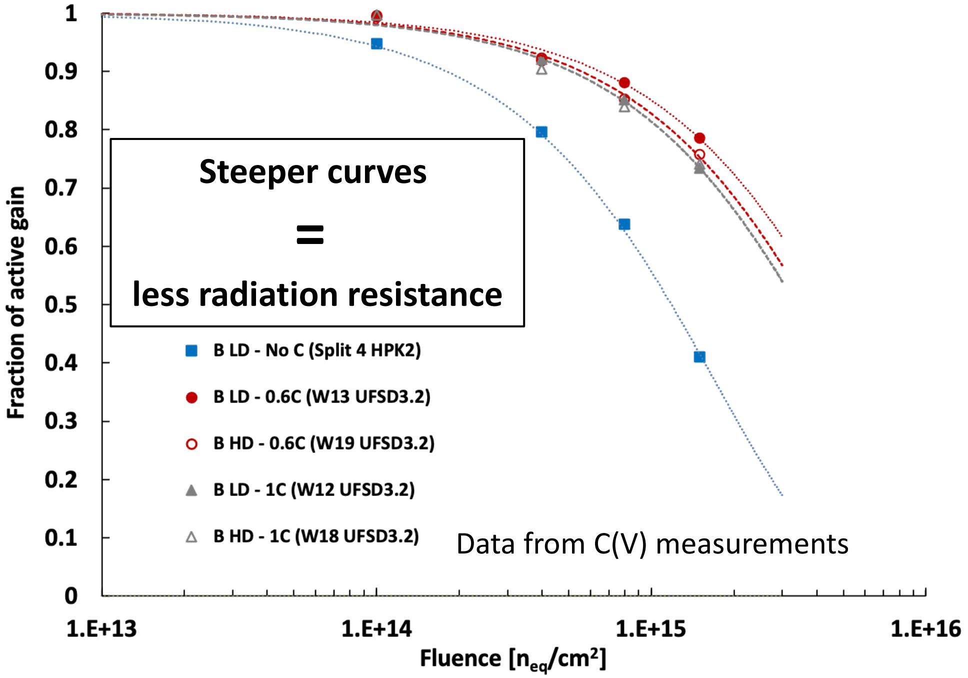
Acceptor removal coefficients of deep-carbonated gain implants

Acceptor removal measurements on ~40 gain layer designs, of which 20 carbonated: (*i*) Shallow and deep gain implant; (*ii*) carbonated and not carbonated; (*iii*) High and low activation thermal load; (*iv*) Different p-dose

Deep Low Diffused gain implants
CBL/H activation scheme



Steeper curves

=

less radiation resistance

Data from C(V) measurements

Acceptor removal's law

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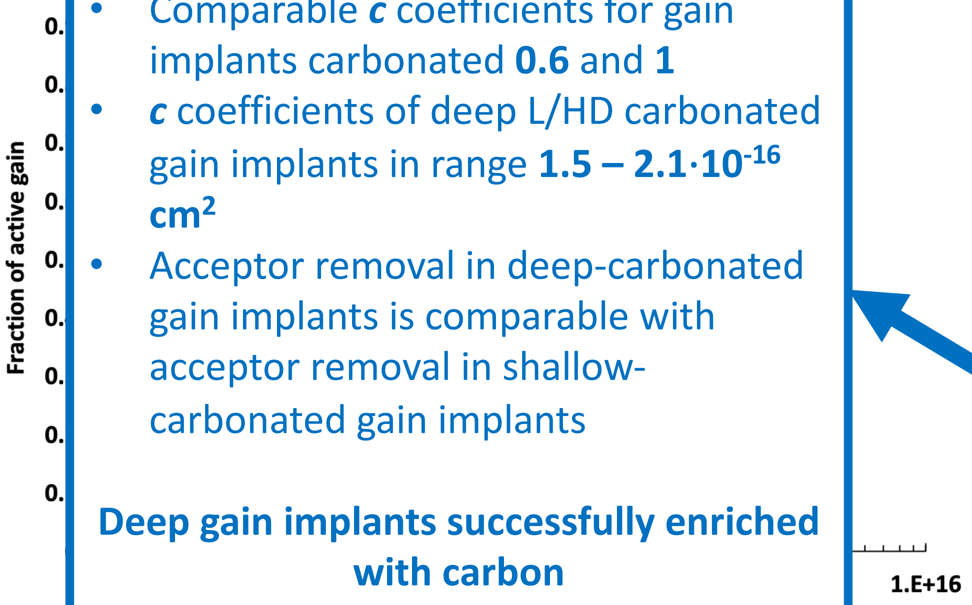
Wafer	C-dose [a.u.]	c [10^{-16} cm^2]	$\emptyset_0$ [$10^{15} n_{eq}/cm^2$]
HPK2 Split4	0	5.6±0.6	1.8±0.2
13 (CBL)	0.6	1.6±0.2	6.1±0.4
19 (CBH)		1.9±0.3	5.3±0.4
12 (CBL)	1	2.1±0.3	4.9±0.4
18 (CBH)		2.1±0.3	4.9±0.4

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

Acceptor removal coefficients of deep-carbonated gain implants

Acceptor removal measurements on ~40 gain layer designs, of which 20 carbonated: (*i*) Shallow and deep gain implant; (*ii*) carbonated and not carbonated; (*iii*) High and low activation thermal load; (*iv*) Different p-dose

Deep Low Diffused gain implants
CBL/H activation scheme



- Comparable ***c*** coefficients for gain implants carbonated **0.6** and **1**
- ***c*** coefficients of deep L/HD carbonated gain implants in range **1.5 – 2.1·10^{-16} cm^2**
- Acceptor removal in deep-carbonated gain implants is comparable with acceptor removal in shallow-carbonated gain implants

Deep gain implants successfully enriched with carbon

Acceptor removal's law

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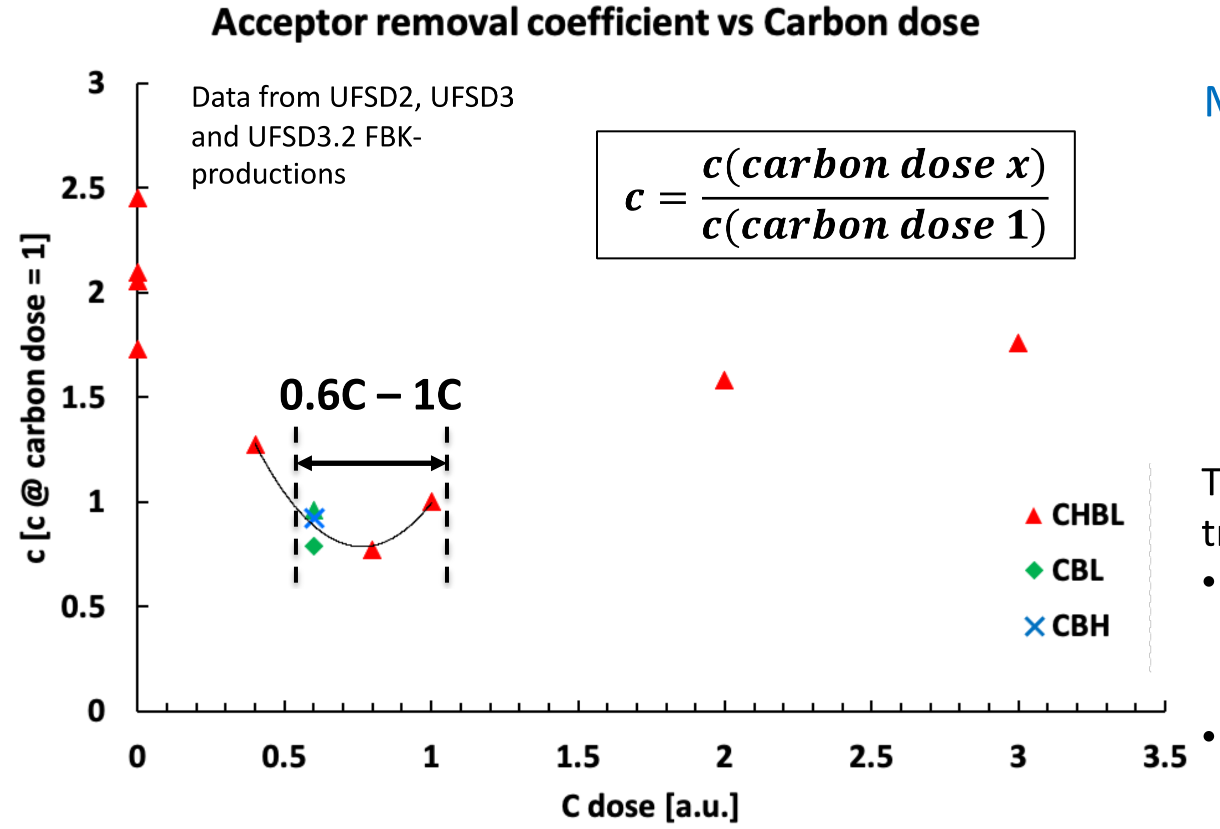
12 (CBL)	1	2.1±0.3	4.9±0.4
18 (CBH)		2.1±0.3	4.9±0.4

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

Minimization of the *c* coefficient - relationship between *c* and C-dose



$$c = \frac{c(carbon\ dose\ x)}{c(carbon\ dose\ 1)}$$

Minimum of the acceptor removal coefficient (maximum of the radiation resistance) in the **carbon range 0.6 - 1 a.u.**

Two factor determine the ***c*(C-dose)** trend:

- The relationship between the acceptor removal coefficient and the initial acceptor density;
- The intrinsic radiation resistant of a gain implant design

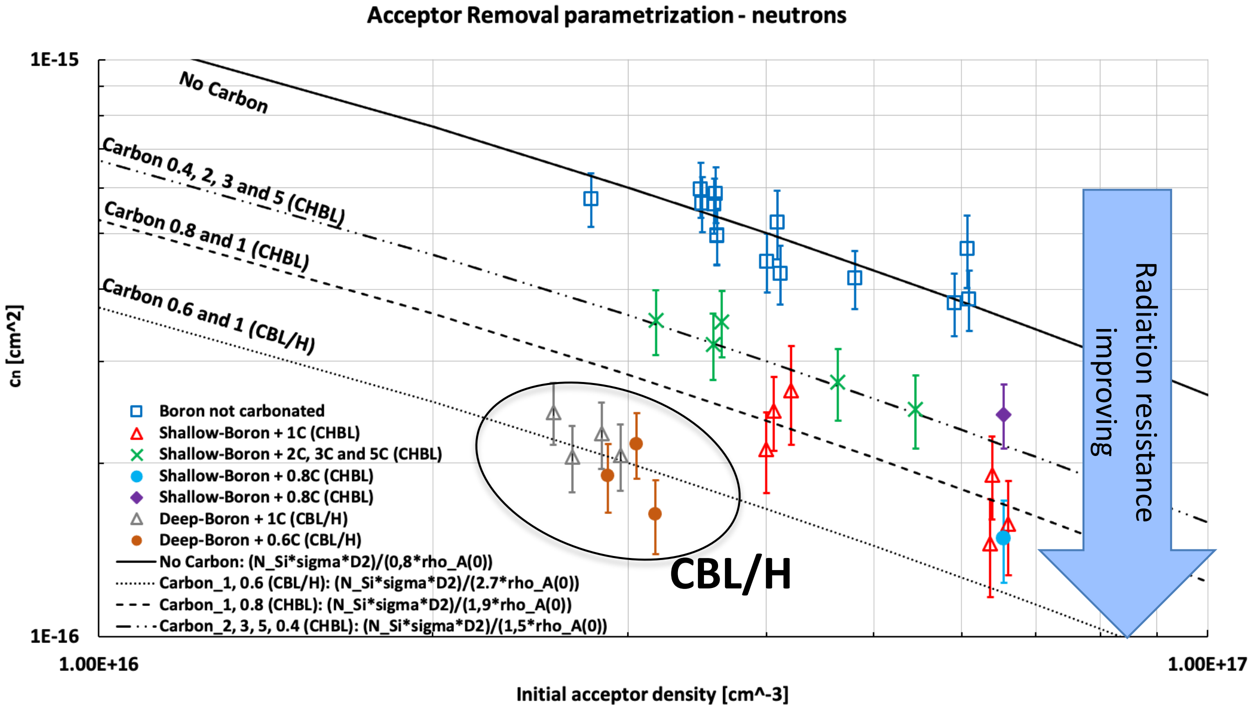
Acceptor removal parametrization

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

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

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/H 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 inactivation

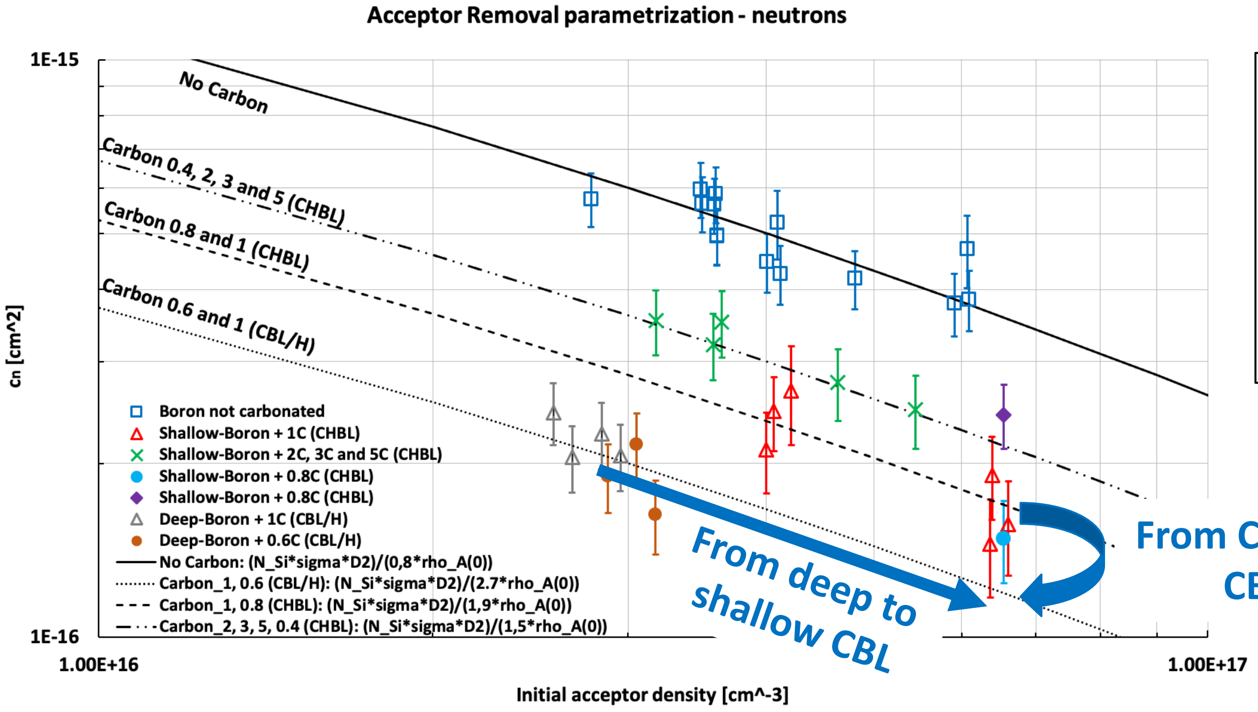
Shallow-CBL gain implant
Next step in radiation resistance improvement

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

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

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

Moving through parametrizations → different intrinsic radiation resistance



From deep to shallow CBL

From CHBL to CBL

Expected radiation resistance improvement:

Deep-CBL –> Shallow-CBL

Shallow-CHBL –> Shallow-CBL

Shallow-CBL gain implant
Next step in radiation resistance improvement

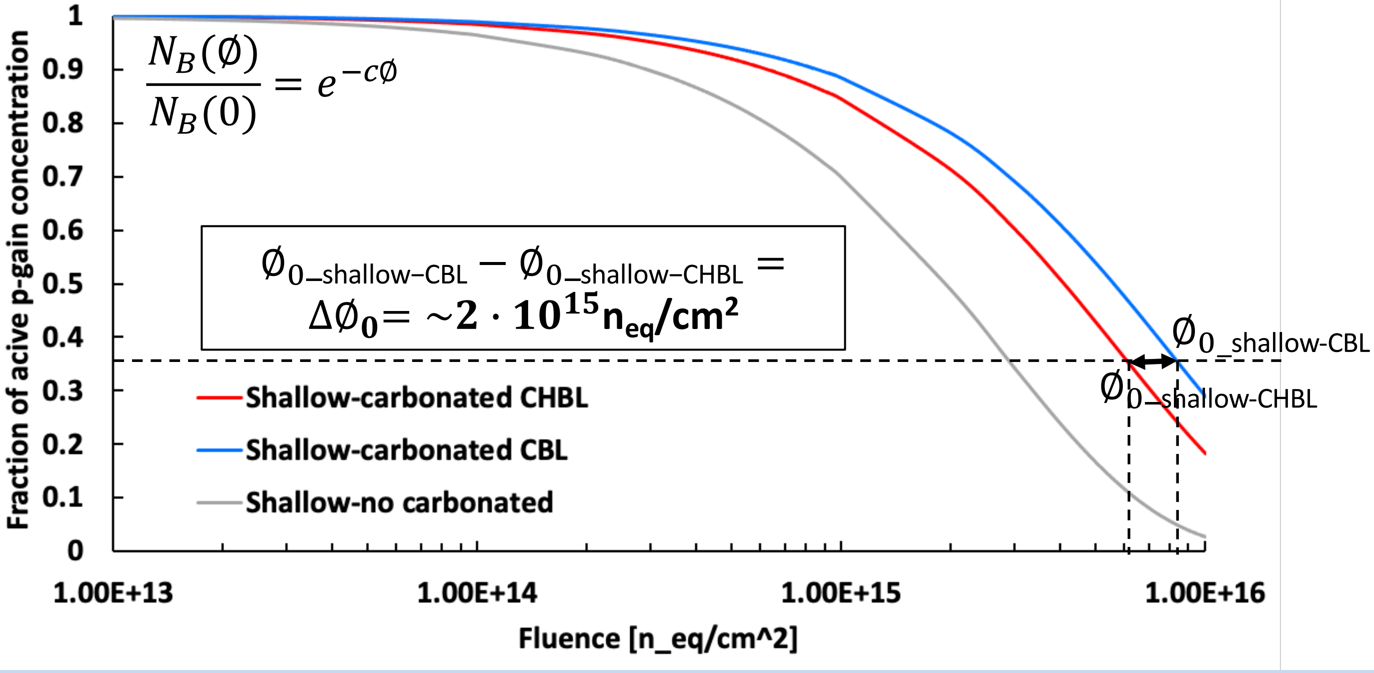
Advantages in radiation resistance of a Shallow-CBL gain layer:

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

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

- **Worst gain recovery than deep-gain implant, using external bias**

Expected acceptor removal difference between Shallow CHBL and CBL gain implants



$$\frac{N_B(\emptyset)}{N_B(0)} = e^{-c\emptyset}$$

$$\boxed{\begin{gathered}\emptyset_{0-\text{shallow-CBL}} - \emptyset_{0-\text{shallow-CHBL}} = \\ \Delta\emptyset_0 = \sim 2 \cdot 10^{15} \mathrm{n_{eq}/cm^2}\end{gathered}}$$

From Shallow-CHBL to CBL gain implant

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

CBL process should **improves of ~30%** the acceptor removal coefficient compared to CHBL process

Summary

- Carbon-enrichment of deep implants for the first time in FBK-UFSD3.2 production

- **Leakage current increase** and **Carbon-Boron Inactivation (CBI)** have been mapped at different carbon doses, in un-irradiated UFSDs with deep and shallow-gain implants:
  - CBI is stronger in deep-carbonated implants

- Acceptor removal coefficients of deep-carbonated gain implants are comparable with shallow-carbonated ones:
  - Carbon-enrichment of deep implants was successful
  - **c in range $1.5\text{-}2.1\cdot10^{-16}$ cm^2**

- **Carbon dose in range 0.6C-1 a.u.** maximizes the radiation resistance of deep- and shallow-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 **30% more radiation resistance** than Shallow-CHBL gain layer design,

Acknowledgements

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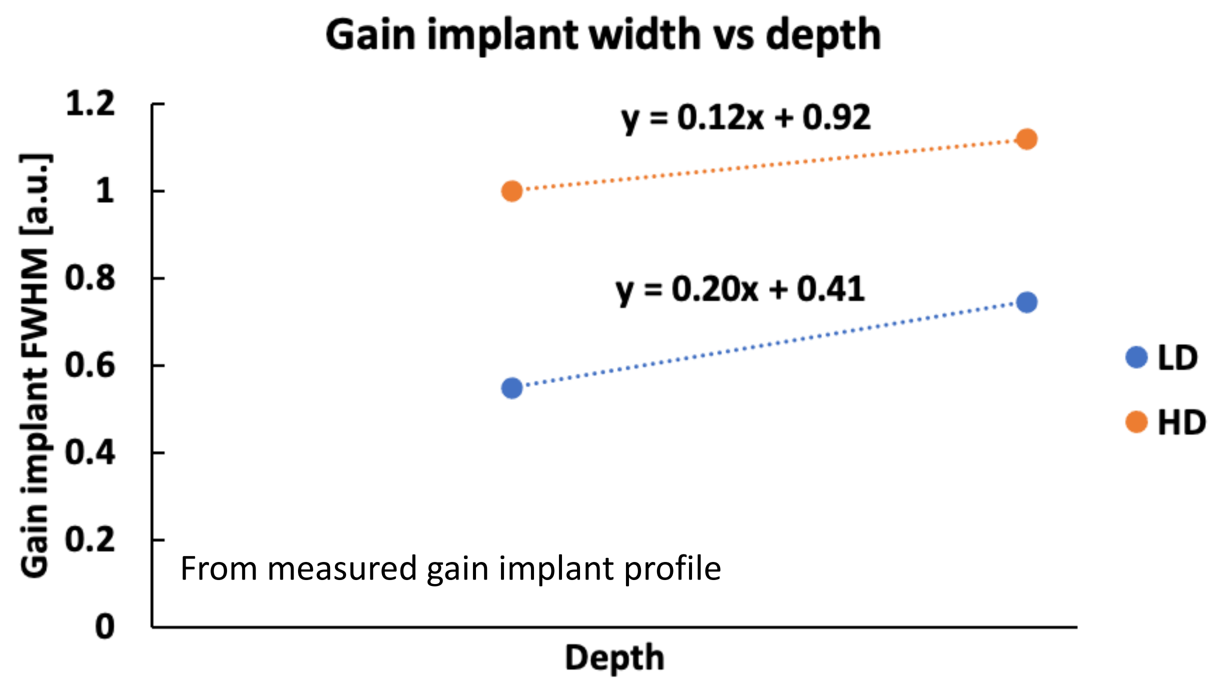
- Progetto FARE, MIUR, R165xr8frt_fare
- Dipartimenti di Eccellenza, Torino Physics Dep. (ex L. 232/2016, art. 1, cc. 314, 337)

Backup

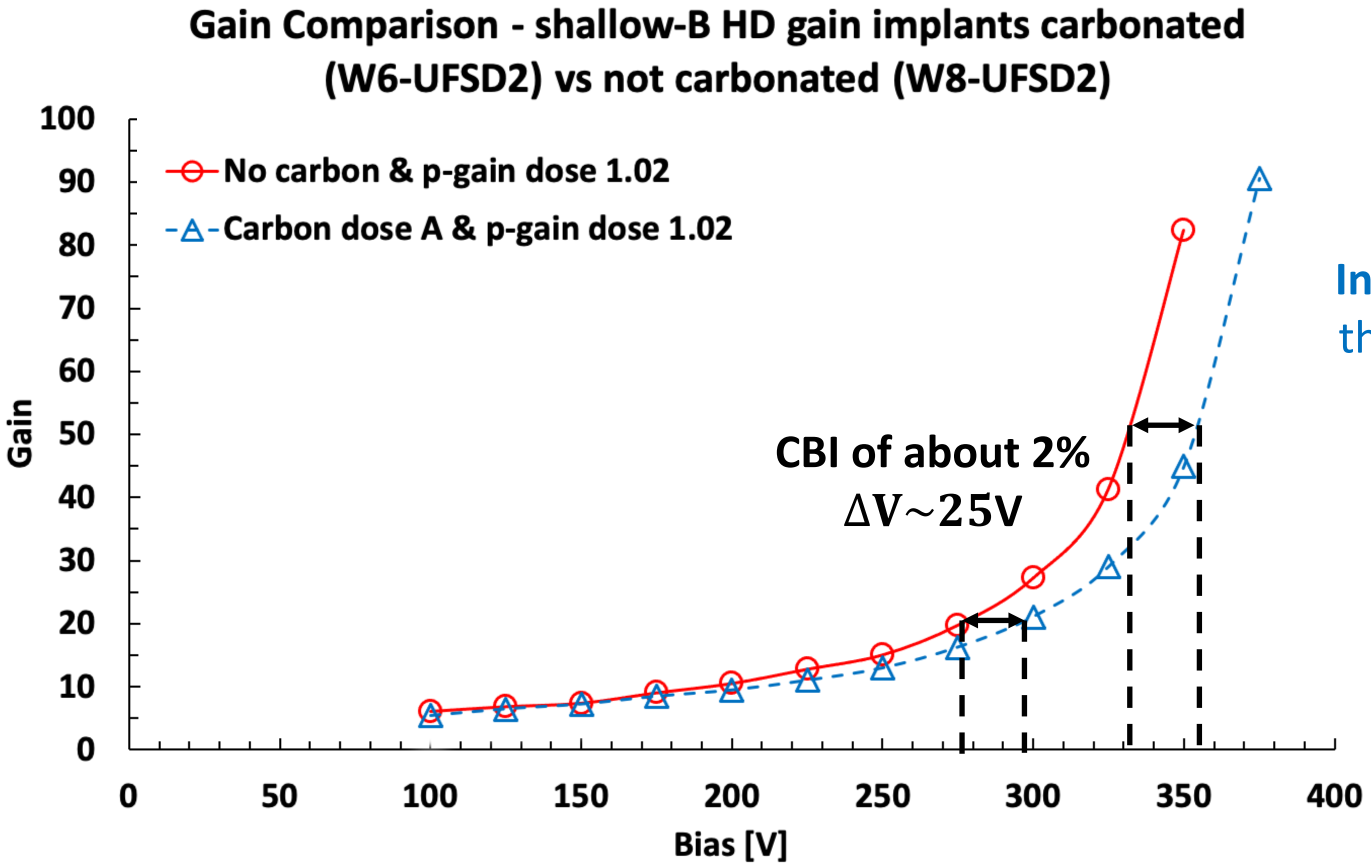
Deep and shallow gain implant width



Implant width as a function of the depth (energy) of implantation

Deep implants are wider than shallow ones

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


Gain Comparison - shallow-B HD gain implants carbonated (W6-UFSD2) vs not carbonated (W8-UFSD2)

CBI of about 2%
$\Delta \mathbf{V} \sim \mathbf{25V}$

Carbon-Boron Inactivation determines the sensor working bias

Δp-dose of 1%
is equivalent to
$\Delta \mathbf{V}_{\mathbf{working}} \sim \mathbf{12V}$

Irradiation campaigns with neutrons

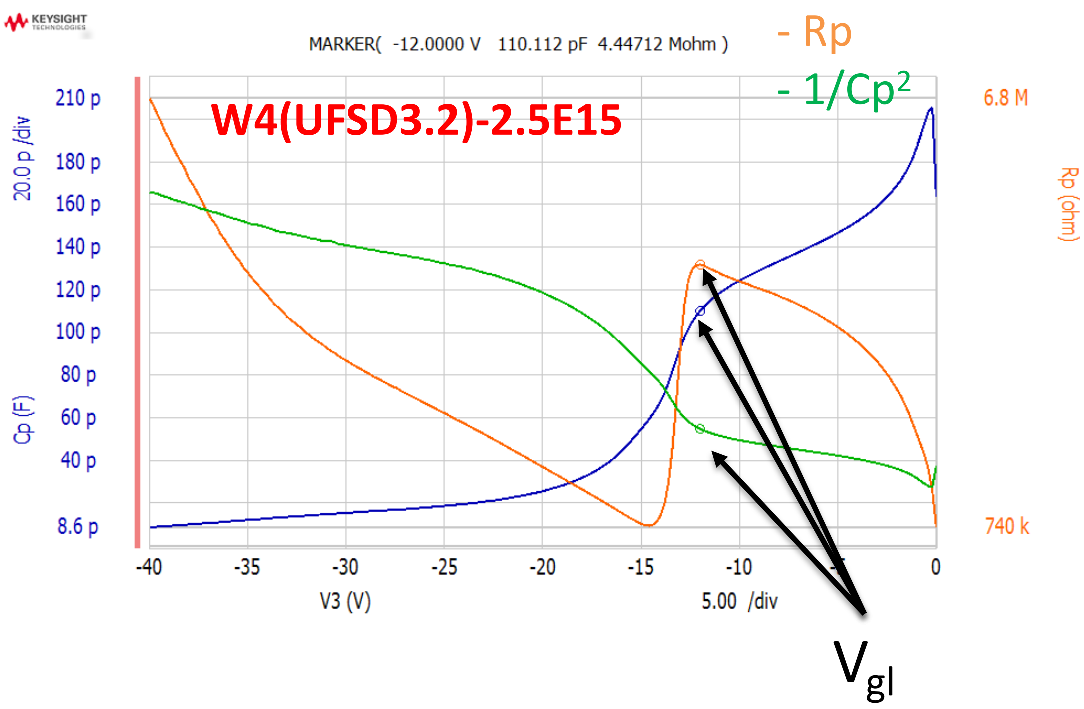
Irradiation campaign with **neutrons** at TRIGA reactor in Ljubjana

FBK production	Wafer	Fluence [10^{14} n_{eq}/cm^2]
UFSD2	1, 6, 8, 14, 15, 18	2, 4, 8, 15, 30
UFSD3	1, 4, 5, 7, 9, 11, 12, 13, 14, 15, 18, 20	1, 4, 8, 15
UFSD3.2	3, 4, 7, 8, 10, 12, 13, 14, 18, 19	1, 4, 8, 15, 25

Each irradiated sensor has been annealed 80 min @ 60℃**,**
before testing

V_GL extraction method

Legend:
- Cp
- Rp
- $1/Cp^2$



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

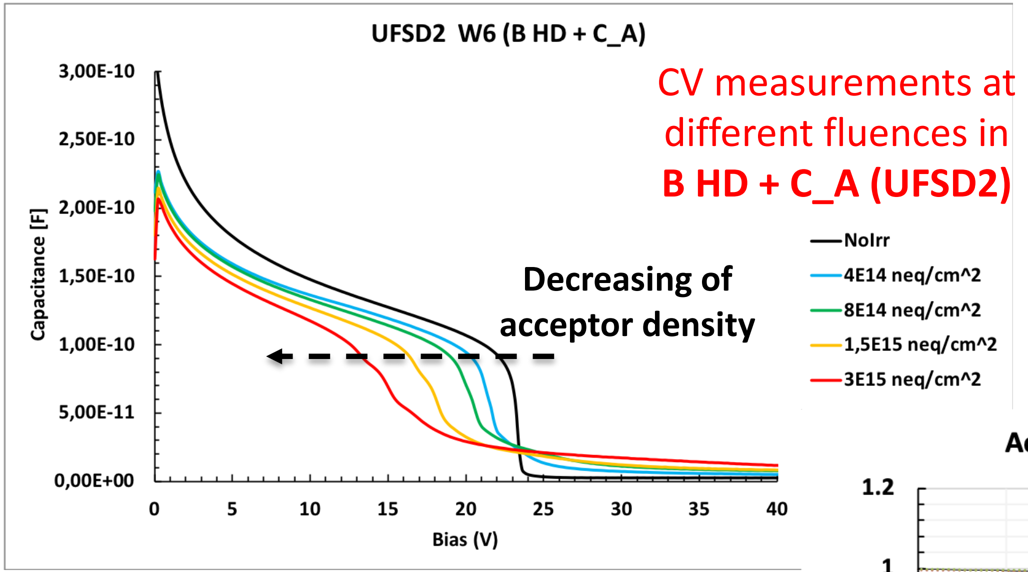
Depletion voltage of the gain layer (**V_{GL}**) proportional to the active acceptor density of the gain implant

$$\mathbf{V_{GL} \propto N_B}$$

C(V) measurement 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

CV on irradiated UFSDs



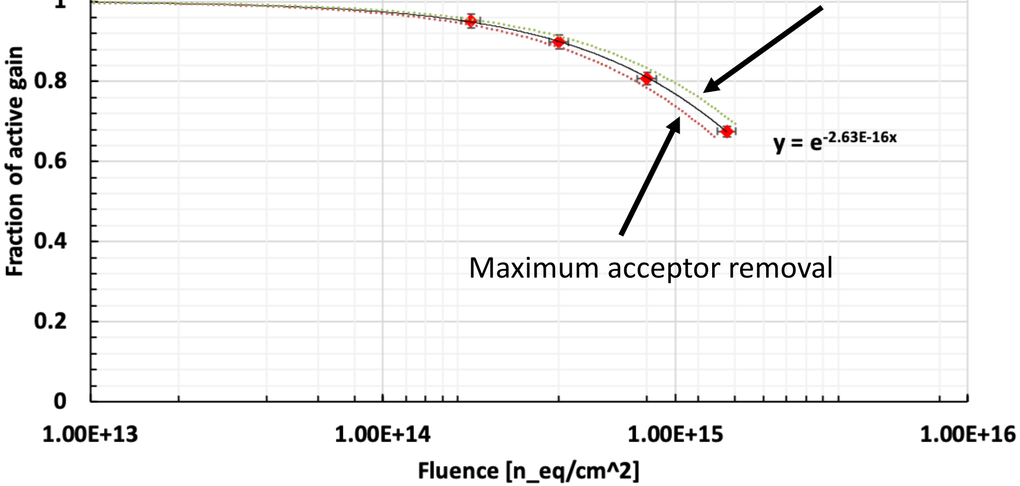
CV measurements at different fluences in **B HD + C_A (UFSD2)**

Decreasing of acceptor density

$$\textbf{\textit{Fraction of active gain}} = \frac{N_B(\phi)}{N_B(0)} = \frac{V_{GL}(\phi)}{V_{GL}(0)}$$

Acceptor Removal B HD+C_A-UFSD2 (W6) - Neutron

Minimum acceptor removal



Maximum acceptor removal

Minimum and maximum acceptor removal curves take into consideration the uncertainty of p-dose on the wafer and of irradiation

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