

Characterization of FBK carbonated gain implants in Ultra Fast Silicon Detectors (UFSD) pre- and post-irradiation

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Outline

- Low gain avalanche Diode:
 - Gain layer designs (deep- and shallow-carbonated gain implants)
 - Effect of irradiation on the gain implant
- Effect of carbon on not-irradiated UFSDs
 - Carbon-Boron Inactivation
 - Leakage Current increase
- Acceptor removal in carbonated gain implants and optimization of the carbon dose to maximize its radiation resistance
- Beta measurements pre- and post-irradiation:
 - Charge collection
 - Time resolution

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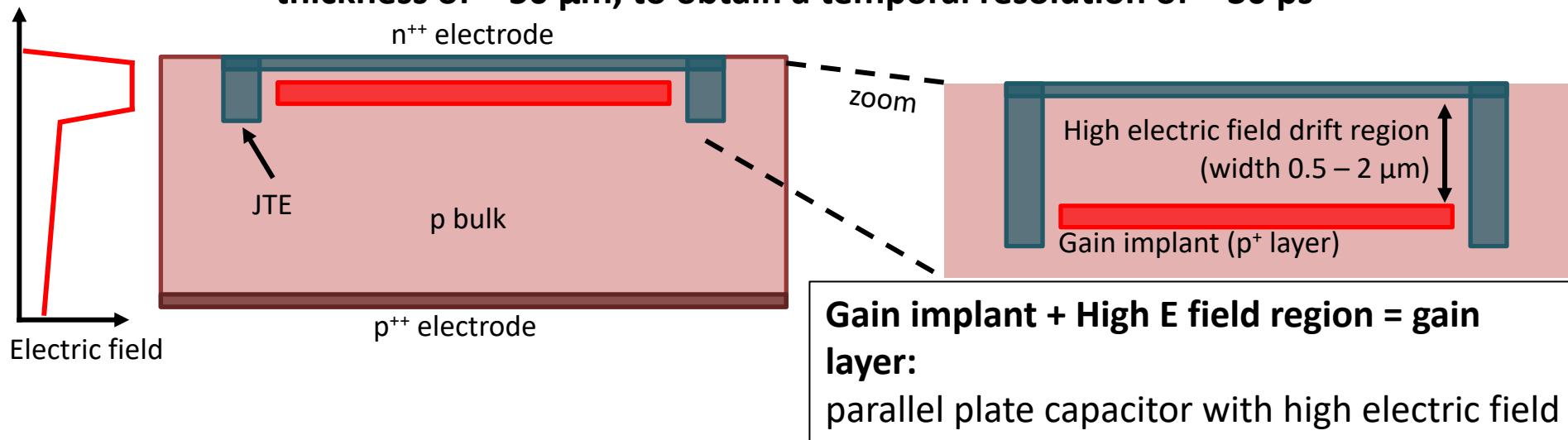
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Low Gain Avalanche Diode (LGAD)

Silicon sensor with an internal moderate gain (10 - 50)

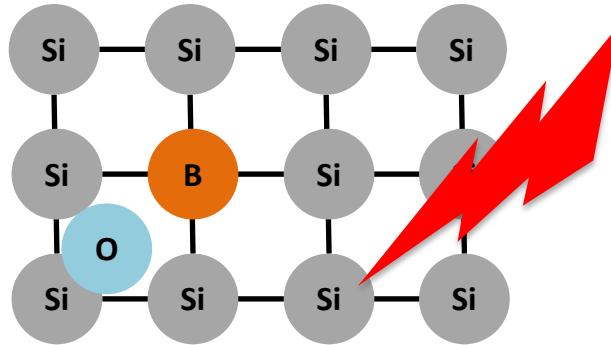
Internal charges multiplication obtained by adding a p⁺ doped layer ($E \geq 300$ kV/cm generated by gain implant)

Ultra Fast Silicon detector (UFSD) combines the LGAD technology with a sensor active thickness of ~50 μm, to obtain a temporal resolution of ~30 ps



The gain implant radiation hardness is a key point for UFSD in HEP applications (MTD of CMS and HGTD of ATLAS)

Radiation damage into gain implant



Radiation

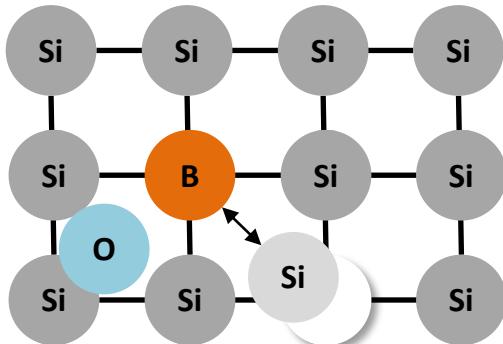


Removal of an acceptor



Creation of a donor complex

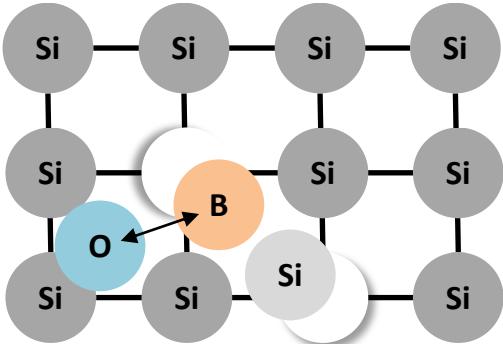
Unbalance of two acceptors



Acceptor removal law:

$$N_A(\phi) = N_A(0)e^{-c(N_A(0))\cdot\phi} = N_A(0)e^{-\phi/\phi_0(N_A(0))}$$

The acceptor removal coefficient $c(N_A(0)) = 1/\phi_0$ depends on:



Carbon enrichment of the gain implant
This technique slows down the acceptor removal
(Carbonated UFSDs produced for the first time by Fondazione Bruno Kessler in Trento, Italy)

Gain implant designs in the FBK productions

3 FBK production (UFSD2, UFSD3 and UFSD3.2) with carbonated UFSDs

(See Marta Tornago's poster *PERFORMANCES OF THE LATEST FBK UFSD PRODUCTION*)

3 gain layer design (shallow-CHBL, deep-CBL and deep-CBH)



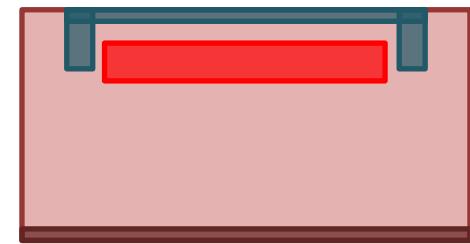
Shallow-CHBL

- Boron diffusion at low thermal load (narrower doping profile)
- Carbon diffusion at High thermal load
- Carbon doses: 0.4, 1*, 2, 3, 5, 10



Deep-CBL

- Boron diffusion at low thermal load (narrower doping profile)
- Carbon diffusion at low thermal load
- Carbon doses: 0.6, 1*



Deep-CBH

- Boron diffusion at high thermal load (broader doping profile)
- Carbon diffusion at high thermal load
- Carbon doses: 0.6, 1*

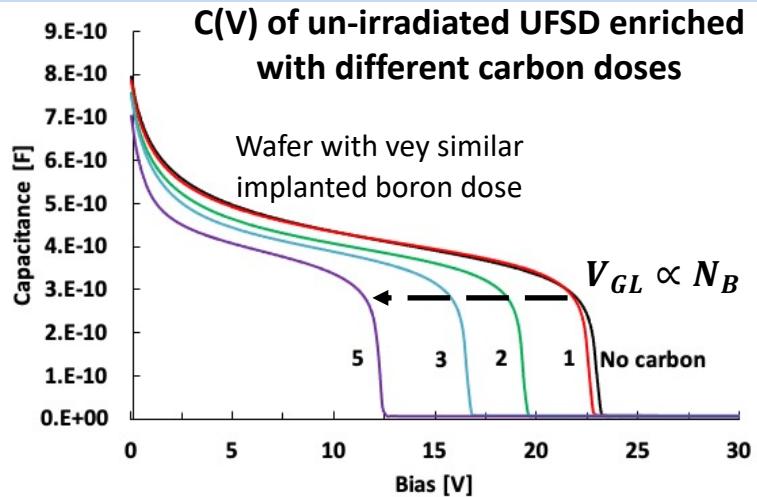
Deep gain implants improve the gain recovery capability of the external bias, in irradiated sensors

* Reference dose

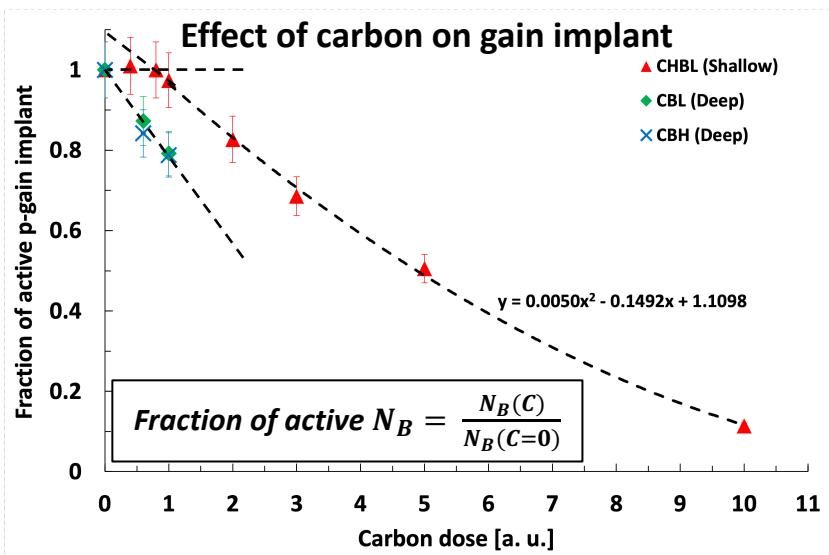
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Carbonated UFSDs – pre-irradiation characteristics – Carbon-Boron Inactivation (CBI)



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

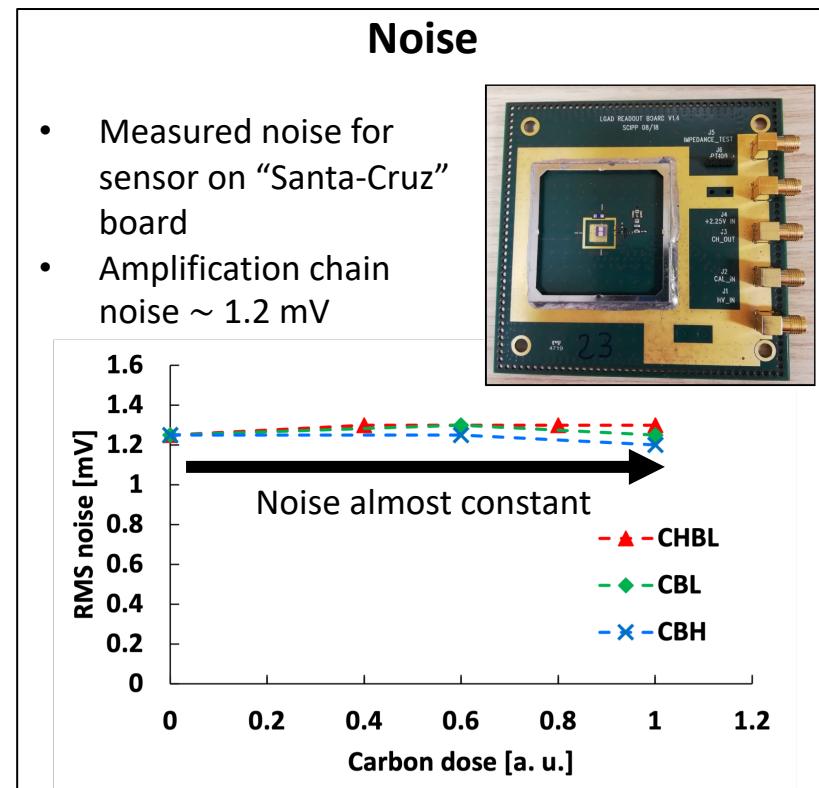
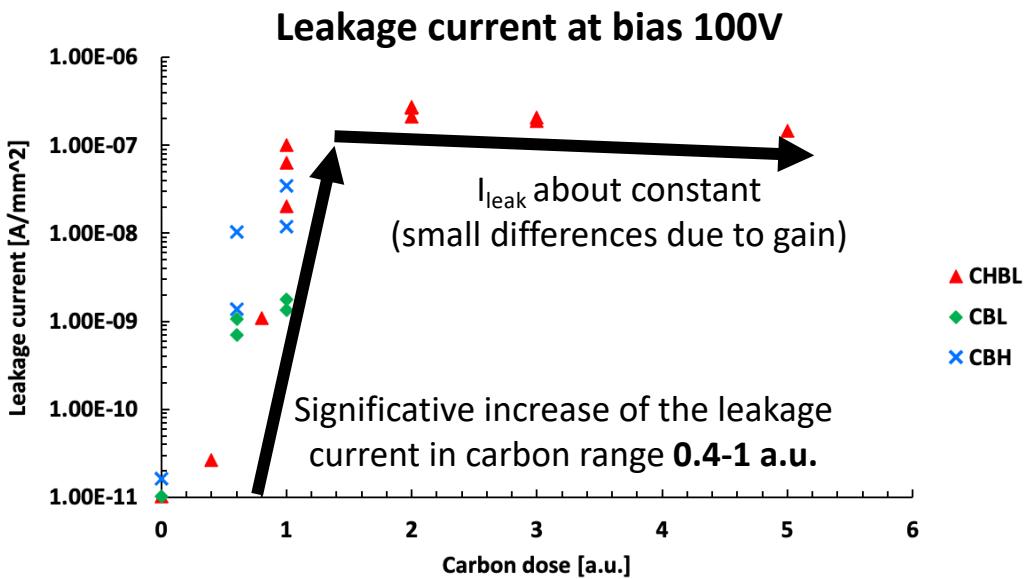


CBI dependent on the gain implant design:

- Stronger in CBL/H implants than in CHBL
- Threshold mechanism in CHBL implant
==> No inactivation below $C_{th} \sim 0.76$

CBI affects the sensor working bias
 $\Delta p\text{-dose} \sim 1\%$ is equivalent to $\Delta V_{\text{working}} \sim 12\text{V}$

Carbonated UFSDs – pre-irradiation characteristics – Leakage current and Noise



- The leakage current increases significantly at low C dose, then it becomes roughly a constant
- The higher leakage current in carbonated UFSDs does not increase the sensor noise

Temporal resolution in carbonated UFSDs expected as good as that in not-carbonated ones

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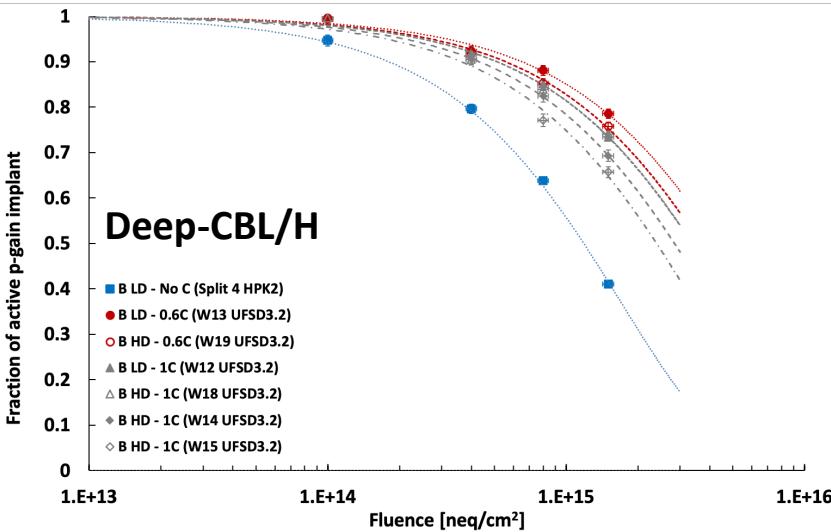
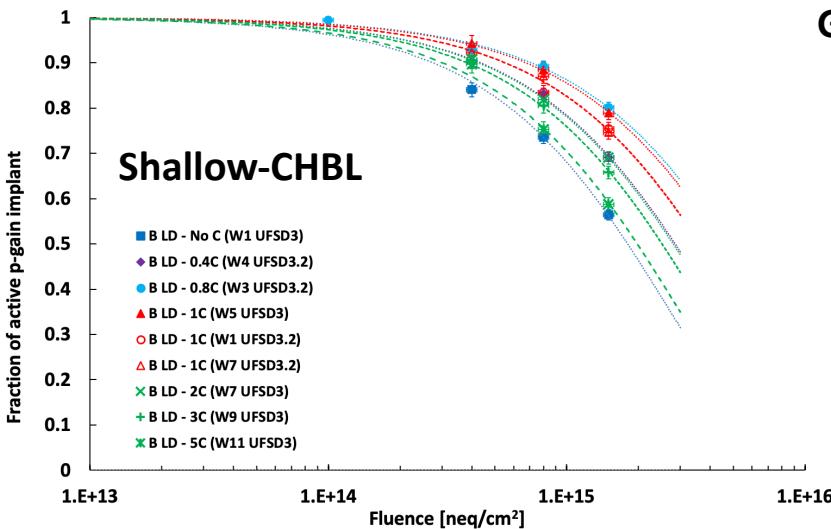
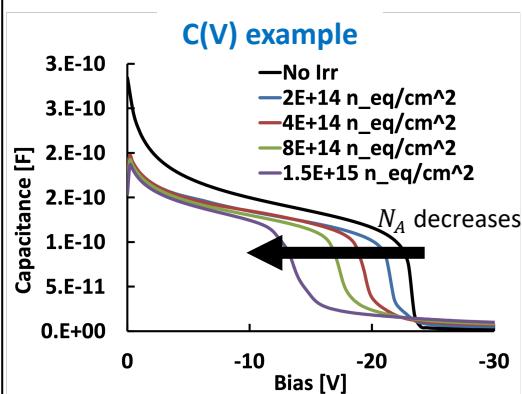
Acceptor removal in shallow- and deep-carbonated Gain Implants (GI)

Fraction of active gain implant

$$N_A(\emptyset)/N_A(0) = e^{-c(N_A(0)) \cdot \emptyset}$$

Steeper curve means less radiation resistance gain implant

Fraction of active gain implant extracted from C(V) or I(V) curves

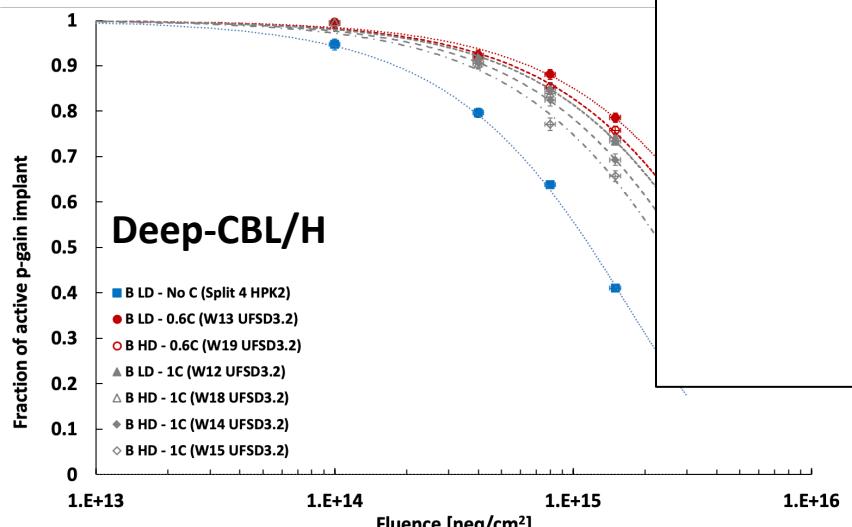
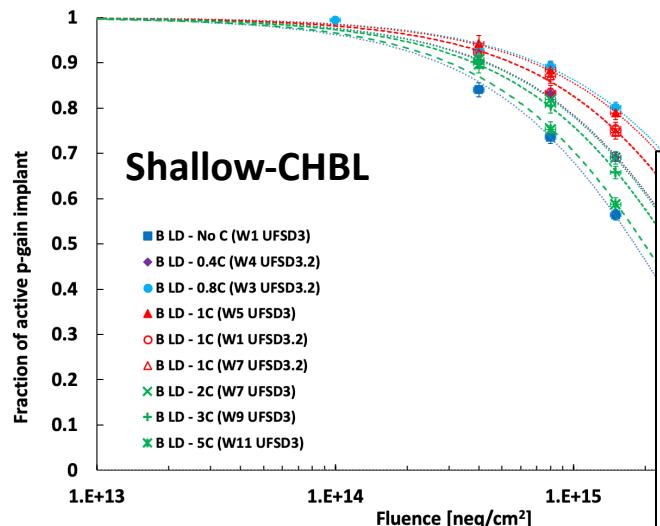


Gain implants irradiated with 1 MeV neutrons up to $\emptyset = 1.5 \cdot 10^{15} n_{eq}/cm^2$

Gain implant	C-dose [a.u.]	c [$10^{-16} cm^2$]
Shallow-CHBL	No C	3.9 ± 0.5
	0.4	2.4 ± 0.3
	0.8	1.5 ± 0.2
	1	1.6 ± 0.3
	2	2.5 ± 0.4
	3	2.8 ± 0.4
Deep-CBL/H	No C	5.6 ± 0.6
	0.6	1.6 ± 0.2
	1	1.9 ± 0.3
	1	2.1 ± 0.3
	1	2.1 ± 0.3

~20% error estimated on c

Acceptor removal in shallow- and deep-carbonated Gain Implants (GI)



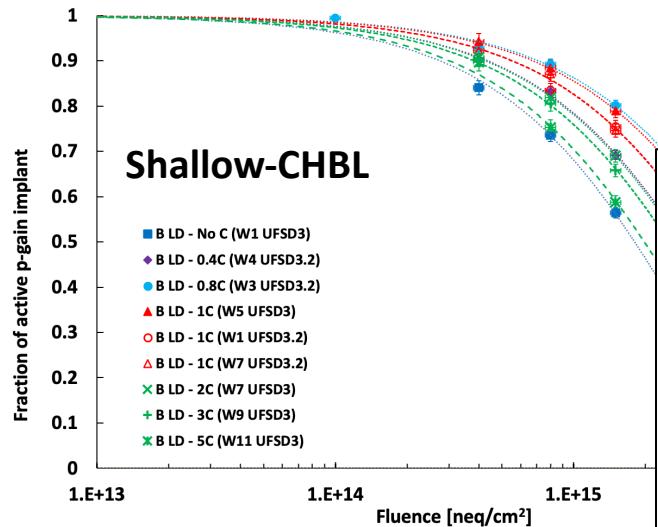
Deep- and shallow-carbonated gain implants are comparable in term of radiation resistance

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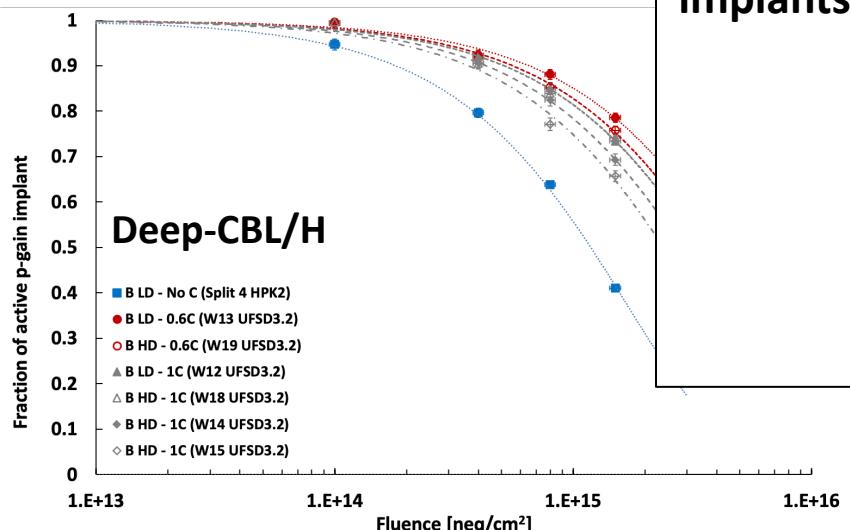
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Acceptor removal in shallow- and deep-carbonated Gain Implants (GI)



Deep- and shallow-carbonated gain implants are comparable in term of radiation resistance

c coefficients of carbonated gain implants in range $1.5 - 3 \cdot 10^{-16} \text{ cm}^2$

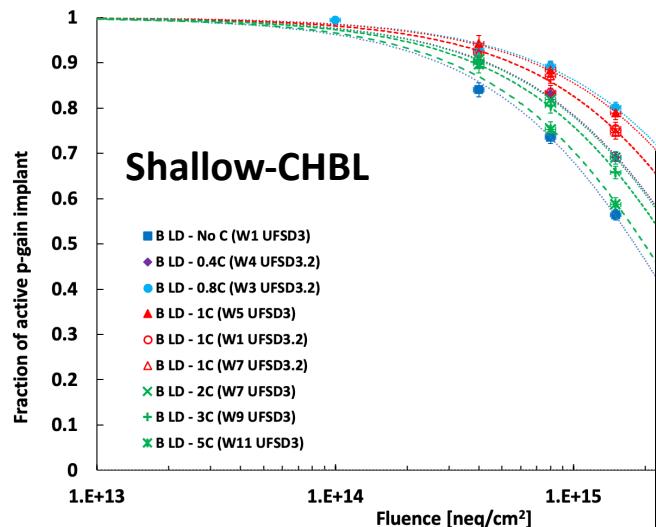


Gain implants irradiated with 1 MeV neutrons up to $\emptyset = 1.5 \cdot 10^{15} n_{eq}/\text{cm}^2$

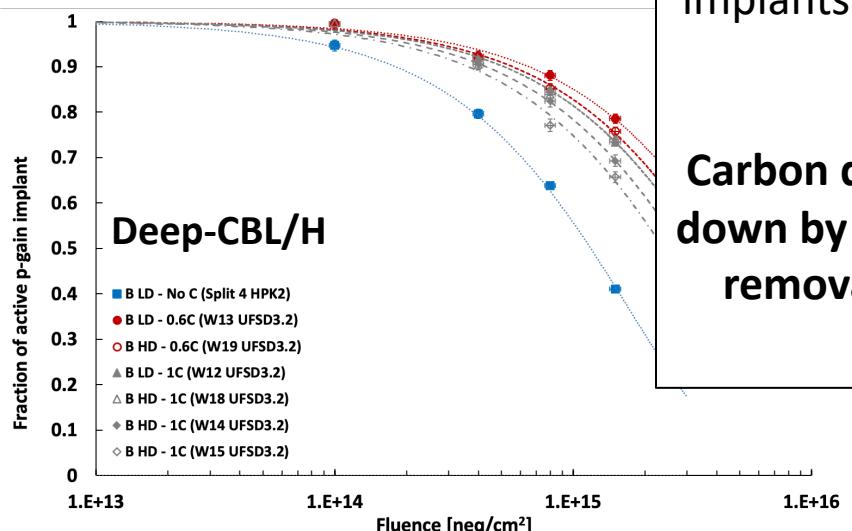
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Acceptor removal in shallow- and deep-carbonated Gain Implants (GI)



Deep- and shallow-carbonated gain implants are comparable in term of radiation resistance



Carbon doses **0.6, 0.8 and 1** slow down by a factor 2-3 the acceptor removal in the multiplication layer

Gain implants irradiated with 1 MeV neutrons up to $\emptyset = 1.5 \cdot 10^{15} n_{ep}/cm^2$

Gain implant	C-dose [a.u.]	c [$10^{-16} cm^2$]
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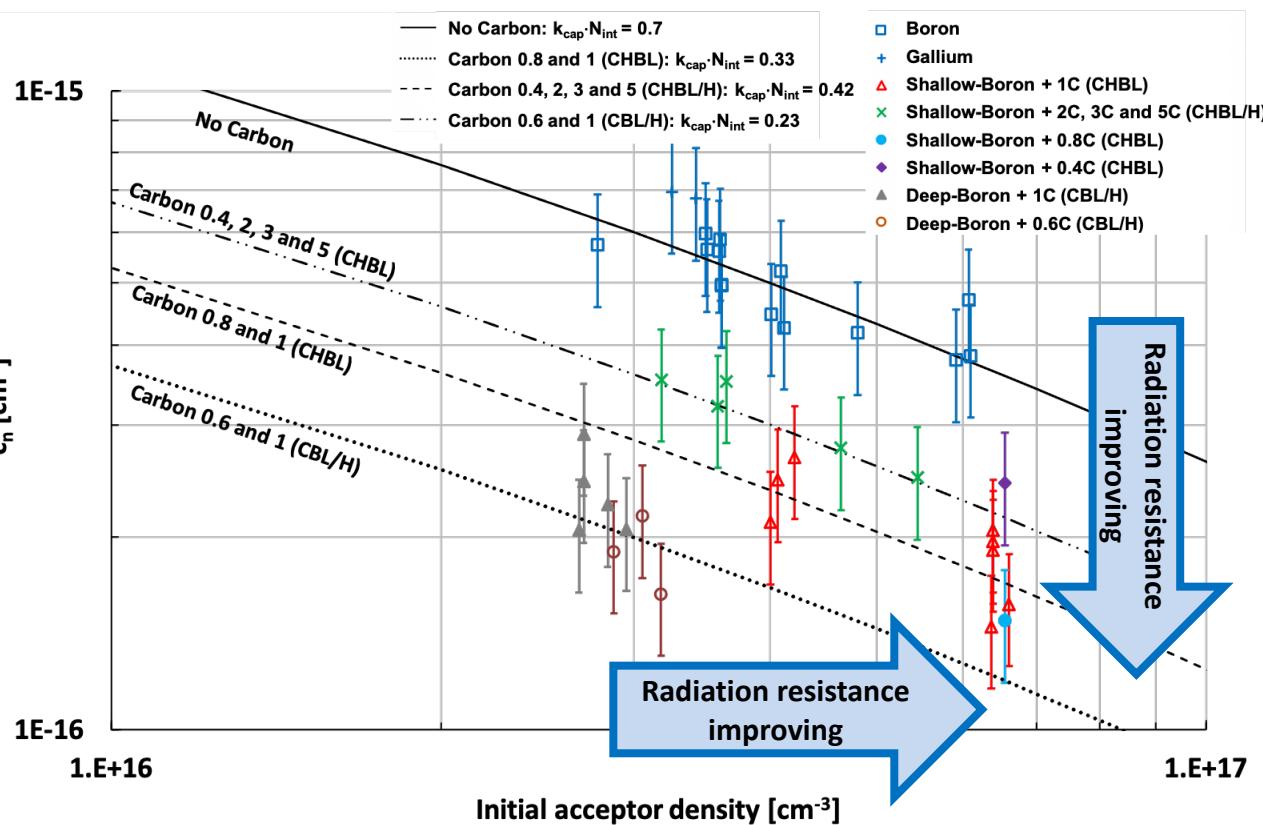
~20% error estimated on c

Acceptor removal parametrization

Relationship between acceptor removal and initial acceptor density

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

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



Four family of gain implants with different intrinsic radiation resistance:

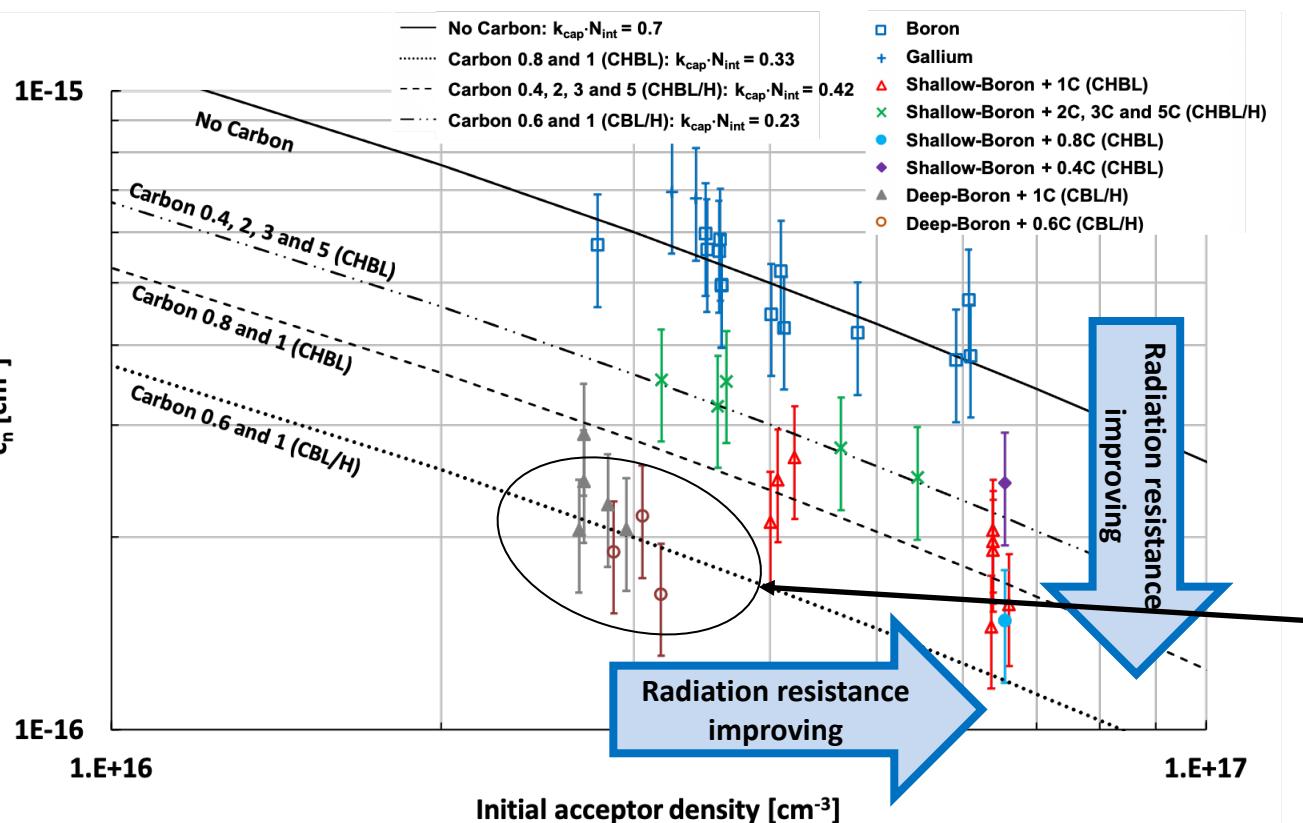
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- Carbon 0.8, 1 (CHBL)
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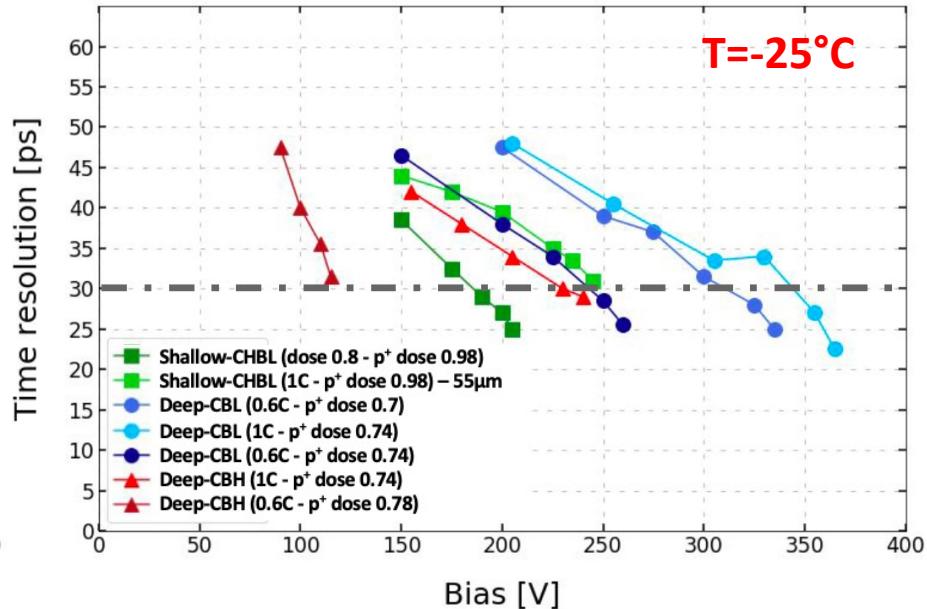
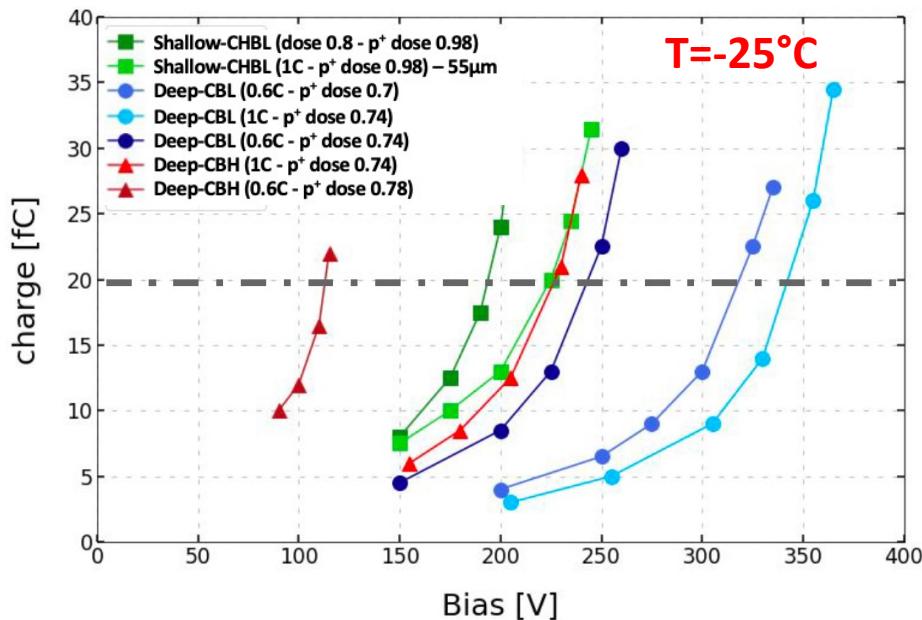
- No carbon
- Carbon 0.4, 2, 3, 5 (CHBL)
- Carbon 0.8, 1 (CHBL)
- Carbon 0.6, 1 (CBL/H)

Deep CBL/H design is the more intrinsic radiation resistant

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Performances of pre-rad UFSDs

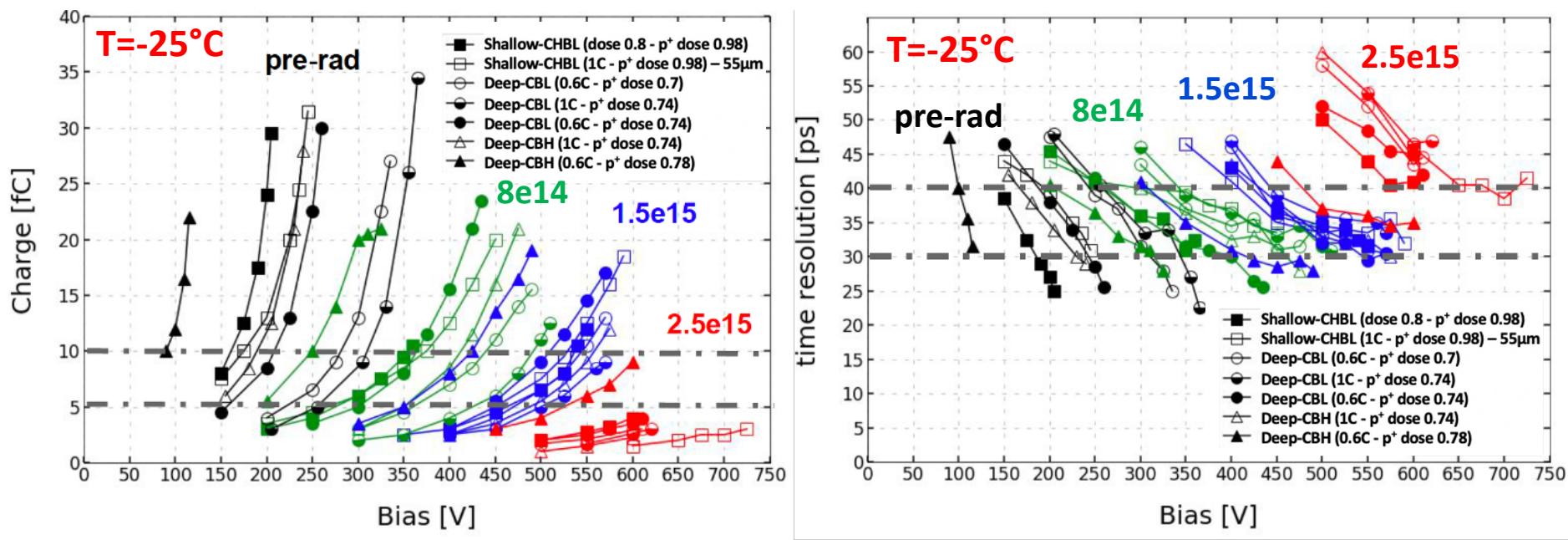


Excellent performances of all un-irradiated UFSDs

20fC of collected charge and 30ps of time resolution achieved in a range of bias 100 – 350V

Time resolution not degraded by the presence of carbon

Performances of irradiated FBK UFSDs



All sensor irradiated up to **1.5E15 n_{eq}/cm²** collect **10fC** and reach **30ps** of time resolution

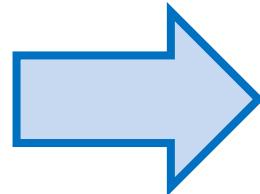
Sensor irradiated at **2.5E15 n_{eq}/cm²** collect **~5fC** and reach a time resolution of **40ps**

Both deep- and shallow-Carbonated gain implants allow to achieve excellent time performances post-irradiation

Most radiation resistance design

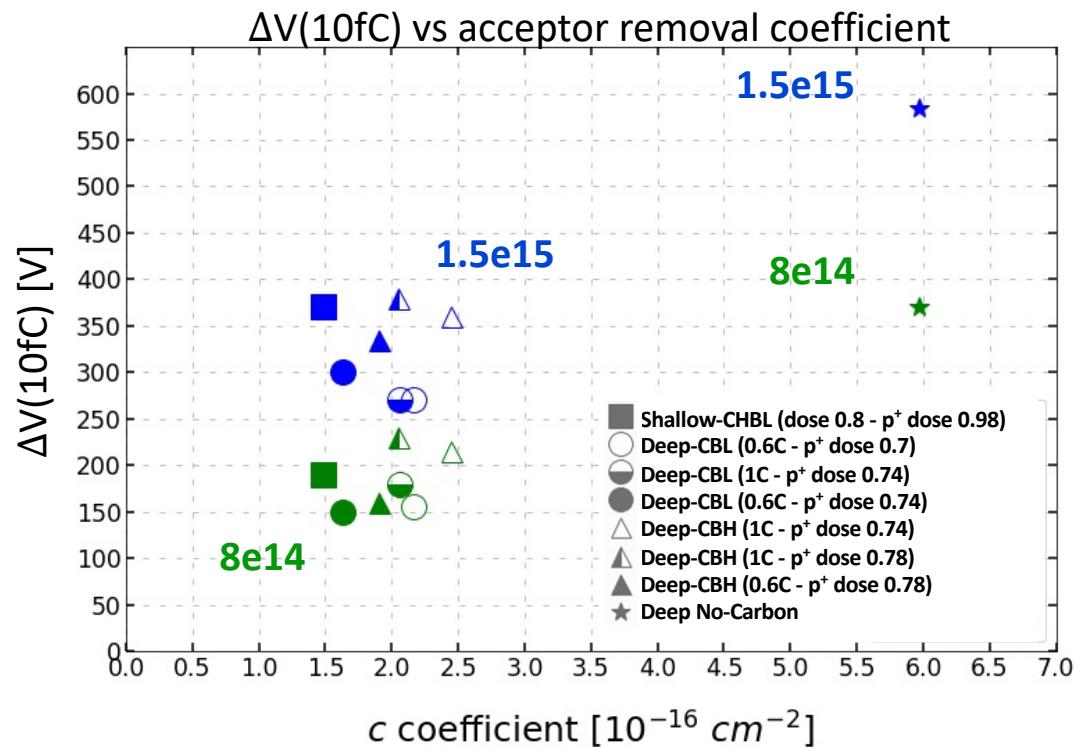
FIGURE OF MERIT

Bias increase required to deliver 10fC compared to pre-rad condition
 $\Delta V(10fC) = V_{\text{irrad}}(10fC) - V_{\text{pre-rad}}(10fC)$



Smaller $\Delta V(10fC)$ = most radiation resistance:

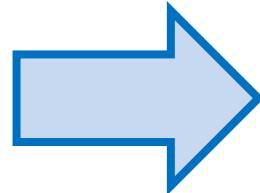
- Lower power consumption
- Safe operation of the device
- Device less affect to non-uniform irradiation



Most radiation resistance design

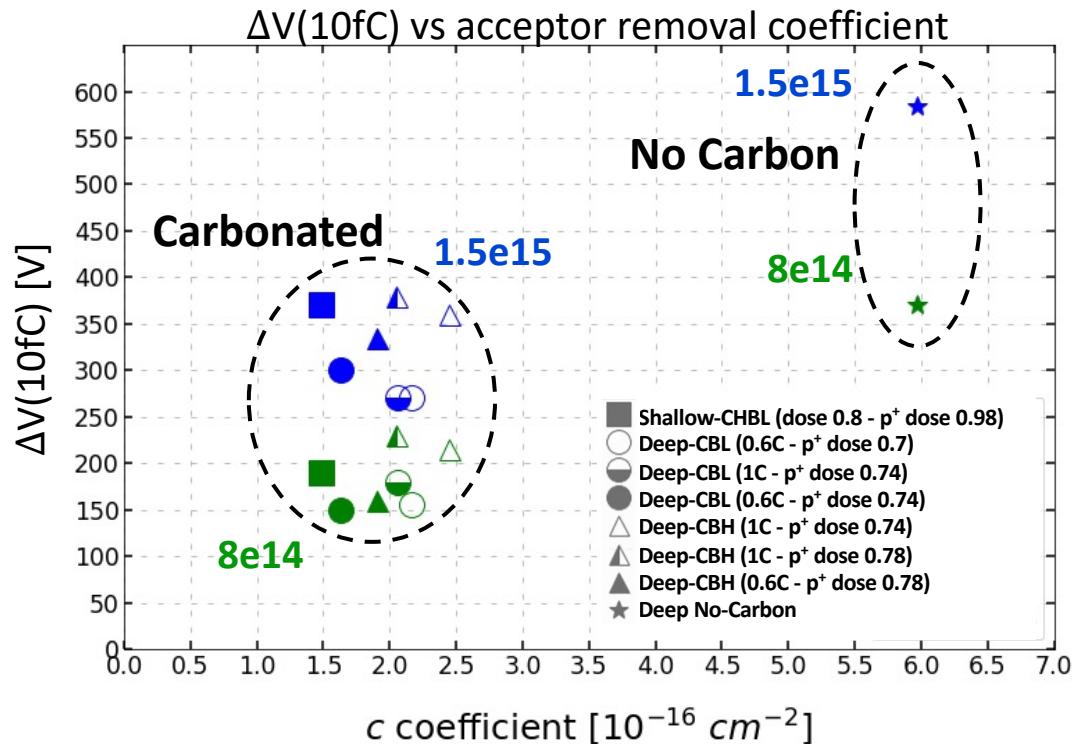
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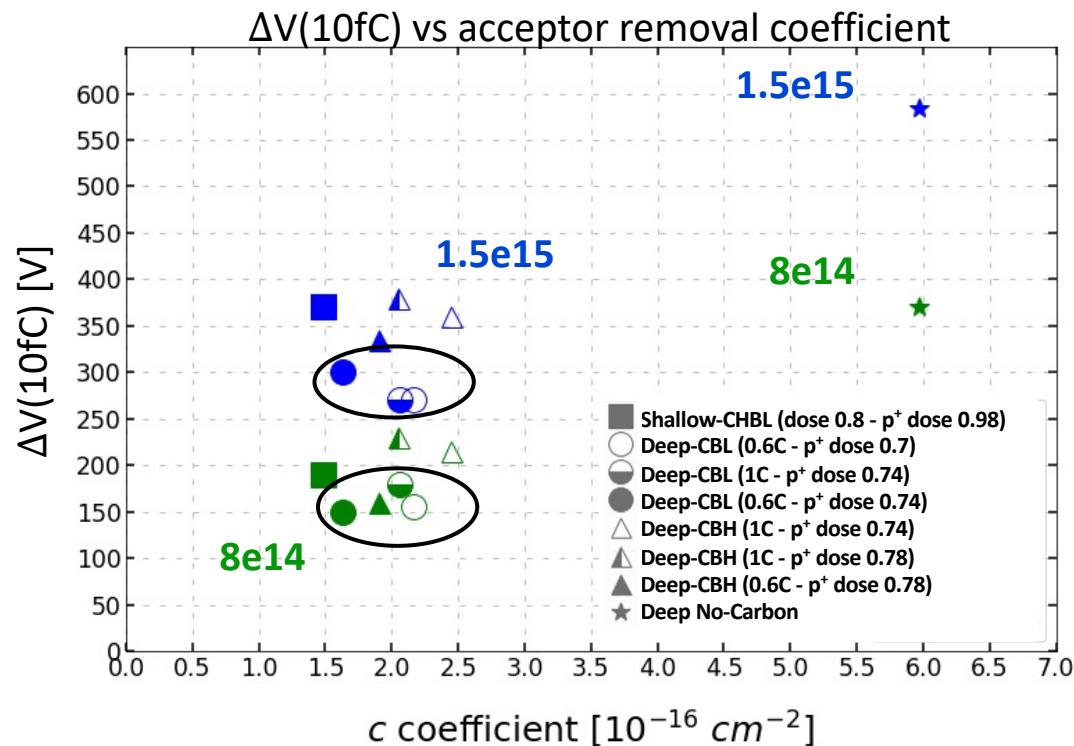
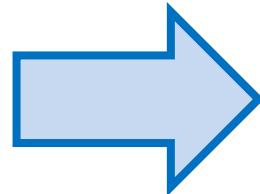
$\Delta V(10fC)$ is lower in sensors with:

- carbonated gain implant compared to not-carbonated

Most radiation resistance design

FIGURE OF MERIT

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- Safe operation of the device
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$\Delta V(10fC)$ is lower in sensors with:

- carbonated gain implant compared to not-carbonated
- deep-CBL gain implants compared to deep-CBH and shallow-CHBL

Conclusions

- In the FBK productions, three different carbonated gain implants have been investigated:
Shallow-CHBL, Deep-CBL and Deep-CBH
- **Leakage current increase** and **Carbon-Boron Inactivation (CBI)** have been mapped as a function of different carbon doses, in un-irradiated UFSDs
 - CBI is stronger in deep-CBL/H than in shallow-CHBL
- Acceptor removal coefficients are comparable between shallow- and deep-implants ($c \sim 1.5 - 3 \cdot 10^{-16} \text{ cm}^2$)
- **Carbon dose in range 0.6-1 a.u.** maximizes the radiation resistance of all gain implant designs
- **Intrinsic radiation resistance** of the gain implant is higher in **deep-CBL/H** than in **shallow-CHBL**
- Excellent time resolution in pre- and post- rad sensors with shallow and deep implant
- The **deep-carbonated gain implant** is the **most radiation resistant**
 - It requires the smallest increase of voltage to compensate the effect of acceptor removal on the gain implant

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- Horizon 2020, grant INFRAIA
- AIDA-2020, grant agreement no. 654168
- INFN, Gruppo V
- Ministero degli Affari Esteri, Italy, MAE, “Progetti di Grande Rilevanza Scientifica”
- MIUR, Dipartimenti di Eccellenza (ex L. 232/2016, art. 1, cc. 314, 337)
- Ministero della Ricerca, Italia , PRIN 2017, progetto 2017L2XKTJ – 4DinSiDe
- Ministero della Ricerca, Italia, FARE, R165xr8frt_fare

Backup

FBK – UFSD production

UFSD2

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
14	Gallium	1.04		Low
15	Gallium	1.04	Low	Low
16	Gallium	1.04	HIGH	Low
18	Gallium	1.08		Low

UFSD3

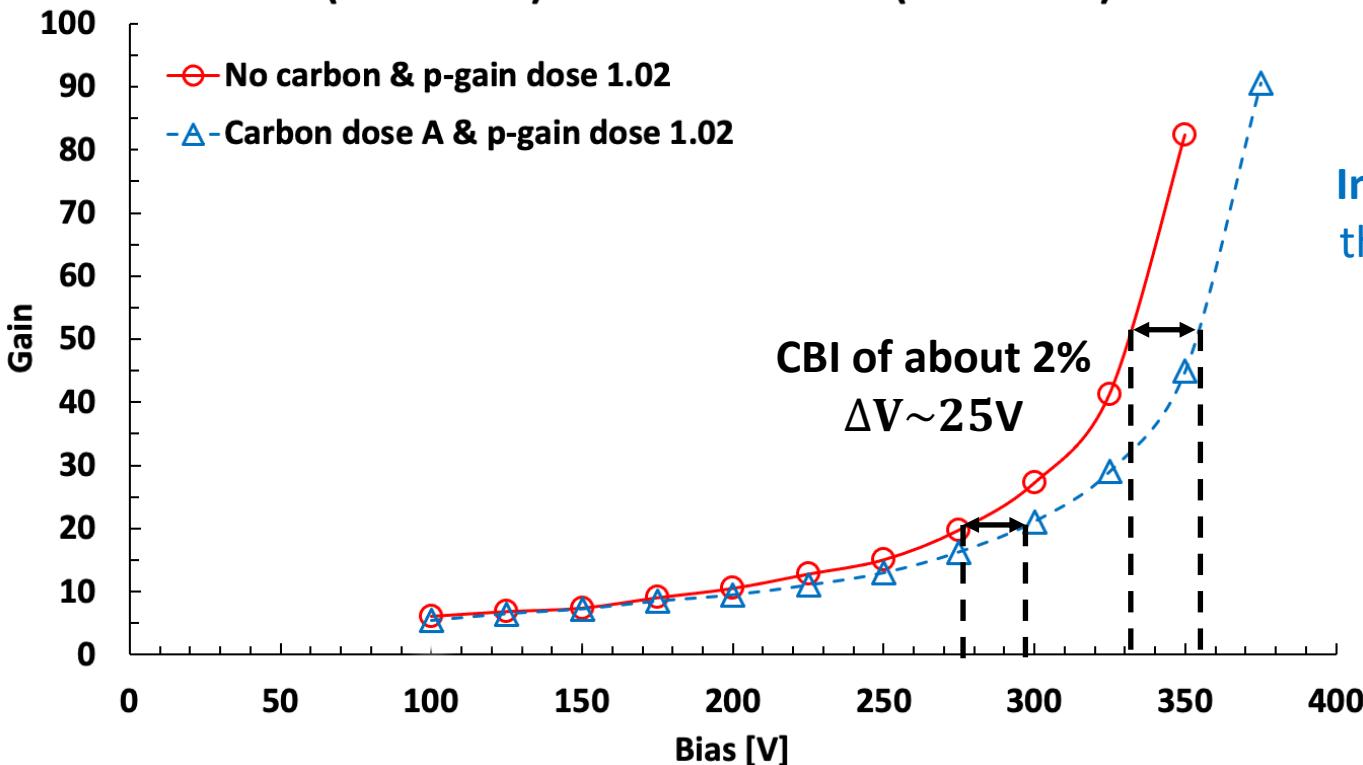
Wafer #	Dose Pgain	Carbon	Diffusion
1	0.98		L
2	0.96		L
3	0.96	A	L
4	0.96	A	L
5	0.98	A	L
6	0.96	B	L
7	0.98	B	L
8	0.98	B	L
9	0.98	C	L
10	1.00	C	L
11	1.00	D	L
12	1.02		H
13	1.00		H
14	1.02	A	H
15	1.00	A	H
16	1.02	B	H
17	1.02	B	H
18	1.04	B	H
19	1.02	C	H
20	1.04	C	H

UFSD3.2

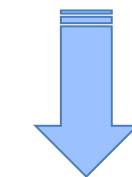
Wafer #	Thickness	DEPTH	Dose Pgain	Carbon	Diffusion
1	45	Standard	0.98	1.*A	CH-BL
2	45	Standard	0.98	1.*Ab	CH-BL
3	45	Standard	0.98	0.8*A	CH-BL
4	45	Standard	0.98	0.4*A	CH-BL
7	55	Standard	0.98	1.*A	CH-BL
8	45	deep	0.70	1.*A	CBL
9	55	deep	0.70	1.*A	CBL
10	45	deep	0.70	0.6*A	CBL
11	45	deep	0.70		BL
12	45	deep	0.74	1*A	CBL
13	45	deep	0.74	0.6*A	CBL
14	45	deep	0.74	1.*A	CBH
15	55	deep	0.74	1.*A	CBH
16	45	deep	0.74	0.6*A	CBH
17	45	deep	0.74		BH
18	45	deep	0.78	A	CBH
19	45	deep	0.78	0.6*A	CBH

Carbon-Boron Inactivation Effect on the sensor gain

Gain Comparison - shallow-B HD gain implants carbonated (W6-UFS2) vs not carbonated (W8-UFS2)



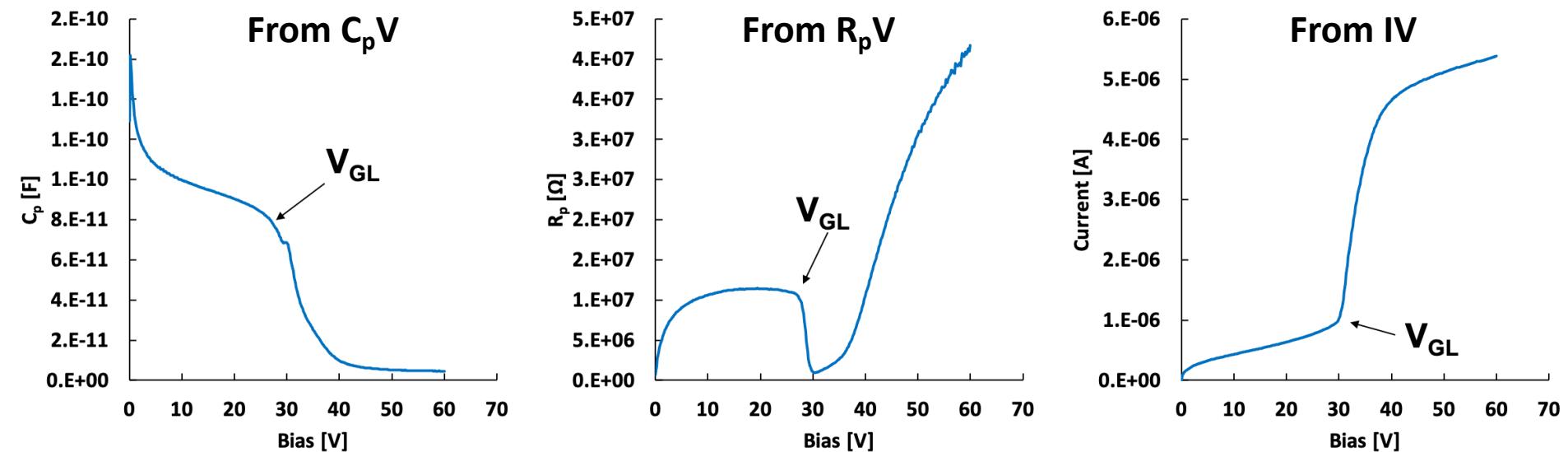
Carbon-Boron
Inactivation determines
the sensor working bias



$\Delta p\text{-dose of } 1\%$
is equivalent to
 $\Delta V_{\text{working}} \sim 12V$

Gain layer depletion voltage Methods of extraction

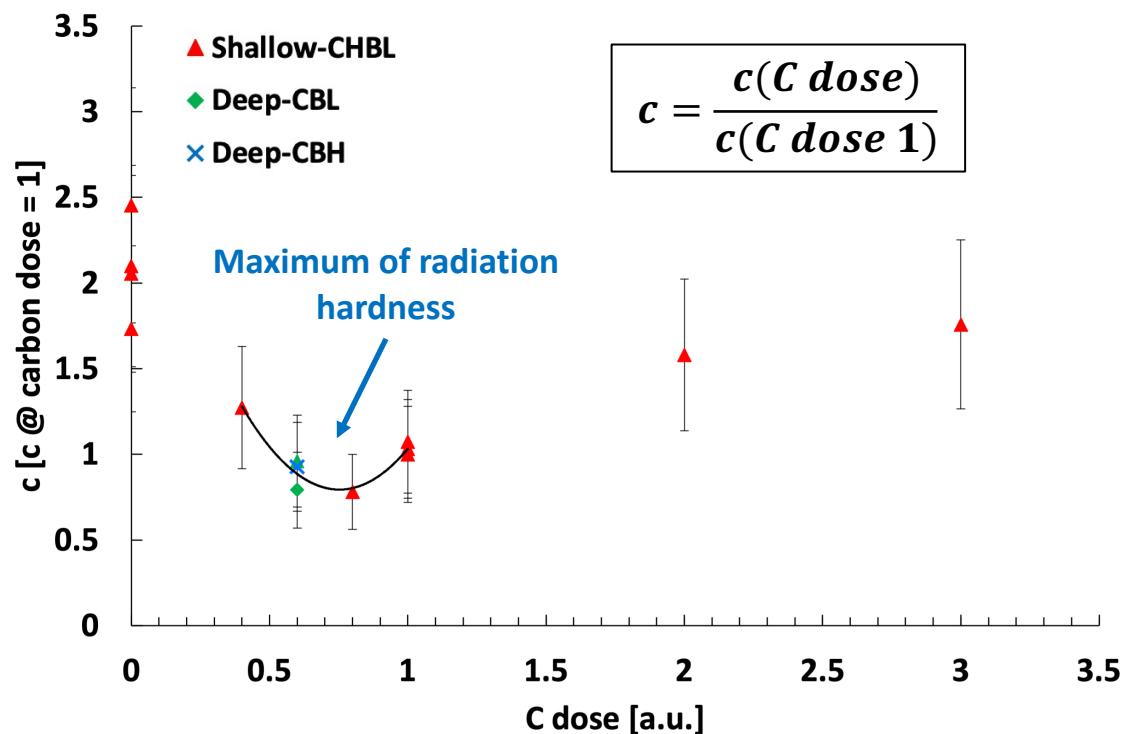
Sensor modelled as a capacitance (C_p) and resistance (R_p) in parallel



Different methods of extraction introduce an uncertainty (~10%-20%) on V_{GL} values

Carbon dose optimization – gain implant's radiation resistance maximization

Acceptor removal coefficient vs carbon dose



Carbon dose in range 0.6 - 1 a.u. maximizes the gain implant radiation resistance

$c(C\text{-dose})$ relationship due to:

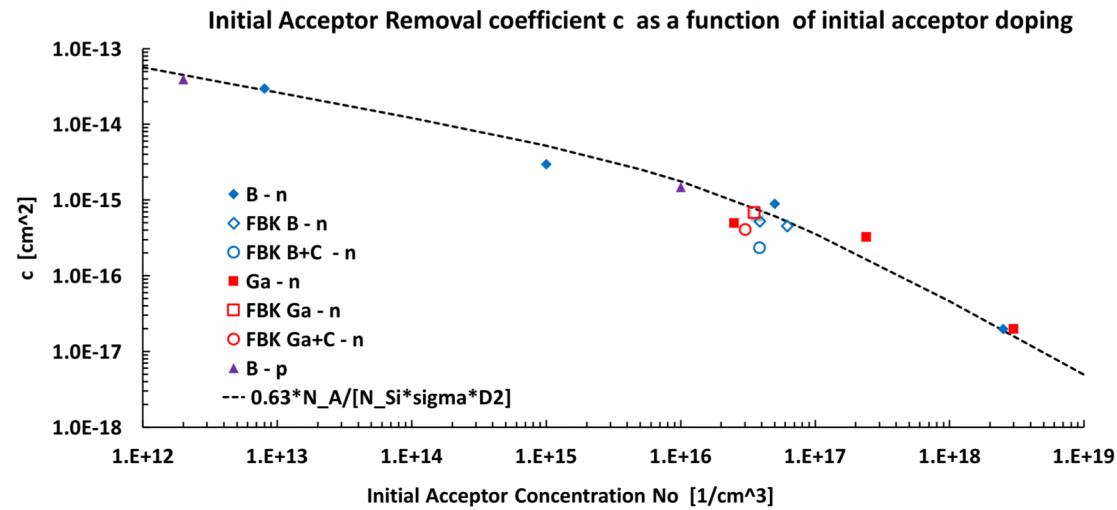
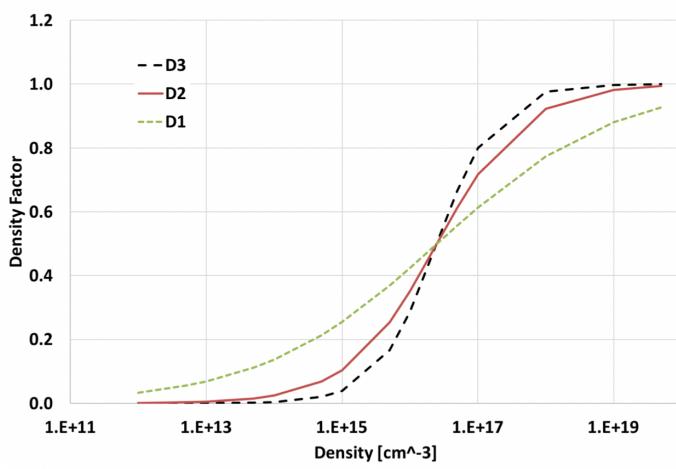
- Carbon-Boron Inactivation effect on initial acceptor density
- Intrinsic radiation resistant of a specific gain implant design

Acceptor removal parametrization

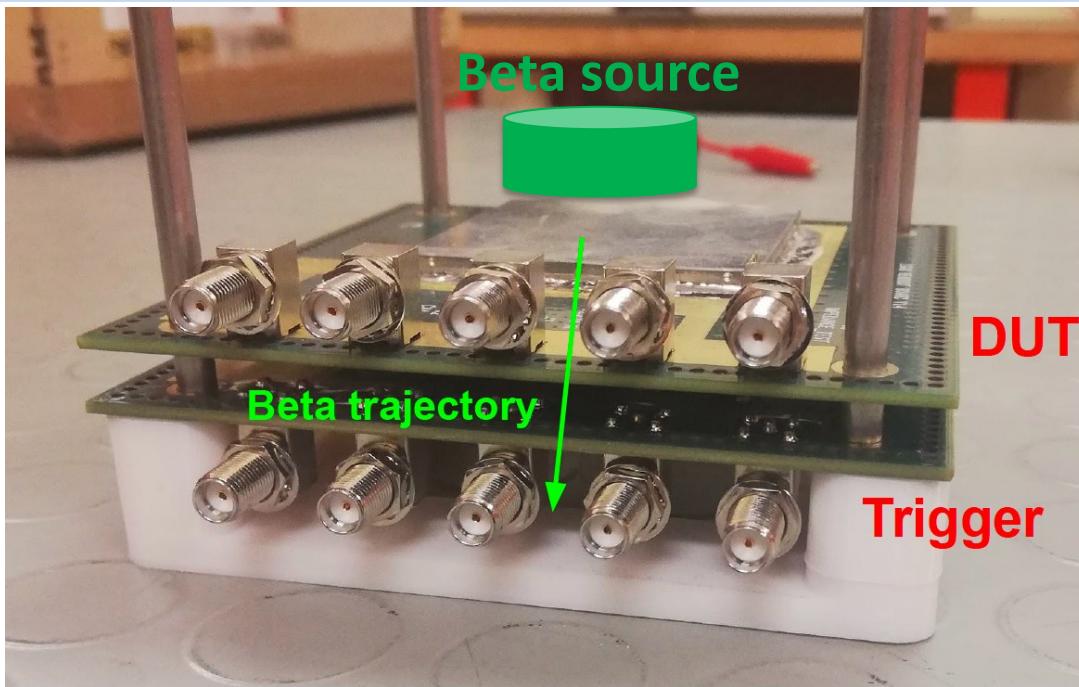
$$D_2 = \frac{k_{cap} * N_{Int}}{1 + \left(\frac{2.5 \cdot 10^{16}}{N_B(0)} \right)^{2/3}}$$

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

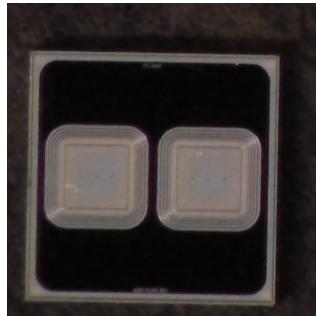
N_{Si} → Silicon density
 σ_{Si} → Cross section
 k_{cap} → capture coefficient
 N_{Int} → Number of defect created
 D_2 → density function



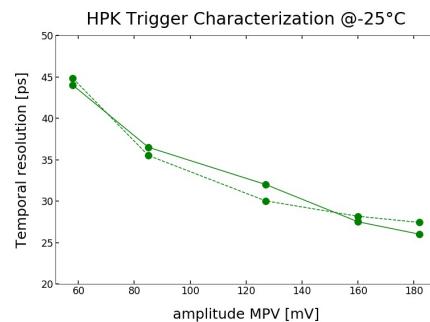
Time resolution measurement setup



- **Beta source (Sr^{90})**
- Read-out with single channel “Santa-Cruz” board;
- DUT and Trigger aligned with a specific 3d-printed structure;
- Trigger plated below DUT ensures that we trigger only on MIPs;
- Amplification chain: “Santa-Cruz” board + 20dB Cividec Broadband amplifier (RMS Noise = 1.2mV);
- Measurement performed in **climatic chamber** at -25°C;
- **Sampling at 20Gs/s** with LeCroy Wave series oscilloscope

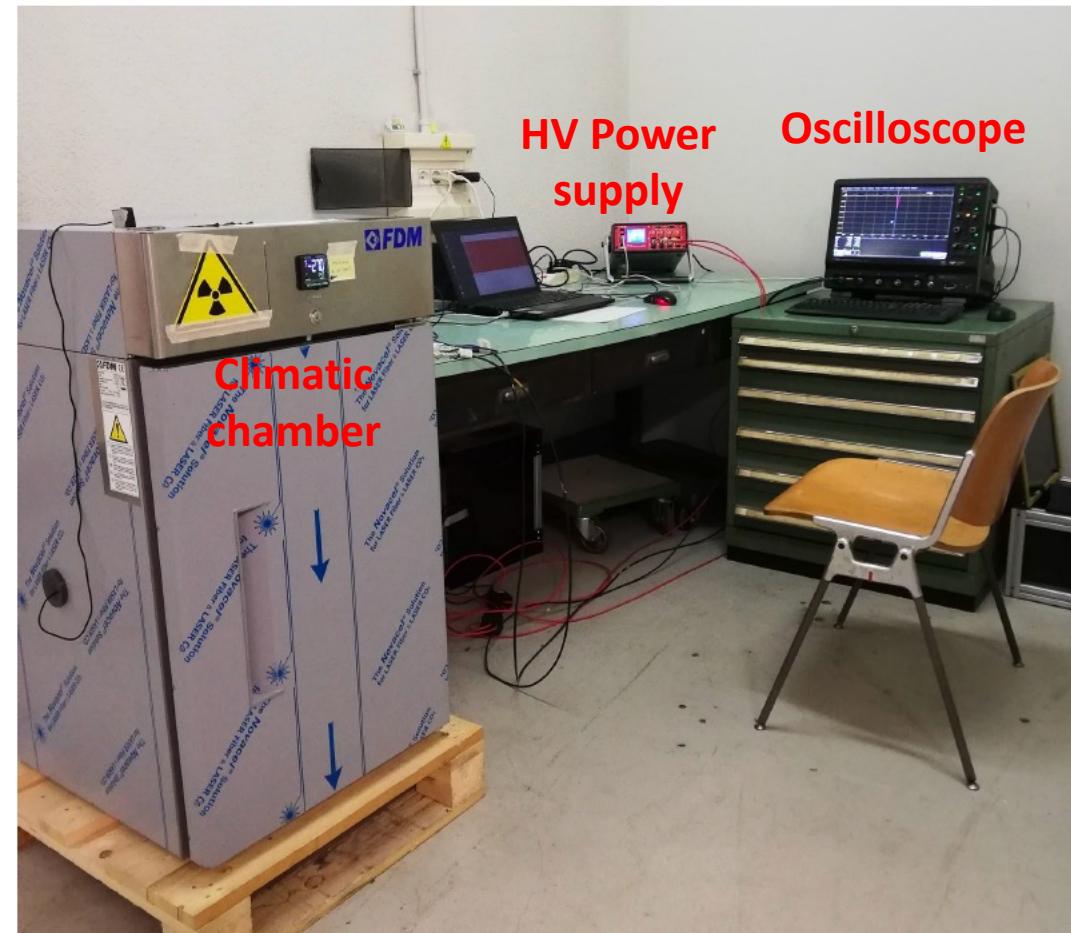


Tested sensors
are $1.3 \times 1.3 \text{ mm}^2$
single pad $45\mu\text{m}$
thick



Trigger is a UFSD sensor with well known resolution

Time resolution and charge collection- Measurement setups

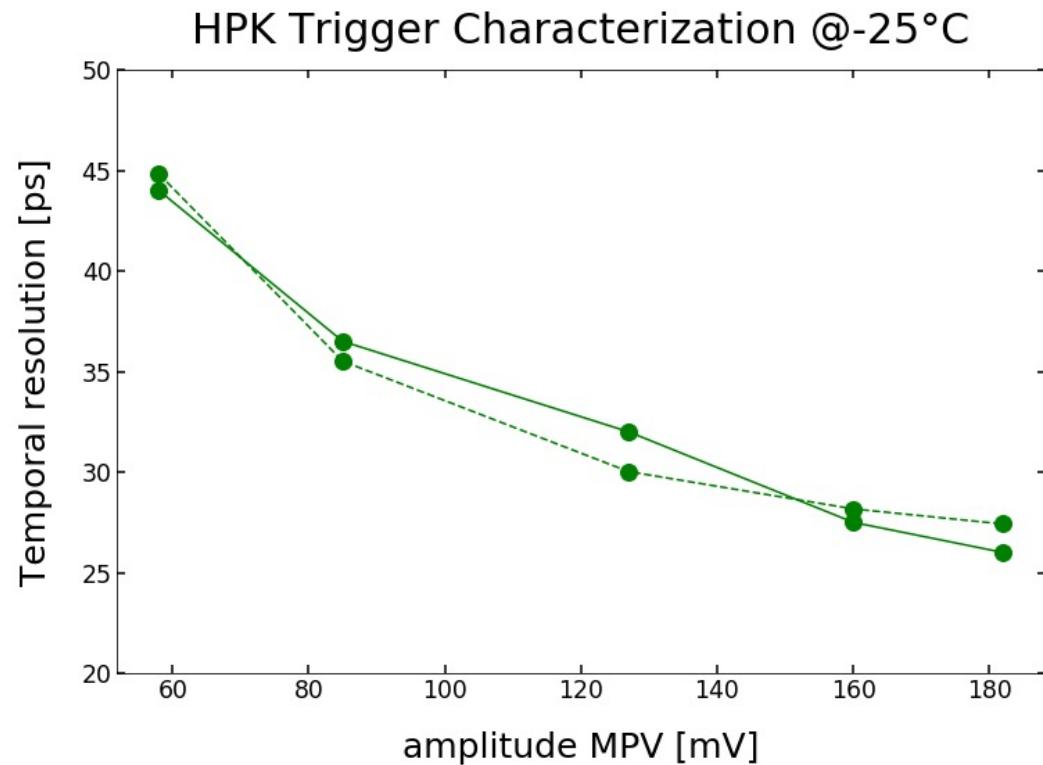


- DAQ and Analysis are fully automated
- Climate chamber
 - Can go down to -30°C with $\pm 0.1^{\circ}\text{C}$ uncertainty
 - $< 10\%$ humidity

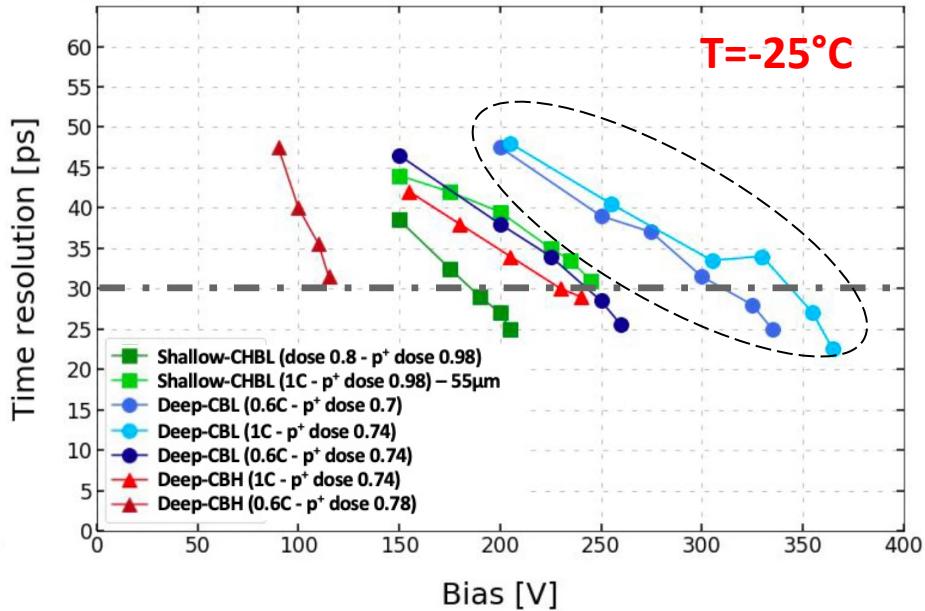
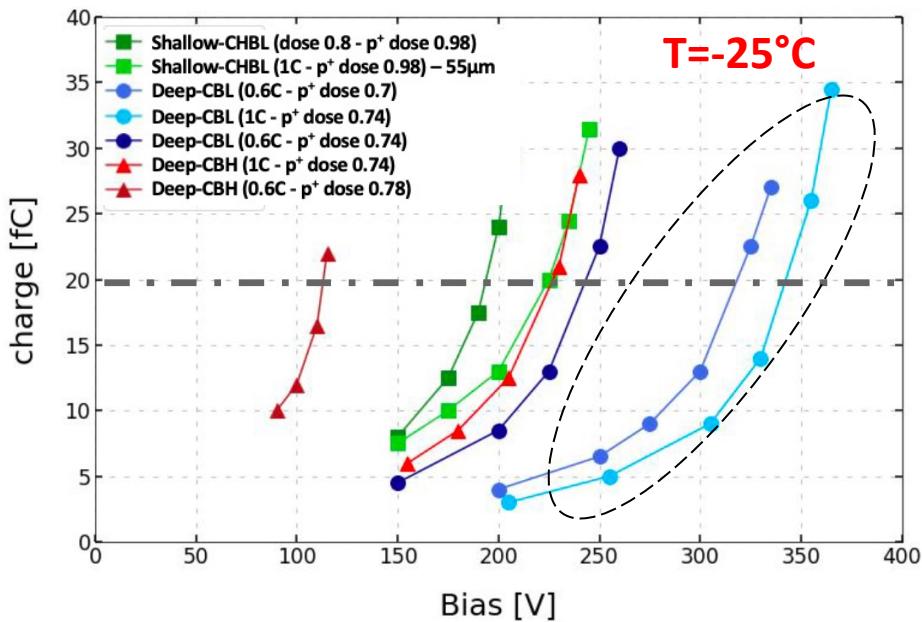
Trigger temporal performances

Trigger:

- HPK-UFSD 45 μ m-thick
- Capacitance = 6pF

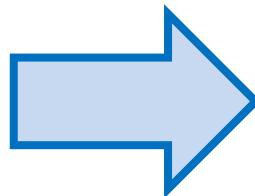


Performances of pre-rad UFSDs

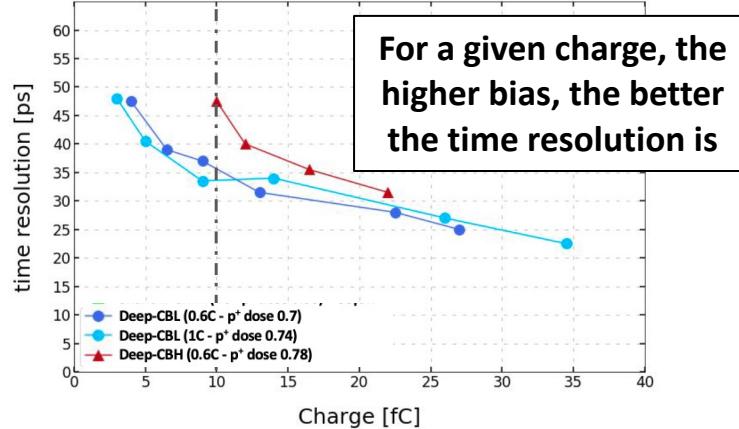


Pre-irradiation is preferred a UFSD with:

- high operating voltage (carrier drift velocity saturated)**
- Smooth gain curve (sensor less affect by p⁺-dose non uniformity)**



For a given charge, the higher bias, the better the time resolution is



Noise

