32nd RD50 Workshop, Hamburg, June 4-6 2018

Effects of protons and neutrons irradiation to the gain layer and bulk of 50-micron thick FBK LGAD sensors doped with Boron, Boron Low diffusion, Gallium, Carbonated Boron and Carbonated Gallium

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Outline

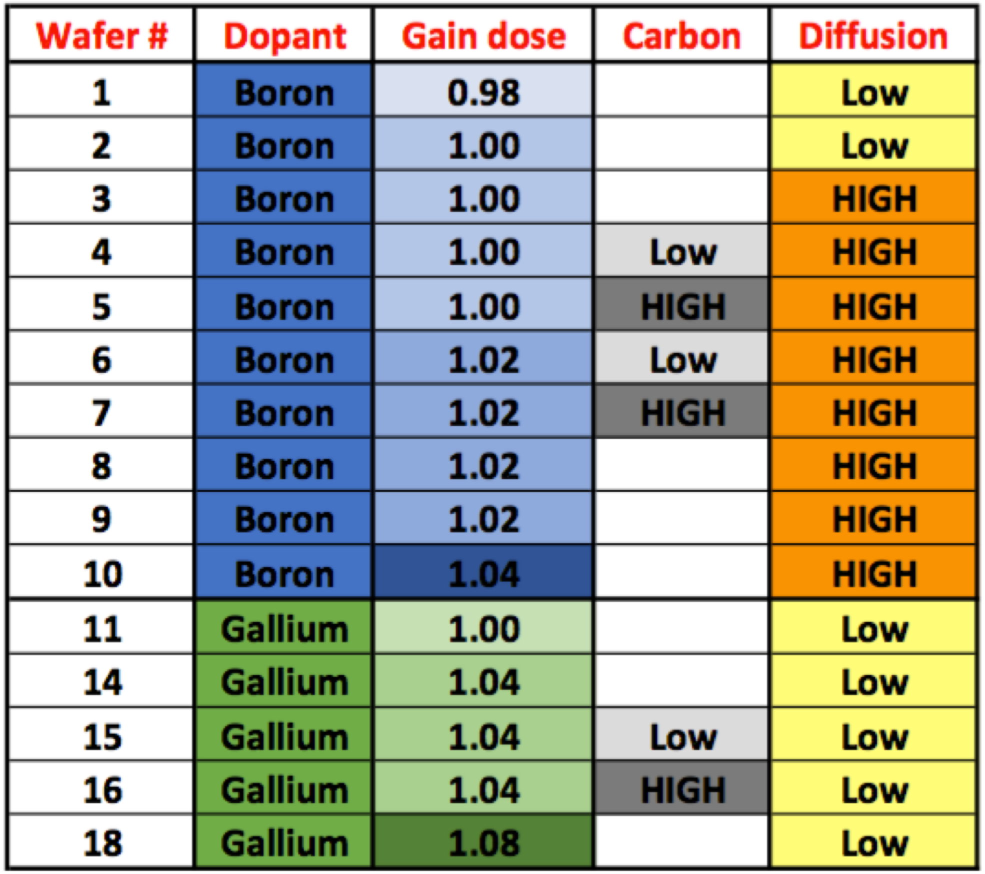
ACCEPTOR REMOVAL

- Acceptor Removal effect on different flavors of gain layer (Boron, Gallium, Boron Low Diffusion, Carbonated Boron and Gallium)
- Comparison between acceptor removal due to Neutrons and Protons (24Gev/c)

ACCEPTOR CREATION

- Measurements of Acceptor Creation on PiN diodes (50µm thick) due to Neutrons & Protons irradiation and comparison with empiric model $N_A = g_{eff} \Phi$ ($g_{eff} = 0{,}02$ cm^{-1});

50µm UFSD, FBK Production



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

- 18 Wafers Silicon on Silicon (FZ), 50µm active thickness;
  p-bulk acceptor density ~ 2/3•10^{12} cm^{-3}

- 5 different gain layer strategies:
  - **Boron** (Low and High Diffusion);
  - **Gallium** (Low Diffusion);
  - **Carbonated Boron** (B High Diffusion);
  - **Carbonated Gallium** (Ga Low Diffusion);

- 4 splits of dose (2% steps) for Boron Implant;

- 3 splits of dose (4% steps) for Gallium Implant;

- 2 carbon concentration (Low & High):
  High Carbon = X10 Low Carbon;

5 Gain layer flavors to investigate the radiation damage

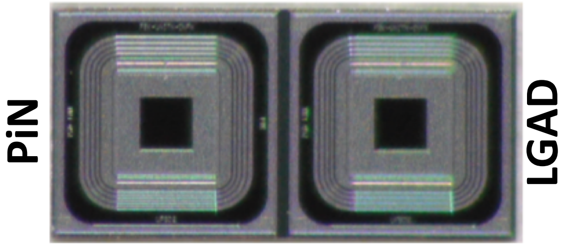
- **B Low Diffusion:** thinner gain implant could be more radiation resistance;
- **Gallium:** Ga could has a lower probability than B to became interstitial;
- **Carbon enrichment:** C could be traped by defects faster than Ga and B;

see G.Paternoster talk:
Production and design of LGAD with high radiation resistance, 13th Trento Workshop, 2018

Irradiation campaign

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

Pairs of *1x1mm^2* **PiN-LGAD**



🟢

Neutron Irradiation in Ljubljana

(AIDA2020) ➔ thank you GK and friends!

Fluence steps:

0,2/0,4/0,8/1,5/3/6/10*10^{15} n_{eq}/cm^2

🔵

Proton Irradiation at CERN, 24Gev/c

(IRRAD) ➔ Thank you Joern!

Fluence steps: 0,1/0,6/1/3/6/9*10^{15} n_{eq}/cm^2 (NIEL Factor = 0,6)

Evolution of active acceptor density with fluence

$$N_A(\phi) = g_{eff}\phi + N_A(\phi = 0)e^{-c\phi}$$

Φ = fluence

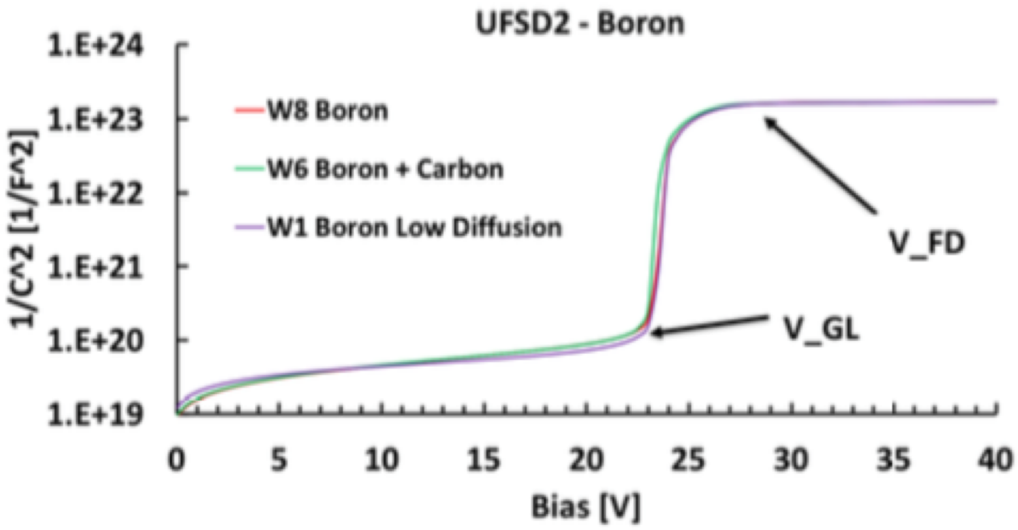
N_A = active acceptor density at fluence *Φ*

g_{eff} = empirical constant (~0,02 cm^{-1}) → to compare with the measurements on irradiated PiN diode

C = coefficient of the acceptor removal→ Dependent upon the irradiation type, the acceptor type and the initial acceptor density

For More detail on the acceptor removal model see the N. Cartiglia talk on thin workshop

Extrapolation of active acceptor density into gain layer (Method)



V_{GL} = Depletion Voltage for Gain Layer
V_{FD} = Full Depletion Voltage of sensor

V_{GL} is proportional to the amount of the active doping of the gain layer

$$V_{GL} = \frac{qN_A}{2\epsilon} w^2$$

N_A = Active doping concentration
ω = thickness of the gain layer (~1 µm)
q = electron electric charge
ε = Dielectric constant of Silicon

Extrapolation of V_{GL}

C-V Measurement parameters:

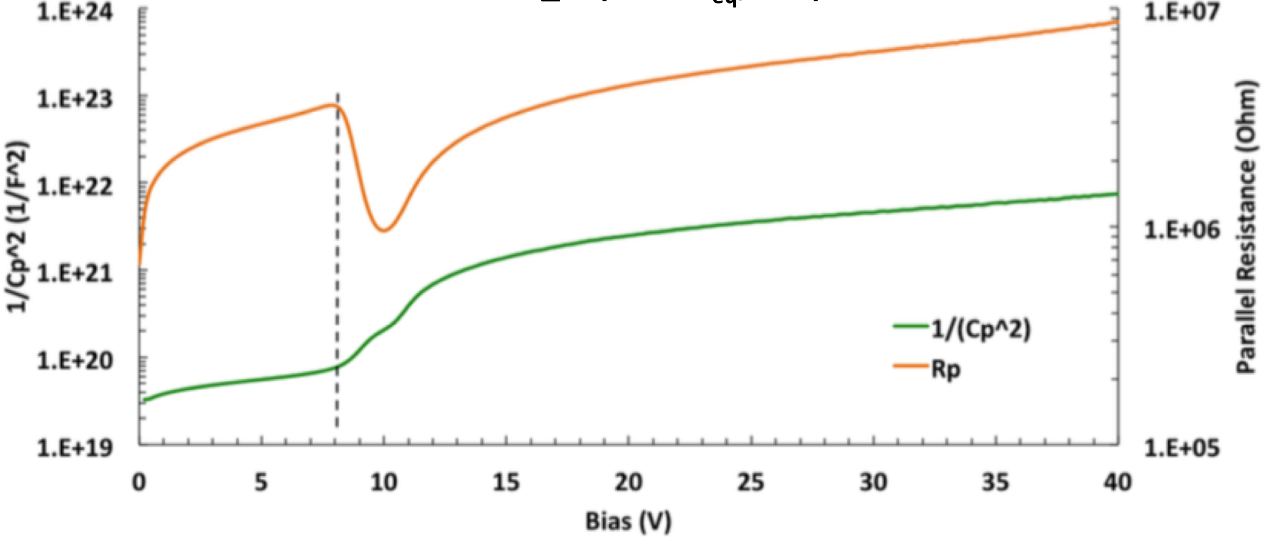
- Measurement Model = $C_p - R_P$
- Measurement Frequency = 1 kHz
- Measurement temperature = Room Temperature
- Sensors measured after annealing (80min @ 60°)

V_{GL} Extrapolation method

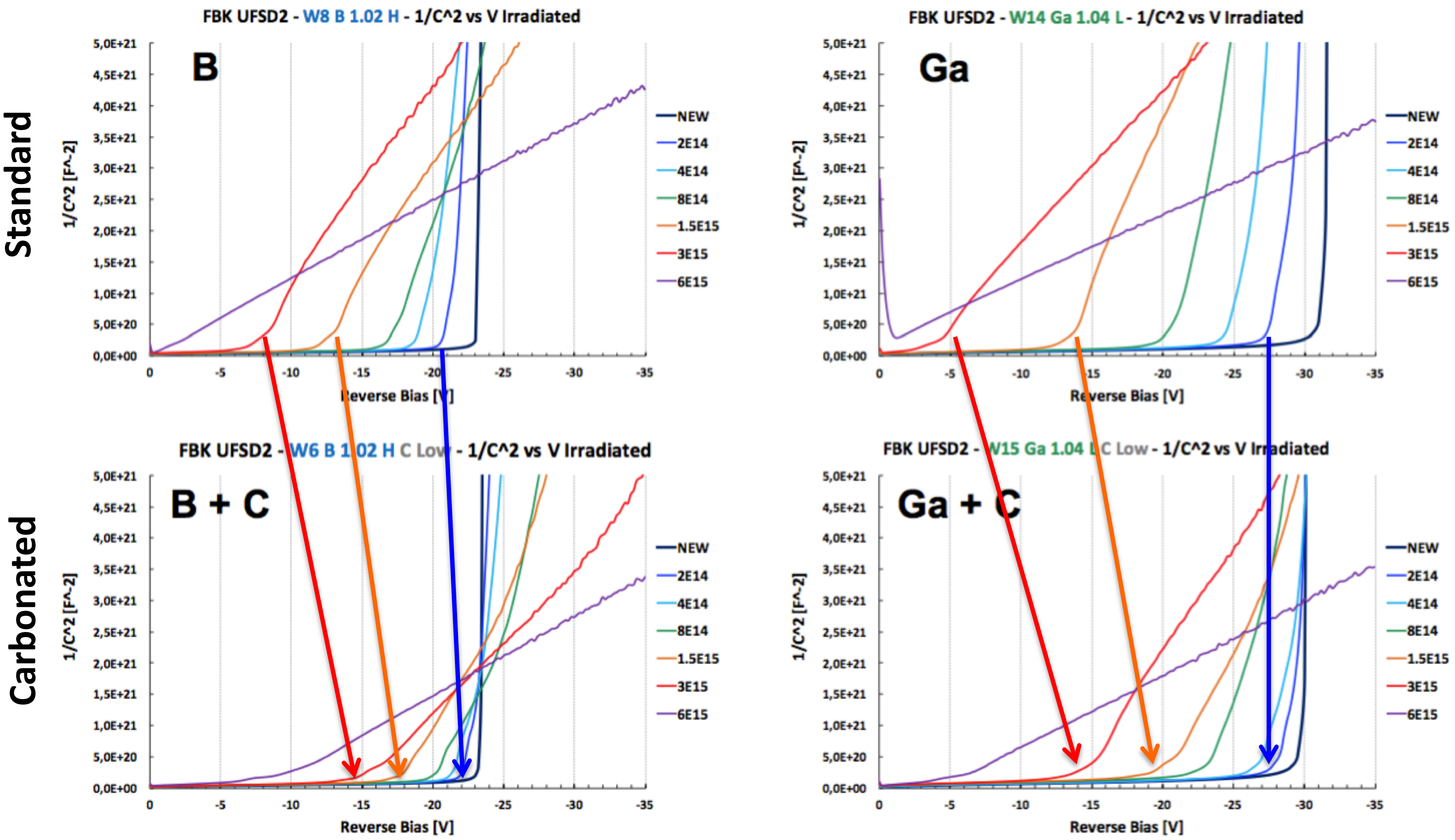
Using the **cusp on the R_p curve**, in coincidence with the **foot in the $1/C_p^2$ curve**

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

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



Neutrons Irradiation effects on Gain layer



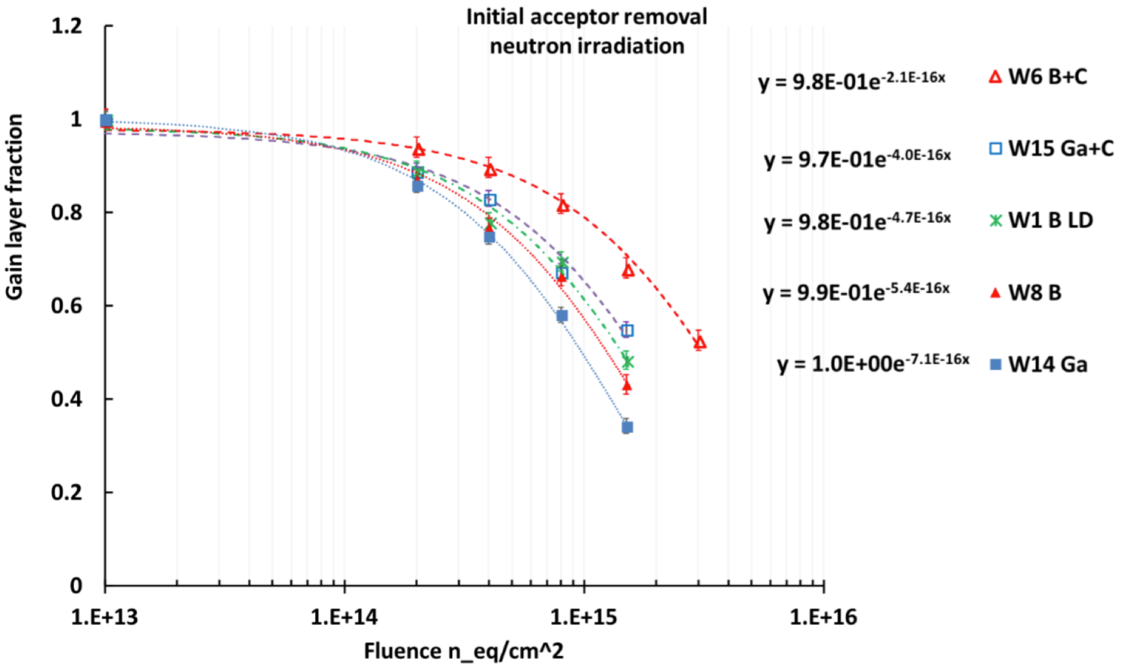
Carbon implant **mitigate** the reduction of the active acceptor density into gain layer

Measurement of coefficient “*c*”

Neutrons

Fraction of active acceptor density

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



Results:

- **Carbonated** sensors are more radiation resistant than not carbonated of a factor ~2
- **Gallium** is less resistant than Boron
- **Boron Low Diffusion** is more resistant than **Boron High Diffusion**

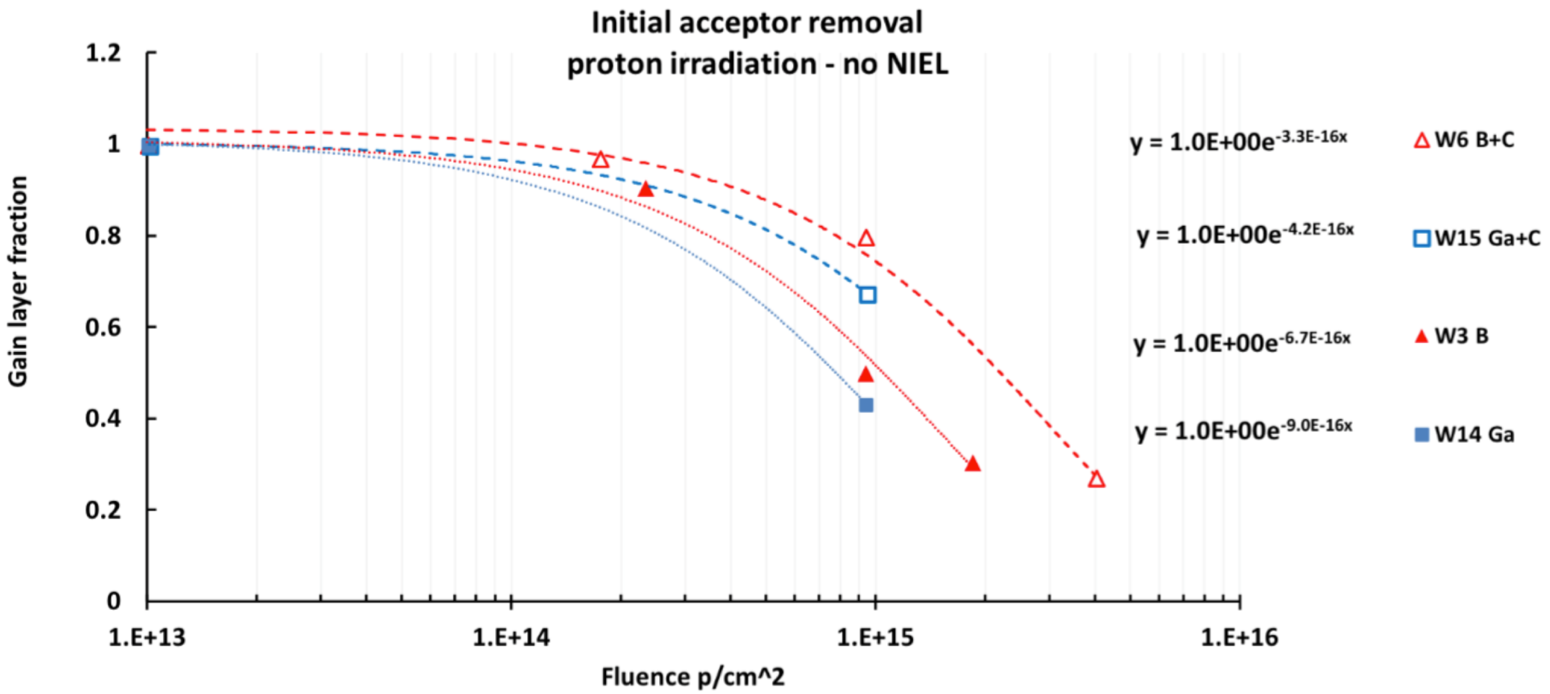
Each point on the plot is the average about two sensors

Measurement of coefficient “*c*”

Protons 24Gev/c

Fraction of active acceptor density

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



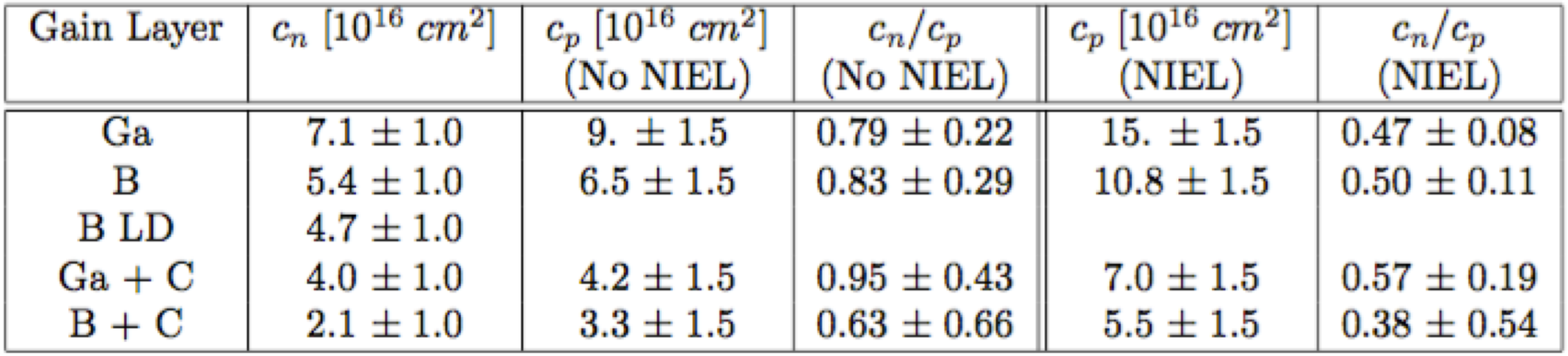
In this plot the NIEL factor of 0,6 was not used

Coefficient "*c*" comparison between Neutrons and Protons

Neutron

Proton (No NIEL)

Proton (NIEL)



Gain Layer	$c_n\ [10^{16}\ cm^2]$	$c_p\ [10^{16}\ cm^2]$ (No NIEL)	c_n/c_p (No NIEL)	$c_p\ [10^{16}\ cm^2]$ (NIEL)	c_n/c_p (NIEL)
Ga	7.1 ± 1.0	$9. \pm 1.5$	0.79 ± 0.22	$15. \pm 1.5$	0.47 ± 0.08
B	5.4 ± 1.0	6.5 ± 1.5	0.83 ± 0.29	10.8 ± 1.5	0.50 ± 0.11
B LD	4.7 ± 1.0				
Ga + C	4.0 ± 1.0	4.2 ± 1.5	0.95 ± 0.43	7.0 ± 1.5	0.57 ± 0.19
B + C	2.1 ± 1.0	3.3 ± 1.5	0.63 ± 0.66	5.5 ± 1.5	0.38 ± 0.54

Considering the **real value of proton fluence** (p/cm^2) the c_p coefficients (proton) and the c_n ones (neutron) are **compatible** with each other.

If the **NIEL factor** was applied the c_p coefficients are almost **twice** c_n

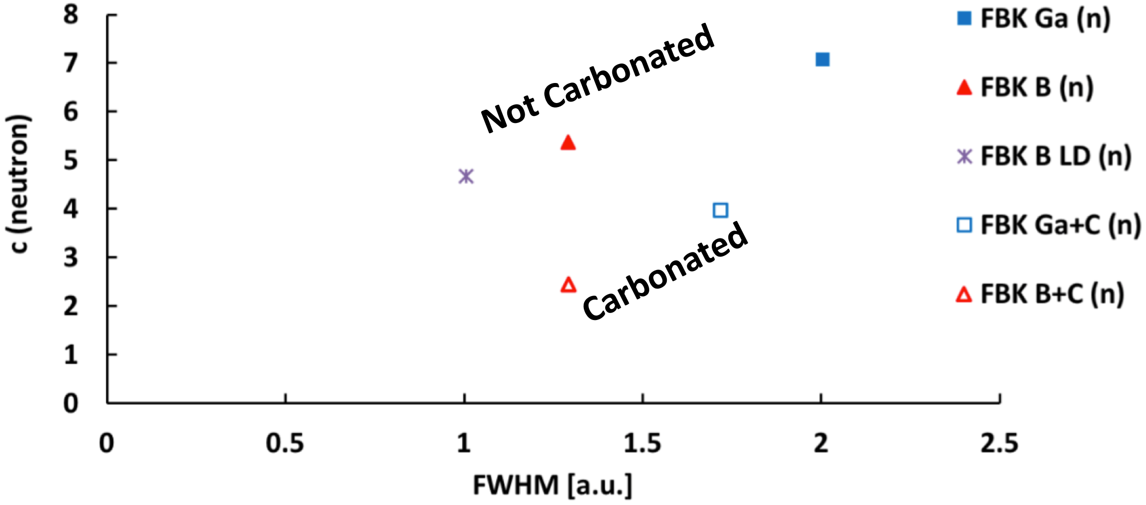
Relationship between c_n and the spatial extension of the gain layer

Wafer #	Dopant	Gain Dose	Width [a.u.]
1	B LD	0.98	1
3	B	1.00	1.3
6	B + C	1.02	1.3
8	B	1.02	1.3
14	Ga	1.04	2.0
15	Ga + C	1.04	1.7

Gain layer width in arbitrary unit extracted at the FWHM of the doping profile of the implant

Boron LD, Boron and Gallium has different spatial extension of gain layer

Value of the acceptor removal coefficient as a function of implant width



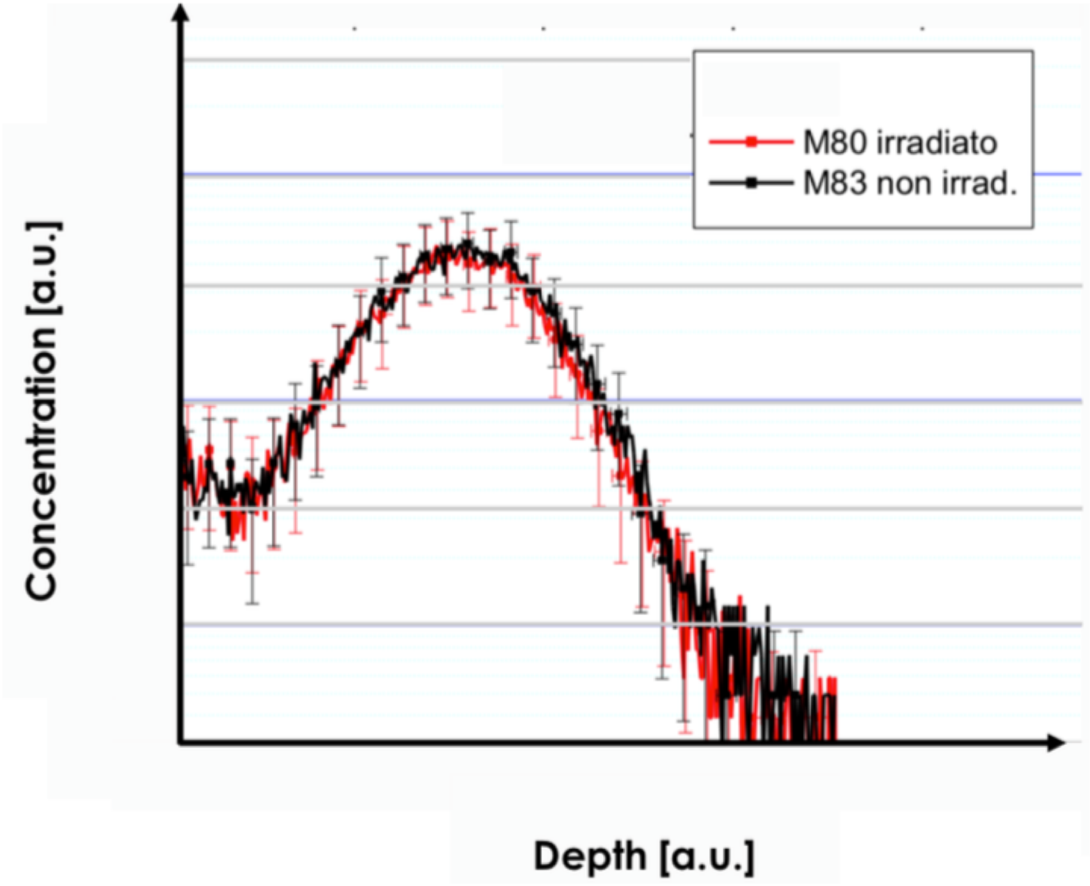
The radiation resistance is inversely proportional to the gain layer width.

The initial acceptor removal mechanism is faster for wider implant

Effect holds true for carbonate and not - carbonated sensors

Secondary Ion Mass Spectrometer (SIMS) on Irradiated LGAD $1\cdot10^{16}$ (n_{eq}/cm^2)

SIMS measurement shows the density of Boron atoms (active and not-active) forming the gain layer



Sensor M83
No Irradiated

Sensor M80
Irradiated $1\cdot10^{16}$ n_{eq}/cm^2

M80 sensor has:

- **No active gain layer left**

however it has

- **The same spatial distribution of Boron atoms than a new sensor**

Acceptor Creation

$$N_A(\phi) = g_{eff}\phi$$

Extrapolation of acceptor density in p-bulk (Method)

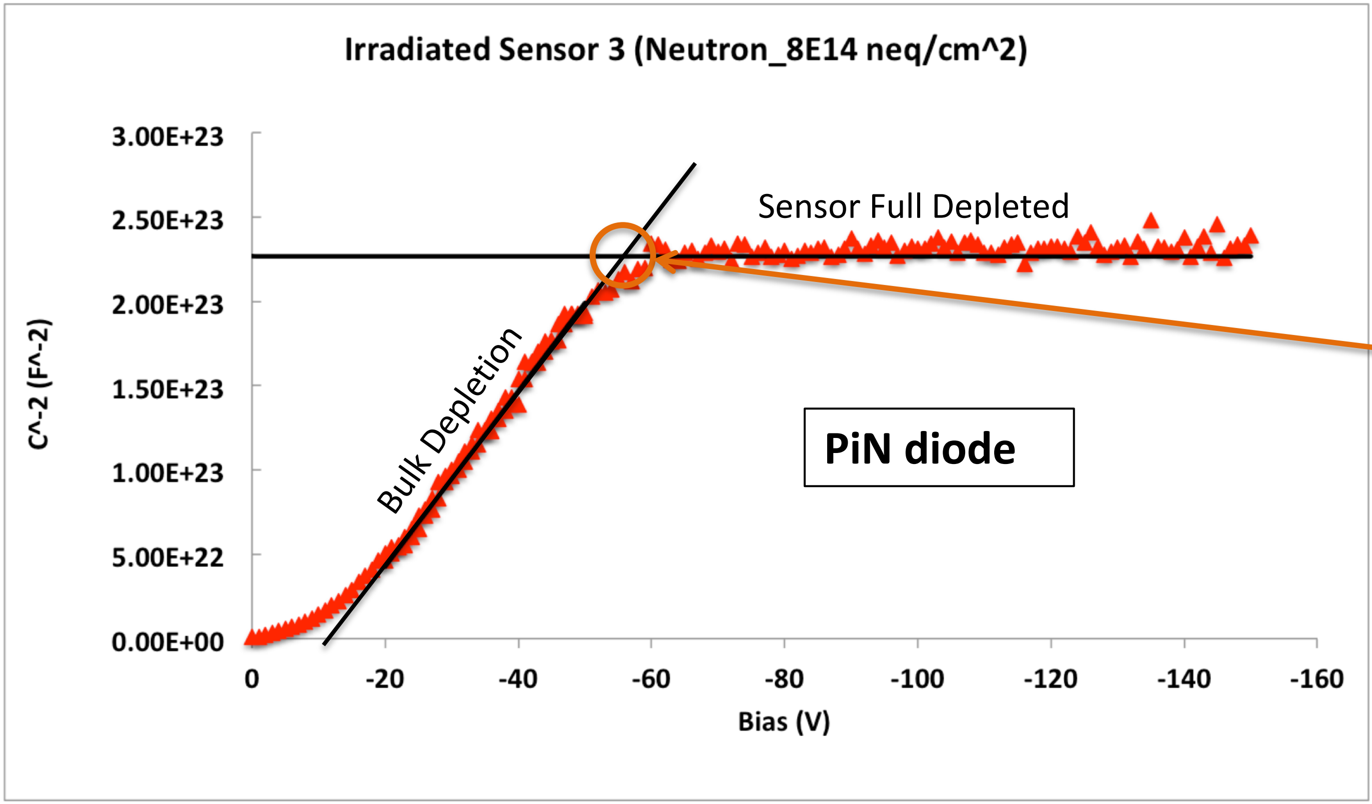
Acceptor Creation Model

$$N_A(\phi) = g_{eff}\phi$$

Extrapolation of acceptor density into the p-bulk

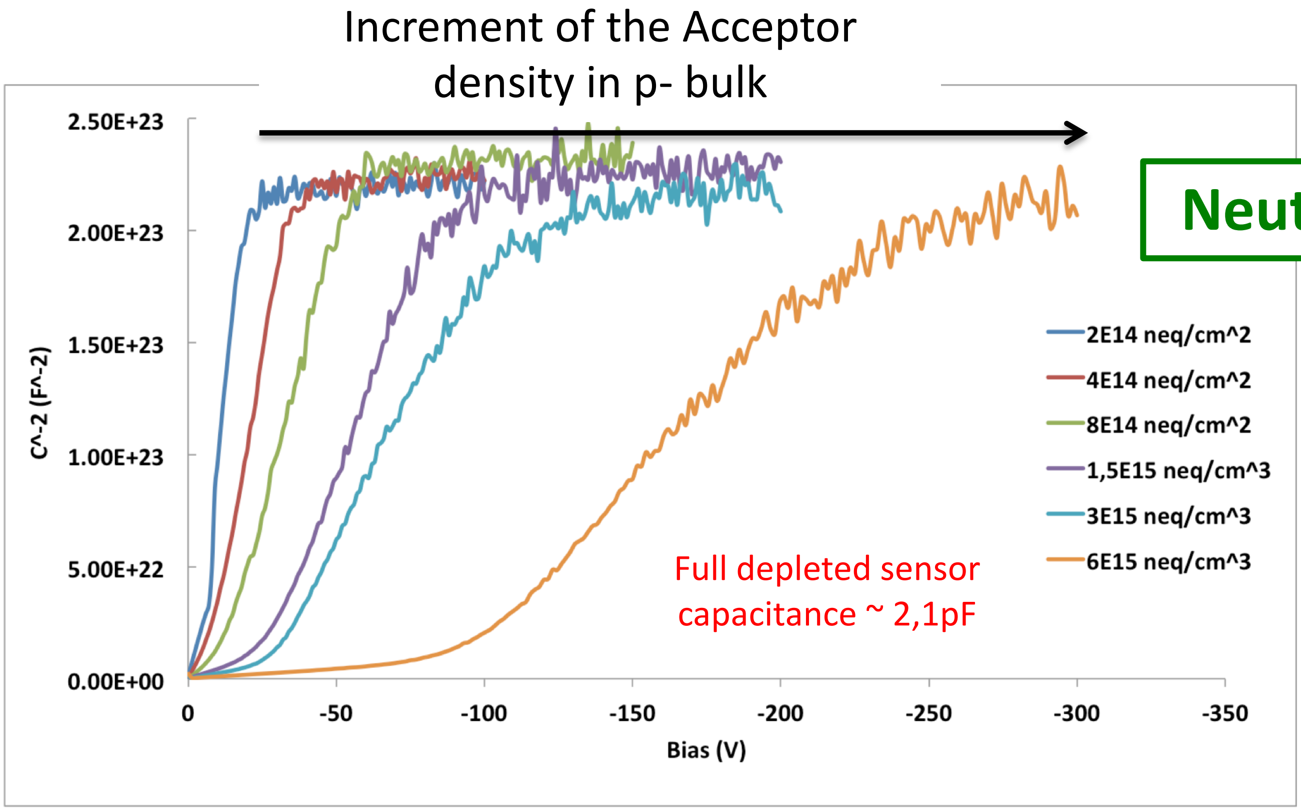
Assuming an uniform acceptor Creation in 50µm thickness

$$N_A = 2V_{FD}C^2/A^2 e\varepsilon_{Si}$$



Full Depletion Voltage

Neutrons Irradiation effects on p-bulk 50µm thick

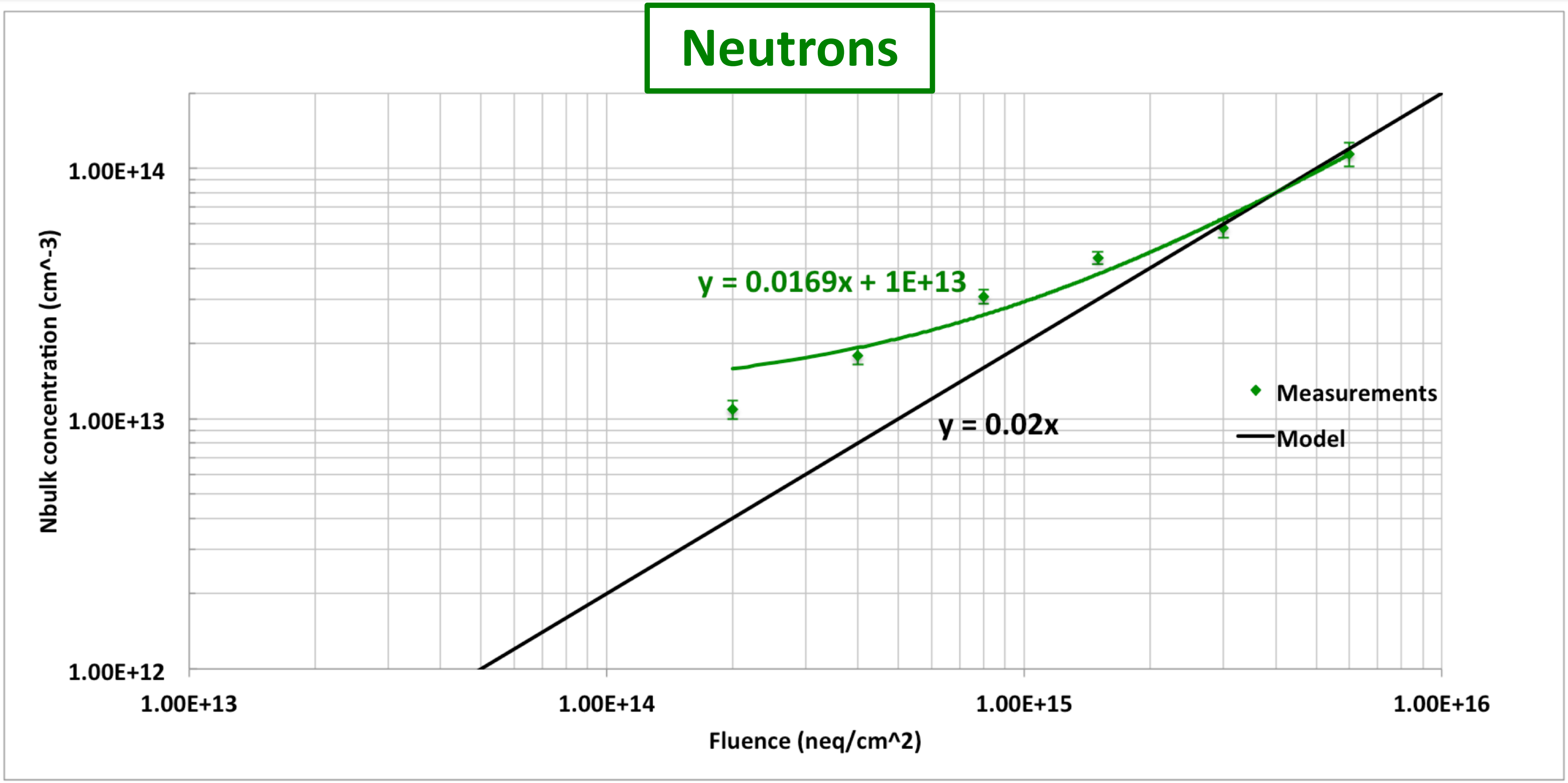


Neutrons

C-V Measurement parameters:

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

Acceptor Creation in 50µm thick PiN diodes

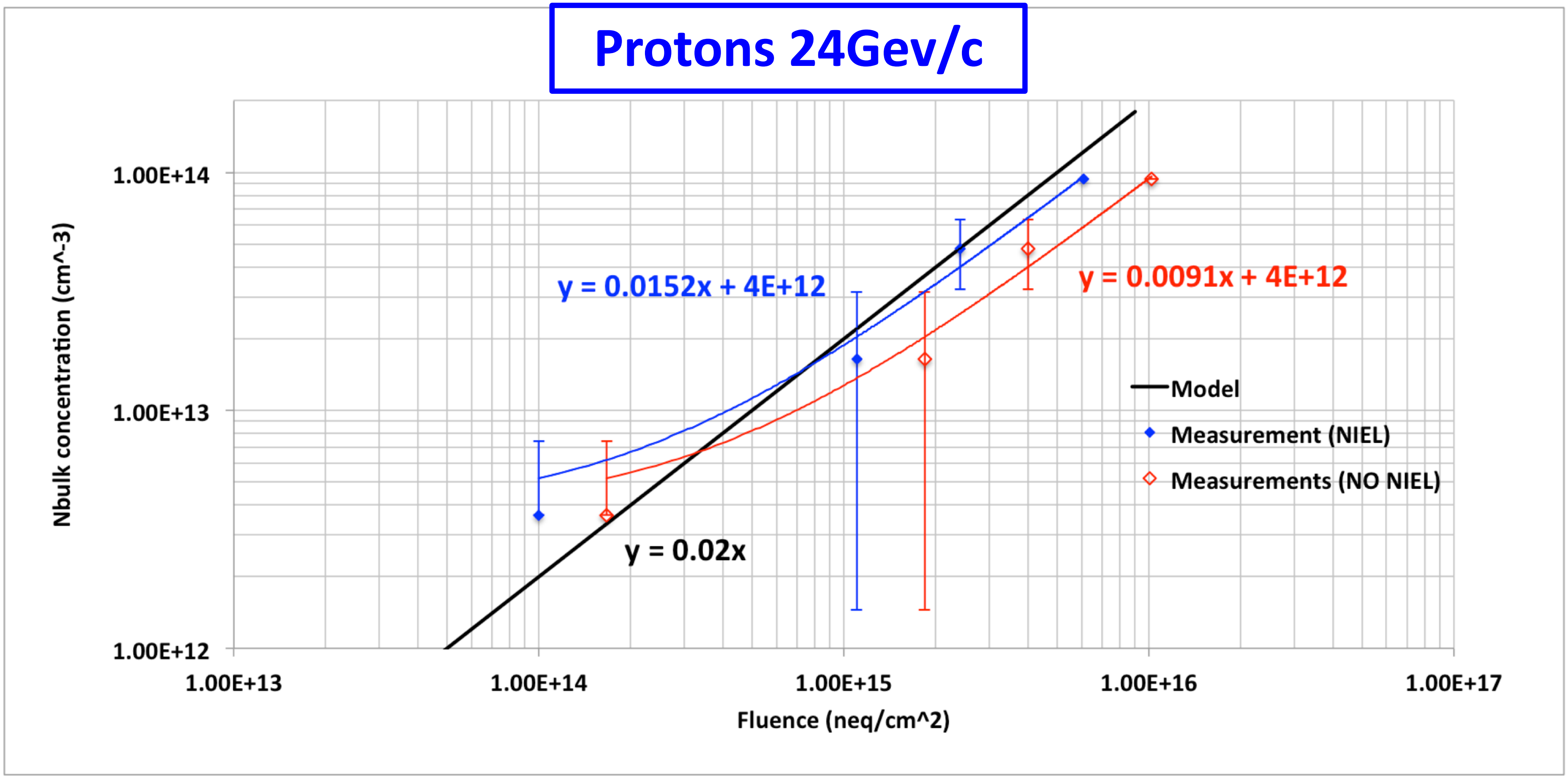


- High fluences (~ 3•10^{15} n_{eq}/cm^2): data in agreement with the model, g_{eff}=0,02cm^{-1} is a good parameterization

- Low fluences (~ 10^{14} n_{eq}/cm^2): increasing of the distance between data and model as fluences decrease, **is it possible a not complete acceptor removal**?

Acceptor Creation in 50µm thick PiN diodes

Protons 24Gev/c



- Applying the NIEL there is an agreement between data and model at fluences ~10^{15} n_{eq}/cm^2
- Without NIEL Factor the parameterization of g_{eff} is lower than 0,02cm^{-1}

Summary

- The addition of Carbon to the gain layer improves the radiation resistance, the *c* coefficients are about a factor of two smaller for B+C and Ga+C than B and Ga
- The c_p coefficients of acceptor removal are comparable with c_n coefficients considering the real protons fluence. Instead applying the NIEL Factor to the protons fluence the c_p coefficients are almost twice c_n.
- Thinner and more doped gain layer implants are less prone to initial acceptor removal: B LD has a lower c_n coefficient than B.
- Acceptor Creation measurements on neutrons irradiated PiN diodes are in agreement with the model $N_A = g_{eff}\Phi$ (g_{eff}= 0,02 cm^{-1}) for fluences above 10^{15} n_{eq}/cm^2
- Acceptor Creation measurements on protons irradiated PiN diodes are comparable with results obtain with neutrons if the NIEL Factor is used. Considering the real protons fluence, the g_{eff} parameter is lower than 0,02 cm^{-1}

Acknowledgements

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- INFN - Gruppo V
- Horizon 2020, grant UFSD669529
- Horizon 2020, grant INFRAIA
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- U.S. Department of Energy grant number DE-SC0010107
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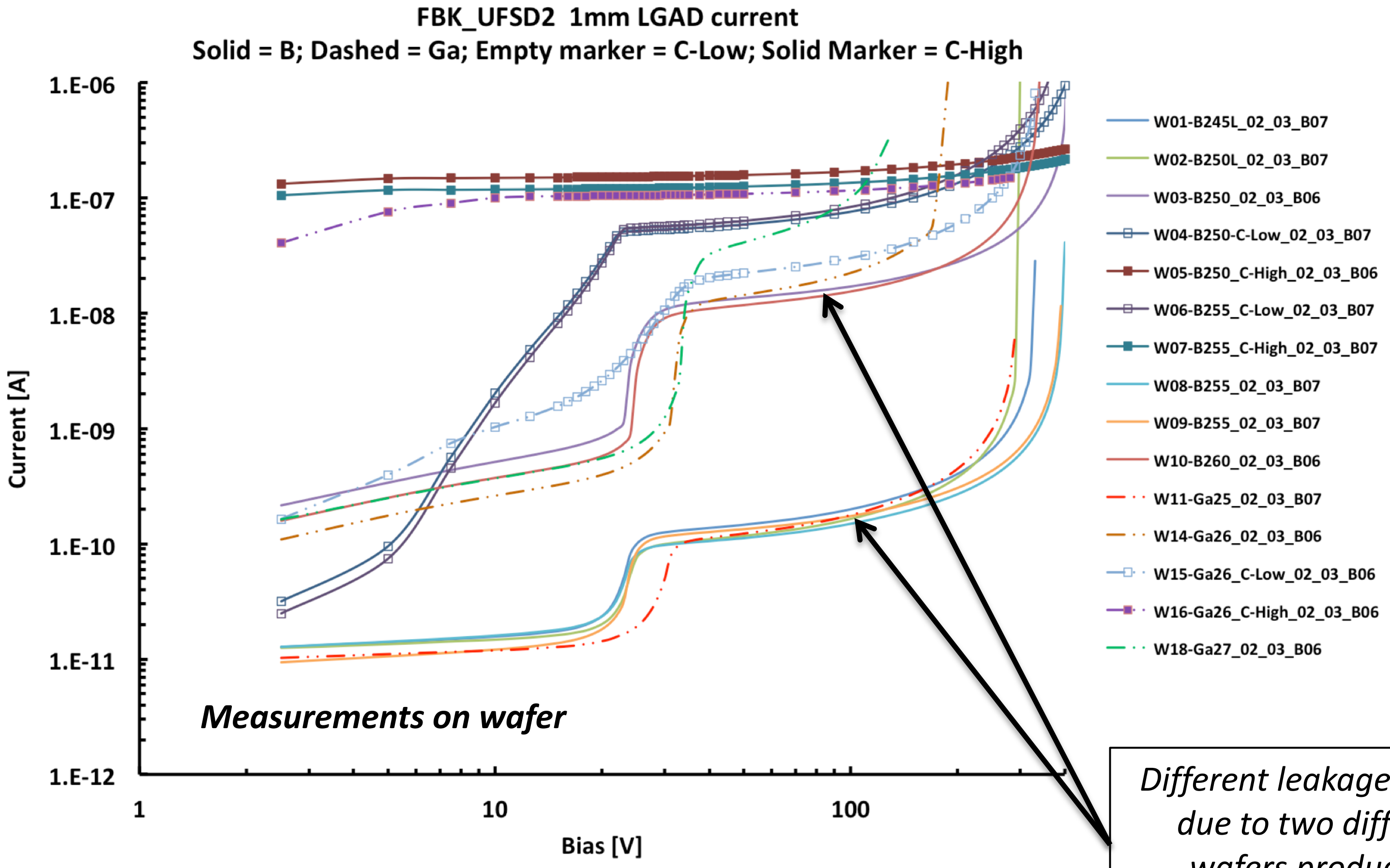
Backup

Marco Ferrero, INFN/Università di Torino, 32^{nd} RD50 Workshop, Hamburg 4-6 June 2018

IV Curve on UFSD2 (Not Irr)



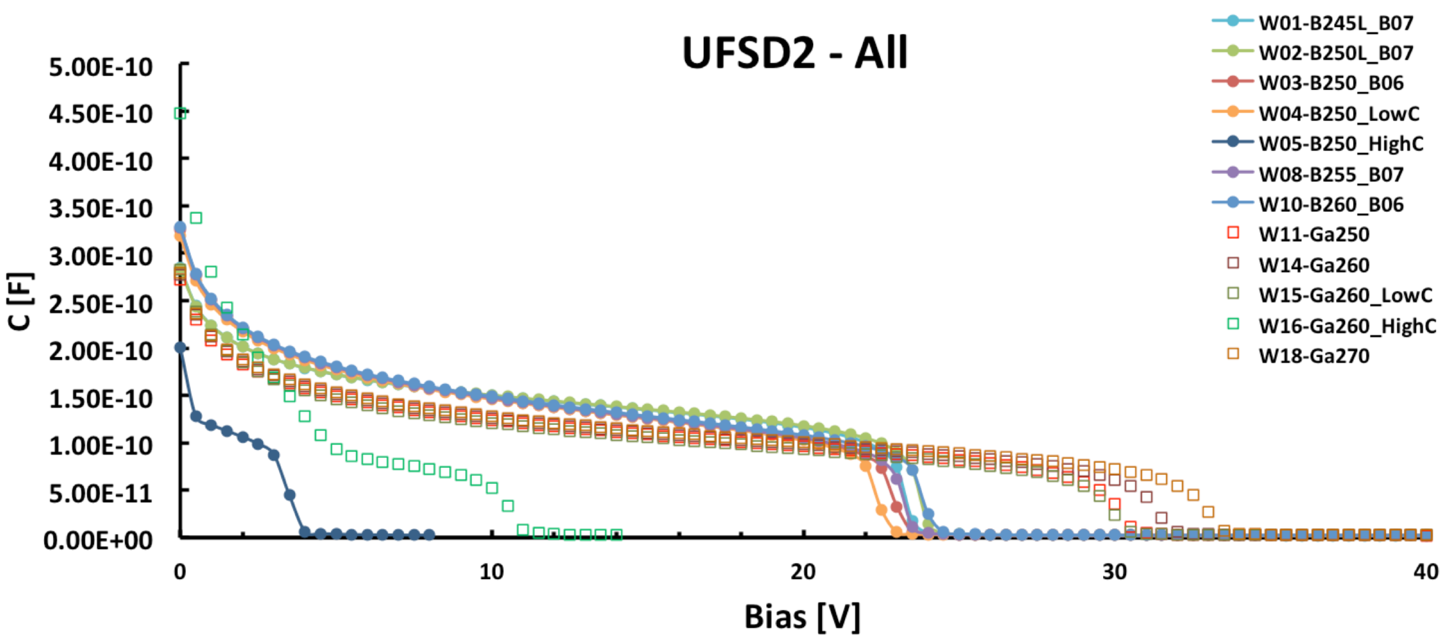
Measurements on wafer

Different leakage current due to two different wafers production batches

IV Curves information:

- ➢ Boron and Gallium doped sensors show the same behavior;
- ➢ Low leakage current (>10s pA; <10s nA);
- ➢ The knee at ~30V proves the gain layer implant;
- ➢ Current Exponential growth gives an information about the internal gain of the sensors;

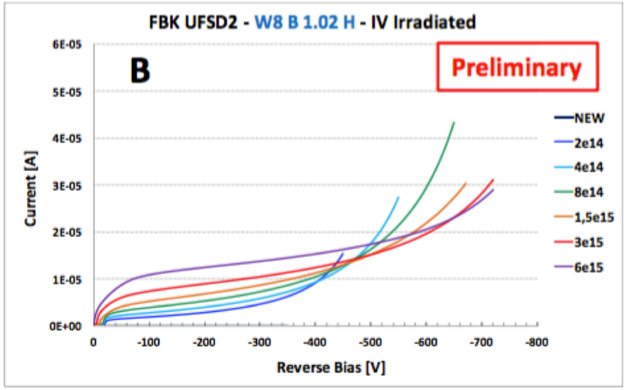
CV Curves of UFSD2 (Not Irr)

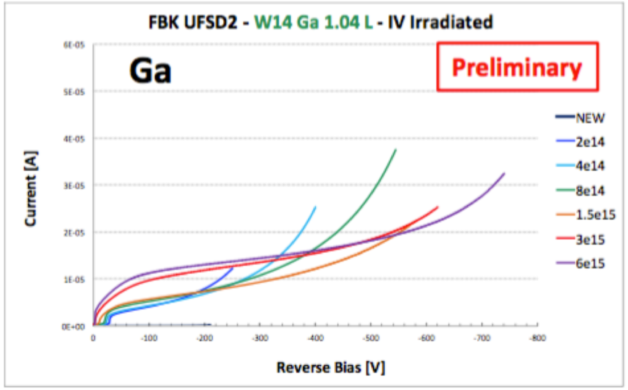


CV Curves of all wafer (B/Ga/B-C/Ga-C)

IV Measurements on Irradiated Sensors

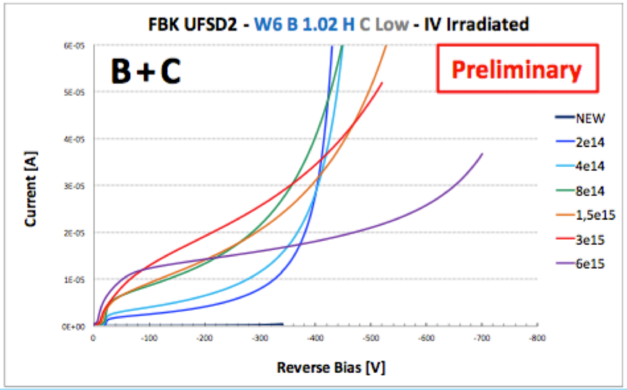
Standard

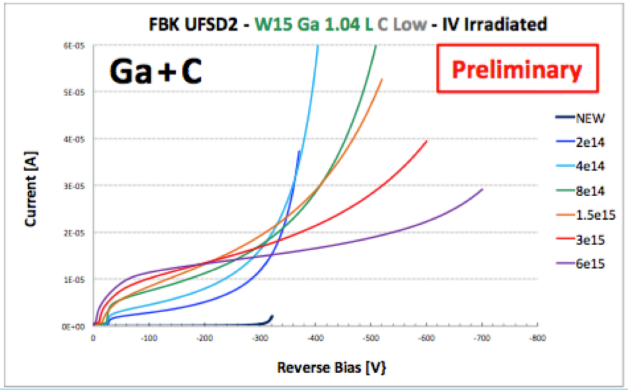

FBK UFSD2 - W8 B 1.02 H - IV Irradiated


FBK UFSD2 - W14 Ga 1.04 L - IV Irradiated

Curvature proportional to gain

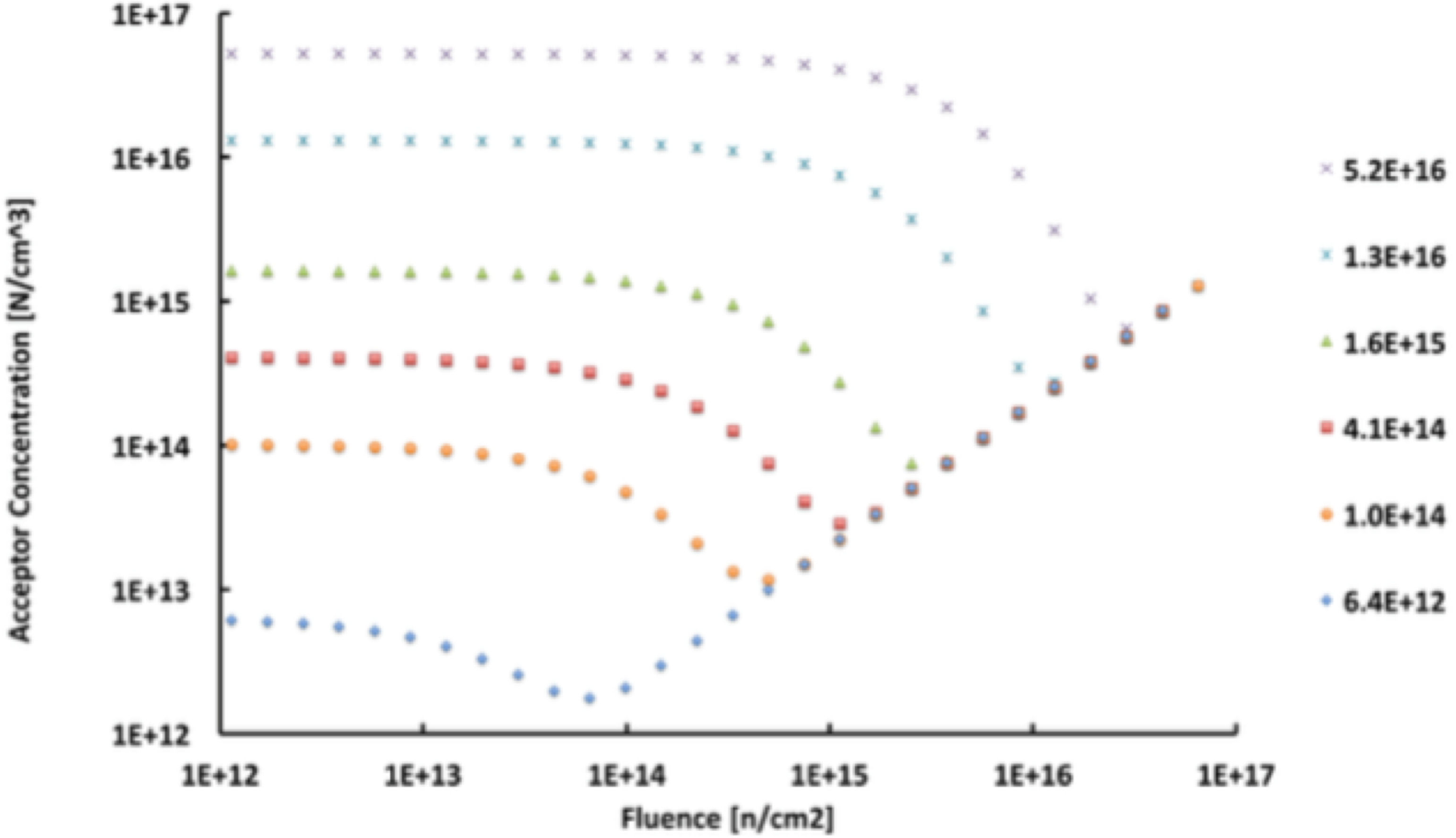
Carbonated


FBK UFSD2 - W6 B 1.02 H C Low - IV Irradiated


FBK UFSD2 - W15 Ga 1.04 L C Low - IV Irradiated

Irradiation extends the operating voltage of the sensors up to ~ 750 V

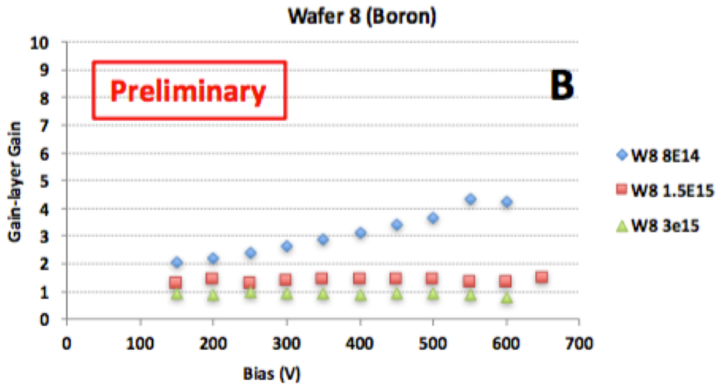
Initial acceptor removal + Acceptor Creation

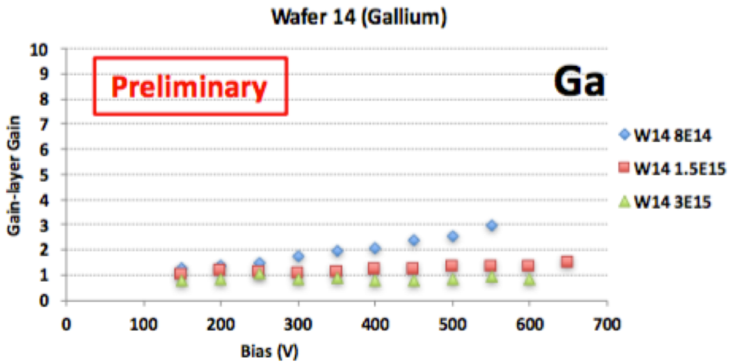


Gain Of Irradiated sensors

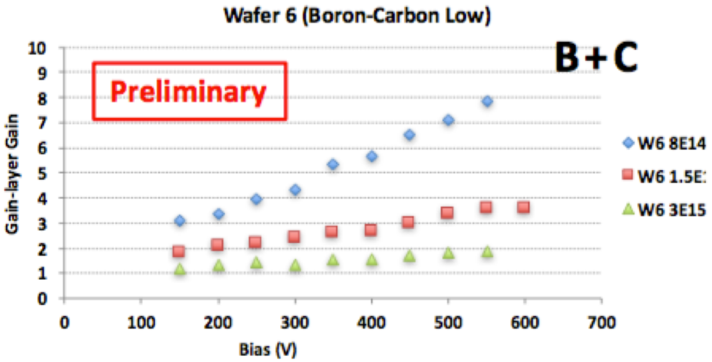
GAIN = (Signal area LGAD)/(Signal area PiN) irradiated at the same fluence → only from gain layer

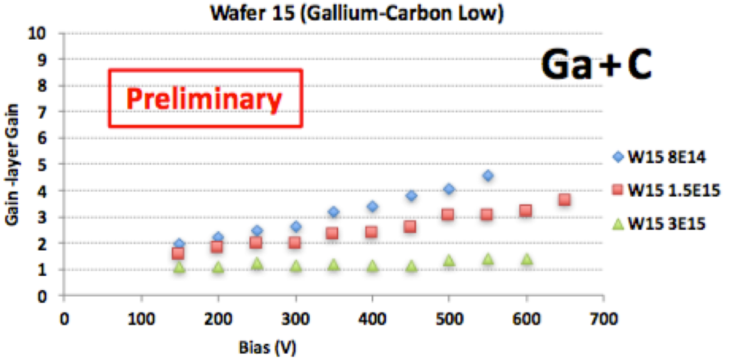
Standard





Carbonated

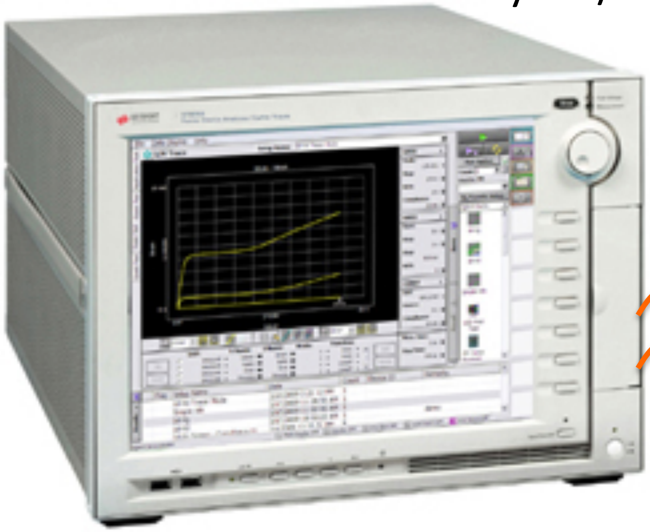




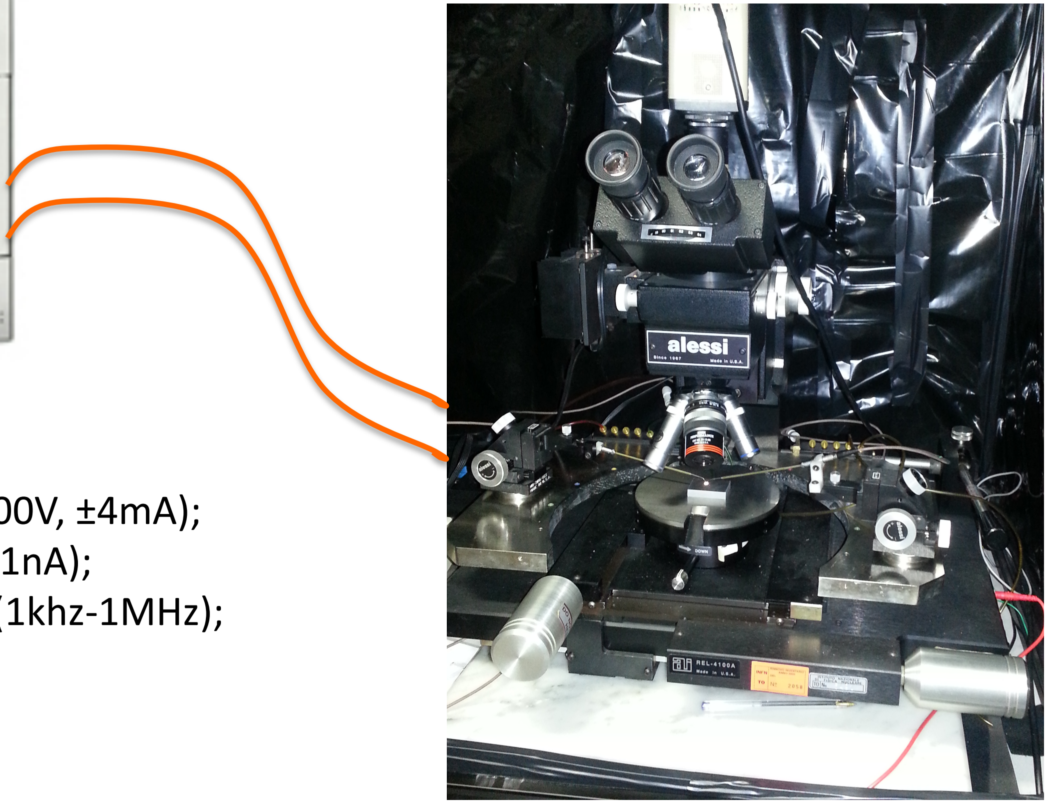
- **Carbonated Boron at ~ 600 V maintains factor 2 higher gain than standard Boron**

CV measurements (laboratory setup)

Keysight
B1505A Power Device Analyzer / Curve Tracer



Probe station



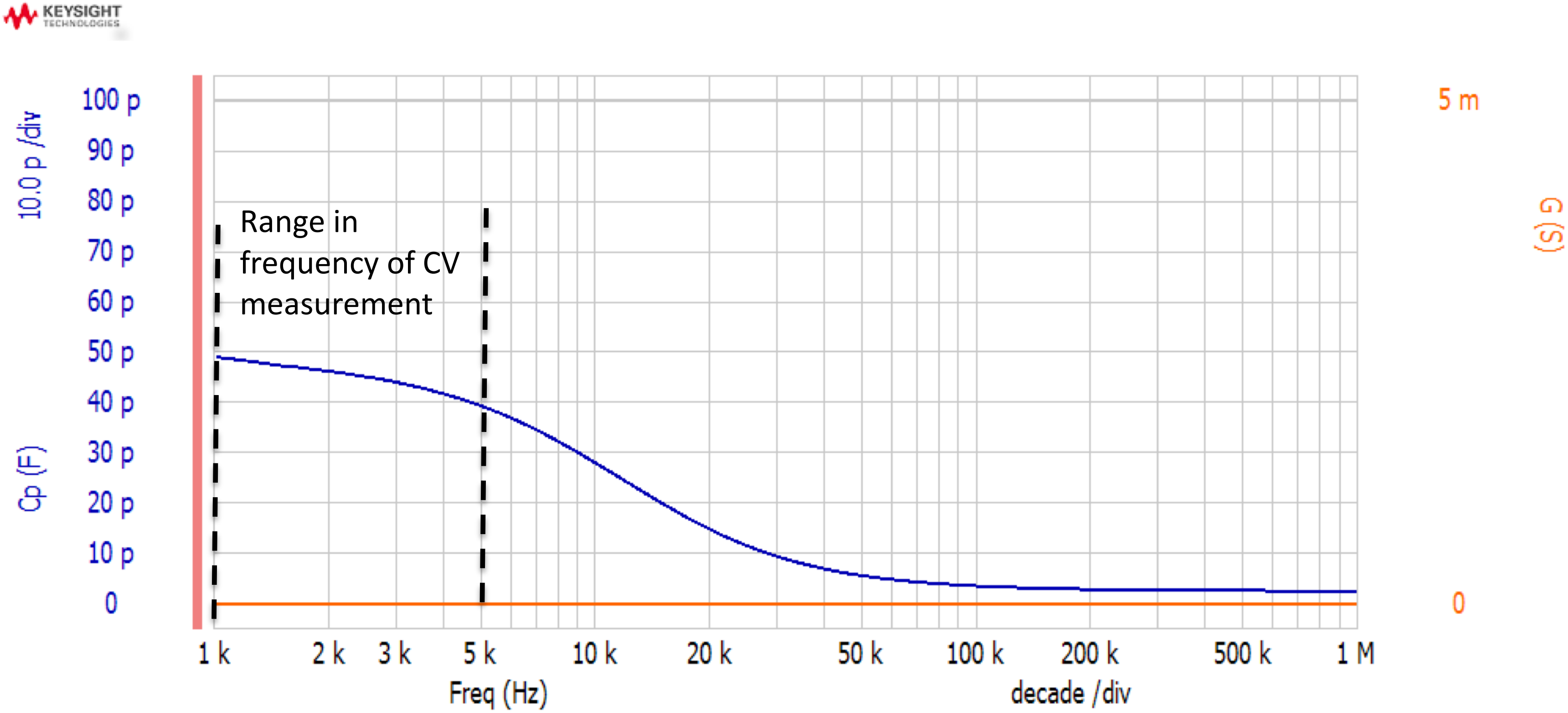
Modules

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

Marco Ferrero, INFN/Università di Torino, 32^{nd} RD50 Workshop, Hamburg 4-6 June 2018

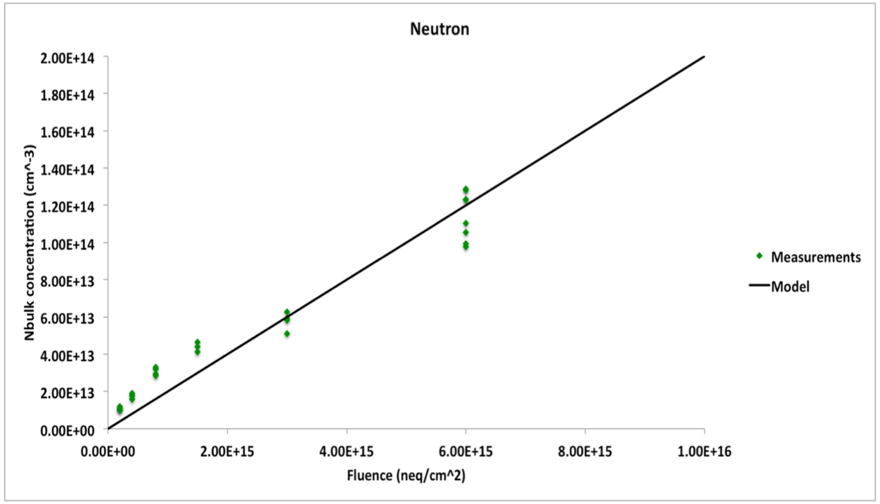
Cf measurements of irradiated sensor ($3•10^{15}$ n_{eq}/cm^2)

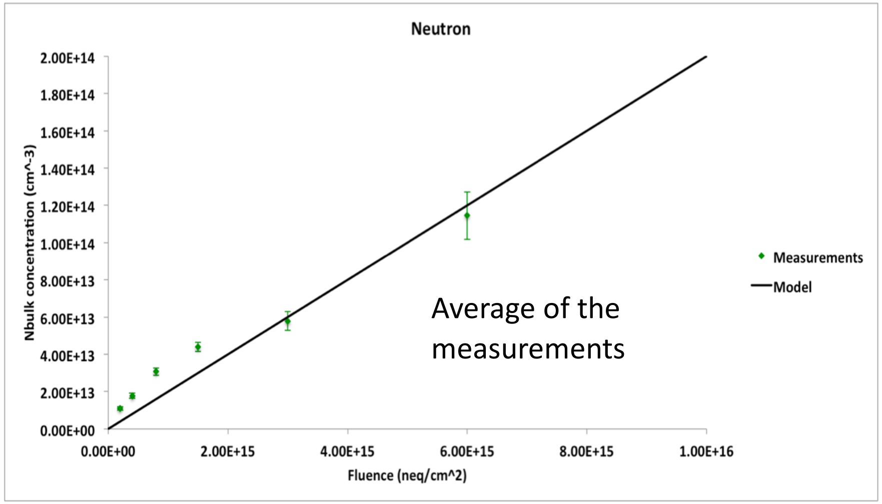
Cf measurements of an LGAD sensors (Wafer 8, Boron) irradiated with neutrons (fluence = $3•10^{15}$ n_{eq}/cm^2)



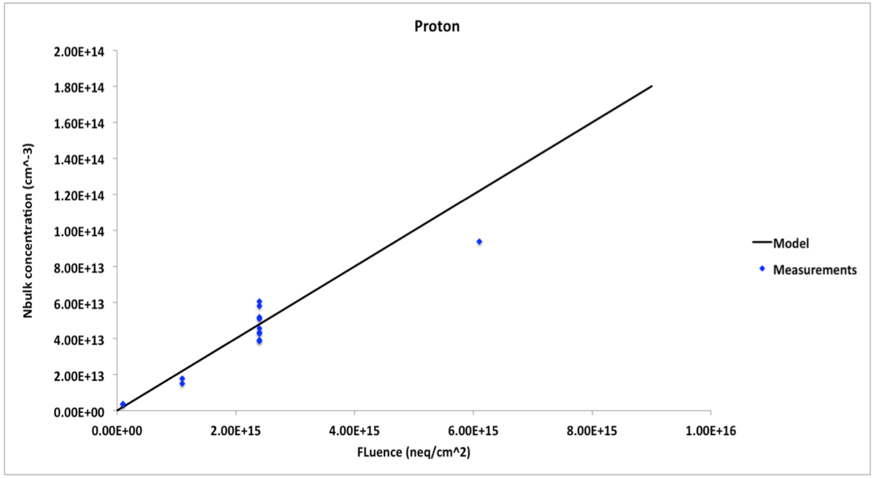
Range in frequency of CV measurement

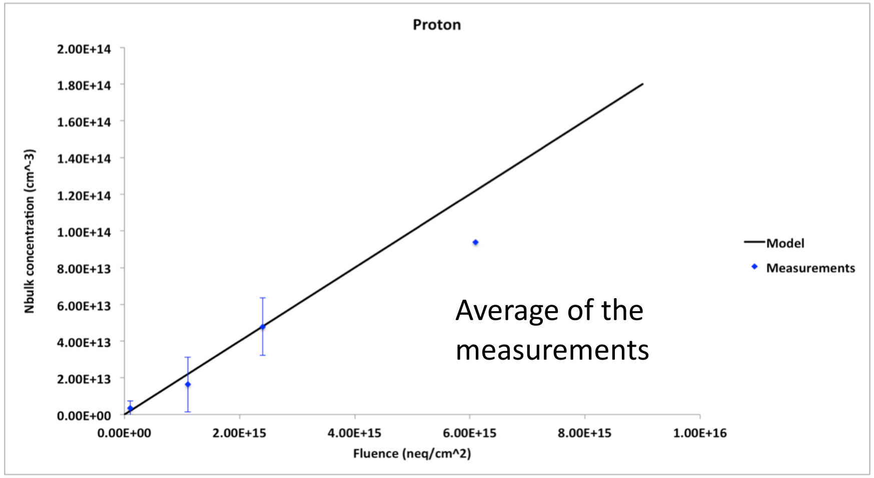
Acceptor Creation





Average of the measurements





Average of the measurements