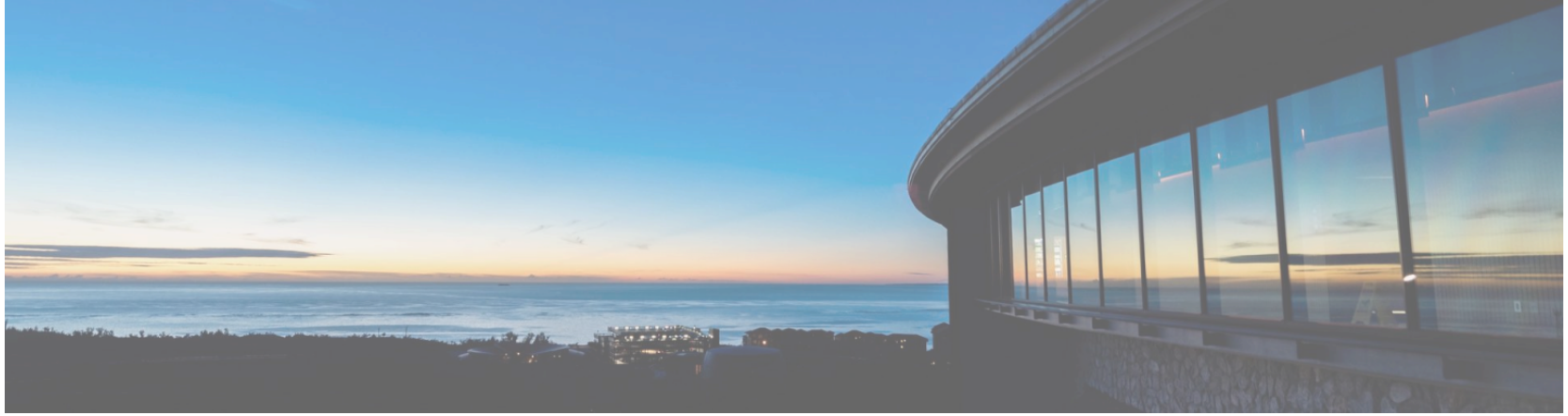


11th International "Hiroshima" Symposium on the Development and Application of Semiconductor Tracking Detectors (HSTD11) in conjunction with 2nd Workshop on SOI Pixel Detectors (SOIPIX2017) at OIST, Okinawa, Japan
10-15 December 2017

First FBK 50 µm UFSD Production

V. Sola[1][2], R. Arcidiacono[1][3], M. Boscardin[4][5], N. Cartiglia[1], G.-F. Dalla Betta[1][6], F. Ficorella[4][5], M. Ferrero[1][2], M. Mandurrino[1], L. Pancheri[1][6], G. Paternoster[4][5], A. Staiano[1]

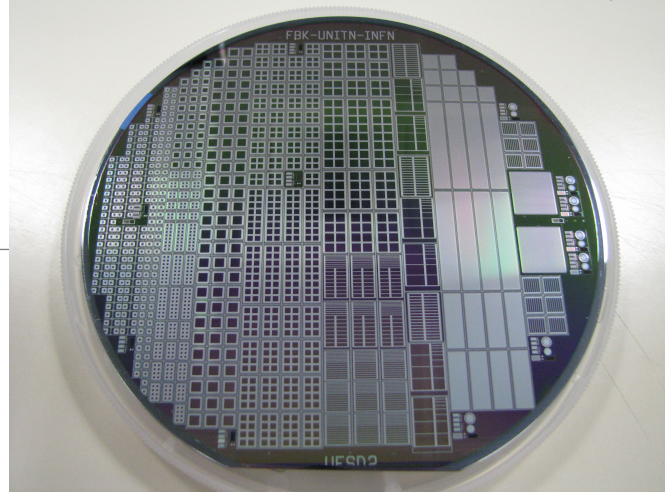
[1]INFN, [2]Università di Torino, [3]Università del Piemonte Orientale, [4]FBK, [5]TIFPA, [6]Università di Trento

OUTLINE

- **Production**
  - Doping strategies
  - IV measurements
  - CV measurements
  - Doping profiles - **Backup**
- **Laboratory Measurements**
  - Gain
  - Time resolution
  - Intra-pad inactive region - **Backup**
- **Simulation**
  - Gain predictions - **Backup**
- **Neutron Irradiated UFSD**
  - CV measurements
  - c-parameter extraction
  - Gain

PRODUCTION

50µm UFSD 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

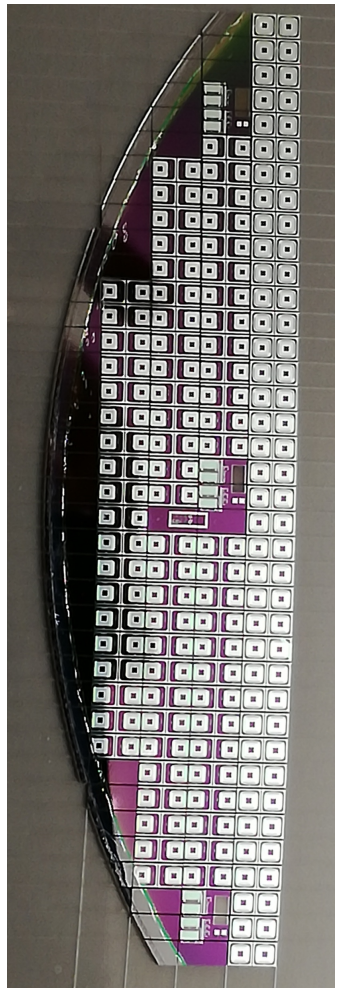
Production:

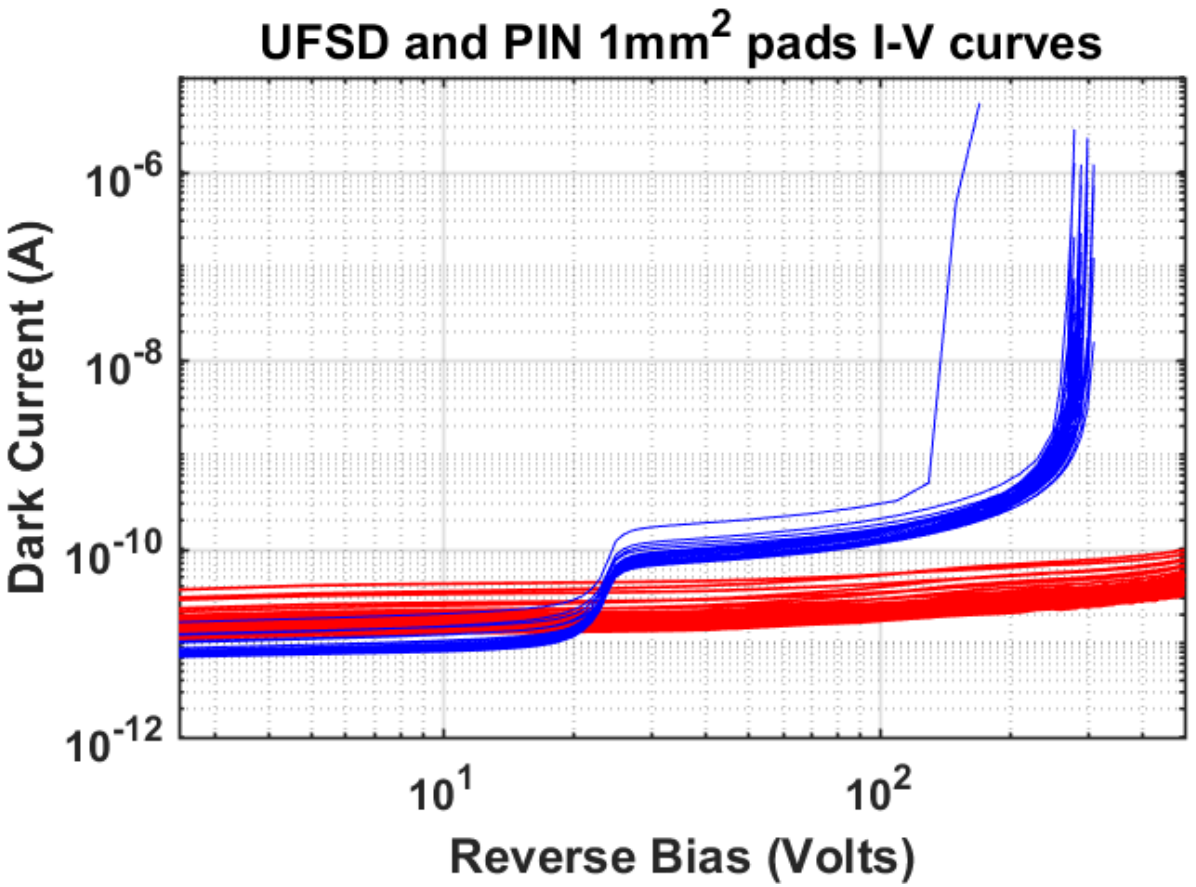
- 18 Silicon-on-Silicon wafers
- 4 different gain layer strategies:
  - **Boron** (Low & High diffusion)
  - **Carbonated Boron** (B High diffusion)
  - **Gallium** (Low diffusion)
  - **Carbonated Gallium** (Ga Low diffusion)
- 4 different doping concentration for Boron implants
- 2 different diffusion temperatures for Boron
- 3 different doping concentration for Gallium implants
- 2 carbon concentration (Low & High)

Carbonated Boron, Gallium & Carbonated Gallium implants to investigate radiation hardness

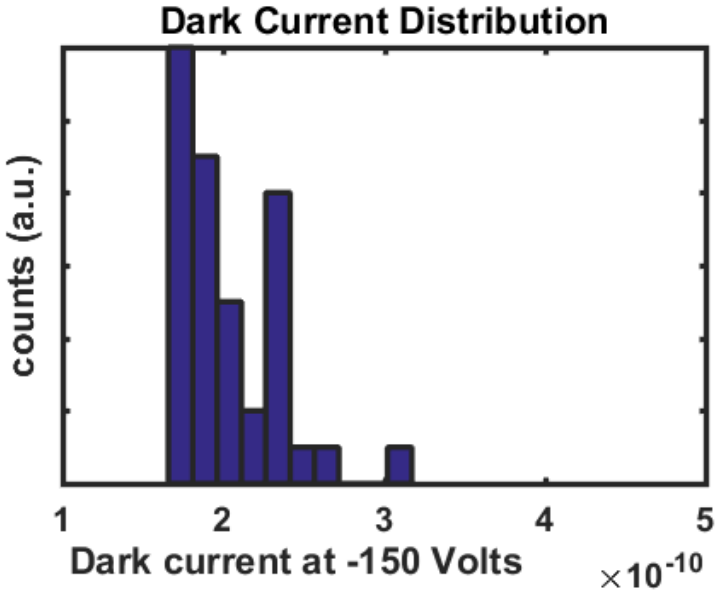
Gallium implant required a complete new simulation, because of implantation energy and diffusion very different from Boron

IV Curves - Wafer Uniformity





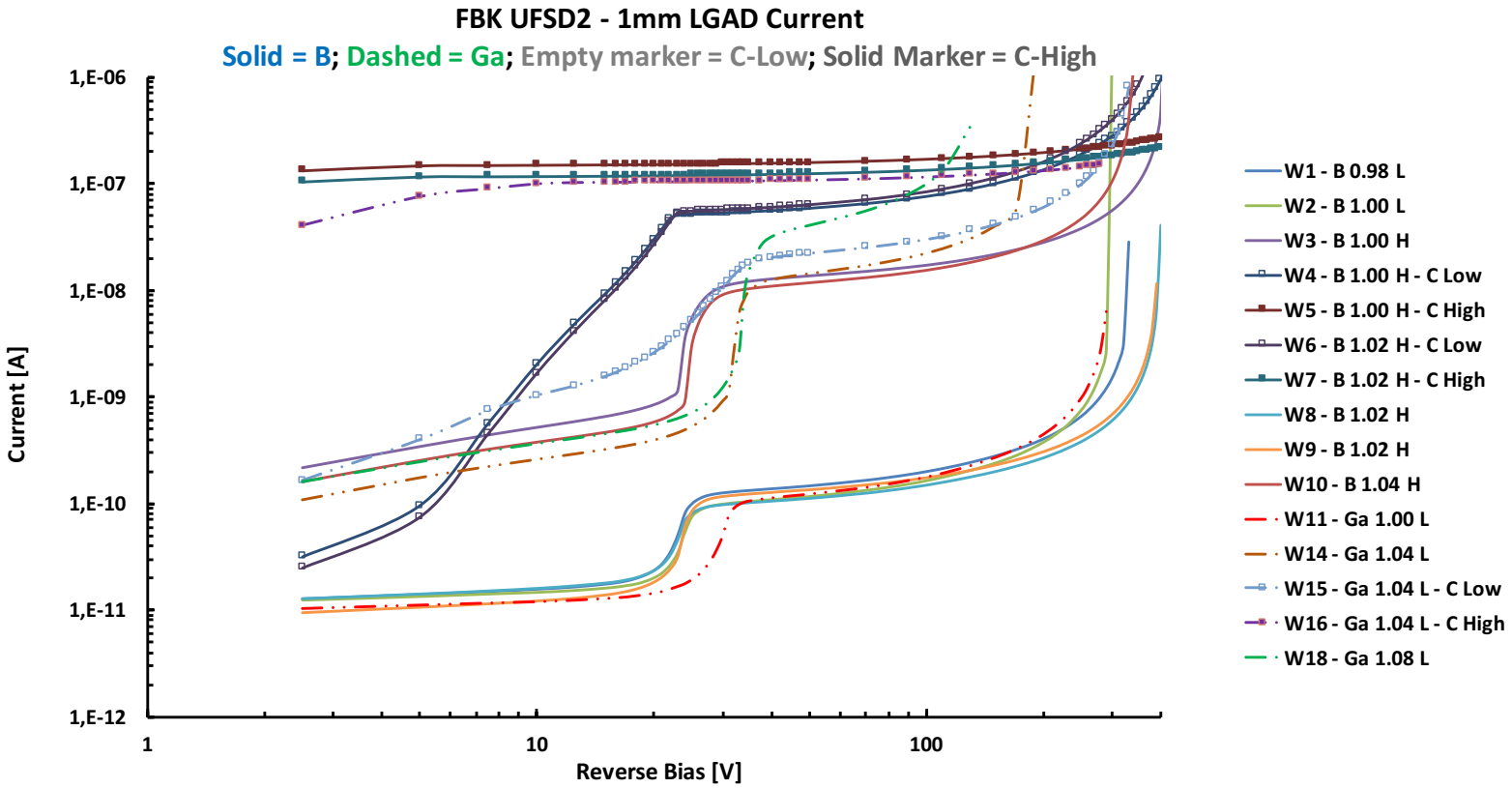
Data from Wafer 2
Boron LD Dose Factor = 1.0
Measurements on wafer



All the 1x1 mm^2 pads are plotted without any die selection

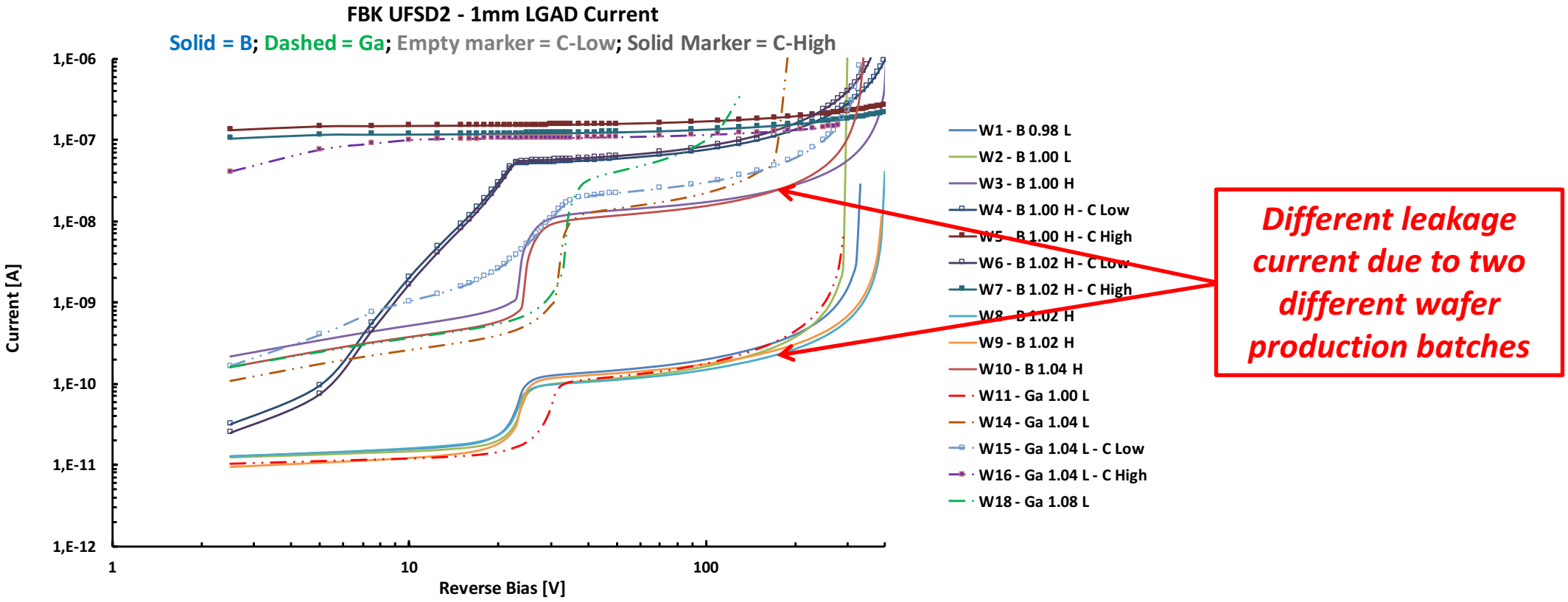
→ **Very high uniformity and low dark current**

IV Curves - All Wafers



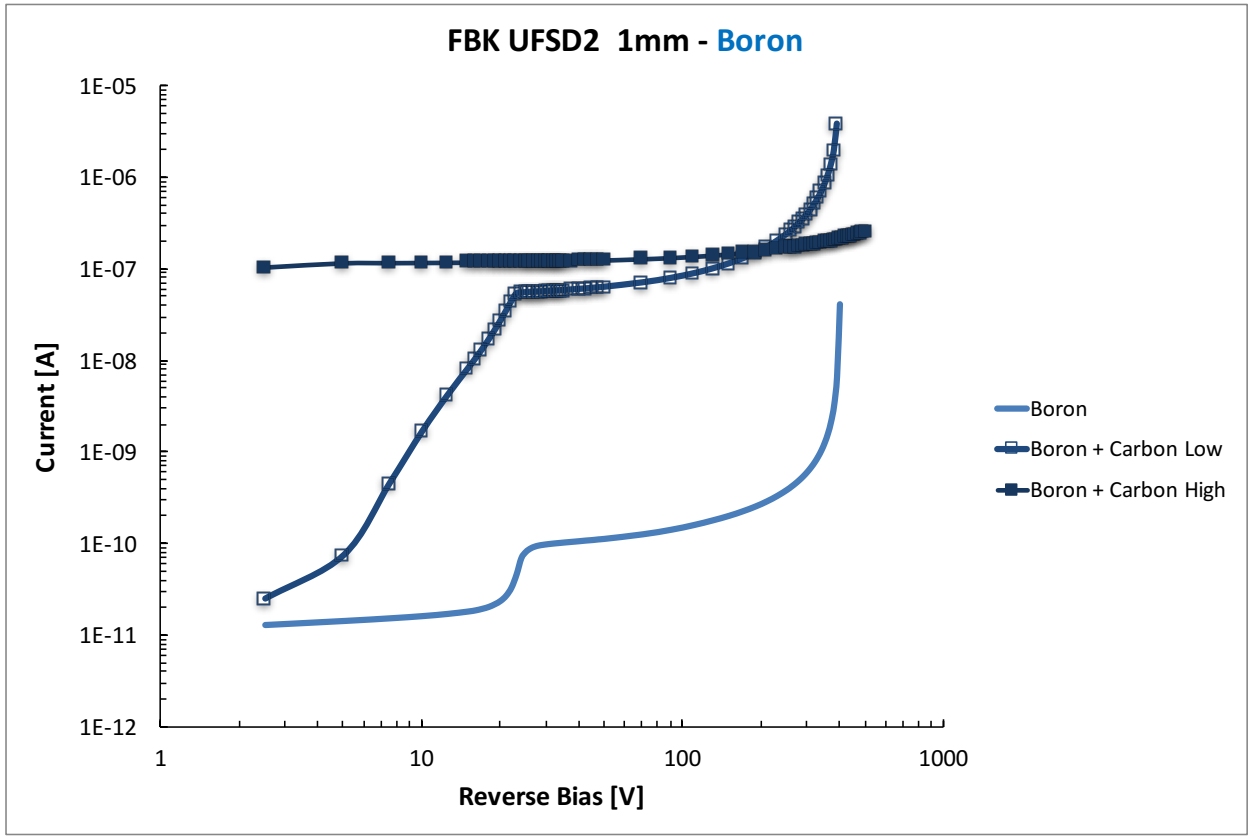
- Boron & Gallium doped sensors show the same behavior
- Low leakage current (10s pA ÷ 10s nA)
- The knee at ~30V indicate the the gain layer depletion voltage
- Exponential growth gives information about the internal gain of the sensors

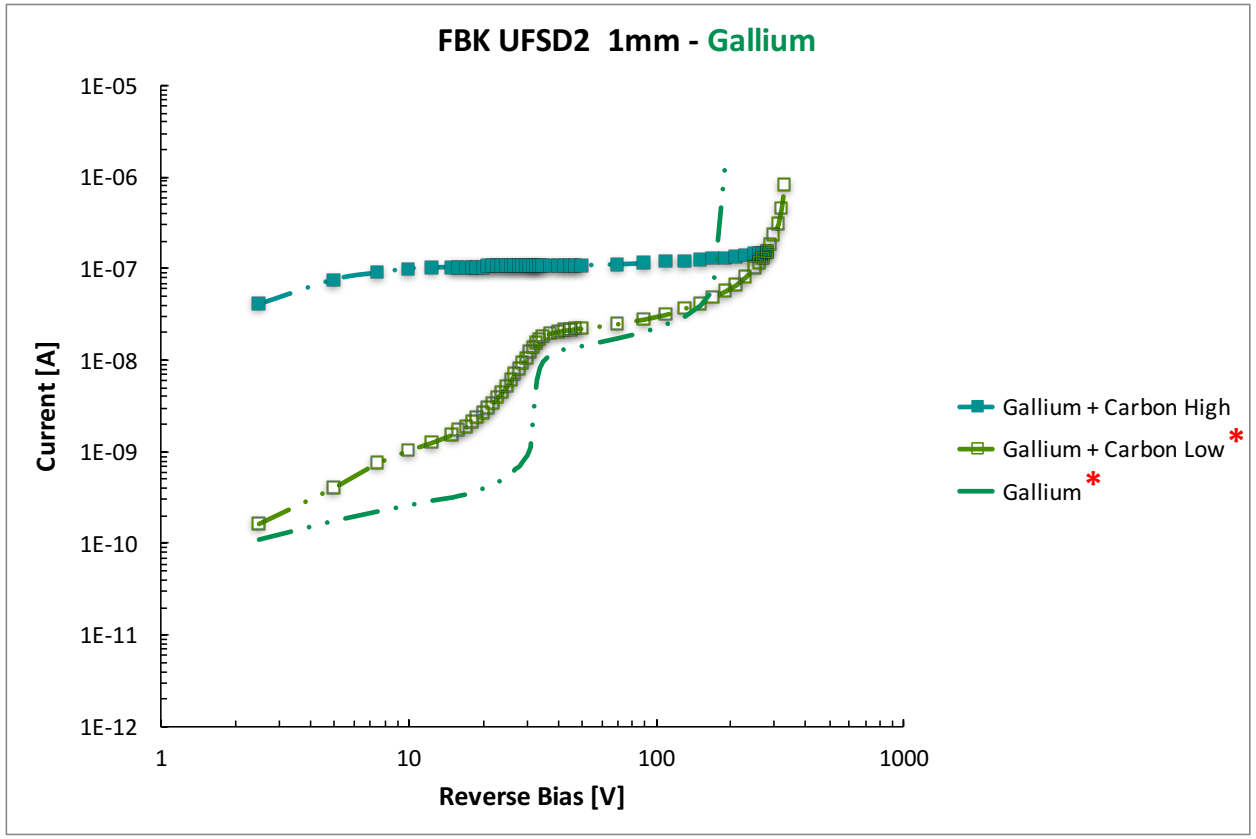
IV Curves - All Wafers



- Boron & Gallium doped sensors show the same behavior
- Low leakage current (10s pA ÷ 10s nA)
- The knee at ~30V indicates the the gain layer depletion voltage
- Exponential growth gives an information about the internal gain of the sensors

IV Curves - Carbon Effect

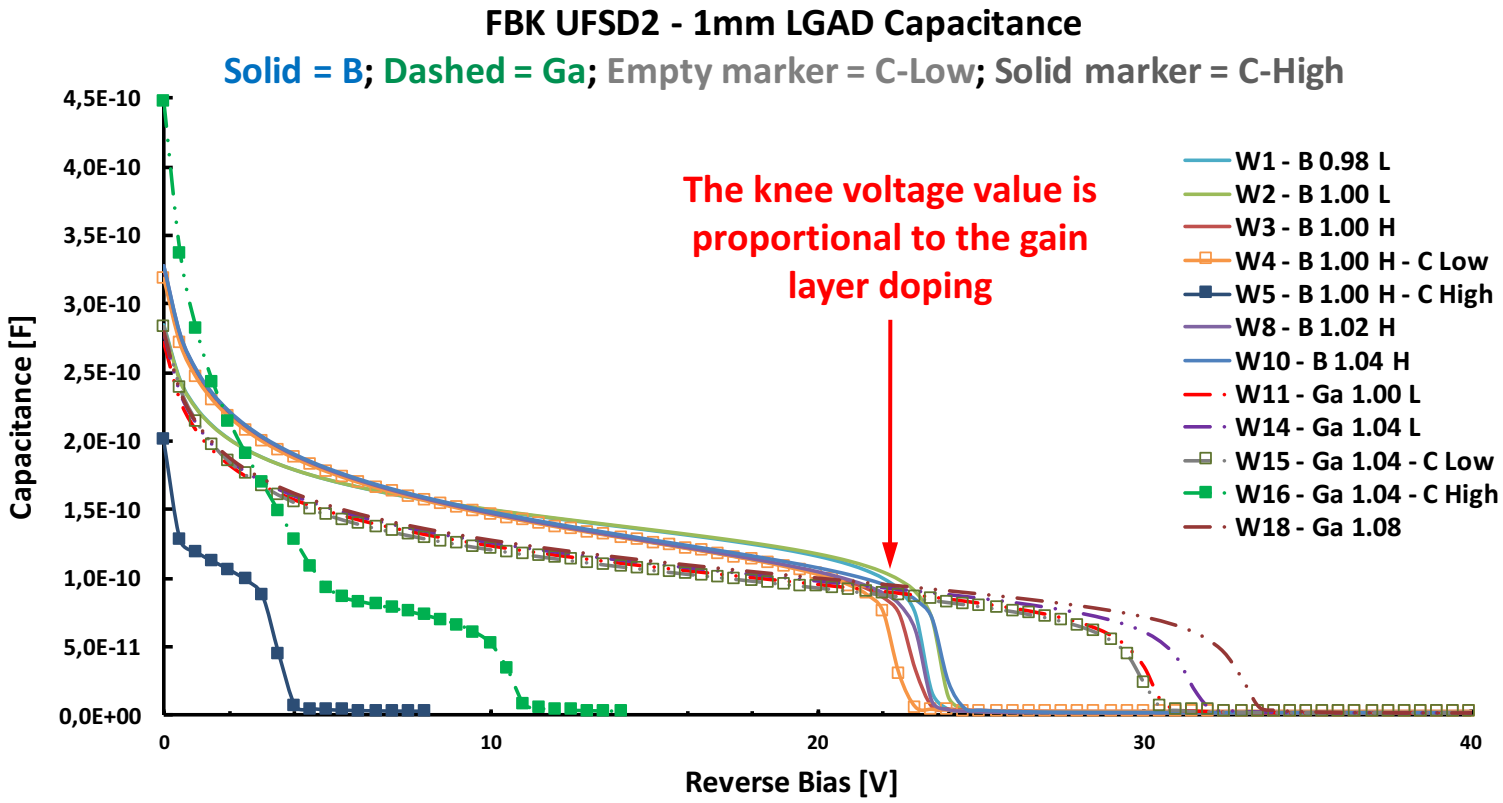




- Carbon implantation increases the leakage current of the sensors (expected)
- Low Carbon: same trend of the leakage current as in the case without Carbon
- High Carbon: high leakage current (~100nA) hides the information about gain

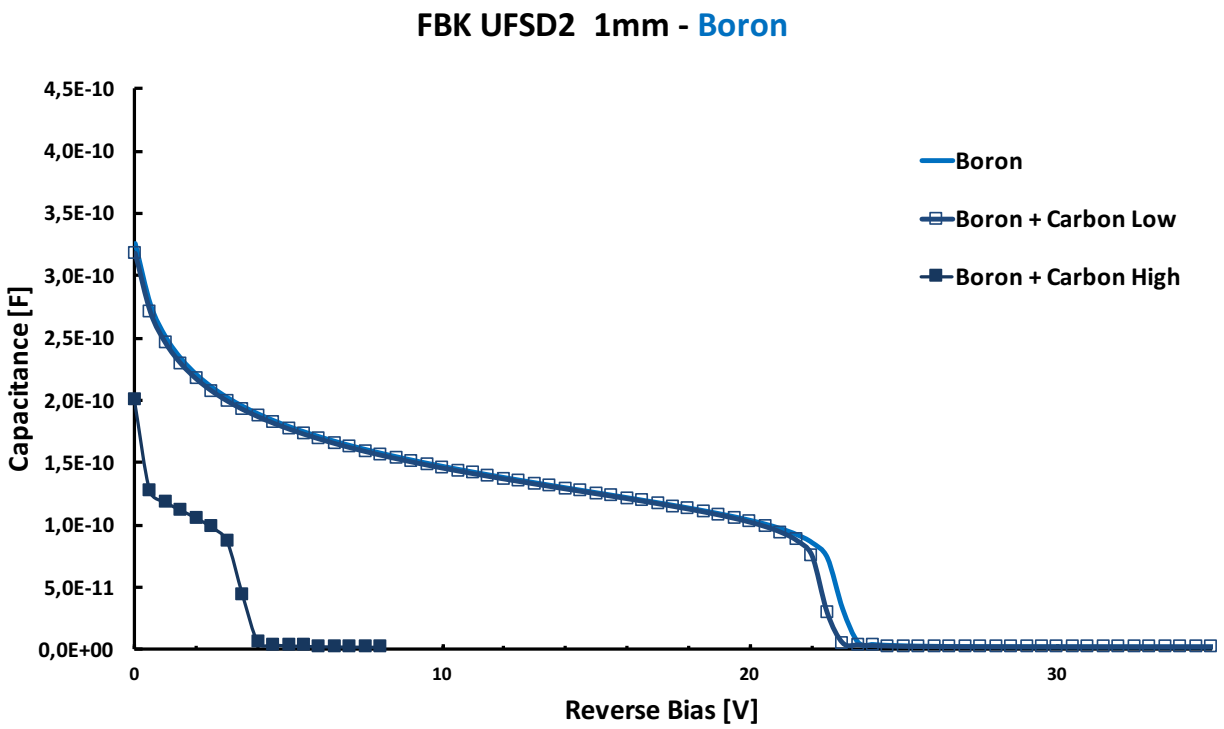
*** Wafers from high I_{leak} batch**

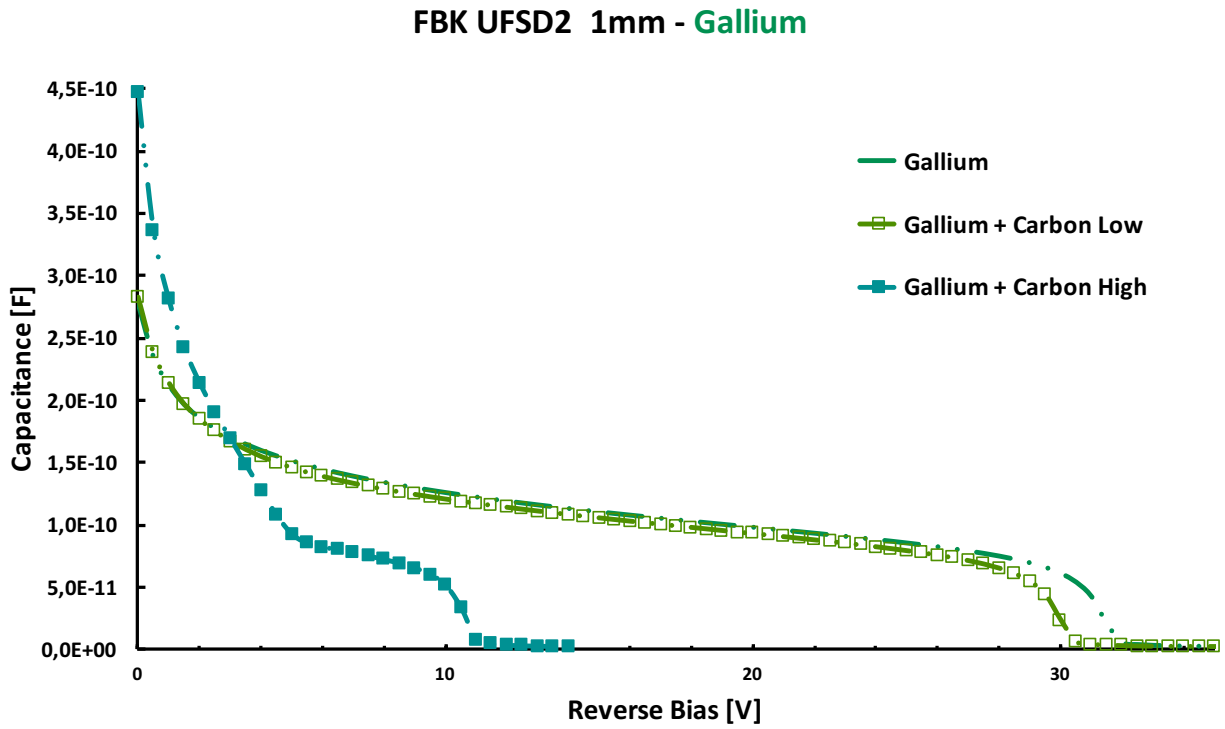
CV Curves - All Wafers



- The knee at ~30V indicates the the gain layer depletion voltage
- Boron & Gallium doped sensors show slightly different behavior due to different gain layer width
- Low Carbon: similar depletion voltage as in the case without Carbon
- High Carbon: depletion voltage occurs much earlier that in the case without Carbon

CV Curves - Carbon Effect

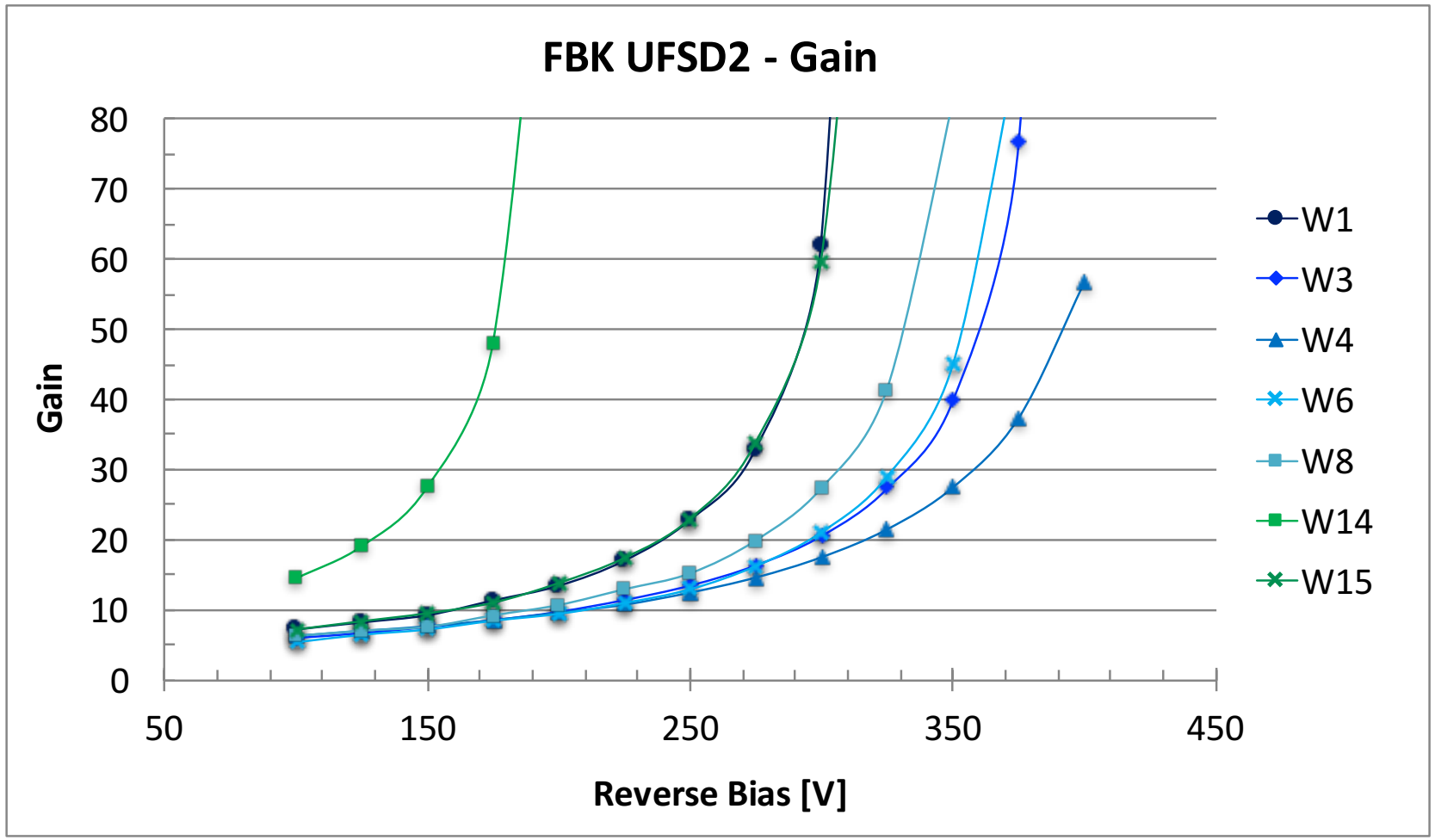




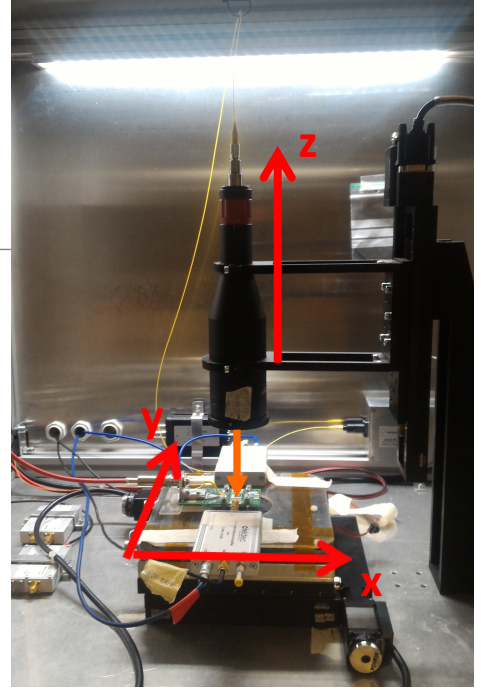
- The knee in CV curves matches with the full depletion of gain layer
- The position of the knee is proportional to the active doping concentration of the gain layer
- The Carbon reduces the active doping concentration of gain layer:
  - High Carbon effect is relevant both in Boron and Gallium
  - Low Carbon effect is more significant in Gallium than in Boron

LABORATORY MEASUREMENTS

Gain Measurement

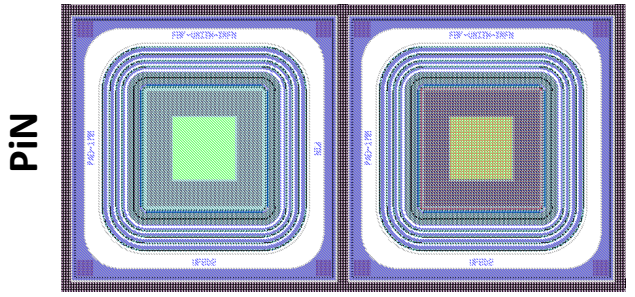


GAIN = (Signal area LGAD)/(Signal area PiN)



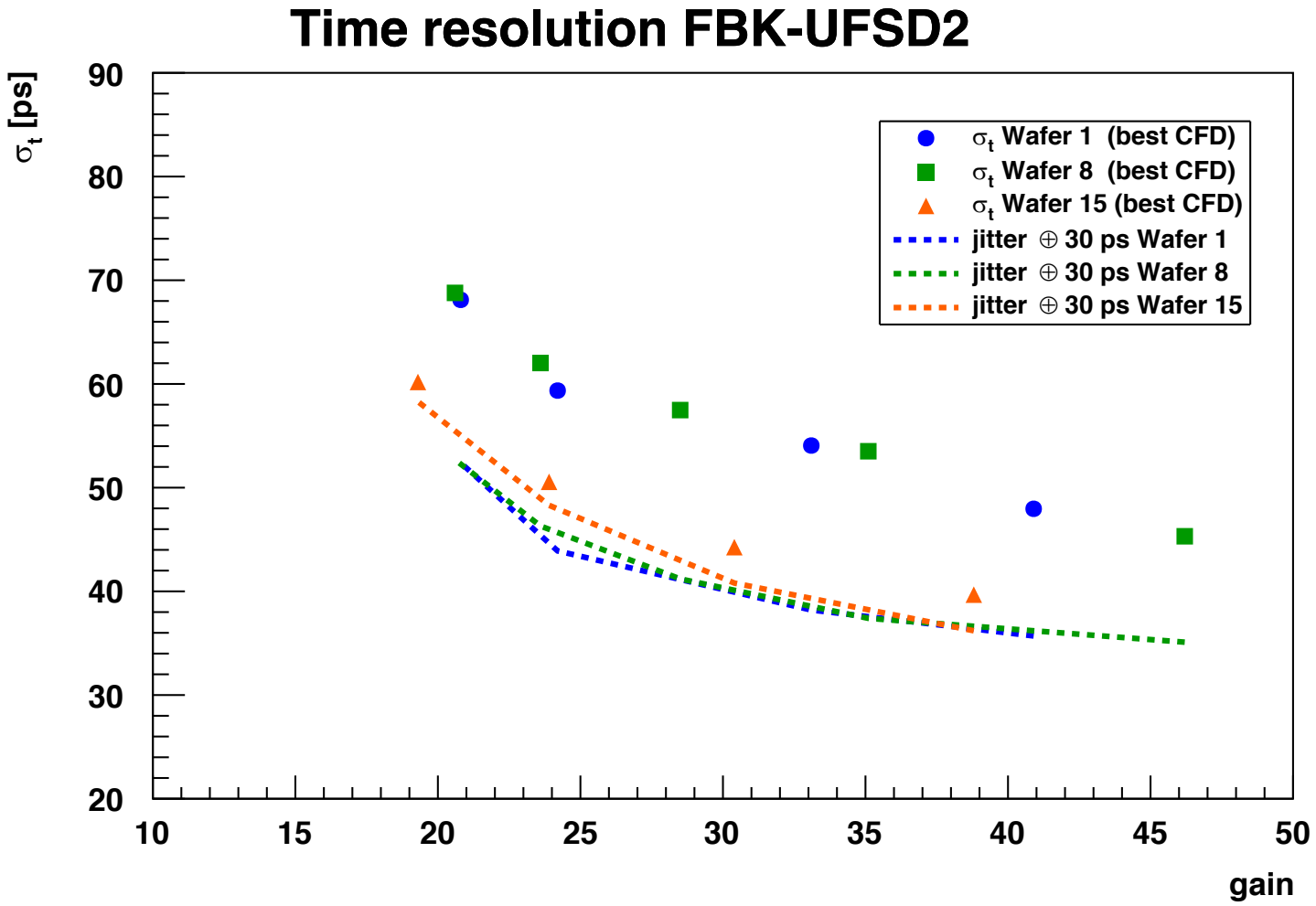
TCT Setup from Particulars

Pico-second IR laser at 1064 nm
Laser spot diameter ~ 50 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope Lecroy 640Zi
Room temperature



Time Resolution from Beam Test

REMINDER:
W1 = B 0.98 LD
W8 = B 1.02 HD
W15 = Ga 1.04 + C Low



Beam Test with 180 GeV/C π at CERN SPS
Sensors on INFN-Torino boards
Cividec Broadband Amplifier (40dB)
Oscilloscope Lecroy 640Zi
(40Gsample/s, bandwith 4GHZ)
Room temperature

Trigger: CNM 50 µm UFSD sensor on UCSC board + 20dB Cividec Broadband amplifier
→ $\sigma_t^{trigger}$ ~ 35 ps (subtracted from results)
Trigger logic: UCSC & (W1 or W8 or W15)

Expected $\sigma_t \sim \sigma_t^{jitter} \oplus \sigma_t^{Landau}$ (30 ps)

→ W15 in line with predictions, investigating W1 and W8, issue with metal/non metal coverage

(see Backup for details)

Time Resolution from Beam Test

REMINDER:
W1 = B 0.98 LD
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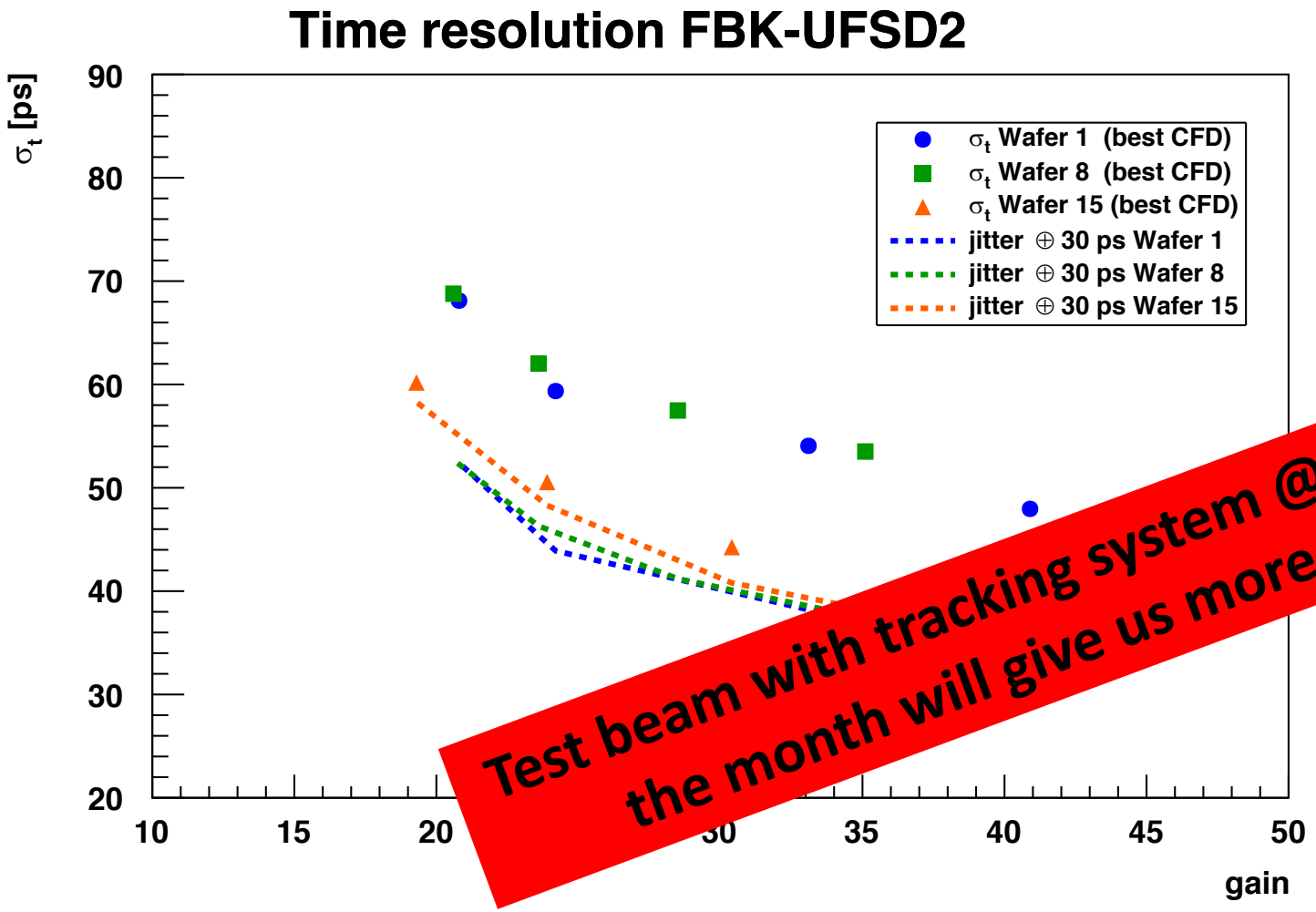

Beam Test with 180 GeV/C π at CERN SPS
Sensors on INFN-Torino boards
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gic: UCSC & (W1 or W8 or W15)

Expected $\sigma_t \sim \sigma_t^{jitter} \oplus \sigma_t^{Landau}$ (30 ps)

→ W15 in line with predictions, investigating W1 and W8, issue with metal/non metal coverage

(see Backup for details)

Test beam with tracking system @ FNAL by the end of the month will give us more precise answers

NEUTRON IRRADIATED UFSD

Irradiation Strategy

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

Sensors from these wafers sent to Ljubljana and CERN PS for irradiation

Neutron irradiation

Fluence steps: 2 - 4 - 8·10^{14} n_{eq}/cm^2

1.5 - 3 - 6 ·10^{15} n_{eq}/cm^2

1·10^{16} n_{eq}/cm^2

→ Irradiated sensors just arrived in Torino

24 GeV/c Proton irradiation

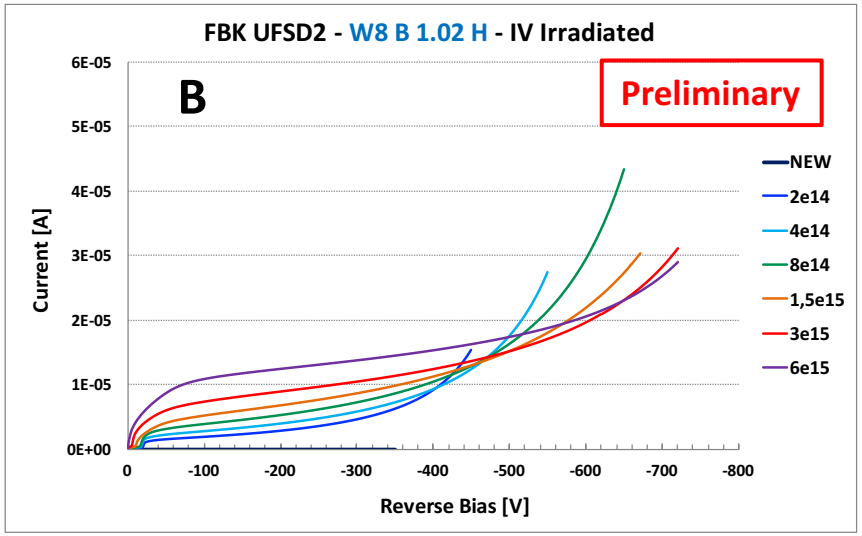
Fluence steps: 1 - 6·10^{14} n_{eq}/cm^2

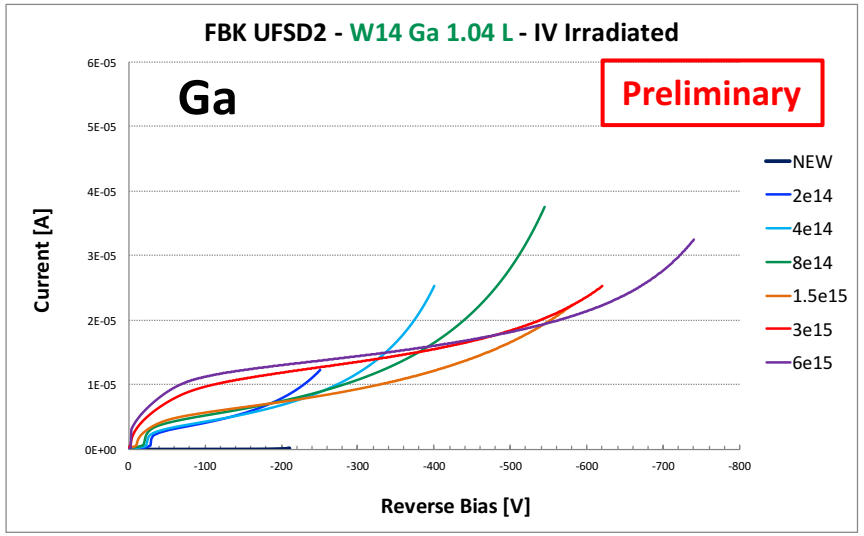
1 - 3 - 6 - 9 ·10^{15} n/cm^2

→ Irradiated sensors on their way to Torino

IV Measurements on Irradiated Sensors

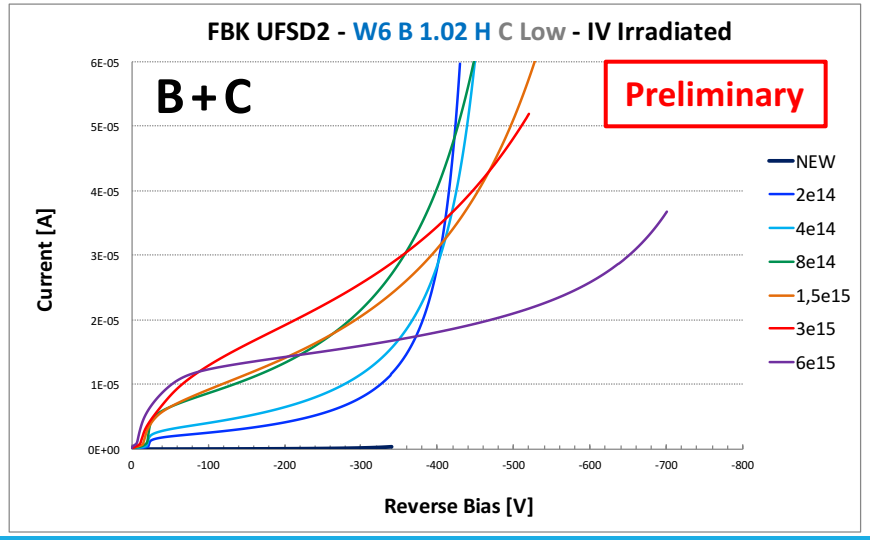
Standard

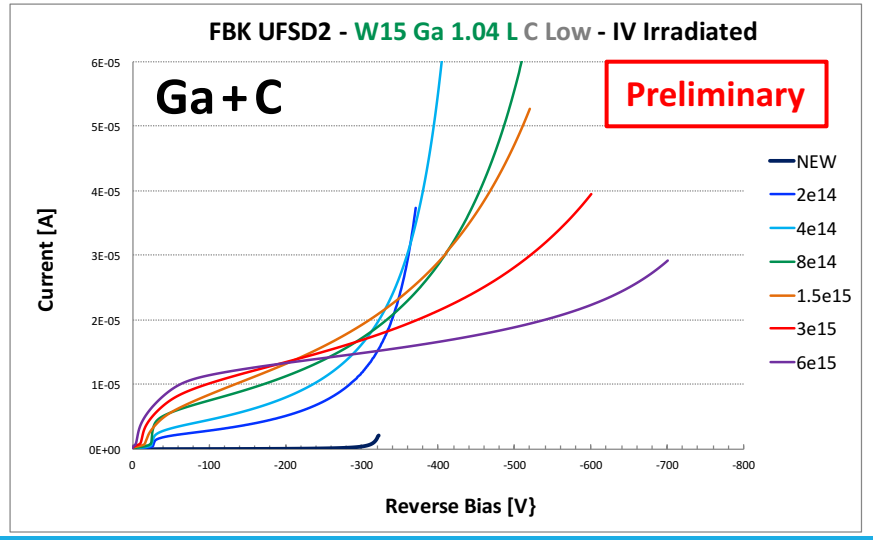




Curvature proportional to gain

Carbonated

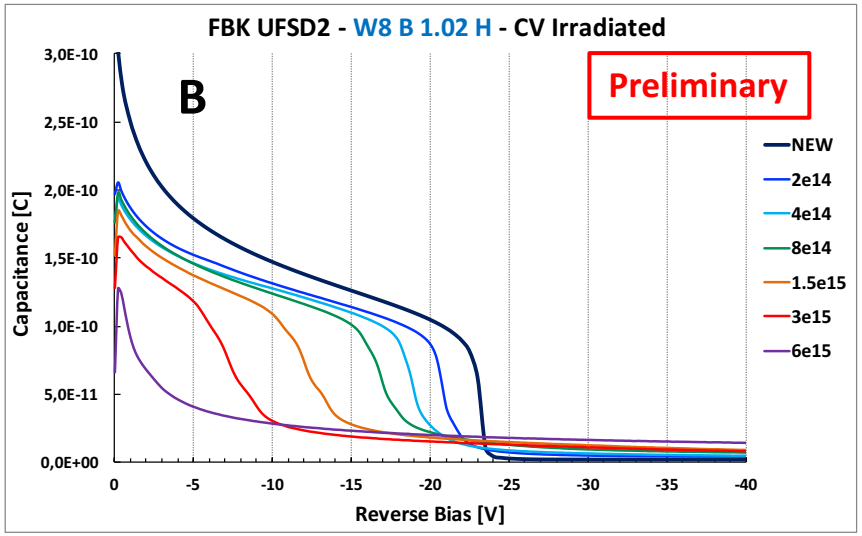


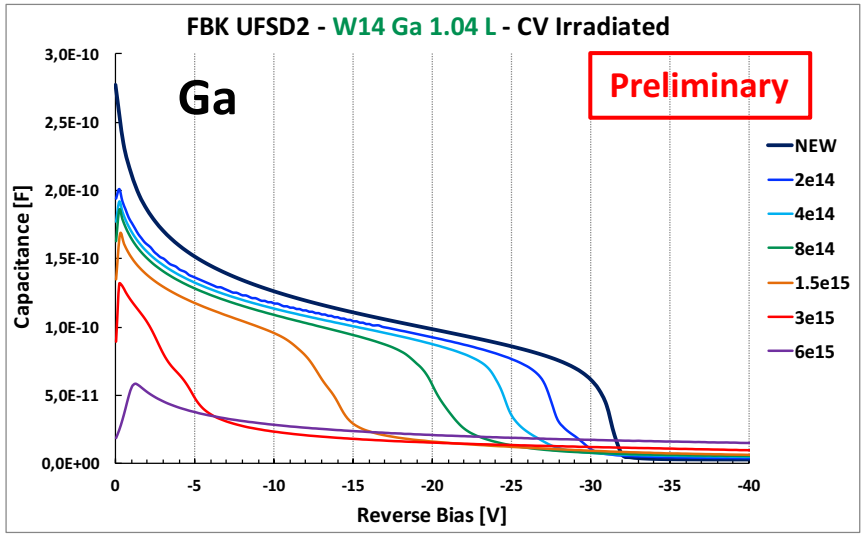


Irradiation extends the operating voltage of the sensors up to ~ 750 V

CV Measurements on Irradiated Sensors

Standard





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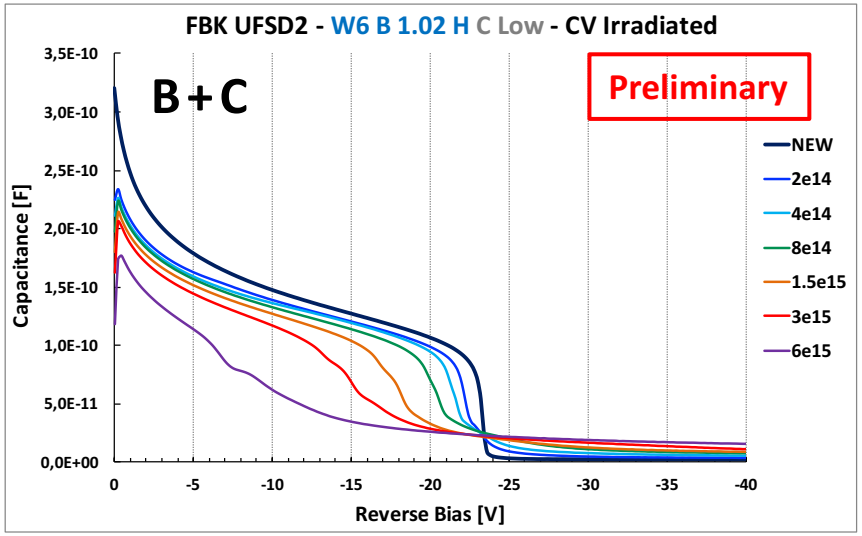
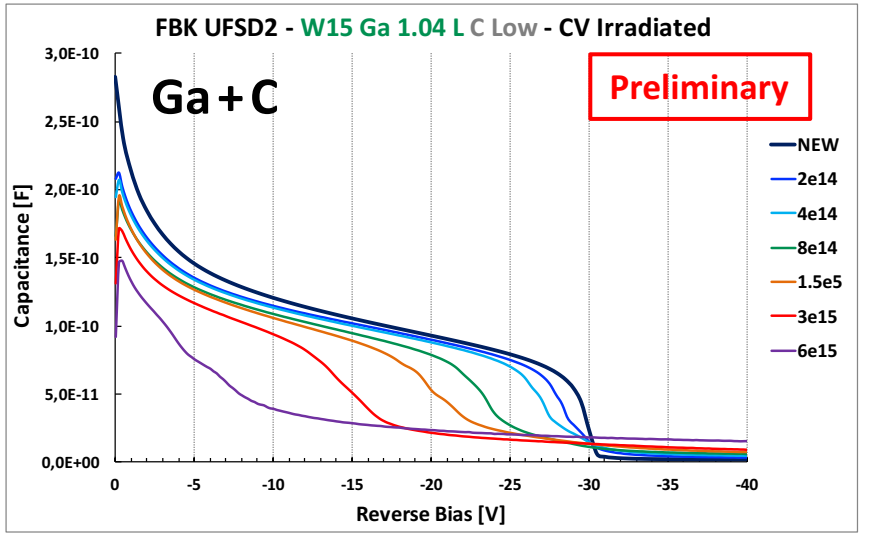




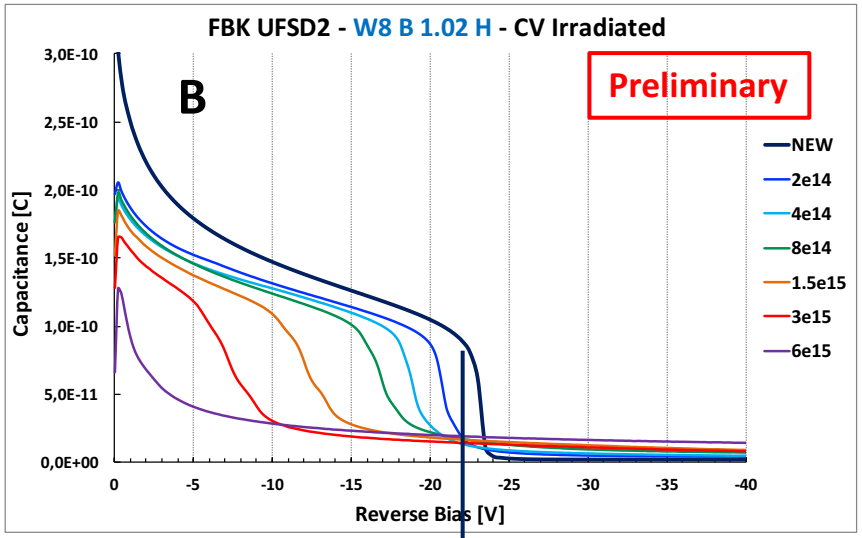
Reminder: fluence doubles at each step

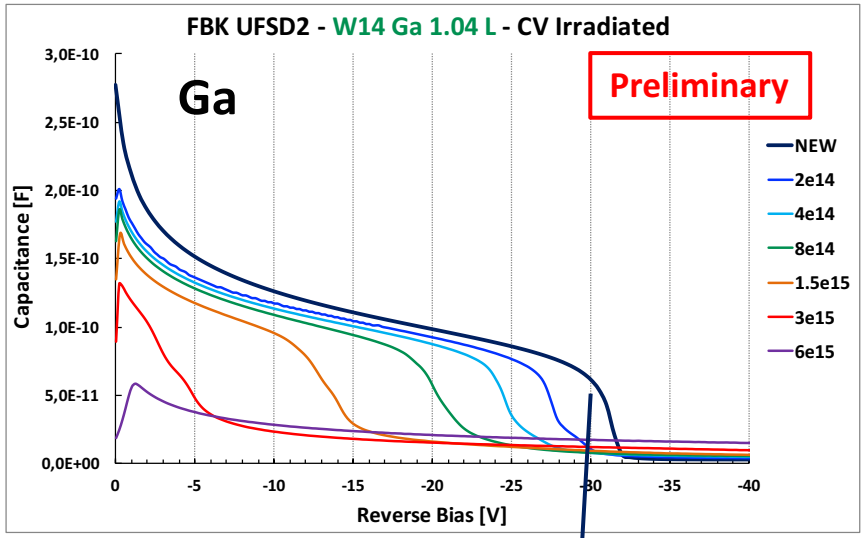
The knee voltage value is proportional to the gain layer doping

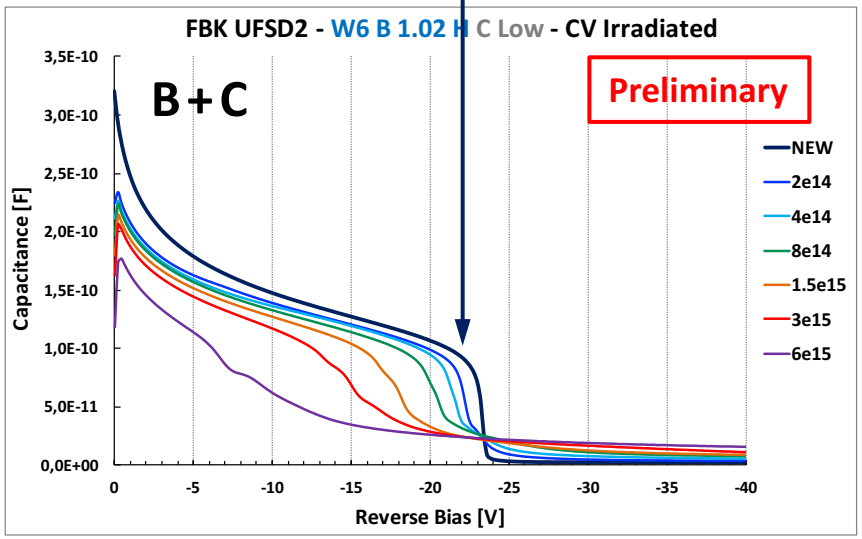
CV Measurements on Irradiated Sensors

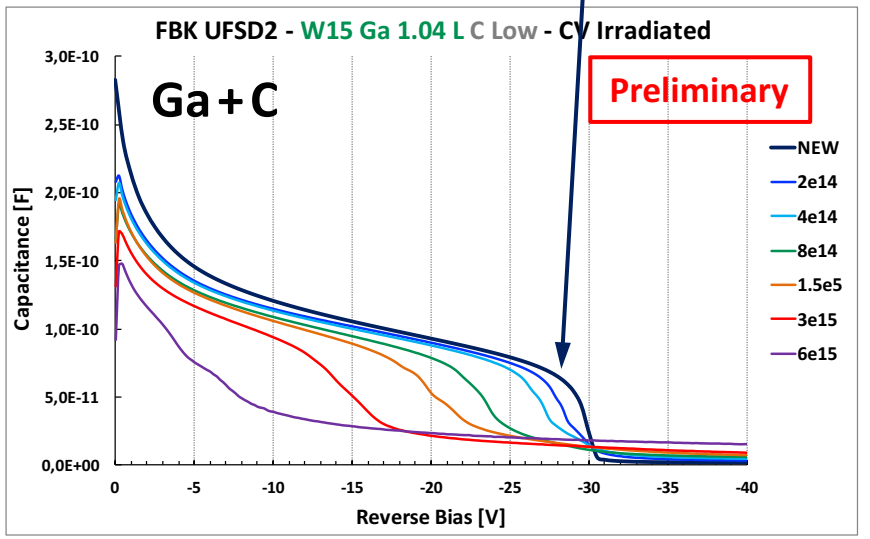
Standard

Carbonated





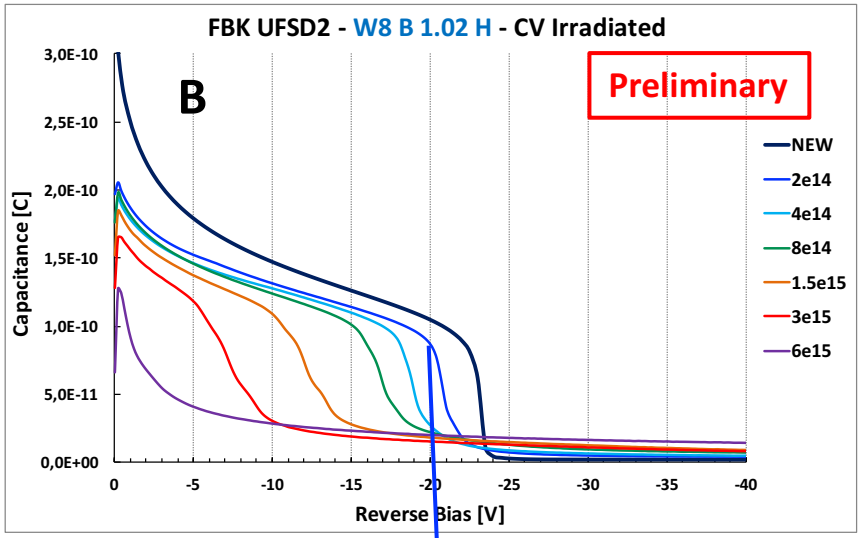


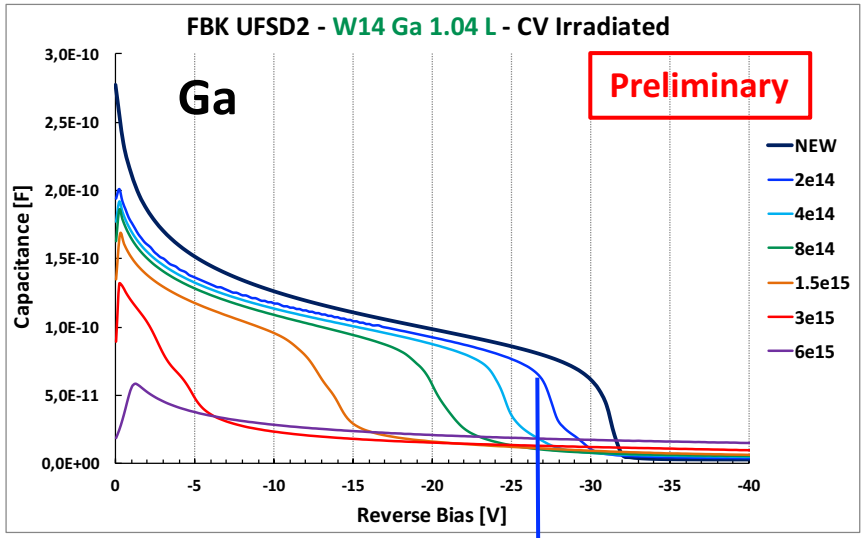


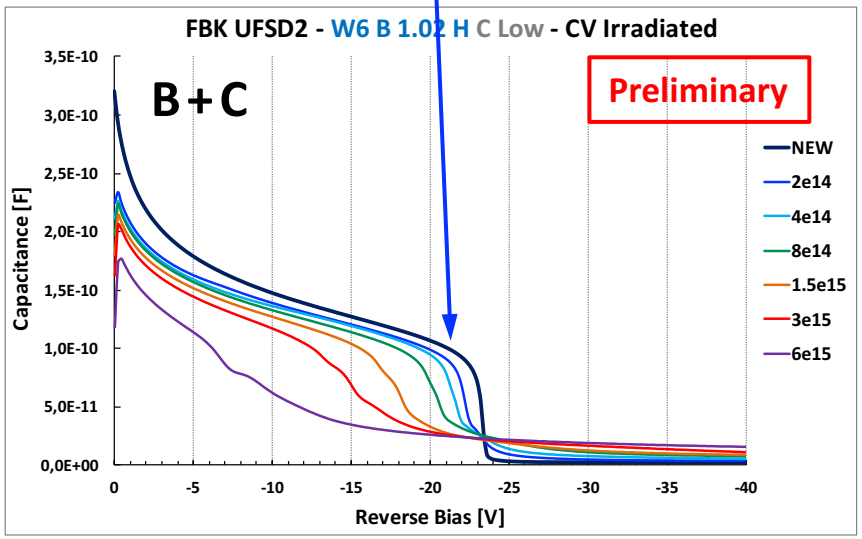
CV Measurements on Irradiated Sensors

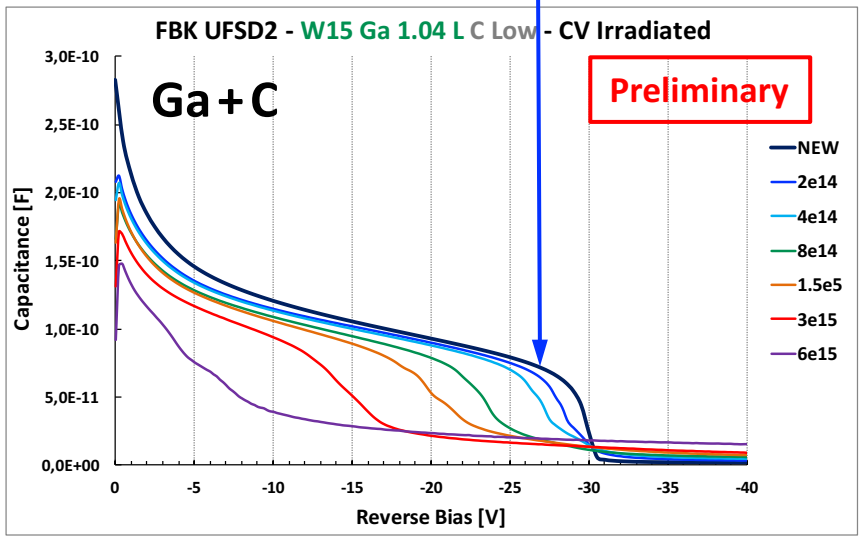
Standard

Carbonated





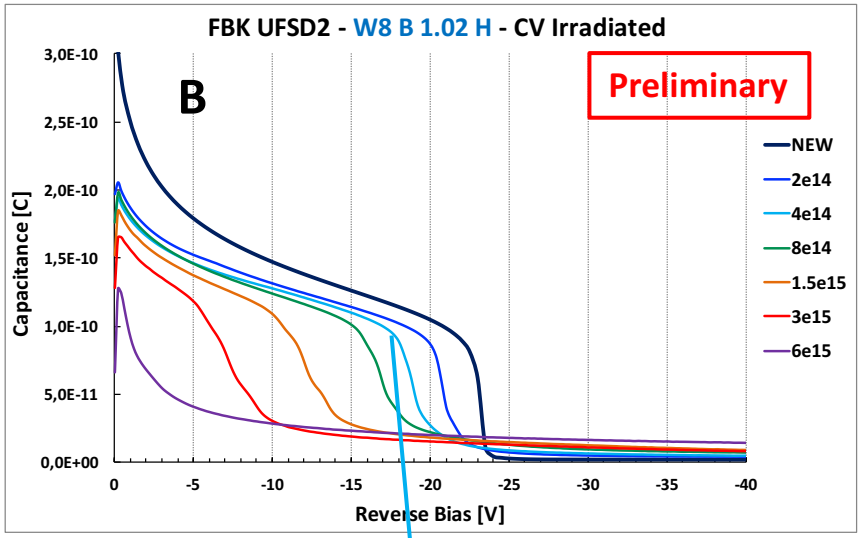


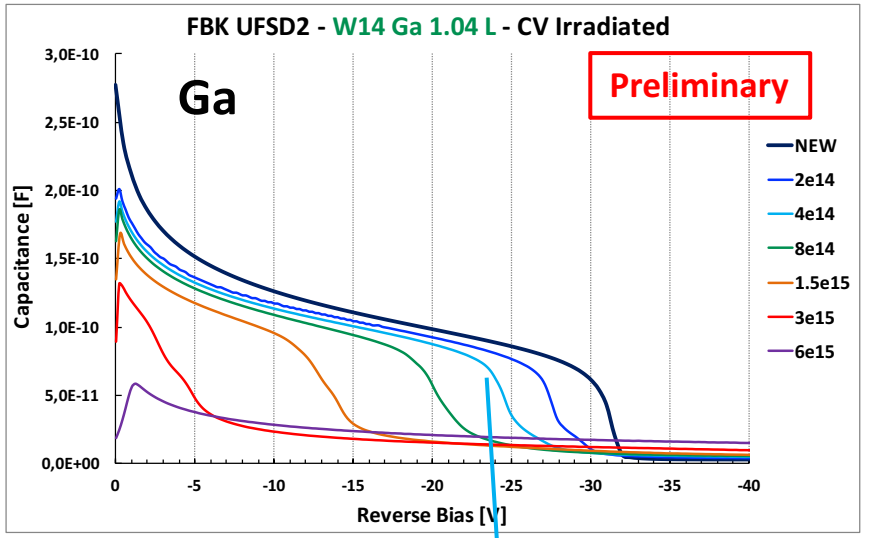


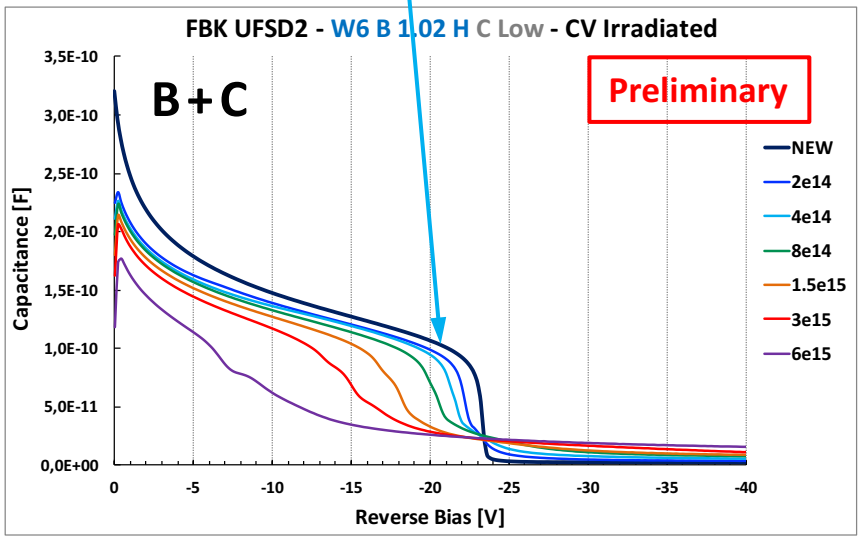
CV Measurements on Irradiated Sensors

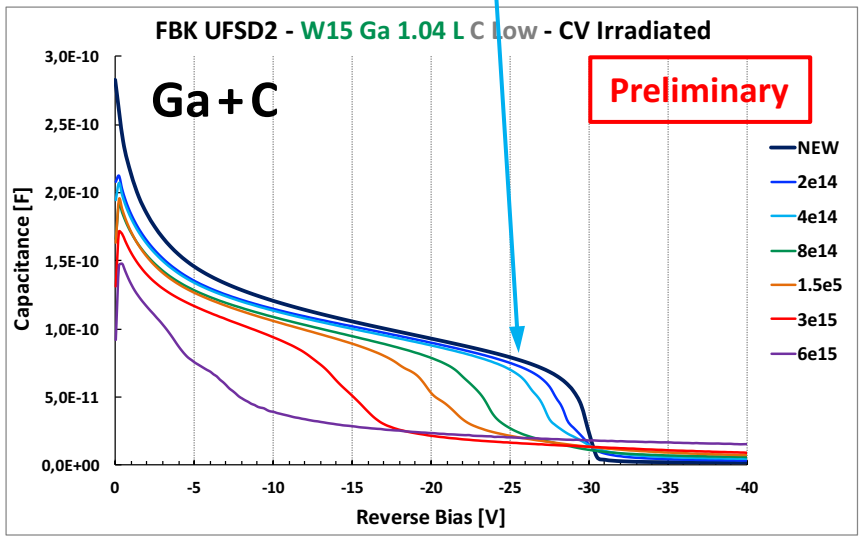
Standard

Carbonated



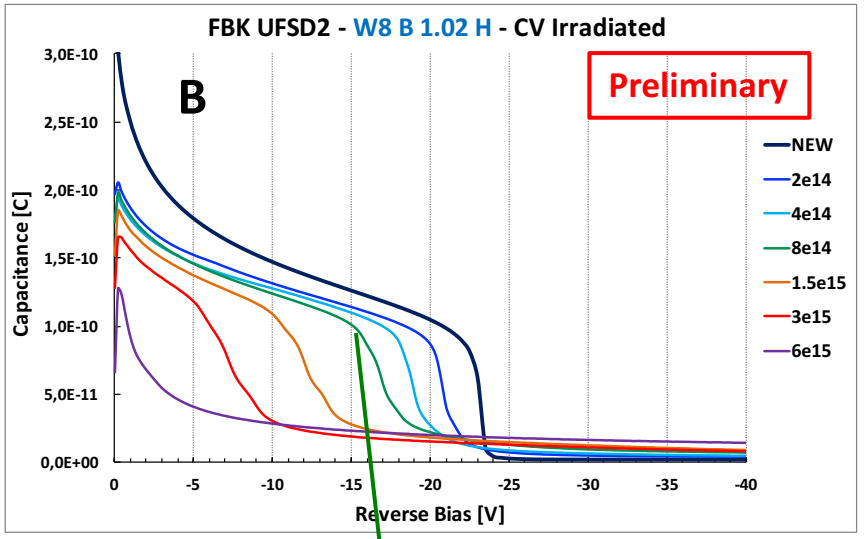


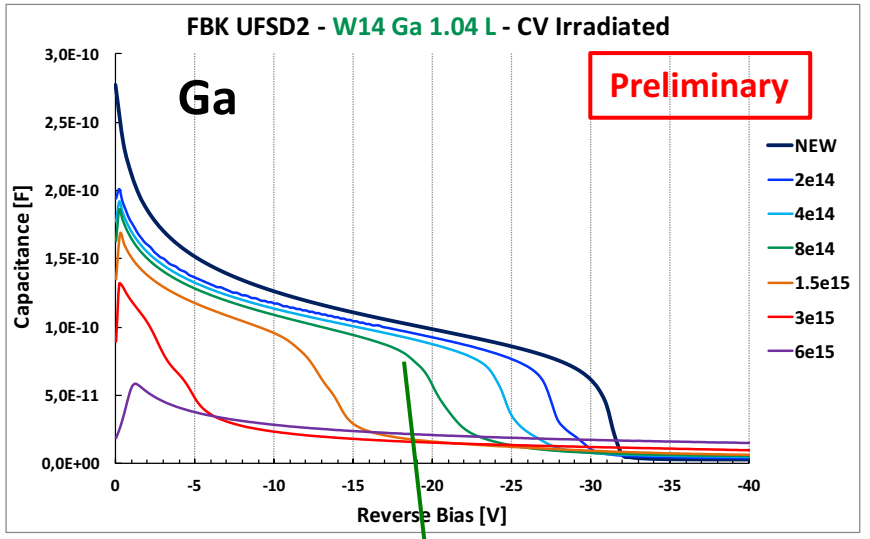




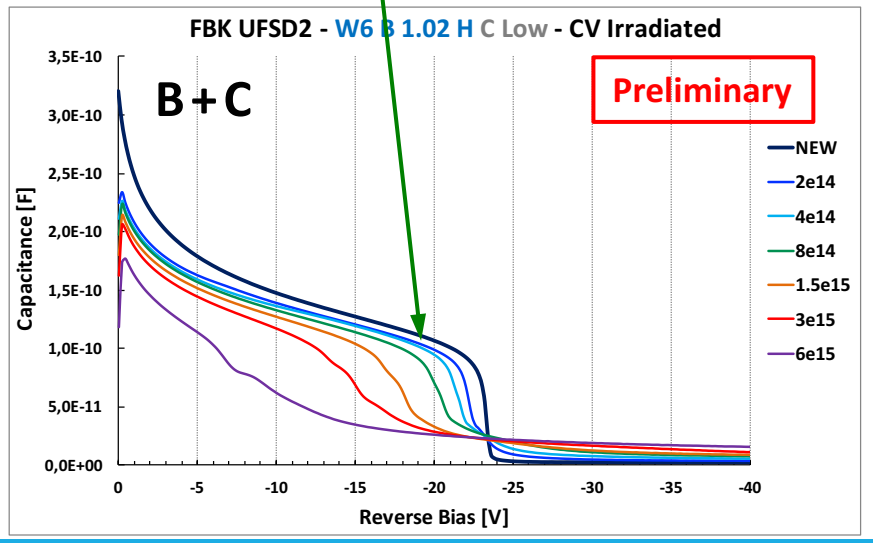
CV Measurements on Irradiated Sensors

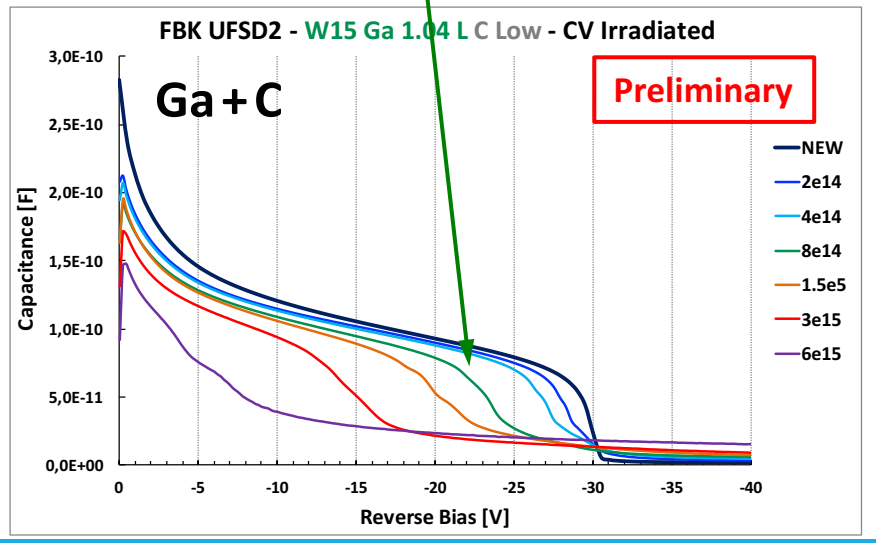
Standard





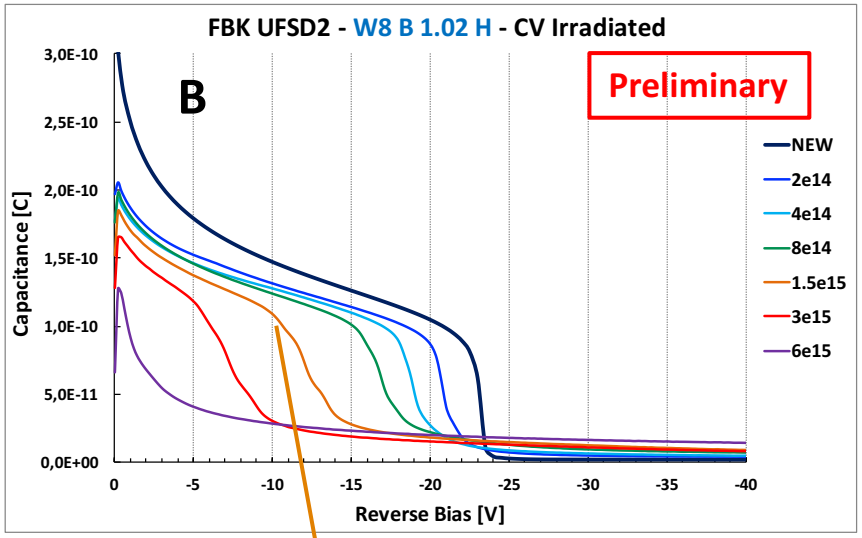
Carbonated

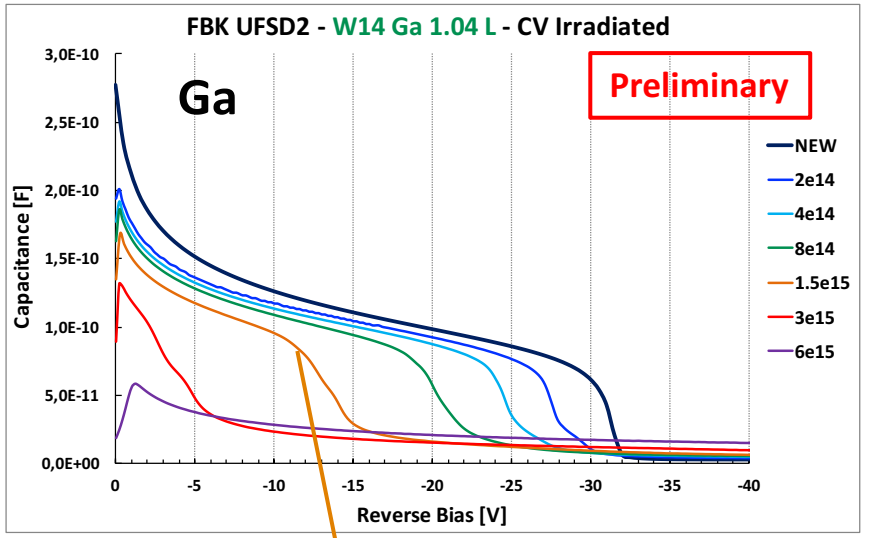




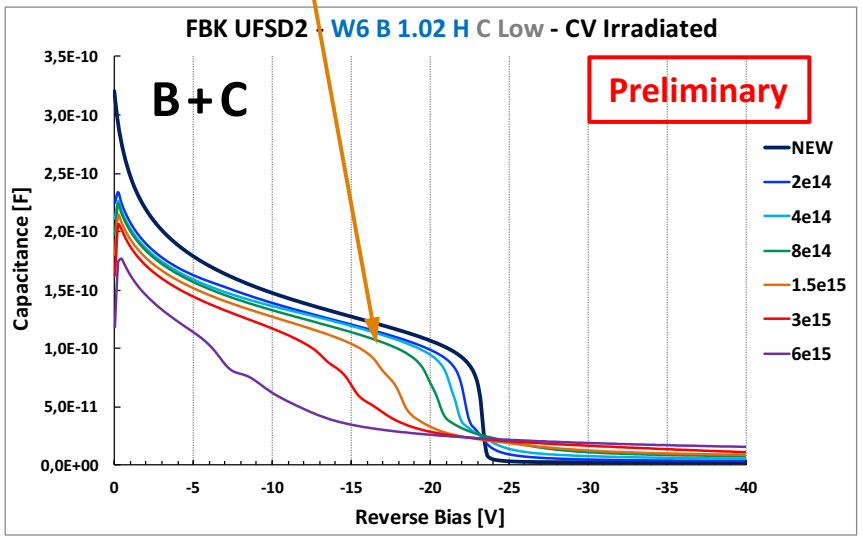
CV Measurements on Irradiated Sensors

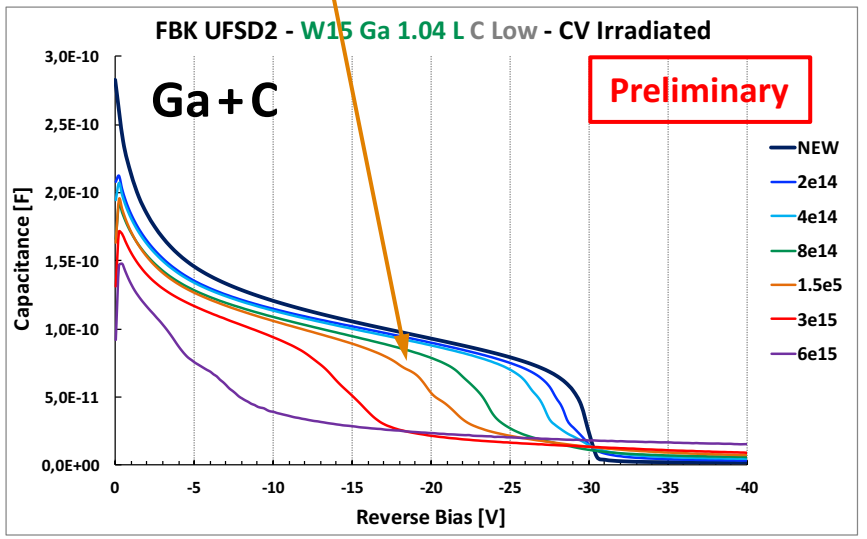
Standard





Carbonated





CV Measurements on Irradiated Sensors

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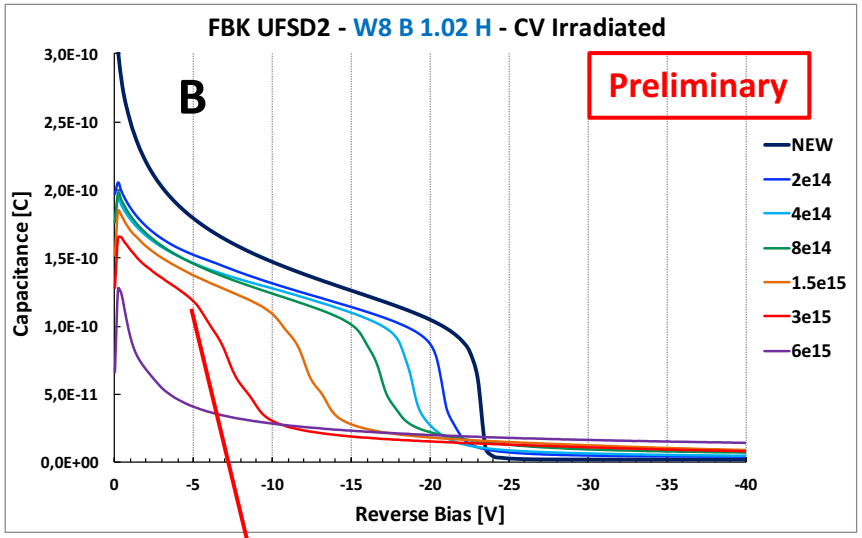
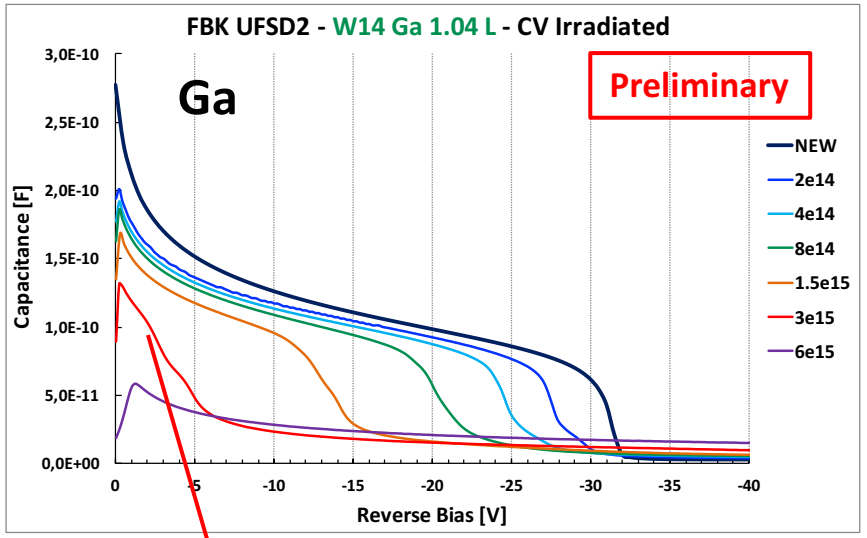
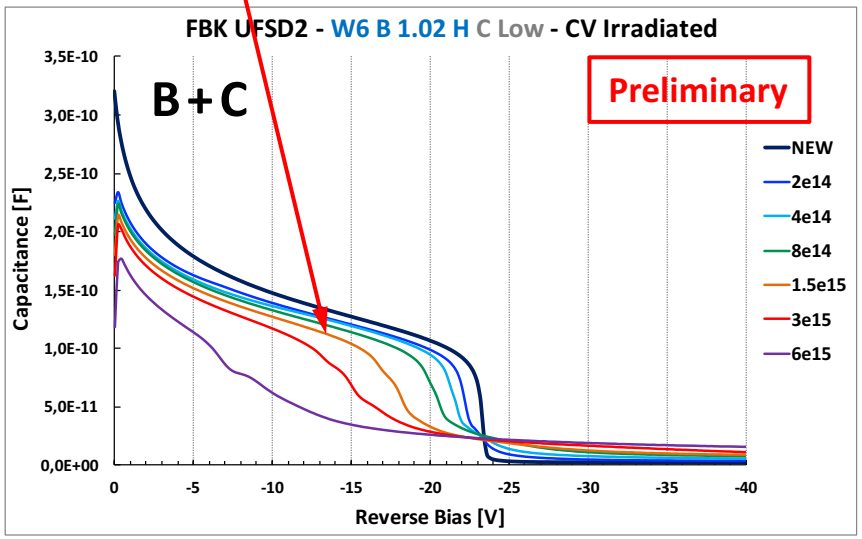
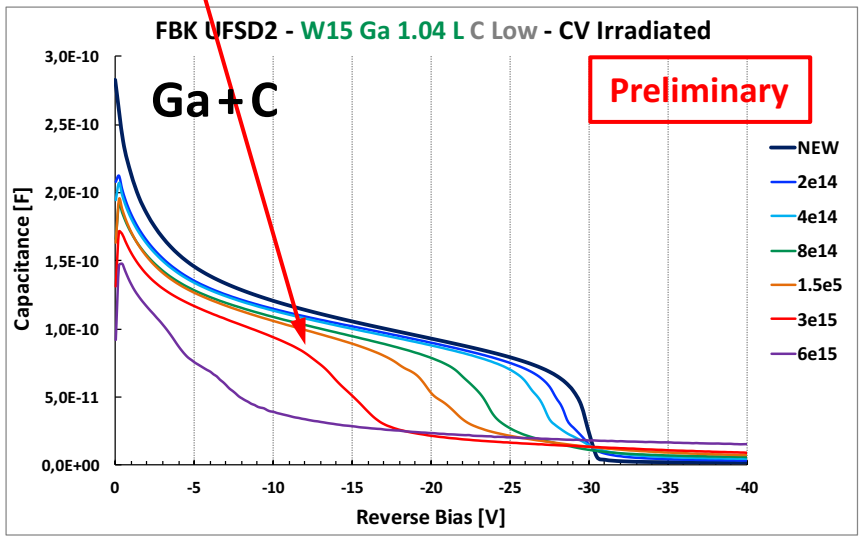




Carbonated





CV Measurements on Irradiated Sensors

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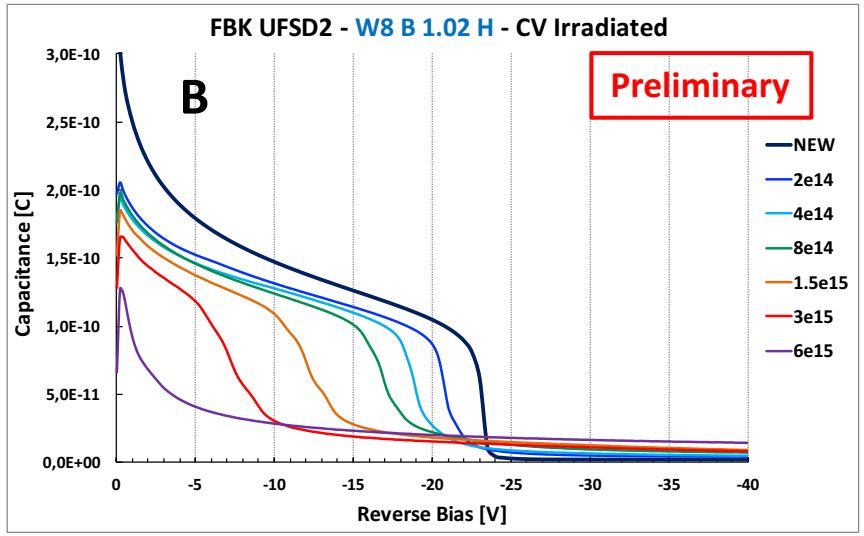
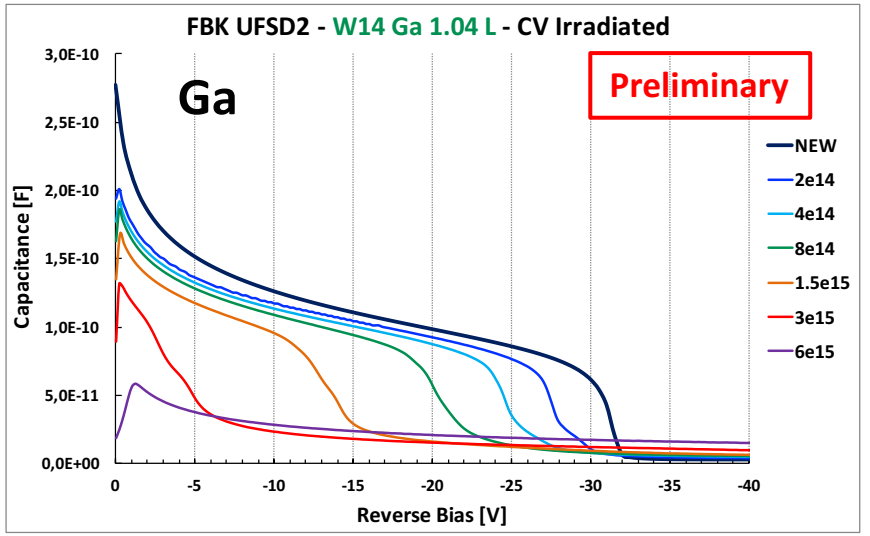
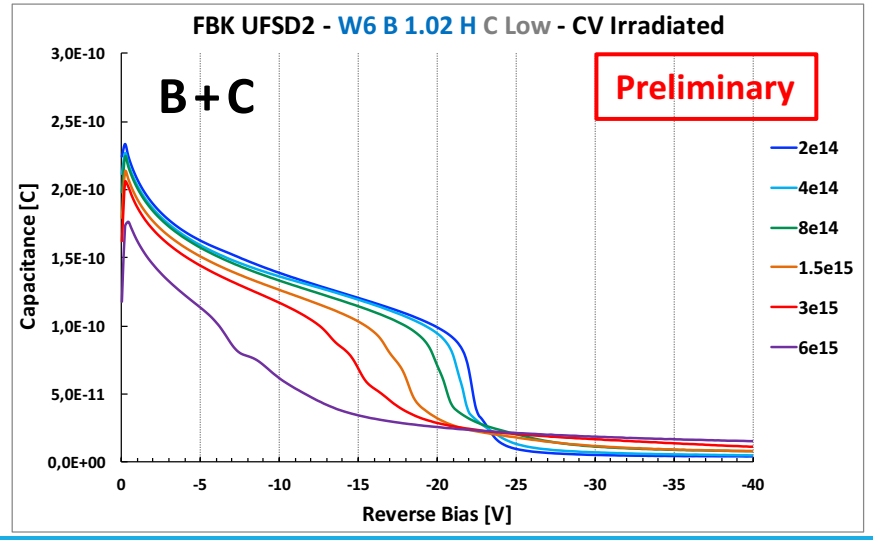
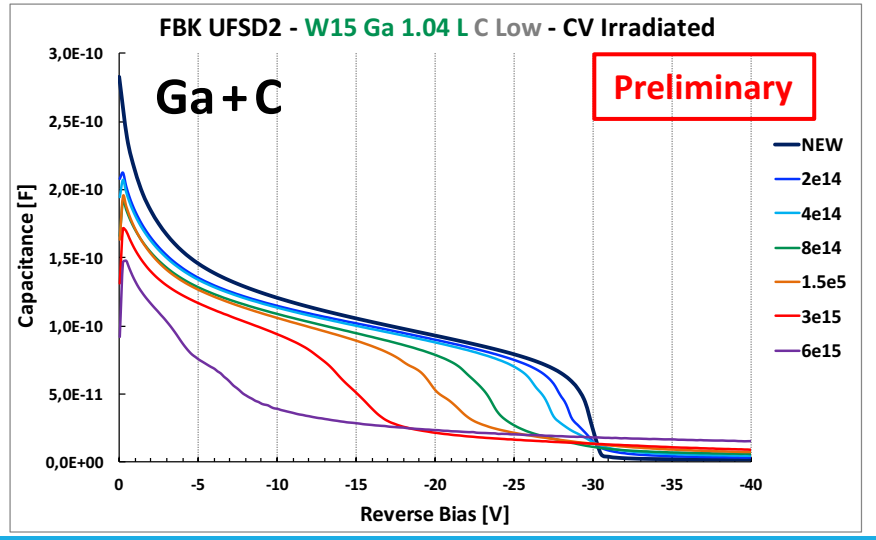




Carbonated





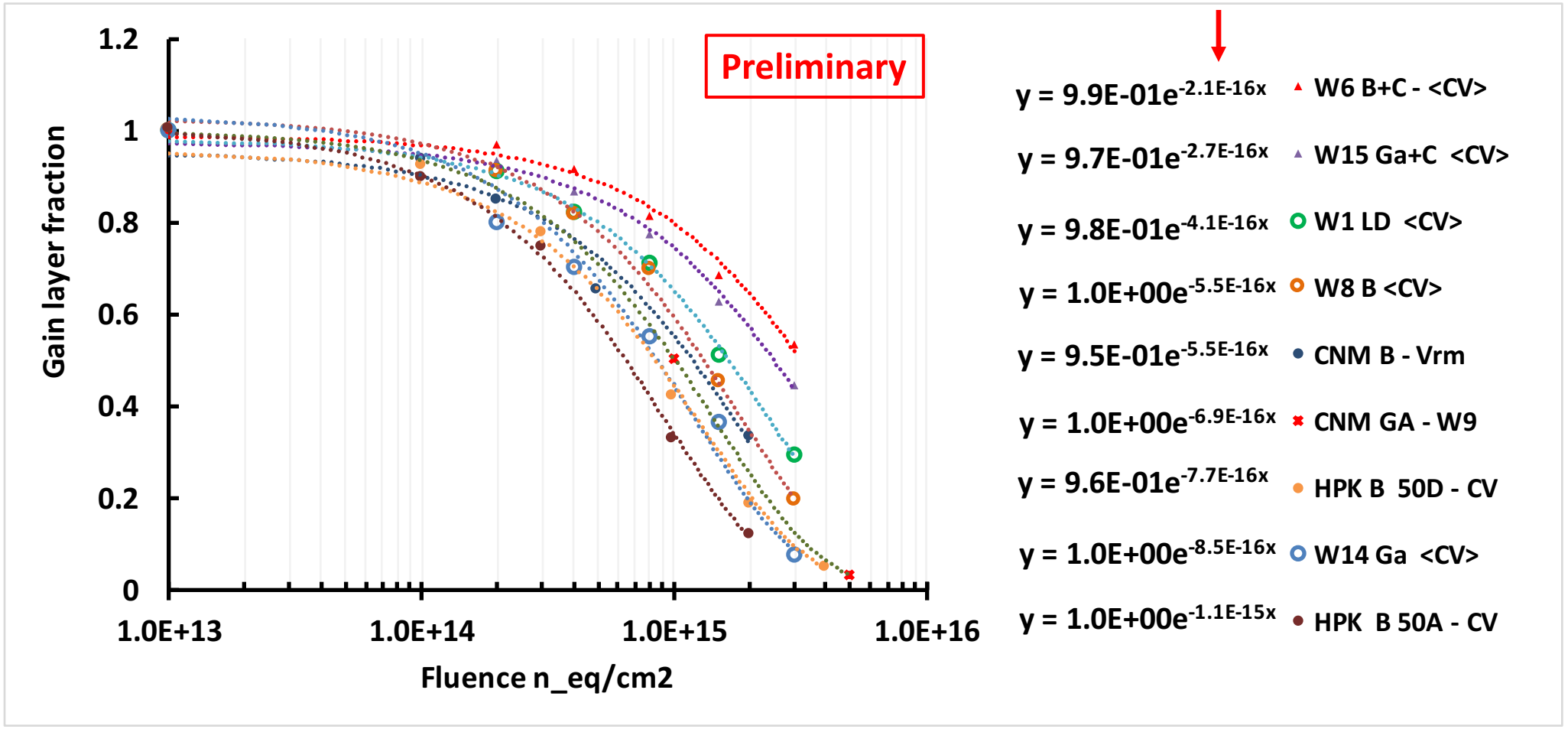
The B+C and Ga+C gain layers are more radiation resistant than those with B or Ga

Acceptor Removal Coefficient

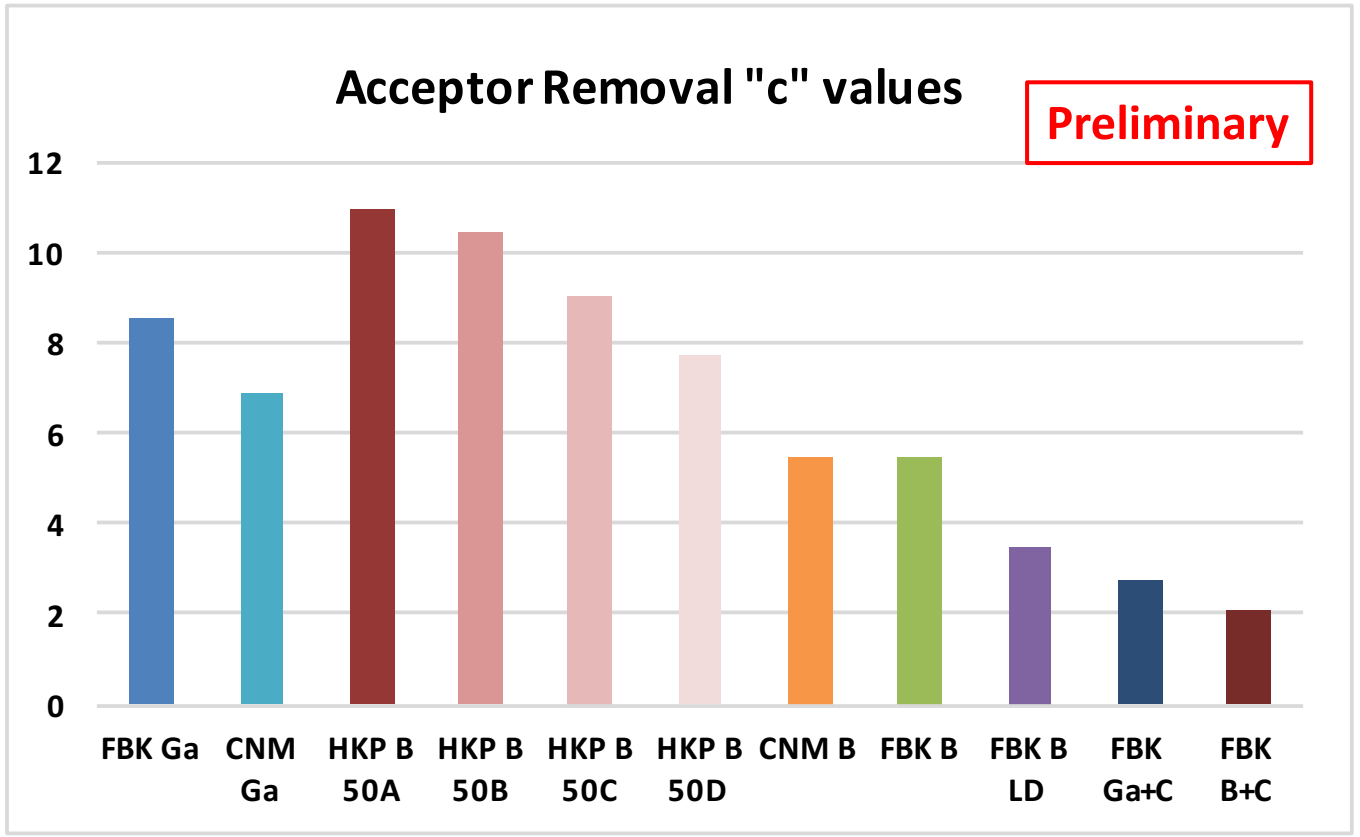
$$N_A = N_{A,0} - N_c \cdot (1 - \exp(-c \cdot \Phi_{eq}))$$

$$dN_A = -\sum_i c_i \cdot N_A \, d\Phi \quad , \quad c = \sum_i c_i([O],[C],[B])$$

From the fraction of gain layer surviving the radiation, it is possible to extract the acceptor removal coefficient c



Acceptor Removal Coefficient Distribution

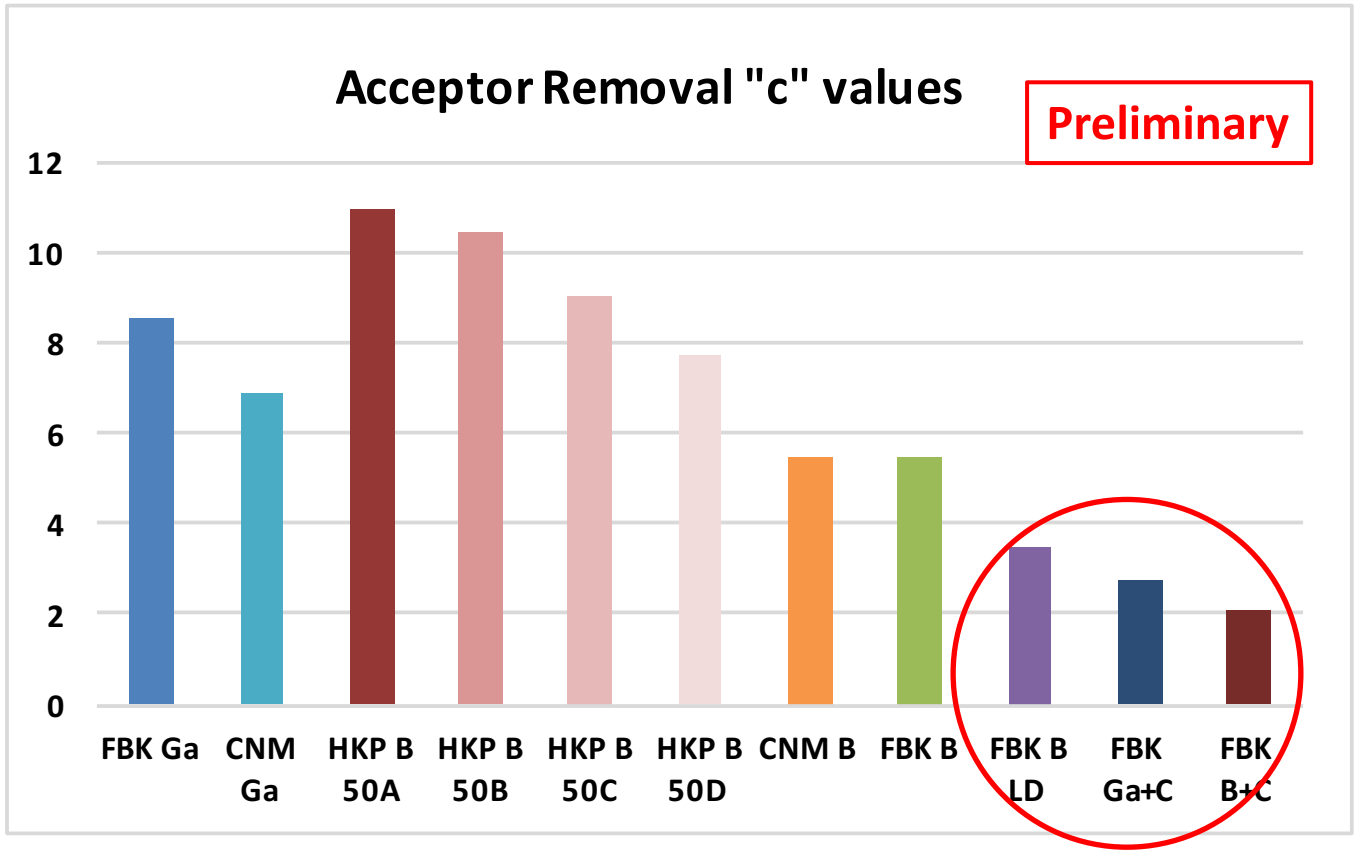


HPK data courtesy of G. Kramberger

- Carbonated sensors have a factor ~ 3 better acceptor removal coefficient
- Among not carbonated sensors, low diffusion Boron has the better response to irradiation

Acceptor Removal Coefficient Distribution

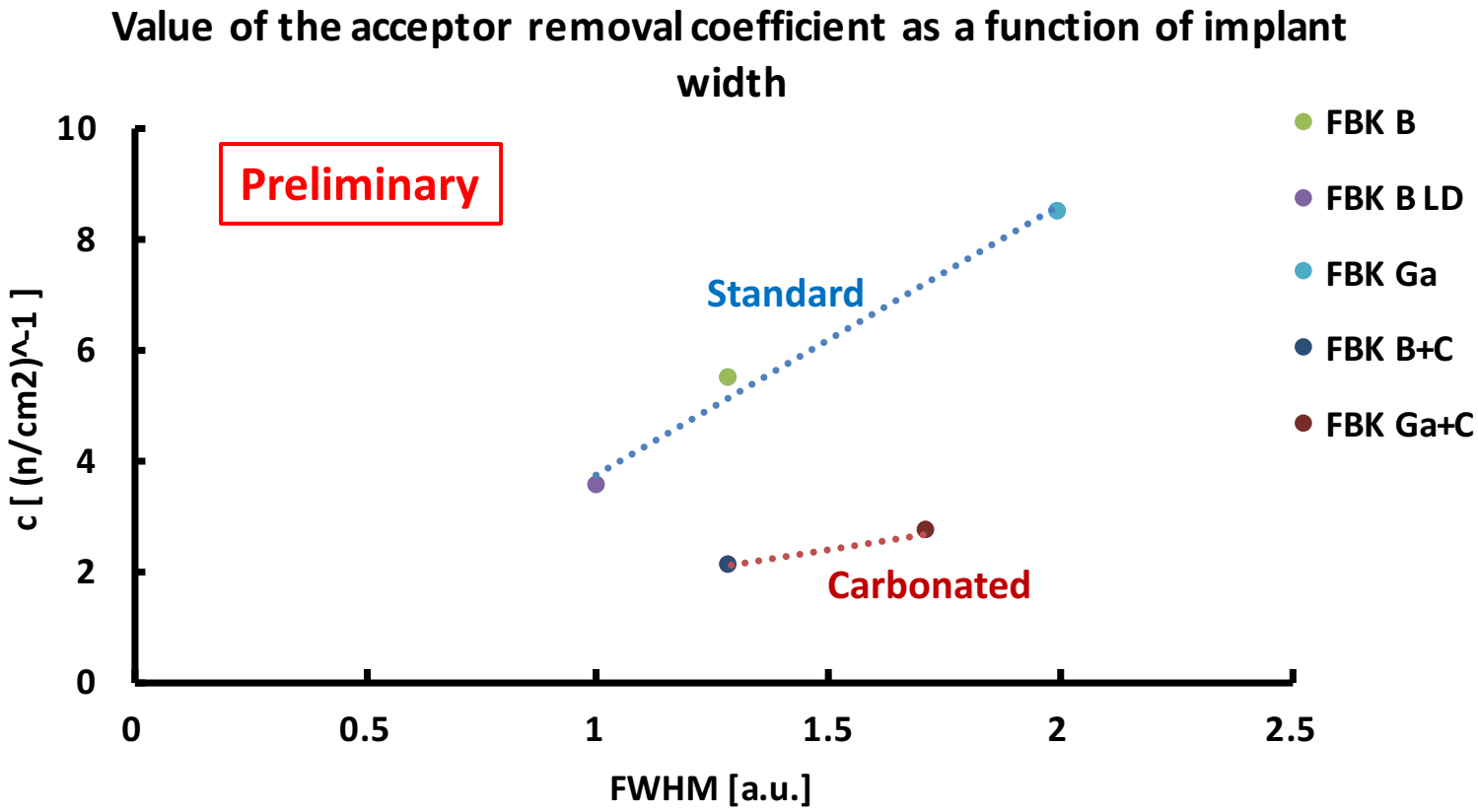
HPK data courtesy of G. Kramberger



- Carbonated sensors have a factor ~ 3 better acceptor removal coefficient
- Among not carbonated sensors, low diffusion Boron has the better response to irradiation

→ **Will be Boron LD + Carbon the most rad-hard option?**

Acceptor Removal and Implant Width

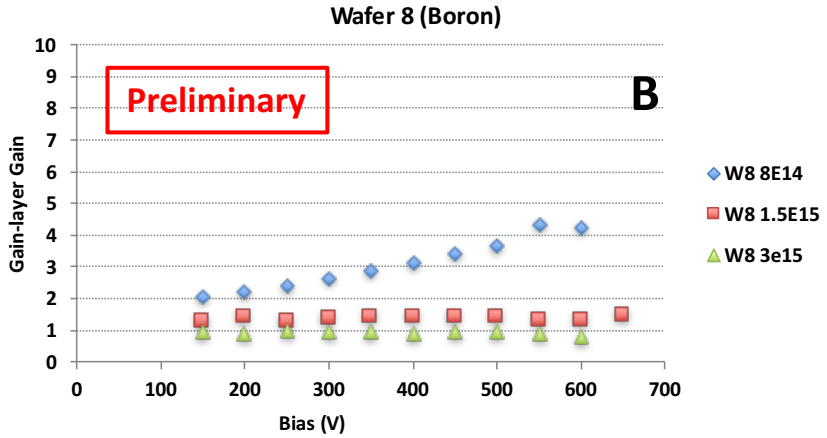


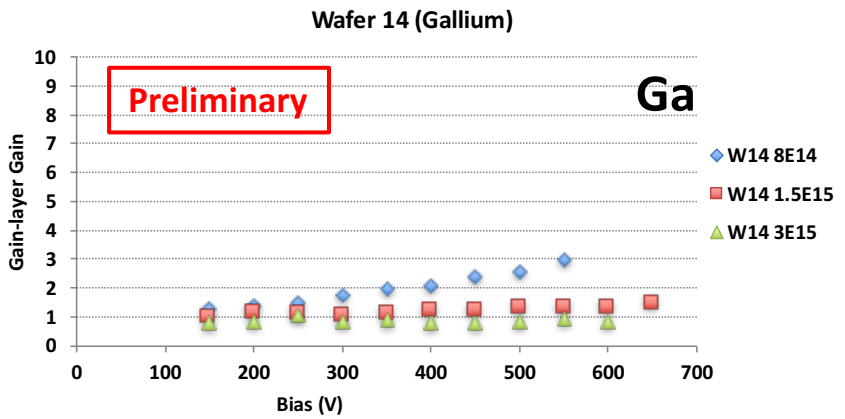
- Carbonated sensors have a similar acceptor removal coefficient
- Strong c dependence on the doping layer width for sensors without Carbon

Gain of Irradiated Sensors

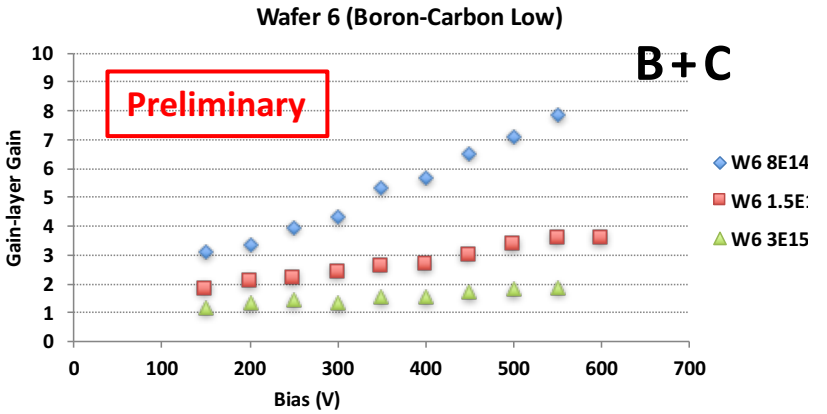
GAIN = (Signal area LGAD)/(Signal area PiN) irradiated at the same fluence → only from gain layer

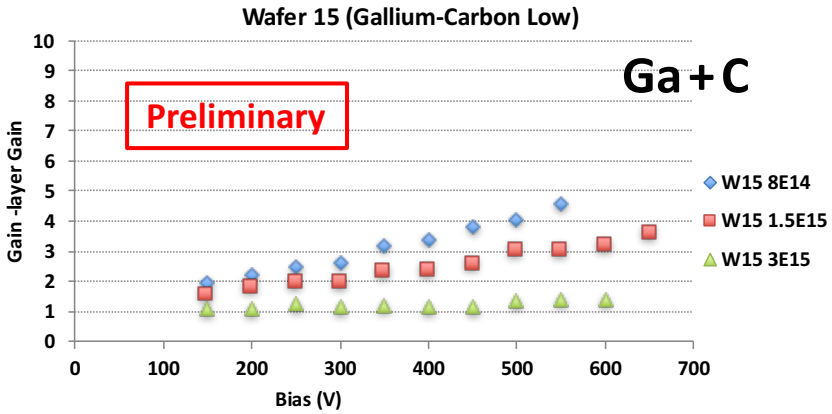
Standard





Carbonated





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

SUMMARY

- First 50 µm UFSD production from FBK of very high quality
  - Different strategies for the gain layer implant have been pursued
  - IV measurements show good uniformity along wafer
  - CV measurements allow extraction of doping concentration profiles
  - Sensors with low Carbon dose show similar behaviour to not carbonated ones
- Laboratory measurement
  - Well controlled moderate gain for all wafers
  - Good timing performances
- Radiation tolerance
  - Acceptor removal coefficient increases with gain implant width
  - Carbon underneath the gain implant halves acceptor removal effect

→ **Will be Boron LD + Carbon the most rad-hard option?**

ACKNOWLEDGEMENTS

We kindly acknowledge the following funding agencies, collaborations:

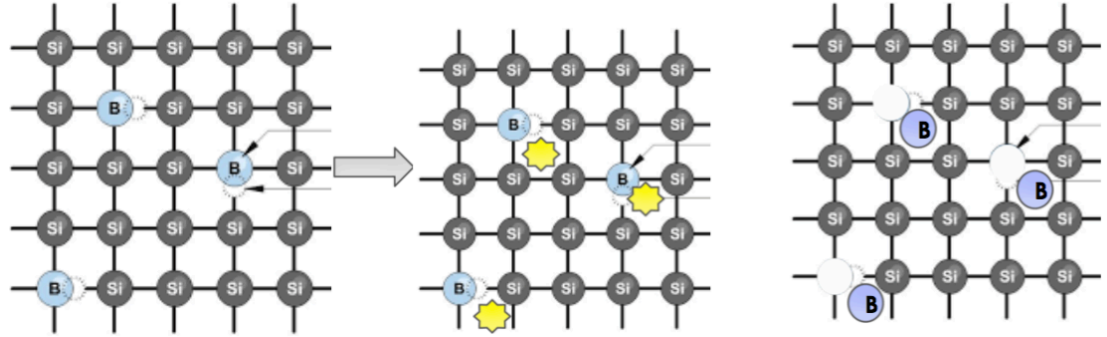
- INFN - Gruppo V
- Horizon 2020, grant UFSD669529
- Horizon 2020, grant INFRAIA
- Ministero degli Affari Esteri, Italy, MAE, “Progetti di Grande Rilevanza Scientifica”
- U.S. Department of Energy grant number DE-SC0010107
- RD50, CERN

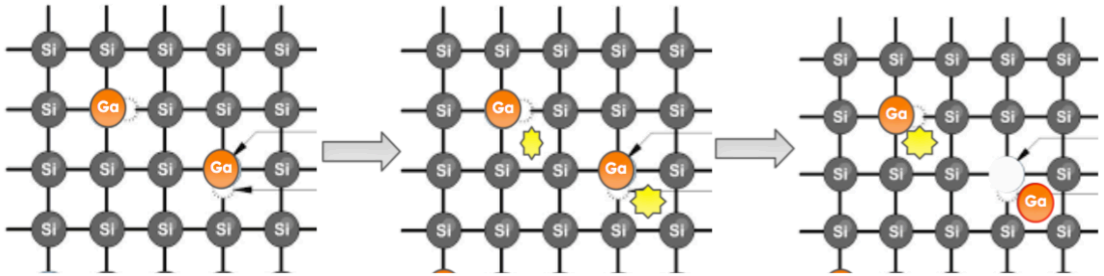
BACKUP

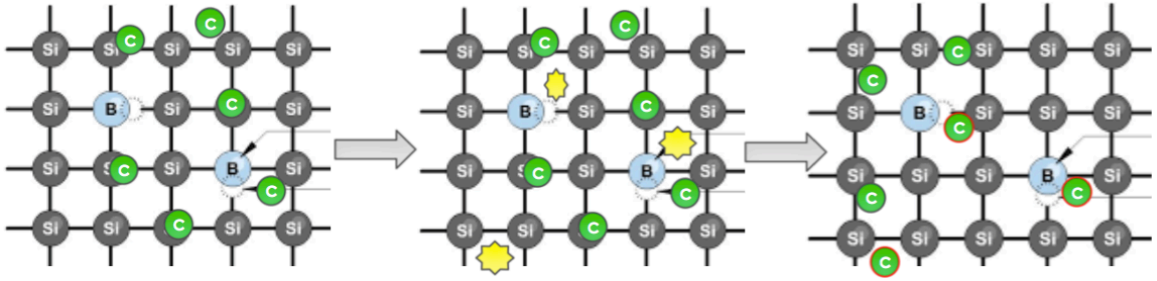
Doping Strategy Motivation

From RD50 Collaboration

Different types of gain layer implant to study the radiation effects on the gain layer





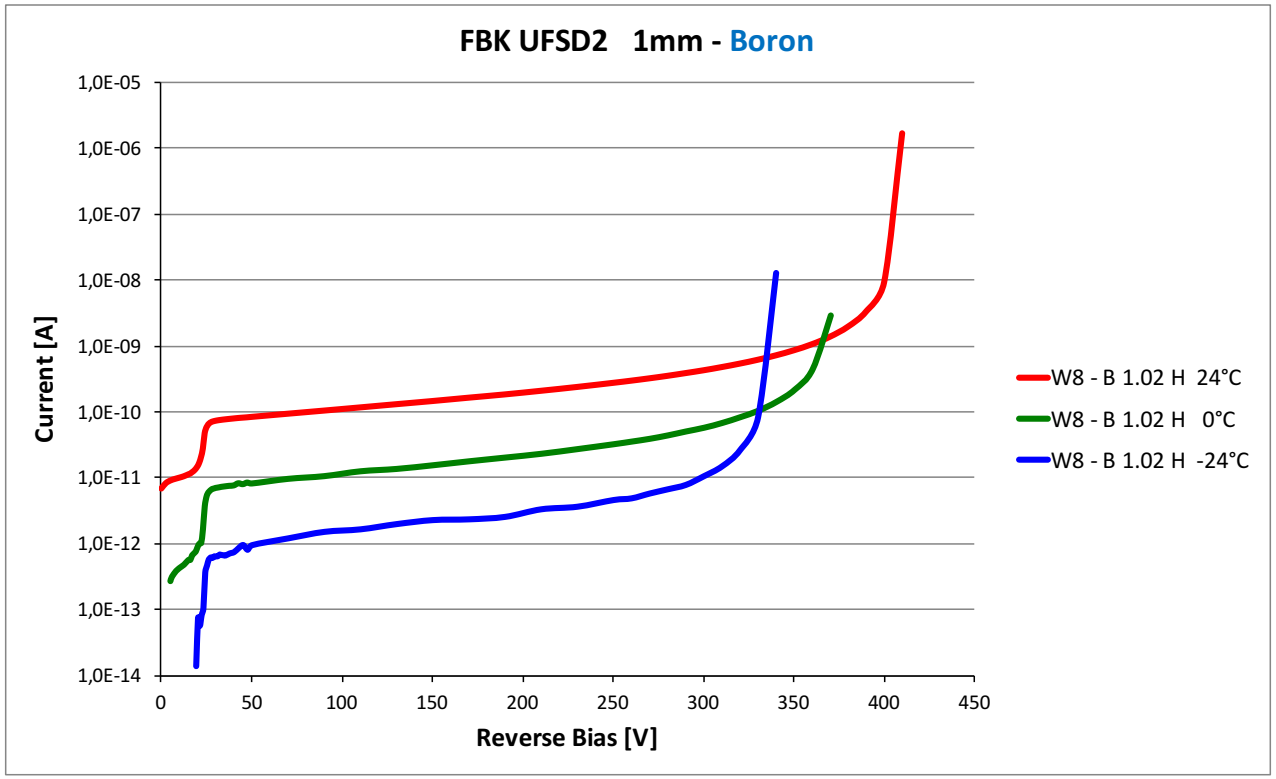


Boron
Radiation creates interstitial defects that inactivate the Boron

Gallium
From literature, Gallium has a lower possibility to become interstitial

Carbon
Interstitial defects filled with Carbon instead of with Boron and Gallium

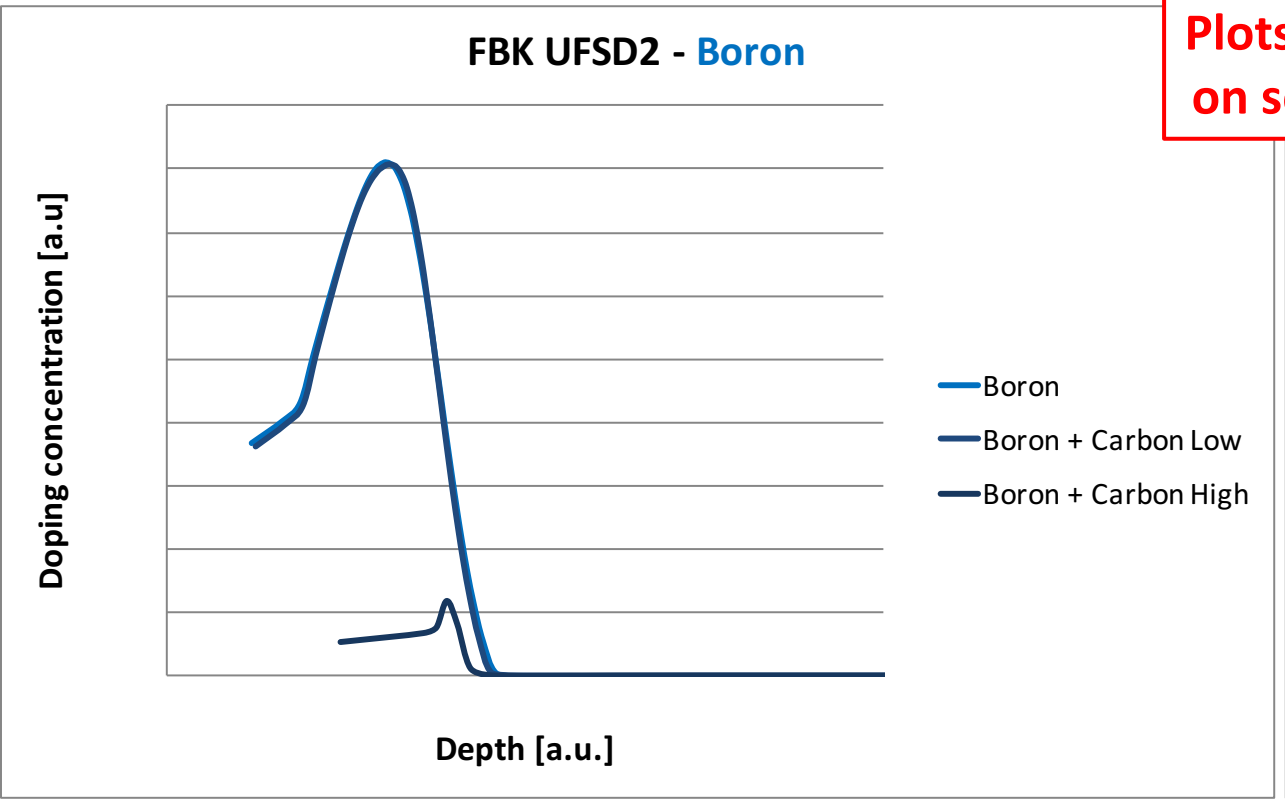
IV Curves - Temperature Dependence



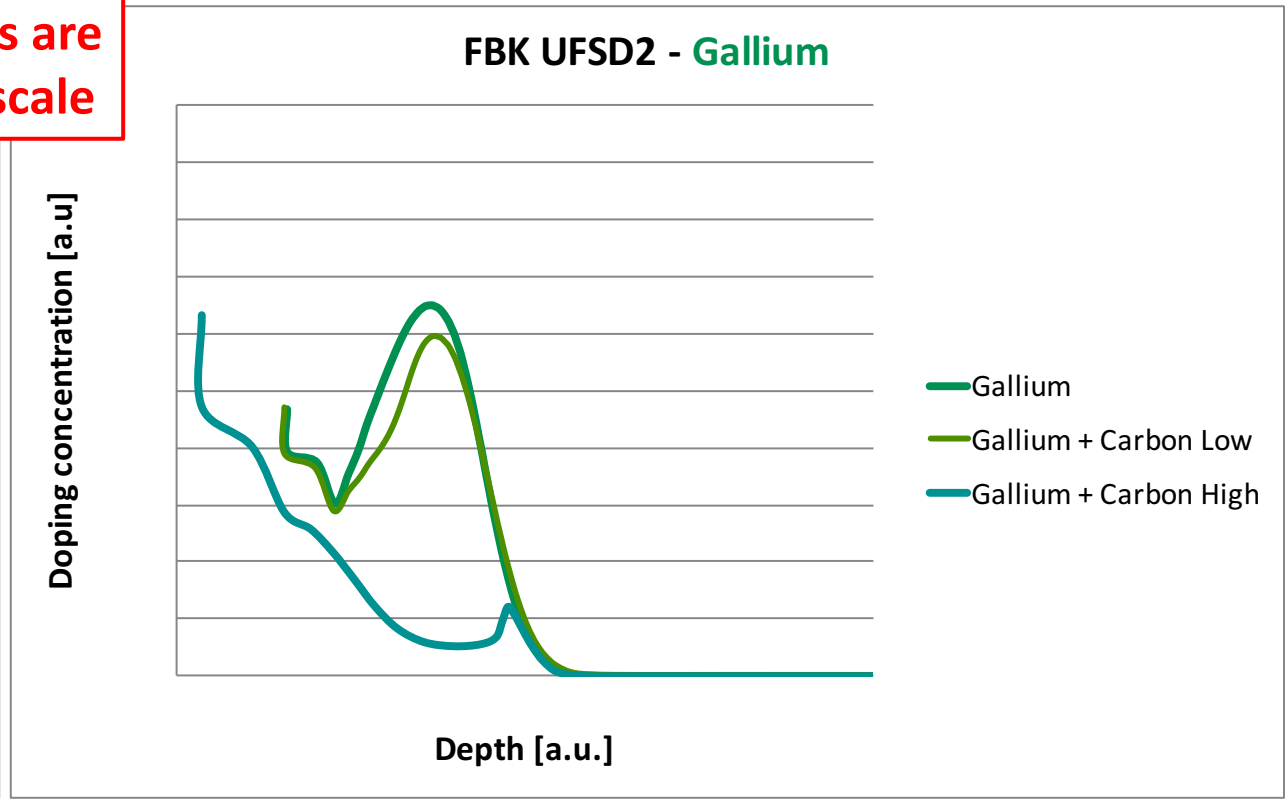
- Leakage current scales with the temperature (expected a factor 2 for every 7°C)
- Expected a gain inversely proportional to the temperature
- Internal Breakdown shift towards lower voltage due to the temperature decreasing

ΔT = 48°C → Current(24°C)/ Current(-24°C)~100 → Result expected

Doping Profiles - Carbon Effects



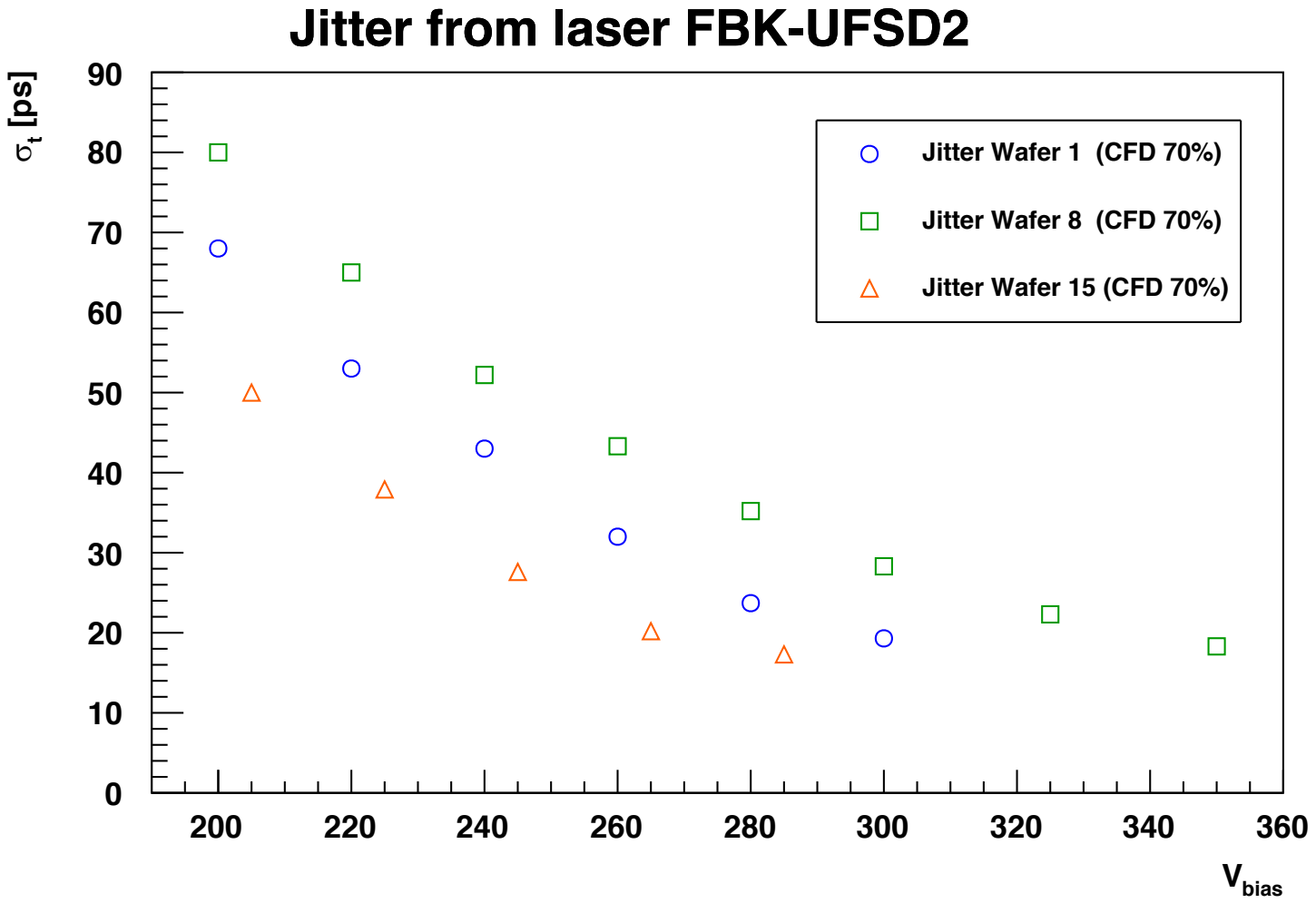
Plots are on scale



- **Carbon reduces the active doping concentration of the gain layer**
- **High Carbon** effect is relevant for both Boron & Gallium
- **Low Carbon** effect is more pronounced in Gallium than in Boron

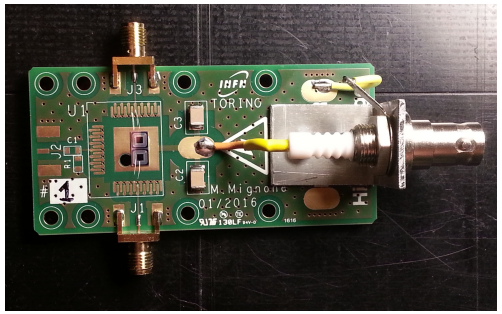
Jitter Measurement

REMINDER:
W1 = B 0.98 LD
W8 = B 1.02 HD
W15 = Ga 1.04 + C Low



TCT Setup from Particulars

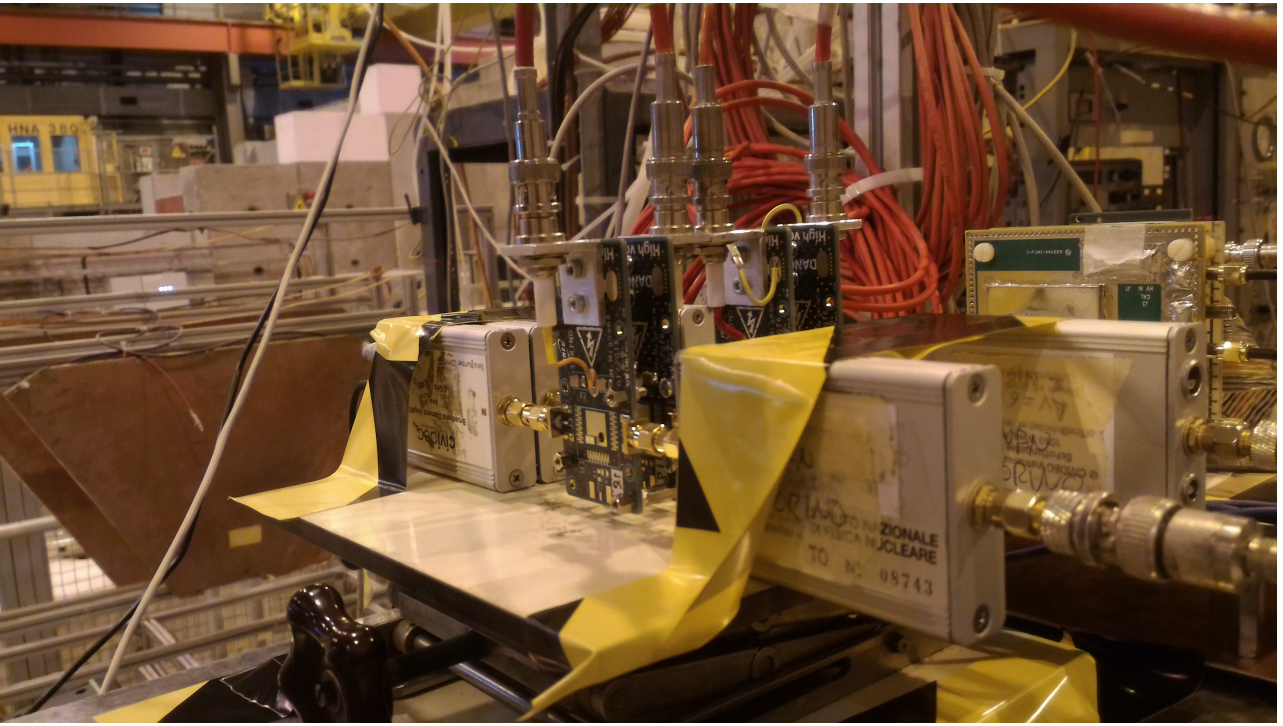
Pico-second IR laser at 1064 nm
Laser spot diameter ~ 50 µm
Cividec Broadband Amplifier (40dB)
Oscilloscope Lecroy 640Zi
(40Gsample/s, bandwith 4GHZ)
Room temperature
Sensors on INFN-Torino boards
(**not optimised for timing measurement**)

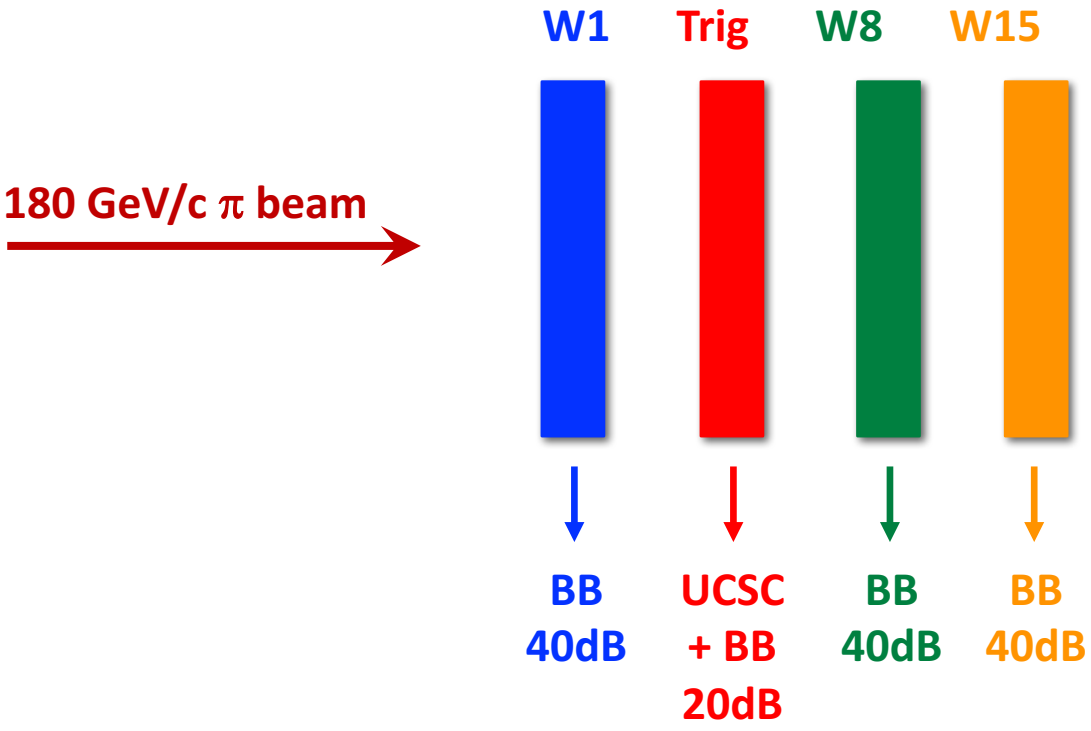


→ **Ga+C sensor has same timing performaces as B ones**

Beam Test Setup at CERN SPS

REMINDER:
W1 = B 0.98 L
W8 = B 1.02 H
W15 = Ga 1.04 + C Low





Trigger logic:
UCSC & (W1 or W8 or W15)

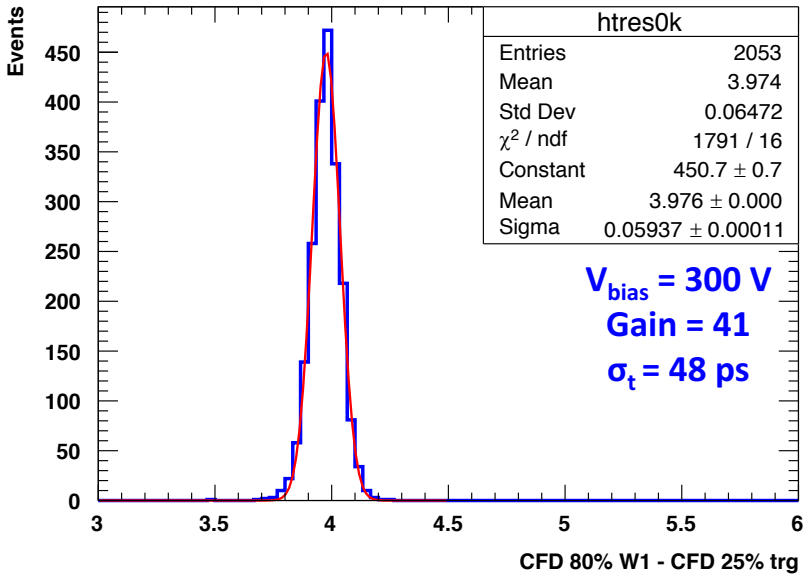
Beam Test Data Analysis

REMINDER:
W1 = B 0.98 L
W8 = B 1.02 H
W15 = Ga 1.04 + C Low

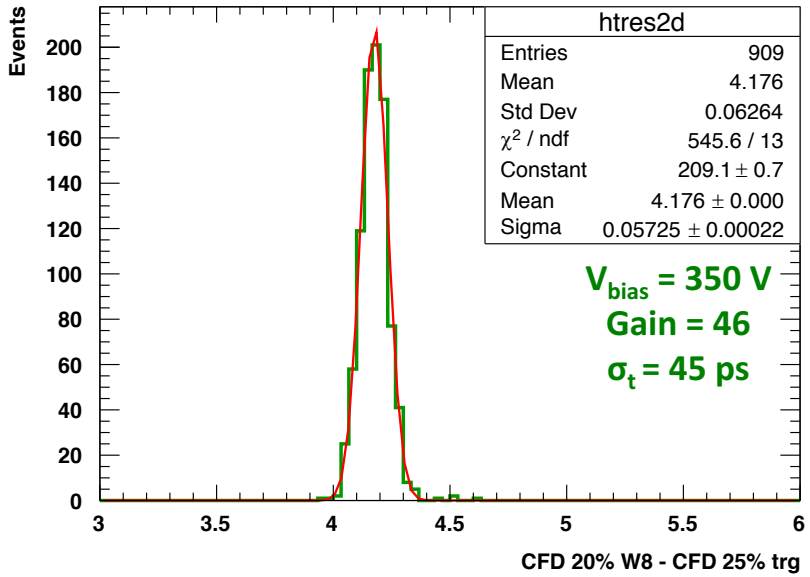
Data analysis:

- Distribution of the time distance between trigger signal and each sensors signal
- Using Constant Fraction Discriminator (CFD) at 25% for trigger and optimised for sensors
- **σ_t is trigger subtracted ($\sigma_t^{trigger}$ ~ 35 ps)**

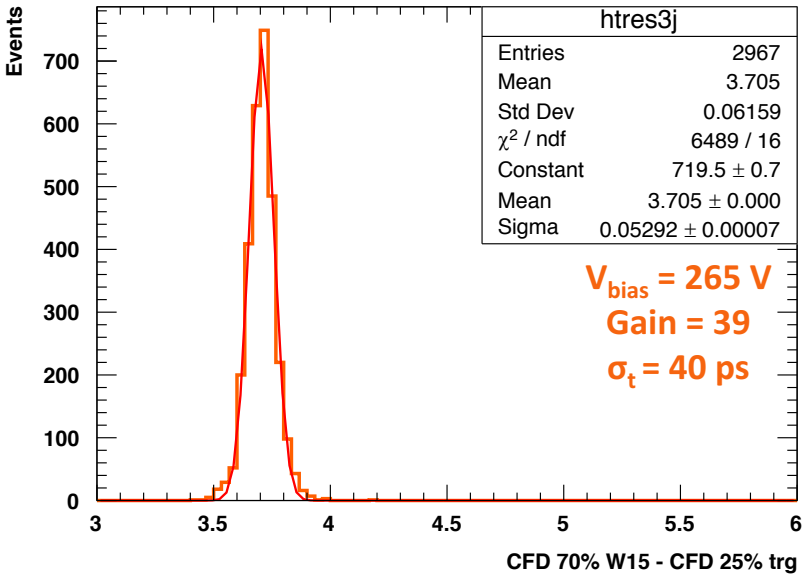
Time Resolution - FBK UFSD2 W1



Time Resolution - FBK UFSD2 W8

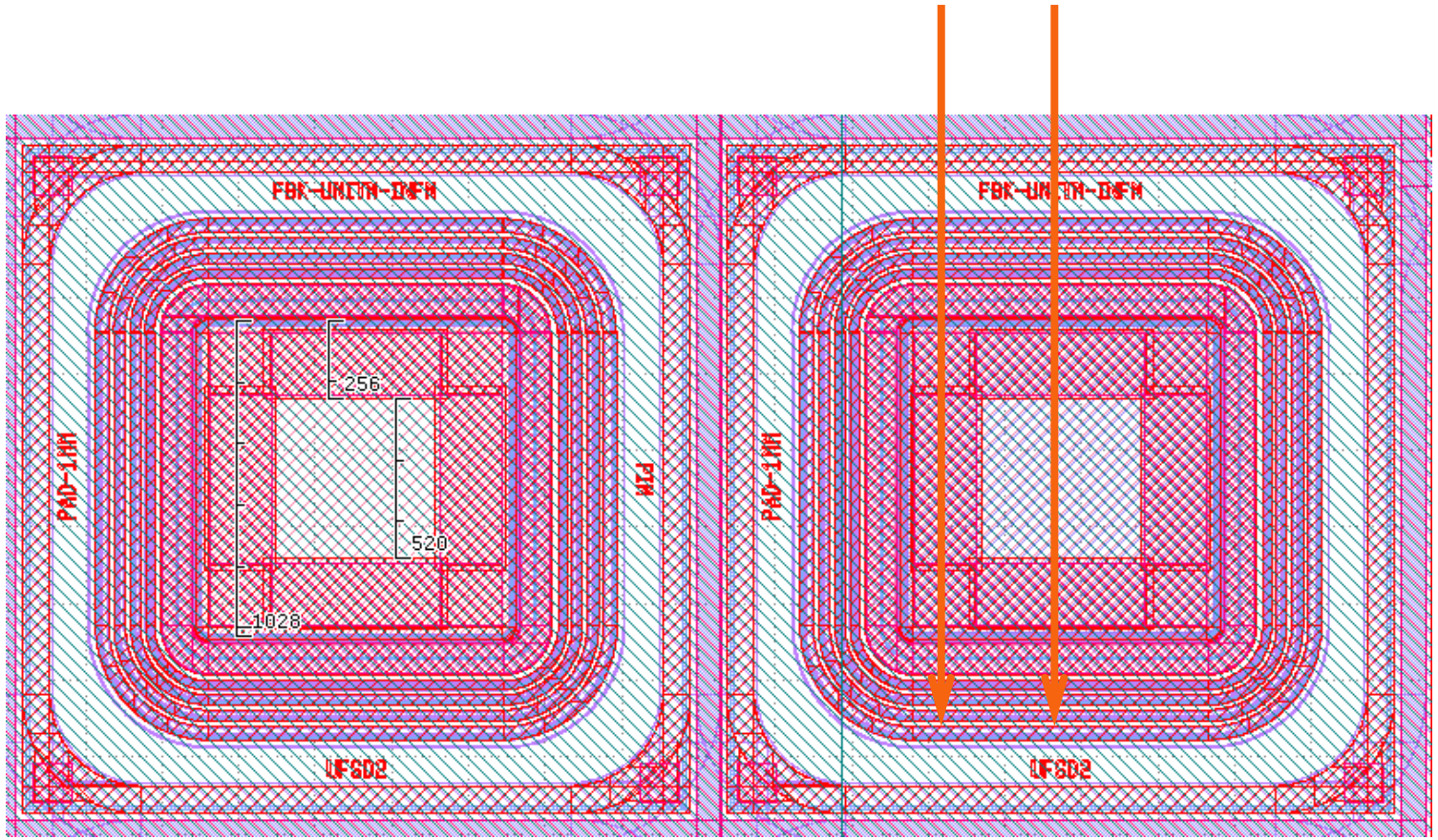


Time Resolution - FBK UFSD2 W15

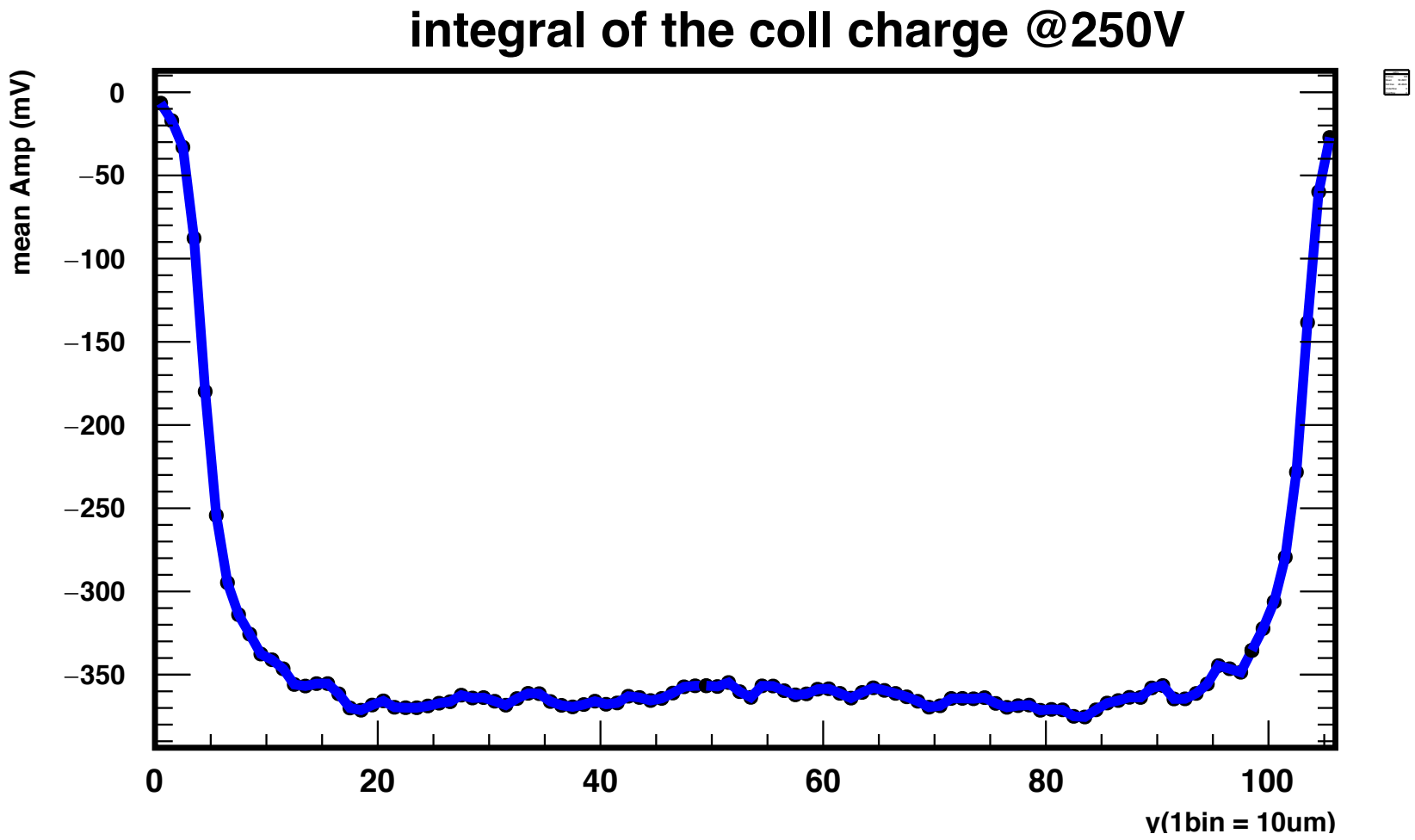


Edge TCT to investigate Hole Effect

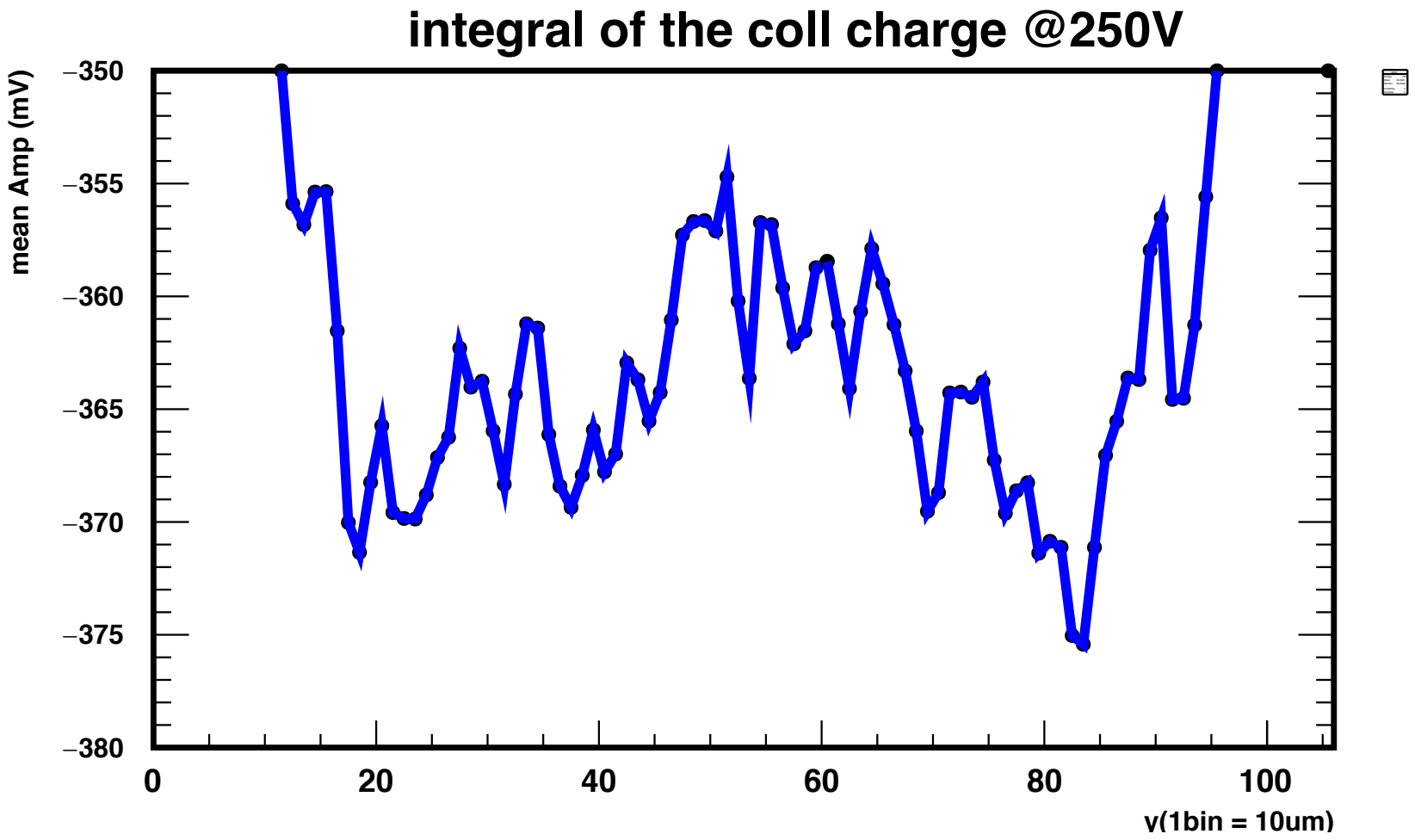
ToA and signal amplitude measurements using edge TCT
W15 board 20 - same as August TB
Laser spot = 9 µm



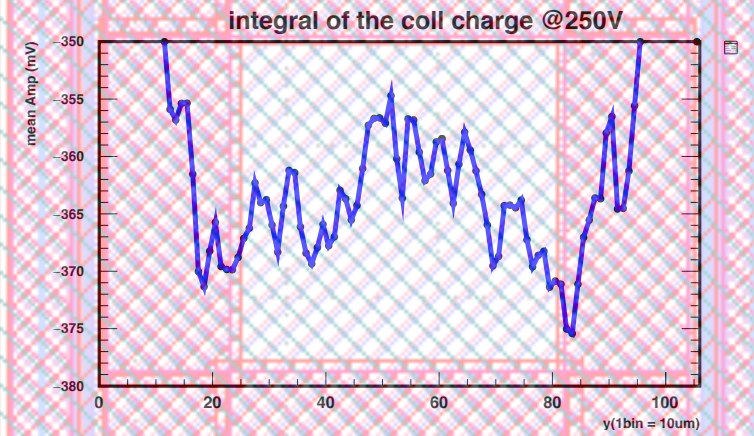
Edge TCT - Signal Amplitude



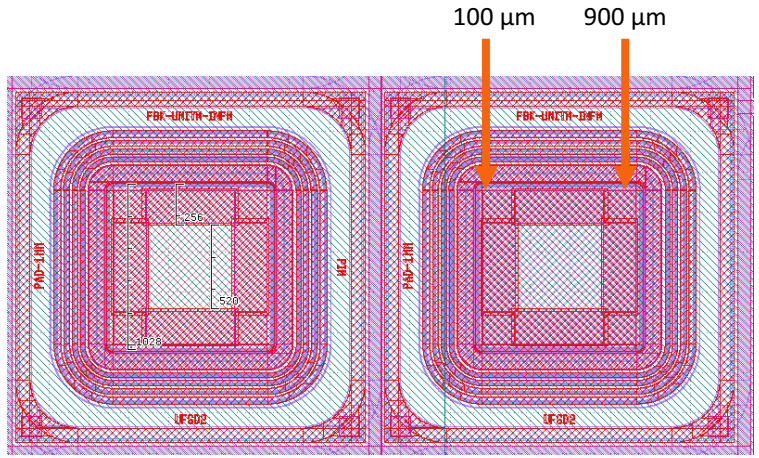
Edge TCT - Signal Amplitude ZOOM

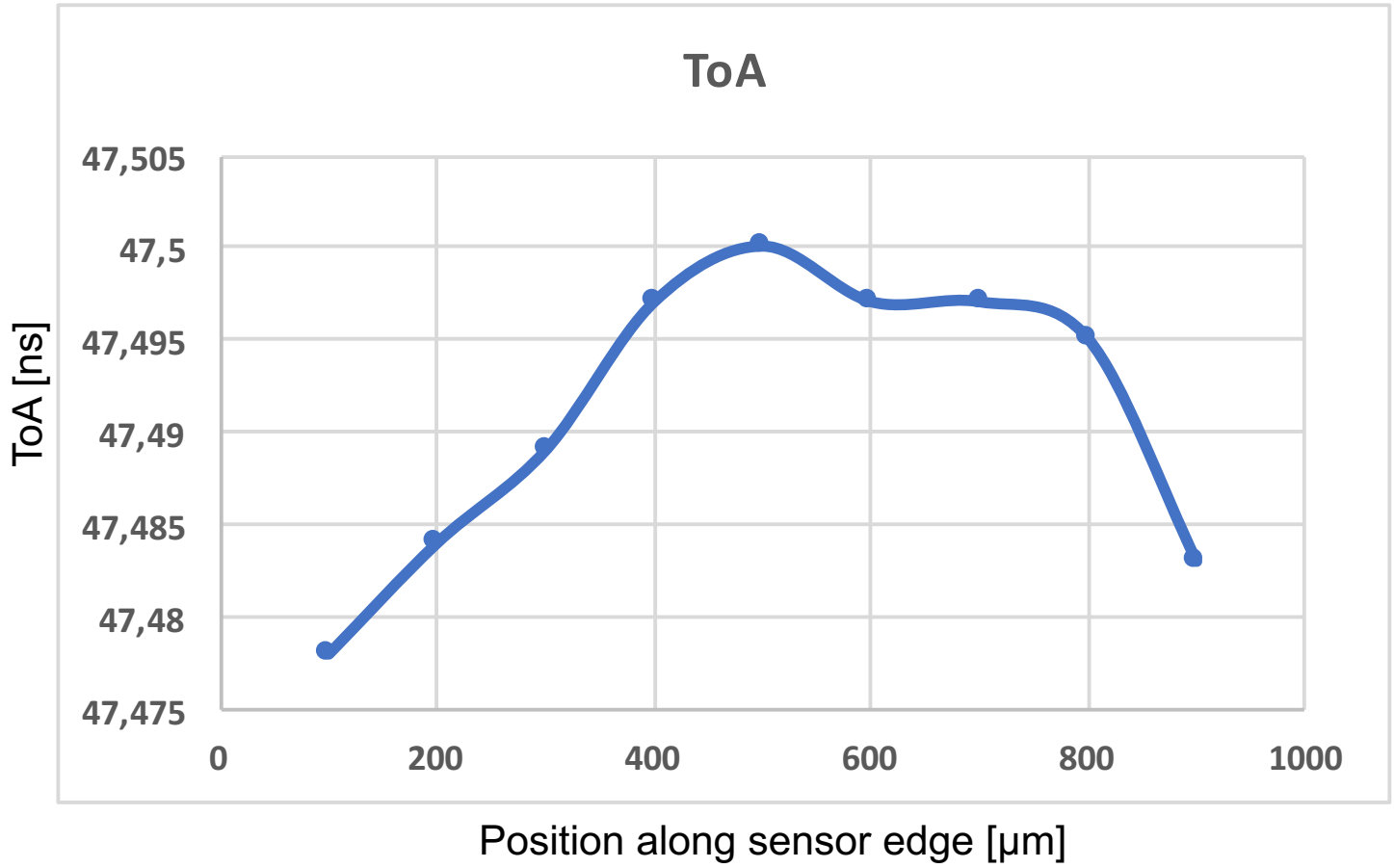


Edge TCT - Signal Amplitude



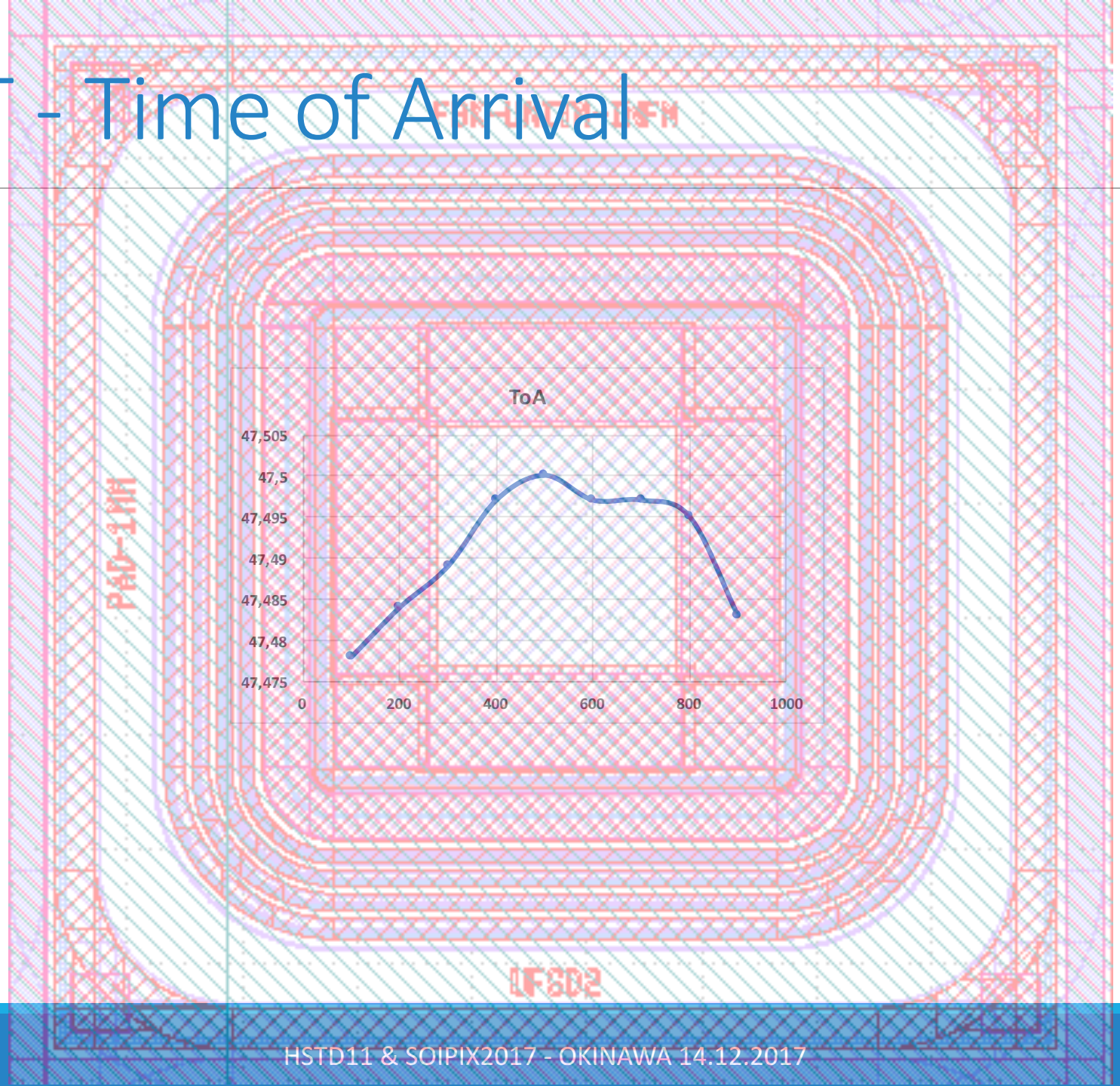
Edge TCT - Time of Arrival



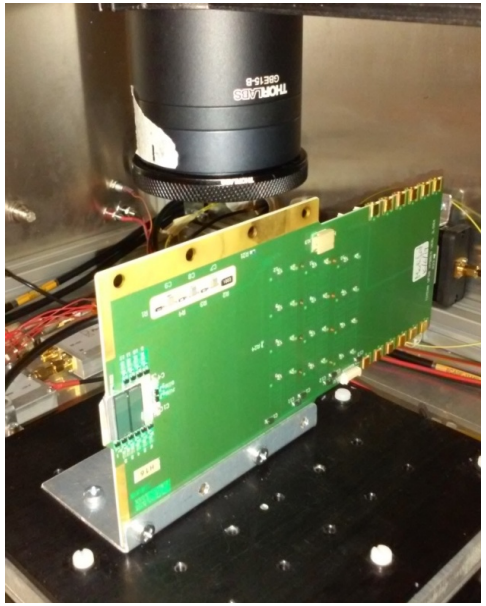


Events crossing the hole region arrive ~ 25 ps later than the events underneath the metal region

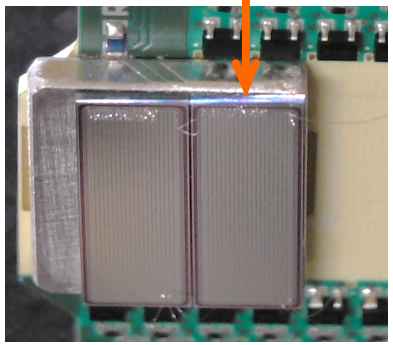
Edge TCT - Time of Arrival



Intra-Strip Inactive Region



Laser beam



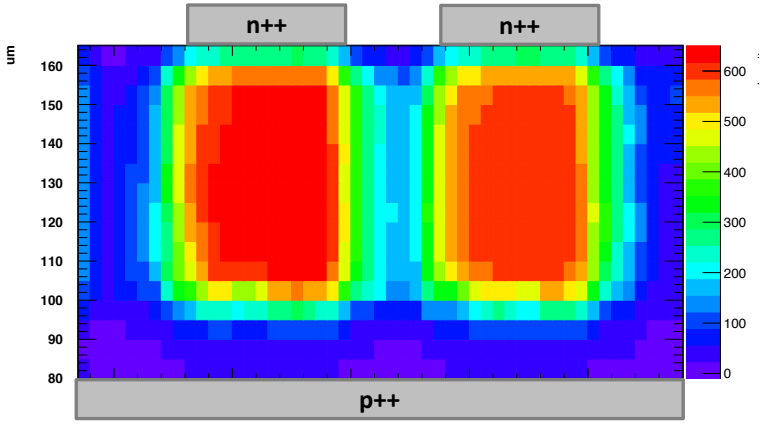
Edge TCT measurement to investigate the intra-structure inactive region

Pico-second IR laser at 1064 nm
Laser spot diameter ~ 10 µm
Multistage readout board by Pilsen University
Oscilloscope Lecroy 640Zi
Room temperature

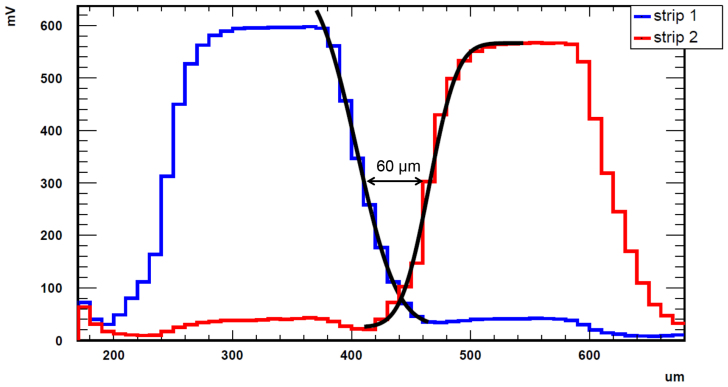
eTCT scan on 2 adiacent strip
W8 V_{bias} = 230 V

→ The inactive region between two adjacent strips has been measured to be ~ 60 µm

2D scan of two adiacent strip edge



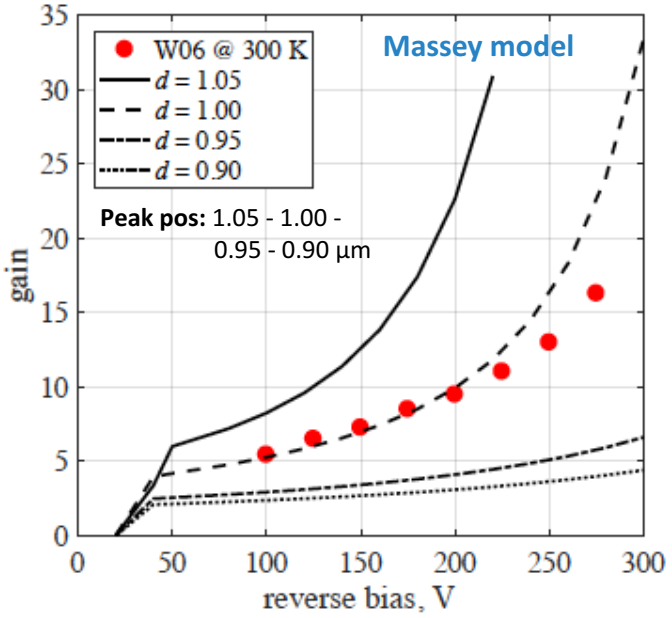
Signal amplitude projection - 2 strips

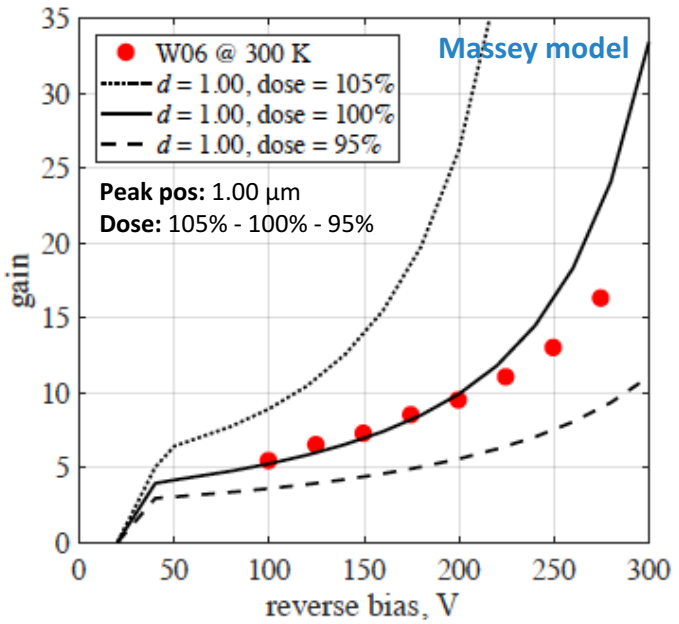


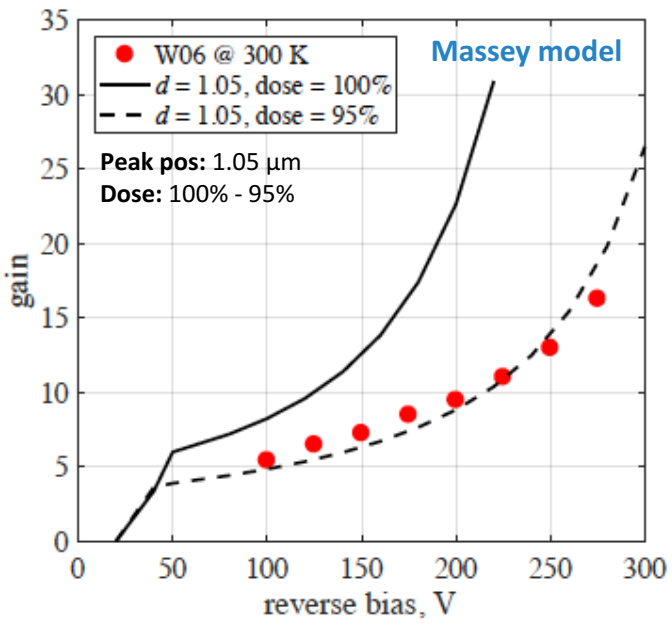
Doping Profile Parametrisation

Data by H. Sadrozinski (UCSC)
Doping concentration profile from CV measurements on Wafer 6
CV measurements give doping concentration profile starting from the n^{++} contact, simulations need doping concentration starting from the junction (~ hundreds nm offset)
Doping concentration profile extracted by CV measurement has ~ % level uncertainty on the peak value
→ A very precise fine tuning is necessary in order to have reliable predictions

Simulation with Synopsys TCAD based on Massey model for gain generation

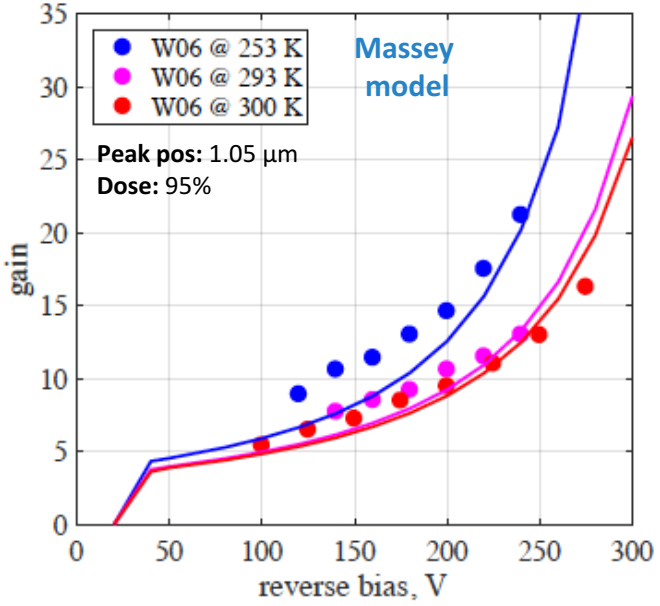


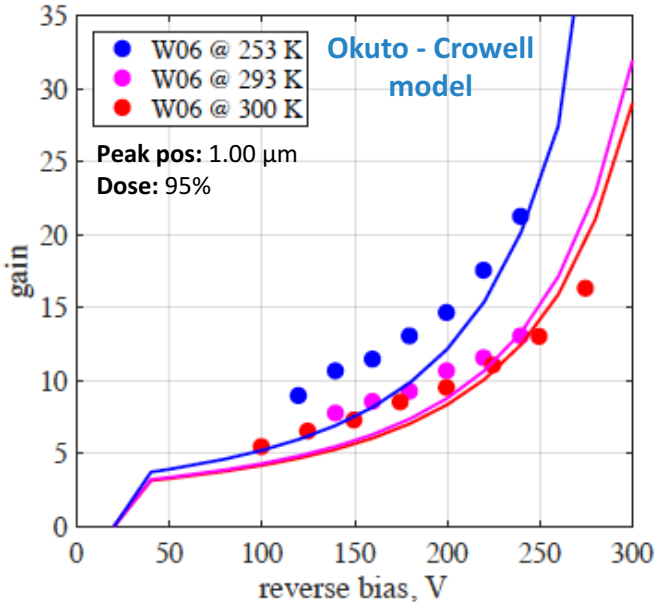


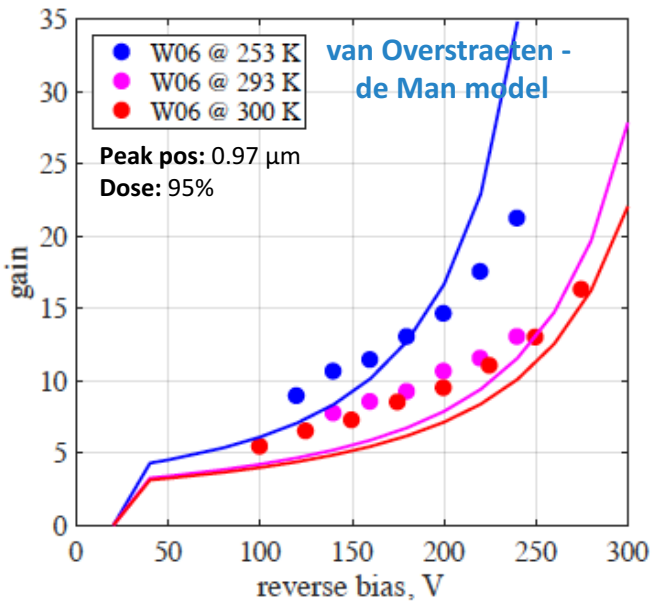


Gain Evolution with Temperature

Data by H. Sadrozinski (UCSC)
Different models for gain generation have been tested
Different tuning of the doping concentration profile extracted for each model
No corrective factors are accounted for in simulation





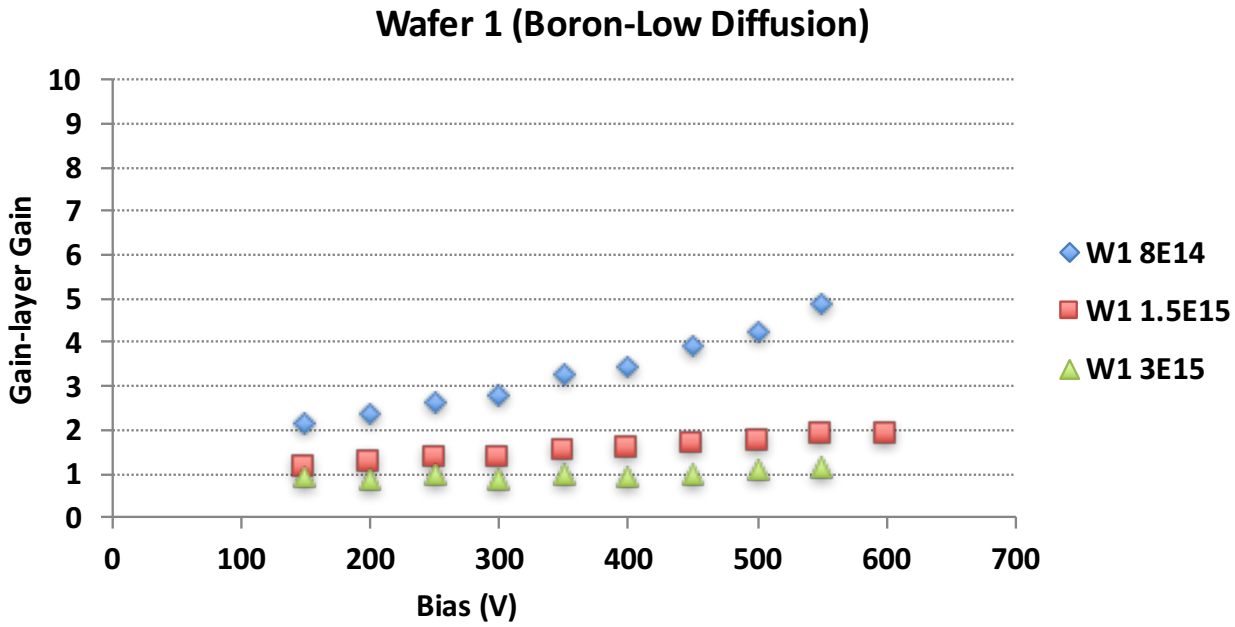


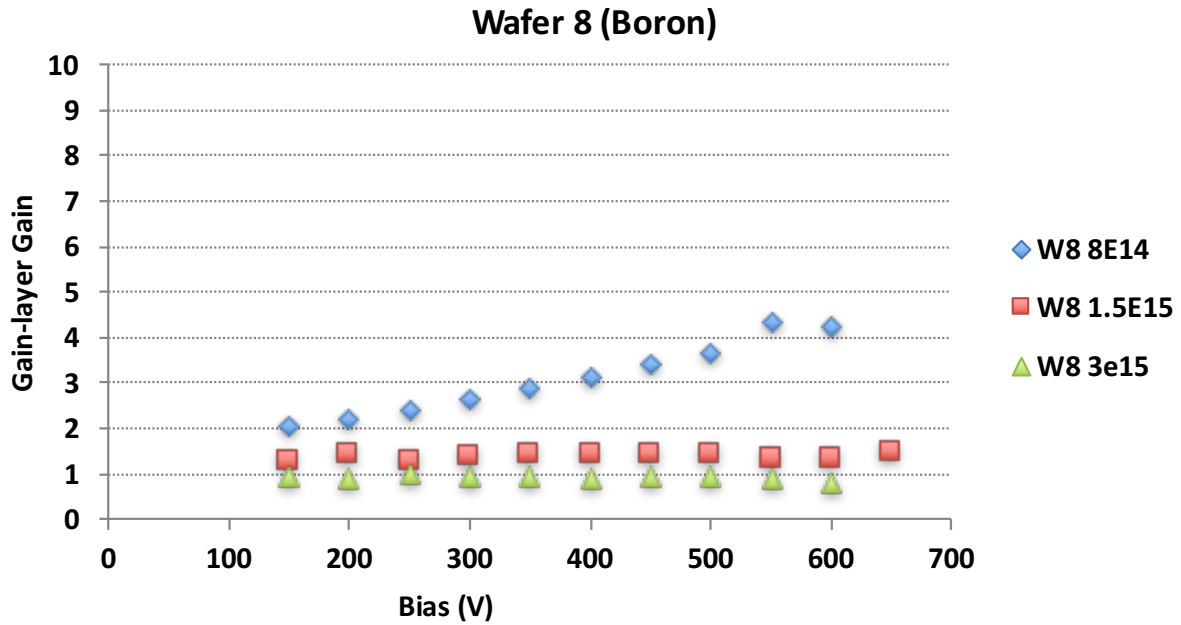
→ A precise prediction of the gain generation and evolution with temperature is crucial to design new UFSD productions

For more details: M. Mandurrino el al., *Numerical simulation of charge multiplication in Ultra-Fast Silicon detectors and comparison with experimental data*, N-03-173, IEEE 2017, Atlanta (USA)

Gain of Irradiated Sensors

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





➢ **Boron low diffusion shows an higher gain than Boron high diffusion**