17th Trento Workshop on Advanced Radiation Sensors

Low Gain Avalanche Diodes

LGAD Process Characterization through Secondary Ion Mass Spectroscopy (SiMS)

Evangelos –Leonidas Gkougkousis

CERN EP-R&D

Geneve – March 2nd, 2022

•Introduction, EP-R&D W.P. 1.1 – Hybrid Sensors

Planar Sensors (J. Haimberger, V. Gkougkousis)

- ✓ Radiation damage and trapping model validation though TCAD
- ✓ Timing and efficiency at < 1e17 n_{eq}/cm^2 using fast neutrons and ps protons (thicknesses 50, 100, 200, 300 μm)

LGADs (V. Gkougkousis)

- ✓ Radiation damage mechanisms and modeling on different dopant types (TIPP2021, ArxiV PrePRrint, PicoSecond Workshop 2021)
- ✓ Indium-Lithium gain layer radiation hardness investigations (Trento2021)
- ✓ **Process simulations and SiMS – Carbon/Boron** (LINK)

Silicon Electron Multiplier (M. Halvorsen, LINK, ArxiV PrePRrint, IEEE)

- ✓ Structure optimization and electrostatic simulations
- ✓ Timing and transient Simulations
- ✓ Process iterations (Metal Assisted Etching)

Talks @ Trento 2022

Small Pitch 3Ds for tacking and timing (V. Gkougkousis, LINK)

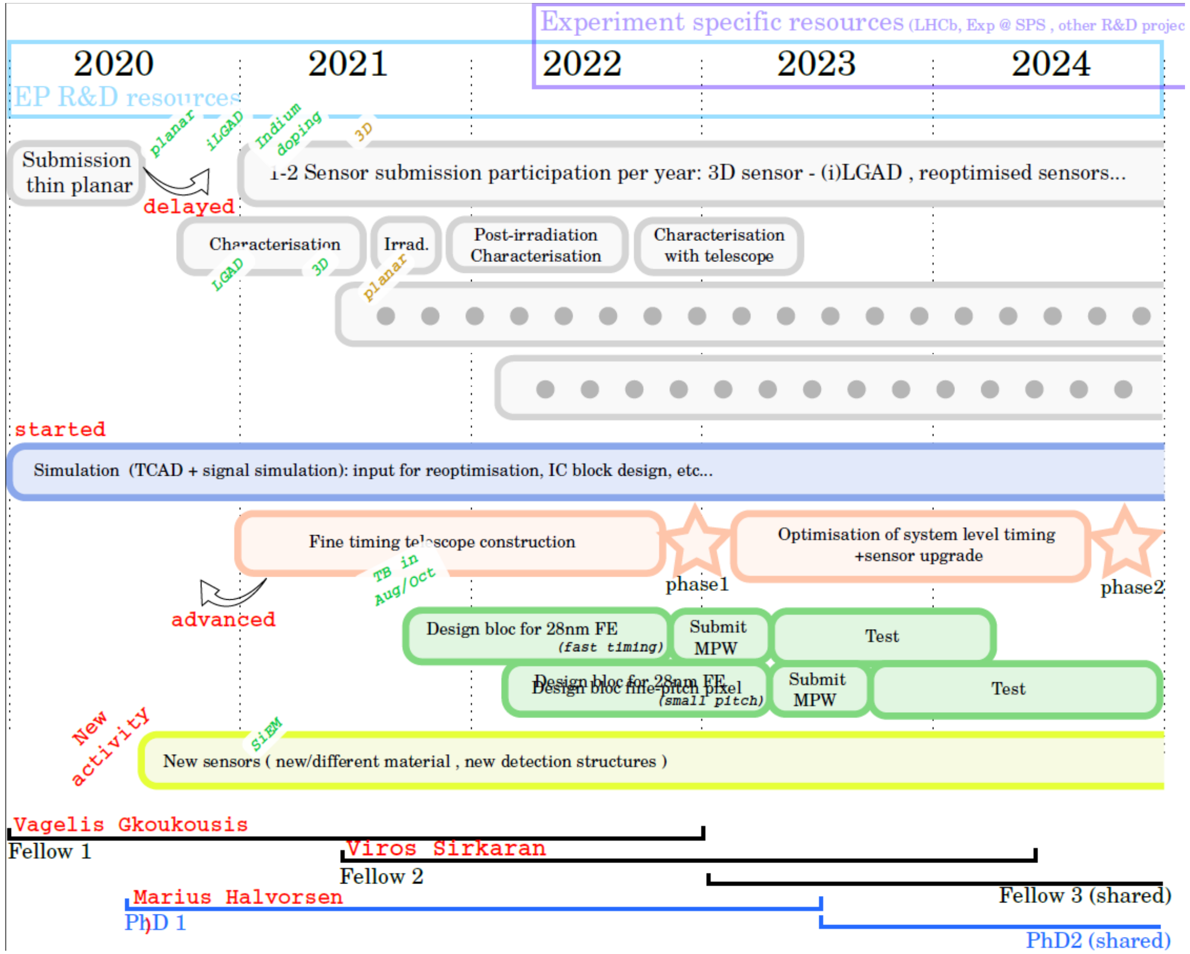
- ✓ β particles timing studies on irradiated and unirradiated devices
- ✓ Test beam with SPS pions (Tracking + Timing)
- ✓ Proton and neutron irradiations > 1e17 n_{eq}/cm^2
- ✓ New small pitch production optimized for gain at the electrode region

Vagelis Gkougkousis

Jakob Haimberger

Marius Halvorsen

Victor Coco



•Introduction – Motivation

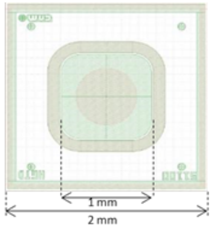
Gkougkousis V., RD50 Workshop Talk, June 2020: link

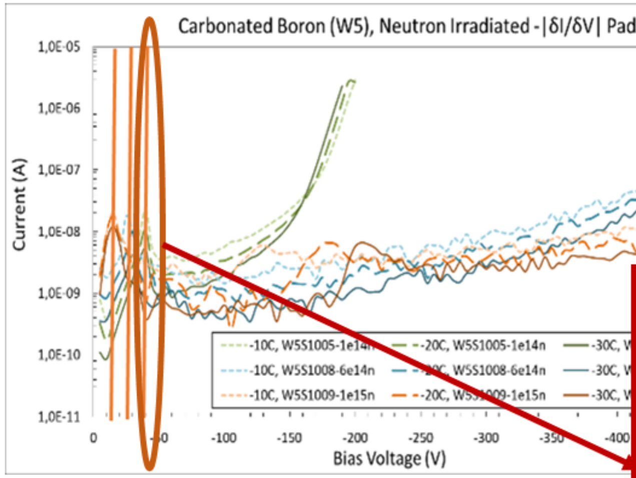
- ✓ 1x1 mm^2 CNM diodes, runs 10478 (W4 & W5) and 10924 (W6)
  - ✓ 50 µm on 250 µm 4" SoI wafers
  - ✓ **Boron**, **Boron + Carbon** diffused and **Gallium** implanted gain layer
- ✓ Irradiations:
  - ✓ 23 GeV PS protons
  - ✓ fast (~10MeV) neutrons at JSI
  - ✓ 5 fluences: 1e14, 6e14, 1e15, 3e15, 6e15 n_{eq}/cm^2
- ✓ Tested at -10C, -20C and -30C

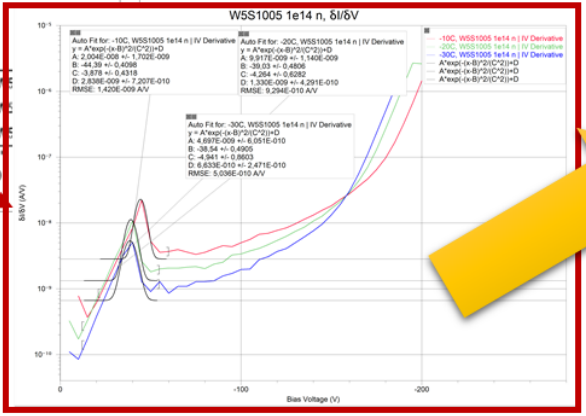
30 sensors x 3 temp.
90 Series of measurements!!

- Depletion voltage by Gaussian fit on IV derivative
- Repeated for -10, -20 & -30°C
- Active dopant extrapolated

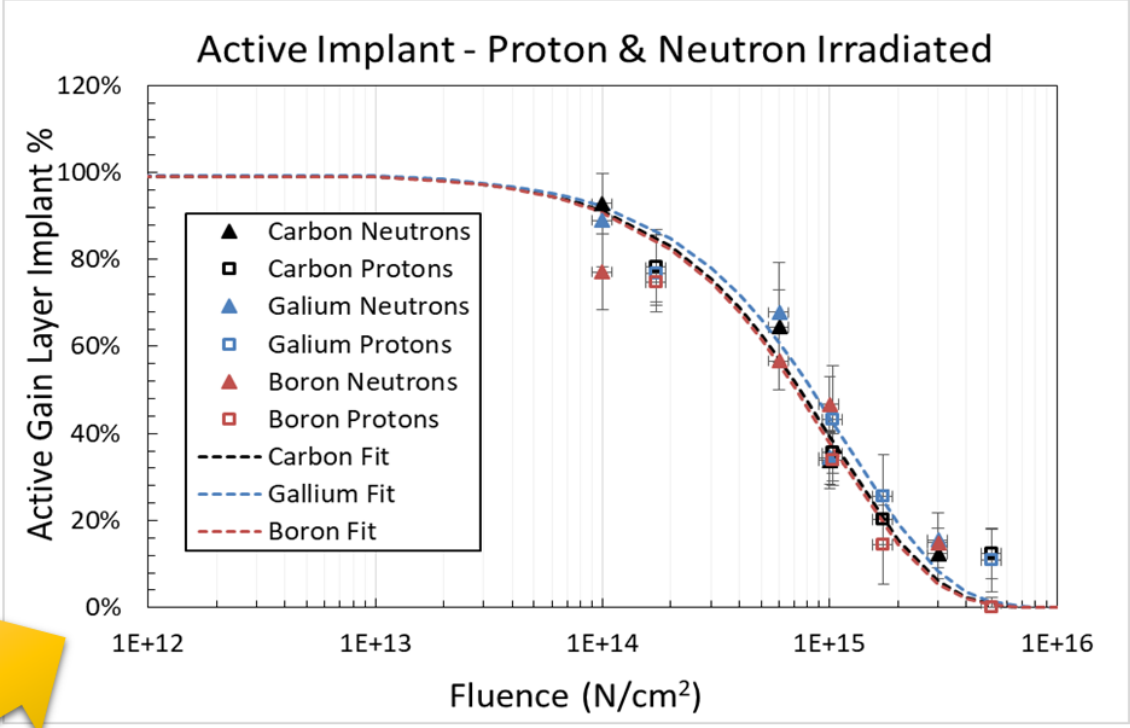
$$G(\%) = e^{-C_G \Phi}$$







$$f(V) = \left|\frac{\partial I}{\partial V}\right|$$

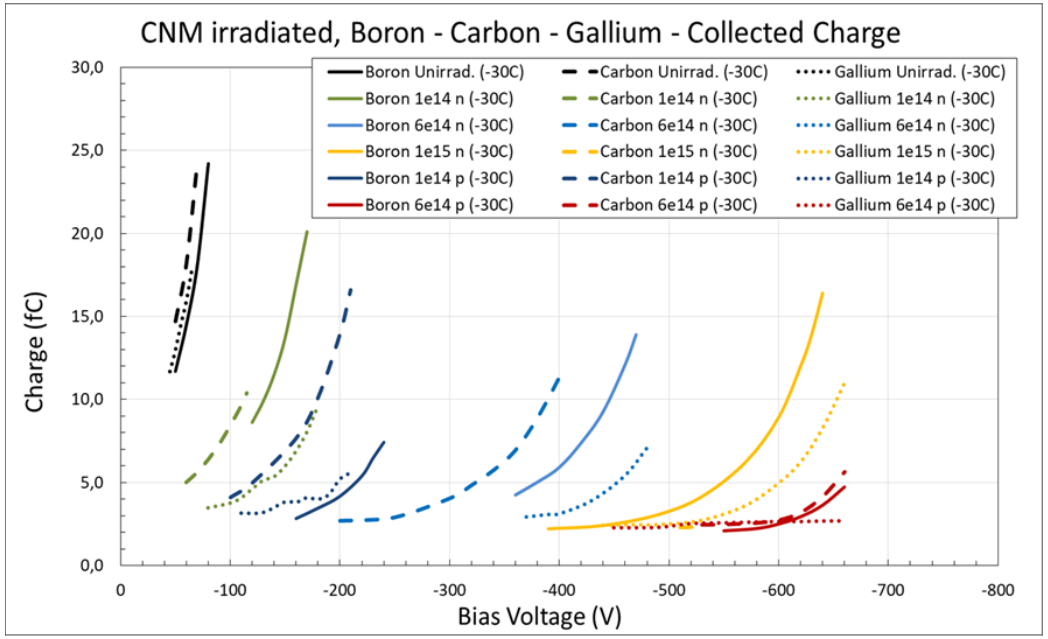


No active dopant difference between different implantation types – neutron/proton

•Introduction - Motivation

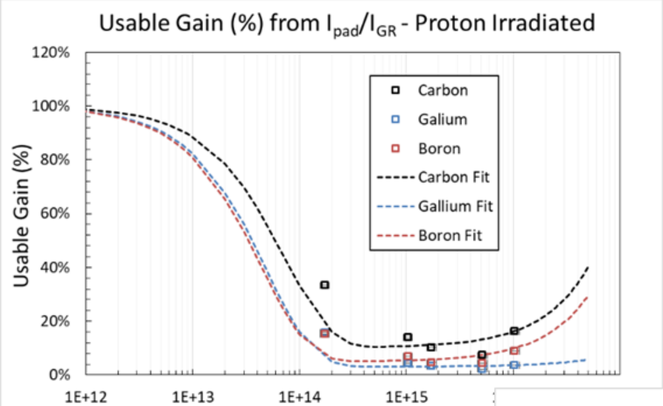
- ✓ Collected charge measured with MIPs
  - ✓ 5k events, beta measurements with Sr90
  - ✓ **Repeated in -10°C, -20°C -30°C with concurrent results**

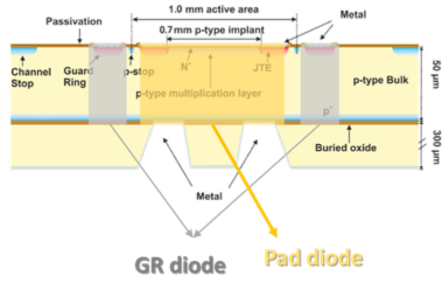
Method 1: Charge Collection



- ✓ Usable gain estimated by comparing GR-pad leakage current
  - ✓ GR – gain region share same cathode
  - ✓ Separate removal factors for Protons/ neutrons
  - ✓ **Exponential behavior in depleted region**

Method 2: GR-Pad IV fit estimation





Fluence (n_{eq}/cm^2)

Acceptor level introduction rate

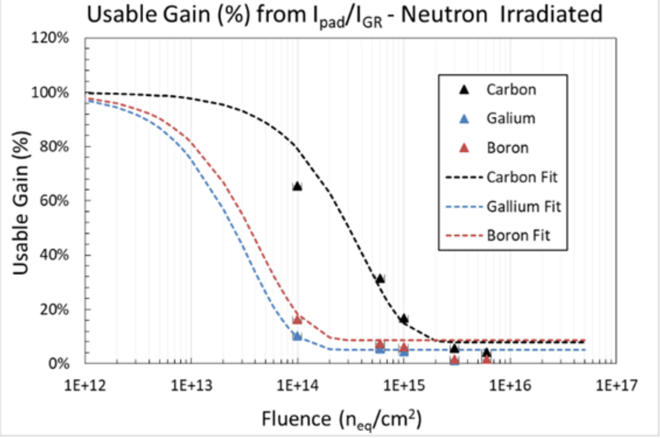
$$N_{eff}(\Phi) = N_{eff_0} - N_c\left(1 - e^{-c\Phi}\right) + g_c\Phi$$

Effective dopant concentration

Initial dopant concentration

Removable dopant

Gain extraction constant

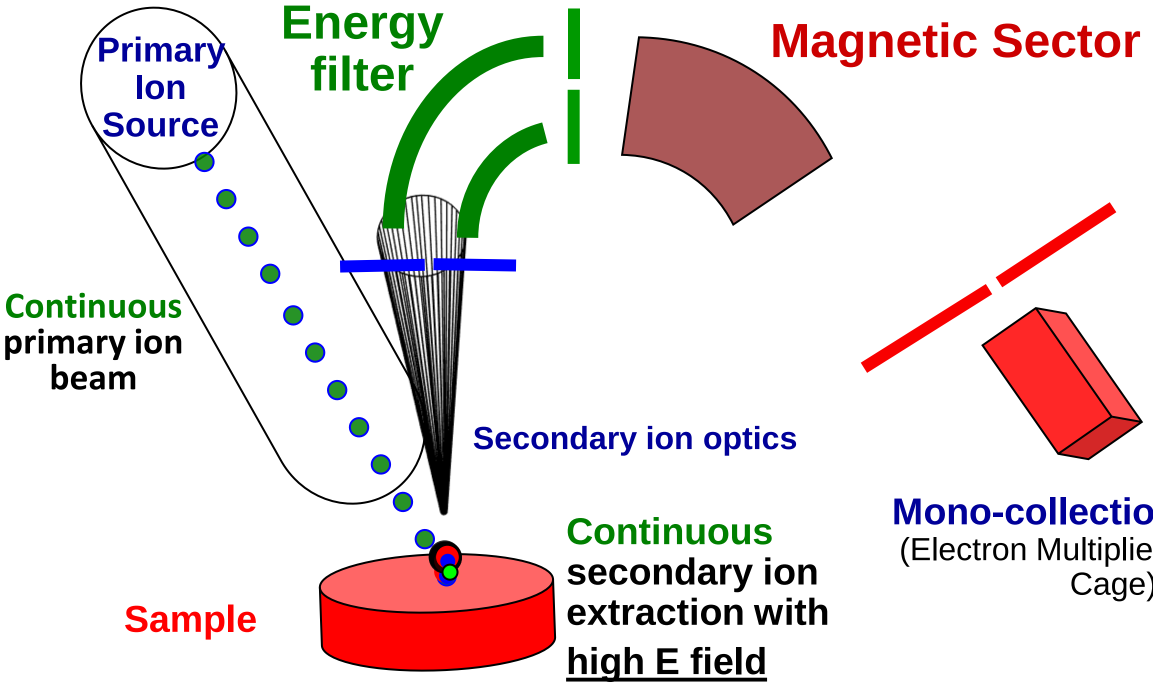


Both methods agree: Gallium ~20% worse, Carbon ~ 20% better wrt Boron sensors calibrated to perform equally

Acceptor removal in all three cases is the same (same fraction of active dopant from V_{GL}), trapping is not (different gain for same fluence, starting from the same point)

•Secondary Ion Mass Spectroscopy

Operating Principals



Primary Ion Source

Energy filter

Magnetic Sector

Continuous primary ion beam

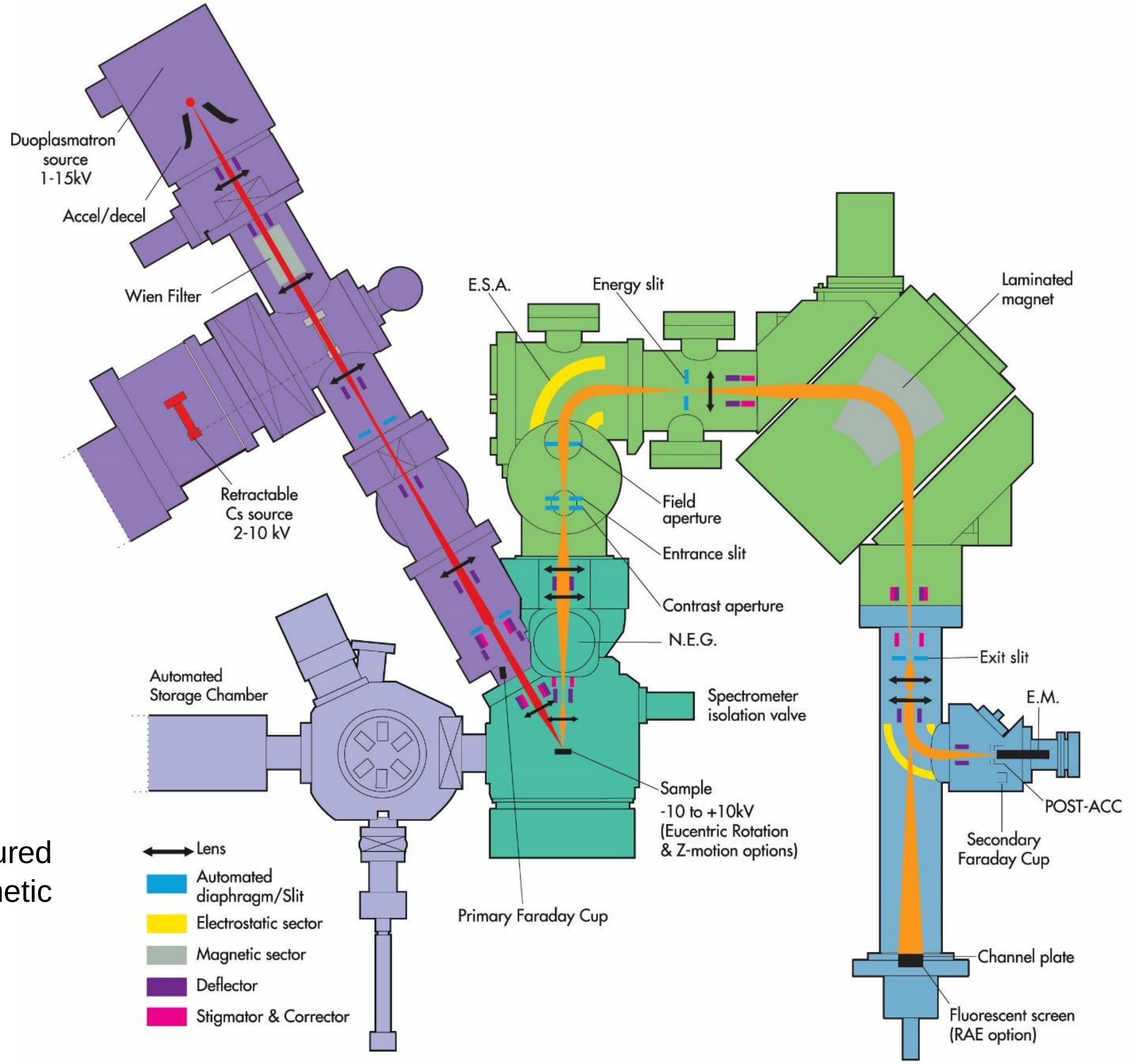
Secondary ion optics

Mono-collection detector
(Electron Multiplier or Faraday Cage)

Sample

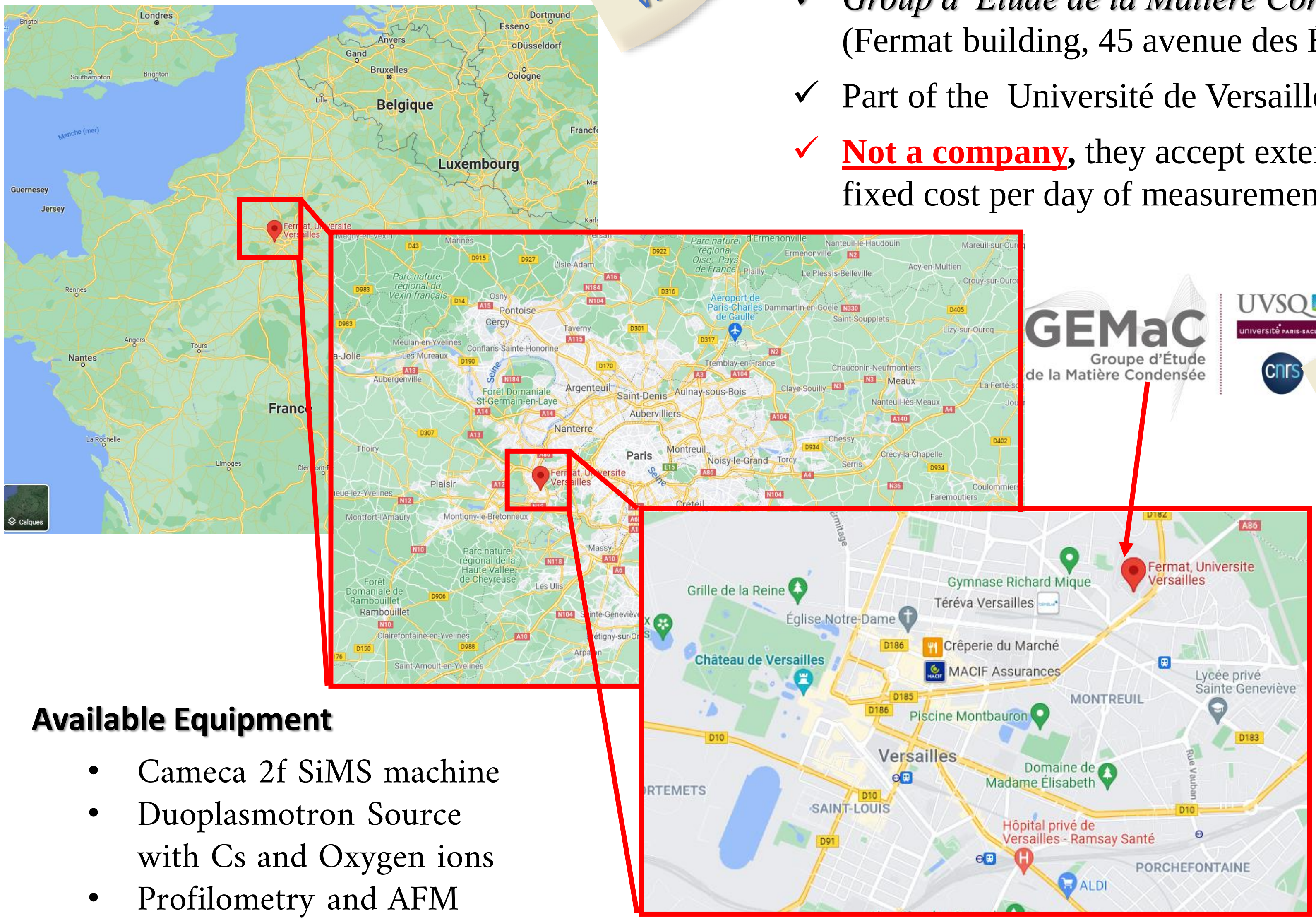
Continuous secondary ion extraction with <u>high E field</u>

Mono-collection: elements measured sequentially by scanning the magnetic field



•Secondary Ion Mass Spectroscopy

Where and why



Where

- ✓ *Group d' Etude de la Matière Condense – GEMaC* in Versailles, France (Fermat building, 45 avenue des États-Unis)
- ✓ Part of the Université de Versailles Saint-Quentin-en-Yvelines, CNRS unit
- ✓ **Not a company**, they accept external users in terms of collaboration with a fixed cost per day of measurement (~ 1500CHF per day of machine)

Why ?

- ➢ Study accurately the gain layer to correctly reproduce impact ionization in simulations
- ➢ Understand radiation damage and acceptor removal vs gain layer geometry
- ➢ Test the Carbon concentration and its relation to radiation damage improvement
- ➢ Evaluate process flow in case of issues and establish failure point

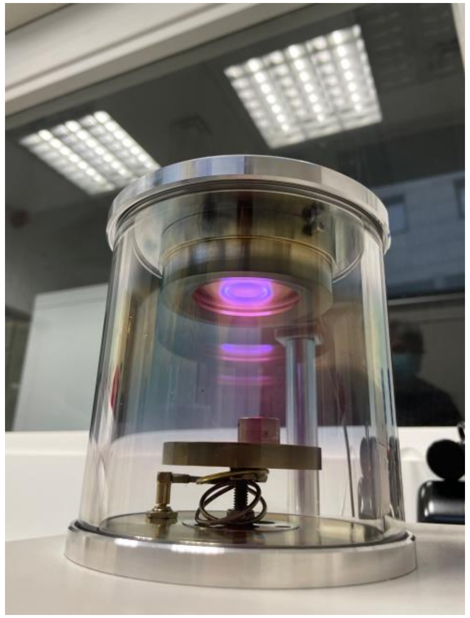
Available Equipment

- Cameca 2f SiMS machine
- Duoplasmotron Source with Cs and Oxygen ions
- Profilometry and AFM

•Secondary Ion Mass Spectroscopy

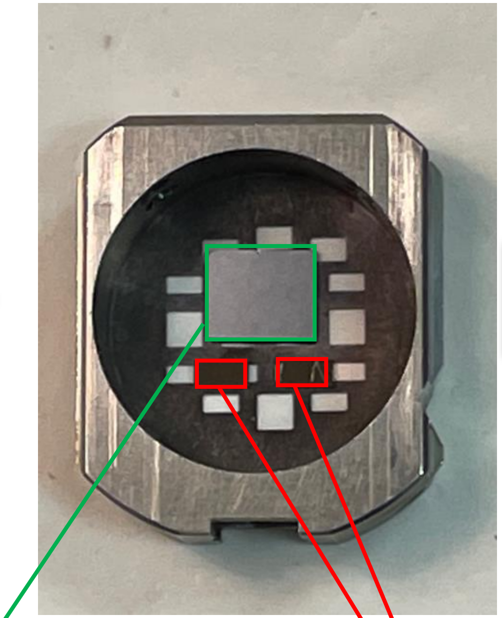
Sample preparation

Step 1: Metallization



PECVD deposition of 50nm Au on sample surface using Ar plasma

Step 2: Mounting



Placement in holder with appropriate calibration sample

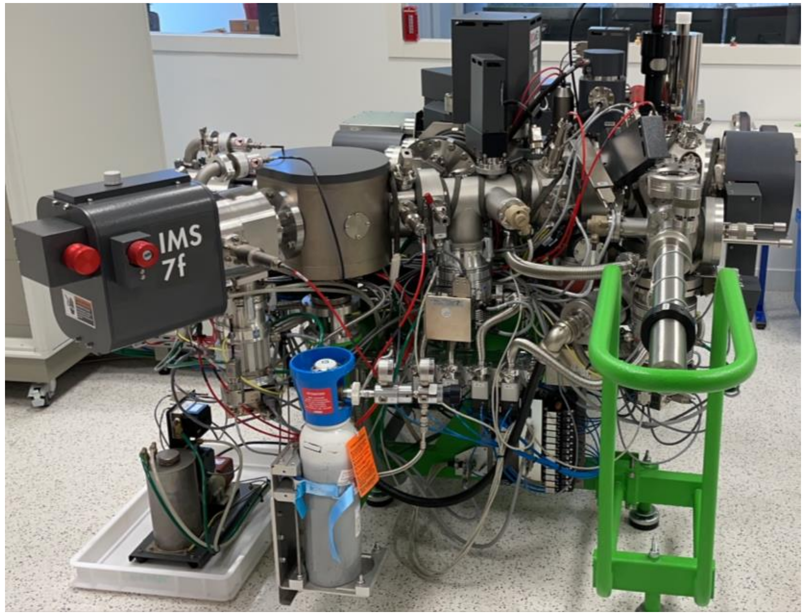
Boron implanted calibration sample

LGADs for testing

Step 3: Fixing-Tensioning

Vertical mounting via spring loaded pressure plate and inspection of planarity

Step 4: Measurements



Introduction to machine secondary vacuum
4.7e-08 mbar introduction vacuum
6.3e-10 mbar primary vacuum
Oxygen or **Cesium** ions

- ✓ Samples must have a clean planar surface with minim size of 2 x 2 mm and a uniformly implanted zone
- ✓ A calibration standard must already exist for the element under study
- ✓ A conductive surface is needed for better precision, metallization can be applied as an alternative

•Analysis Concepts

Scaling Factor, Depth and Integrals

- ✓ SiMS is a comparative technique, starting from standard calibration sample and extrapolating to sample under test
- ✓ Extrapolation done using RSF (Relative Scaling Factor) define as $\boldsymbol{RSF} = C_i^{cal}\frac{I_M^{cal.}}{I_i^{cal.}}$ where:
  - ➢ I_M^{cal} integral of matrix signal for total measurement time: $I_i^{cal.} = (\mathbf{1/T}) \times \int_0^T \boldsymbol{S_i}\partial \boldsymbol{t}$
  - ➢ I_i^{cal} integral of signal of element of choice for total measurement time: $I_M^{cal.} = (\mathbf{1/T}) \times \int_0^T \boldsymbol{S_M}\partial \boldsymbol{t}$
  - ➢ C_i^{cal} concentration integral for element under study (C, B, P) – known from reference implantation

- ✓ Concentration of the **same element** on an **identical matrix** for the sample under test can be expressed as:

$$\boxed{\boldsymbol{C_i^{sample}} = \boldsymbol{RSF}\,\frac{\boldsymbol{S_i^{sample}}}{\boldsymbol{S_M^{sample}}}}$$

- ✓ Primary ions species and beam current must be identical between calibration and measurement

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- ✓ The depth of any given point within a uniform layer L_i can expressed as the sum of the depth of all preceding layers increased by the product of the measurement time within that layer (t - T_{L-1}) with the abrasion speed for the specific layer (v_{Li}):

$$d_{L_i} = \sum_{j=1}^{j=i-1} D_{L_j} + \left(t_i - T_{L_{i-1}}\right) \times v_{L_i}$$

- ✓ Total "in-silicon" implanted dose defined as the integral of point concentration along the silicon dept, assuming linear behavior between consecutive measurements and fixed depth intervals, the integral can be approximated as:

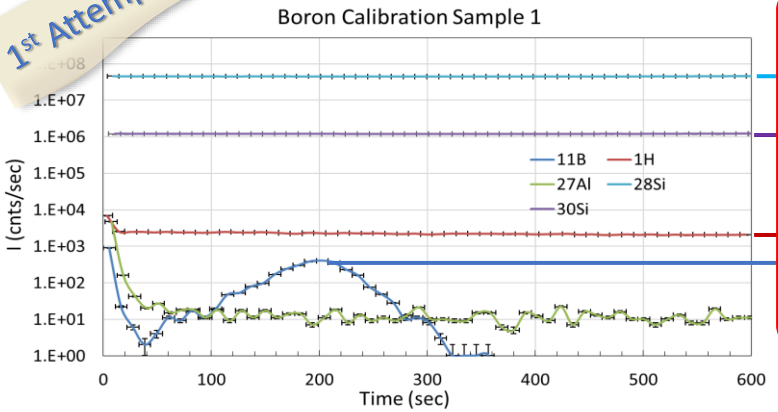
$$C_{Tot.} = \sum_{d_{Si\,Interface}}^{2\%\,of\,c_{max}-1} \frac{1}{2} \times \Delta d_k \times (c_k + c_{k+1}) = \boxed{\boldsymbol{\Delta d_k} \times \left[\sum_{\boldsymbol{d_{Si\,Interface}}}^{\boldsymbol{2\%\,of\,c_{max}}} \boldsymbol{c_k} - \frac{\mathbf{1}}{\mathbf{2}} \times (\boldsymbol{c_0} + \boldsymbol{c_n})\right]}$$

where $\mathbf{\Delta d_k}$ distance between two consecutive measurements
$\mathbf{c_k}$ dopant concentration at point k
$\mathbf{c_0}$ dopant concentration at the silicon interface
$\mathbf{c_n}$ dopant concentration at 2% point of max in-silicon concentration

•Boron Calibration Profiles

Beam Parameter Optimization

1st Attempt



Signal improvement

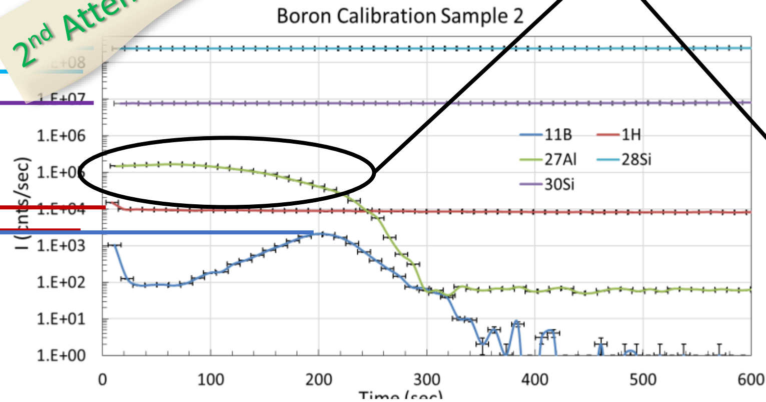
x 5.3

x 6.3

x 6.4

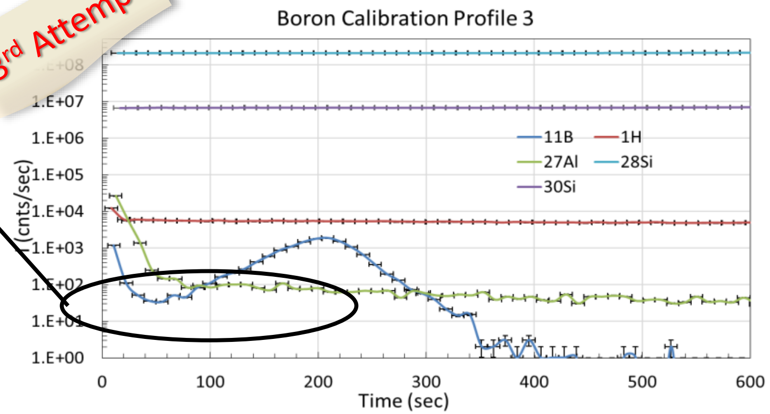
x 11.2

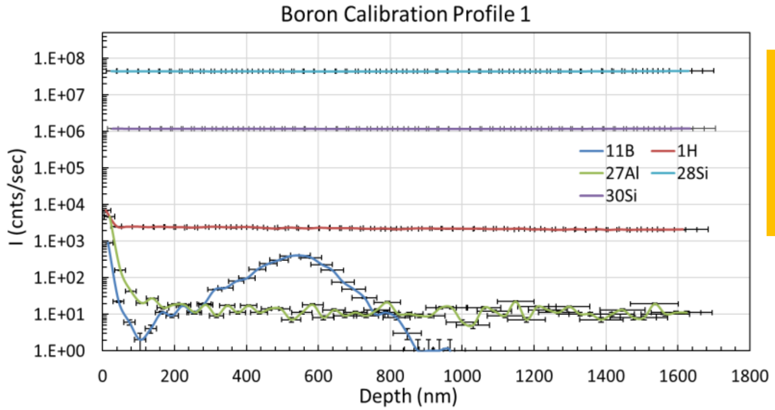
2nd Attempt



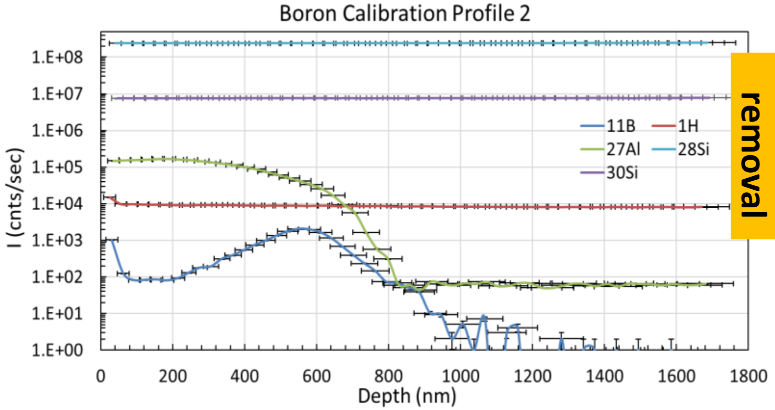
Surface Impurity

3rd Attempt

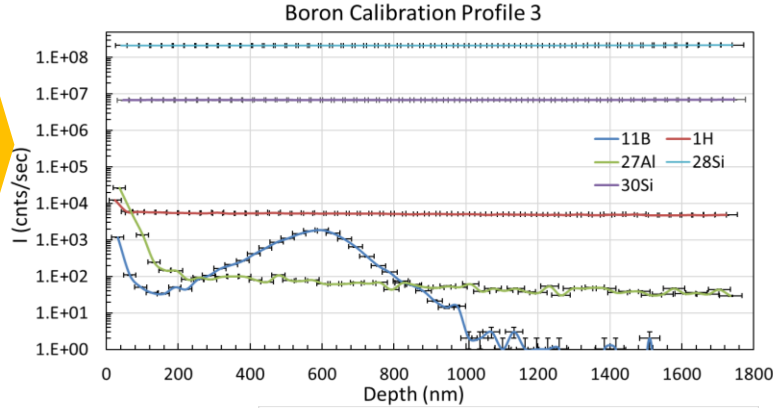


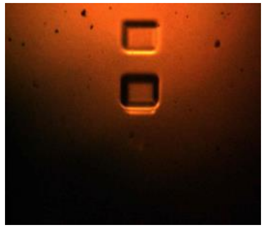


Raster Size Increase



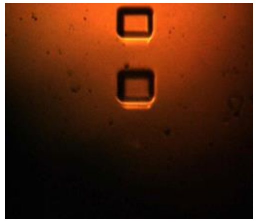
Impurity removal





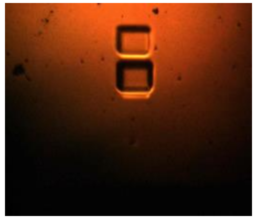
Beam Parameters I & II

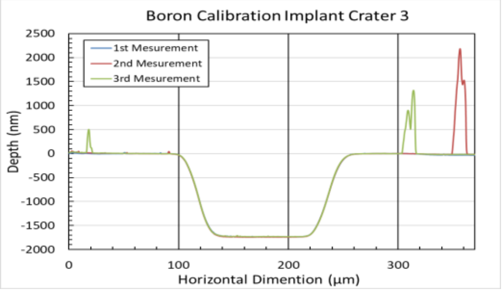
➢ Primary Current	100 nA
➢ Beam size	125 µm
➢ Raster Size	33 µm square



Beam Parameters III

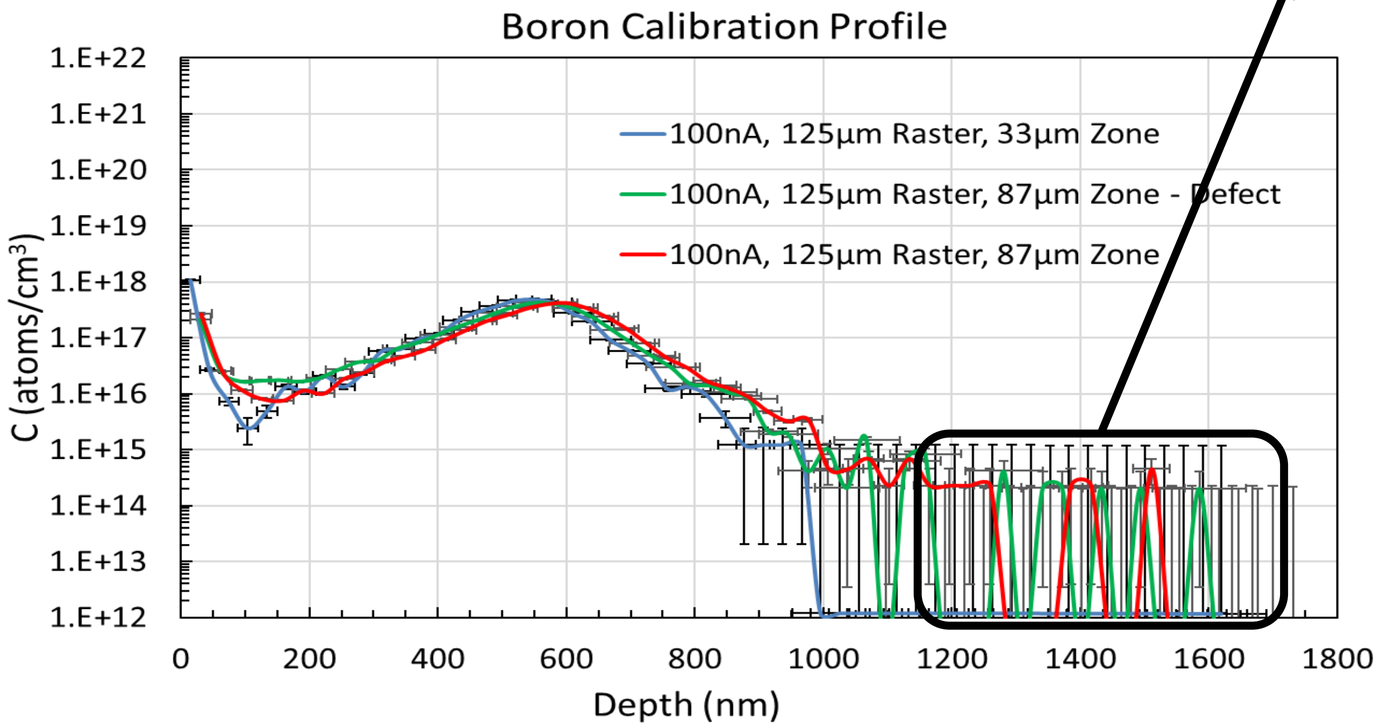
➢ Primary Current	100 nA
➢ Beam size	125 µm
➢ Raster Size	87 µm circle





•Boron Calibration Profiles

Sensitivity – Detection Limits



Gaussian fit on point projection to estimate resolution form σ

Beam Parameters	Abrasion Speed (nm/sec)	RSF (atoms/cm^3)
100nA, 125μm, 33μm	2.71 ± 0.11	(5.38 ± 0.13) ×10^{22}
100nA, 125μm, 87μm - Defect	2.78 ± 0.13	(4.92 ± 0.12) ×10^{22}
100nA, 125μm, 87μm	2.87 ± 0.04	(4.80 ± 0.12) ×10^{22}

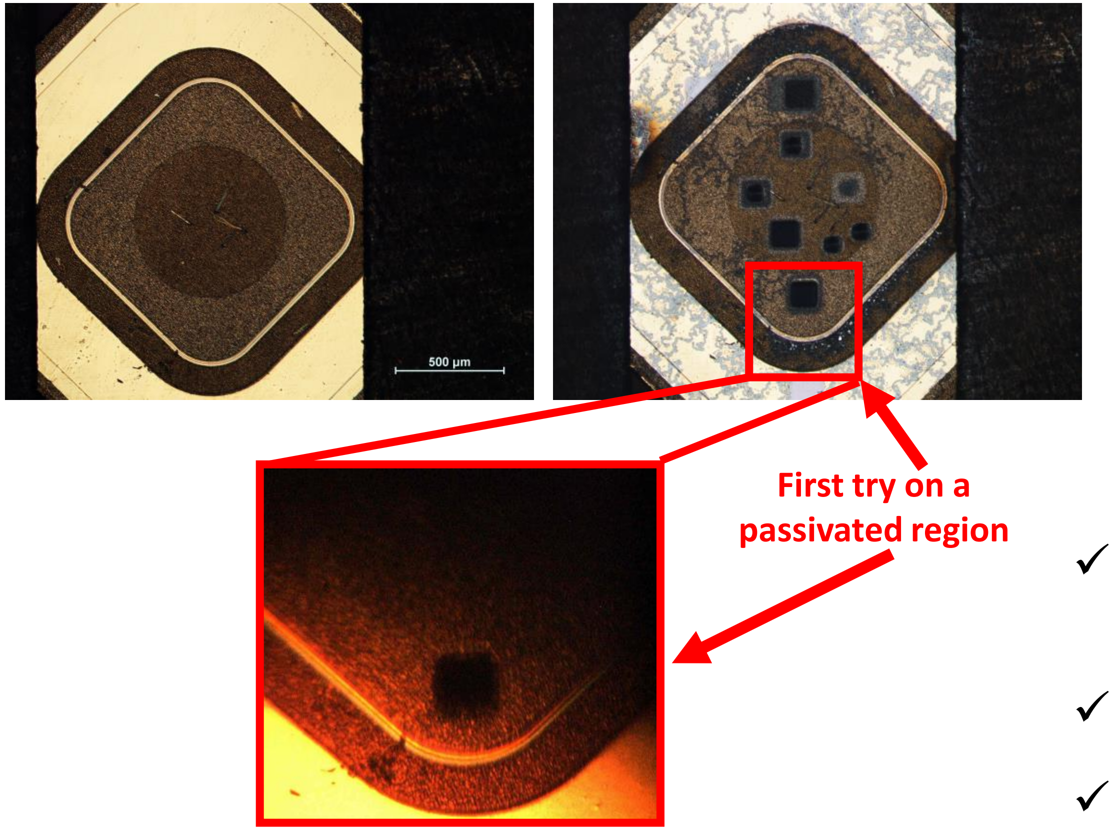
Beam Parameters	Sensitivity (atoms/cm^3)
100nA, 125μm, 33μm	(4.51 ± 2.77) × 10^{14}
100nA, 125μm, 75μm - Defect	(2.35 ± 0.45) × 10^{14}
100nA, 125μm, 75μm	**(1.35 ± 0.58) × 10^{14}**

- ✓ Best sensitivity for an 87 μm raster size (integration area) with 125 μm crater size at 100 nA primary beam current (**Boron Conditions**)
- ✓ Expected abrasion speeds in silicon in the order of 2.8 nm/sec
- ✓ Expected sensitivity for boron in the order of 1.4 × 10^{14} atoms/cm^3 for a silicon matrix
- ✓ Relative scaling factor uncertainty of 2.5 %
- ✓ Not same conditions as for removing insulating layers before silicon

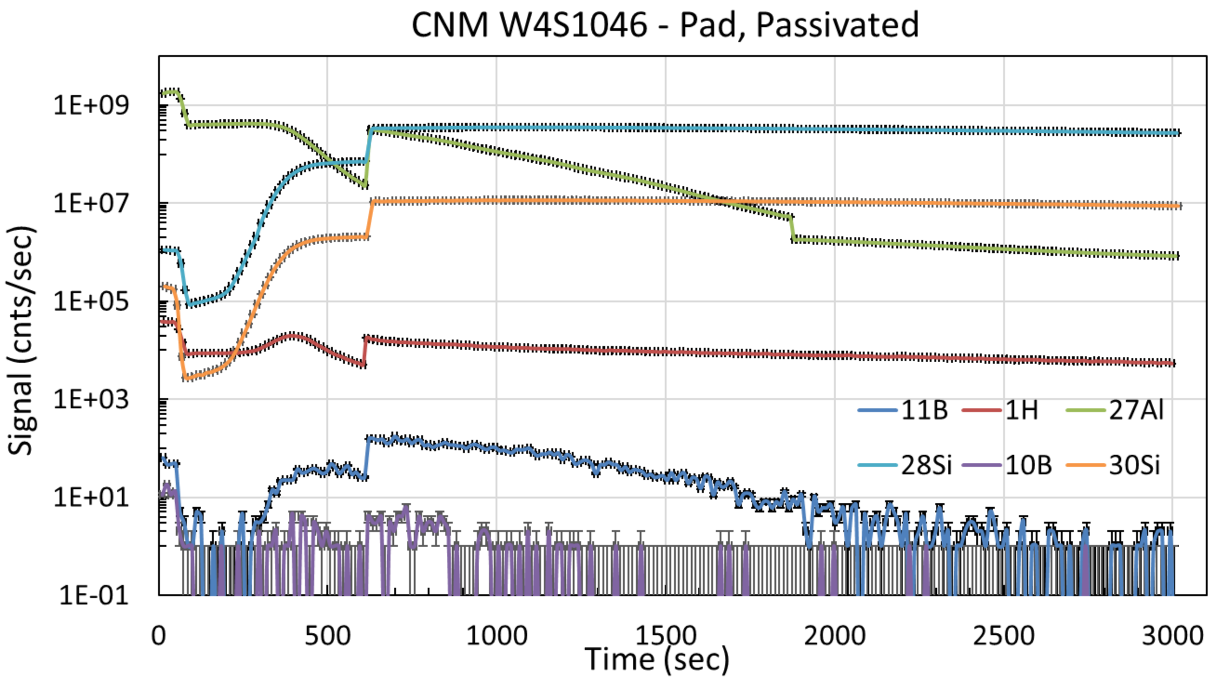
•CNM W4S1046 Gain Layer I

1^{st} Attempt on Passivated region

Before SiMS Measurements **After SiMS Measurements**



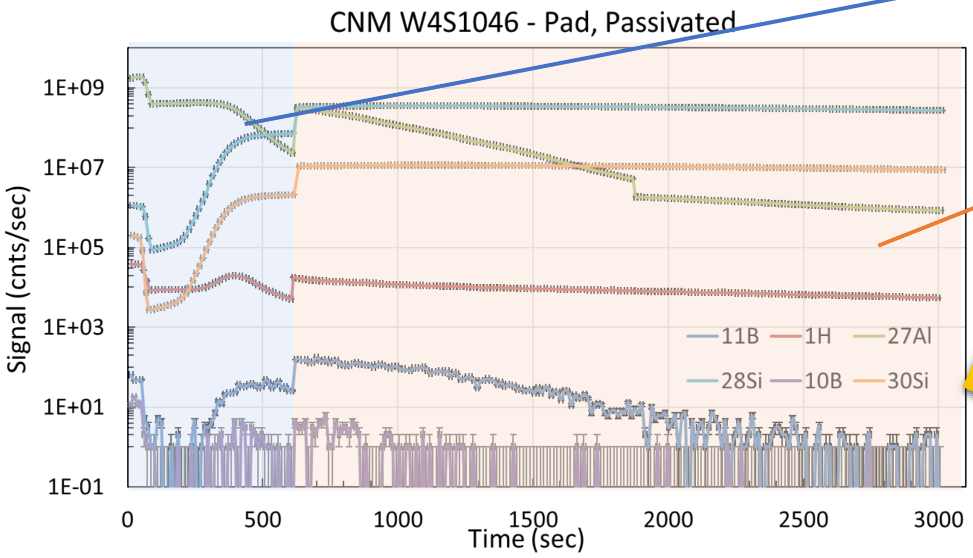
First try on a passivated region



- ✓ Several measurements for tuning, background control and obtaining statistics to combine multiple profiles
- ✓ Measurements on passivated and non-passivated regions
- ✓ Charge compensation to account for accumulated electron modifying extraction potential
- ✓ Consecutive measurements on same spot with different conditions, optimized for probed element/quantities

•CNM W4S1046 Gain Layer I

Profile Stitching and Scaling

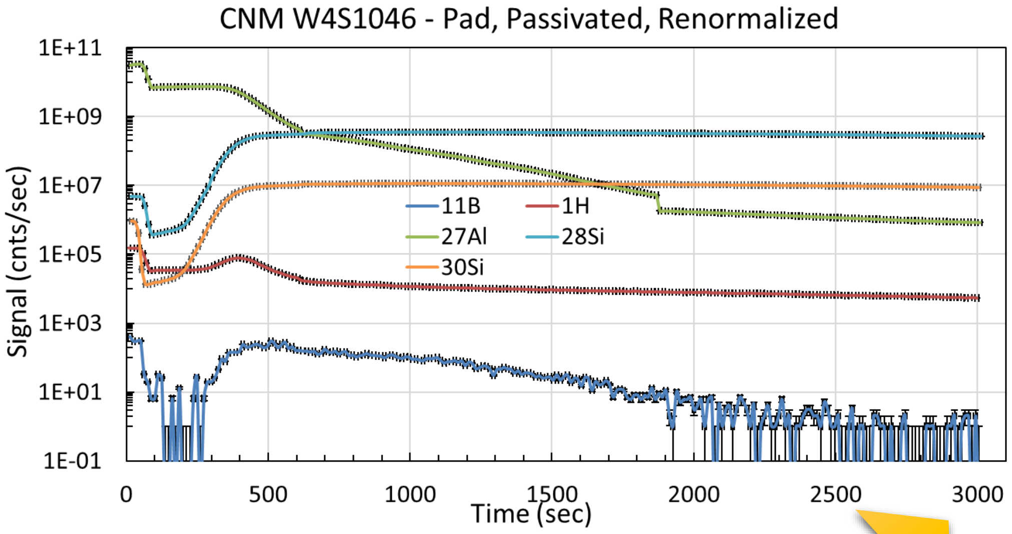


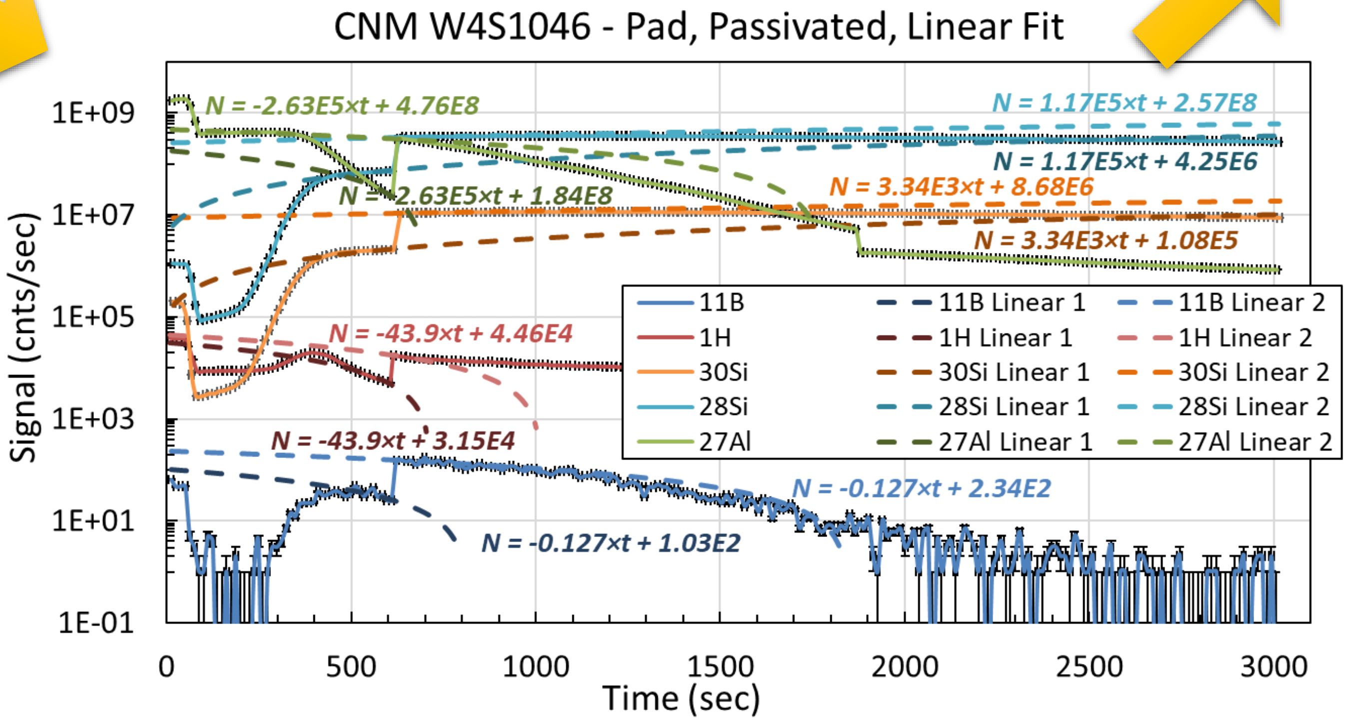
1ST part of profile

100nA, 125µm raster size, 33 µm integration area

2nd part of profile

100nA, 125µm raster size, 75 µm integration area



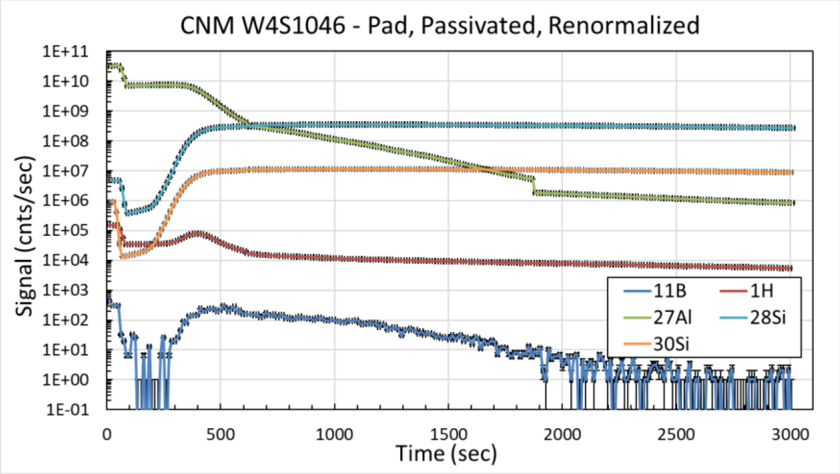


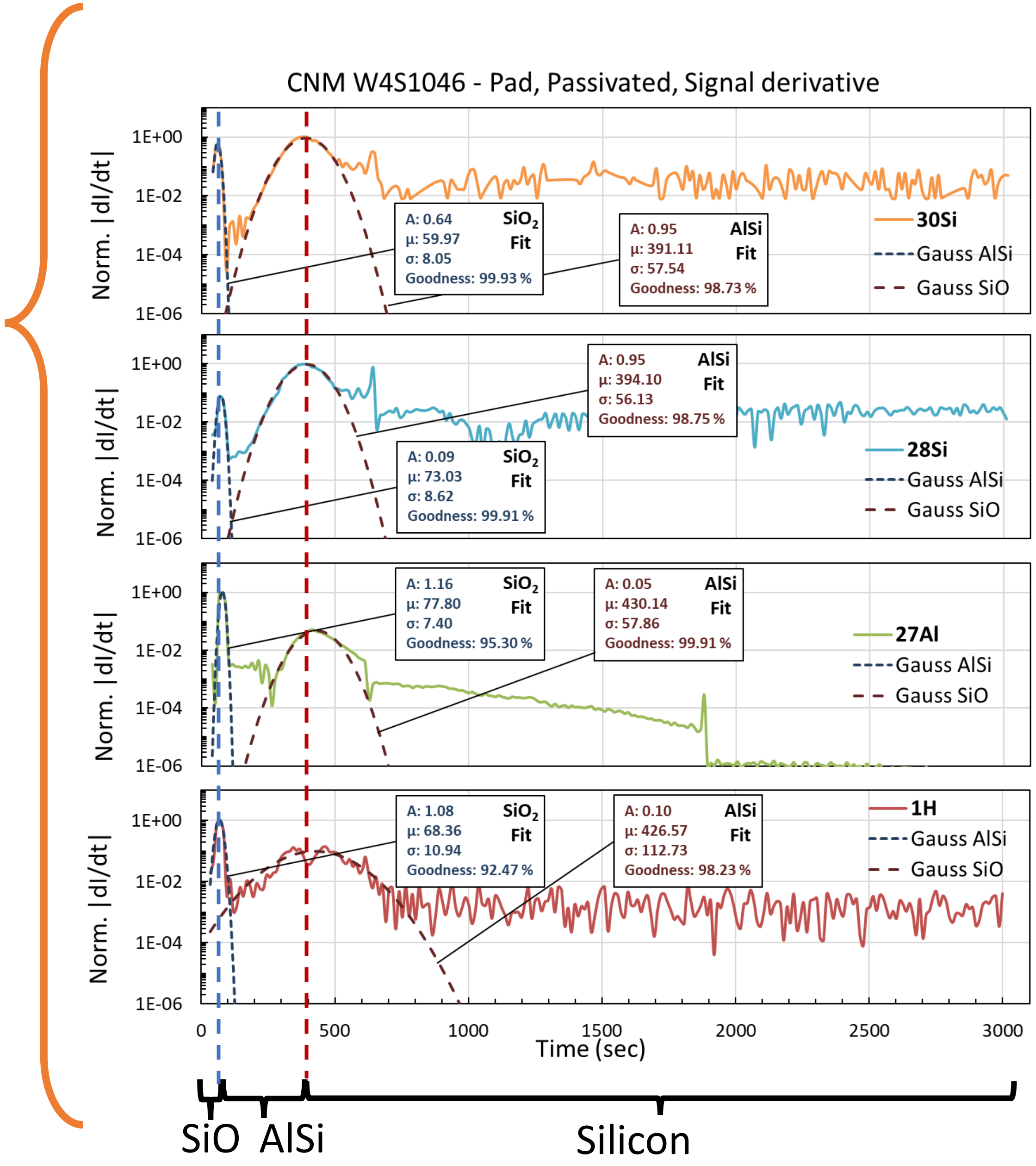
- ✓ Two consecutive measurements at same physical point with different conditions (integration zone)
- ✓ Signal intensities differ for observed elements, need to rescale
- ✓ Signal smoothness and continuity hypothesis at transition point:
  - ➢ Linear fit at boarder after transition to extract slope
  - ➢ Force slope at boarder before transition and calculate intercept
  - ➢ Extrapolate scaling factor by dividing fitted values at boarder region
- ✓ Scaling factor in the form of $\boxed{I_2=A\times I_1}$

•CNM W4S1046 Gain Layer I

Layer Transition evaluation

- ✓ Abrupt signal variation at layer interface
- ✓ Dirac-style derivative expected at layer transition
- ✓ Narrow Gaussian due to inter-layer diffusion and machine resolution
- ✓ Layer transition time extrapolated from fit





Perform separate gaussian fits on the absolute value of the normalized signal derivatives for each of the observed elements

$$I(t) = Ae^{-\frac{(t-\mu)^2}{2\sigma^2}}$$

Initial Fit Conditions

Central Value

$$\mu = t^{I(t)_{nax}}\Big|_{t_{Low}}^{t_{High}}$$

linearly extrapolated

Width - sigma

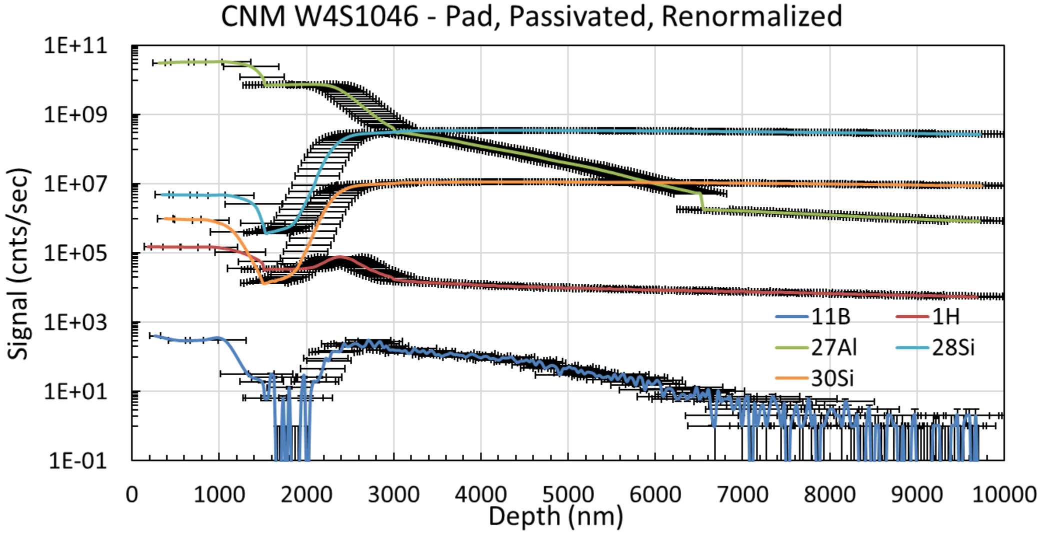
$$H = 2\sqrt{2\ln 2}\,\sigma \rightarrow \sigma = \frac{\left|t_{i+1}(I_{max/2}) - t_i(I_{max/2})\right|}{2\sqrt{2\ln 2}}$$

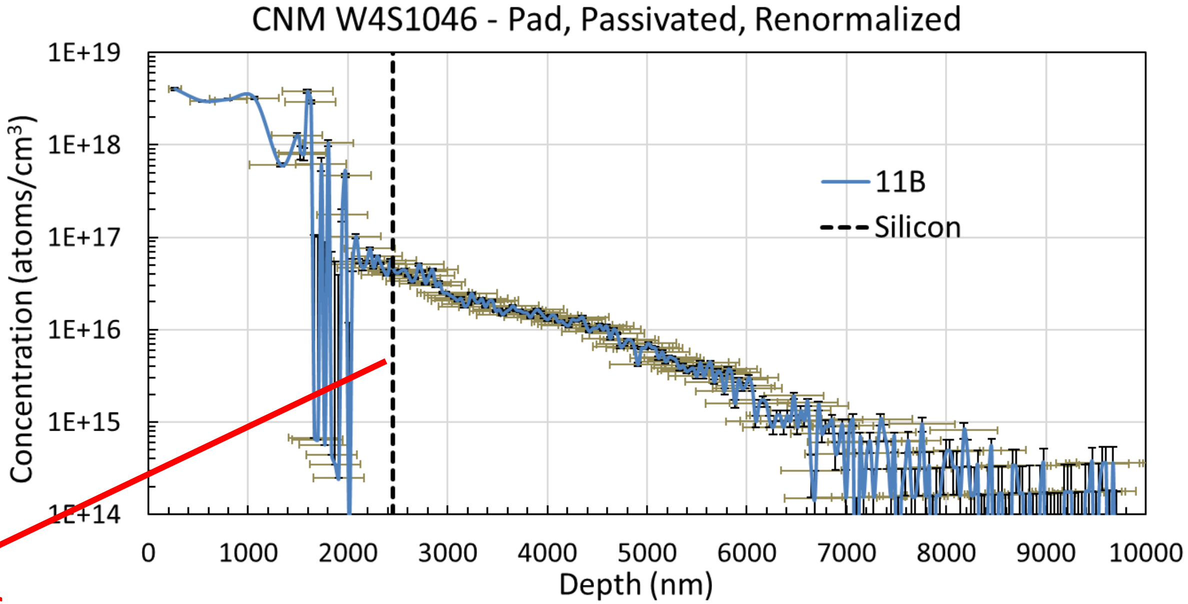
Normalization Constant

$$\int_{-\infty}^{\infty} I(t)\partial t = A\sigma\sqrt{2\pi} \rightarrow A = \frac{\sum_{t_{Low}}^{t_{High}} {\partial \mathrm{I}}/{\partial \mathrm{t}}\,\Delta t}{\sigma\sqrt{2\pi}}$$

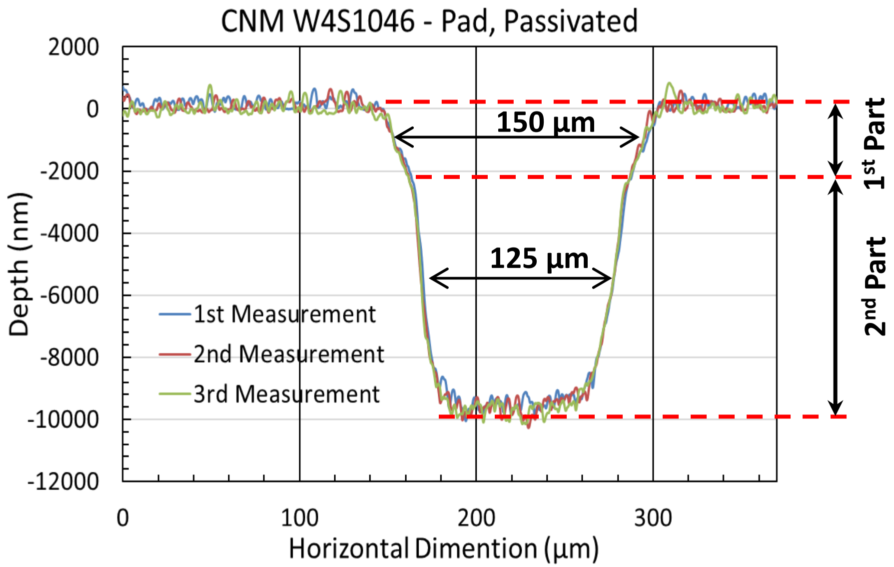
•CNM W4S1046 Gain Layer I

Boron Profile Characterization





Silicon Surface



Layer	Thickness (nm)	Abrasion Speed (nm/sec)
Aluminum	1473 ± 252	21.1 ± 4.9
SiO_2	976 ± 50	2.80 ± 0.09

Defined up to 2 % of peak concentration, Set to twice the detection sensitivity

Boron Profile Properties		
Peak Concentration	$(5.07 \pm 0.13) \times 10^{16}$	atoms/cm^3
Peak Position (in Si)	258 ± 259 (± 20)	nm
Dose Integral (in Si)	$(5.33 \pm 0.18) \times 10^{12}$	atoms/cm^2
50% Integrated Dose Depth (in Si)	822 ± 260 (± 32)	nm
Max Profile depth (in Si)	4892 ± 304 (± 161)	nm

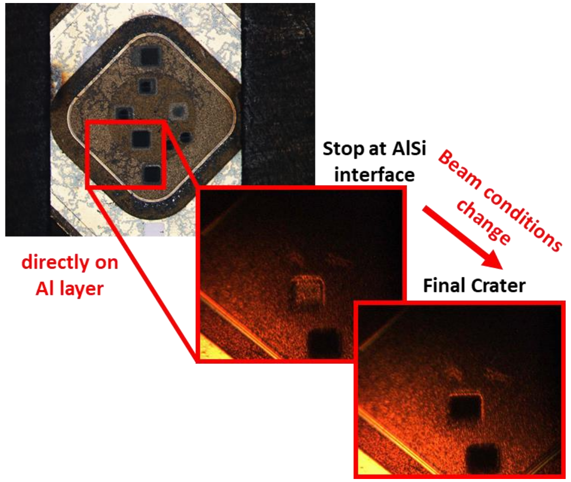
•CNM W4S1046 Gain Layer II

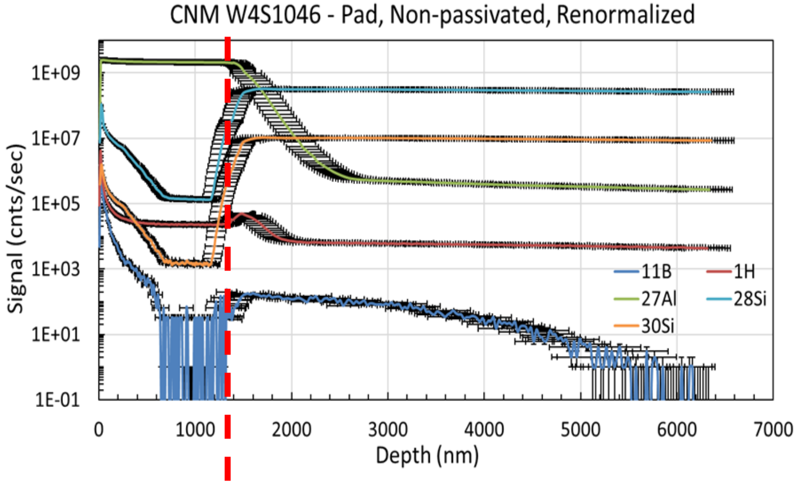
2nd Try on non-passivated region

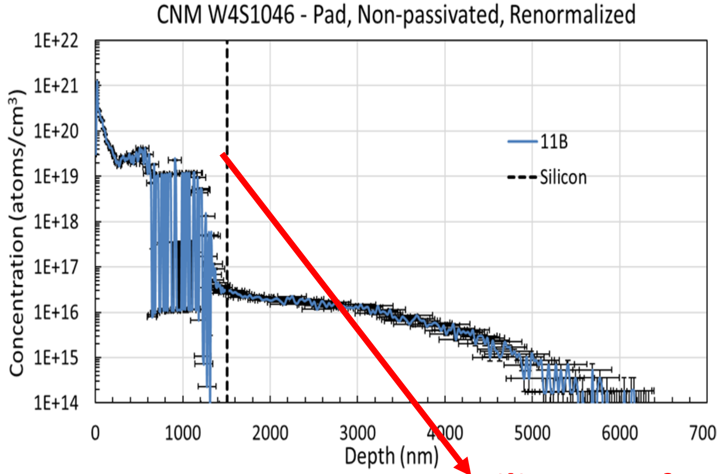
Signal vs Depth

Concentration in Silicon

Non-Carbonated Wafers

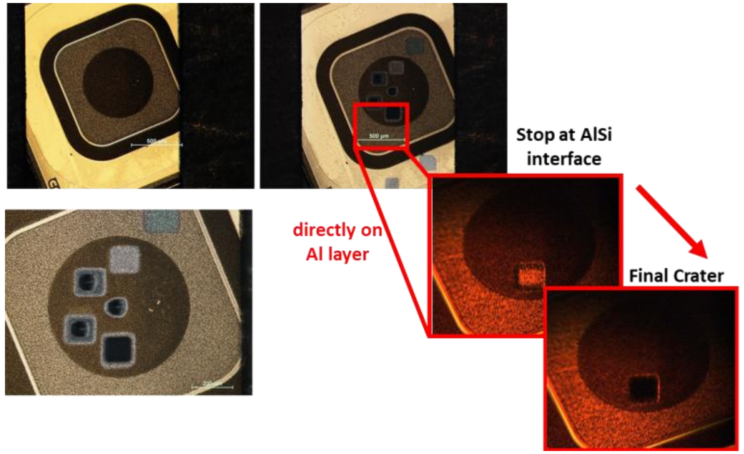


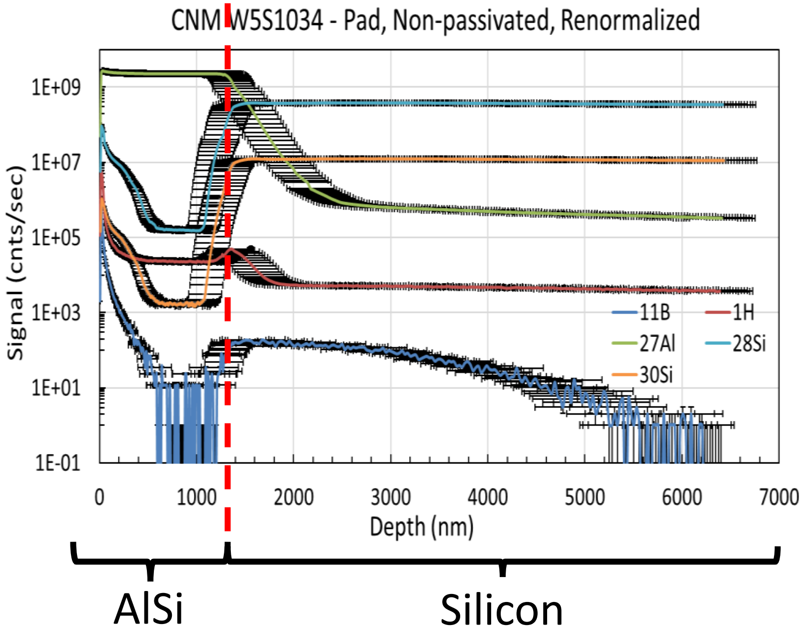


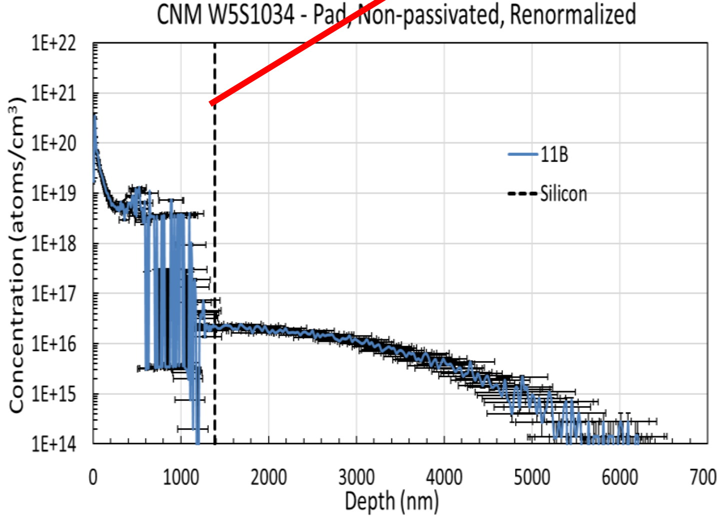


Silicon Surface

Carbonated Wafer





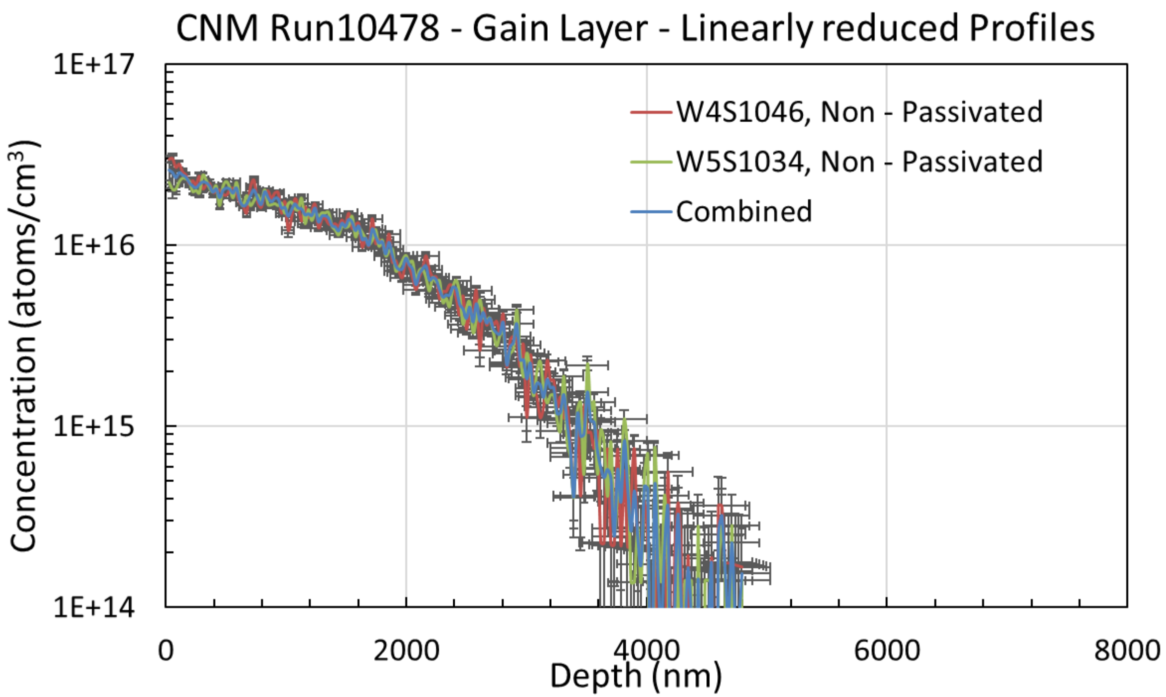


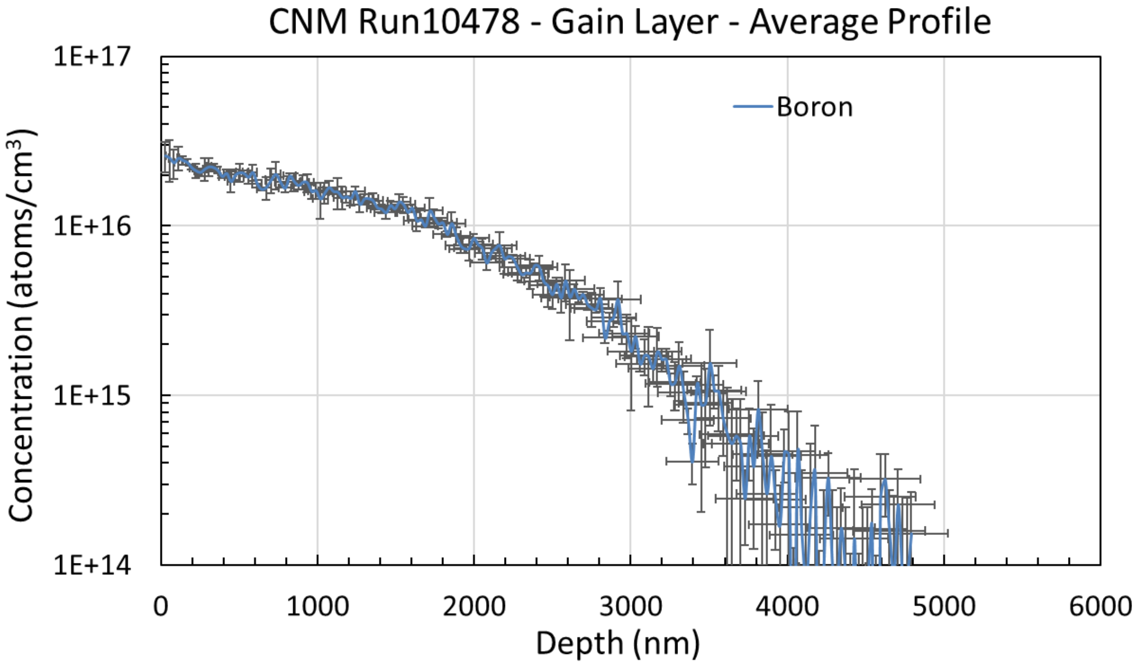
•CNM Gain Layer Combined

Doping Profile Synthesis & Properties

- ✓ A general “average profile” can be generated by combining the three measurements
- ✓ Profiles are composed of a set of discrete measurements of concentration at a specific depth
- ✓ Using one profile as a reference, the expected values of the other profiles for each point are estimated via linear extrapolation:

$$c_i = \left(\frac{c_{H,i} - c_{L,i}}{d_{H,i} - d_{L,i}}\right) \times (d_i - d_{Li}) + c_{Li}$$





- ✓ Main profile quantities recalculated on the combined profile

CNM Boron gain Layer		
Peak Concentration	$(2.59 \pm 0.54) \times 10^{16}$	atoms/cm^3
Peak Position (in Si)	27 ± 14	nm
Dose Integral (in Si)	$(3.74 \pm 0.24) \times 10^{12}$	atoms/cm^2
50% Integrated Dose Depth (in Si)	933 ± 47	nm
Max Profile depth (in Si)	3812 ± 189	nm

Defined up to 2 % of peak concentration, Set to twice the detection sensitivity

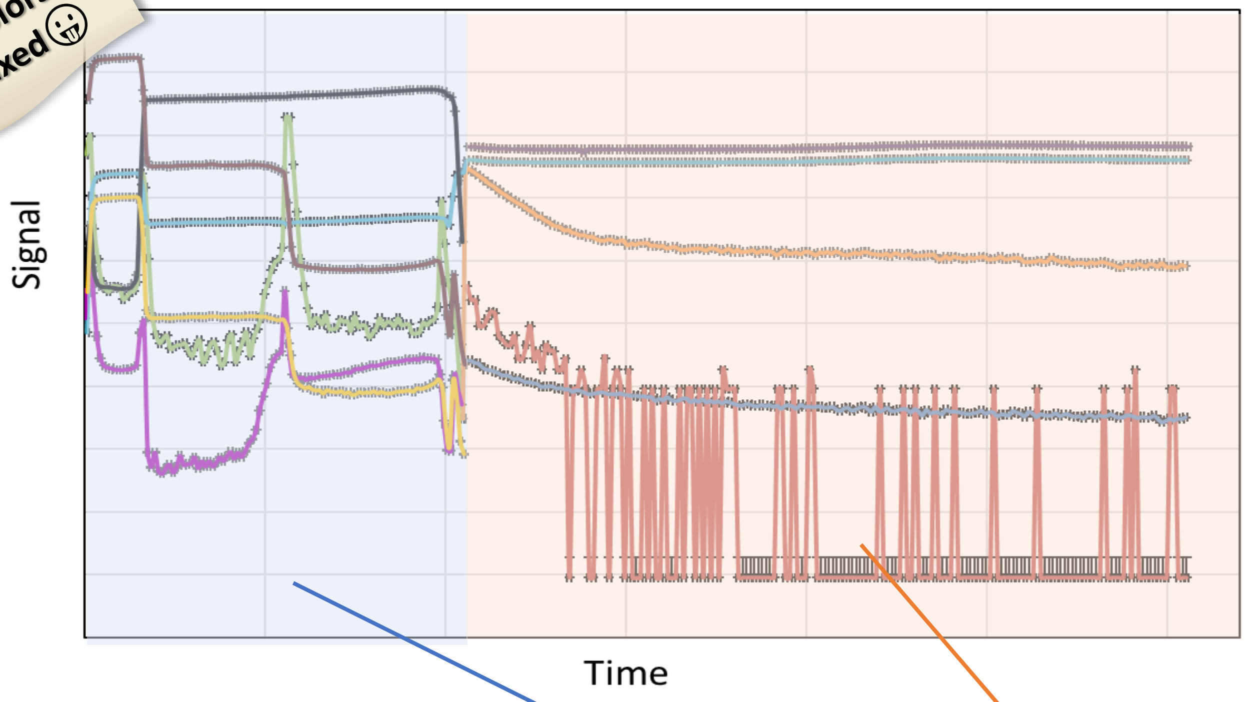
•FBK Gain Layer - UFSD 2, Low Carbon

Craters and profile stitching

- ✓ Combination of two series of measurements with different polarities to probe interfaces:
  - ➢ **^{55}Cs** ion source (positive ions) to probe $_{14}N$ $_{28}Si$, $_{31}P$, $_{12}C$ allowing to abrade pre-silicon layers
  - ➢ **^{16}O** ion source (negative ions) for boron profile characterization
- ✓ Presented profiles result of “Stitching” of the two series with appropriate time scaling
- ✓ Consecutive measurements on the same crater spot
- ✓ Charge compensation to correct E field distortions due to accumulated charge on insulating layers

The colors are mixed 😜

FBK UFSD2, Low Carbon - Pad, Passivated



1ST part of profile

Cesion primary ions

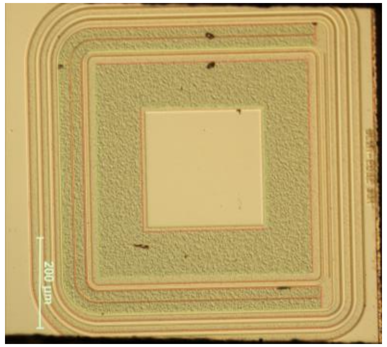
40 nA, 125 µm raster size, 33 µm integration area

2nd part of profile

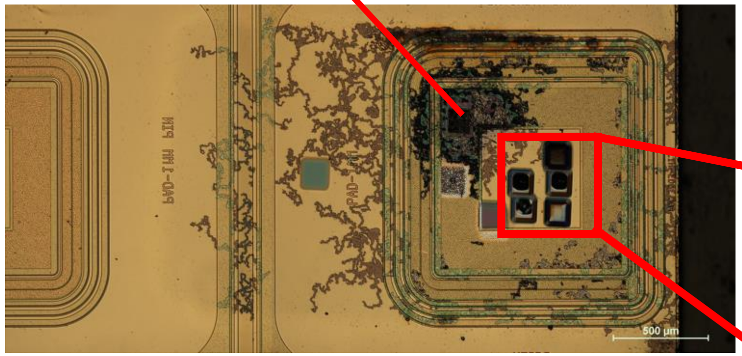
Oxygen primary ions

100 nA, 125 µm raster size, 75 µm integration area

Non-charge compensated measurement



Before SiMS measurements



After SiMS measurements (each crater corresponds to a profile)

crater for this measurement

•FBK Gain Layer - UFSD 2, Low Carbon

Interfaces and layer Characterization

1st Interface

Element	Fit Transition [sec]	Average [sec]	Uncertainty			Total Uncertainty
			Stat.	σ [sec]	Syst.	
1st element	171.49	166.70	3.16	4.39	2.4	3.97
2nd element	165.69			4.34		
3rd element	162.75			5.78		
4th element	165.07			5.60		
5th element	169.33			8.60		
6th element	165.84			5.56		

1st transition time

(166 ± 4) sec

1st - 2nd Interface

Element	Fit Transition [sec]	Average [sec]	Uncertainty			Total Uncertainty
			Stat.	σ [sec]	Syst.	
1st element	559.48	567.31	6.98	5.95	2.97	7.59
2nd element	567.94			8.10		
3rd element	569.15			7.56		
4th element	564.45			5.73		
5th element	579.69			4.20		
6th element	563.17			10.39		

2nd transition time

(567 ± 8) sec

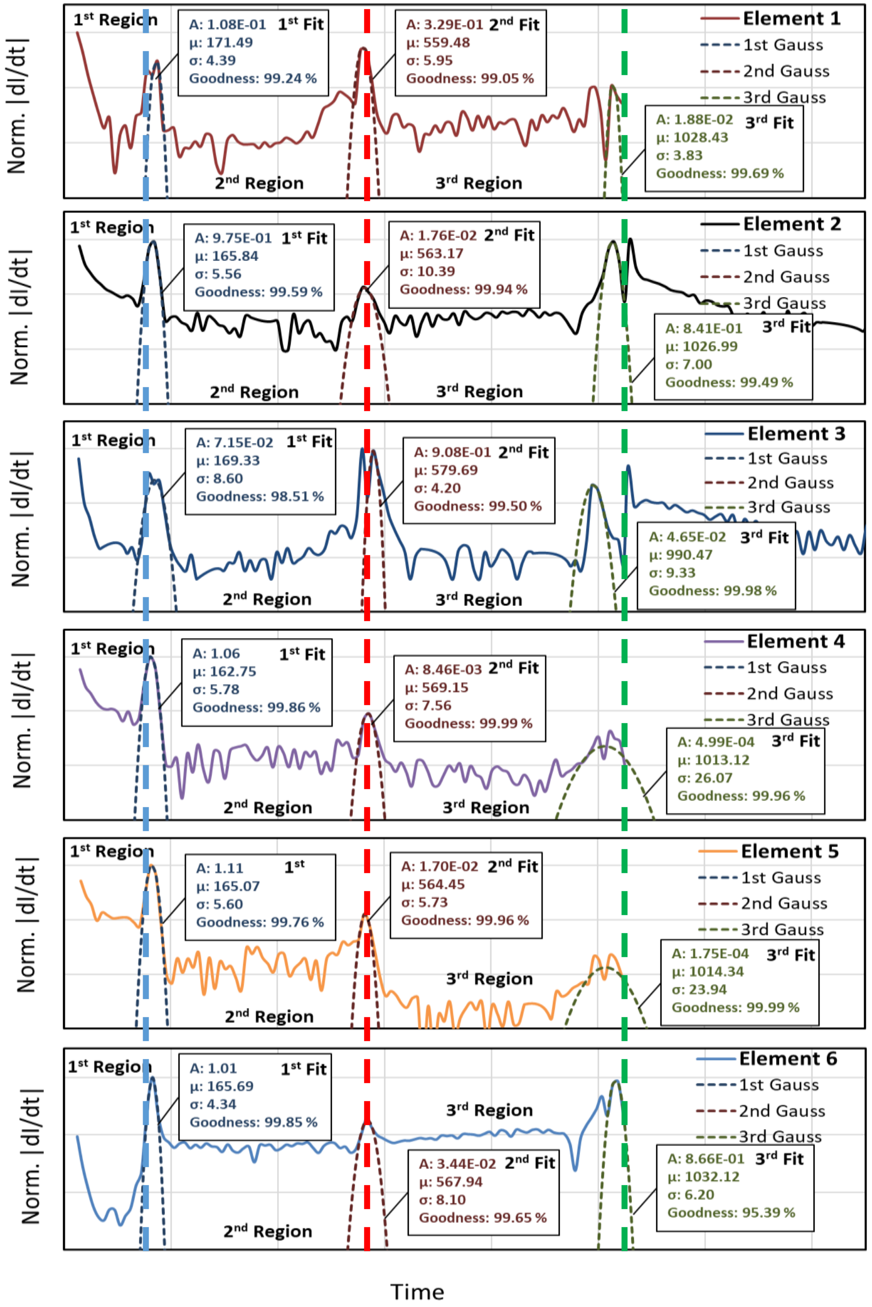
2nd – 3rd Interface

Element	Fit Transition [sec]	Average [sec]	Uncertainty			Total Uncertainty
			Stat.	σ [sec]	Syst.	
1st element	1028.43	1017.58	15.38	3.83	6.33	16.63
2nd element	1032.12			6.20		
3rd element	1013.12			26.07		
4th element	1014.34			23.94		
5th element	990.47			9.33		
6th element	1026.99			7.00		

3rd transition time

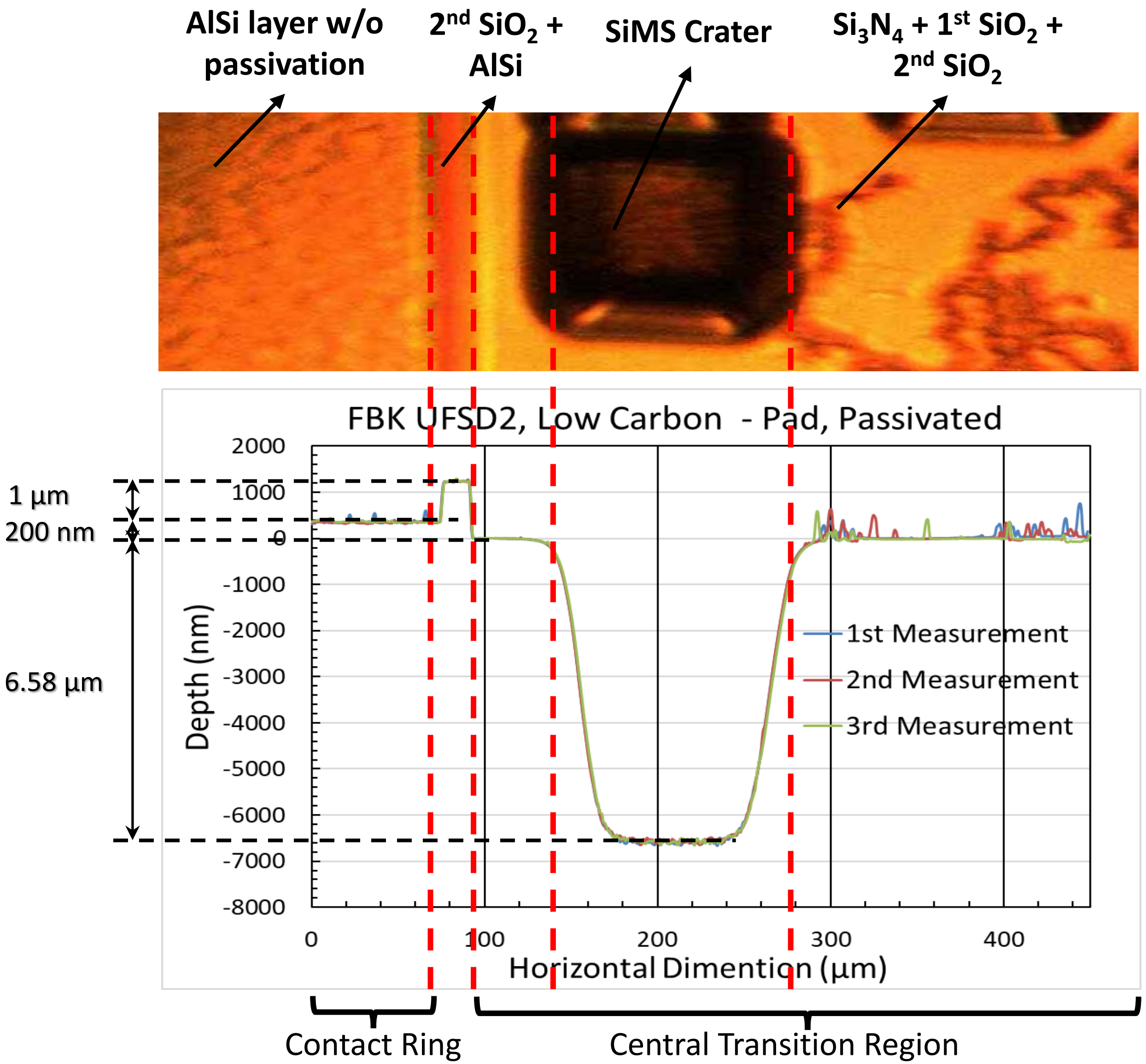
(1018 ± 17) sec

FBK UFSD2, Low Carbon - Pad, Passivated, Signal derivative



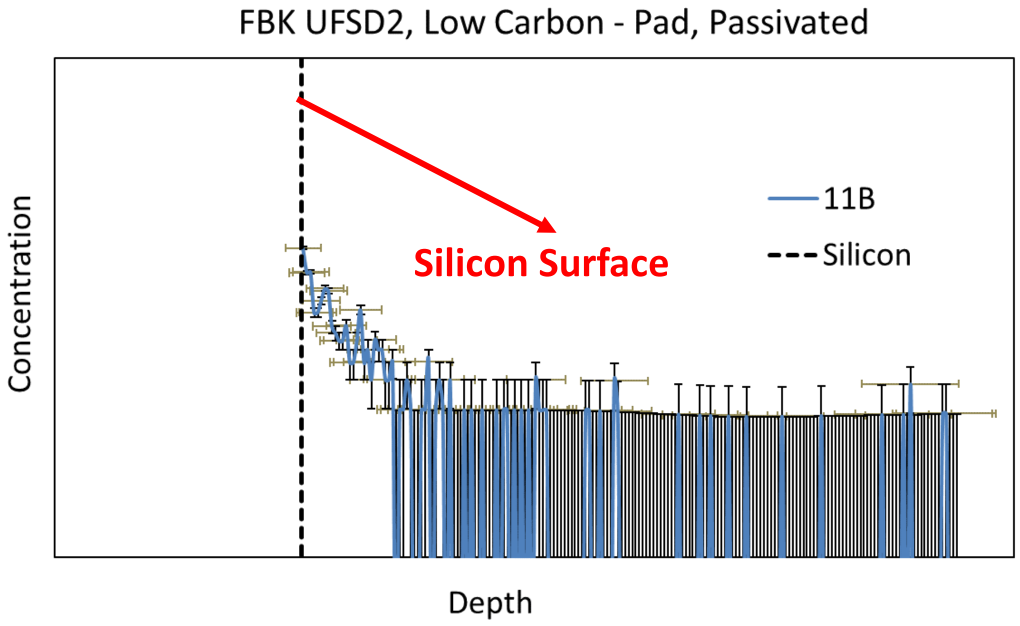
•FBK Gain Layer - UFSD 2, Low Carbon

Layer thickness evaluation



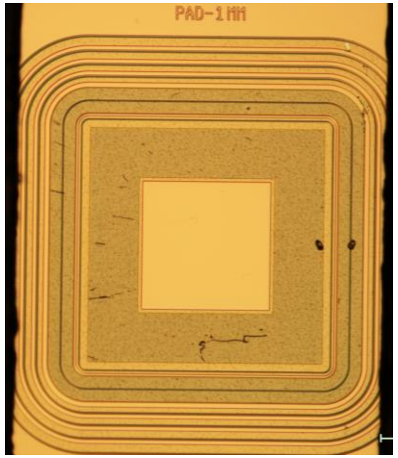
- ✓ Through depth profile measurement, layer depth can be extrapolated
- ✓ Abrasion speed is considered constant for all non-silicon (insulating) layers

Layer	Thickness (nm)	Abrasion Speed (nm/sec)
1^{st} Layer	X ± 21.3	1.69 ± 0.12
2^{nd} Layer	Y ± 50.7	
3^{rd} Layer	Z ± 62.7	
Insulating Layers	W ± 120	
Silicon		2.39 ± 0.06

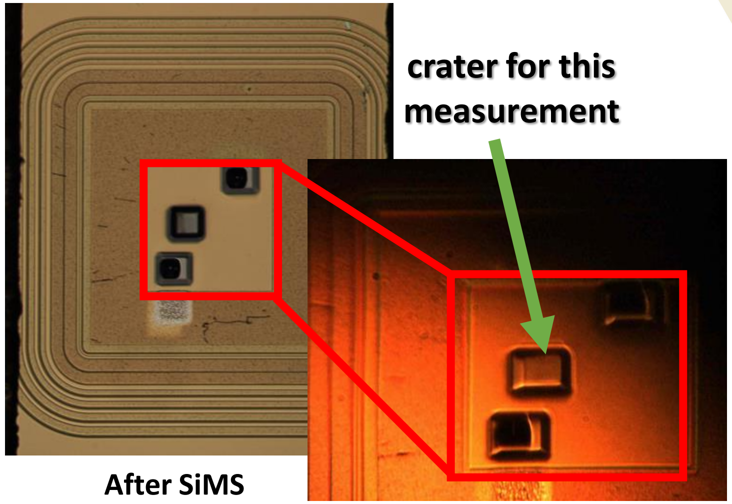


•FBK Gain Layer - UFSD 2, High Carbon

Craters and profile stitching



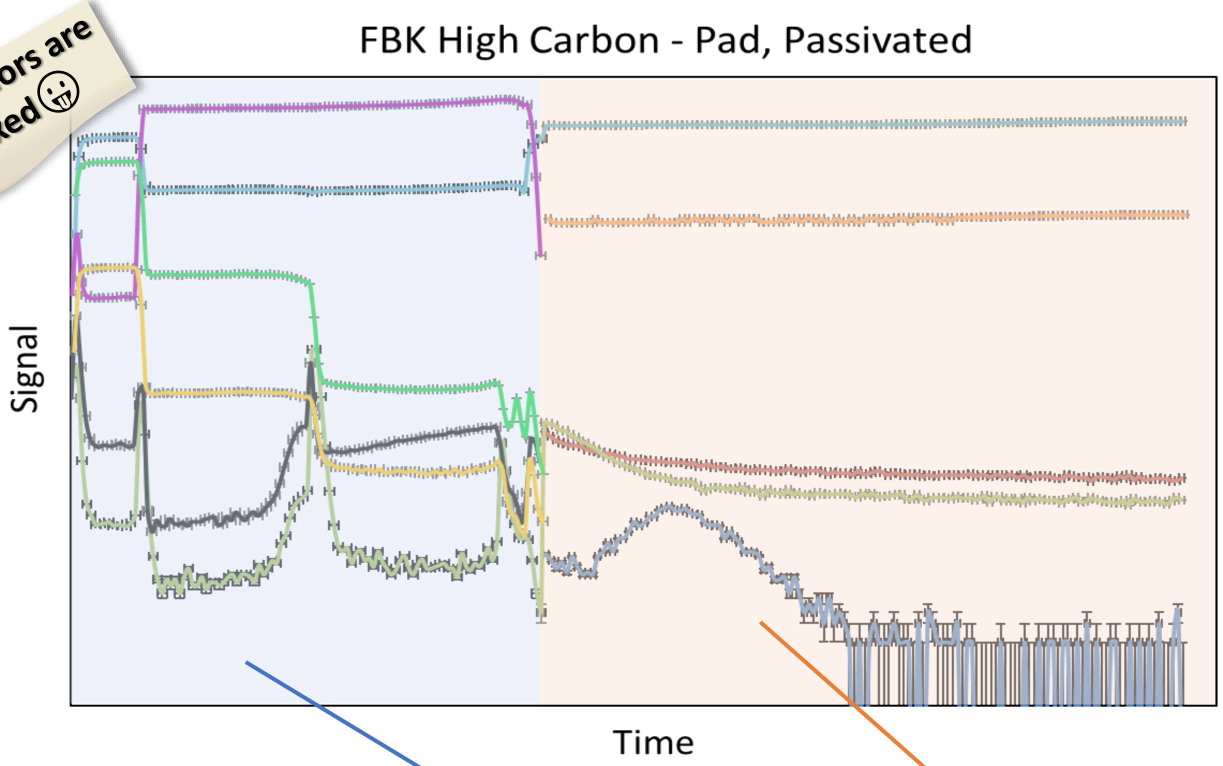
Before SiMS measurements



crater for this measurement

After SiMS measurements

The colors are mixed 😛



1ST part of profile

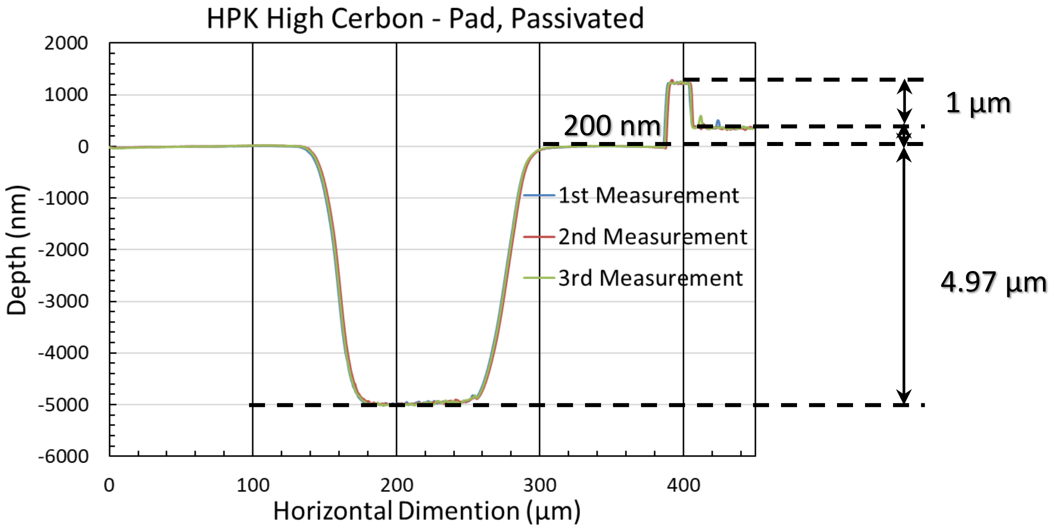
Oxygen primary ions

40 nA, 125 µm raster size, 33 µm integration area

2nd part of profile

Cesium primary ions

100 nA, 125 µm raster size, 75 µm integration area

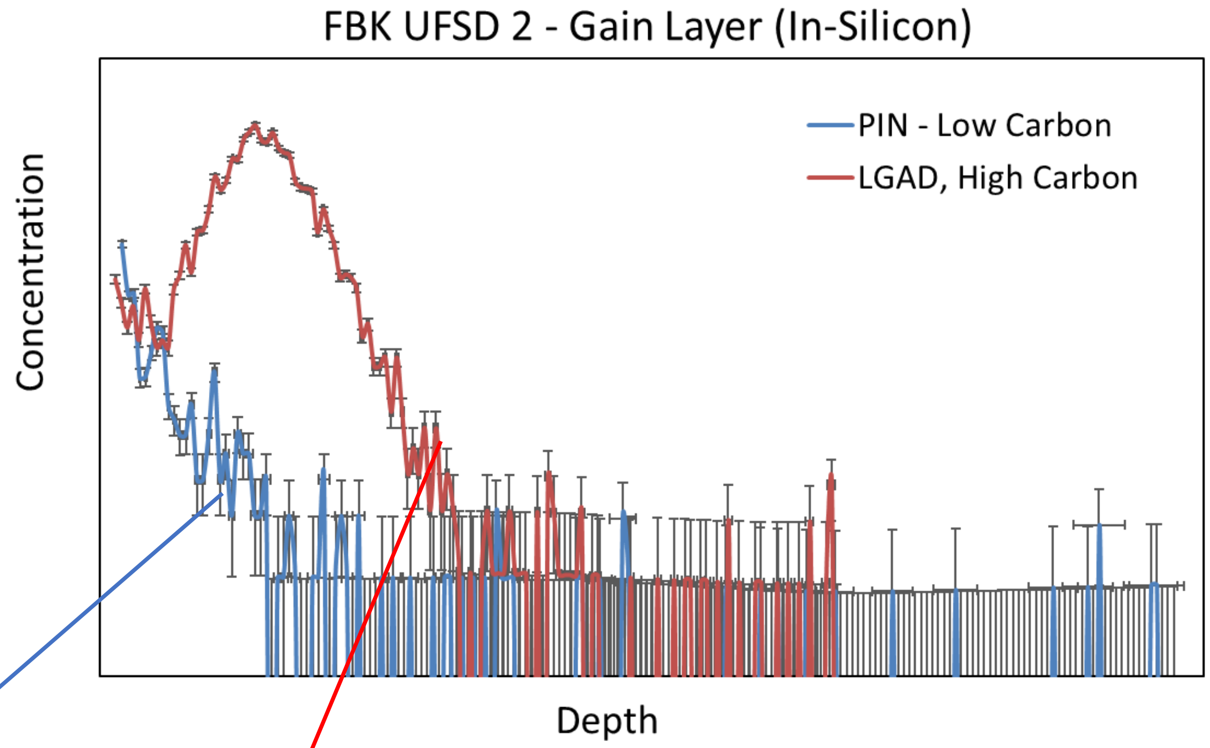


- ✓ Consecutive measurements on the same crater spot
- ✓ Charge compensation to correct E field distortions due to accumulated charge on insulating layers (Si_3N_4, SiO_2, ect..)

•FBK Gain Layer Combined - UFSD 2

Layers and profiles

- ✓ Combination of measurements on the High and Low carbonated samples
- ✓ No gain layer detected for the low carbonated sample (PIN)
- ✓ Consistent Boron gain layer on the high carbonated sample
- ✓ SiMS concentration consistent in integral, peak position and peak concentration to what we would expect from the producer
- ✓ Extremely precise measurements with very small uncertainties

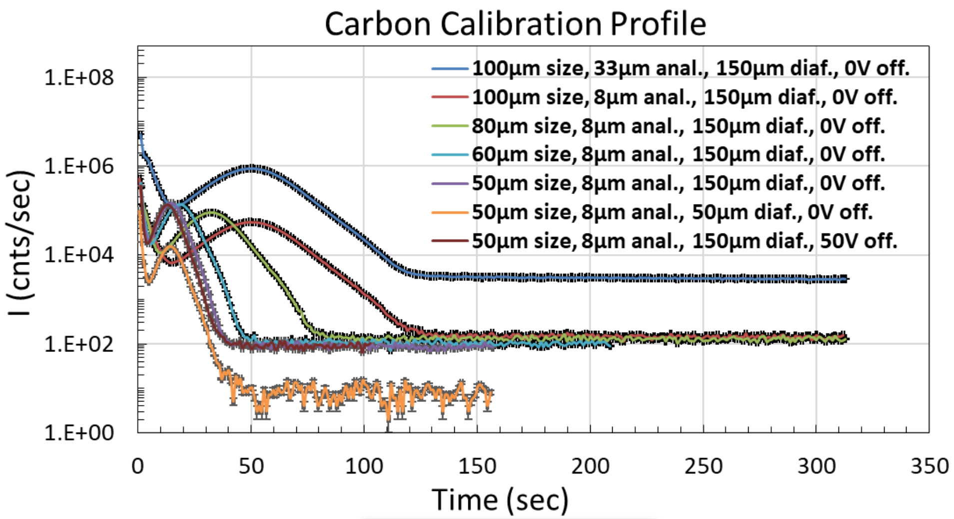


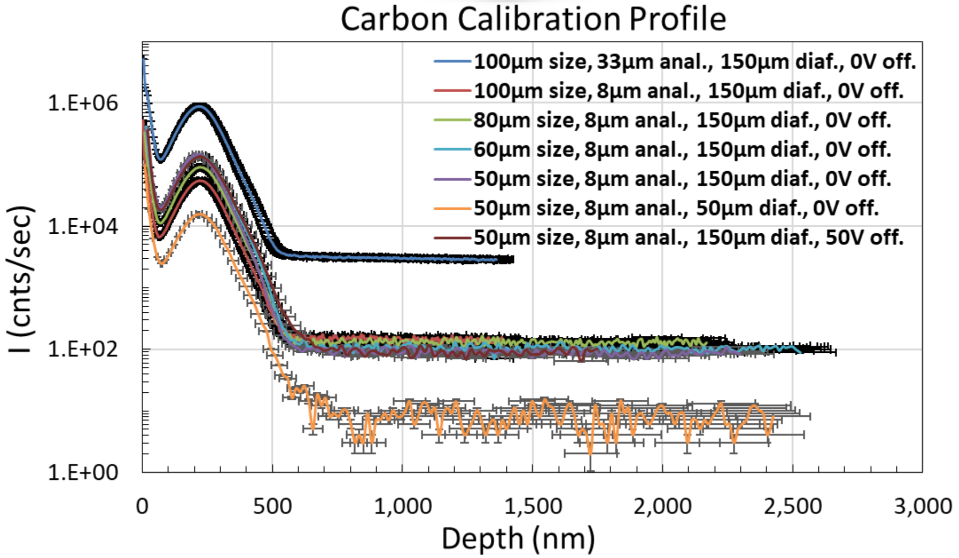
Boron profile consistent with p-spray observed at the PIN pad region

Boron profile consistent with a gain layer (+p-spray) with no deviation from expectation

•Carbon Calibration Profiles

Beam Parameter Optimization





- ✓ Carbon probing using Oxygen primary atoms
- ✓ Due to the atmospheric presence of Carbon, significant detection limits are much harder to attain
- ✓ Background baseline significant – correction needed for appropriate signal and matrix integral estimation

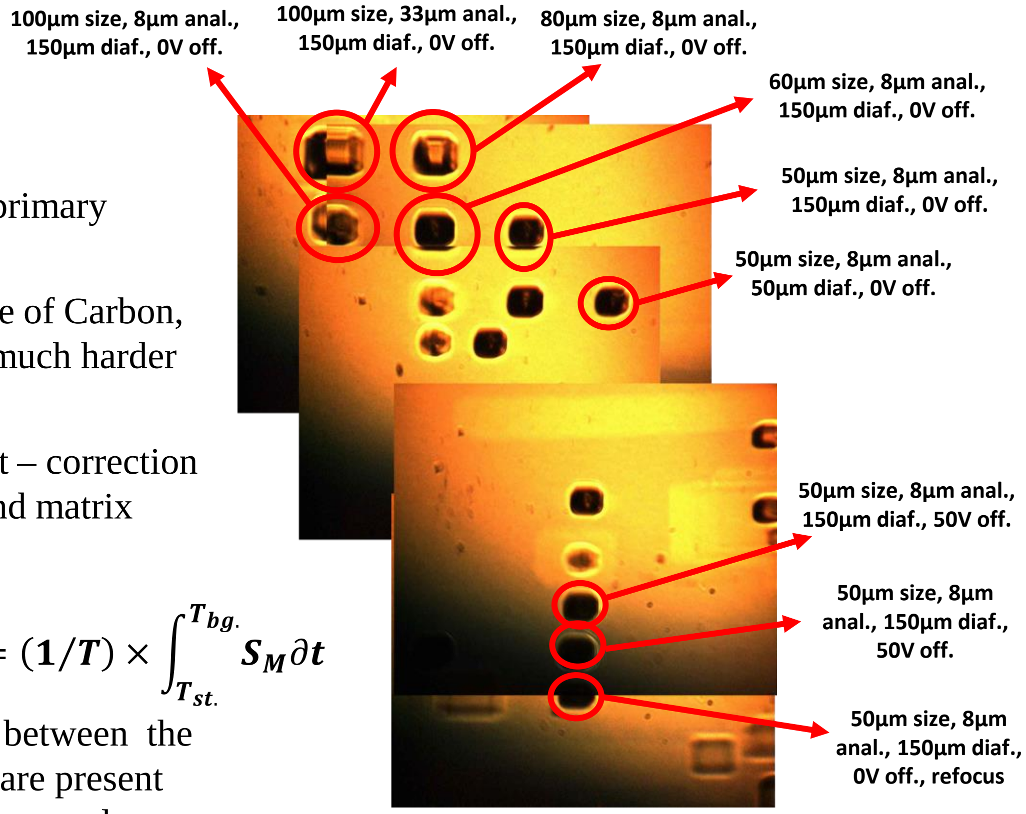
$$I_i^{cal.} = (\mathbf{1/T}) \times \int_{T_{st.}}^{T_{bg.}} \boldsymbol{S_i \partial t} \qquad I_M^{cal.} = (\mathbf{1/T}) \times \int_{T_{st.}}^{T_{bg.}} \boldsymbol{S_M \partial t}$$

- ✓ Start and stop times are defines between the points where no surface effects are present (T_{stat}) and the point where the observed signal reaches within 2σ of the background fluctuation

$$\boldsymbol{T_{bg.}} = \boldsymbol{t}\Big|_{S \geq \overline{S_{bg}} + 2\times\sigma(S_{bg})} \qquad \boldsymbol{T_{st.}} = \boldsymbol{t}\Big|_{\frac{\partial I}{\partial t} \rightarrow min} \qquad \boldsymbol{T} = \boldsymbol{T_{bg.}} - \boldsymbol{T_{st.}}$$

- ✓ Total RSF can be evaluated with these approximations for each case following:

$$\boldsymbol{RSF} = \frac{implanted\ dose\ \ (C)}{v_{abr.} \times T} \times \frac{\int_{T_{st.}}^{T_{bg.}} \boldsymbol{S_M \partial t}}{\int_{T_{st.}}^{T_{bg.}} \boldsymbol{S_i \partial t}}$$



•Carbon Calibration Profiles

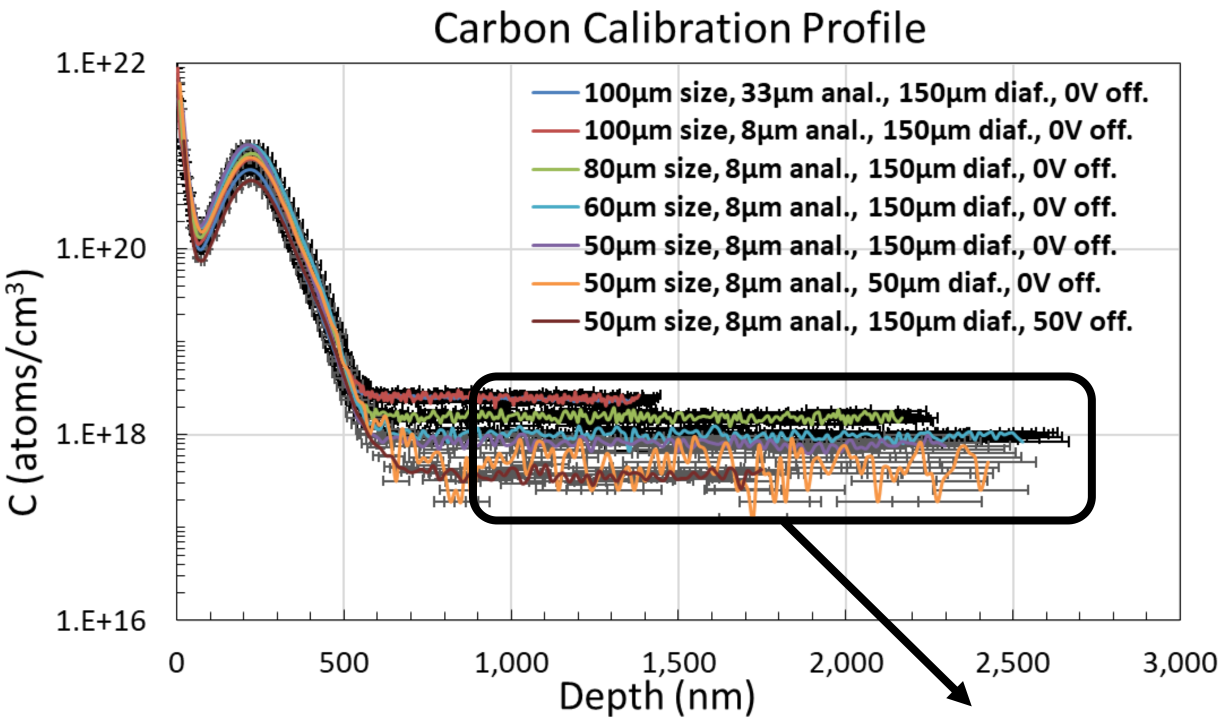
Sensitivity Optimization

- ✓ The implant concentration is estimated in each case following:

$$C = RSF \times \frac{i_i^{cal.}}{i_M^{cal.}}$$

$$\delta C = \sqrt{\left(\frac{i_i^{cal.}}{i_M^{cal.}} \times \delta RSF\right)^2 + \left(\frac{RSF}{i_M^{cal.}} \times \frac{1}{\sqrt{i_i^{cal.}}}\right)^2 + \left(RSF \times \frac{i_i^{cal.}}{\left(i_M^{cal.}\right)^2} \times \frac{1}{\sqrt{i_M^{cal.}}}\right)^2}$$

- ✓ Without any additional optimization, a resolution of (4.71 ± 0.03) × 10^{16} atoms/cm^3 can be achieved
- ✓ The resolution increased for smaller raster sizes while maintain same beam intensity, resulting in higher observant signal intensity
- ✓ Downside of such an approach higher abrasion speed, lees points
- ✓ In essence this is the equivalent in measurement terms of statistical smoothing of profiles.
- ✓ Points recorded every 17 nm, limit of feature size one can probe for achieving such resolution



Gaussian fit on point projection to estimate resolution form σ

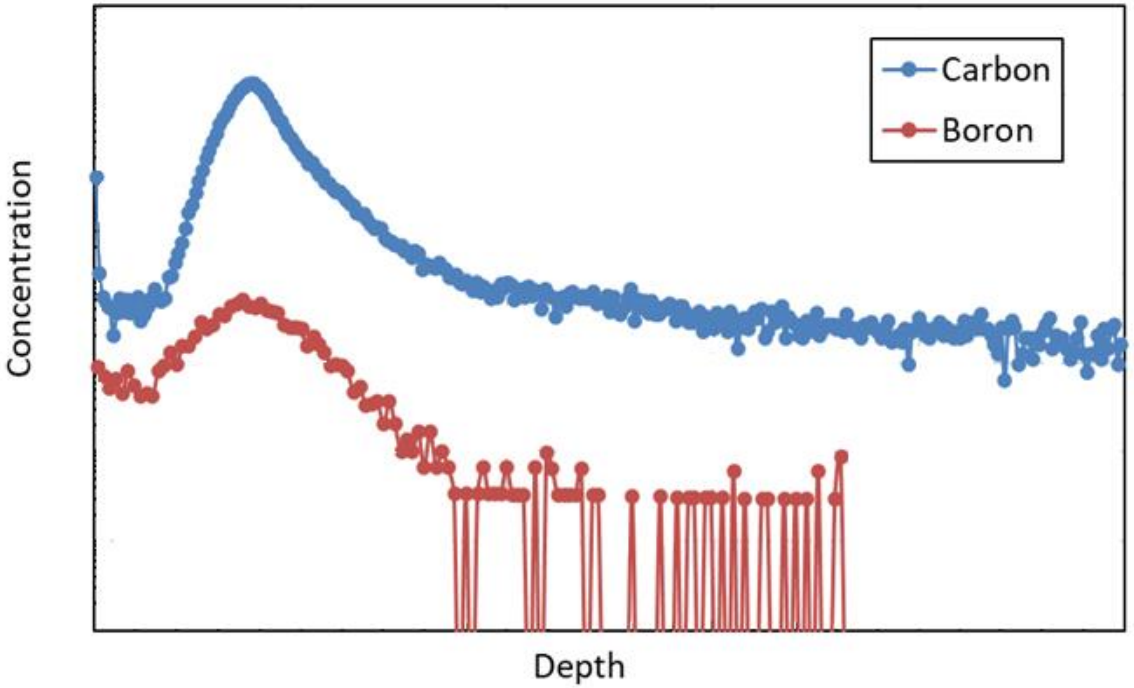
Beam Parameters	**Abrasion Speed** v (nm/sec)	**Scaling Factor** RSF (atoms/cm3)	**Sensitivity** S (atoms/cm3)
100µm size, 33µm reg., 150µm dia., 0V off.	4.35 ± 0.20	(2.77 ± 0.06) × 10^{22}	(4.85 ± 0.11) × 10^{16}
100µm size, 8µm reg., 150µm dia., 0V off.	4.43 ± 0.21	(3.61 ± 0.08) × 10^{22}	(1.80 ± 0.01) × 10^{17}
80µm size, 8µm reg., 150µm dia., 0V off.	6.93 ± 0.34	(2.62 ± 0.06) × 10^{22}	(1.48 0.005) × 10^{17}
60µm size, 8µm reg., 150µm dia., 0V off.	12.11 ± 0.65	(1.82 ± 0.04) × 10^{22}	(7.89 ± 0.02) × 10^{16}
50µm size, 8µm reg., 150µm dia., 0V off.	14.64 ± 0.84	(1.45 ± 0.03) × 10^{22}	(7.44 ± 0.01) × 10^{16}
50µm size, 8µm reg., 50µm dia., 0V off.	15.55 ± 0.91	(1.05 ± 0.02) × 10^{22}	(1.78 ± 0.002) × 10^{17}
50µm size, 8µm reg., 150µm dia., 50V off.	**17.00 ± 1.04**	**(5.56 ± 0.14) × 10^{22}**	**(4.71 ± 0.03) × 10^{16}**

•FBK and CNM Carbon

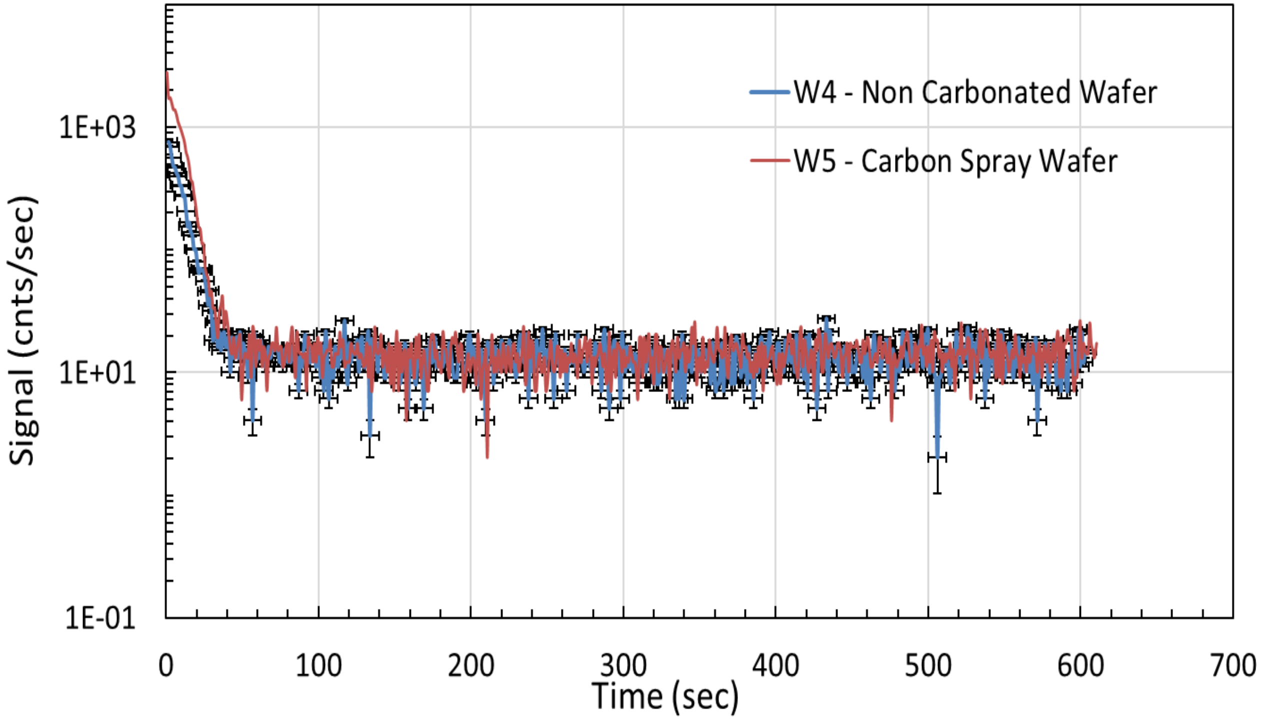
In-Silicon Carbon Profiles

- ✓ No Carbon detected to the level of > 4×10^{16} atoms/cm^3 for the CNM samples and the FBK PIN low carbonated sample
- ✓ CNM Carbonated-Noncarbonated samples at the same background level concerning carbon signals
- ✓ FBK Carbon peak in agreement with gain layer peak as expected though their process
- ✓ Carbon tails at higher end due to measurements and crater edge effects

FBK UFSD2, High Carbon



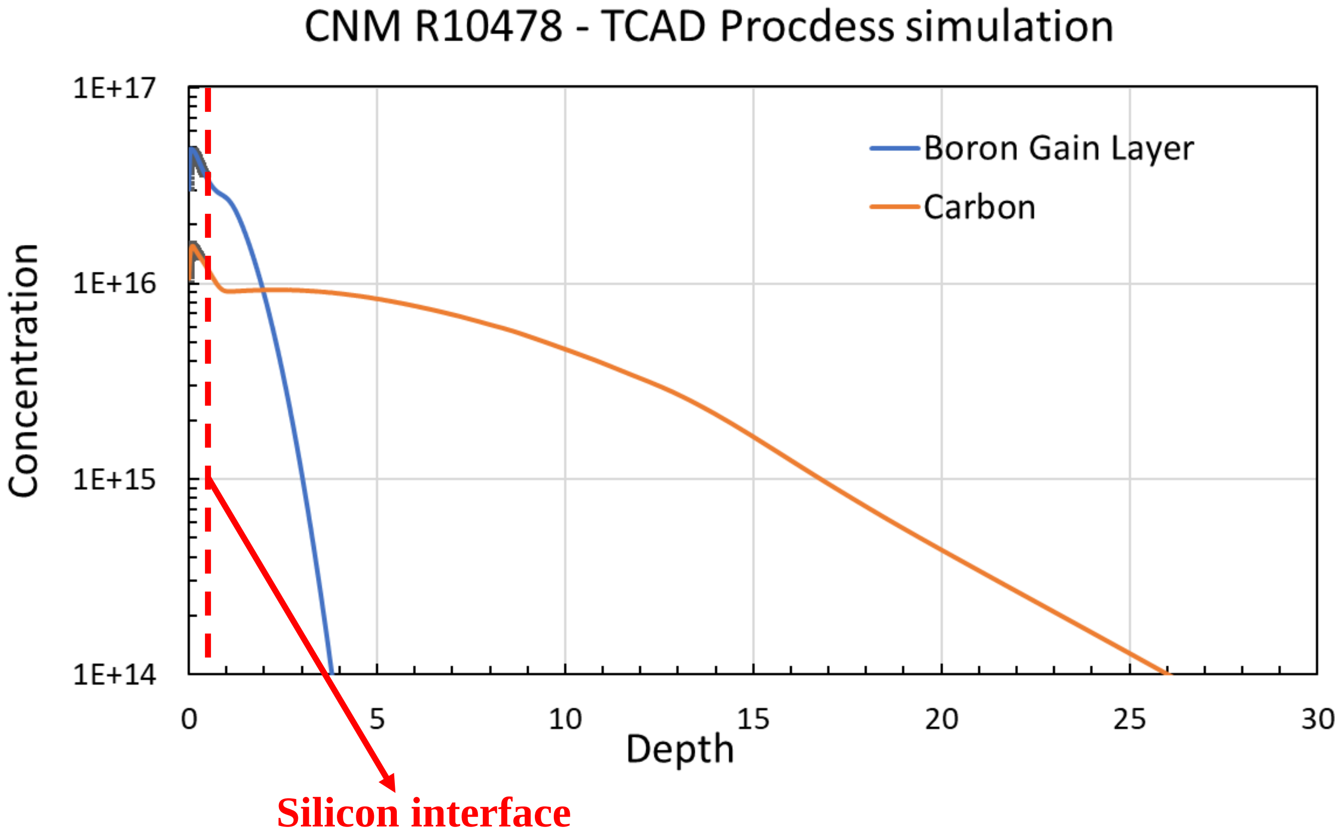
CNM R10478 - Carbon



•CNM Carbon Layer Simulation

Where is the Carbon and why it deactivates boron?

- ✓ Complete TCAD Simulation of the total thermal budget and implantation step for boron and Carbon
- ✓ Results for Boron in agreement with SiMS measurements in both depth and dose
- ✓ Carbon Profile deep diffused with average concentrations at the limit of detection



Simulation Parameters

- ➢ **Cz High Resistivity Si substrate**
  - ➢ <100> orientation (dicing, radiation hardness)
  - ➢ Resistivity >4 kΩhm*cm
  - ➢ P concentration of 10^{12} atoms/cm^3
  - ➢ Active thickness 50 μm
- ➢ **Native oxide: 1.9 nm**
- ➢ **Screen Oxide: 50 nm (deposited)**
- ➢ **MC implantation:**
  - ✓ 3000 tracks
  - ✓ Max track splits 6, splints per element 3
  - ✓ CristalTRIM algorithm
  - ✓ Clock seed randomization
  - ✓ Optimization error: ± 10^{14} atoms/cm^3
  - ✓ Full cascade BCA damage (binary collision approx.,)
- ➢ **Diffusion (Transport) Mode: Dopant dependent**
  - ➢ Boron ⟶ Charged Pair
  - ➢ Phosphorus ⟶ Charged Pair
  - ➢ Carbon ⟶ Neutral React
- ➢ **Activation Models (See next slide)**
- ➢ **Synopsys info**
  - ✓ Version 2019.12 with Advanced Calibration
  - ✓ MGOALS meshing algorithm

•Carbon-Boron (De)activation model

The ComplexCluster and the BIC (boron interstitial) models

Dopant Defect Cluster Models

- ✓ **Boron activation model:**
  - ✓ Boron activation is mainly interstitial driven
  - ✓ BIC (**B**oron **I**nterstitial **C**luster) model simulates the process via clustering reactions: **$B_i I_j + V/I \rightarrow B_i I_{j-1} / B_i I_{j+1}$**
    $B_i I_j + BI \rightarrow B_{i+1} I_{j+1}$
  - ✓ User demined cluster sizes to consider: **B, BI, BI_2, B_2I_1, B_3I_1, B_3I_2**
  - ✓ Reaction rates can be set by user for each reaction **(**eg 0.3×10^{-10} **)**
- ✓ **Carbon activation model:**
  - ✓ The CarbonCluster or Neutral Cluster Model sets initial cluster concentrations to 0 unless in amorphous regions
  - ✓ No charged clusters are considered, solutions to $A_iI_j + I \leftrightarrow A_iI_{j+1}$ $A_iI_j + AI \leftrightarrow A_{i+1}I_{j+1}$ $A_iI_j + V \leftrightarrow A_iI_{j-1}$
  - ✓ For Carbon, the following dedicated clusters are computed: C_3I_2, C_4I_2, C_4I_3, C_5I_3, C_5I_4
- ✓ **Boron/Carbon activation/deactivation models:**
  - ✓ The ComplexCluster Model considers cluster formation between dopants and Vacancies / Interstitials in Si
  - ✓ Such process can be described generally as: **$n_1 \times Imp.A + n_2 \times Imp.B + n_3 \times V/I + n_4 \times e^- \rightarrow A_{n1}B_{n2}(V/I)n_5 + n_6e^-$**
  - ✓ In the carbon/boron case, the simplest reaction to consider is: $C + B + I \rightarrow BCI + e$
  - ✓ A final charge of 1.0 is expected in such a case
  - ✓ For the moment using the Initial concentration as provided after MC implantation by Crystal Trim

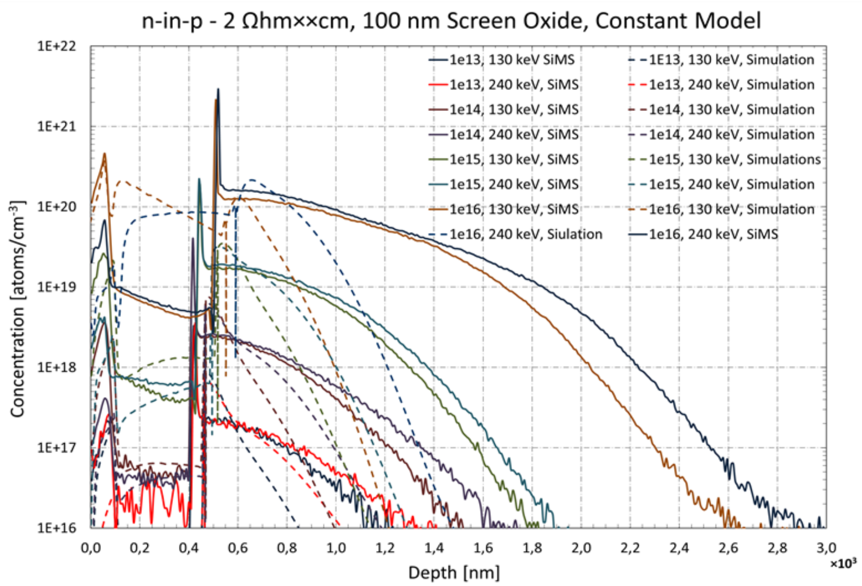
•Conclusions

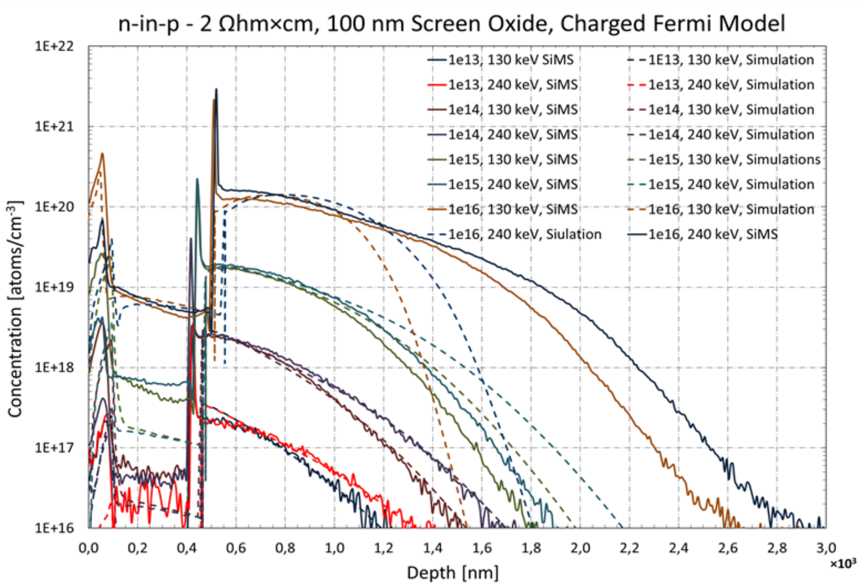
Outlook and Plans

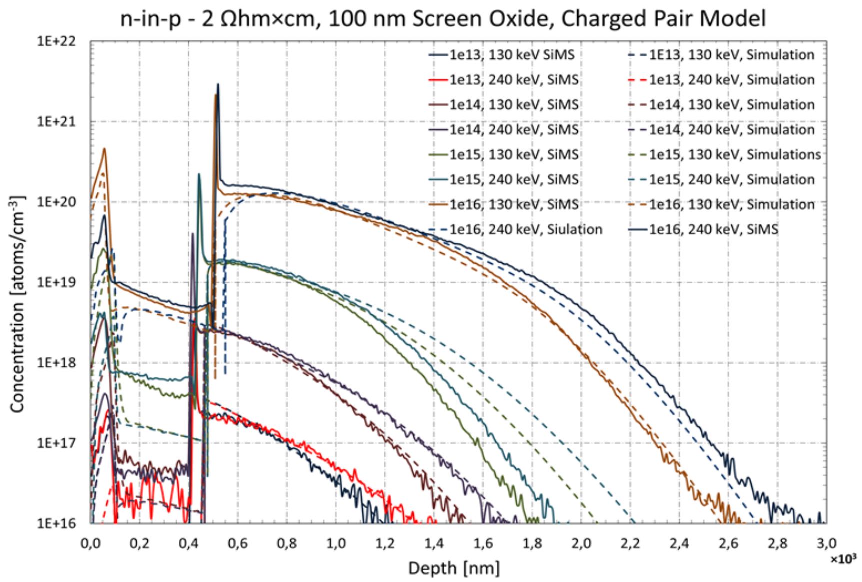
- Very good agreement of SiMS with Simulations for the CNM Process
- Carbon present in the samples in concentrations < 10^{16} and high depth
- **Deep carbon diffusion does not impact gain layer de-activation but improves the radiation efficiency of high resistivity p-substrates with an at least 20% improvement in charge collection**
- FBK high Carbonated process as expected with carbon and boron peaks aligned
- **Carbon/Boron activation/deactivation implemented in the simulation with the ComlexCluster model being the best candidate to describe Boron deactivation**
- Boron deactivation is not an LGAD effect, has been observed in the past and models were developed mainly for the Semiconductor industry focused on Carbon-Arsenic deactivation

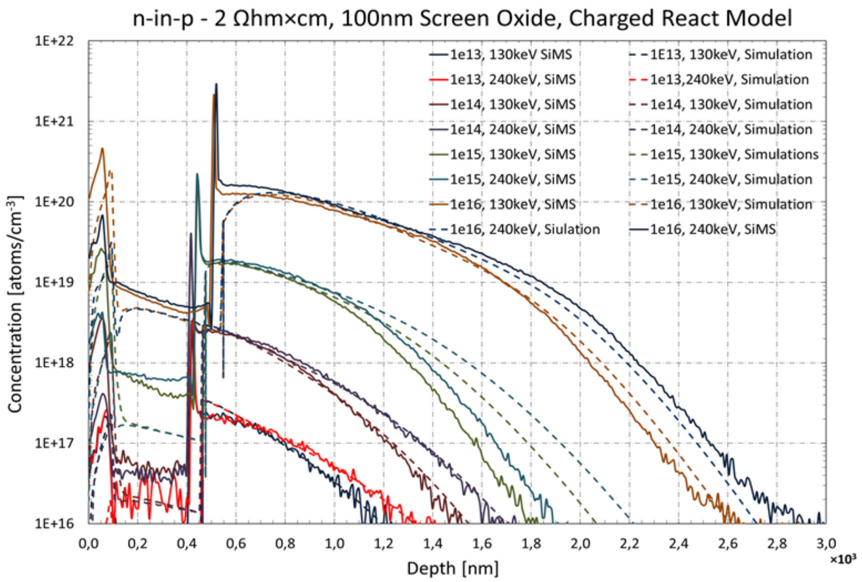
•Diffusion Model Comparison - Backup

Gkougkousis V., 10th Trento Workshop Talk, February 2015: link









- ✓ Different diffusion models tested
- ✓ Simulations compared with SiMS on n-in-p samples
- ✓ Constant model only good for very low doses < 1e13 cm^{-2}
- ✓ Charged Fermi model successfully describes dopant behavior up to doses of 1e15 cm^{-2}
- ✓ Pair model, taking into account binary interactions, covers the entire dose range up to 1e16 cm^{-2}
- ✓ Charged versions of the models take into account ion charge (not relevant here)
- ✓ React models should be used when chemical reactions are expected