Innovative Methods for Si Detector Doping Profile Analysis

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Journées thématiques du Réseau Semi-conducteurs IN2P3-IRFU. Méthodes de test orientées simulation

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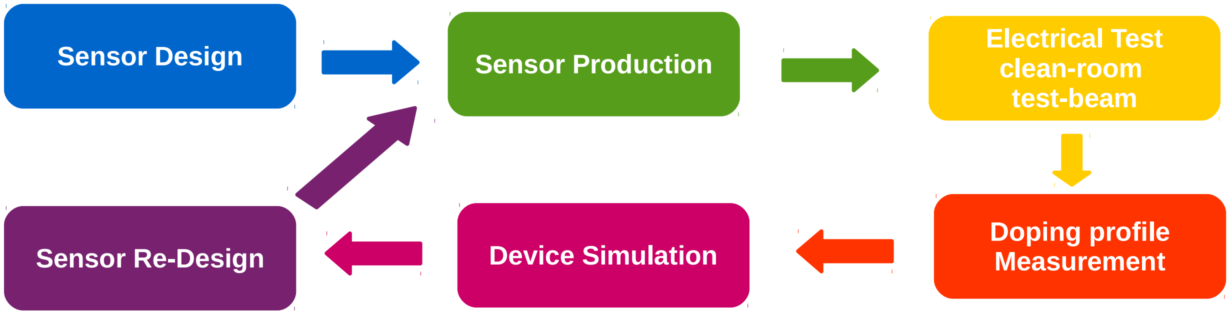
Outline

- Motivation
- Secondary Ion Mass Spectrometry (SIMS) method
- Transmission Line Matrix (TLM) method
- Summary

Introduction

<u>Detector Development in HEP:</u>

Development, production and integration of cutting-edge, efficient and cost-effective semiconductor sensors for particle detection purposes :



Understanding the structure of the silicon detectors, by measuring the doping profile, is important:

- To complete electrical characterization and explain operational behaviour

- Production testing: process control, in particular diffusion, identification of contaminants and failure in the fabrication.

- Provide an important inputs to simulations in order to get precise results

Introduction

This talk is mainly aimed to present two innovative methods:

- Provide a high lateral resolution technique to study the doping profile at the pixel level inside the complex structure

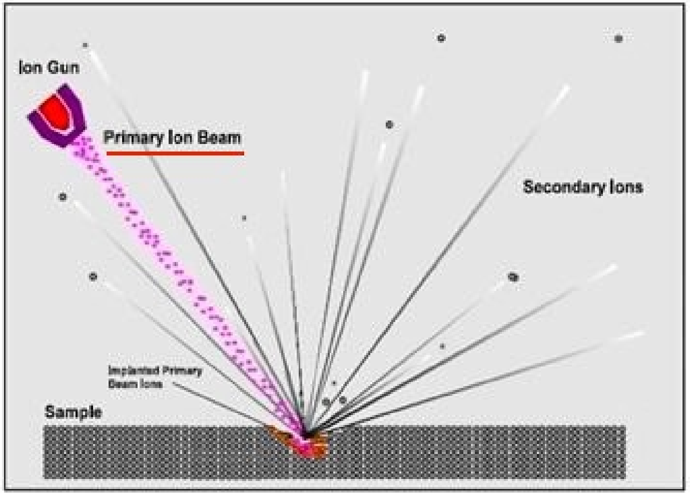
- Quantify irradiation effects on active dopant concentration, hence, provide us with another way to study the radiation damage and its effects on the detector performance

SIMS Method

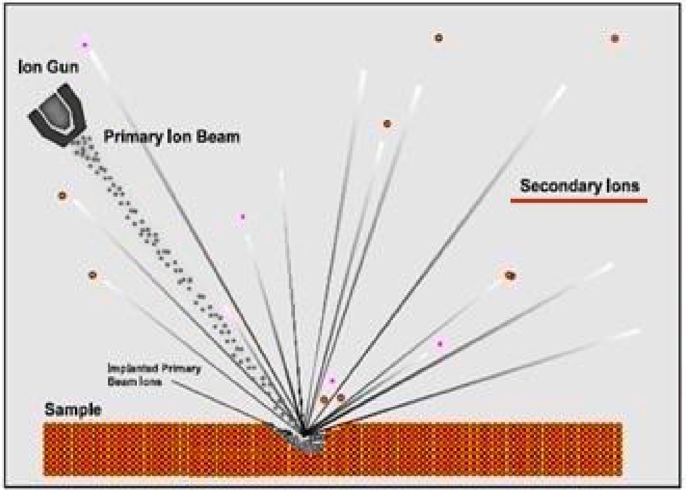
SIMS Method

Secondary Ion Mass Spectrometry (SIMS):

- Analytical method used to measure doping profile. Depending on measuring the secondary ions Intensity ejected from a sample surface when bombarded by a primary beam.



Sputtering on the sample surface with a focused primary ion beam.



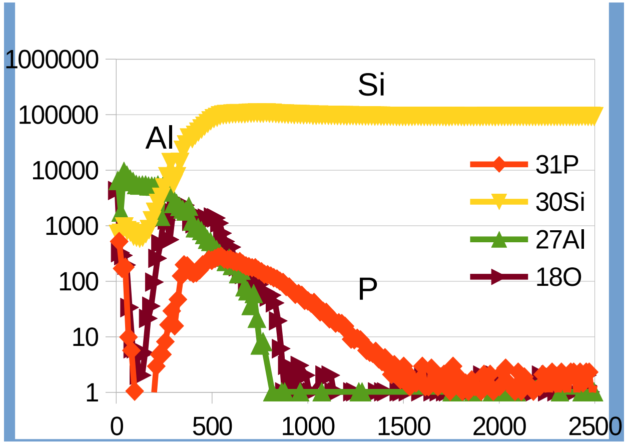
Collecting and analysing ejected secondary ions using mass spectrometer

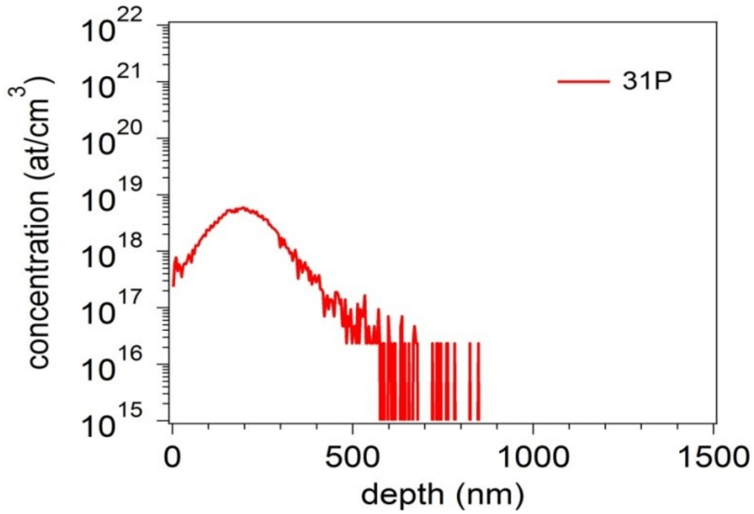
SIMS Measurement

Secondary Ion Mass Spectrometry (SIMS):

- Analytical method used to measure doping profile. Depending on measuring the secondary ions Intensity ejected from a sample surface when bombarded by a primary beam.

- Destructive method but a powerful tool to extract doping profiles of different layers in Si detectors



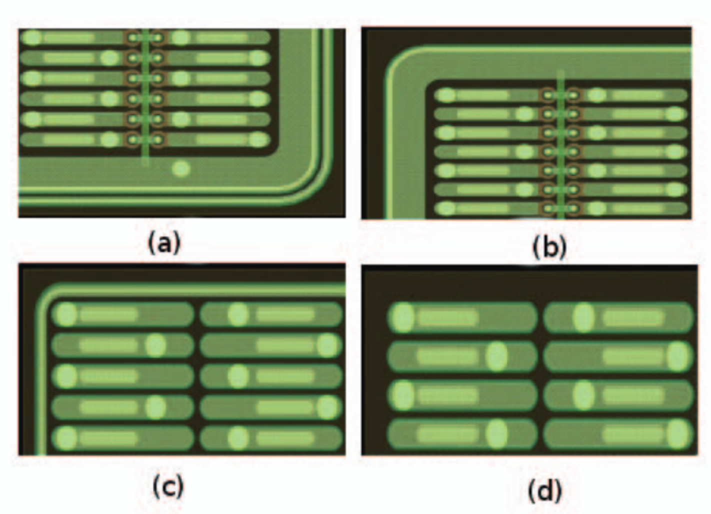


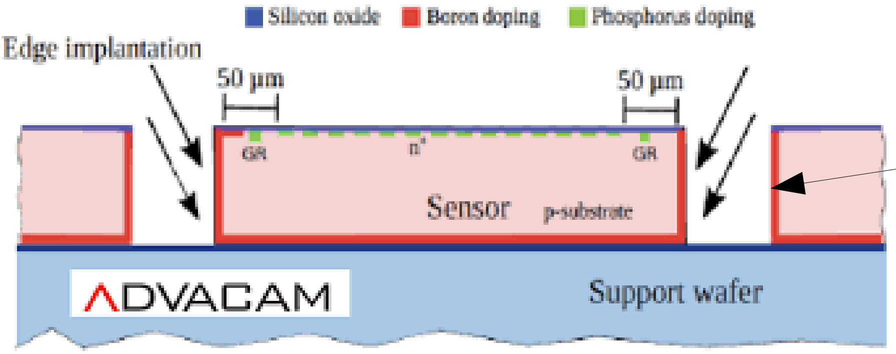
- Row data is quantified to get the concentration and depth

Why new SIMS?

ADVACAM Active Edge Sensors:

- n-in-p planar pixel.
- Thickness: 50 µm - 150 µm.
- Matrix size: 5 mm x 5 mm.
- Pixel size: 25 µm x 200 µm.
- Inactive regions: 47 µm – 100 µm



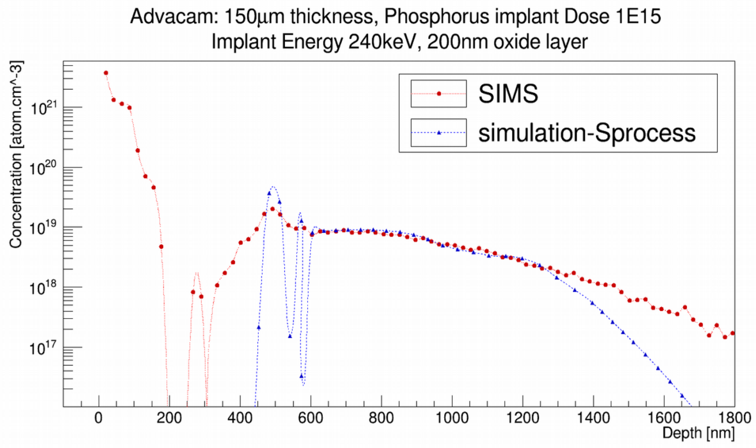


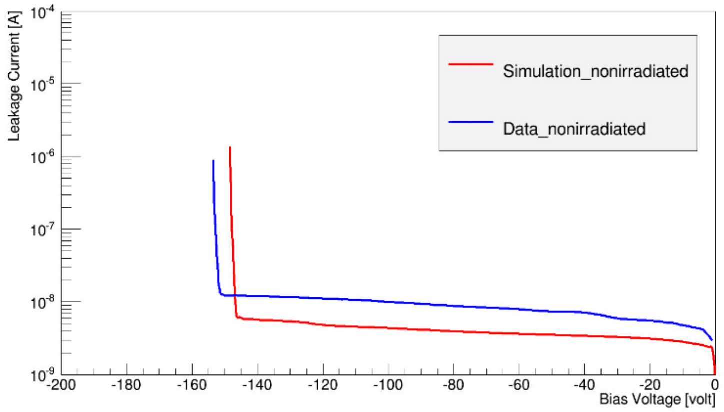
Boron backside implantation is extended to the edge (known as active edge)

Why new SIMS?

ADVACAM Active Edge Sensors challenges:

- Study the doping profile at the pixel level (complex structure, active edge).
- Divergence in TCAD simulation in doping profile Simulation as well as in electrical Device Simulation





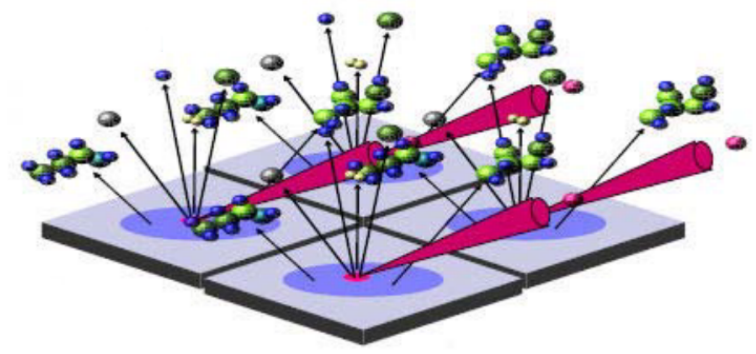
→ Need to find another method to measure with higher precision doping profiles in different implanted regions, specially in the small active edge region.

SIMS 3D Imaging

- Motivation: Study the total doping profile at the pixel level (25 x 200 μm^2) inside a complex structure with a high lateral resolution.

- SIMS Imaging is a technique that give us a unique combination of chemical and spatial information to identify the different component of the analysed surface based on the mass.

- By scanning the samples surface and depth we can obtain three-dimensional dopant maps.



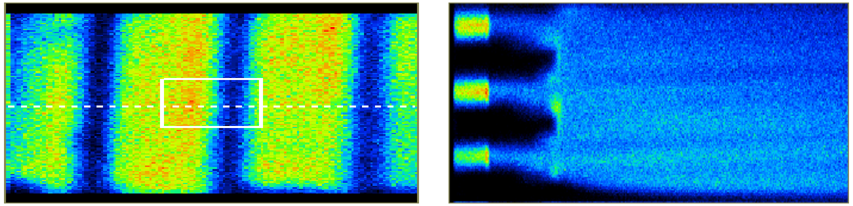
Focussed ion beam stepped from point to point, 2D data generated

SIMS 3D Imaging

- Improvement with the new 3D SIMS Imaging technique:

  - high lateral resolution up to 5 µm, is mandatory to analysing small ROI
  - high surface sensitivity at ppm level.
  - Allow a scan for the samples surface and depth.
  - Depth profiling and imaging can be combined to yield very powerful three-dimensional dopant maps

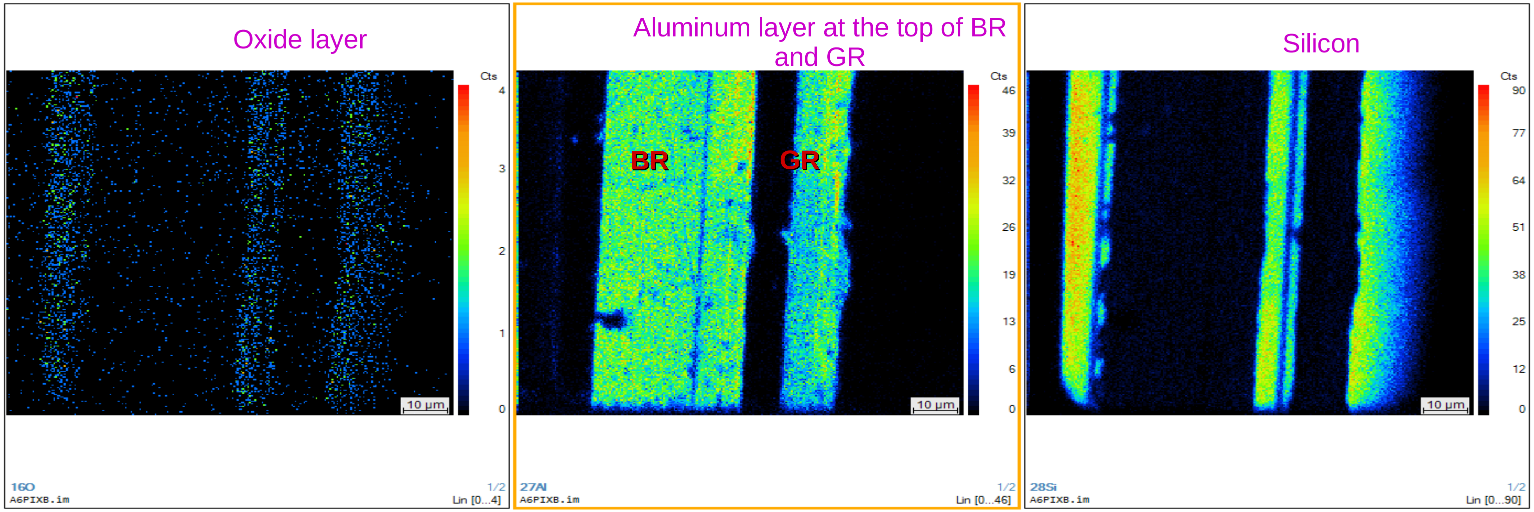
- Method used for the first time in the HEP domain, developed in collaboration with GEMAC Lab, Versailles.



Top View of the sample surface (left) and a cross-section through the depth of the sample.

SIMS 3D Imaging

Results (1):

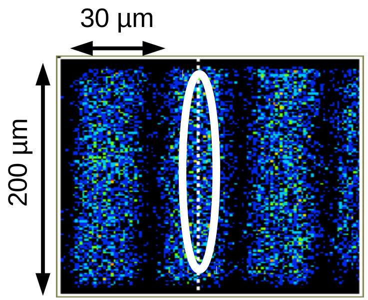


- 2D doping map of different components (Aluminium, Silicon Oxide and Silicon) found at the edge of the Adavacam sample analysed using SIMS Imaging method

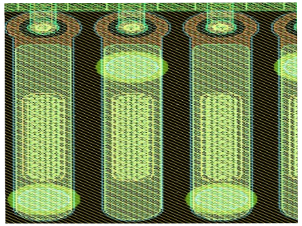
- The Silicon substrate has been reached without any significant signal of Boron → Fabrication failure for this batch

SIMS 3D Imaging

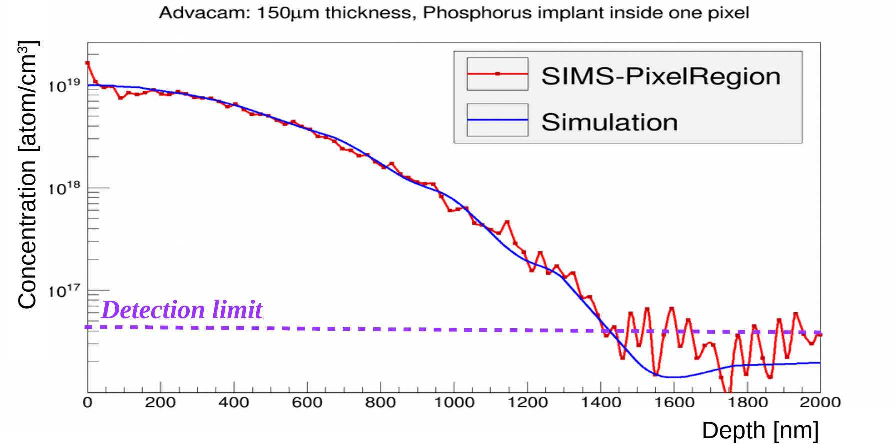
Results (2):



Measurement



Layout



- Top view of the Phosphorus implant in a region that covers three pixels

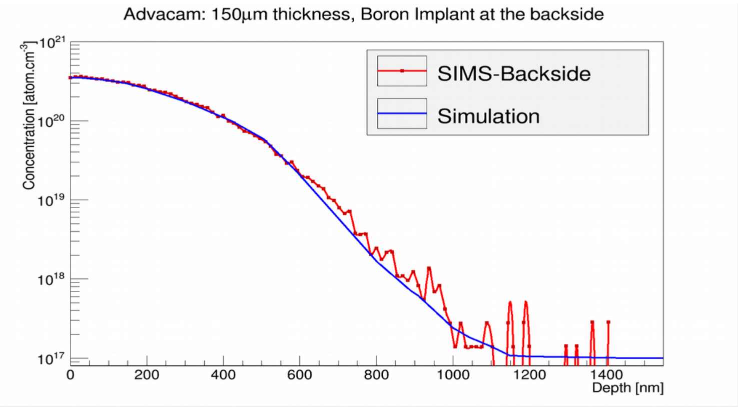
- Peak concentration 1 x 10^{19} atom.cm^{-3} and detection limit around 2 x 10^{16} atom.cm^{-3}. The implants extend to 1.5 µm in depth.

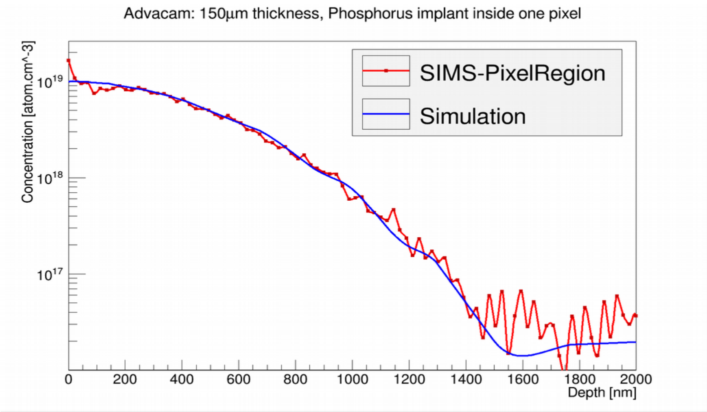
- Calibrate simulation with SIMS measurement, and a good agreement between measured and simulated doping profiles is obtained

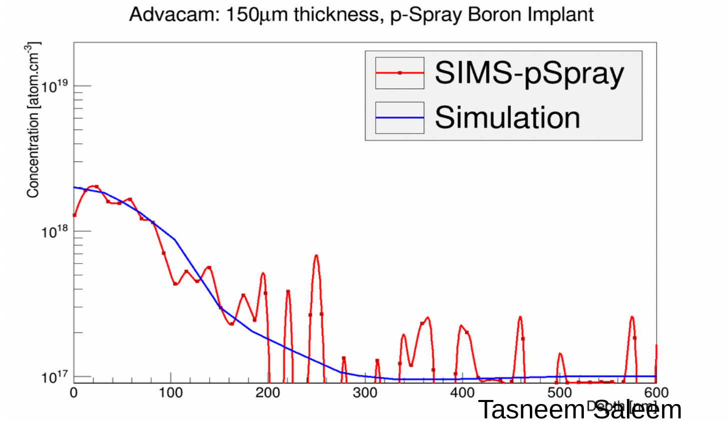
SIMS 3D Imaging

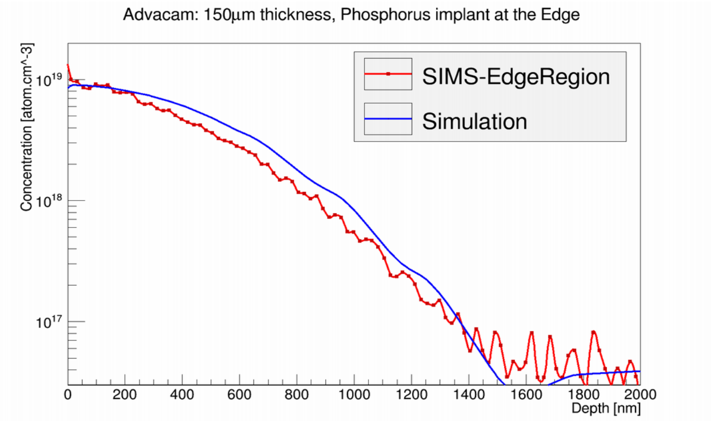
IEEE publication, Oct 2016, DOI: 10.1109/NSSMIC.2016.8069766

Results (3):









TLM Method

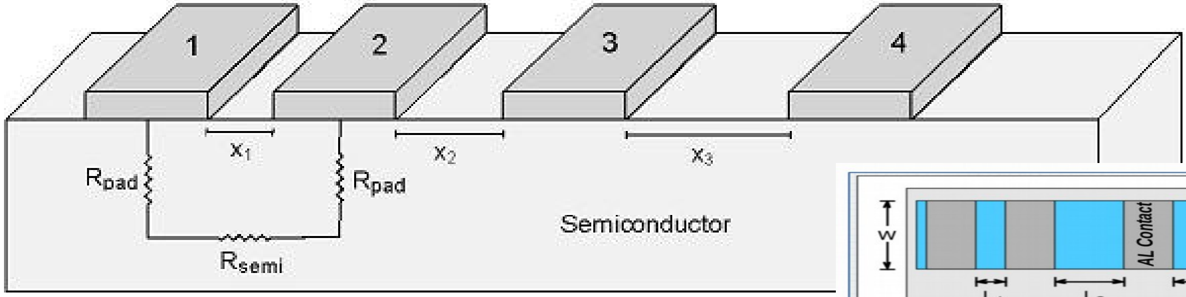
TLM Method

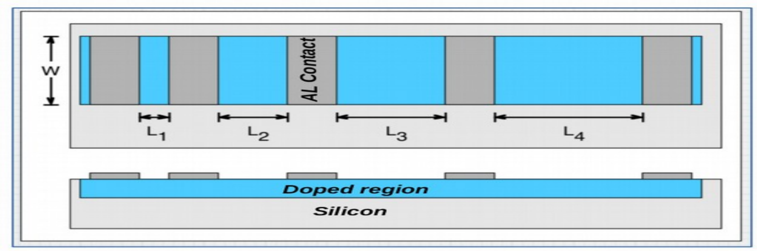
- Motivation: Measure the electrically active dopant. Study irradiation effects on the active dopant concentration. Hence, on detector performance.

- Transmission Line Matrix (TLM) based on measuring the resistance of doped silicon layers at depths increasing incrementally in the implanted area.

- Resistance measurement gives access to the layer resistivity and so active carrier concentration: $\rho = R\, tW/L$, $N_D = 1/e\mu\rho$

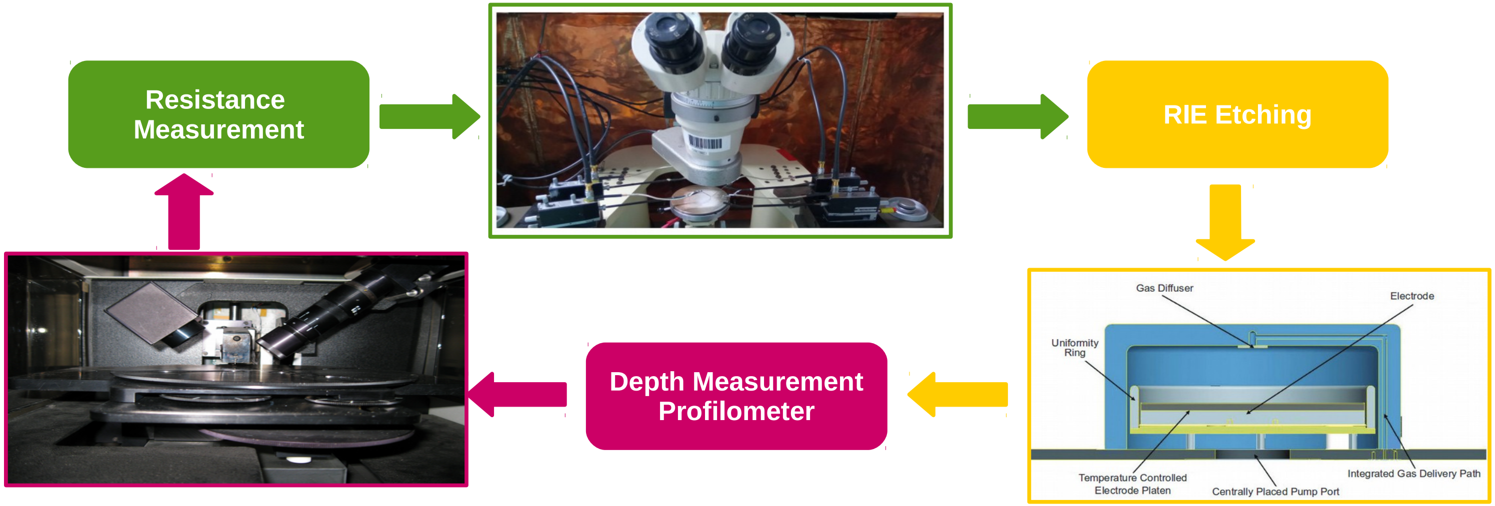
- In order to carry out this measurement, samples with special geometry & layout have been designed and fabricated at CNM, Barcelona.





TLM Measurement

- Measurement: performed in three main steps, that is done repetitively:



1. Resistance measurement done using two point probe station.

2. RIE Etching: the sample is placed in the etching chamber shown here where a 200 nm SI layer is removed each time.

3. Depth measurement: the sample surface is scanned by profilometer to measure the depth of the etched layer.

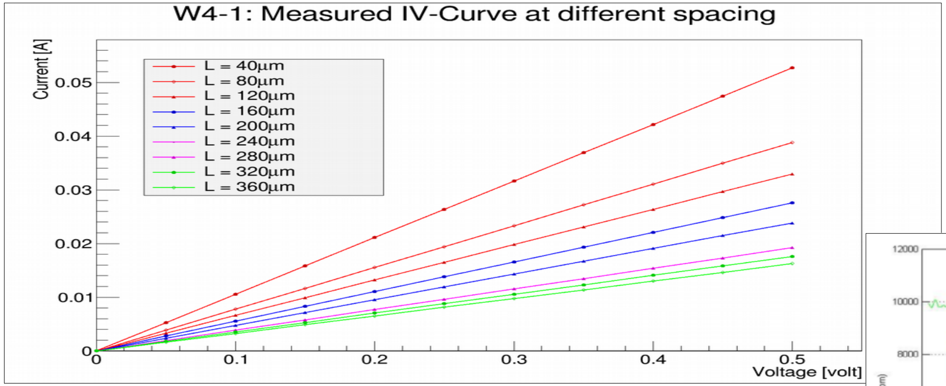
These three steps are repetitively done, many times, until the doped region is all removed.

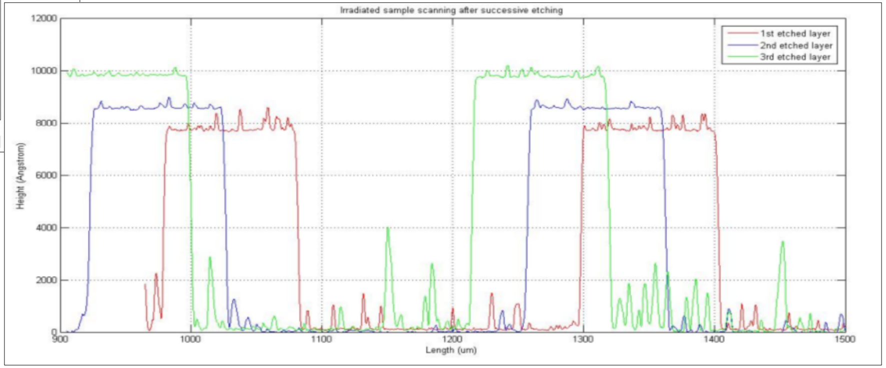
TLM Measurement

- <u>Results (1)</u>:

- Measured Current as function of bias Voltage of a non irradiated boron doped sample at different spacing between contacts.

- Three consecutive profilometer measurement of an irradiated sample obtained after the first, second and third etching was performed. A layer of thickness 200 nm is etched in each step.

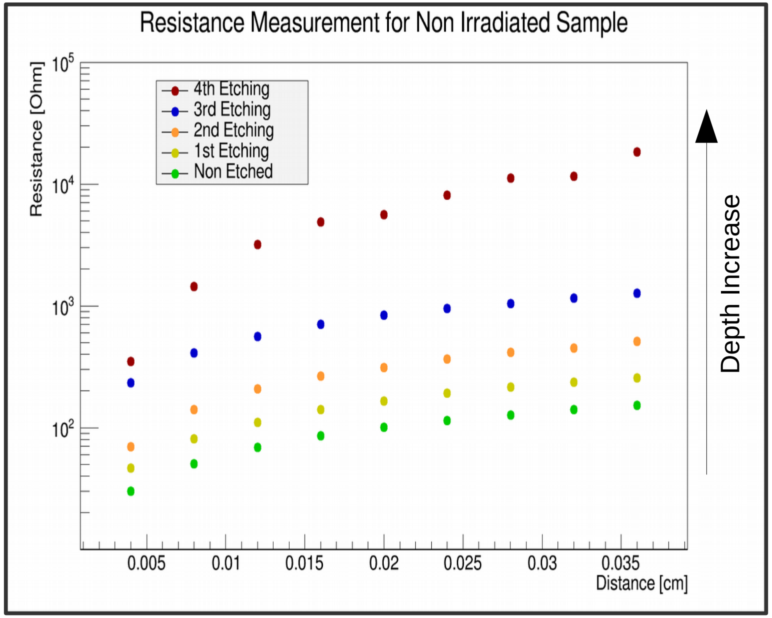


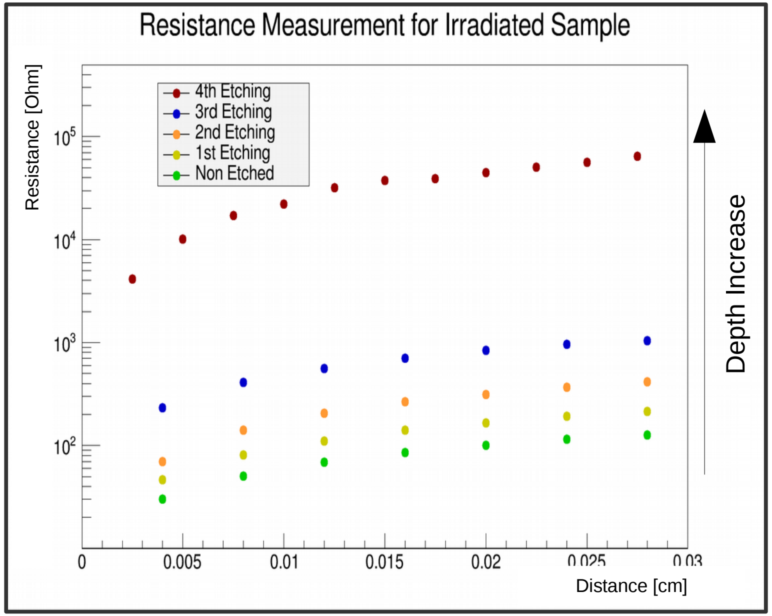


TLM Measurement

- Results (2):

- The resistance is directly proportional to the spacing distance as expected.
- The resistance increase with more and more etching, less electrically active carriers present.
- These observations confirm the reliability of our measurement

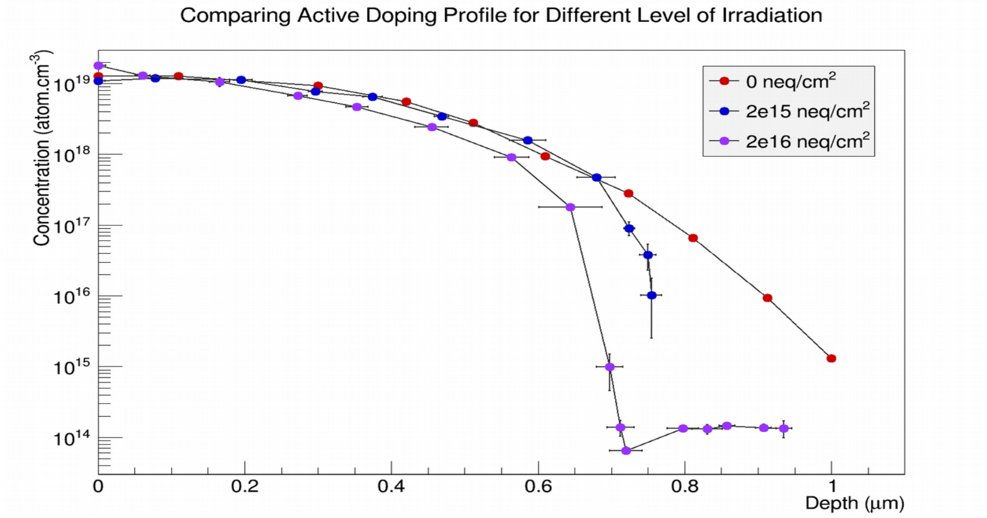




TLM Measurement

- Results (3):

  - Active carrier concentration as a function of depth.



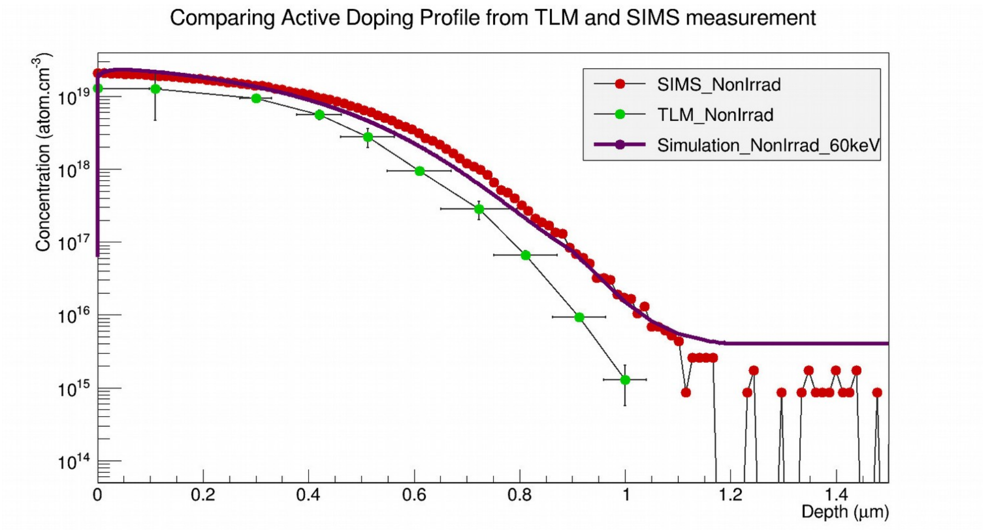
- Peak concentration ~ 10^{19} atom.cm^{-3}, which is in a good agreement with the expected value provided by the manufacturer
- Loss of active carriers due to irradiation is more visible at deeper layers, start appearing at depth of 350-400 nm.
- at the deepest level (~ 700 nm), loss of active carriers is around 95% (less irradiated sample) and 99.8%, caused by exposure to higher radiation dose

TLM Measurement

NIM-A Journal, Mar 2019, DOI: 10.1109/NSSMIC.2016.8069766

- Results (4):

- TLM Validation: Comparison with SIMS and Simulation for non-irradiated

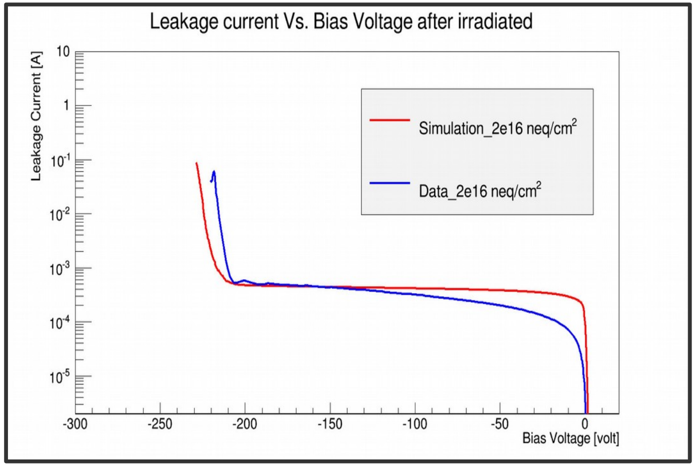


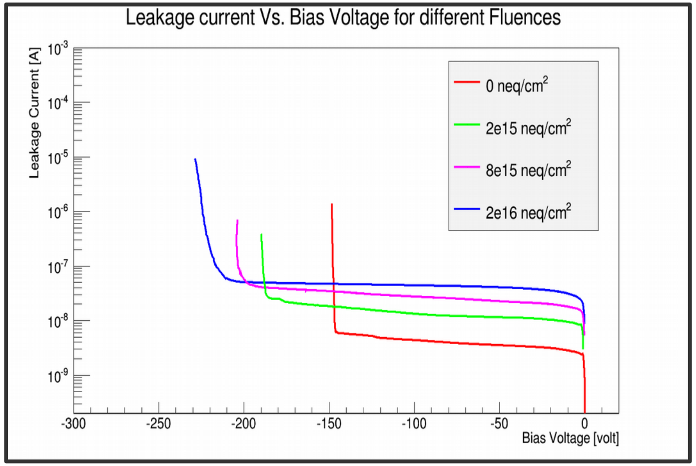
- Good agreement between SIMS and simulated doping profiles

- Discrepancy between the TLM measurement and both SIMS measurement and simulation is expected!

Radiation Damage Modelling

- TCAD Simulation of radiation damage in silicon detectors
  - Good agreement between data and simulation even for high irradiated sensor
  - Radiation damage in the detector results in increasing the breakdown voltage and the leakage current of the detector with irradiation dose
  - important role of doping profile to tune the irradiation model and get precise results from simulation.





Summary

- Development of two methods to measure doping profile in Si detectors has been presented

- SIMS 3D imaging method:
    - Promising method to obtain 3D doping profile maps
    - High lateral resolution
    - Ideal for samples with complex structure.

- Transmission Line Matrix (TLM) method:
    - Reliable to study irradiation effect on electrically active dopant
    - Significant loss of active dopant after high irradiation is observed

- Results have been validated and cross-checked against SIMS measurement, as well as, simulated doping profile.

- This study reflects the important role of doping profile measurement in tuning radiation models and get better agreement with simulation even at very high irradiation doses.

Acknowledgement

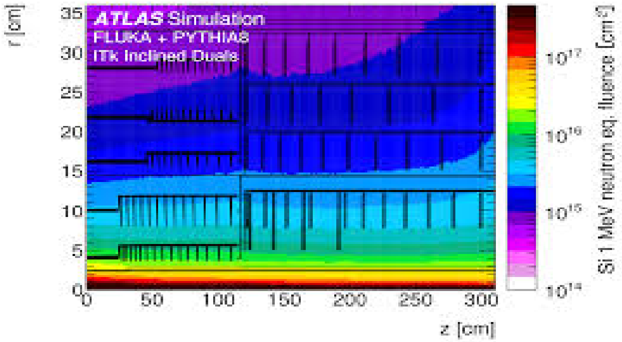
Funding: This work was funded by and carried out under the framework of the CERN, Switzerland RD50 collaboration.

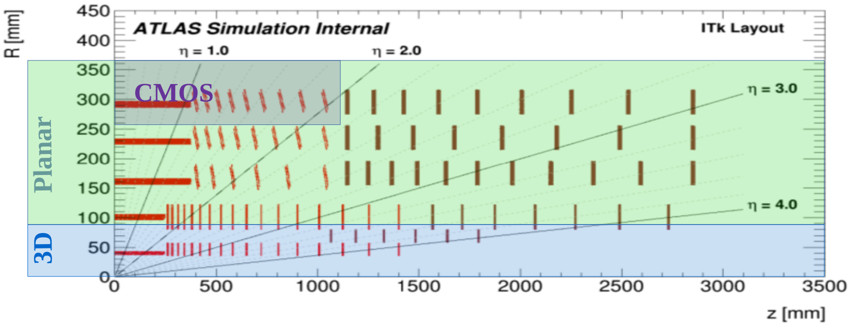
Collaborators: This work has been done in collaboration with GEMAC lab versaille and the Institut d'Électronique Fondamentale (IEF) at the University Paris-Saclay. We are thankful to our colleagues from these institutes for their collaboration and for sharing their expertise that has greatly assisted this research

Backup

Inner Traker ATLAS

ITk Upgrade Project:





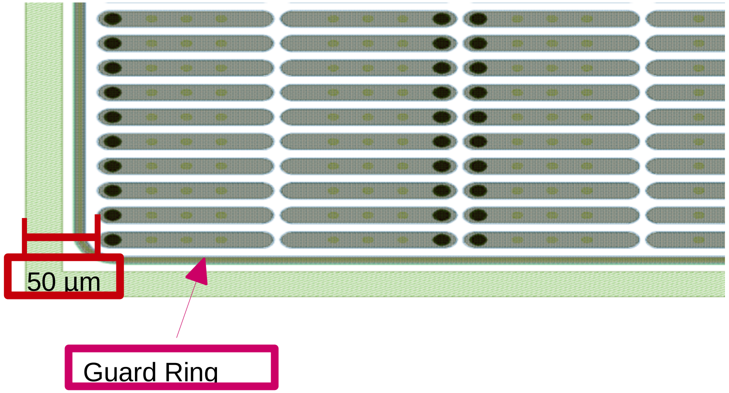
- The current inner detector will be replaced with a new all-silicon inner tracker (ITK).

ITK Challenges:
1. High Event rate (7x the nominal luminosity)
2. High occupancy (4x #Interaction/bunch crossing)
3. High radiation level (2 x 10^{16} n_{eq}/cm^2) (high particle fluence)

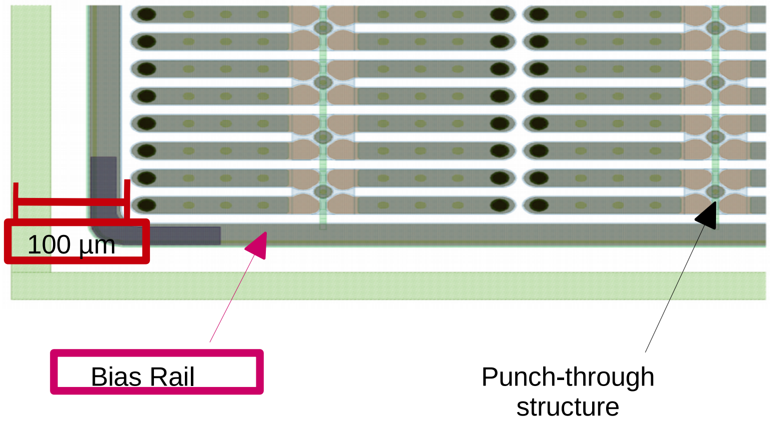
ITK Requirement:
1. Radiation hard detector: New pixel technology such as 3D, n-in-p planar.
2. Good tracking performance, increase spatial resolution: reduce pixel size.
3. Increase active area: active edge technology.

Active Edge Sensor Technology

ADVACAM NP150-6-1A
Active edge, 150 µm thickness
Pixel size: 50 x 250 µm²



ADVACAM NP100-7-2A
Slim edge, 100 µm thickness
Pixel size: 50 x 250 µm²



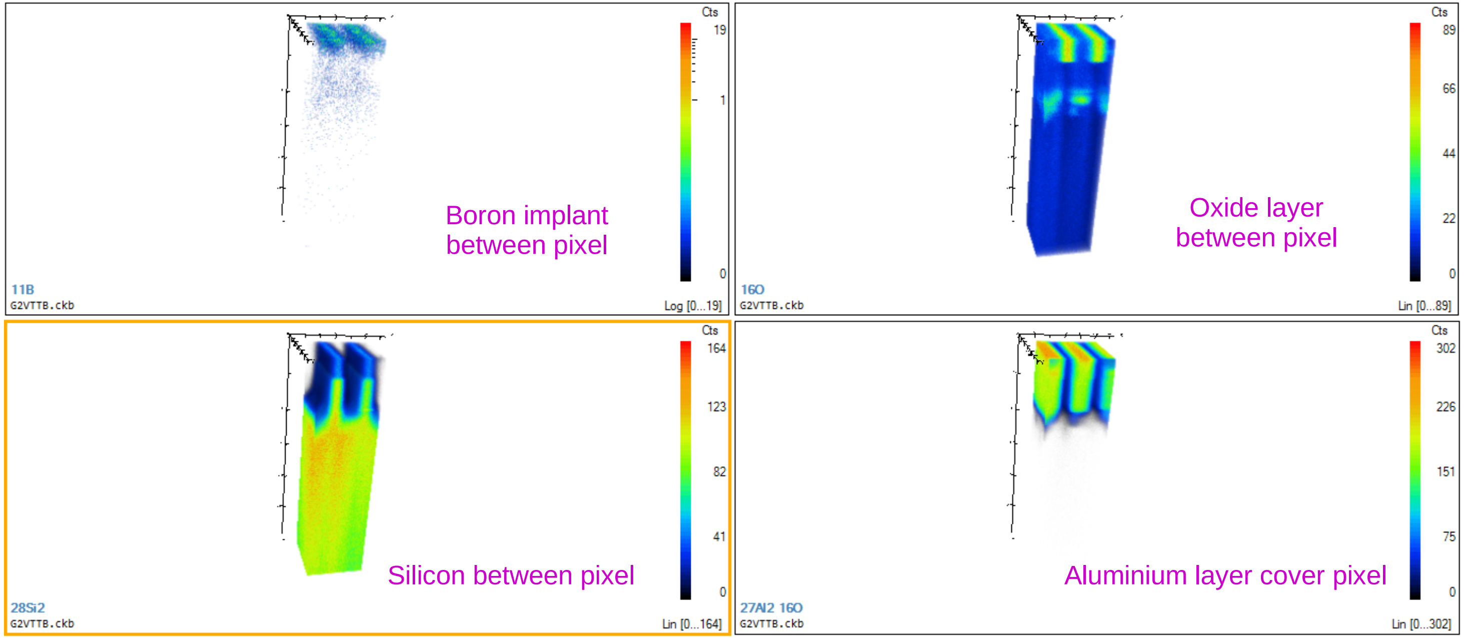
SIMS 3D Imaging

- “CAMECA IMF 7F” at GEMAC Lab, Versailles.

“CAMECA IMF 7F” specifications:

- Vacuum roughly 10^{-6} mbar
- Ions: Ar+, O2+, Cs+
- Ions energy: 1 – 30 keV
- sensitivity 10^{12} – 10^{16} atoms/cm3
- beam focus down to 1 µm
- reference samples with known composition necessary for quantitative analysis

SIMS 3D Imaging



SIMS 3D Imaging

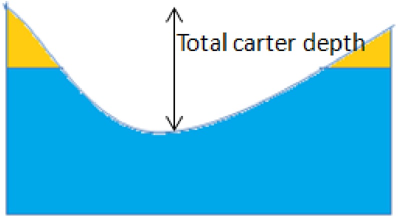
1. Time to depth conversion:

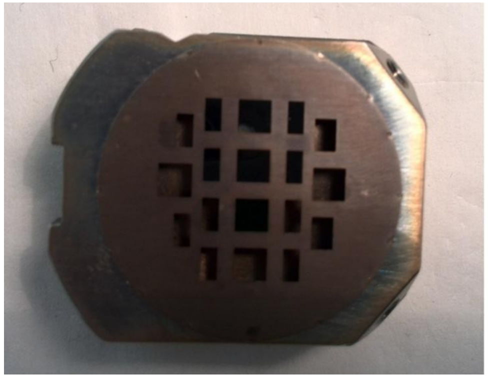
depth = average sputtering rate . time

average sputtering rate = total crater depth . total sputter time.

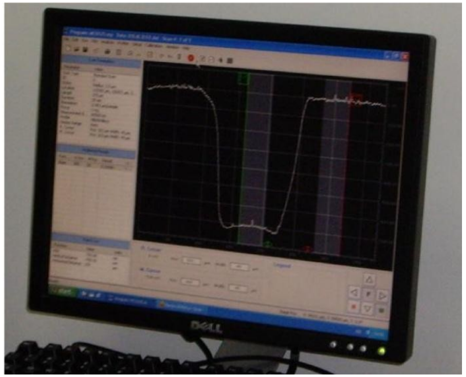
Measured using profilometer

The maximum time in the raw data plot





SIMS Sample holder



Profilometer measurement

SIMS 3D Imaging

2. Ion counts (intensity) into concentration conversion :

$$C_E = RSF \cdot \frac{I_E}{I_M}$$

Where C_E: concentration of the element of interest.
I_E: secondary ion intensity for the element of interest.
I_M: secondary ion intensity for the matrix element.

- RSF(relative sensitivity factor) determined by measuring a calibrated sample(Si sample implanted with a well known dose of the analyzed element)

$$RSF = \frac{dose}{crater\ depth} \cdot \frac{I_M}{I_{Eref}}$$

Where all variables refer to the calibrated sample