LAL Doping profile measurements

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LAL ATLAS PIXEL GROUP

RD50 Collaboration Meeting NoV2014

THE PURPOSE

- **Aim** : to measure the dopant density profiles on the test- structures inserted in the wafer production of the ATLAS and/or RD50 pixels sensors. Such measurements will allow us to calibrate the model of the pixel sensors developed using TCAD simulations and to improve the design of the sensors under investigation for High energy applications with respect to traditional design.

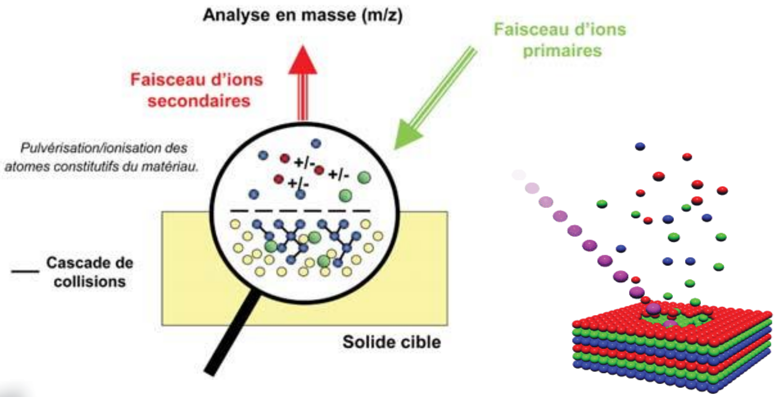
- **Two ideas were envisaged**:

- The measurement of the dopant density profiles using well known techniques as: **Secondary Ion Mass Spectrometry (SIMS):**
- The development of a higher resolution profiling method called "**Scanning Spreading Resistance Microscopy (SSRM)**"(Atomic Force Microscopy based),
- Note that SIMS could measure ultra-shallow profiles but it cannot distinguish between electrically active and inactive impurities. Whereas SRP senses electrically active species almost exclusively.

For spreading resistance profiling (SRP), the semiconductor sample is angle lapped and then a pair of closely spaced probes, having ultra-small contact areas, are stepped down the bevel. A small voltage (0.005v) is applied and the resistance is recorded. Then the resistivity-depth and the carrier concentration-depth can be determined.

Secondary Ion Mass Spectrometry

Secondary Ion Mass Spectrometry employs a primary ion beam to bombard the silicon surface. The ion bombardment causes sputtering of the sample to occur, resulting in secondary ion emission from the silicon surface. Cs is used as the primary beam for creating negative ions (P, As, Sb) and O_2 is used to create positive ions (B, Al). The emitted secondary ions are collected and mass analysed in order to obtain the surface elemental composition. Since sputerring is enherent in the measurement, depth profiling is built-in.



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Caractéristiques
du SIMS IMS 7f

Destiné principalement aux analyses de matériaux solides en ultra-vide, cet équipement présente les spécificités suivantes, nécessaires à l'étude des matériaux de demain :

- un vide poussé (10^{-10} mbar soit 1000 milliards de fois inférieur à la pression atmosphérique) indispensable pour l'analyse des éléments légers (hydrogène, carbone, oxygène…) ;
- une facilité à choisir l'énergie d'impact entre les ions primaires et le matériau ;
- une résolution en profondeur de quelques nanomètres faisant du SIMS l'une des techniques les plus sensibles à la surface ;
- une grande sensibilité et d'excellentes limites de détection (1e14 at.cm-3) ;
- l'accès à la haute résolution en masse (M/ΔM = 10000) ;
- une automatisation de la machine, afin de changer les conditions d'analyses plus facilement.

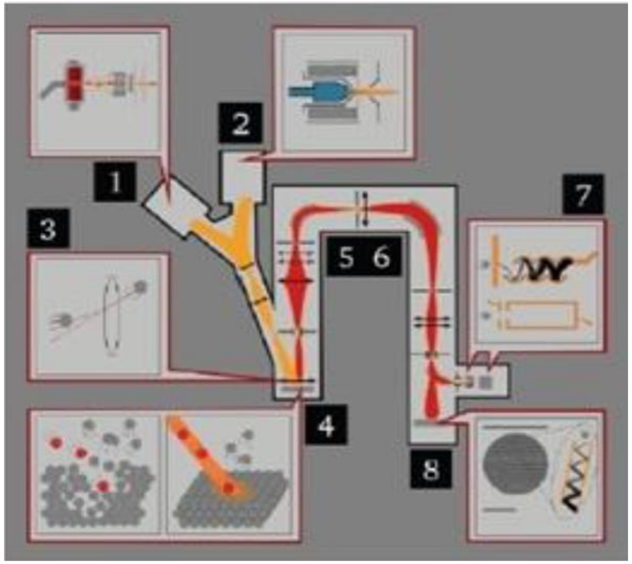
Un nouvel instrument pour explorer la matière

Le spectromètre de masse d'ions secondaires - SIMS IMS 7f

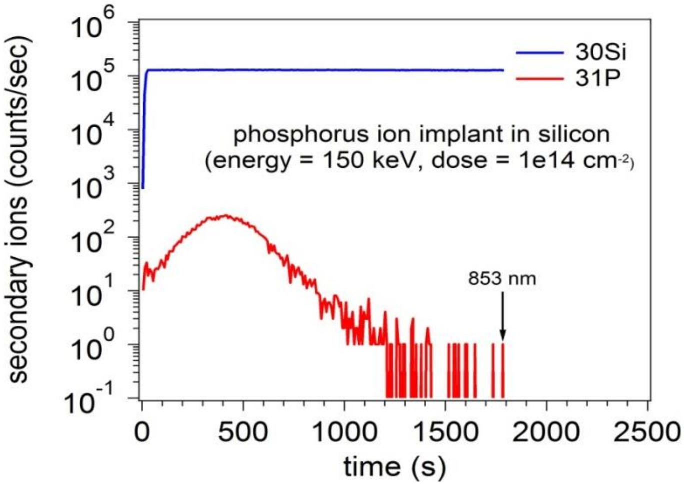
GEMAC
Groupe d'Etude de la Matière Condensée
UMR 8635

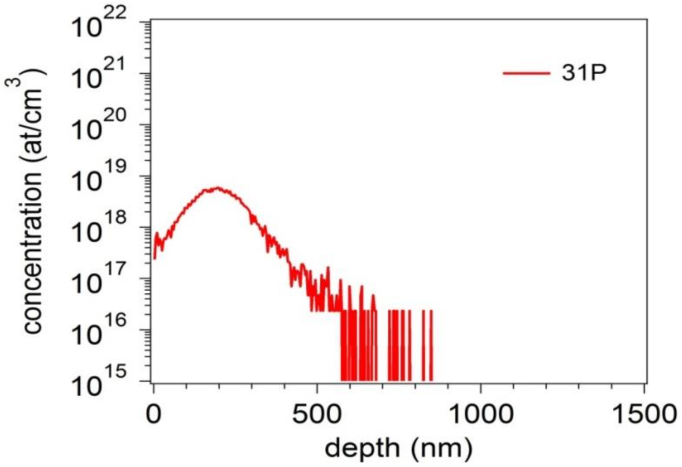
Secondary Ion Mass Spectrometry (SIMS)

SIMS is an analysis method measuring the secondary ions ejected from a sample surface when bombarded by a primary beam



1&2 – **Primary ion source** (O, Cs)
3 – Primary ion column
4 – Secondary ion extraction and transfer (location of the **sample**)
5 – Ion energy analyzer
6 – Mass analyzer
7 & 8 – **Secondary ion detectors**
  - 7- Faraday cup
  - 8- Ion counting electron multipliers





"RAW DATA" → **Concentration profile vs. depth**

Methods

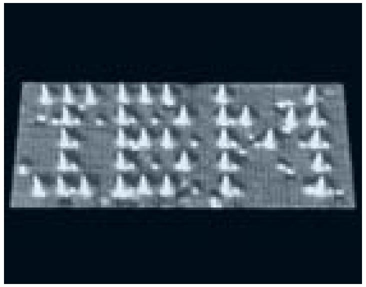
- Scanning Spreading Resistance Microscopy (SSRM)

This method employs an Atomic Force Microscopy (AFM) technology to move a sharp conductive tip over a sample, measuring a local spreading resistance between the tip and a large back surface contact and performing simultaneously an image of the sample topography.

The advantage of such method is an improved geometrical resolution, allowing the characterization of very shallow dopant profiles (tens of nm).

Heinrich ROHRER

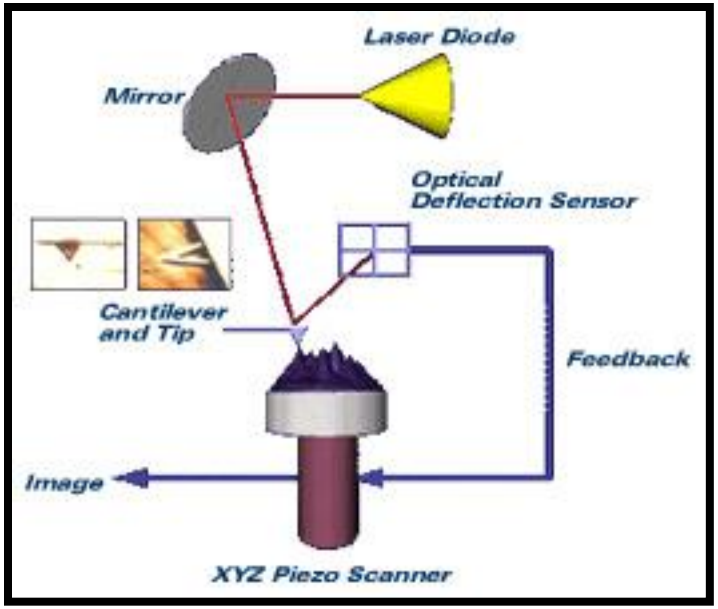
Gerd BINNIG

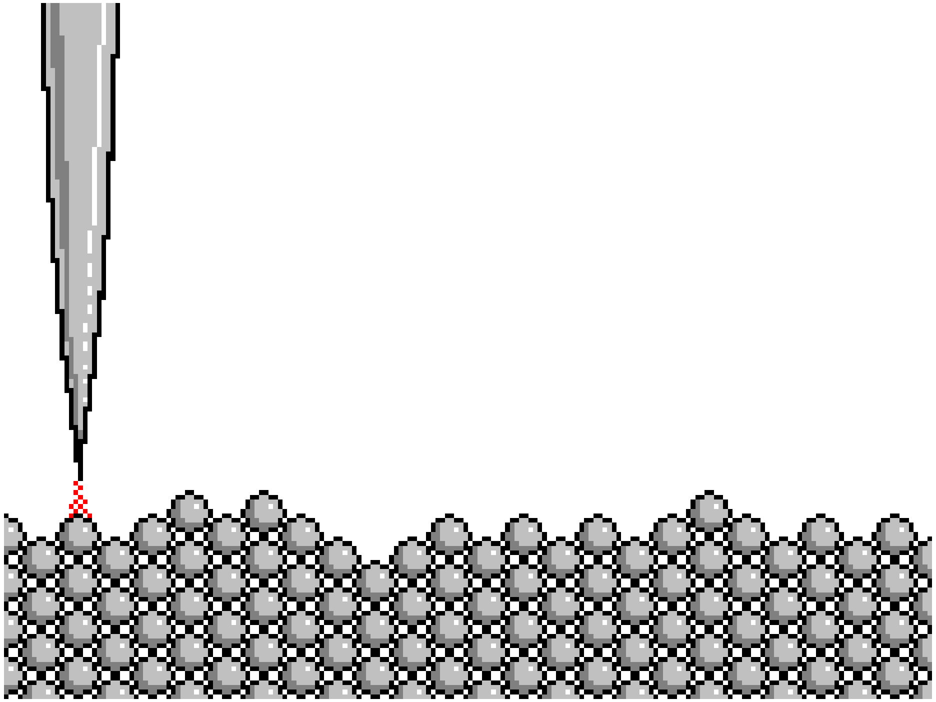


1986 :NOBEL PRICE physics for the invention of the scanning tunneling microscope

How the AFM works.

A schematic of an atomic force microscope is shown in the diagram above. The sample is mounted on a piezo ceramic which can be moved extremely accurately in the x, y and z directions. The sample is then rastered in the x and y directions under a sharp tip. This tip is mounted at the free end of a cantilever (as shown) onto which a laser beam is focussed. The beam is reflected from the back of the cantilever to a set of four photosensitive diodes. These act to detect any deflection of the laser beam arising from the cantilever moving as the sample is rastered. A feedback loop then acts to move the piezo in the z direction taking the laser beam back to its original position. In this way the sample is scanned with a constant force and the resulting z piezo motion produce topographical map of the region scanned with a vertical resolution much smaller than



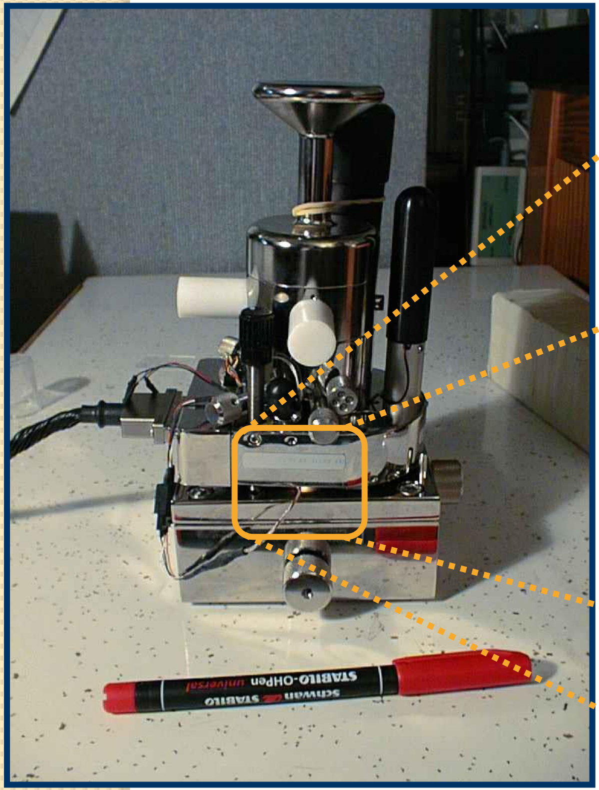


If the tunneling current is kept constant the Z position of the tip must be moved up and down. If this movement is recorded then the topography of the specimen can be inferred.

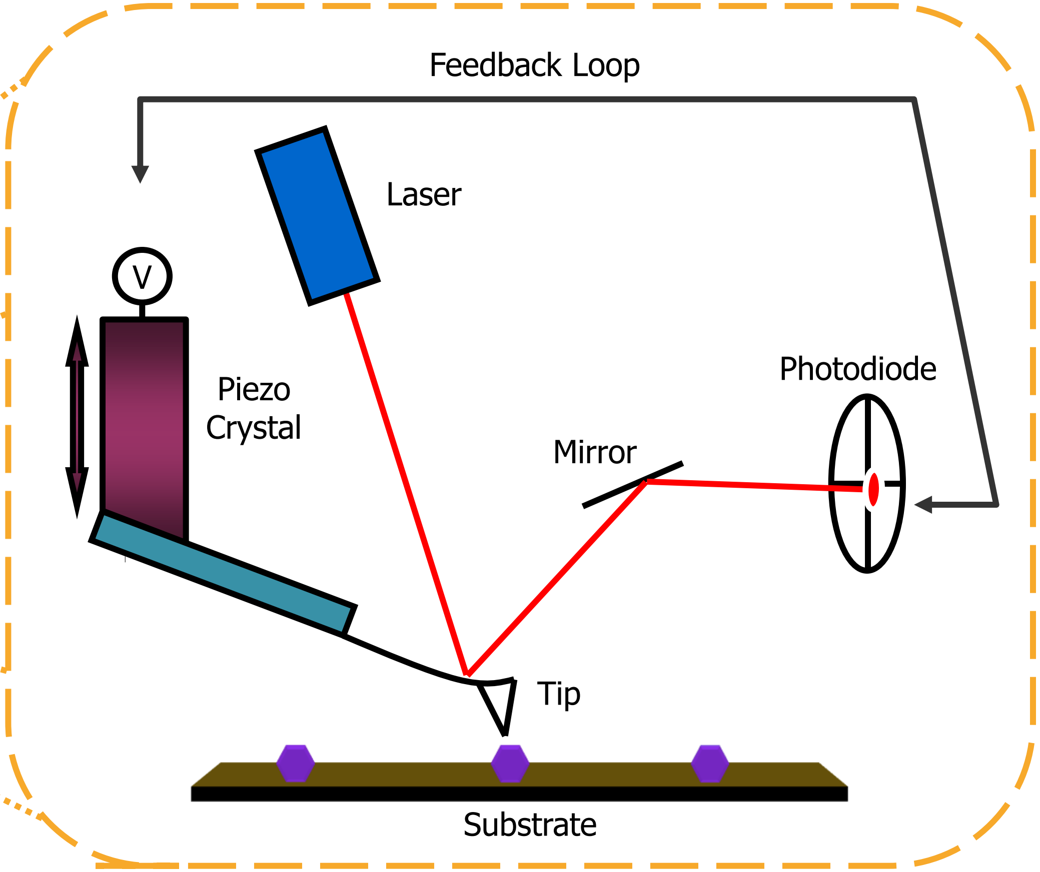
ATOMIC FORCE MICROSCOPY

~ ATOMIC FORCE MICROSCOPE ~

HOW DOES IT WORK?



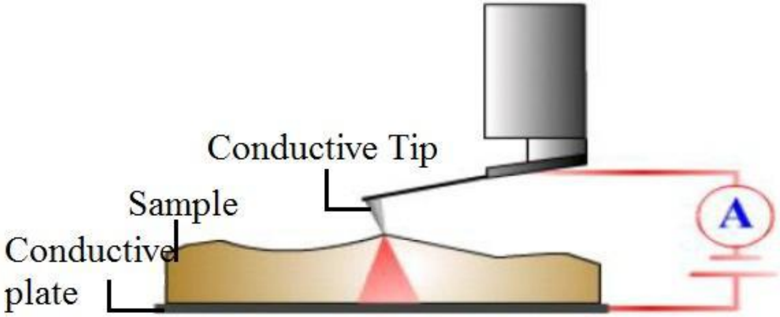
ThermoMicroscopes Explorer AFM



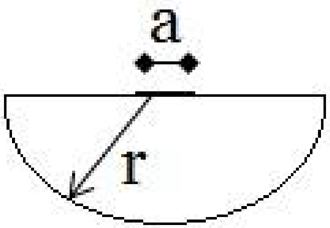
The atomic force microscope (AFM), uses a sharp tip attached to the end of a cantilever rasters across an area while a laser and photodiode are used to monitor the tip force on the surface. A feedback loop between the photodiode and the piezo crystal maintains a constant force during contact mode imaging and constant amplitude during intermittent contact mode imaging.

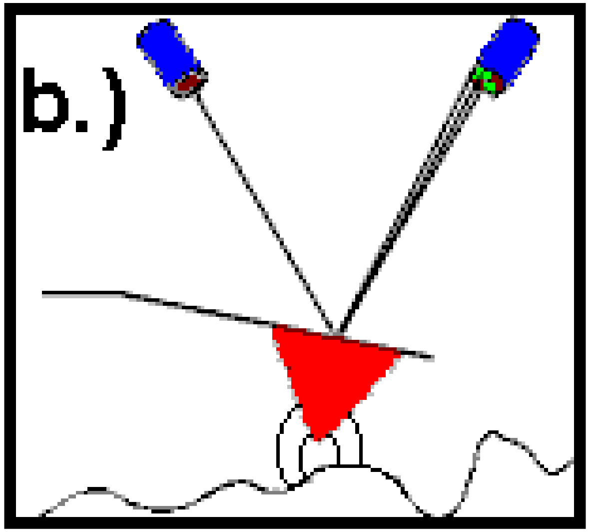
Scanning Spreading Resistance Microscopy (SSRM)

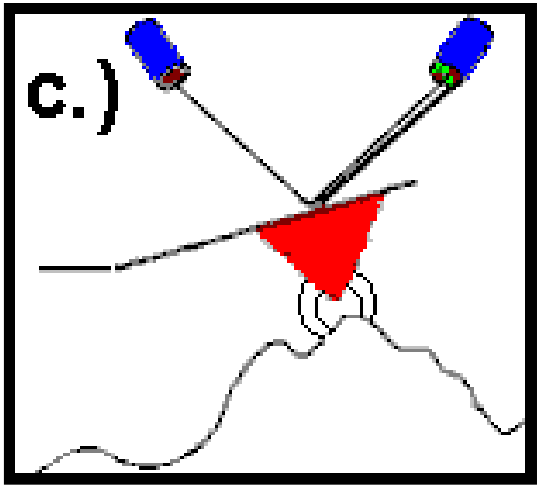
SSRM technique is implemented on a Atomic Force Microscopy (AFM) system and uses a dedicated SSRM sensor that performs the measurements of the local resistance under the tip in contact with the sample surface.



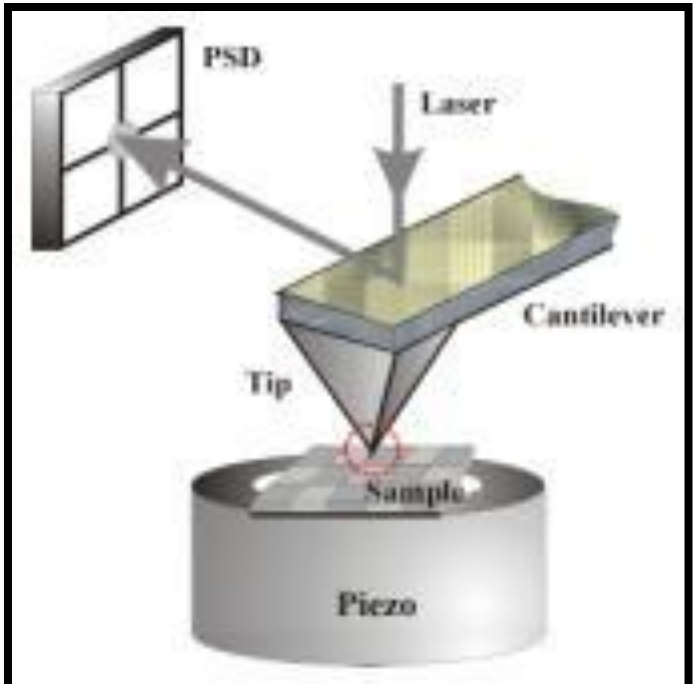
The theoretical approach to the spreading resistance can be described by a simple model consisting of a flat circular ohmic contact and a hemispherical ohmic contact







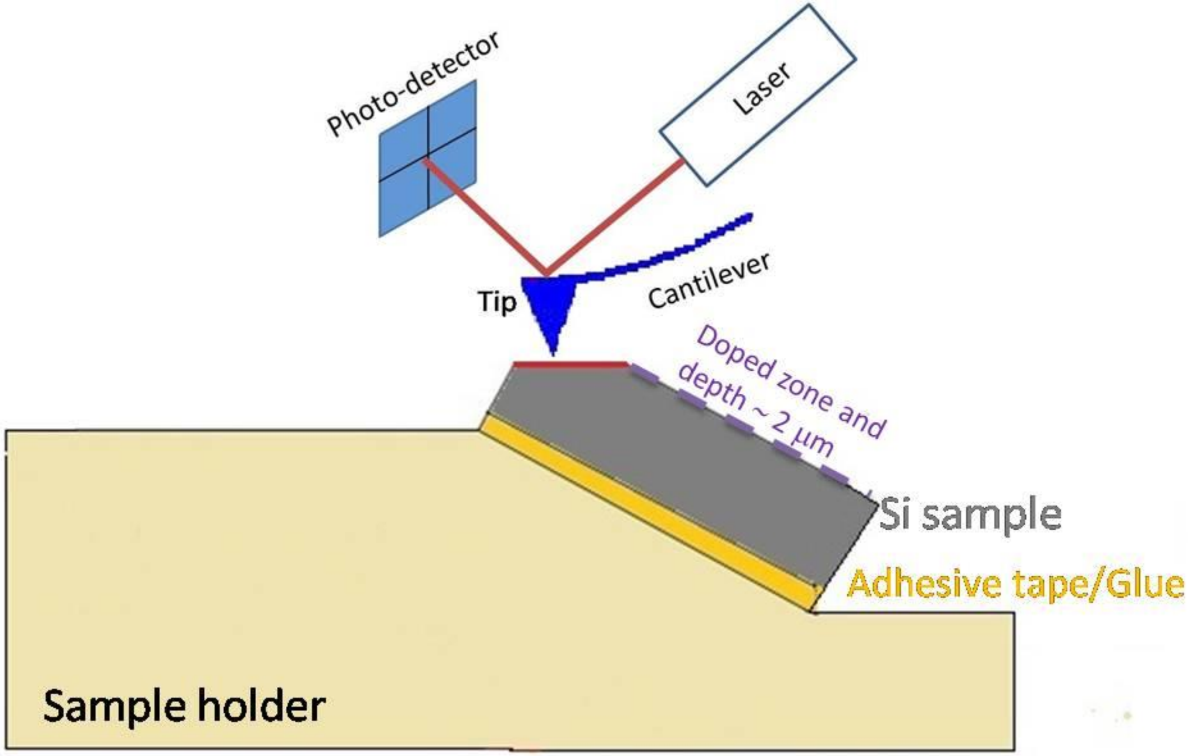
The AFM records the position of the probe by bouncing a laser off the back surface of the probe and recording how the light is deflected



By using a four quadrant detector the relative amount of laser light hitting each quadrant can be used to determine how the tip has been deflected as it moves over the surface of the specimen

SSRM measurement technique

❖During SSRM measurements, AFM can be operated:



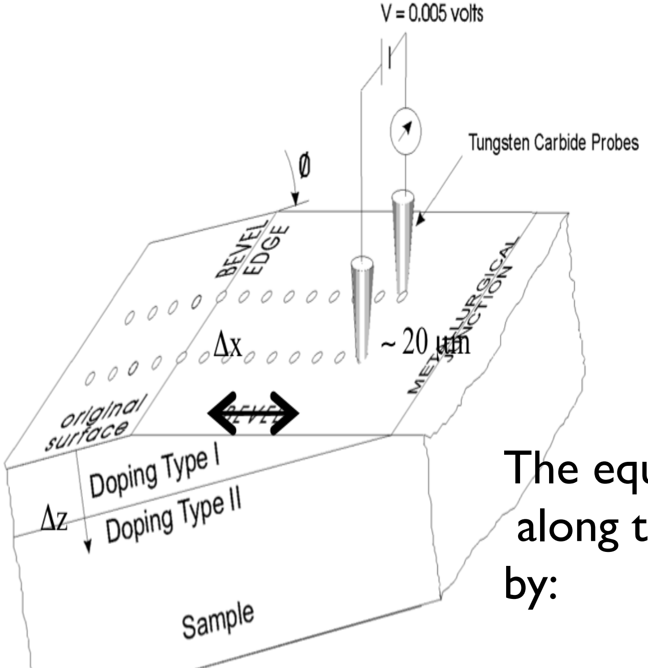
•with feedback control:
-constant force
- faithful topographical image

•without feedback control or deflection mode:
-constant height
-used for very flat samples at high resolution

A SCHEMATIC VIEW

- Illustration of spreading resistance measurment

Blocks with different bevel angles are usually available and are chosen to provide a desired resolution profiling: typically 1°-5° for junction depths of 1-2 μm and ≤0.5° for junction depths less than 0.5 μm.

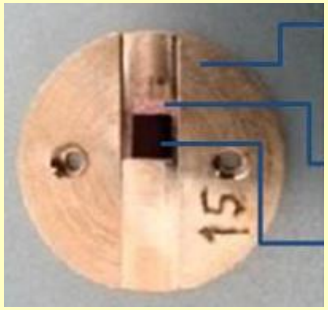


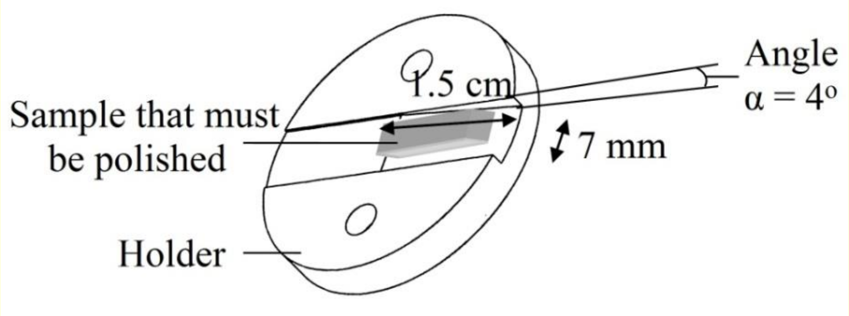
The equivalent depth, Δz, at each Δx step along the surface beveled at angle θ is given by: $\Delta z = \Delta x \sin\theta$

Measuring doping profiles of silicon detectors with a custom-designed probe station, W. Treberspurg, T. Bergauer, M. Dragicevic, J. Hrubec, M. Krammer and M. Valentan, 2012 JINST 7 P11009

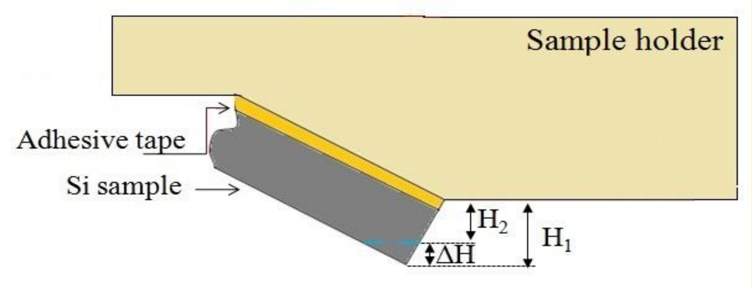
Polishing equipments for SSRM sample preparation

Holder





Support for holder



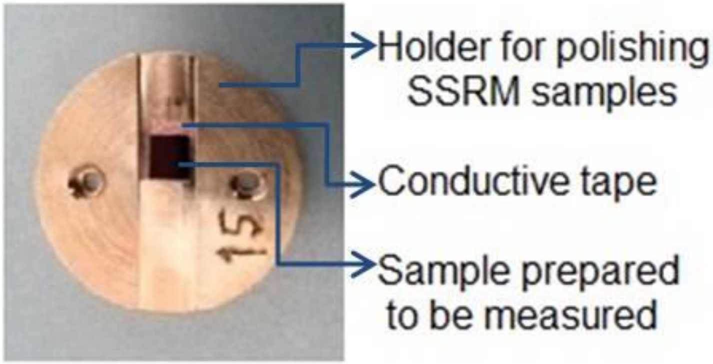
Polishing machine

Escil ESC 300 GTL :

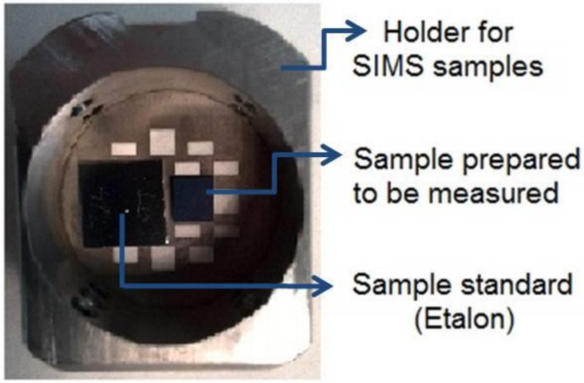
Rotating plate:
  - Φ= 300 mm
- Rotating speed:
  - 1 to 100 rppm
- Diamond paper
  - granulation: 9 to 0.1 µm

Sample preparation

- Scanning Spreading Resistance Microscopy
  - Dicing & Cleavage
  - Etching
  - Gluing
  - Polishing



- Secondary Ion Mass Spectrometry (SIMS)
  - Dicing & Cleavage
  - Etching (if necessary)



http://www.ief.u-psud.fr/?page_id=72

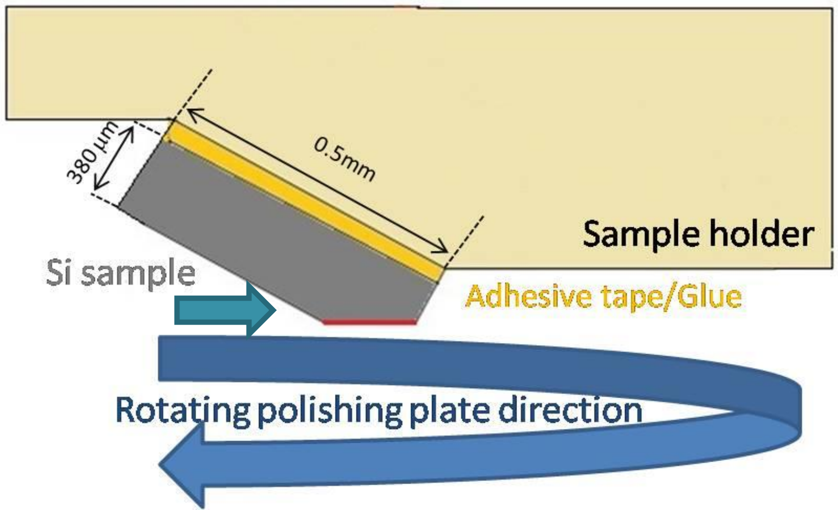
Polishing parameters

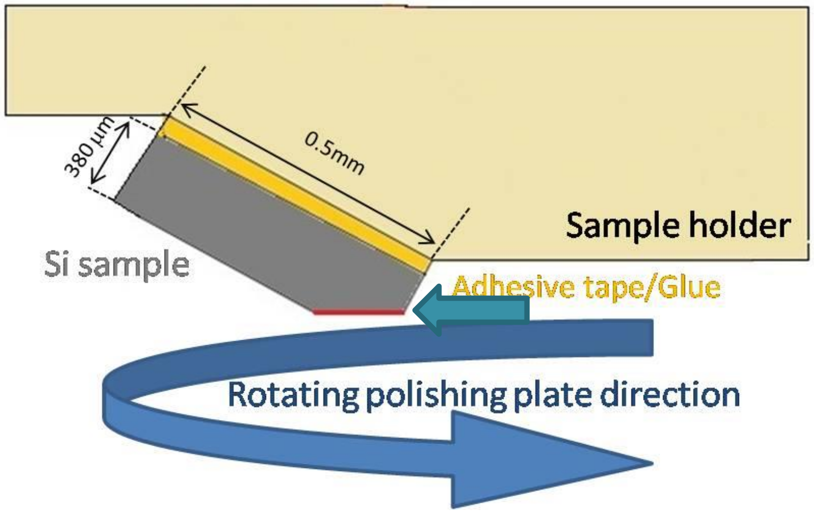
❖Primary polishing parameters

- Rotation speed
- Polishing paper
- Granulation size

❖Secondary parameters playing an important role during polishing

- Gluing: Conductive adhesive tape
  Conductive glue
- Polishing position:

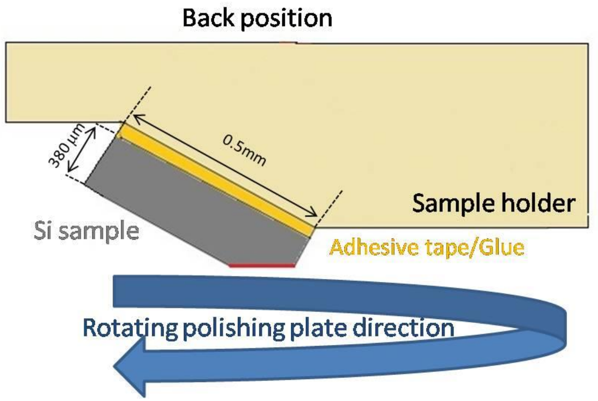

Back position

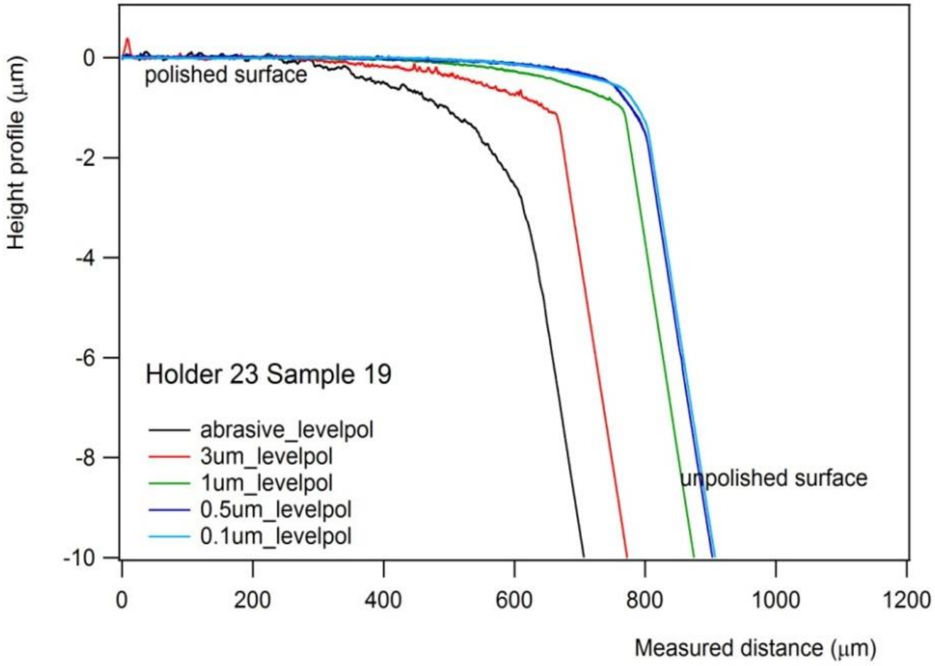

Frontal position

Compromise between safety and a sharp angle !

Topographical measurements on samples fixed with glue

Back polishing position





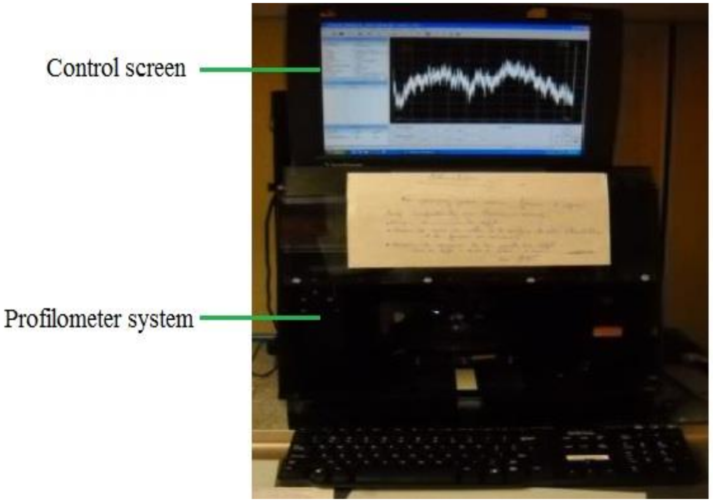
α=4.74°

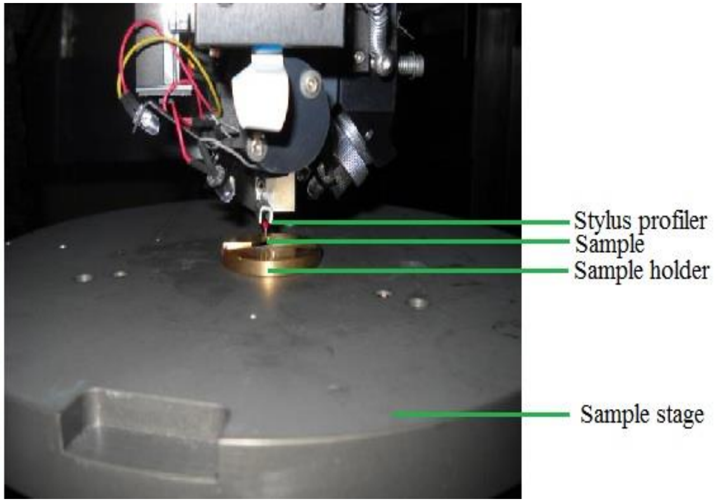
Rq=6495.3 A

Fixation with conductive glue seems to be useful.
Result of a flat polished surface

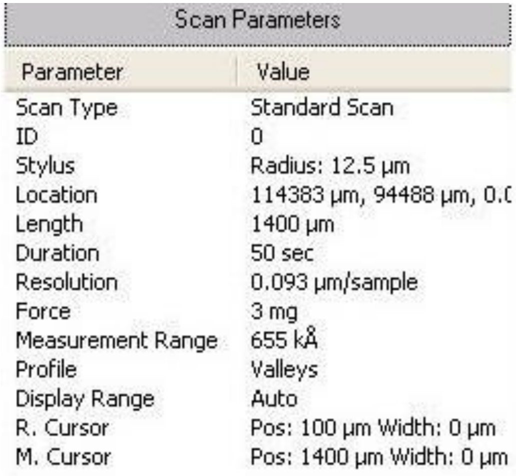
Stylus profilometer. Veeco Dektak 8

- ❖ Primary function: surface roughness, film thickness, planarity



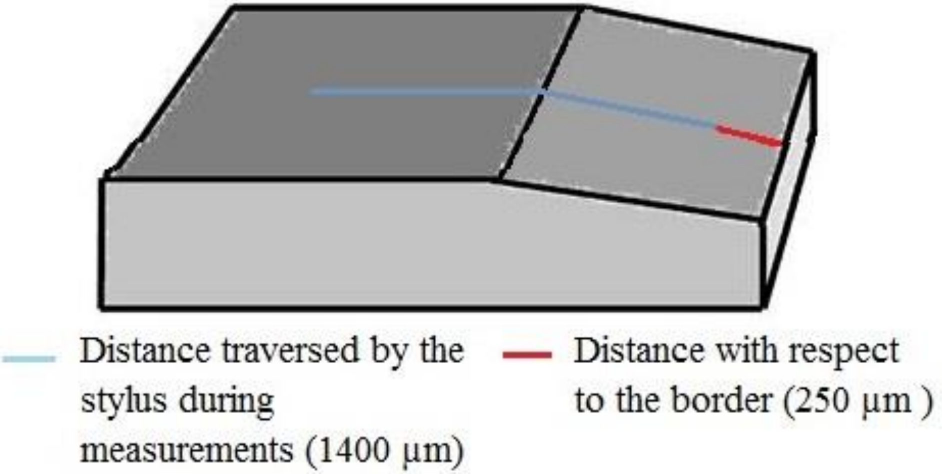


- ❖ Scan convention for comparable measurements

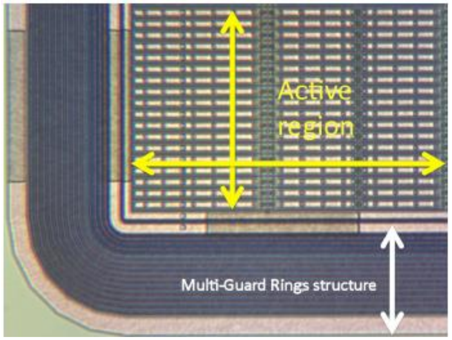


Scan Parameters

Parameter	Value
Scan Type	Standard Scan
ID	0
Stylus	Radius: 12.5 µm
Location	114383 µm, 94488 µm, 0.
Length	1400 µm
Duration	50 sec
Resolution	0.093 µm/sample
Force	3 mg
Measurement Range	655 kÅ
Profile	Valleys
Display Range	Auto
R. Cursor	Pos: 100 µm Width: 0 µm
M. Cursor	Pos: 1400 µm Width: 0 µm



TCAD simulations

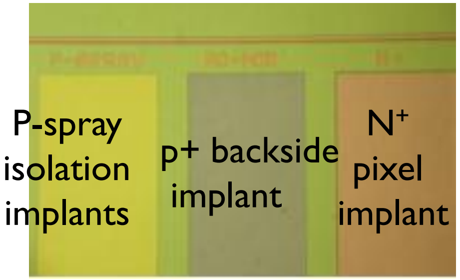


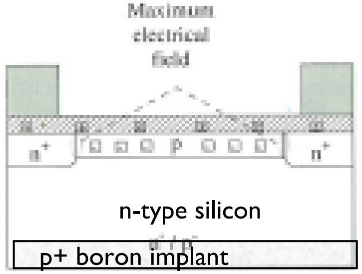
Input parameters for TCAD tool:

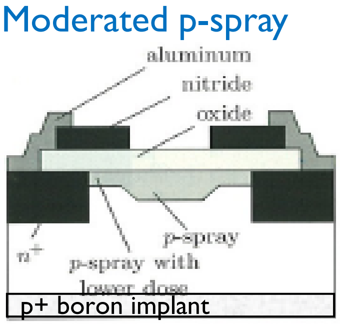
- Doping concentration and junction depth
  - Pixels, inter-pixels isolation, Guard Rings, backside
- GR's - number, width, gap size, metal overhang width

Experimental measurements required for TCAD calibration:

- SIMS & SRP measurements on test-structures inserted in the mask design
  - Doping concentration and junction depth




Homogeneous p-spray


Moderated p-spray

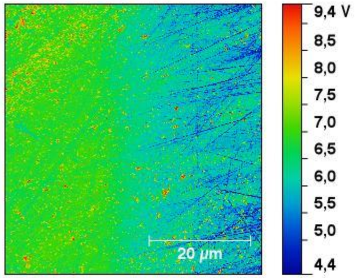
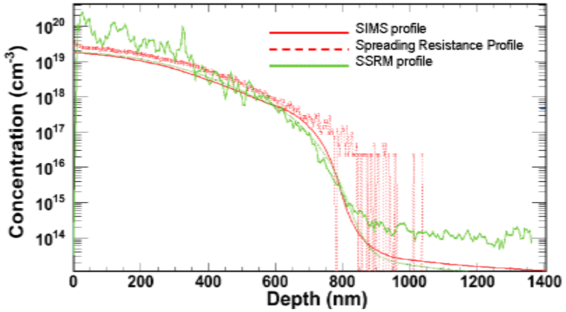


Fig 1: (left) SSRM - (x,y) imaging on beveled zone (3,8°)

Fig 2 : (right) absolute dopant profiles by 3 methods : SIMS, SRP, SSRM

Measurements performed on ATLAS planar pixel sensors (dopage n+)



SSRM

To allow a calibration of the SSRM method, wafers with different implantation conditions have been ordered by LAL group to two pixels producers:

1. CiS company (Erfurt, Germany)
   - **n-type wafers (4”) of low (0.25 Ω·cm) and high (>4 kΩ·cm) resistivities**; each wafer has been processed in a given condition of initial thermal oxide screen, phosphorus implantation dose and energy, annealing as presented in the Tables 1a and b.
2. Advacam company (Erfurt, Germany) spin-off company of VTT (Technical Research Center of Finland).
   - **p-type wafers (6”) of low (2 Ω·cm) and high (>10 kΩ·cm) resistivities**; each wafer has been processed in a given condition of initial oxide screen, phosphorus implantation dose and energy, annealing as presented in the Tables 2a and b.

14 Wafers	Cz, p-type substrate/ n-type implantation (phosphorus); $\rho=2\ \Omega\cdot cm$ ($7\cdot 10^{15}\ cm^{-3}$); <100>; 675 μm thickness															
Oxide thickness (nm)	100								200							
Phosphorus implantation doses (cm^{-2})	10^{13}		10^{14}		10^{15}		10^{16}		10^{13}		10^{14}		10^{15}		10^{16}	
Implantation energies (keV)	130	240	130	240	130	240	130	240	130	240	130	240	130	240	130	240
Annealing	1000°C; ambient annealing/1h; wet oxidation H_2O/1h; dry oxidation O_2/1h															

Table 2a. Advacam low resistiviy wafers

14 Wafers	Fz, p-type substrate/ n-type implantation (phosphorus); $\rho> 10\ k\Omega\cdot cm$ ($<1.3\cdot 10^{12}\ cm^{-3}$); <100>; 525 μm thickness															
Oxide thickness (nm)	100								200							
Phosphorus implantation doses (cm^{-2})	10^{13}		10^{14}		10^{15}		10^{16}		10^{13}		10^{14}		10^{15}		10^{16}	
Implantation energies (keV)	130	240	130	240	130	240	130	240	130	240	130	240	130	240	130	240
Annealing	1000°C; ambient annealing/1h; wet oxidation H_2O/1h; dry oxidation O_2/1h															

Table 2b. Advacam high resistiviy wafers

Issues to study

Due to radiation induced lattice defects a variety of additional energy levels inside the band gap is induced, which leads to degradations in sensor performance. At a depleted sensor those defects act as generation and trapping centres inside the Space Charge Region (SCR). But also the properties of the non depleted sensor, in other words of the Electrical Neutral Bulk (ENB) material crucially change. Inside the homogeneously doped bulk and the non homogeneously doped backside donor removal effects result in an increased material resistivity ρ.

Hence also the profiles of electrically active dopants are modified.

Our measurements are meant to investigate the homogeneous distributed bulk material resistivity . And also

- How heavy irradiations affect the electrical (active) dopant profiles ?

Ref : Backside doping profiles of irradiated silicon detectors

- **W. Treberspurg, 1 T. Bergauer, M. Dragicevic, M. Krammer and M. Valentan** *Institute of High Energy Physics, Austrian Academy of Sciences, Nikolsdorfer Gasse 18, 1050 Wien (Vienna), Austria , JINST Published by IOP Sissa , Medialab, 19/04/2013*

Conclusions

- These methodes have been used (and will be used) to feed our simulators with precise input parameters for the conception and understanding of innovative designs (edgless PlanarPixel Sensors, LGAD…)
- We (hope) to learn how irradiations affect the active doping profiles, electric fied shape near the implants, at the borders, in the amplifying zone …(electric field shape, critical zones…)
- This work needs a lot of work preparation (for SSR: bevels…) and manpower investiments is rather important
- A good partneships with CNRS institutions (for both U. versailles, IEF orsay) and get certainly a good return on investment.
- A good opportunity to join us in this effort to share this project (sample productions, knowledge, expertise, cost production,…PHD students or postdoc are welcome to participate..)

Welcome to new partners

Cost issues:

- SAMPLES (if @VTT, @Cis or @CNM) : xxxxx €

Common wafer production (ATLAS)

- Irradiations 3500€
- SIMS (U.Versailles) : 500€/day (## 10days)== 5000 €
- SPR ## 3500 €
- AFM #### 2000 €,

Total ## 14000€

Thank you

Type: Uniformly doped samples with an estimated doping depth of 5-7µm. A 100nm oxide layer is present in all samples, used for screening during implantation. In the VTT samples, an additional oxidation further expands this layer to 500-600nm.

Size: 5mm x 5mm

Implanted Dose	Screen Oxide	Energy	Sample Type	Substrate type	Manufacture	Resistivity
10^{14}/cm^2	100nm	130keV	n in n (Phosphorus)	525µm – Fz Si	CiS	4kΩ/cm
10^{14}/cm^2	100nm	240keV	n in n (Phosphorus)	525µm – Fz Si	CiS	4kΩ/cm
10^{15}/cm^2	100nm	130keV	n in n (Phosphorus)	525µm – Fz Si	CiS	4kΩ/cm
10^{15}/cm^2	100nm	240keV	n in n (Phosphorus)	525µm – Fz Si	CiS	4kΩ/cm
10^{14}/cm^2	100nm	130keV	n in n (Phosphorus)	380µm – Cz Si	CiS	0.25kΩ/cm
10^{14}/cm^2	100nm	240keV	n in n (Phosphorus)	380µm – Cz Si	CiS	0.25kΩ/cm
10^{15}/cm^2	100nm	130keV	n in n (Phosphorus)	380µm – Cz Si	CiS	0.25kΩ/cm
10^{15}/cm^2	100nm	240keV	n in n (Phosphorus)	380µm – Cz Si	CiS	0.25kΩ/cm
10^{14}/cm^2	500nm	130keV	n in p (Phosphorus)	525µm – Fz Si	VTT	10kΩ/cm
10^{14}/cm^2	500nm	240keV	n in p (Phosphorus)	525µm – Fz Si	VTT	10kΩ/cm
10^{15}/cm^2	500nm	130keV	n in p (Phosphorus)	525µm – Fz Si	VTT	10kΩ/cm
10^{15}/cm^2	500nm	240keV	n in p (Phosphorus)	525µm – Fz Si	VTT	10kΩ/cm
10^{14}/cm^2	500nm	130keV	n in p (Phosphorus)	675µm – Cz Si	VTT	2Ω/cm
10^{14}/cm^2	500nm	240keV	n in p (Phosphorus)	675µm – Cz Si	VTT	2Ω/cm
10^{15}/cm^2	500nm	130keV	n in p (Phosphorus)	675µm – Cz Si	VTT	2Ω/cm
10^{15}/cm^2	500nm	240keV	n in p (Phosphorus)	675µm – Cz Si	VTT	2Ω/cm

The Quotation:

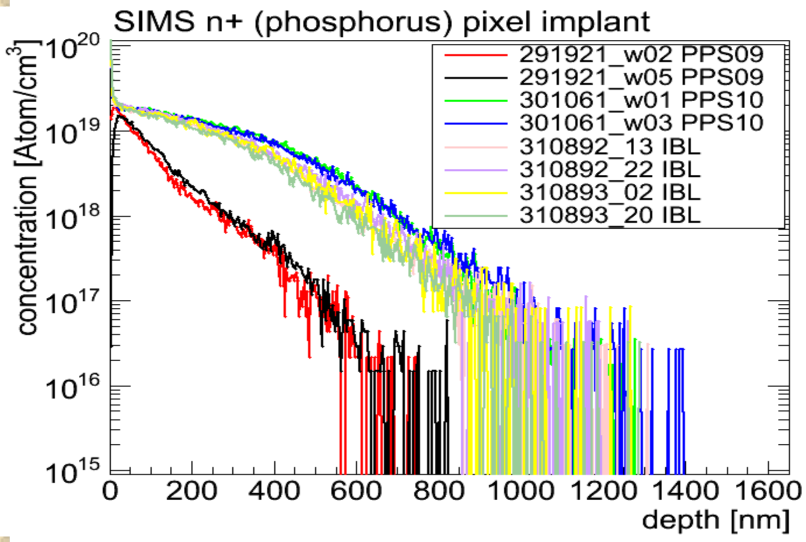
The srp profiles will require 1 unit/profile @ cost of €250/unit.
Total cost for the sixteen srp profiles will be €4000 less a 10% volume discount = €3600.

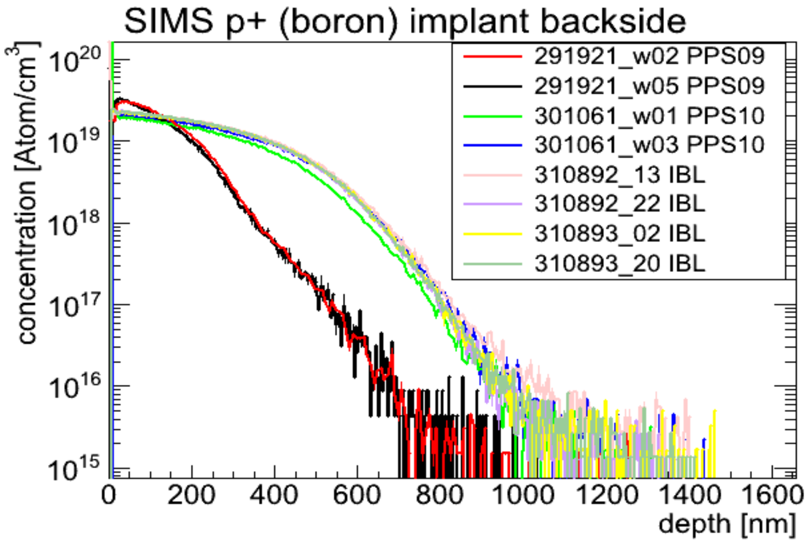
Cost for return shipping of samples = €50

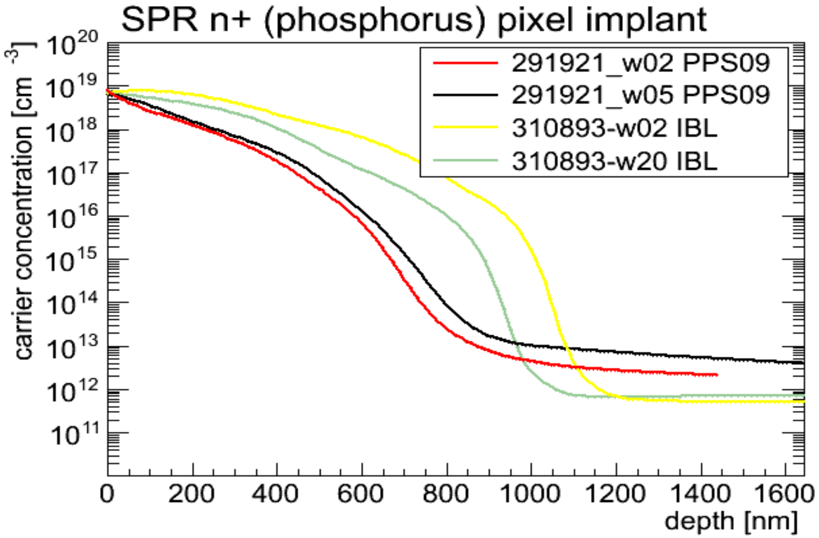
Total cost for analysis + return shipping = €3650

Doping profiles of ATLAS n-in-n PPS (1)

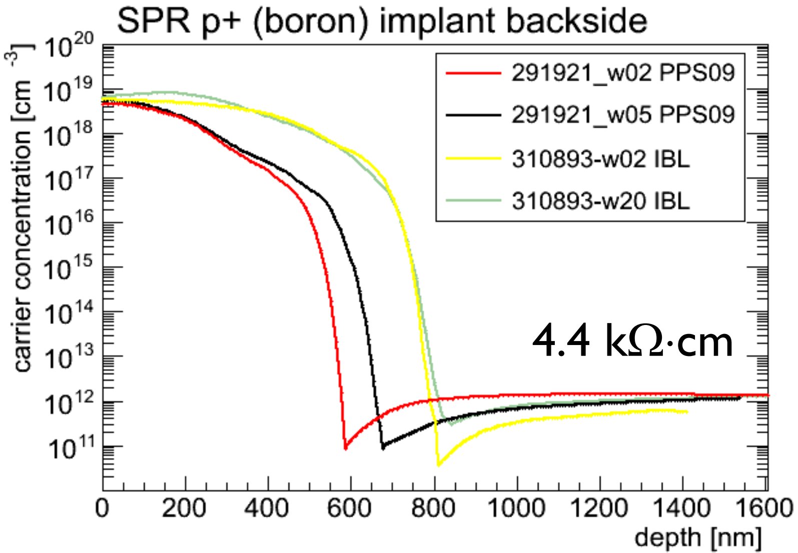
SIMS measurements: collaboration with GEMaC laboratory, CNRS







SRP measurements: EAG lab, Ireland



IBL samples have been fabricated in different technological conditions with respect to PPS09 samples:

- *longer annealing time*