Active doping profile using Transmission Line Matrix method

A. Lounis*, E. Gkougkoussis[1], T. Rashid**, S. Zacharias***
Jean Luc Perrossier[2], J.R coudeyville[2], C. Villebasse[2],

Basics of TLM

The methodology

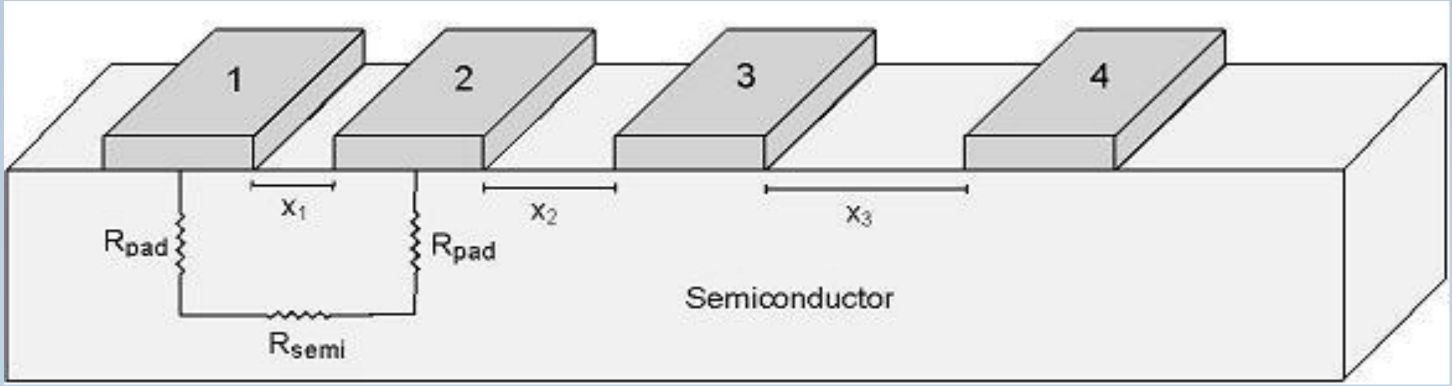
Results of doping profile

Conclusions

* Université de Paris-Sud XI, Laboratoire de l'Accélérateur Linéaire
** Phd student Université de Paris-sud XI, Orsay
*** Master 1 Student, Université de Paris Sud XI-Orsay
[1] CNM Barcelona
[2] Institut Electronique Fondamentale, Orsay

What is the TLM method?

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



$$R = \rho \frac{L}{A} \longrightarrow \rho = \frac{1}{e N_D \mu_e} \longrightarrow N_D$$

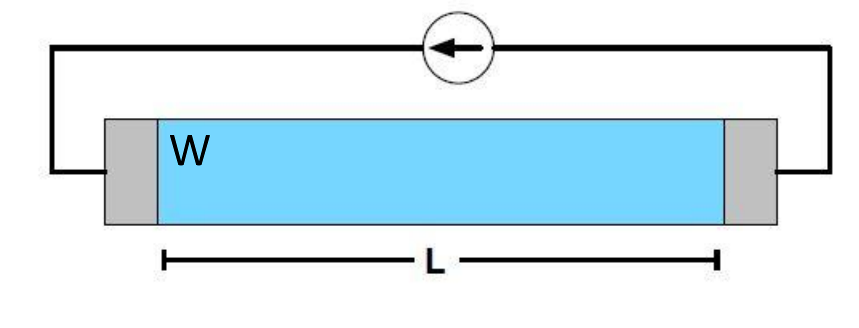
Doping profile measurement

This method consists in :

- Measuring sheet resistances by TLM
- Perform incremental depth steps in the implanted zone
- Use Reactive Ionic etching

The Method

In measuring resistance with the four point probe or Van der Pauw methods, Four contacts are used (2 for I, 2 for V) to determine the sheet resistance of a layer while minimizing effects of contact resistance.



Two contacts are located at the ends of the bar and each has a contact area Ac.
The measured total resistance consists of several components:

$$R_T = 2R_m + 2R_c + R_{semi}$$

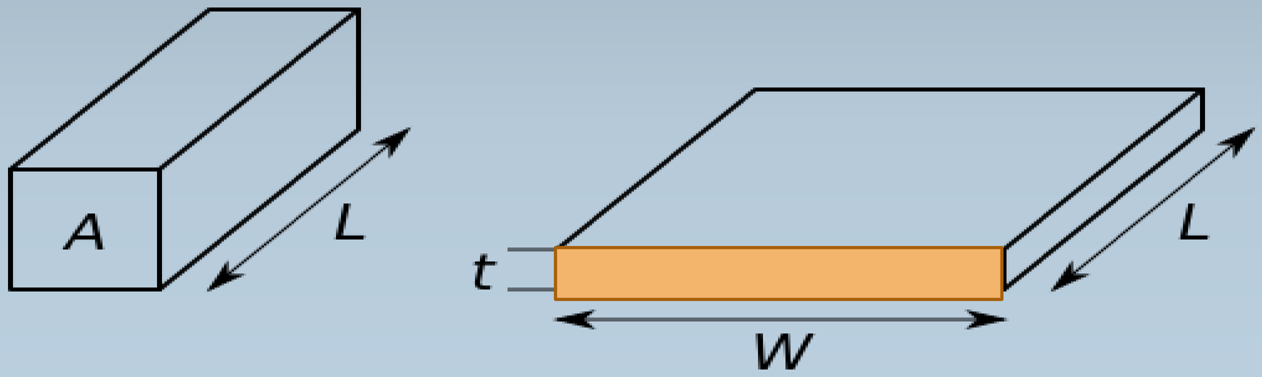
R_m is the contact resistance, R_C is the metal/Semiconductor, R_{semi} is the semiconductor Resistance; $R_m << R_c$

The semi conductor resistance is explained as: $R_T = 2R_c + R_{semi}$

Sheet resistance of the semiconductor

In regular 3D resistance (current along the L arrow), the resistance :

$$R = \rho \frac{L}{A} = \rho \frac{L}{Wt},$$



where ρ is the resistivity, **A** is the cross-sectional area, and **L** is the length. The cross-sectional area can be split into the width **w** and the sheet thickness **t** . We can this write the resistance as :

$$R = \frac{\rho}{t} \frac{L}{W} = R_s \frac{L}{W},$$

where $\mathbf{R_s}$ is the sheet resistance. If the film thickness **t** is known, the bulk Resistivity ρ (in Ohm·cm) can be calculated by multiplying the sheet resistance by the film thickness in cm:

$$\rho = R_s \cdot t.$$

Sheet resistance

For semiconductors doped through diffusion or surface peaked ion implantation we define the sheet resistance using the average resistivity of the material:

$$R_s = \overline{\rho}/x_j = (\overline{\sigma} x_j)^{-1} = \frac{1}{\int_0^{x_j} \sigma(x)\,dx},$$

which in materials with majority-carrier properties can be approximated by:

$$R_s = \frac{1}{\int_0^{x_j} \mu q N(x)\,dx},$$

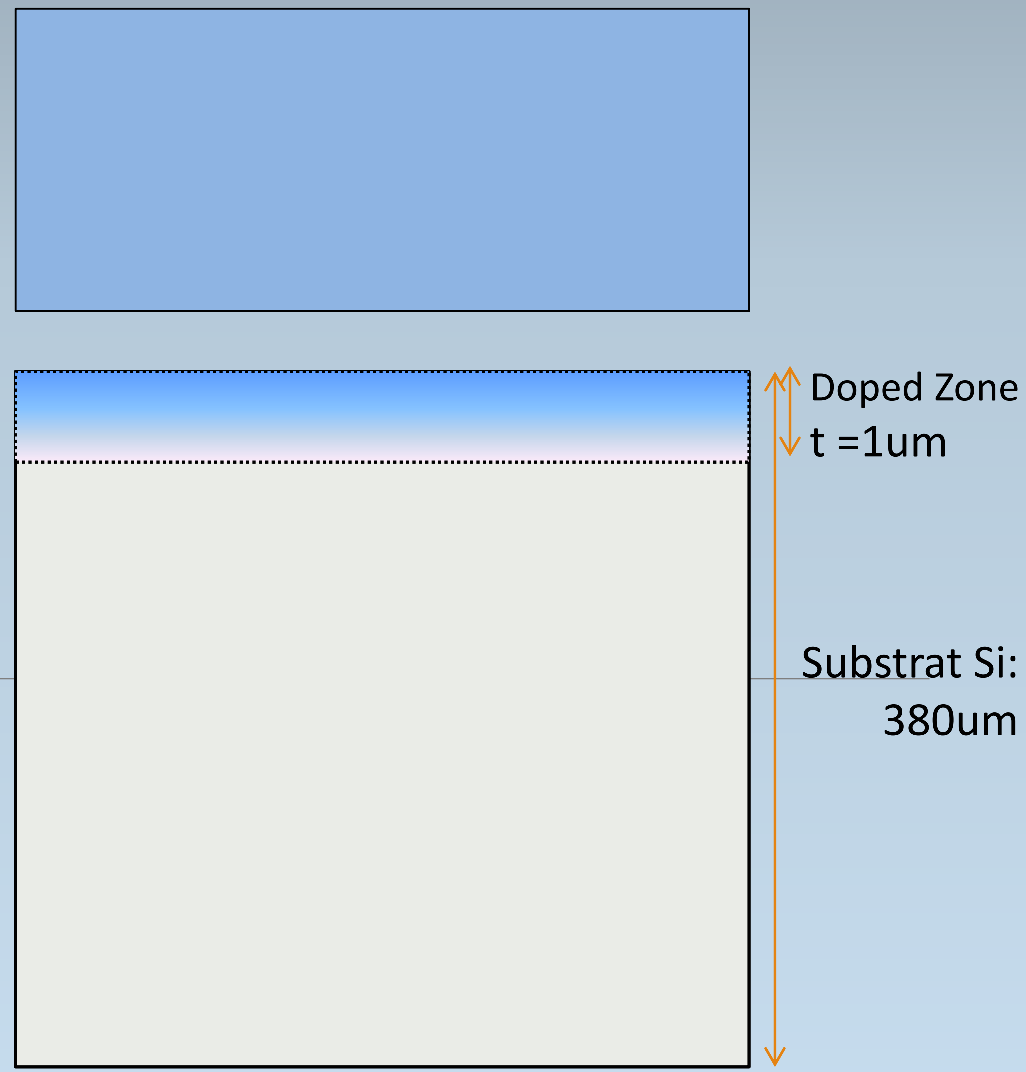
Where x_j is the junction depth, μ is the majority-carrier mobility, q is the carrier charge, and N(x) is the net impurity concentration.

Implanted sample

Sample before implantation

- **Implanted sample**
- Photoresist coating
- Photoresist opening
- Wet etching
- Al deposition
- Al Lift Off
- Profile measurement
- I-V measurement
- Reactive Ion Etching

n times



n >= t / 200nm

Time ≥ n x 7 mn

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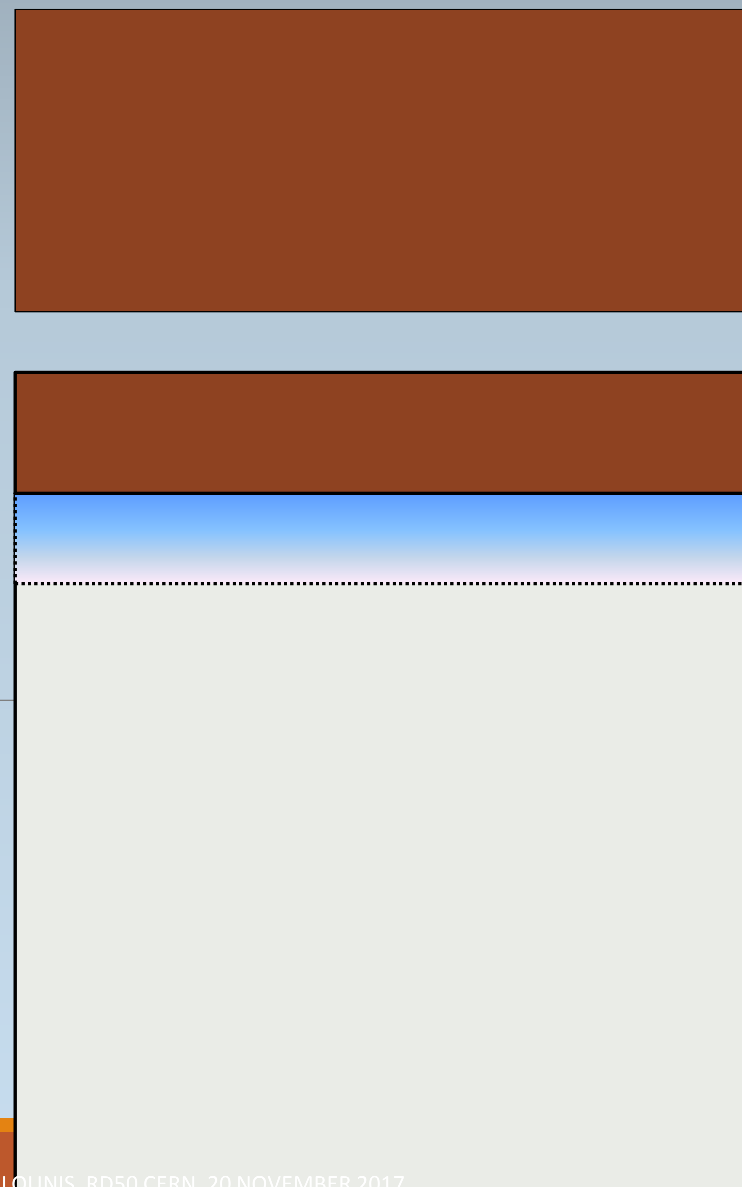
Photoresist coating/coating resin

S1813 / 4000 rpm / 30s

- Implanted sample
- **Photoresist coating**
- photoresist opening
- Wet etching
- Al deposition
- Al Lift Off
- Profile measurement
- I-V measurement
- Reactive Ion Etching

n fois



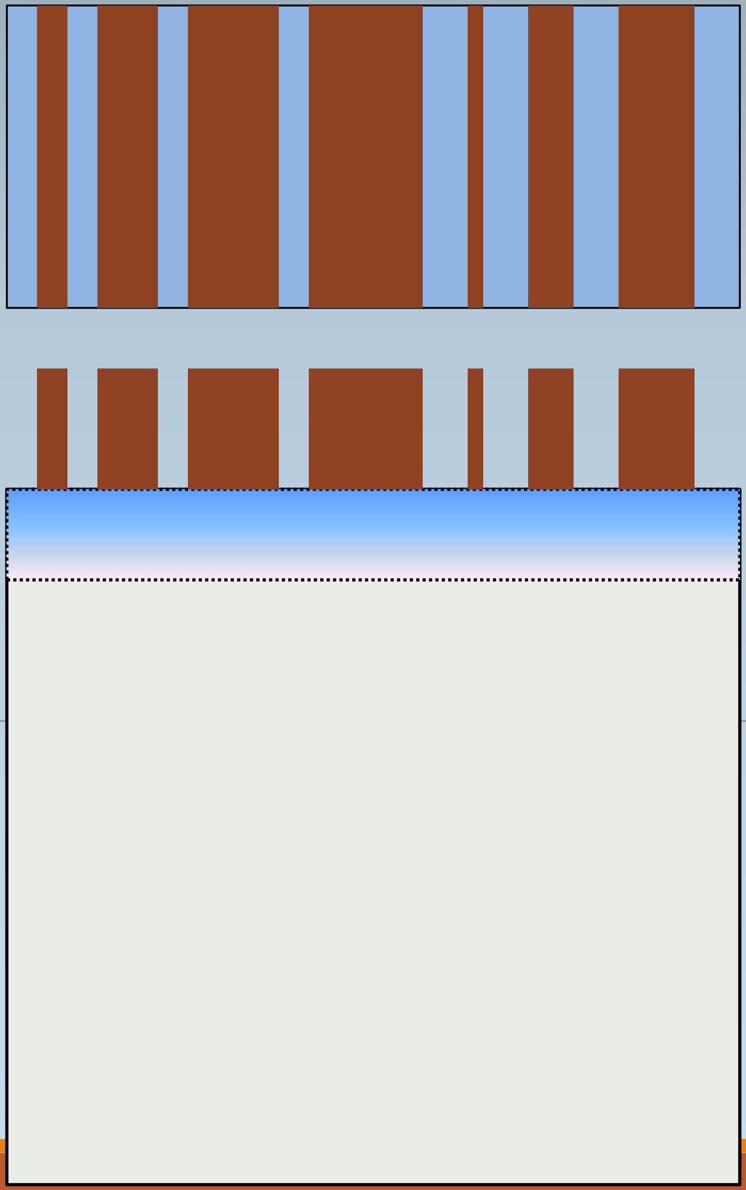
n >= t / 200nm

Time ≥ n x 7 mn

Photoresist opening

- •Implanted sample
- •Photoresist coating
- •**photoresist opening**
- •Wet etching
- •Al deposition
- •Al Lift Off
- •Profile measurement
- •I-V measurement
- •Reactive Ion Etching

} n fois



n >= t / 200nm

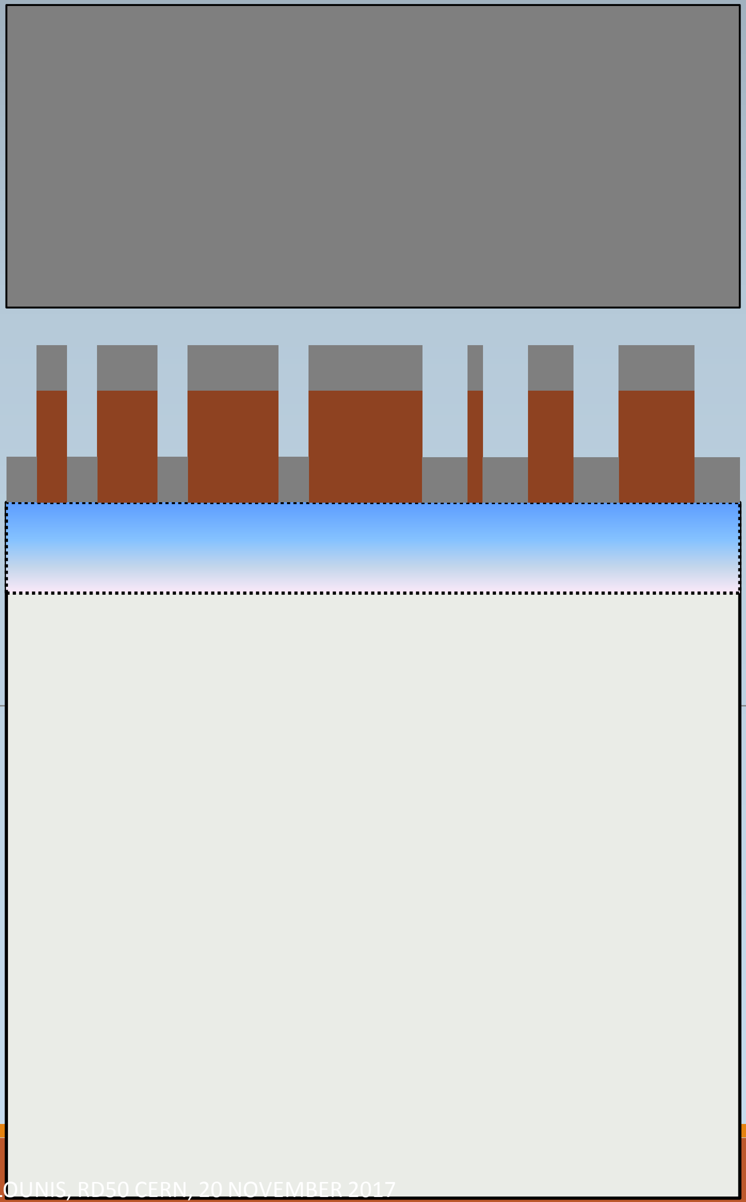
Time ≥ n x 7 mn

Aluminium deposition : 300nm , Plassys

(immediatly after cleaning and wet etching BHF 30-60s)

- Implanted sample
- Photoresist coating
- photoresist opening
- Wet etching
- **Al deposition**
- Al Lift Off
- Profile measurement
- I-V measurement
- Reactive Ion Etching

N times



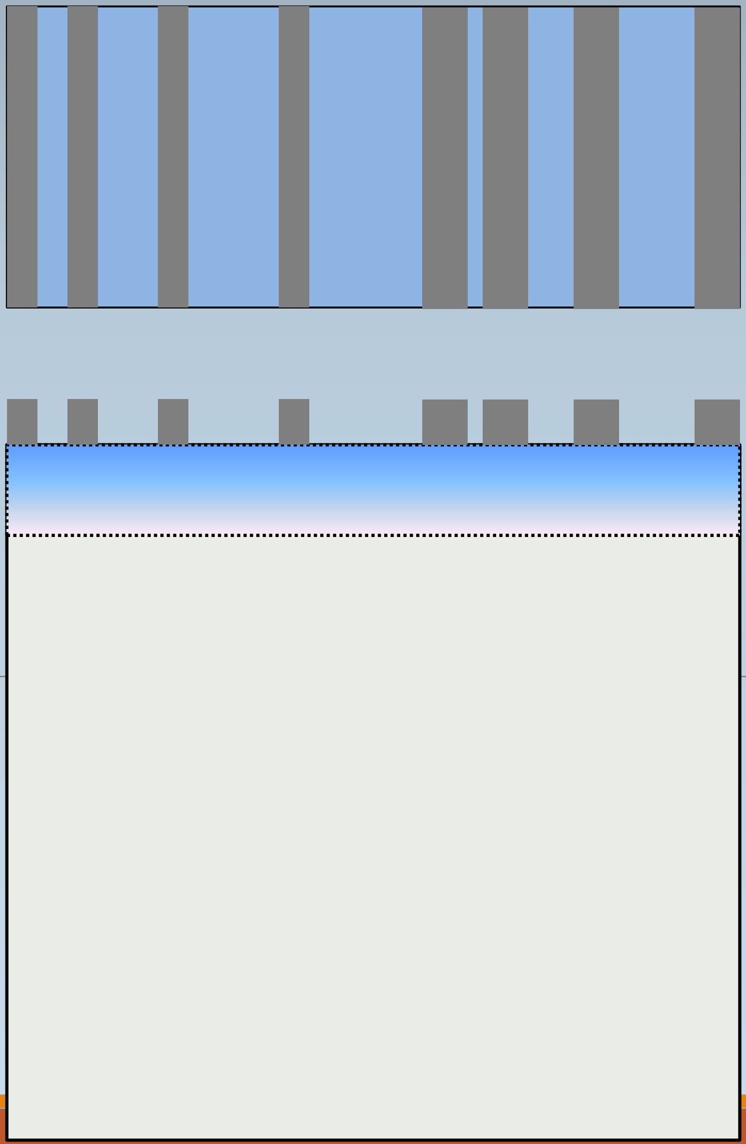
n >= t / 200nm

Time ≥ n x 7 mn

Aluminium Lift Off

- Implanted sample
- Photoresist coating
- photoresist opening
- Wet etching
- Al deposition
- **Al Lift Off**
- Profile measurement
- I-V measurement
- Reactive Ion Etching

n times



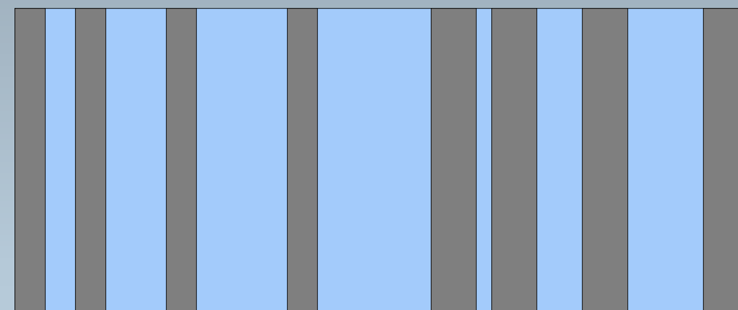
n >= t / 200nm

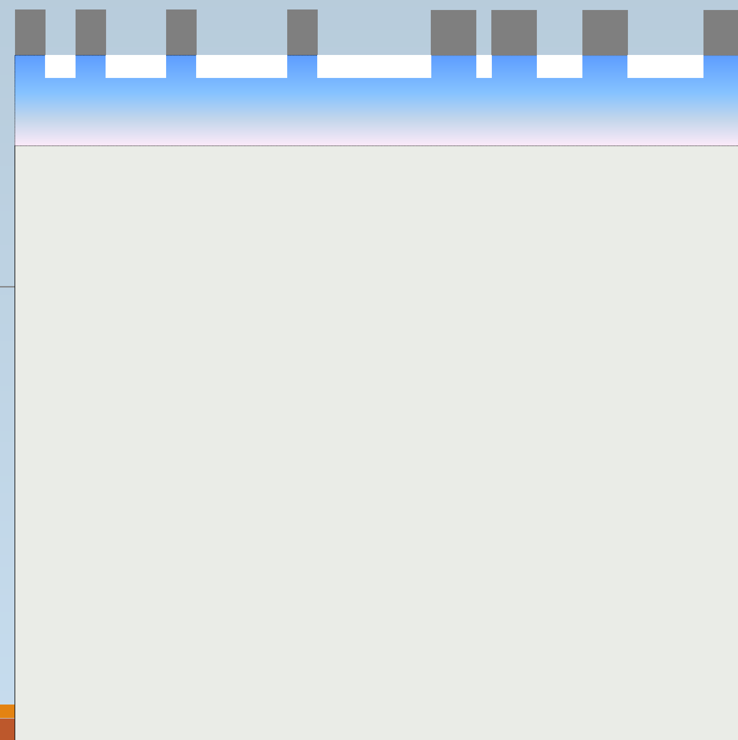
Time ≥ n x 7 mn

Engraving Zone Si* doped

- Implanted sample
- Photoresist coating
- photoresist opening
- Wet etching
- Al deposition
- Al Lift Off
- Profile measurement
- I-V measurement
- **Reactive Ion Etching**

n times





*gravure RIE J-R. Coudevylle/X. Le Roux

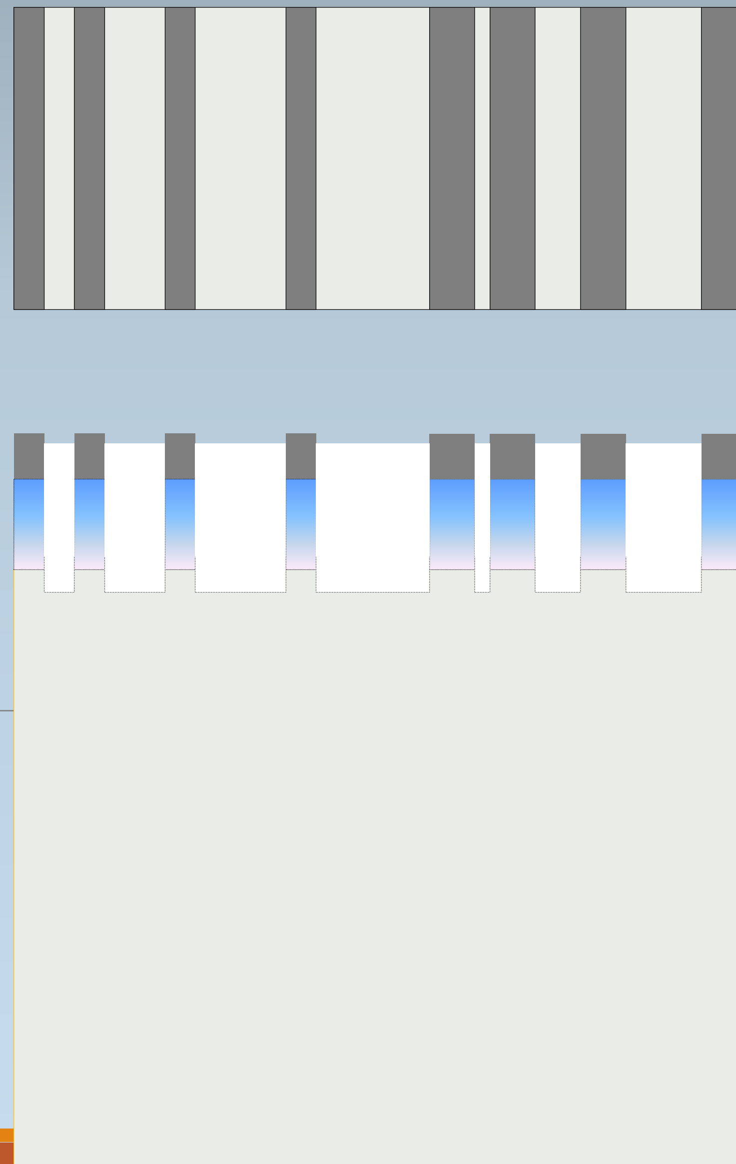
n >= t / 200nm

Time ≥ n x 7 mn

Engraving of Si*

- Implanted sample
- Photoresist coating
- photoresist opening
- Wet etching
- Al deposition
- Al Lift Off
- Profile measurement
- I-V measurement
- **Reactive Ion Etching**

n times



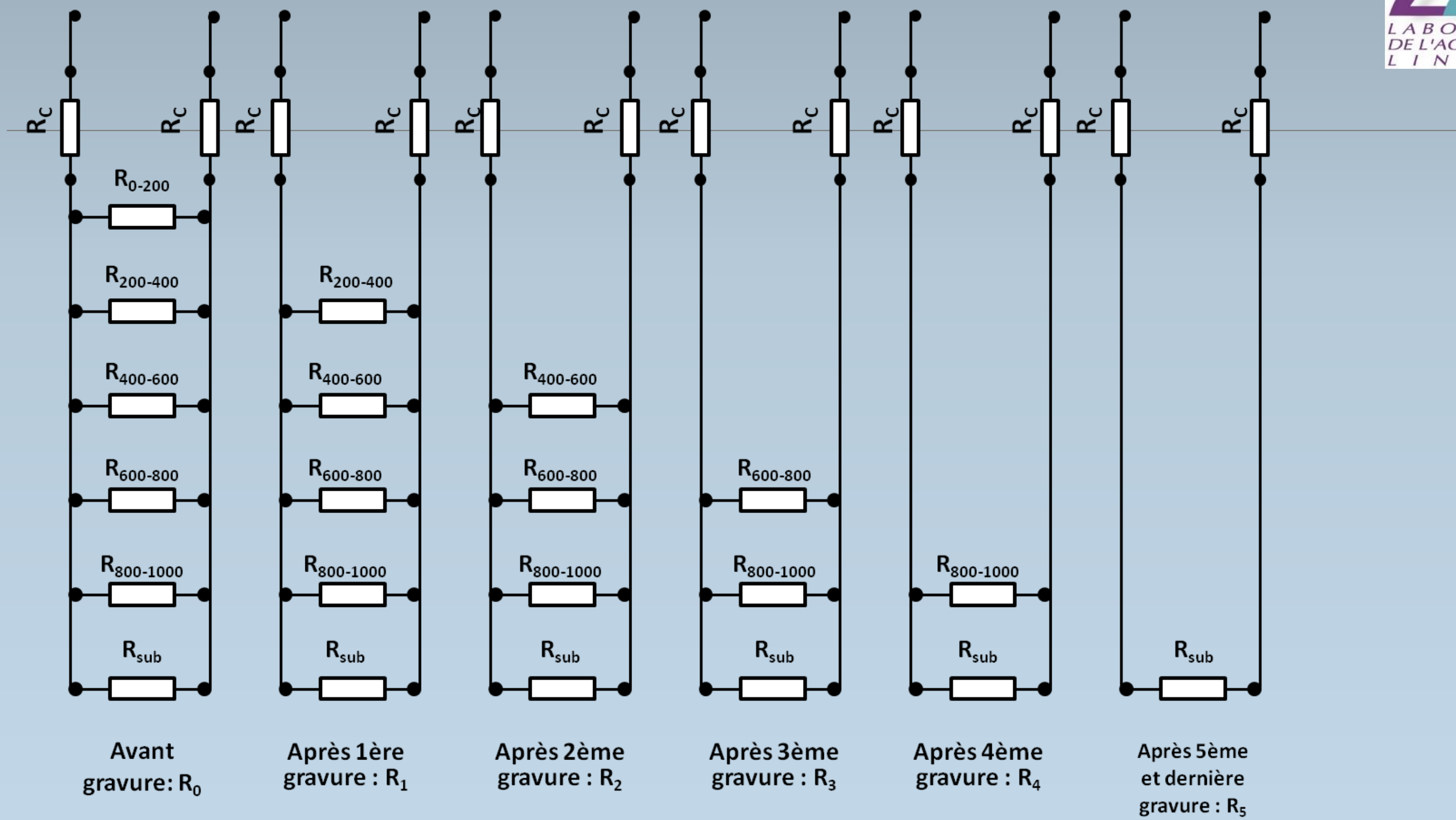
*Etching RIE

Thanks of
J-R. Coudevylle/X. Le Roux

n >= t / 200nm
Time ≥ n x 7 mn

Resistance in-depth measurement (TLM method)
in trenches obtained by Reactive Ion Etching

$$R = 2\,R_c + R_l = 2\,R_c + \rho_l \frac{L}{t_l\,W}$$



$$\rho_{sub} = (R_5 - 2\,R_c)\,\frac{t_{sub}\,W}{L}$$

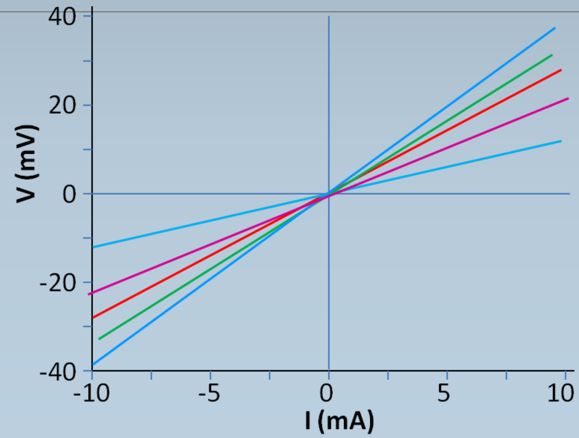
Example : etching steps of 200 nm in a sample with an implanted depth of 1µm

$$\rho_{800-1000} = \frac{(R_4 - 2R_C)\,R_{sub}}{R_{sub} - (R_4 - 2R_C)}\,\frac{W}{L}\,200$$

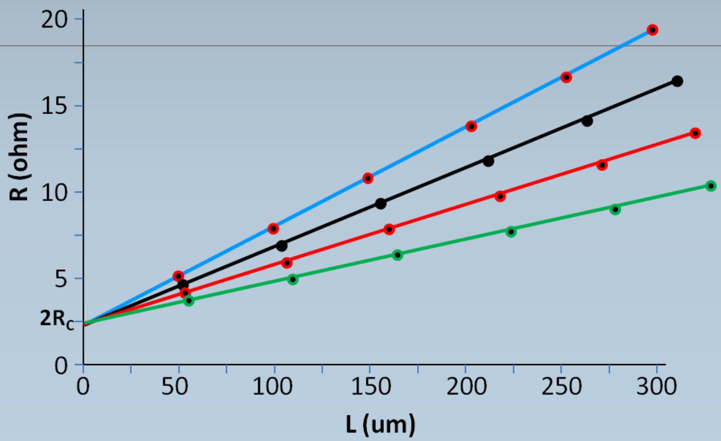
….etc..

TLM method

I-V measurements
at one depth
for different lengths



R=f(L) at various depths



$$R = V/I$$

$$R = 2\,R_c + R_l = 2\,R_c + \rho_l \frac{L}{t_l\,W}$$

R_c : ohmic contact resistance of aluminium/silicon surface
R_l : resistance of the layer between 2 contacts separeted by a distance of l

TLM samples geometry & layout

Four wafers with special geometry have been produced in CNM, with both Phosphorus and Boron implantation:

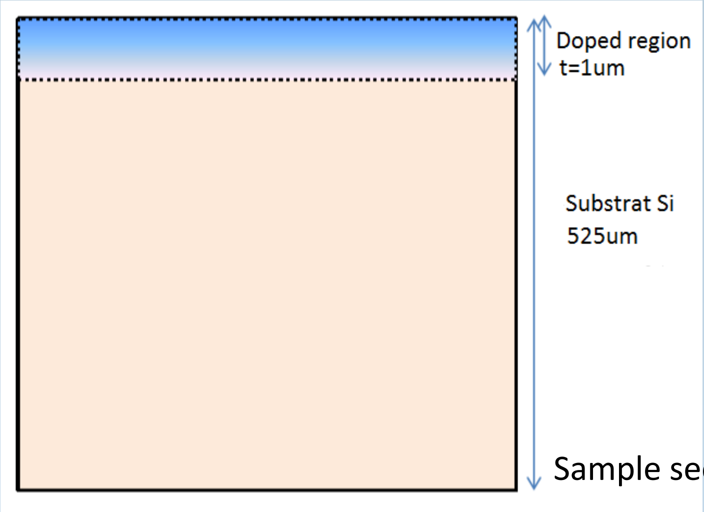
Wafer #	Implantation Ion	Implantation Dose	Expected Peak Concentration
Wafer 1	Phosphorus	1e14 atom/cm^2	1.5e18 atom/cm^3
Wafer 2	Phosphorus	1e15 atom/cm^2	1.5e19 atom/cm^3
Wafer 3	Boron	1e14 atom/cm^2	1.3e18 atom/cm^3
Wafer 4	Boon	1e15 atom/cm^2	1.3e19 atom/cm^3

Wafer				Implantation				Annealing		
#	Type	Resistivity	Thickness	Oxide	Ion	Energy	Dosis	Temperature	Time	Ambient
		(Ω.cm)	(um)	(nm)		(keV)	(at/cm^2)	(ºC)	(min)	
9877-DET-1	P	0,1-1,4	525	100	P	130	1,0E+14	1000	180	N2
9877-DET-2	P	0,1-1,4	525	100	P	130	1,0E+15	1000	180	N2
9877-DET-3	N	1-12	525	100	B	60	1,0E+14	1000	180	N2
9877-DET-4	N	1-12	525	100	B	60	1,0E+15	1000	180	N2

Samples characteristics

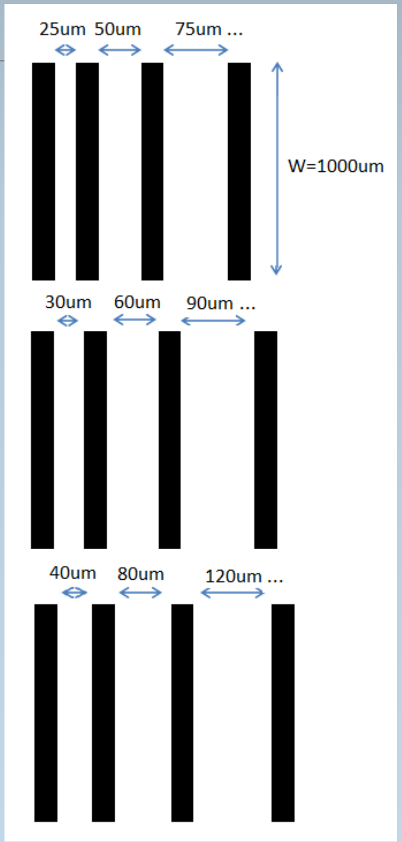
4 wafers each with a different expected implantation concentration:

-Wafer 1⟶ $1.5x10^{18}\ atoms/cm^3$ (P type)
-Wafer 2⟶ $1.5x10^{19}\ atoms/cm^3$ (P type)
-Wafer 3⟶ $1.3x10^{18}\ atoms/cm^3$ (N type)
-Wafer 4⟶ $1.3x10^{19}\ atoms/cm^3$ (N type)



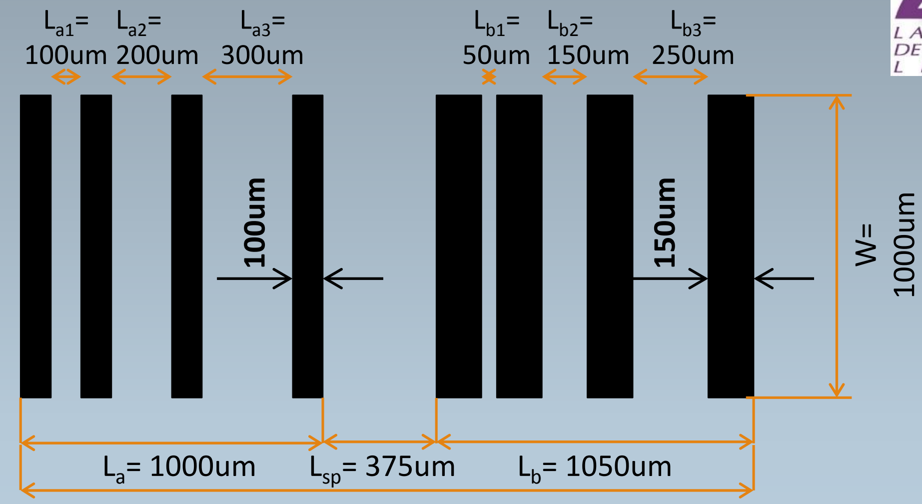
Sample seen from the side

Sample seen from above



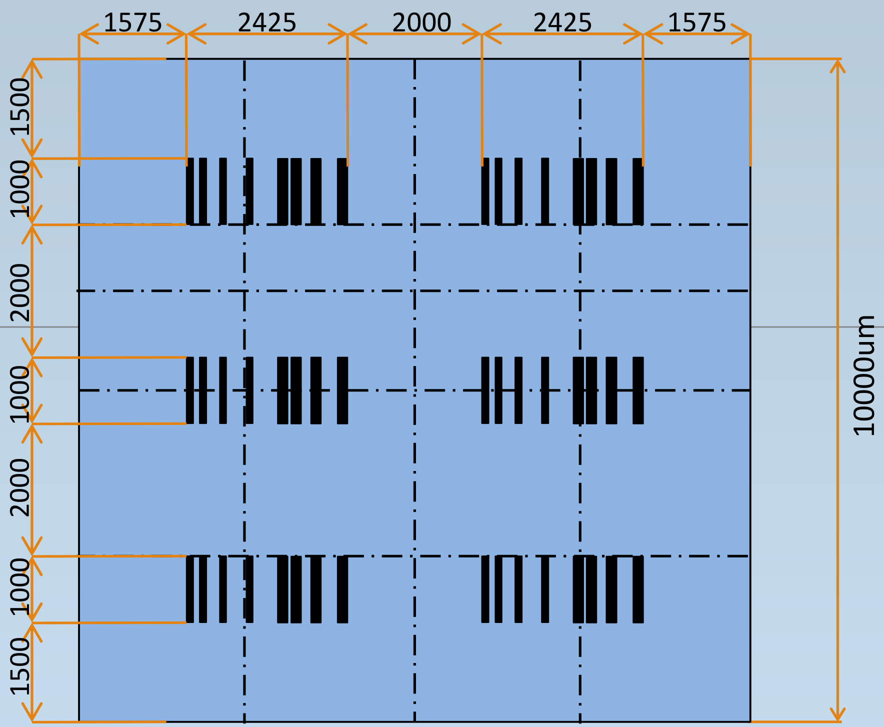
From Guido Pelligrini

Mask: Direct laser writing



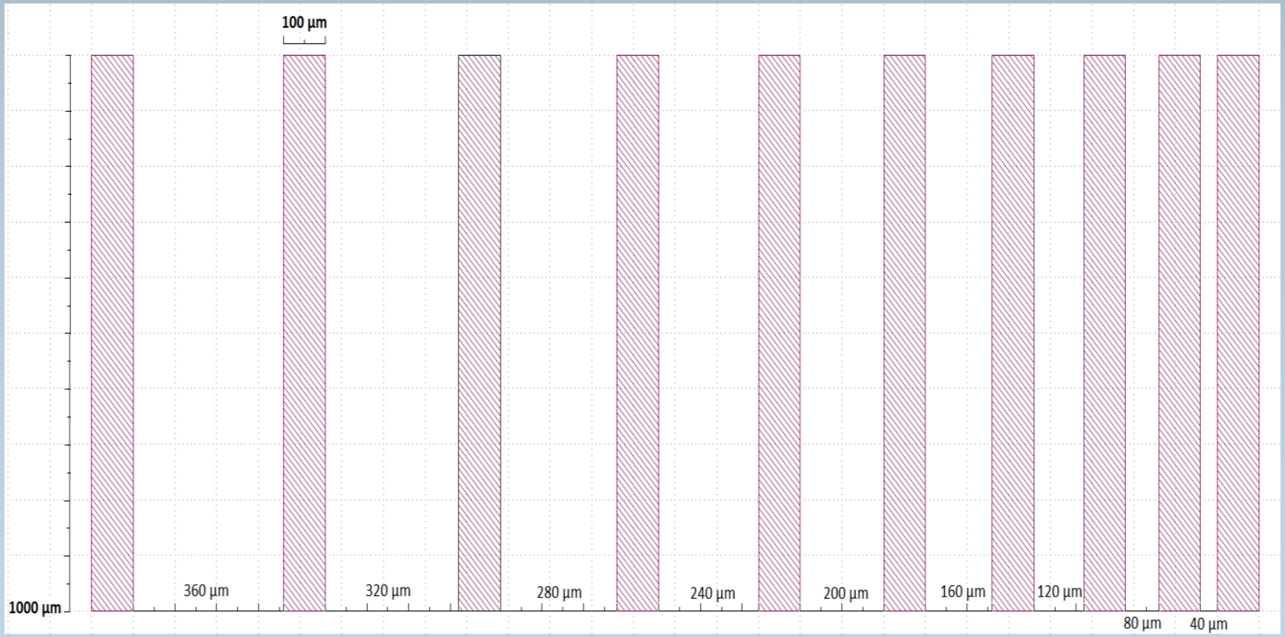
Mask

- W>>L (W/L ~ 2-3)
- L_i>t



Layout on a 10mm square piece of silicon

Test structure layout



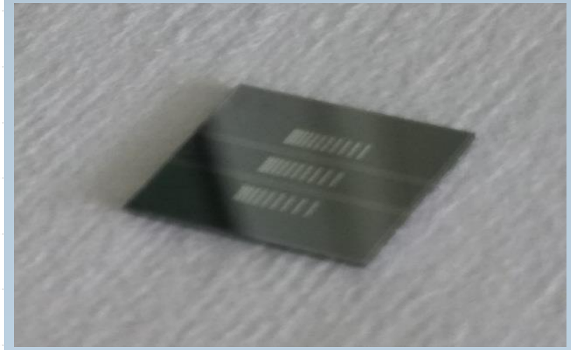


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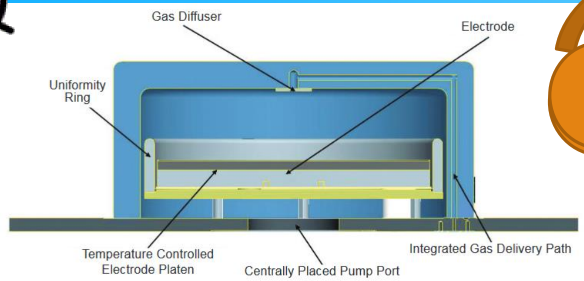
Illustration of the different operational steps

Dry etching process.

- Use chemically reactive plasma to remove material depsited on wafers (Silicon in our case).
- The plasma is generated under low pressure (vacuum): typical process pressure = 10^-5 mbar.
- Plasma density: 1 - 5 x 10^9 / cm2.
- High energy ions from the plasma attack the wafer surface and react with it , typical energy ~ 30 eV.
- The etching process of Silicon is a Fluoride base process, so both CHF3 and SF6 gases were used.
- Pre-etching cleaning of the sample, a factory plasma with O2 is used.

40 Min

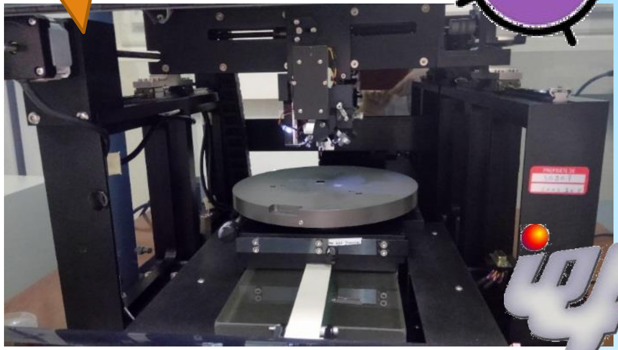


Etching

1

Profilometer

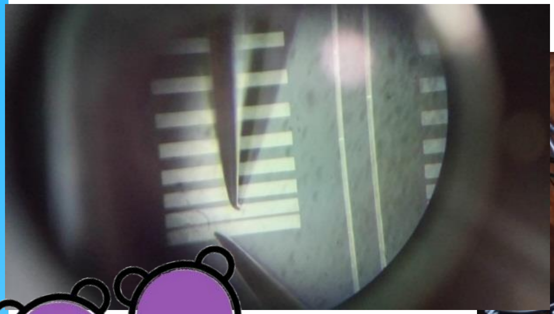
50 Min



Measures distance between Al contacts and silicon)

2

IV-curves



Probe station

3

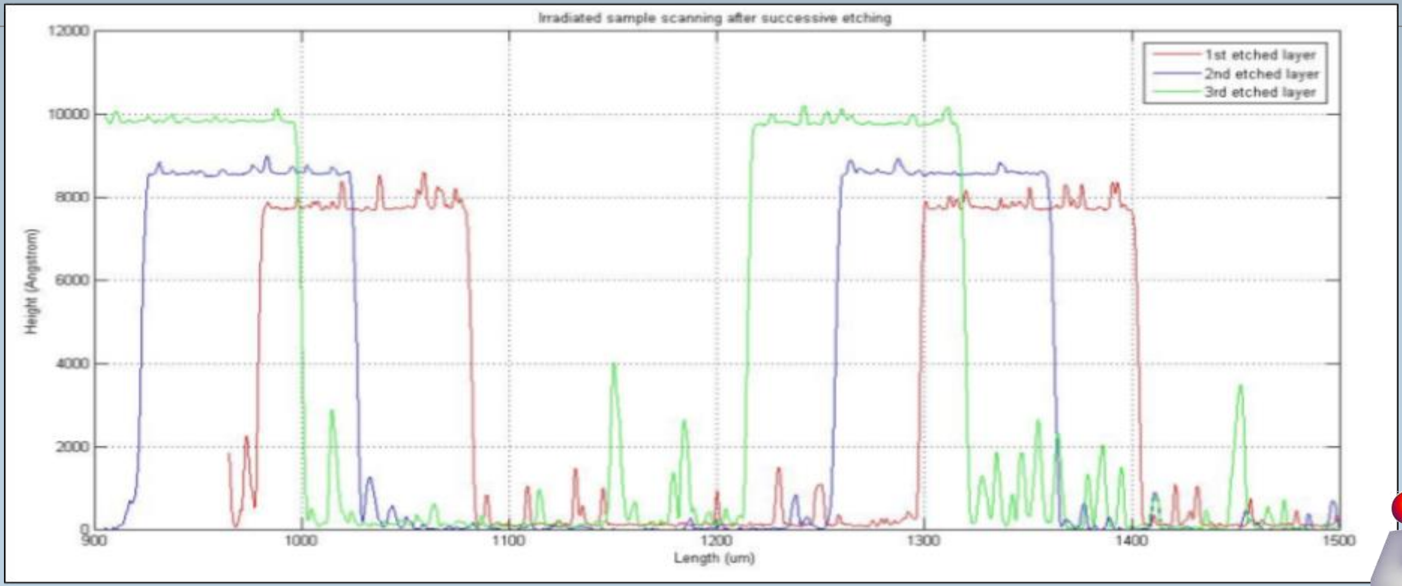
2 Hours

Resistance measurement

Collaboration LAL-IEF.

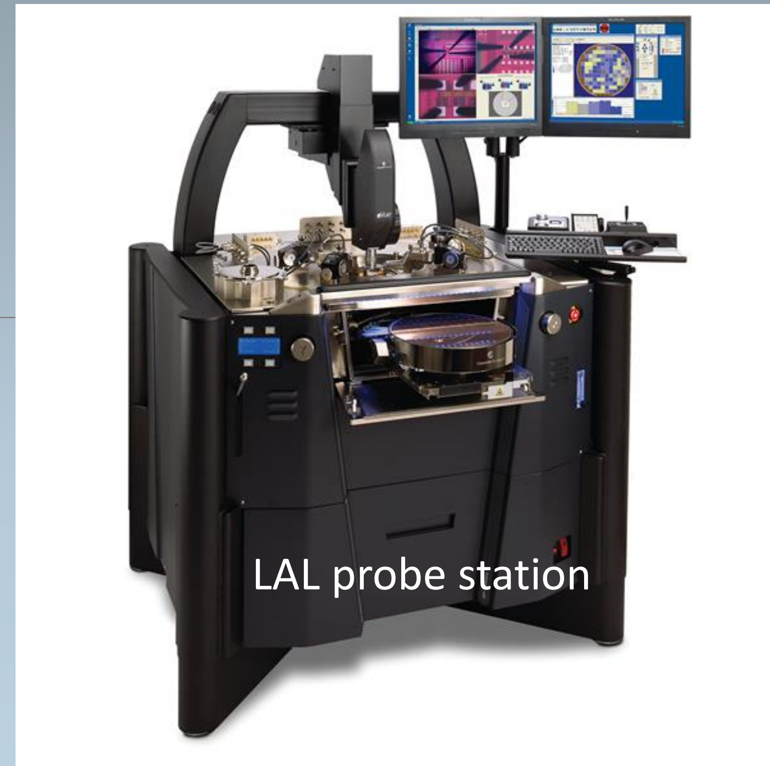
11

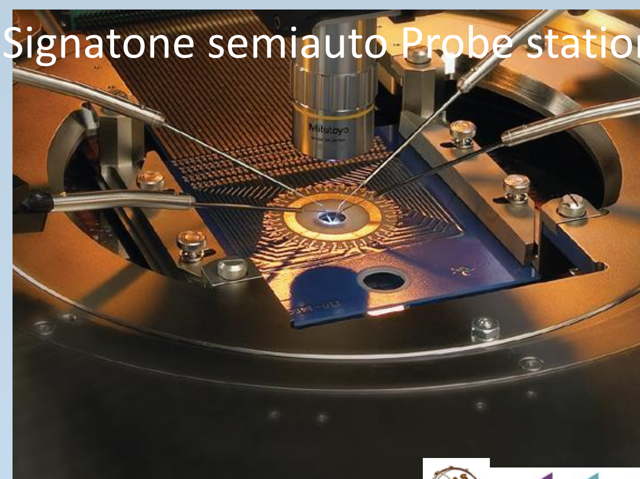
Profilometer



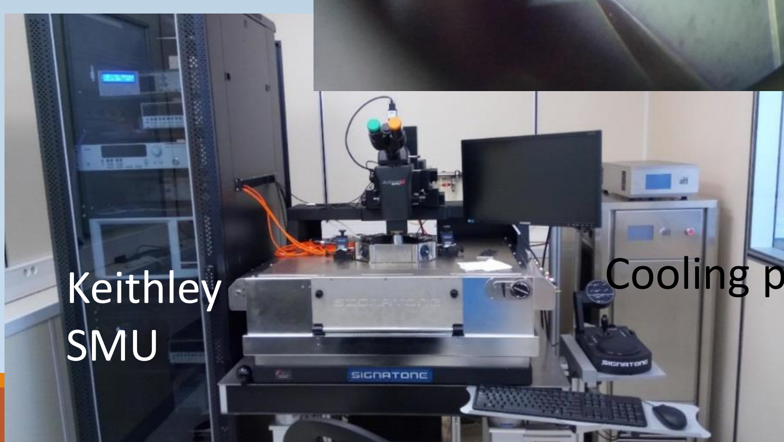
Check the distance between Alu Pads
Measure the Etched depth

Aditionnal Instrumentation- Tools



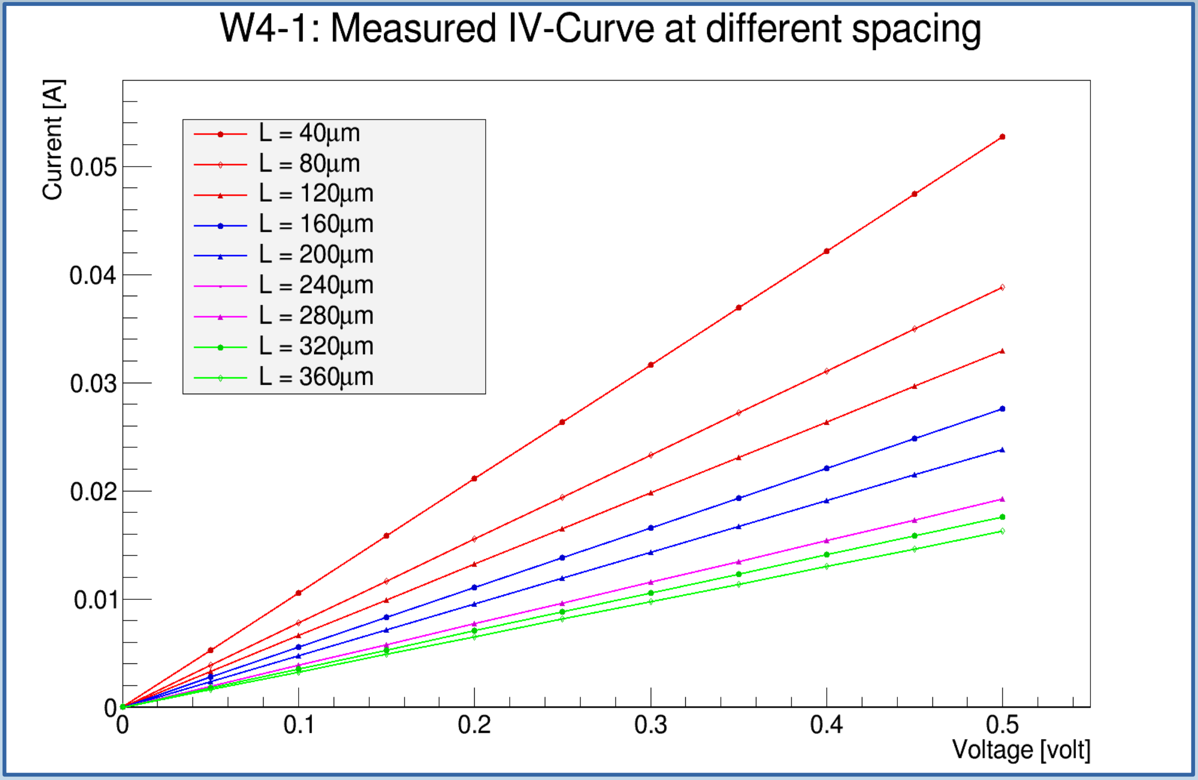


LAL Clean room



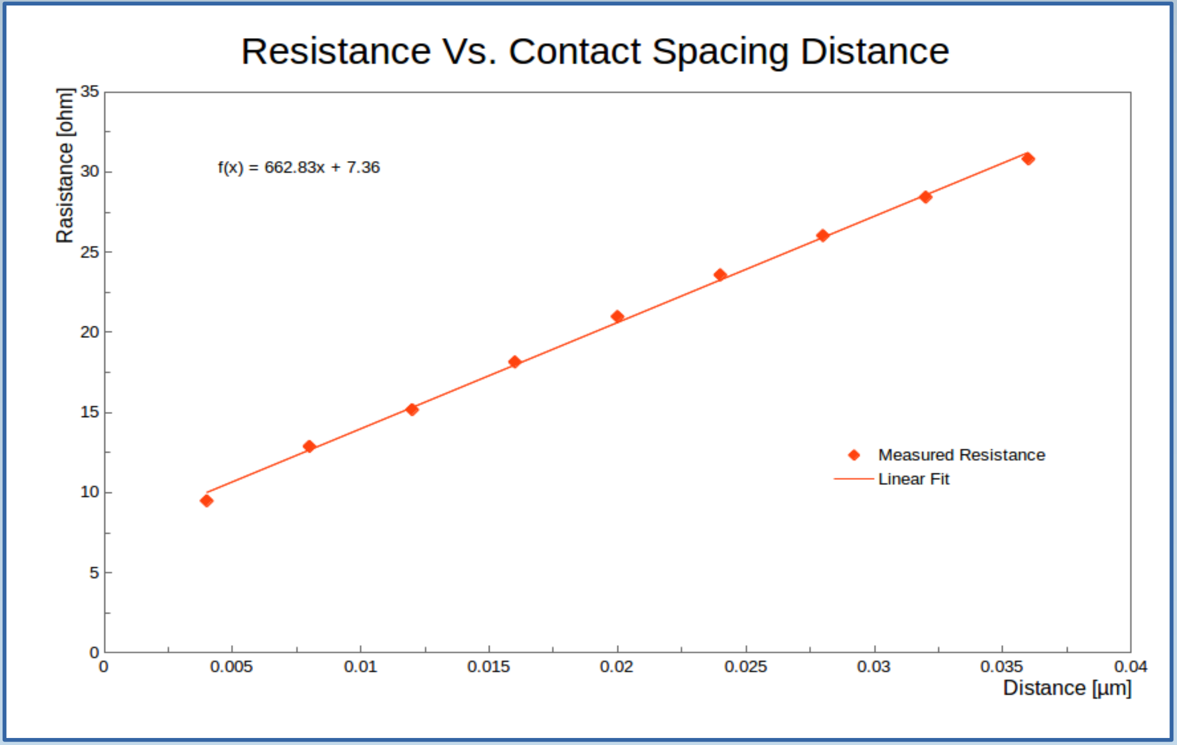
TLM measurement

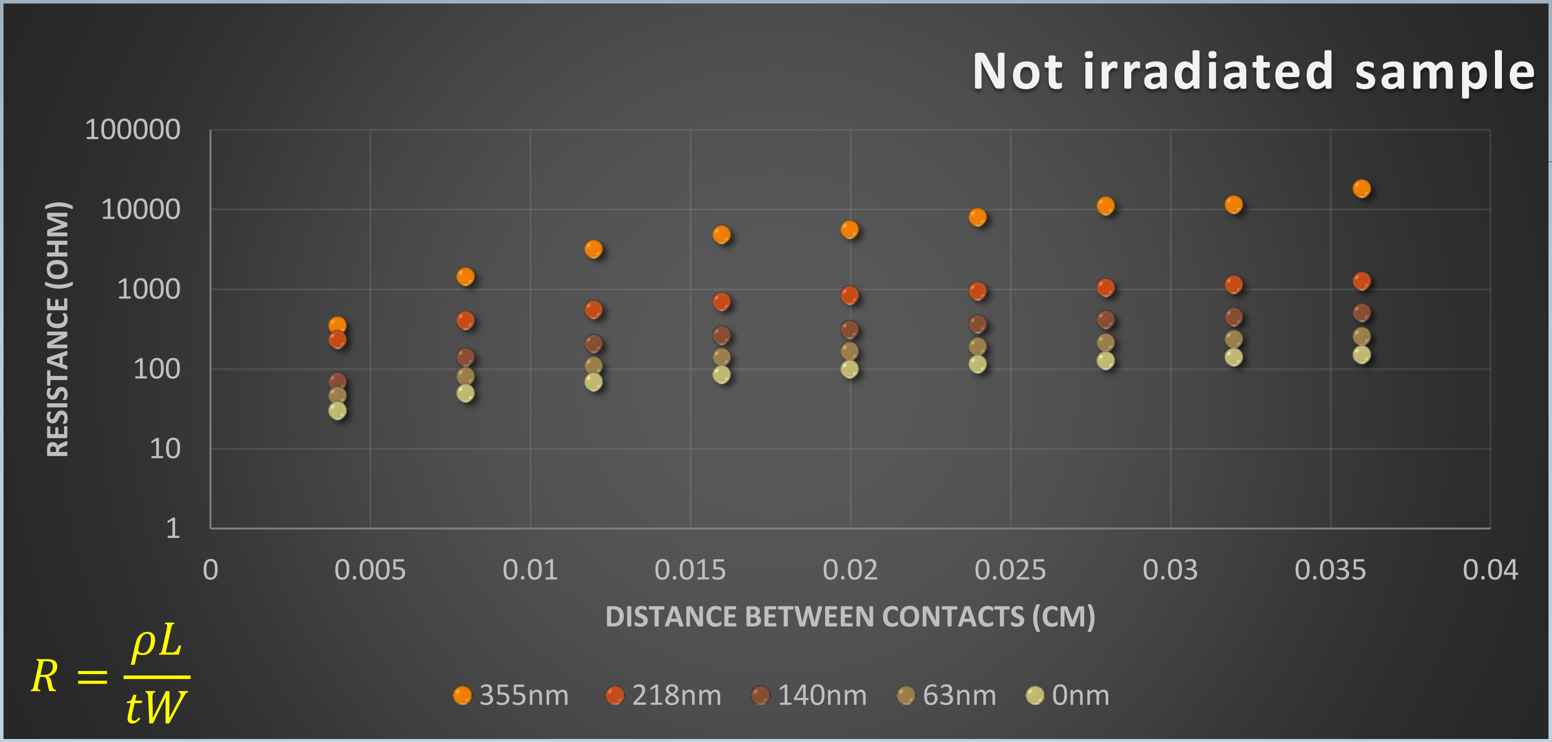
Measured Current as function of bias Voltage of a sample from wafer # 4 at different spacing between contacts.



TLM measurement

Measured Resistance as a function of contact spacing distance of a sample from wafer # 4.

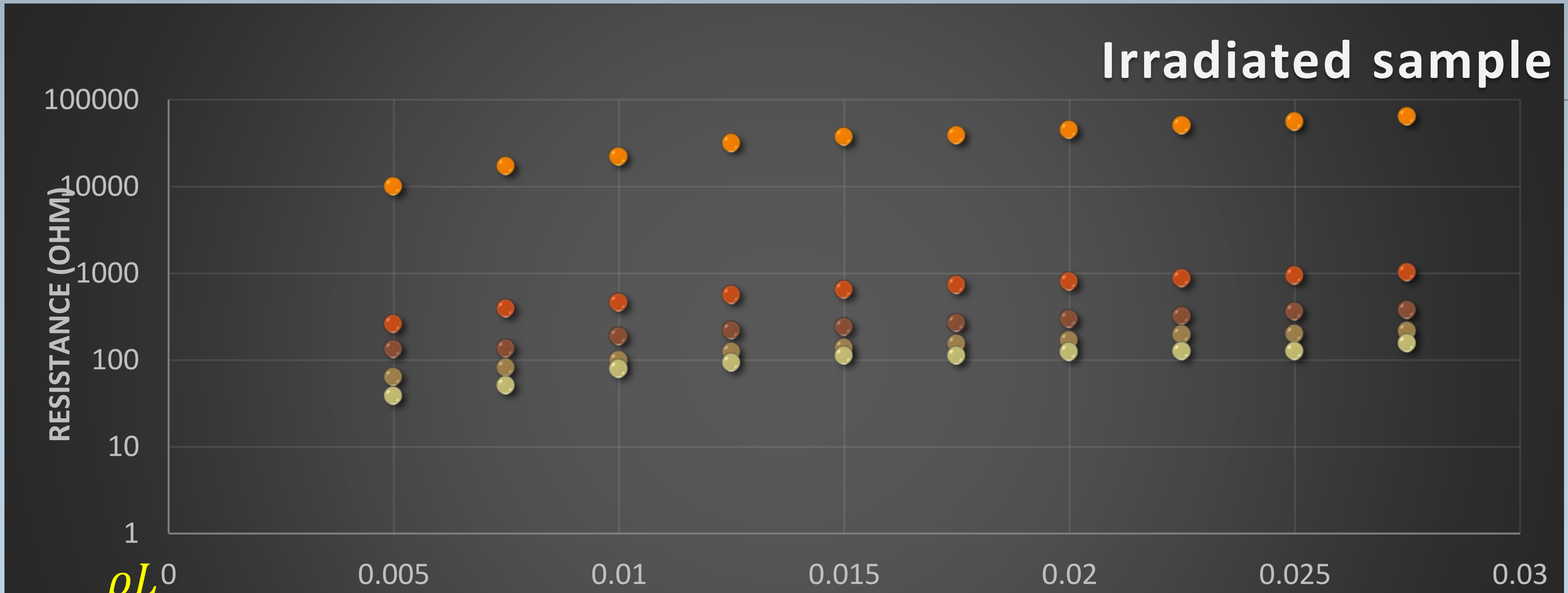




$$R = \frac{\rho L}{tW}$$

	Wafer 2 (atom/cm^3)	Wafer 3 (atom/cm^3)	Wafer 4 (atom/cm^3)
Expected peak concentration	$1.5x10^{19}$	$1.5x10^{18}$	$1.3x10^{19}$
Measured peak concentration	$1.9x10^{19} + 1x10^{18}$	$3.5x10^{18} + 1x10^{17}$	$2.0x10^{19} + 2x10^{18}$

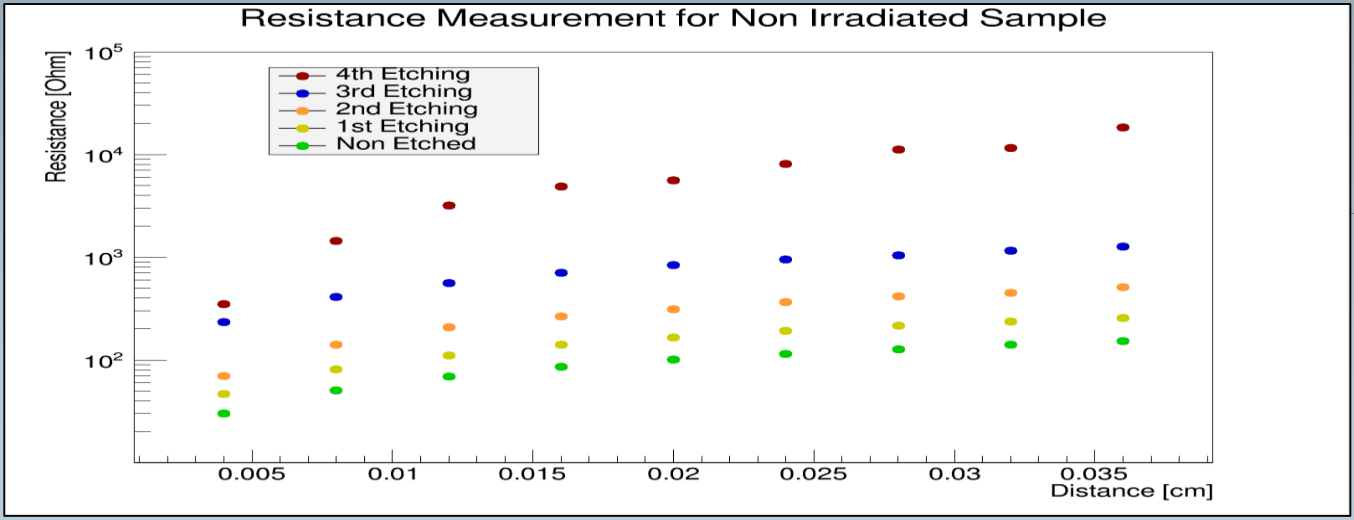
Resistance versus contact distance

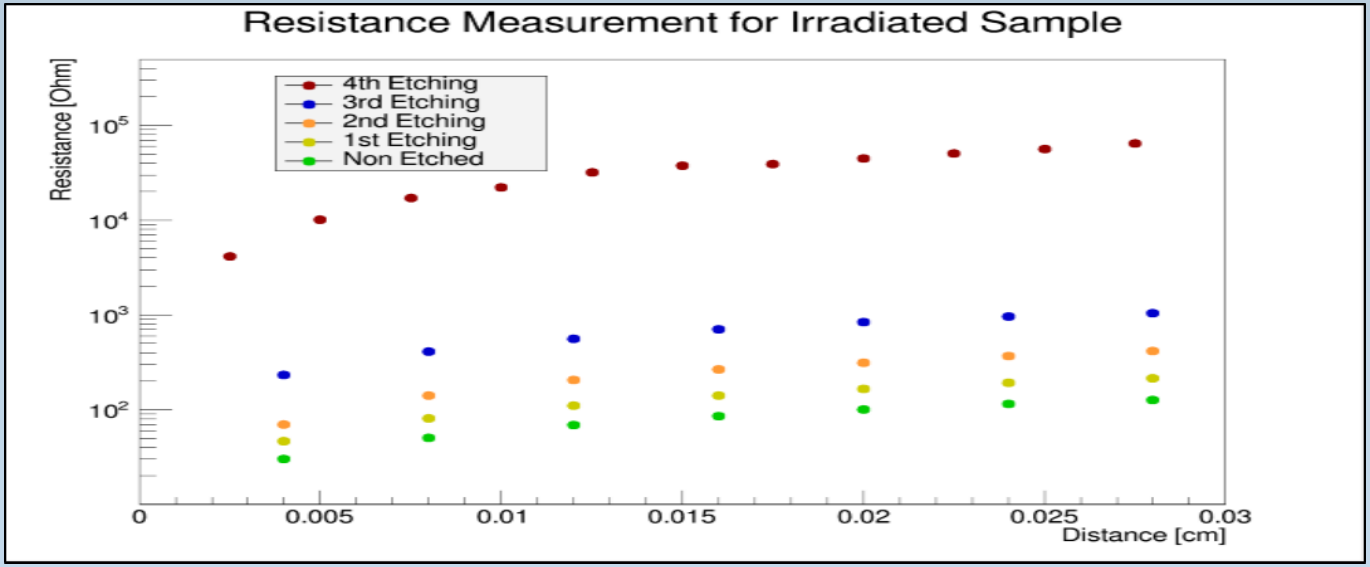


$$R = \frac{\rho L}{tW}$$

Peak concentration after irradiation could be deduced form the measurements
Some TLM samples have been irradiated at Lubjana 2×10^{15} Neq/cm^2 and 2×10^{16}

Resistance Measurements

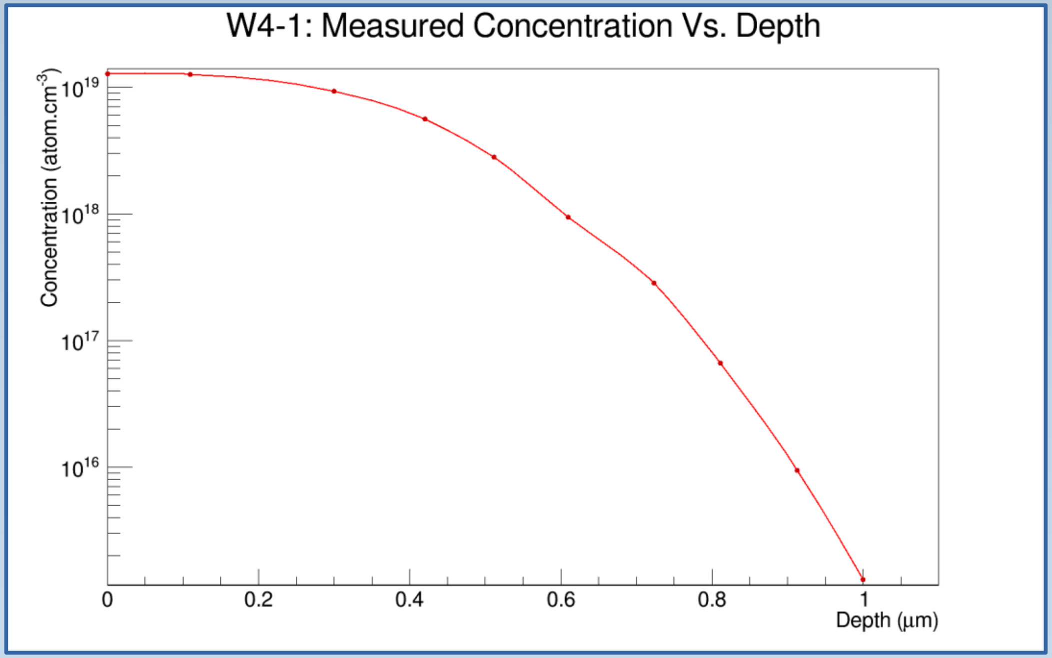




Measured Resistance as a function of contact spacing distance of (non and) Irradiated sample for different etching steps.

From Resistivity profile to Concentration profile

- Resistivity of doped silicon at different depth have been found using TLM Method.
- Carrier concentration has been calculated
- Active dopant profile has been extracted.
- Measured peak concentration was found to be of order 1e19 atom.cm^{-3} and is in a good agreement with expected value provided by manufacturer.



Before irradition

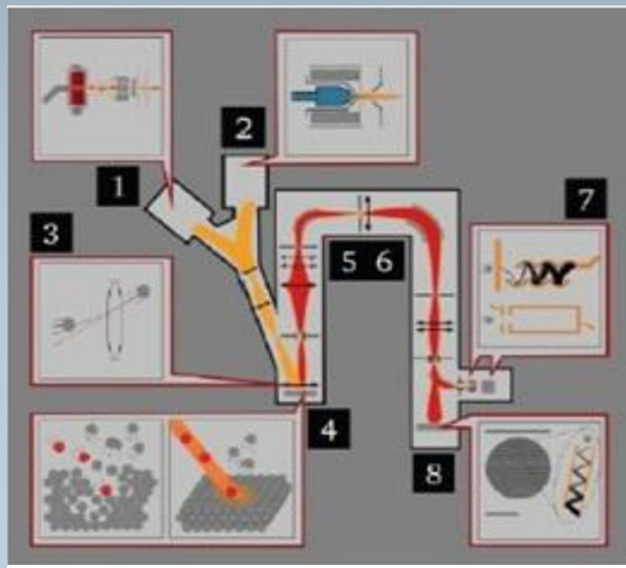
What is the total doping concentration and how does it compare with Active doping profile?

Secondary Ion Mass Spectrometry (SIMS)

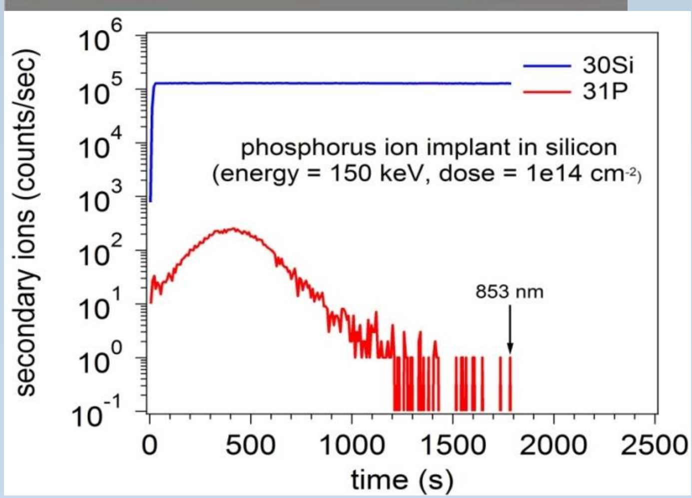
- General characteristics of sims
  - Analytical technique to *characterize the impurities in the surface and near surface (~30 μm) region* of solids (e.g. semiconductors) or some liquids;
  - It relies on the sputtering of a *primary energetic ion beam (0.5-20 keV*) on the surface sample and the analysis of the produced ionized secondary particles by mass spectrometry;
  - It has good detection sensitivity for many elements: *it can detect dopant densities as low as 10^{14} cm^{-3};*
  - It allows simultaneous detection of different elements, *has a depth resolution of 1 to 5 nm* and can give a lateral surface characterization on a scale of several microns;
  - It is a destructive method, since the act of the removing material by sputtering leaves a crater in a sample;
  - It determines the *total dopant density profile* and not the electrically active impurity density (e.g. electrical methods as spreading resistance profiling, TLM, Hall effect etc..).

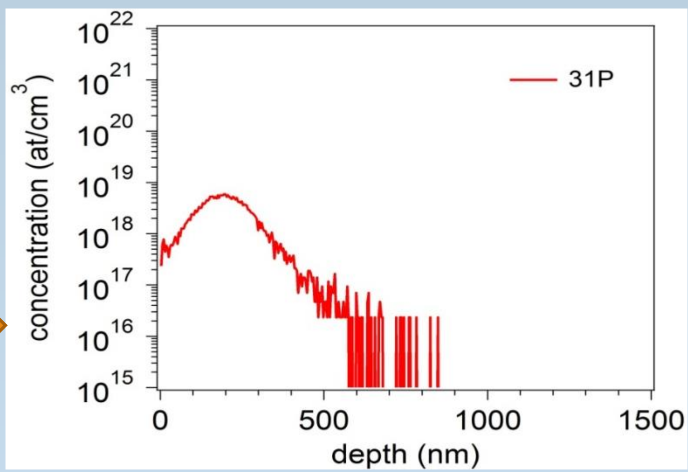
Secondary Ion Mass Spectrometry (SIMS)

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**

further on SIMS Imaging Method

What is SIMS imaging?

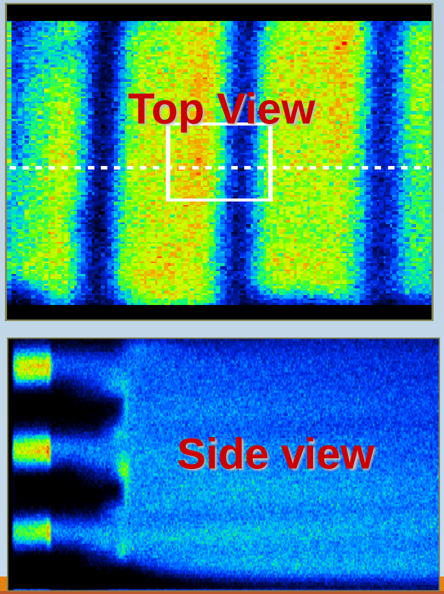
- Allow a scan for the samples surface and depth.
- Depth profiling and imaging can be combined to yield very powerful three-dimensional dopant maps

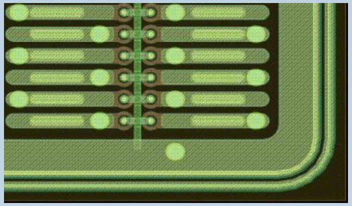
✓ Can achieve lateral resolutions up to 5 µm .

✓ High surface sensitivity at ppb level can be reached.

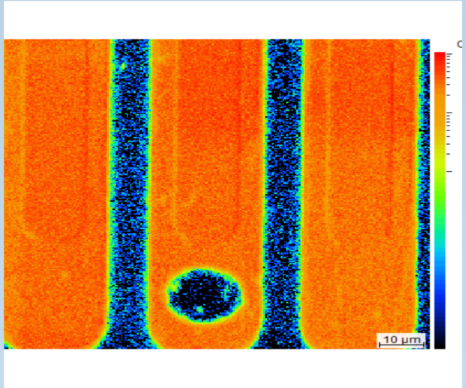
✓ Sample preparation is rather simple.

✓ Equivalent measuring time with standard 1D SiMS.



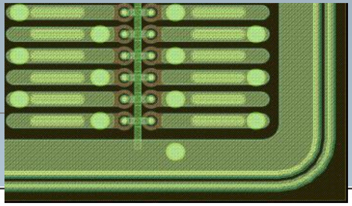


N-in-P Pixel Advacam

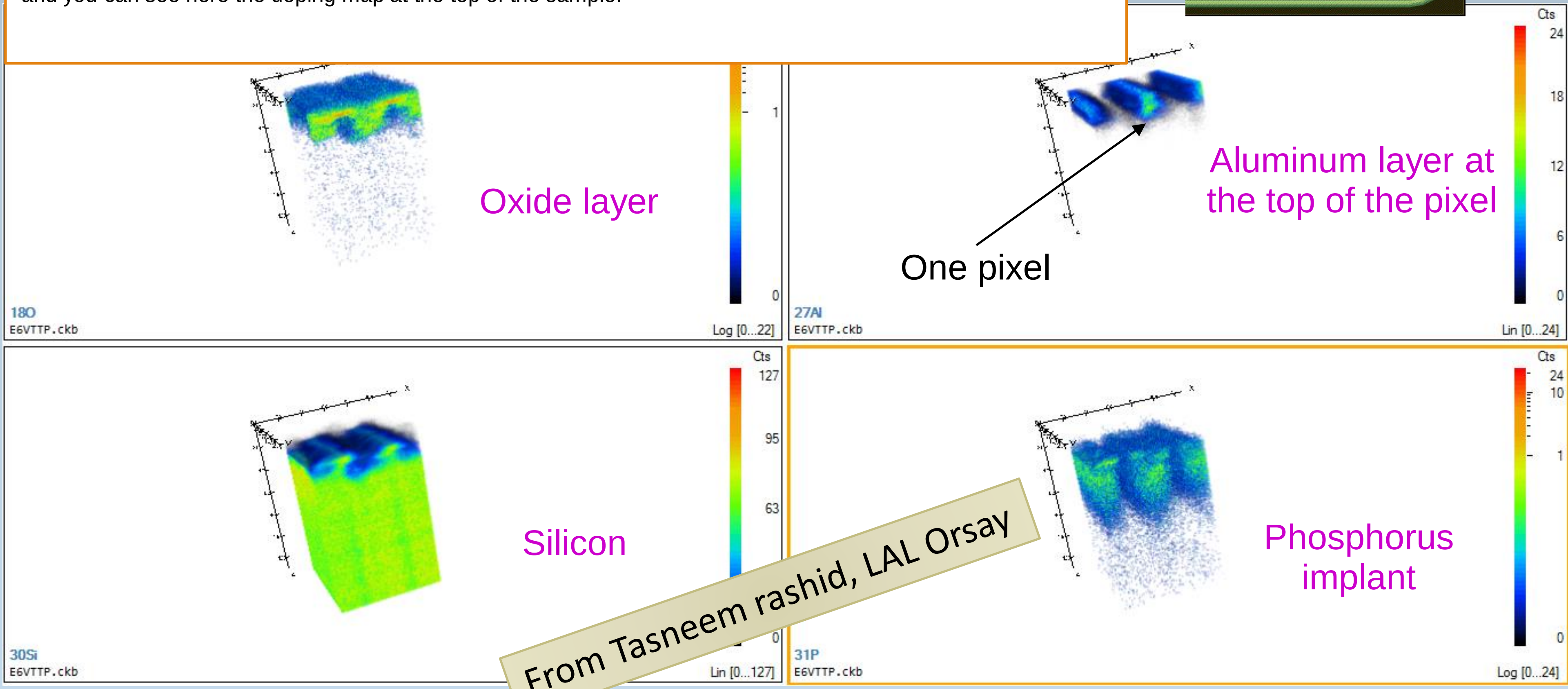


Phosphorus Implant 3D SIMS Doping Map

- *SIMS of ADVACAM Planar pixel .*

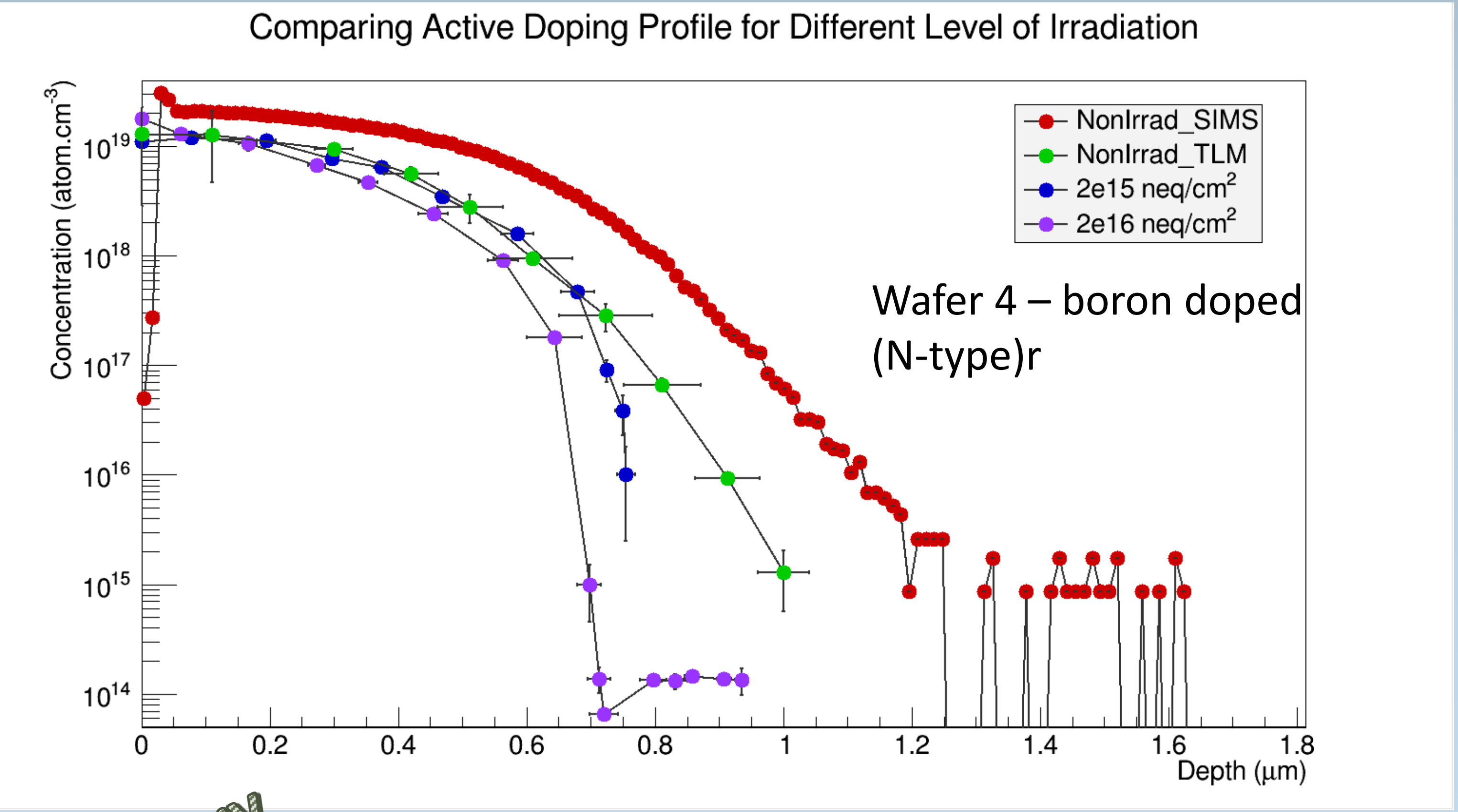


Sputtering the sample layer after layer we could find AL layer of thinkness 500 nm covering the pixel region then an Oxide layer of about 100 nm on the pixel and between the pixels then we could see the phosphorus implantation inside the pixelThe phosphorus implantation go through the silicon about 1 µm in depth and you can see here the doping map at the top of the sample.



From Tasneem rashid, LAL Orsay

Comparison of TLM active doping profile at different fluences and total concentration using SIMS



Wafer 4 – boron doped (N-type)r

preliminary

Conclusions and prospects

- TLM method seems to be a promising method to measure active dopant concentration.
- Preliminary results shows that the measured peak concentration of active carriers using TLM Method is in a good agreement with expected value from the foundry producer (CNM),
- Measurements using TLM and SIMS methods, for N type Silicon has been compared and behave as predicted,
- Several samples from different wafers have been sent to be irradiated with Neutrons (Ljubljana) to fluences (2×10^{15} n_{eq}/cm^2 and 2×10^{16} n_{eq}/cm^2). Changing of active dopant profile before and after irradiation have been investigated.
- Loss of active carriers as function of depth are clearly seen and could be evaluated from the measurements
- Next actions :
  - Phosphorous P-Type case should be investigated using the same TLM method
  - Study proton irradiation at high fluences
  - Quantitative active doping concentration from TeraHertz method (non destructive) or SPR can be cross-checked with TLM
  - Active doping profile with TLM can be usefully used in TCAD simulations (reliability of TCAD framework)

2015-04-RD50 Project LAL Implication
Proposed Actions

Method	Type	Process Step	Cost	Timeline
TLM	Active dopant profile estimation	Design and mask production	1200 €	2.5 months
		N-type, Fz Silicon, 3kOh wafers	300 €	
		Implantation: 1e15 / 5e14 / 5e15	330 €	
		Wafer Processing	285 €	
		Dicing and Expedition	150 €	
		Measuring	500 €	6 months
Total:			3000 €	