The needs and challenges of electrical measurements for micro/nanoelectronic devices.

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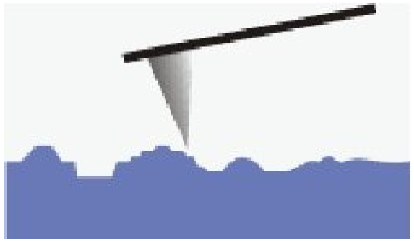

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Outline

Motivations :
The needs in electrical measurements : why go nano ?

Existing tools :
A wonderful tool which allows electrical measurement at the nanoscale :
Techniques based on **Atomic force microscopy** : a short overview

Some problems :
Increasing the quality of electrical measurement at the nanoscale : **where are the challenges ?**

- Overview of sources of errors in AFM based electrical measurements
- The area of contact
- The environment
- The signal to noise ratio

Wish list for future improvements

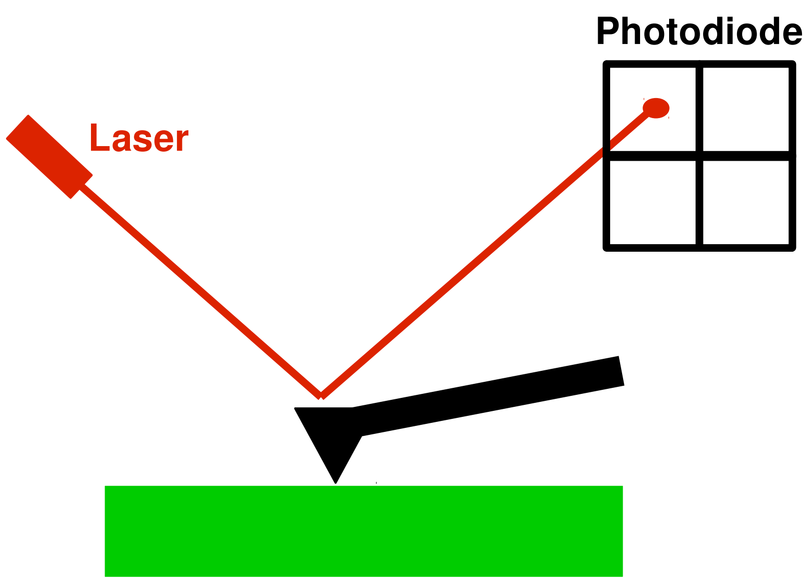
Electrical measurements at the nanoscale : what for ?

Social issue	Device	Figures of merit	
Calculation power	Transistors	Speed	Reliability : failure analysis
Energy consumption	Memories	Energy yield	Lifetime Retention time Fatigue
Data storage	Sensors	Power	Metrology Accuracy, repeatability, trueness, reproducibility
Measurement	Photovoltaic cells	Density of integration	
	MEMS / NEMS	Cost	
	interconnexions		

Electrical measurements at the nanoscale : how ?

Near Field Microscopies :

A <u>nanometric electrode</u> positionned with a <u>nanometric precision</u>



Electronic Microscopies

Scanning Electronic Microscopy (SEM)

Transmission Electronic Microscopy (TEM)

=> Holographic TEM for dopant mapping
=> sample preparation !

Spatially resolved Electronic spectroscopies : PEEM and derived methods

=> Work function measurement under UHV

Electrical measurements at the nanoscale : how ?

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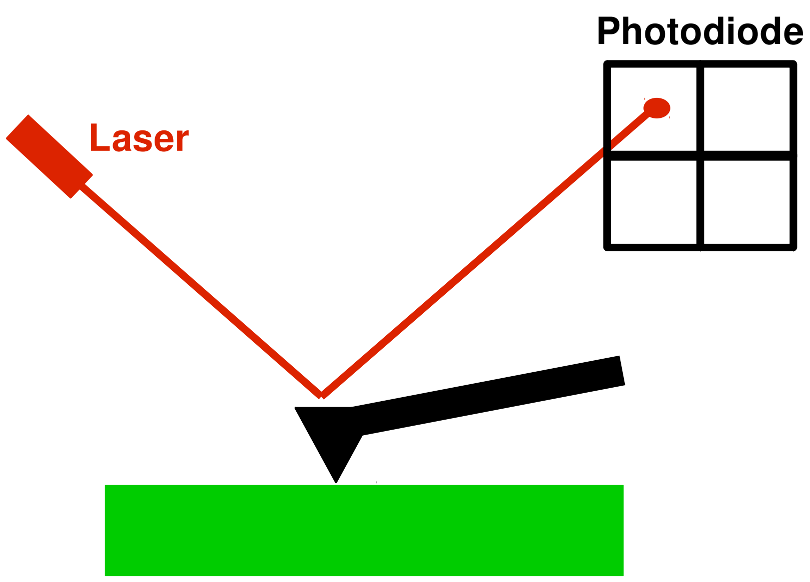

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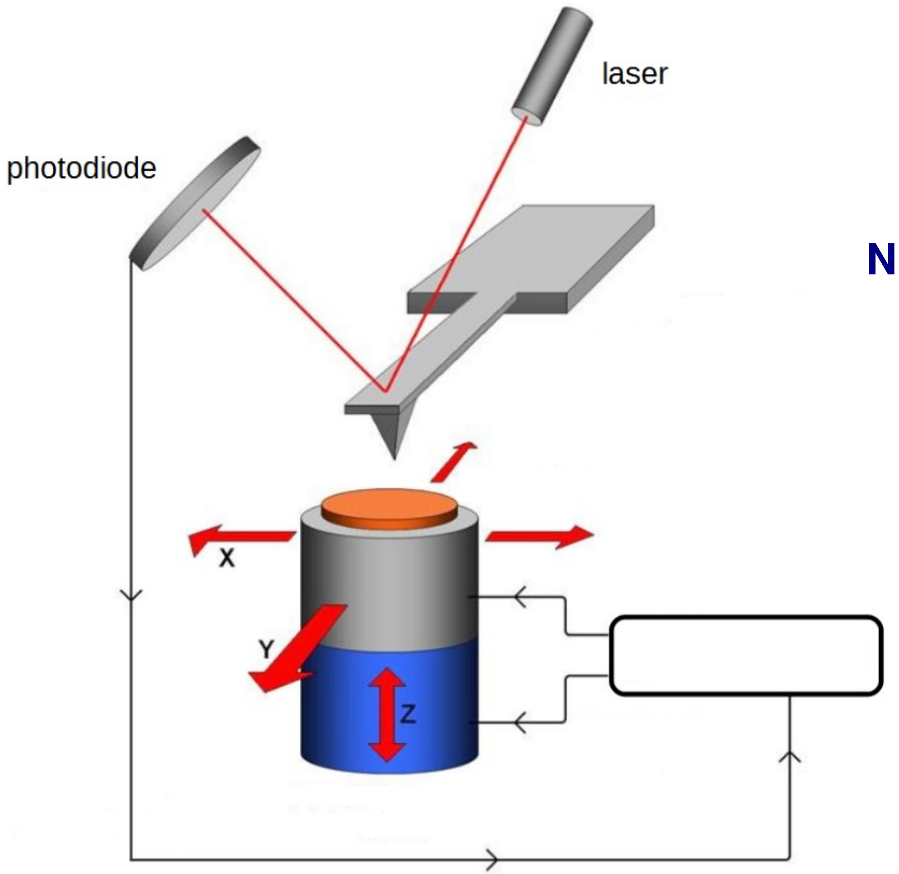
Atomic Force Microscopy

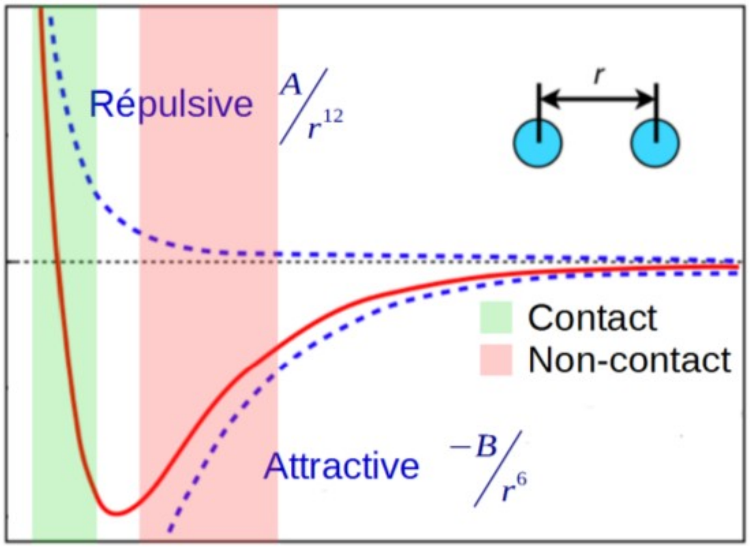


Contact mode :

Tip in **contact** with sample
High strain applied on the surface
Act as a metallic electrode
Silicon, metal-coated tips (PtIr5, diamond, CoCr...)

Non-contact mode :

Tip in **oscillation** above the sample
No (little) strain applied on the surface
Interaction modifies the frequency of oscillation



Designed for topography but allows wide choice of electric modes

EFM

Electric field

SCM

SMM

Capacitance

PFM

DART PFM

BE-PFM

Ferroelectricity

Contact

Non-contact

C-AFM

TUNA

SSRM

« resiscope »

Resistance

KFM

single pass KFM

double pass KFM

AM - KFM

FM - KFM

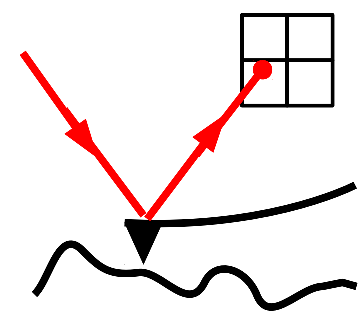
Surface potential

ESM

Ionic conduction

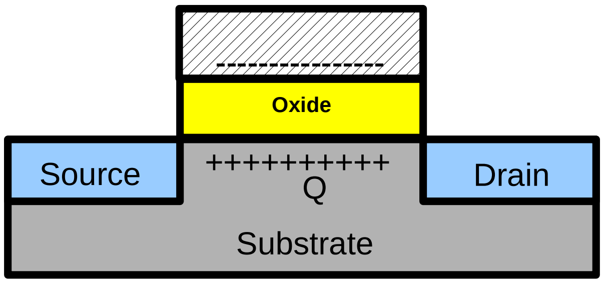
MFM

Magnetisation



Why go nano ? The exemple of micro/nanoelectronics

MOS cell



RAM Memories, MOS and CMOS transistors

Gain space ! , but with the same available power (or higher) !

$$C = \frac{Q}{U}$$

Q : charge => available current I

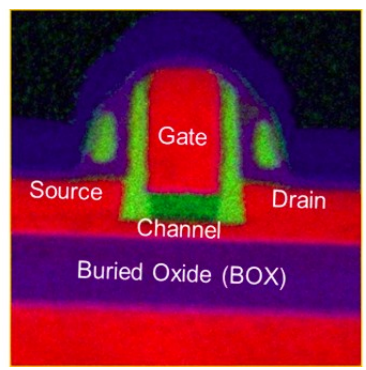
U : applied voltage

$$P = U \; I$$

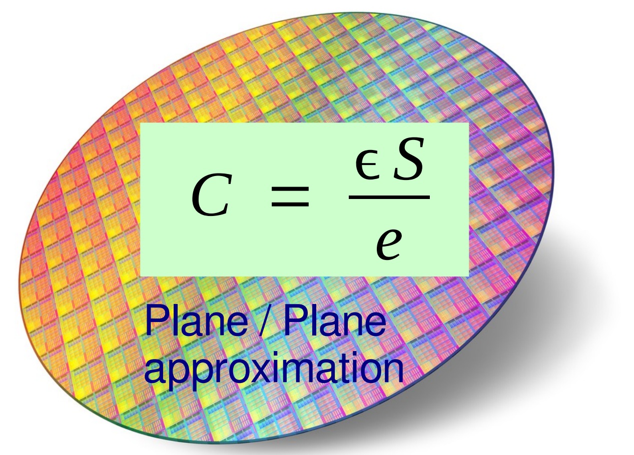
Electrical power

=> Capacitance must be preserved in spite of the scaling : portable devices (phones, computers…)

=> ~~Greatest areas~~
=> Smaller thicknesses e
=> Higher permittivity ε



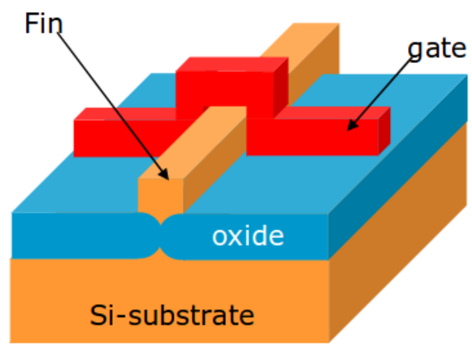
***14 nm** Fully Depleted Silicon on Insulator (FDSOI)*



$$C = \frac{\epsilon S}{e}$$

Work faster !

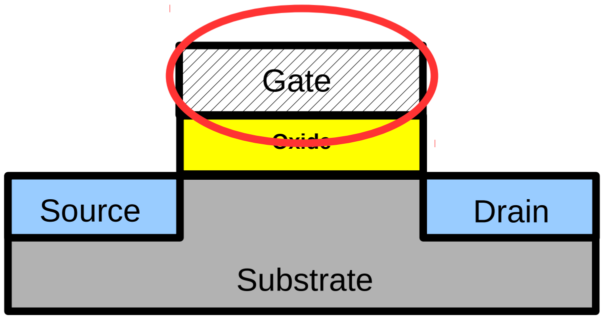
Increase frequencies of operation by reducing size



3D FINFET

The size of basic devices is of the order of several nanometers

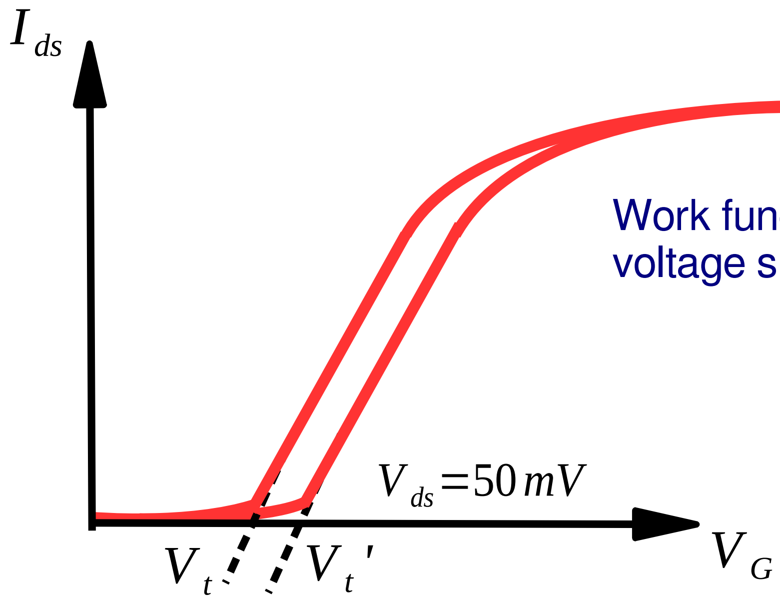
Overview of the characterization needs for the MOS gate



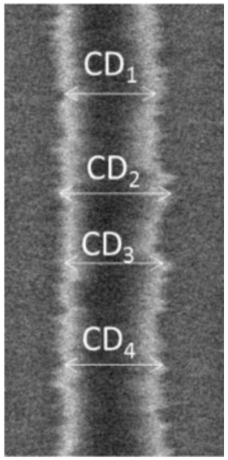
Gate and contacts

Properties under investigation :

- **Work function** : threshold voltage V_{th} shift



(another challenge for the metrology of dimensions !)

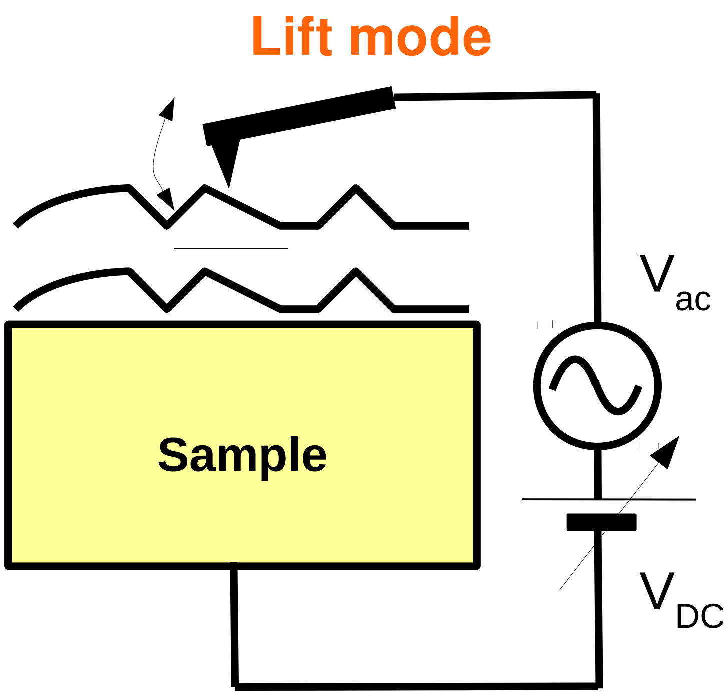


SEM view of the roughness on MOS transistor

Court. J. JUSSOT, CEA-LETI

- **Resistivity**
- **Line Edge Roughness (LER)**
  1,7 nm desired, 4-5 nm achieved

Mesurement of work function with nanometric spatial resolution

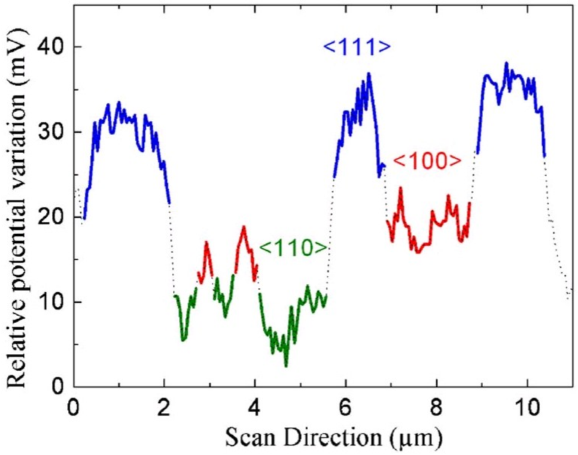


$$V = V_{DC} - V_0 + V_{AC}\ cos(\omega t)$$

$$F_\omega = -\frac{\partial C}{\partial z}(V_{DC} - V_0)\ V_{AC}$$

N. Gaillard, M. Gros-Jean, D. Mariolle, F. Bertin, A. Bsiesy, Appl. Phys. Lett. 2006

Measurement of V_0 (surface potential) by the cancellation of F_ω by adjusting V_{DC}



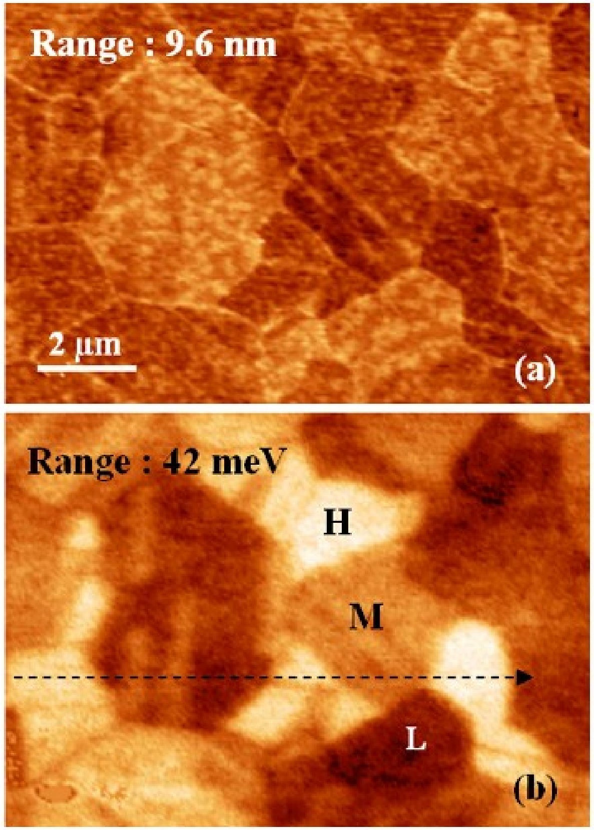


FIG. 4. (Color online) (a) Topography and (b) WF mappings of the same polished copper area ($12\times8\ \mu m^2$).

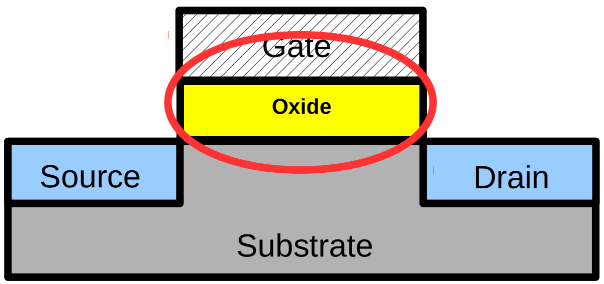
Double pass (lift mode, to remove any interference from the topography**)**

Simple pass (harmonics)

Overview of the characterization needs for the MOS oxide

Regardless of the geometry, always the same components :

gate, oxide, source, drain



$$C = \frac{\epsilon S}{e}$$

Plane / Plane approximation

Oxide

Properties under investigation :

- **Permittivity** ε : high-k materials
- **Leakage currents**
- **Charged defects** in the volume and at the interfaces

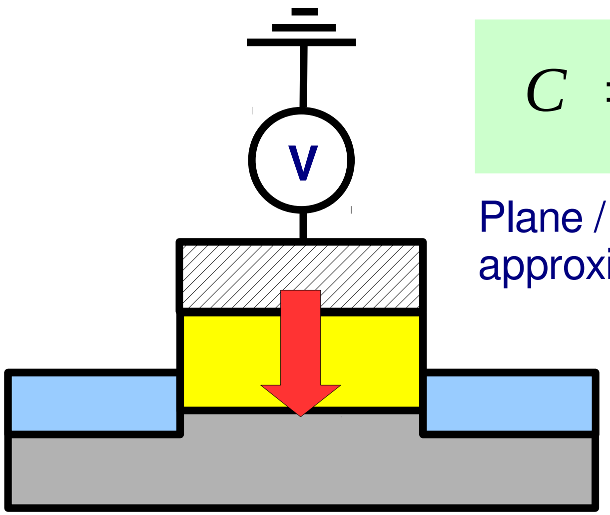
Life-time : breakdown at low voltages (time dependent dielectric breakdown)

Endurance: evolution of the electrical parameters when in use

Ageing : evolution of the electrical parameters when not in use (agressive environment)

All require a description at the nanoscale, not (only) because the size of the object is small but also because **the phenomenon to describe is active at the nanoscale !**

Leakage currents in MOS structure



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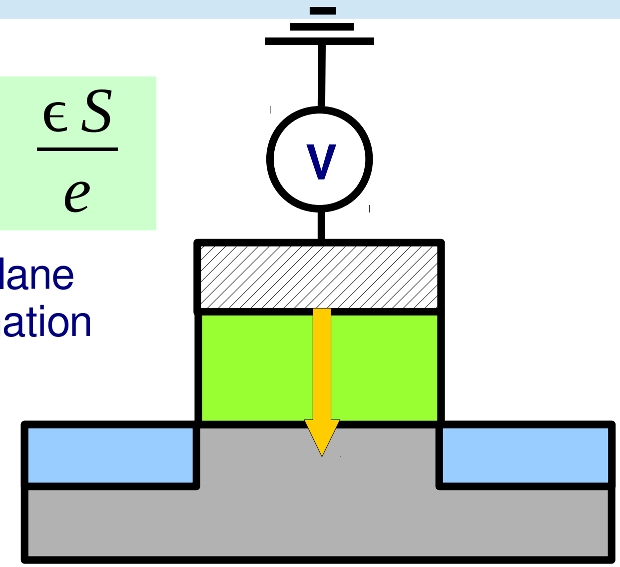
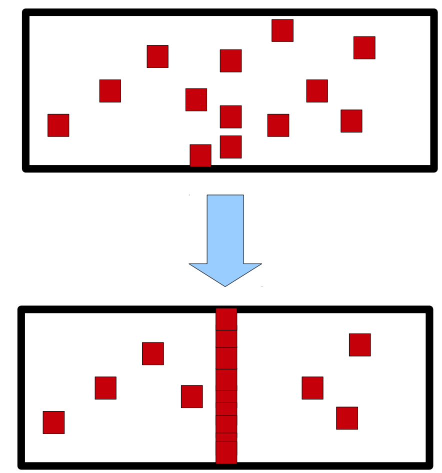
Plane / Plane approximation





SiO_2 : less than 1 nm

Direct tunnel
Fowler Nordheim
=
High leakage

High-k materials (e.g. HfO_2)

Higher ε
Same capacitance
Higher thickness

Defects in the oxide volume => Poole Frenkel transport mechanisms

Percolation model

J. Sune, IEEE trans. Electron. Dev. 22:392, 2001

Radius of the conducting channel in the nanometer range

Leakage currents => injection of defects in the oxide => ageing of the transistor => failure

Dielectric breakdown is an intrinsically nanometric phenomenon

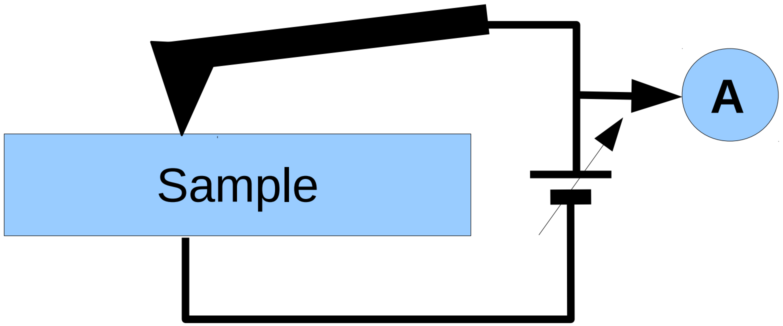
Detection of leakage currents : conducting AFM

TUNA (Tunneling AFM, linear amplifier) : 60 fA – 100 pA

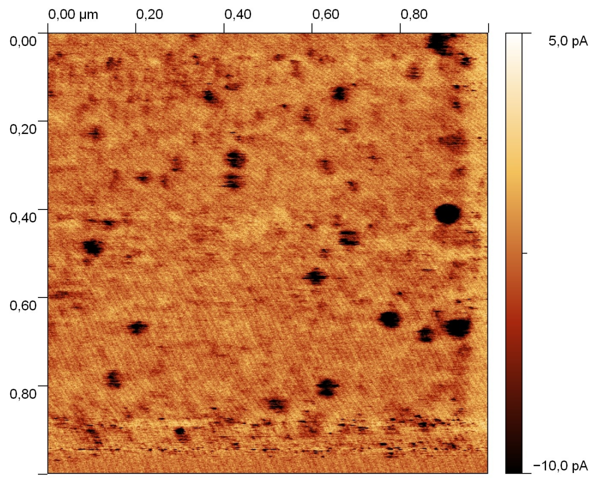
C-AFM (Conductive AFM, linear amplifier) : 10 pA – 1 µA

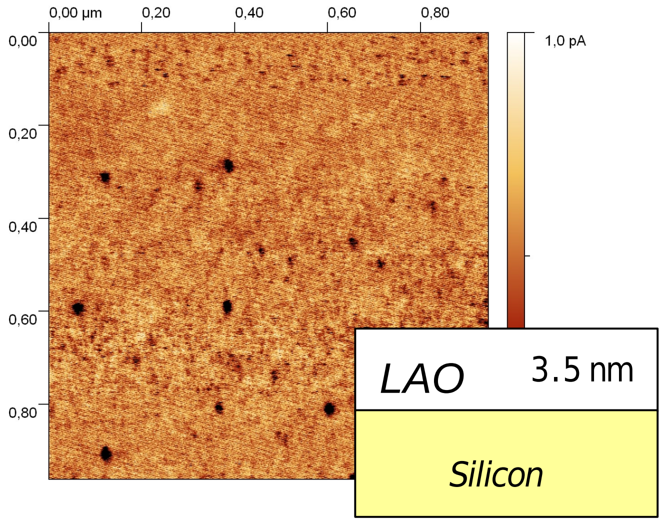
SSRM : (Scanning Spreading Resistance Microscopy, logarithmic amplifier) => 1 mA

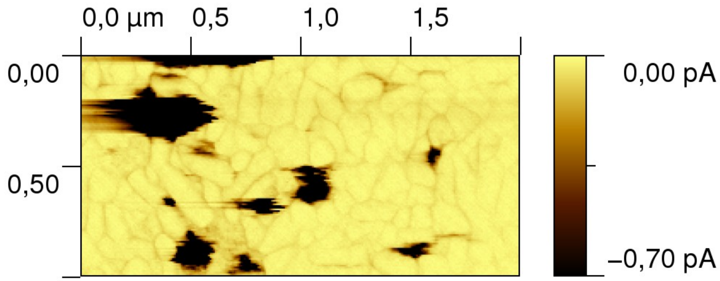
Resiscope : (logarithmic amplifier) : 100 fA – 1 mA



Leakage and breakdown : « Hot spots » in a dielectric layer







Amorphous $LaAlO_3$ (LAO), MBE, thickness = 3 nm

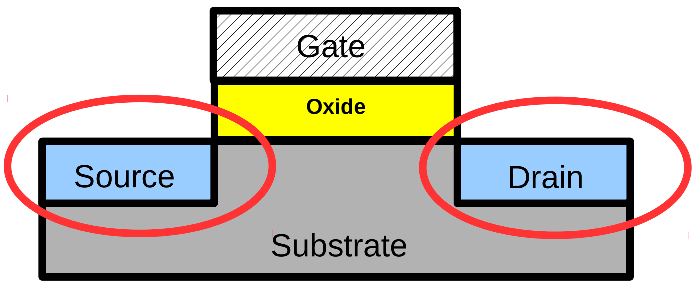
***atomic oxygen** versus **molecular oxygen** on the density of oxygen vacancies / hot spots in very thin LAO*

Negative voltage applied on the substrate : dark areas indicate high currents
(**Positive** voltage applied on the substrate : bright areas indicate high currents)

Source and drain

Properties under investigation :

- **Doping level**



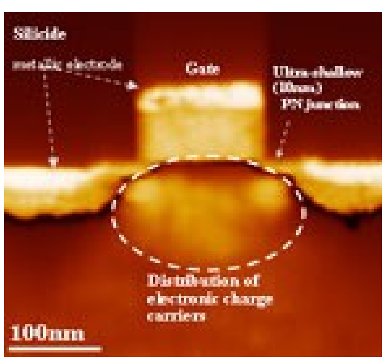
Low resistivity of contact, high currents for such a small size =

High levels of doping (> 10^{19} at/cm^3)

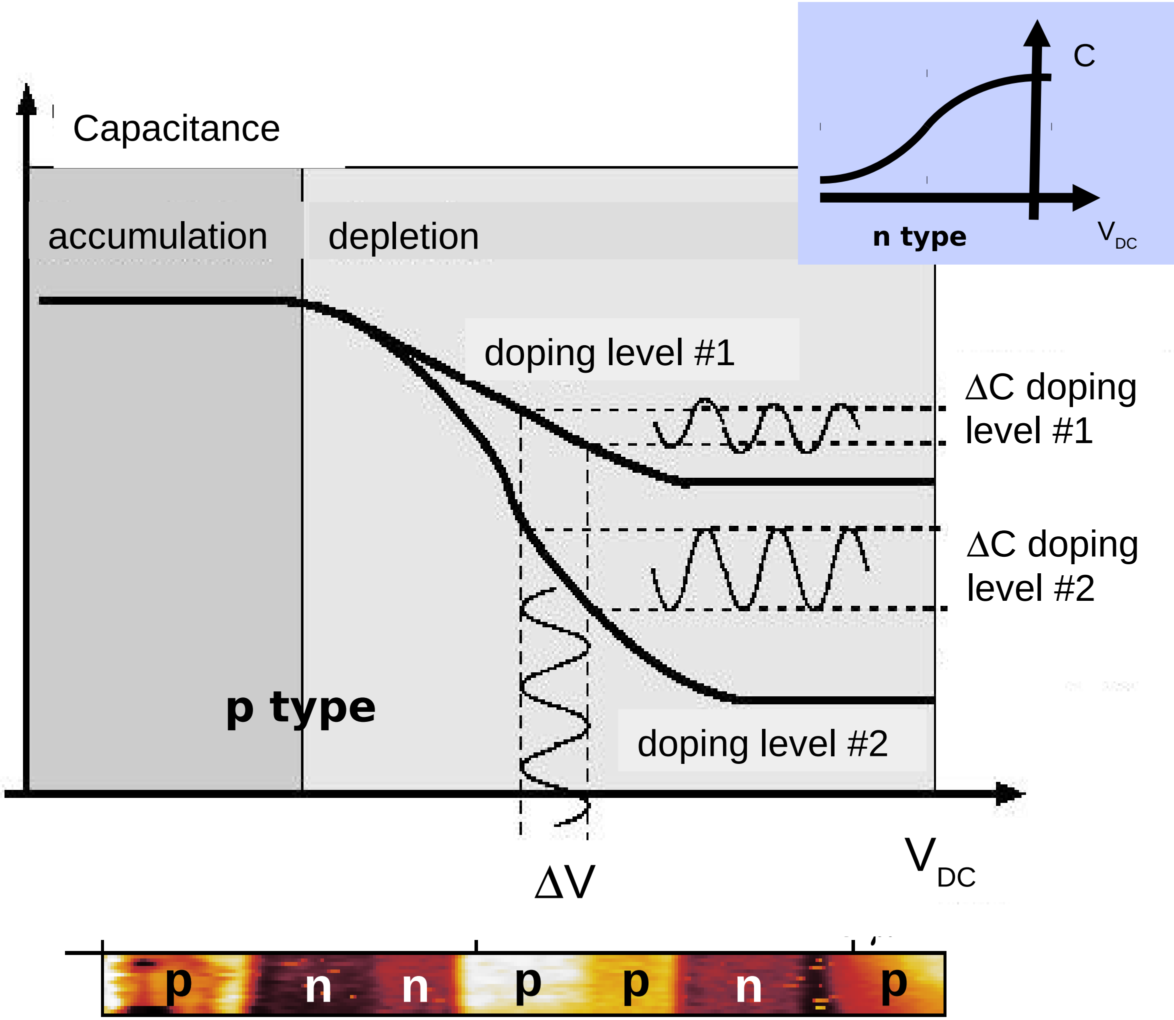
Degenerate semiconductors

Need for :

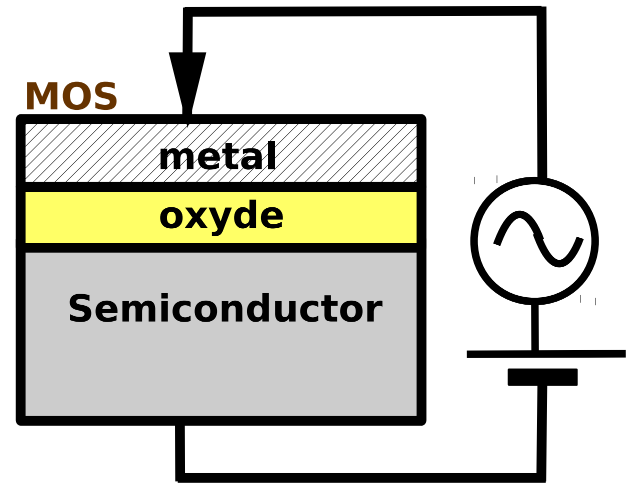
- **2D measurement of the dopants concentration**
- **Precision < 4 %**
- **Spatial resolution ~ several nanometer**
- **Ease of use**



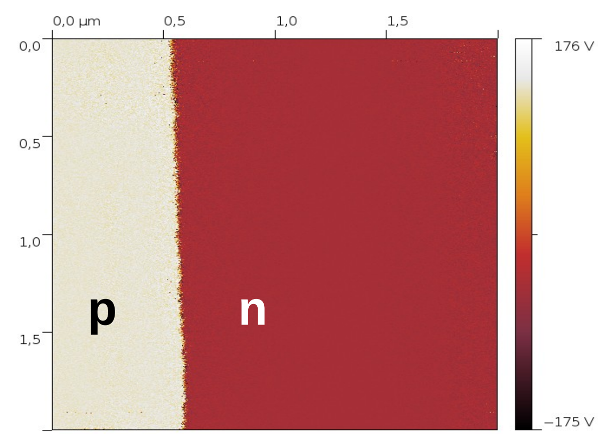
Dopant mapping with an AFM : Scanning Capacitance Microscopy (SCM)



SCM image of a sample containing pn junctions @ 0.125 Vdc

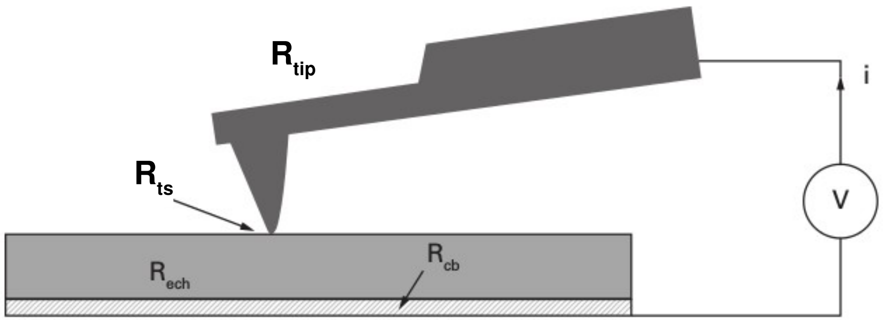


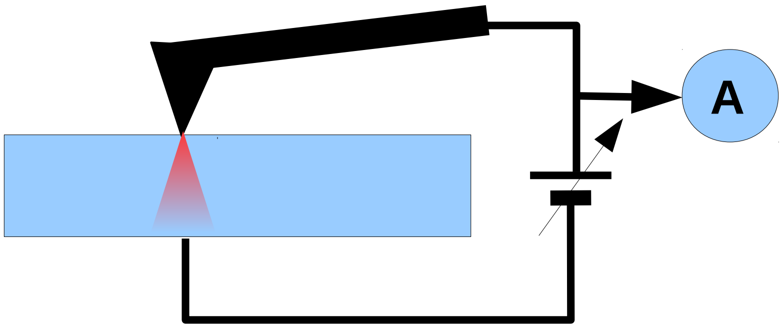
The variation of C_{MOS} is inversely proportionnal to the doping level.



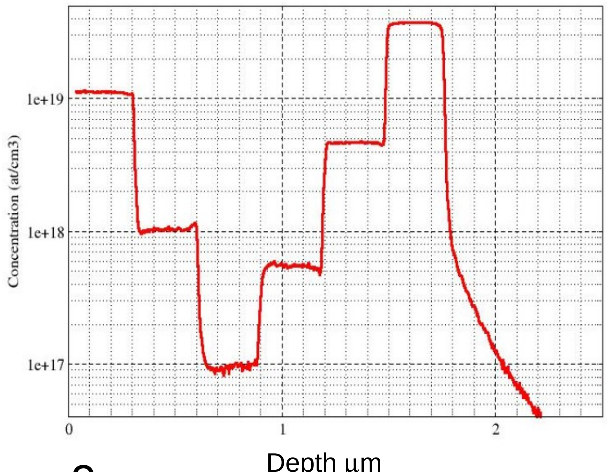
Phase signal

Dopant mapping with an AFM : Scanning Spreading Resistance Microscopy (SSRM)





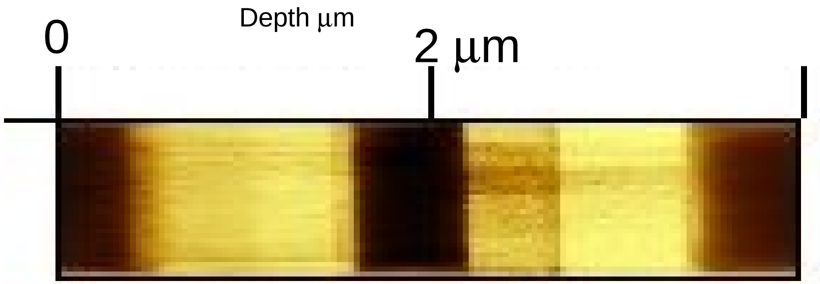
Measurement of the spreading resistance



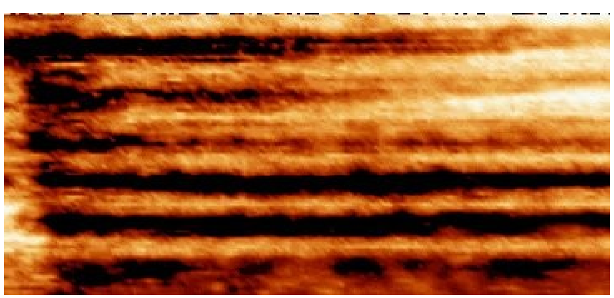
- **C-AFM with logarithmic amplifier**
- **Hard force** required on silicon

=> hard tips, surface damage

$$\rho = \frac{1}{q(\mu_n n + \mu_p p)}.$$



SSRM profile of a staircase sample



D-doped layer (Si:B), spacing 20 nm

Photovoltaïcs

Organic solar cells

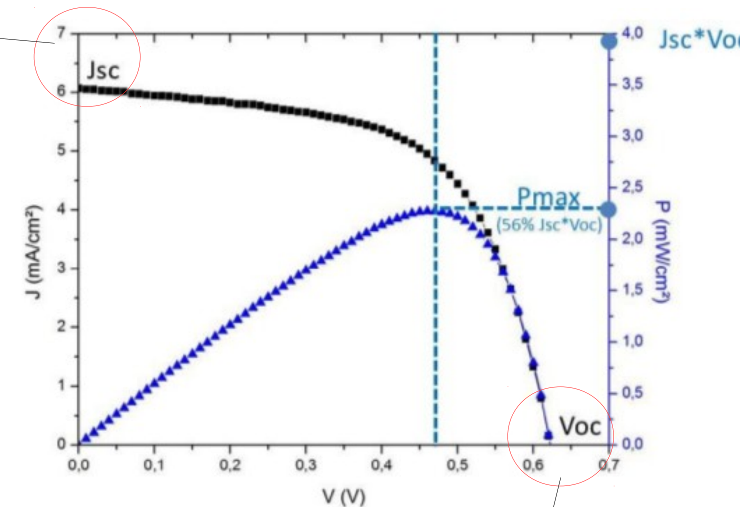
p-n junction with creation of electron-holes pair by interaction with light

Donor and acceptor materials are intermixed with typical spacings of several nanometers

Solar cell characteristics :
Open circuit **voltage** and short-circuit **current** with nanometric spatial resolution

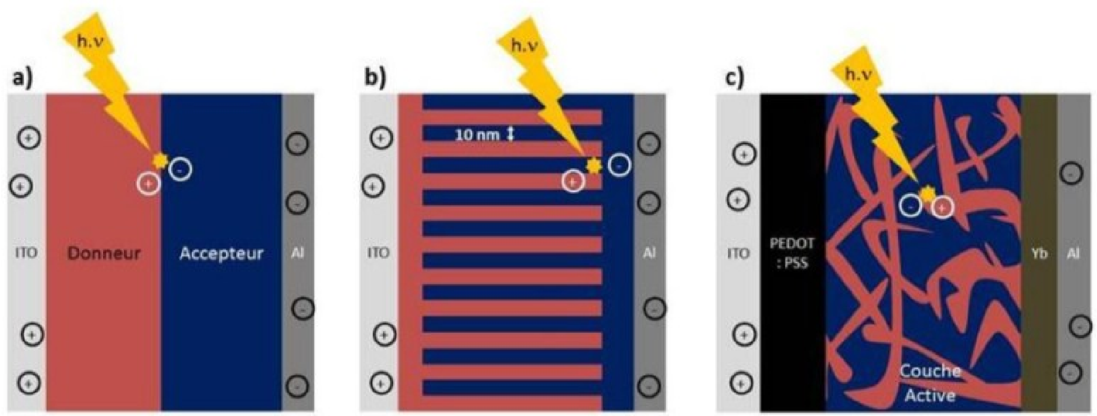
=> power and **yield** of the solar cell

short-circuit current



Open circuit voltage

Carriers life-time



Illustrations : courtesy Roland Roche PhD thesis, IM2NP, 2014

All solar cells :

Combine **nanometric** resolution with **large samples** (several centimeters)

Summary of the needs

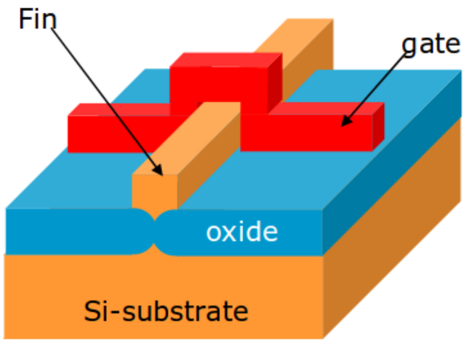
Dopant concentrations : all electronic devices

Work function : threshold voltage, ohmic/Shottky contacts, open circuit voltage for PV

Current : dielectric breakdown, ferroelectricity, thermo/pyro electricity

Resistance of contacts

Time resolved measurement (life time of carriers for PV)



Capacitance : permittivity (high-k materials…), sensors…

Electro-mechanical coupling (piezoelectricity) : MEMS / NEMS

Temporary conclusion

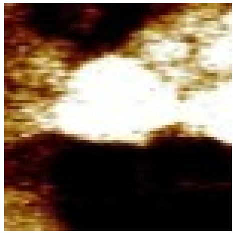
Tools exist.

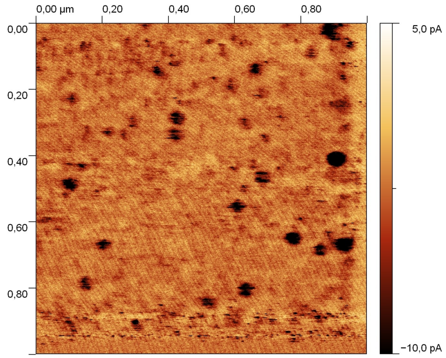
Their spatial resolution is indeed **nanometric**

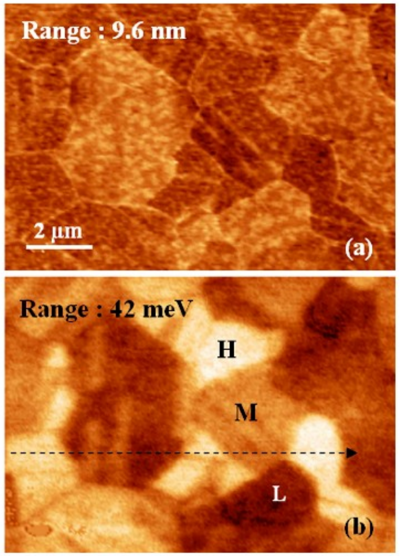
Their develoment is now **mature**

They are **wide spread** in the labs

What are their performances from a metrological point of view ?







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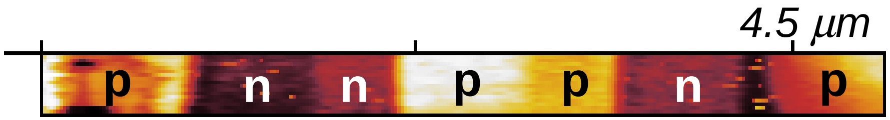
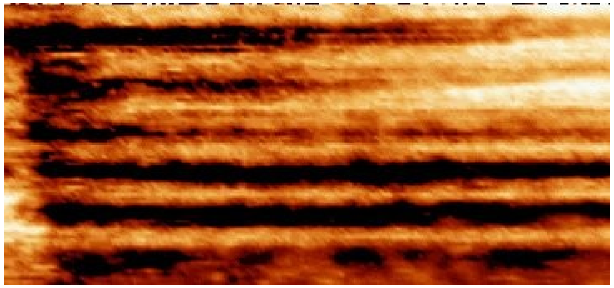
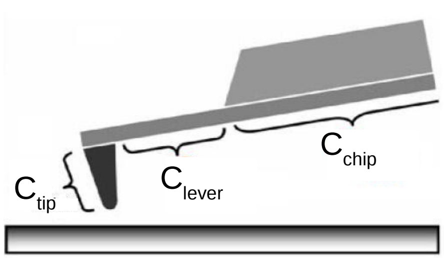


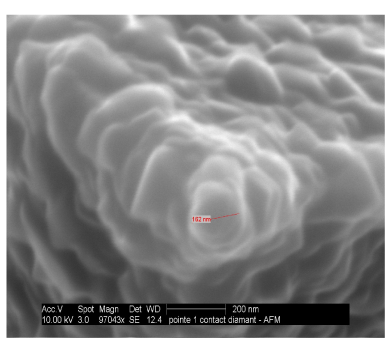


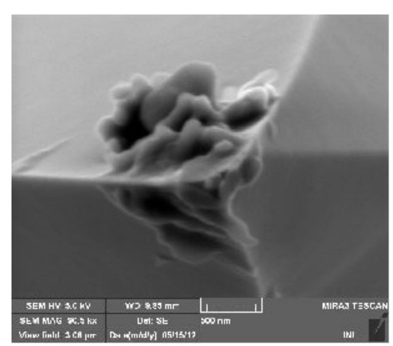
The problems

Overview of the parameters hindering reliability of AFM based measurements

● **Coating** of the tip	Repeatability
● **Shape of the tip**	Repeatability
● **Parasitic capacitances** : chip – sample, tip – sample, apex – sample...	Accuracy
● **Nature of the tip – sample contact**	Trueness, reproducibility
● **Tip – sample area of contact**	Trueness
● **Species present on the surface** : e.g. water (polar solvant, containing ions)	Trueness Reproducibility
● What happens if you apply a **huge electric field** ? Electrochemistry ? Field driven diffusion ? What happens when current flows : Joule heating ?	Trueness Reproducibility







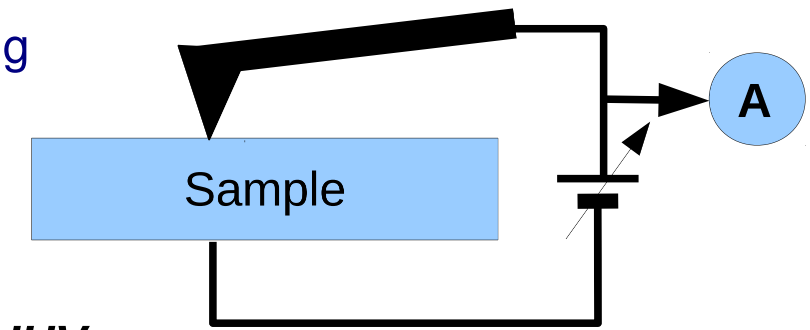
Reaching metrological quality of measurements seems to be a tough task !

Instrumental Challenges : TUNA

Size of the tip / contact area ?

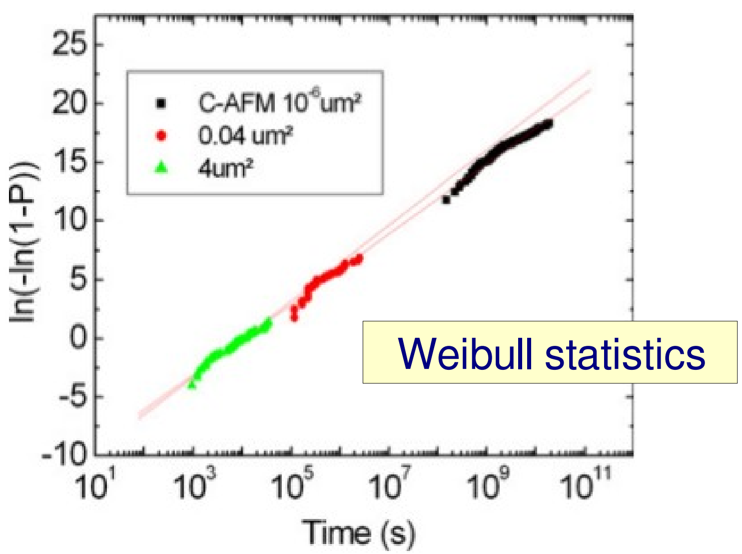
Radius of the tip : 10 – 100 nm depending on the coating

Area of contact important to compare measurements

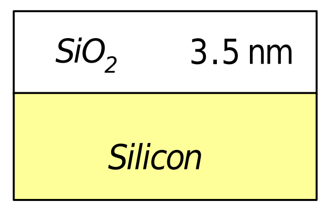


$PtIr_5$ coated tip

Estimated radius : less than 2 nm in UHV.



P. Delcroix et al. Microelectronic Engineering 88 (2011) 1376–1379
Estimated surface in UHV : 10 ± 6 nm²



Red and green points : measurements on **know surfaces** of contact (large electrodes)

+ **scale laws** of Weibull statistics

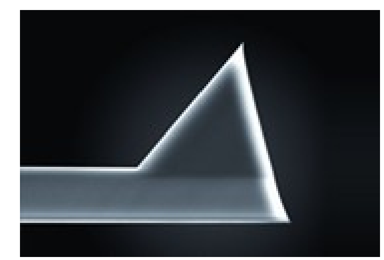


Image : nanoandmore

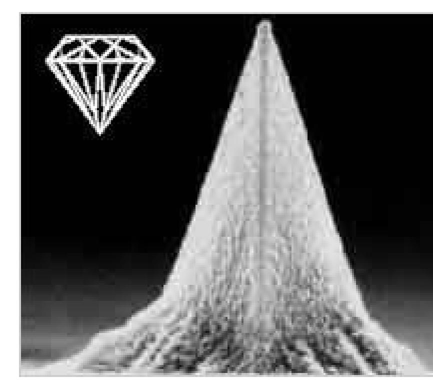


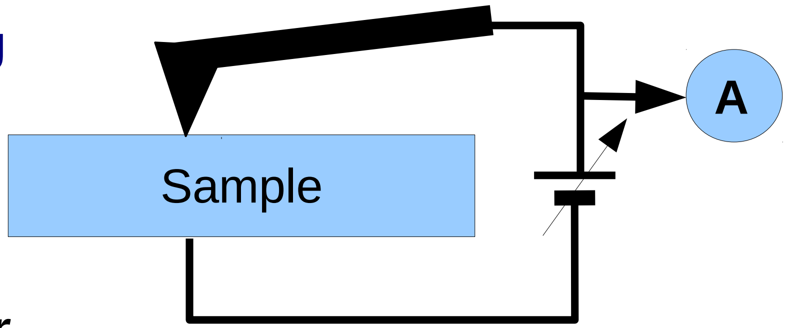
Image : nanoworld

Instrumental Challenges : TUNA

Size of the tip / contact area ?

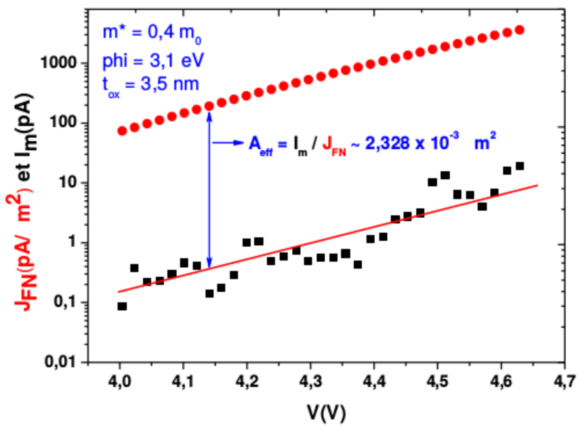
Radius of the tip : 10 – 100 nm depending on the coating

Very small area of contact



$PtIr_5$ coated tip

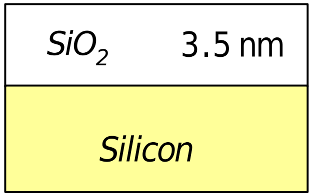
Estimated radius : 13 nm in air.

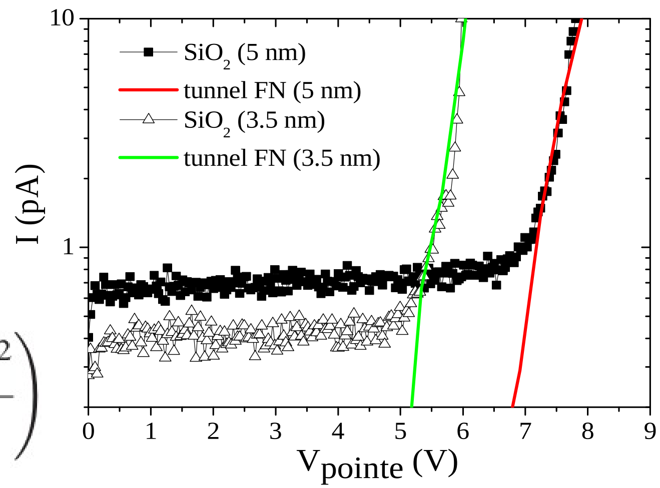


W. Hourani et al. (PhD thesis, INSA Lyon)

Fowler Nordheim injection

$$I = \pi a_c^2 \frac{e^3}{16\pi^2 \hbar \phi} (E_{ox})^2 \exp\left(- \frac{4}{3} \frac{(2m_{ox})^{1/2}}{\hbar e} \frac{f \phi^{3/2}}{E_{ox}} \right)$$





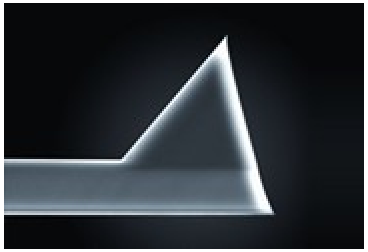


Image : nanoandmore

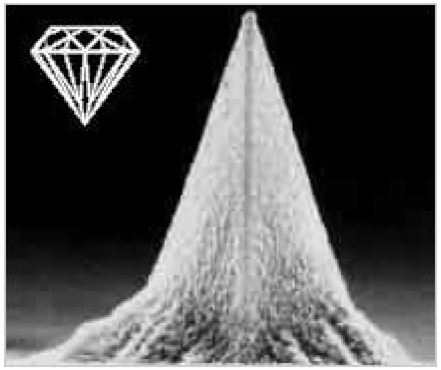


Image : nanoworld

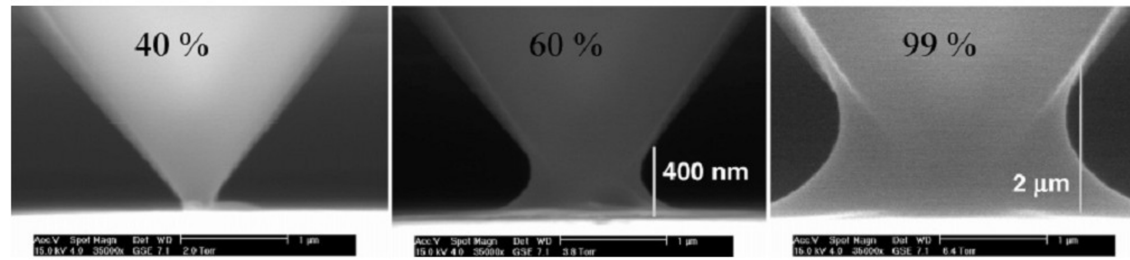
Here comes the water meniscus

Measurement in air :

A water meniscus is present at the tip apex

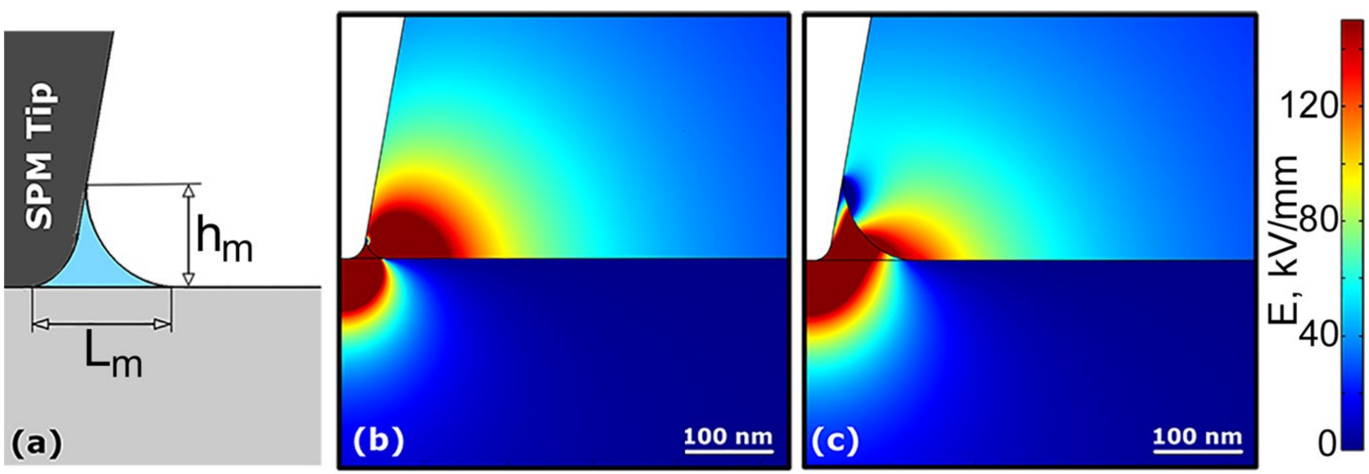
Water is a (bad) conductor

Water modifies the distribution of electric field lines



*Weeks et al., Langmuir **21**, 8096 (2005)*

Water increases the size of the contact area



Ievlev et al. Appl. Phys. Lett. 104(9), 2014

Force applied on the surface (setpoint)

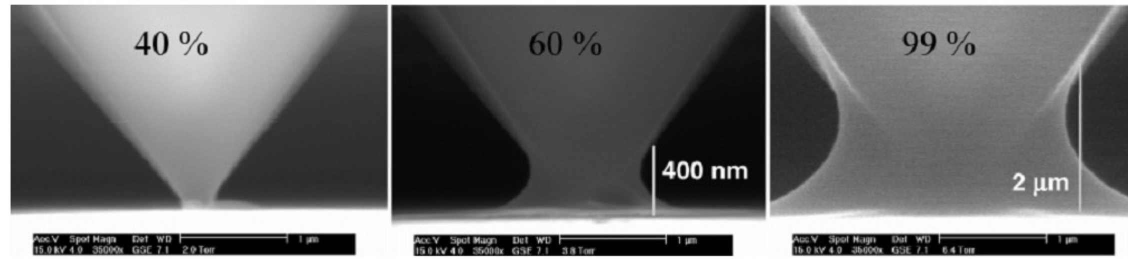
Roughness of the surface

Coating

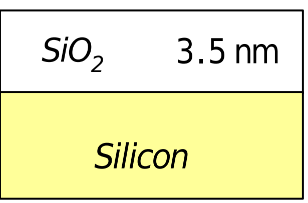
Does environment play a role on the result of electrical measurement ?

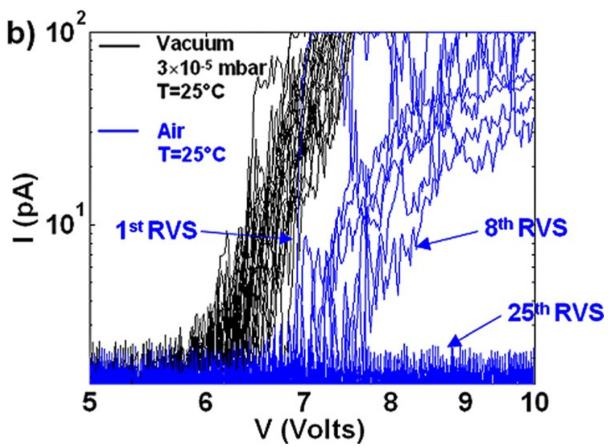
Obviously : Yes !

Oxidation of the tip-coating



Weeks et al., Langmuir ***21****, 8096 (2005)*



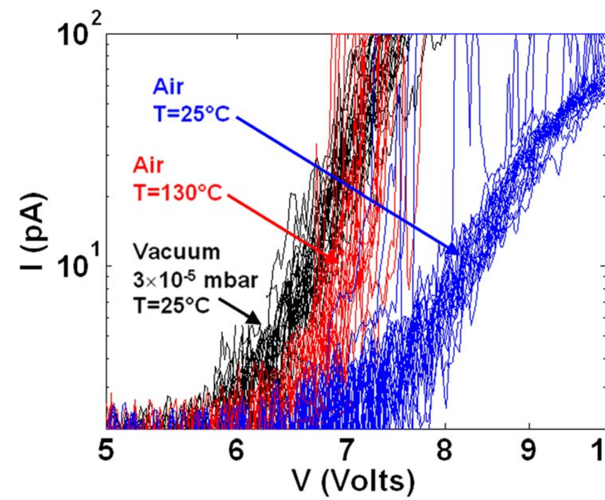


RVS : ramped voltage stress

In air : permanent degradation of the tip after 8 RVS

Oxidation ?

No degradation @ 130°C (less water) may confirm oxidation

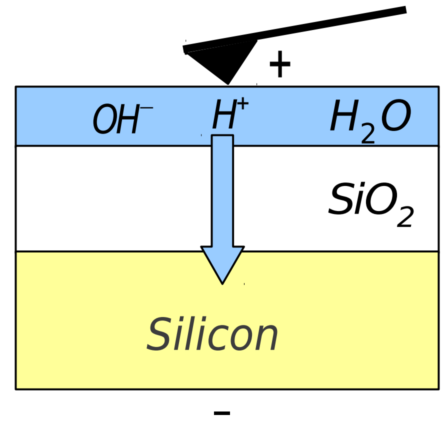


$$Pt + nH_20 \rightarrow PtO_n + 2nH^+ + 2ne^-$$

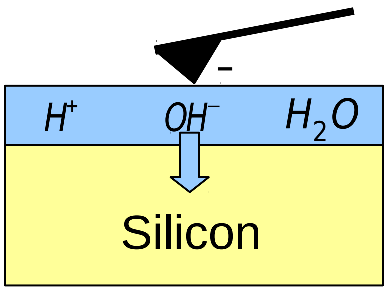
R. Arinero et al. J. Appl. Phys.110 (014304), 2011,

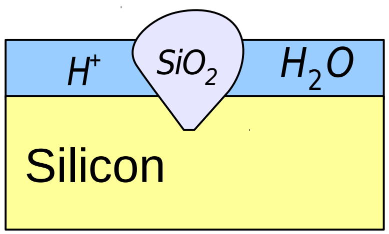
Obviously : Yes !

Oxidation and dégradation of the sample



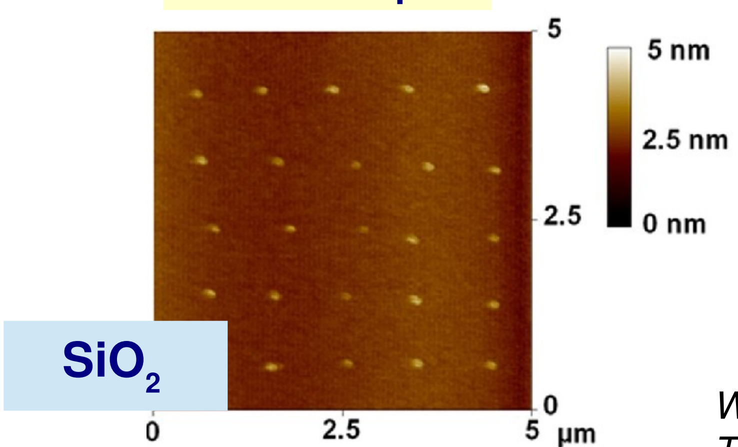
OH^- versus H^+ injection under high electric field





Oxidation of the sample
(V<0 on sample)

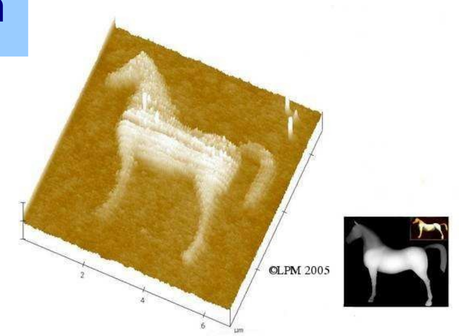
V>0 on sample



Surface degradation after poling of a 3,5 nm thick SiO_2 layer on Si

surface degradation

oxidation



W. Hourani et al, J. Vac. Sci. Technol. B 29, 01AA06, 2011

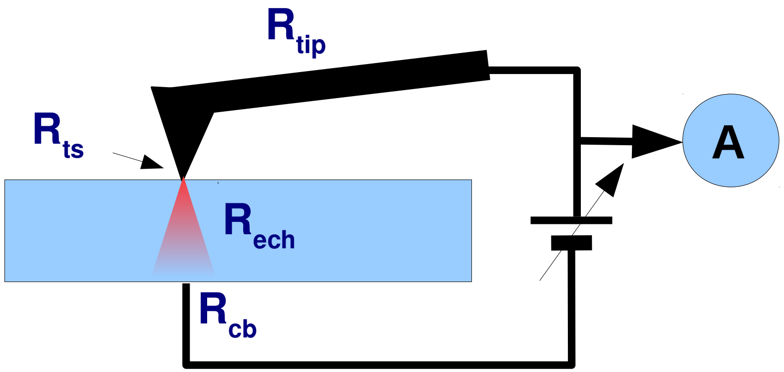
W. Hourani et al, Microelec. Reliability 51:2097, 2011

(SSRM : same problem with the exact area of contact)

$$R_{ech} + R_{tip} + R_{cb} + R_{ts} > 1\ k\Omega$$

$R_{tip} \sim 1\ k\Omega$

What if $R_{ech} < 1\ k\Omega$?



Measurement of extremely high doping levels ?

Modulation of the force applied to the sample in order to modulate the spreading resistance

Schulze et al. Ultramicroscopy 161, 2016

R_{ech} : Spreading Resistance

R_{tip} : resistance of the tip

R_{cb} : resistance of back contact

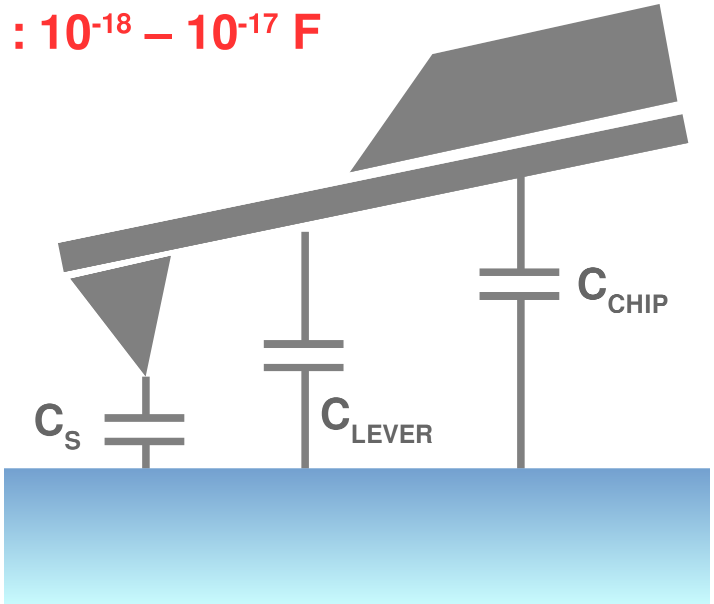
R_{ts} : resistance of the contact between the tip and the sample

Measurement of conductors ?

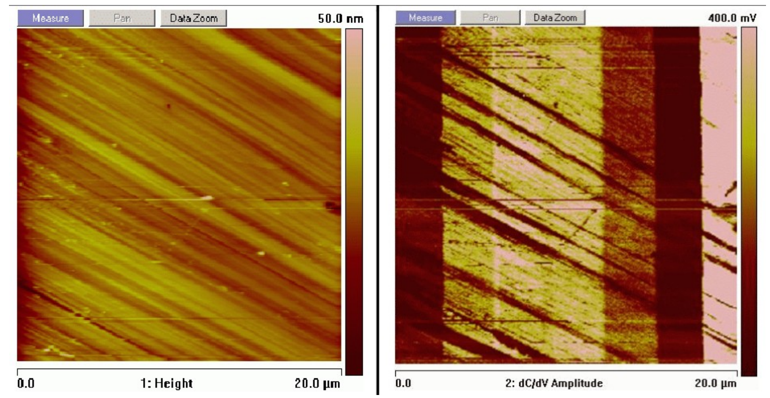
2, 3 or 4 probes systems => resolution = tens of nanometers

Instrumental challenges : SCM

C_S : $10^{-18} – 10^{-17}$ F

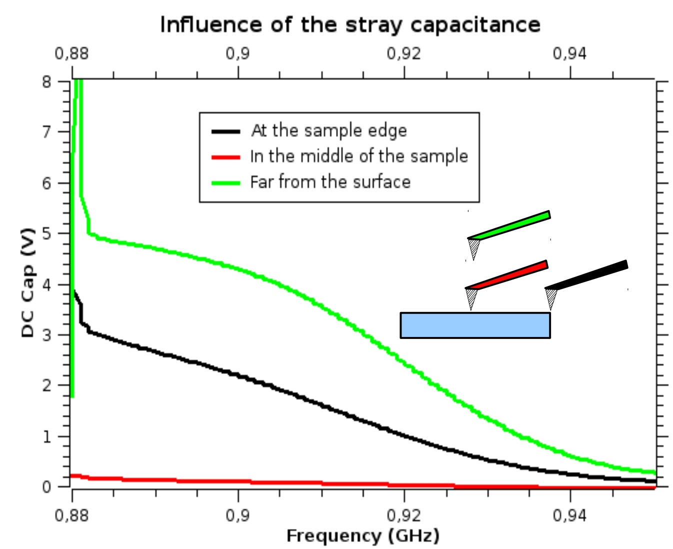


$C_{ECH} + C_{LEVER} + C_{CHIP}$: ~ 5.10^{-13} F ! (0,65 pF with our system)



Influence of topograhy on SCM signal

Resonance curve of the SCM sensor



Variation of the ***sensitivity*** *of the SCM sensor as a function of the position of the levier on the sample*

SCM **signal extremely small** due to very small area of contact

Signal **drops** for **high** dopant concentrations

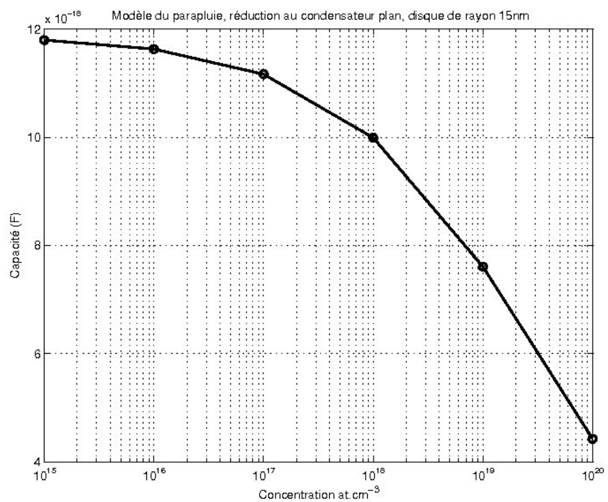
Signal to noise ratio drops because of **stray capacitance**

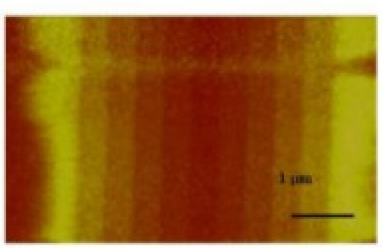
Inversion of contrast in SCM

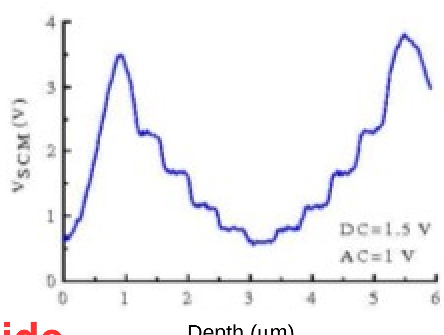
Errors in the determination of carrier type in case of worn tip (loss of metal coating)

Inversions of contrast expected also **when the quality of the top oxide is bad** (SCM signal vs concentration not monotonous any more)

How to grow a good quality oxide when dopant profile is needed ? (Temperature of growth must be kept low)





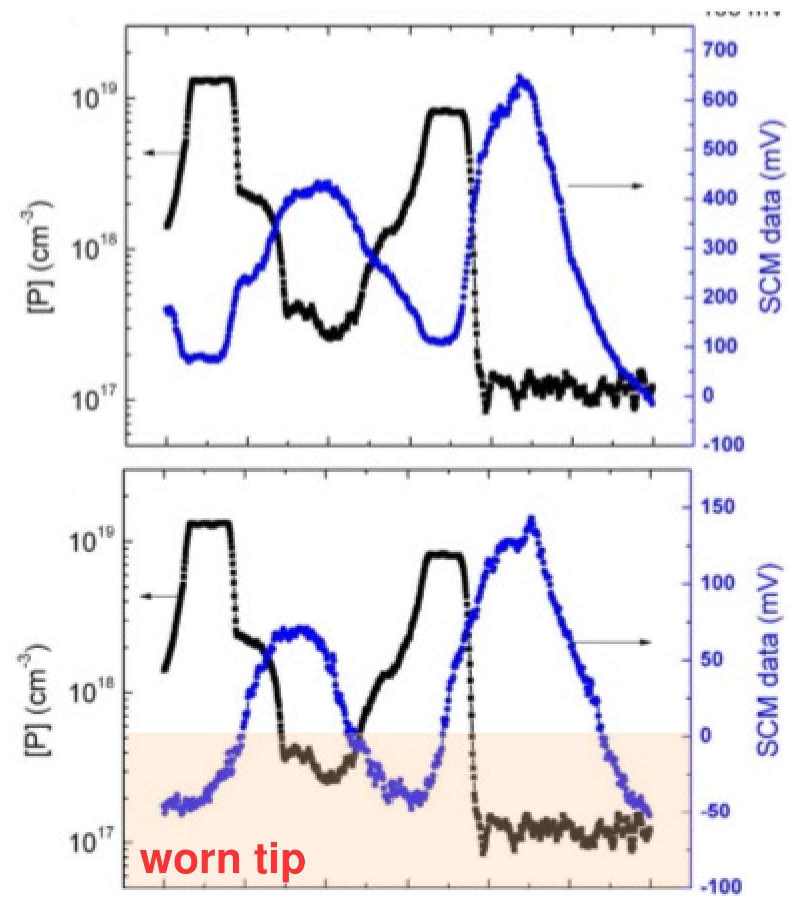


Bad oxide

Investigation of tip-depletion-induced fail in scanning capacitance microscopy for the determination of carrier type

Lin Wang*, Brice Gautier, Andrei Sabac, Georges Bremond

Ultramicroscopy 174 (2017) 46–49



SCM analyses of n-type staircases : SCM data of opposite sign compared to lower concentrations

Lowering the stray capacitance

Solutions to enhance the signal to noise ratio ?

Subtract the parasitic capacitance

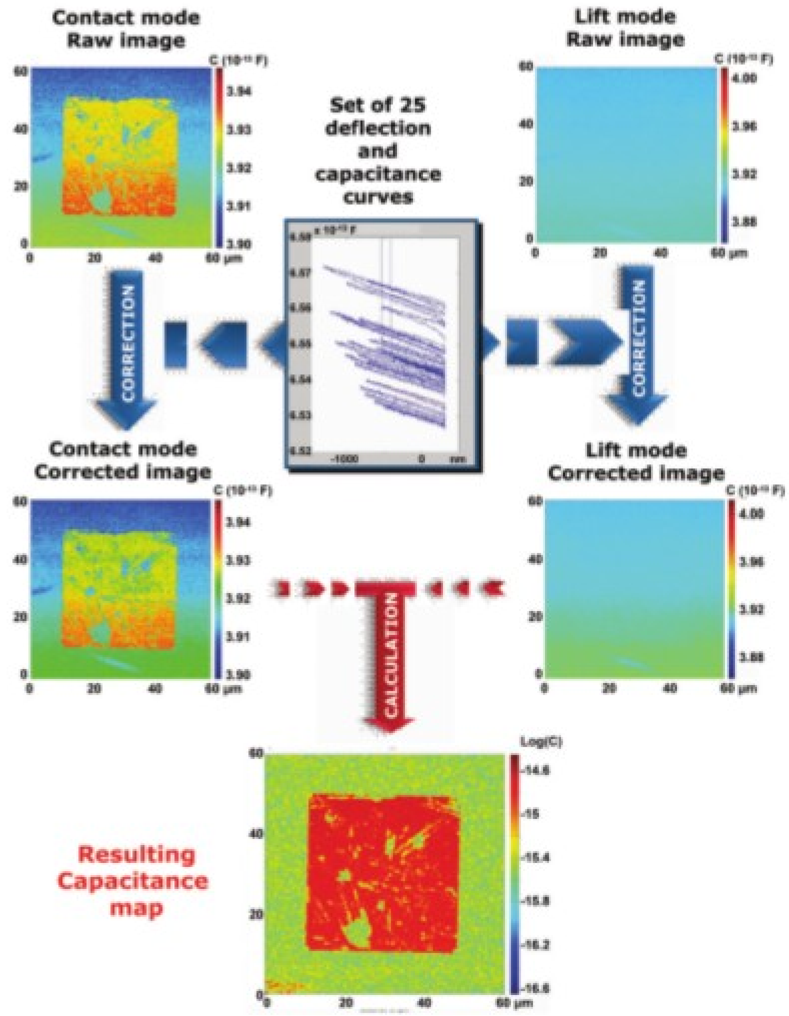
Estevez et al. Appl. Phys. Lett. 104, 083108 (2014)

Subtract the displacement current due to stray capacitance in order to extract the information of interest. (e.g. polarisation switching current)

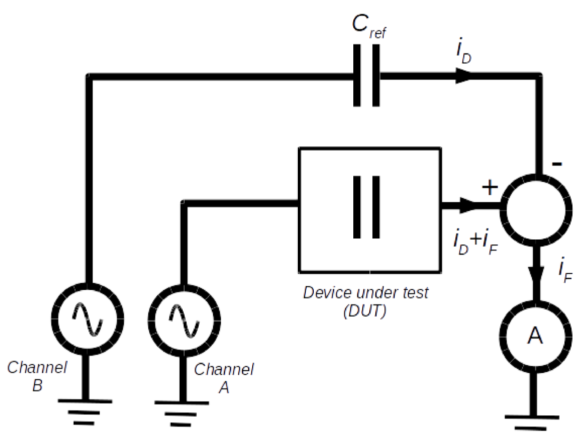
Simon et al. Rev. Sci. Instr. 88, 023901 (2017)

Increase frequency + impedance matching => Scanning Microwave Microscopy

Huber et al, Rev. Sci. Instrum. 81, 113701, 2010



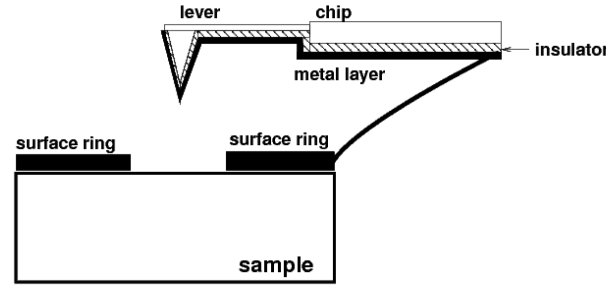
Estevez et al. Appl. Phys. Lett. 104, 083108 (2014)



$I_D = C\ dV / dt$

Simon et al. Rev. Sci. Instr. 88, 023901 (2017)

Lowering the stray capacitance



Piezoelectric detection of the deflexion => sensitivity !

Replace all AFMs !

Lower parasitic capacitance ?

Suppression of the lever and chip

Shielding

High aspect ratio tips

Hydrophobic tips

Surface and tip at the same potential

Non contact / tapping modes

Mechanical behaviour ?

Coating ?

Full metal tips and Joule effect

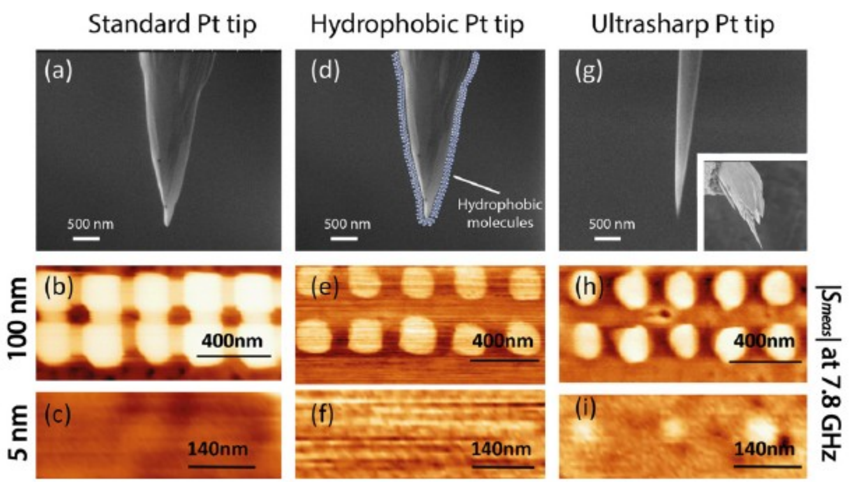
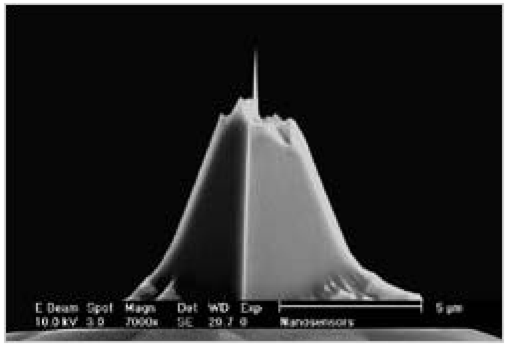


Figure 2. SEM images of three tips used in the experiments: (a) a commercial Pt tip (Rocky Mountain Nanotechnology© [51]), (d) a standard tip coated with a hydrophobic self-assembled monolayer (C_8H_{17}-SH), and (g) an ultrasharp tip refined by FIB. (b), (e), (h) $|S_{meas}|$ amplitude images at 7.8 GHz for an 100 nm nanodot using these three tips acquired separately. (c), (f), (i) A digital zoom to highlight the 5 nm dot resolution in three cases. We did not zoom for the smallest dots when scanning because we need images with the calibration kit to deduce their capacitance values.

Wang et al. Nanotechnology 25, 405703, 2014



https://www.nanoandmore.com/AFM-Probe-AR10-NCHR.html

Calibration samples

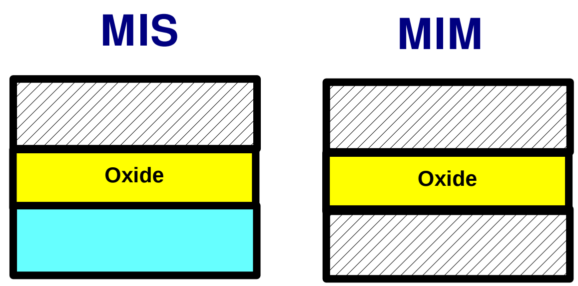
Capacitance and resistance

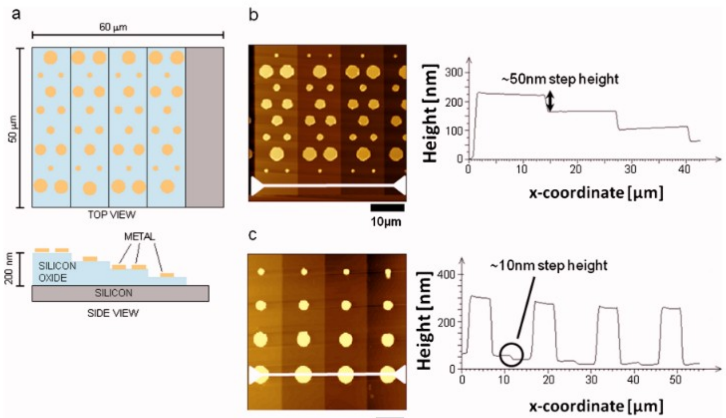
- Known metal => know work function
- Known, reproducible and « perfect » oxide : SiO_2, microelectronics fabrication facilities => known permittivity = 3,9
- Known semiconductor substrate (MIS)

Support from modelisation required

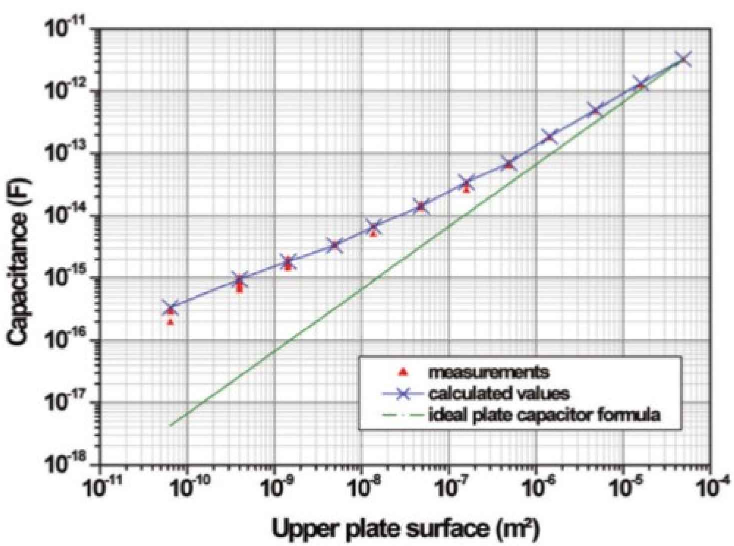
Complex geometries including AFM tips
Simulation of the field lines
cross talk

Capacitor

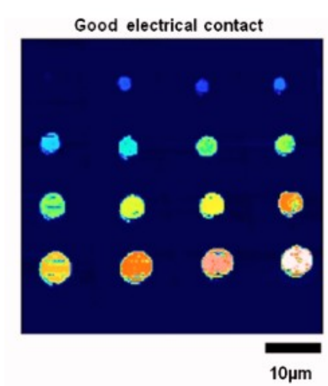




Huber *et al.*
REVIEW OF SCIENTIFIC INSTRUMENTS **81**, 113701 (2010)



Estevez et al. Appl. Phys. Lett. 104, 083108 (2014)



The needs : a summary

Magic tips

Conductive (metallic)
Constant shape (no more coating loss)
Good mechanical properties => predictible shape => modelling
High aspect ratio if no instrumental evolution

New instrumentation

2-or-more probes AFM instruments
Low capacitance set-up (remove cantilever and chip)
Combine instruments (e.g. SCM + SSRM => impedance measurement)
Combine **large samples** with nanometric spatial resolution (arrays of tips?)

Control of environment

Remove water
Find a compromise between ultra-high vacuum / controlled atmosphere
Beware of material modification due to absence / presence of water

Thank you for your attention