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

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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
- Calculation power
- Energy consumption
- Data storage
- Measurement

Device
- Transistors
- Memories
- Sensors
- Photovoltaic cells
- MEMS / NEMS
- Interconnexions

Figures of merit
- Speed
- Energy yield
- Power
- Density of integration
- Cost
- Reliability: failure analysis
- Lifetime
- Retention time
- Fatigue
- Metrology: accuracy, repeatability, trueness, reproducibility

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BIPM, Paris
Electrical measurements at the nanoscale: how?

Near Field Microscopies:

A nanometric electrode positioned with a nanometric precision

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?

Near Field Microscopies:

- A nanometric electrode positionned with a nanometric precision

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
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
AFM modes for electric and magnetic measurements

Designed for topography but allows wide choice of electric modes

- **EFM**
  - Electric field
  - Capacitance

- **C-AFM**
  - Resistance

- **TUNA**

- **SSRM**
  - « resiscope »

- **SCM**
  - Capacitance

- **SMM**

- **KFM**
  - Single pass KFM
  - Double pass KFM
  - AM - KFM
  - FM - KFM

- **PFM**
  - Ferroelectricity

- **DART PFM**

- **BE-PFM**

- **ESM**
  - Ionic conduction

- **MFM**
  - Magnetisation

**Contact**

**Non-contact**
Why go nano? The example of micro/nanoelectronics

**MOS cell**

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**RAM Memories, MOS and CMOS transistors**

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

\[
C = \frac{Q}{U}
\]

- \(Q\): charge \(\Rightarrow\) available current \(I\)
- \(U\): applied voltage

\[
P = UI
\]

Electrical power

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

=> Greatest areas

=> Smaller thicknesses \(e\)

=> Higher permittivity \(\varepsilon\)

**Work faster!**

Increase frequencies of operation by reducing size

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

**3D FINFET**

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

**Plane / Plane approximation**

\[
C = \frac{\varepsilon S}{e}
\]
Overview of the characterization needs for the MOS gate

Gate and contacts

Properties under investigation:

- **Work function**: threshold voltage $V_{th}$ shift
  
  $I_{ds} \quad V_G$

  $V_{ds} = 50 \text{ mV}$

- **Resistivity**

- **Line Edge Roughness (LER)**
  
  1.7 nm desired, 4-5 nm achieved

(Another challenge for the metrology of dimensions!)

SEM view of the roughness on MOS transistor

Court. J. JUSSOT, CEA-LETI
Mesurement of work function with nanometric spatial resolution

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

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

Measurement of $V_0$ (surface potential) by the cancellation of $F_\omega$ by adjusting $V_{DC}$

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

FIG. 4. (Color online) (a) Topography and (b) WF mappings of the same polished copper area (12 × 8 μm²).
Overview of the characterization needs for the MOS oxide

Regardless of the geometry, always the same components:

- gate, oxide, source, drain

Oxide

Properties under investigation:

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

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

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

Endurance: evolution of the electrical parameters when in use

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

SiO$_2$: less than 1 nm

- Direct tunnel
- Fowler Nordheim
  - High leakage

High-k materials (e.g. HfO$_2$)

- Higher $\varepsilon$
- Same capacitance
- Higher thickness

Defects in the oxide volume $\Rightarrow$
- Poole Frenkel transport mechanisms

Leakage currents $\Rightarrow$ injection of defects in the oxide $\Rightarrow$ ageing of the transistor $\Rightarrow$ 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)
Overview of the characterization needs for the MOS source and drain

**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)

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

Capacitance

accumulation depletion

$\Delta V$ $V_{DC}$

p type

doping level #1

$\Delta C$ doping level #1

doping level #2

$\Delta C$ doping level #2

Phase signal

SCM image of a sample containing $pn$ junctions @ 0.125 $V_{dc}$
Dopant mapping with an AFM: Scanning Spreading Resistance Microscopy (SSRM)

- 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

Carriers life-time

All solar cells:
Combine nanometric resolution with large samples (several centimeters)

Illustrations: courtesy Roland Roche PhD thesis, IM2NP, 2014
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 development is now **mature**

They are **wide spread** in the labs

What are their performances from a metrological point of view?
The problems
Overview of the parameters hindering reliability of AFM based measurements

- **Coating** of the tip
- **Shape of the tip**
- **Parasitic capacitances**: chip – sample, tip – sample, apex – sample...
- **Nature of the tip – sample contact**
- **Tip – sample area of contact**
- **Species present on the surface**: e.g. water (polar solvant, containing ions)

- What happens if you apply a huge electric field? Electrochemistry? Field driven diffusion? What happens when current flows: Joule heating?

Reaching metrological quality of measurements seems to be a tough task!
Size of the tip / contact area?

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

Area of contact important to compare measurements.

Estimated radius: less than 2 nm in UHV.

*Image: nanoandmore

Weibull statistics

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

+ **scale laws** of Weibull statistics


Estimated surface in UHV: $10 \pm 6 \text{ nm}^2$
Size of the tip / contact area?

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

Very small area of contact

Estimated radius: 13 nm in air.

PtIr$_5$ coated tip

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

Fowler Nordheim injection

\( m^* = 0.4 \, m_e \)
\( \phi = 3.1 \, \text{eV} \)
\( t_{ox} = 3.5 \, \text{nm} \)

\( A_{m} = \frac{l_{m}}{J_{m}} = 2.328 \times 10^{-9} \, \text{m}^2 \)

Silicon

Image: nanoandmore

Image: nanoworld

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

Water increases the size of the contact area

Force applied on the surface (setpoint)
Roughness of the surface
Coating

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

Obviously: Yes!

Oxidation of the tip-coating

RVS: ramped voltage stress

In air: permanent degradation of the tip after 8 RVS

Oxidation?

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

\[
\text{Pt} + n\text{H}_2\text{O} \rightarrow \text{PtO}_n + 2n\text{H}^+ + 2n\text{e}^-
\]

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

Influence of the environment on the electrical measurements

Obviously: Yes!

Oxidation and dégradation of the sample

Surface degradation after poling of a 3.5 nm thick SiO$_2$ layer on Si

$\text{SiO}_2$

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

Oxidation of the sample (V<0 on sample)

$\text{SiO}_2 + \text{H}^+ + \text{H}_2\text{O} \rightarrow \text{SiO}_2\cdot\text{H}_2\text{O}$

Silicon


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

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

\[ R_{\text{ech}} + R_{\text{tip}} + R_{\text{cb}} + R_{\text{ts}} > 1 \, k\Omega \]

\( R_{\text{tip}} \sim 1 \, k\Omega \)

What if \( R_{\text{ech}} < 1 \, k\Omega \)?

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

Measurement of conductors?

2, 3 or 4 probes systems \(\Rightarrow\) resolution = tens of nanometers

\( R_{\text{ech}} \): Spreading Resistance
\( R_{\text{tip}} \): resistance of the tip
\( R_{\text{cb}} \): resistance of back contact
\( R_{\text{ts}} \): resistance of the contact between the tip and the sample
Instrumental challenges : SCM

\[ C_S : 10^{-18} - 10^{-17} \, \text{F} \]

\[ C_{ECH} + C_{LEVER} + C_{CHIP} : \sim 5.10^{-13} \, \text{F} \! (0,65 \, \text{pF with our system}) \]

**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**

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

**Influence of topography on SCM signal**
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)

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


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


Increase frequency + impedance matching

=> Scanning Microwave Microscopy

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

\[ I_D = \frac{C}{dt} \]

Lowering the stray capacitance

Lower parasitic capacitance?
Suppression of the lever and chip
Shielding
High aspect ratio tips
Hydrophobic tips

Piezoelectric detection of the deflexion => sensitivity!
Replace all AFMs!

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 (C₆H₁₂-SH), and (g) an ultrasharp tip refined by FIB. (b), (e), (h) Sₐmₜₐₜ amplitude images at 7.8 GHz for a 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
The needs: a summary

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

The needs: a summary

Magic tips

- **Conductive** (metallic)
- **Constant shape** (no more coating loss)
- **Good mechanical properties** => predictable 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