Physics of Failure based Lifetime estimation of MEMS devices

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ID : FIALAB

- Our core business
  - **Analyses & expertise Laboratory** (100% service delivery)

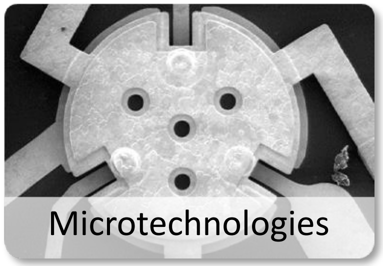
- Key figures
  - NOVA MEMS creation in 2003, rebranding in 2013 (NOVA MEMS -> FIALAB)
  - SAS, Privately held (familial shareholding - X. Lafontan)
  - 2012 turnover : 777.000€ (CNES + R&D funding + Customers)

- Our staff & infrastructures
  - 9 collaborators (8 technical : 1 PhD., 4 engineers, 3 technician)
  - Technical operations : CNES, Toulouse (950m^2) ; Admin/Sales : TIC Valley, Labège

- Our major partners
  - CNES - Toulouse, Industrial partner
  - LAAS - Toulouse, Research partner

FIALAB : Markets & references

- Your products : Our markets



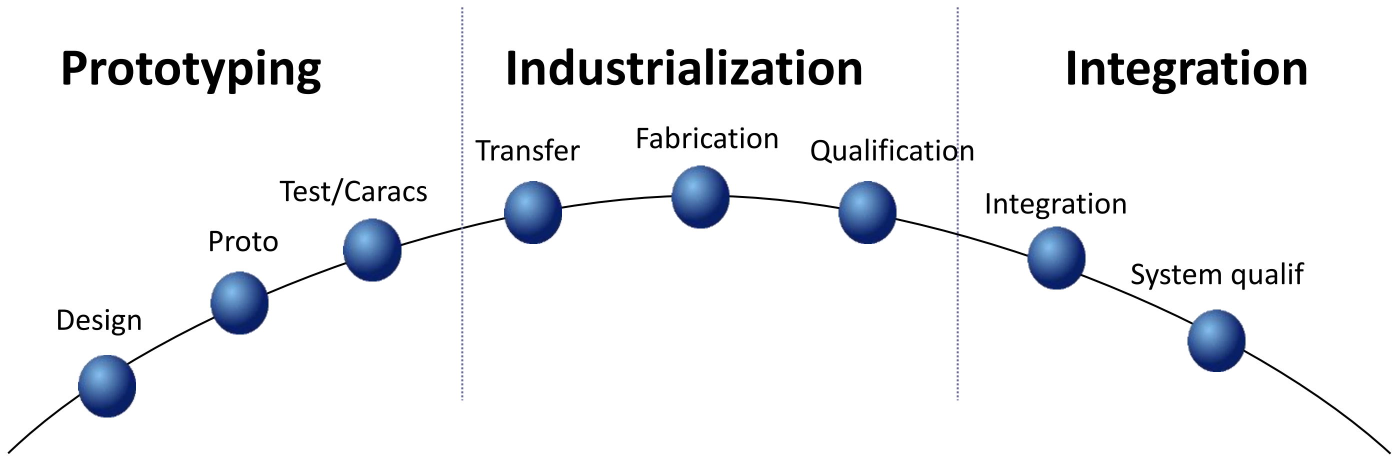
- Your industrial field : our references

Semiconductor	Aerospace	Ground transport.	Energy	Security
Esterline	Astrium	Actia	Areva	Cobham
Exelia	Cnes	Alstom	Schlumberger	Gemalto
Freescale	Crane Aerospace & Electronics	Bosch	Schneider Electric	MBDA
Measurement Specialties	Liebherr	Continental	Total	Sagem Défense Sécurité
Meggitt	Technofan	Valeo		Thales Security Systems
Sofradir	Nexeya			
ST	Thales Alenia Space			
Tronics microsystems	Zodiac Aerospace			

Other industries & Public research

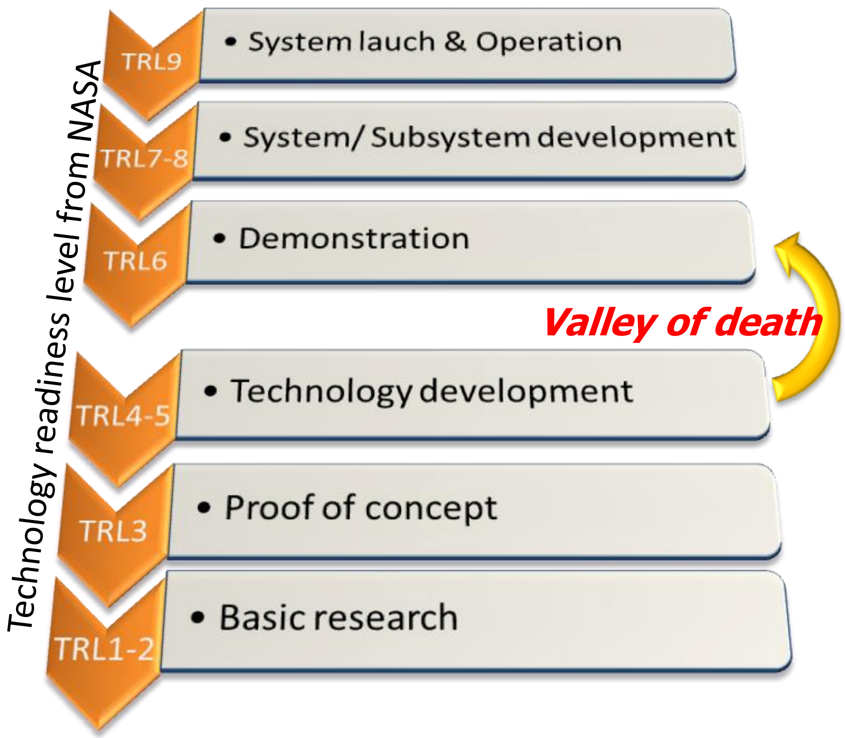
Essilor, Pierre Fabre, Sorin Group, IMS, LAAS-CNRS, ONERA

Maturité technologique



- **Development cost**
  - Sensors: 10 – 100 M€
  - Actuators: 100 – 1 000 Mn€

Product development pitfalls



Valley of death: between prototyping and integration / end-use

Main causes :

- » Lack of reliability data
  - » No statistical models
  - » No ageing laws
- » High development costs
  - » Low visibility on the budget required to develop a MEMS device (active structure + packaging+ electronics + tests + qualification)
  - » Difficult to reach volume production
  - » Need to reach a threshold confidence level to enable the use of new technologies

The reliability assessment process flow

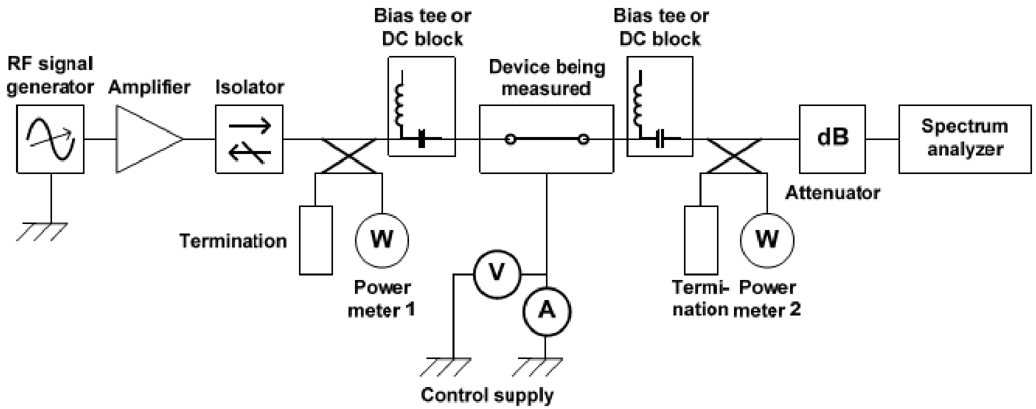
Maturity of the product	Tests performed		Output
Development: 10s to 100 pieces manufactured	HALT (Highly accelerated lifetest): stress the device far beyond its expected specifications to evaluate the margins. (thermal, mechanical, electrical stresses, and coupled)	Loop	Design verification / modification Process validation Optimization **No lifetime quantification**
	When completed, go on to the next step. But mind the gap!		
Industrialization: 10 to 10000 pieces Stabilized process	HASS (Highly accelerated Stress Screen) = **reliability evaluation** of devices representative of the production Temperature, humidity, mechanical tests, radiations…	Loop	Lifetime assessment in any given environment Failure rate Fine tuning of the process / design
Mass production: up to Billion pieces	**Qualification** = check the functionality of the devices after the accelerated aging conditions **defined by the mission profile (customer input)**		Go / no Go information

Need some standards

- Which standards use to evaluate the reliability and qualify the MEMS devices?
  - ESCC approach: evaluation / qualification
  - Evaluation testing:
    - Electrical stress (Life test, HTOL…)
    - Mechanical stress (shocks, vibrations…)
    - Environmental stress (temp. shock and cycling, seal tests…)
    - Assembly capability
    - Radiation testing
  - Other standards:
    - CEI 60068 – environmental testing, CEI 60749 – Semiconductor devices
    - MIL-883-STD
    - JESD22
- How to we account for the specificities of MEMS devices?
  - Multi-physic system
  - Specific failure mechanisms
  - Acceleration factors unknown

The RF-MEMS case study

- Standard for testing: ISO 62047-5
  - Definitions (actuation voltage, RF parameters, resonant frequency, etc.)
  - Methodology to measure the actuation voltage, the impedance, S Parameters



  - Reliability: « to characterize the lifetime of a RF-MEMS switch, it has to be actuated in a repetitive way until failure » (approx. translation from french…)
    - Cold switching
    - Hot switching
    - Other environmental tests (TCy, HBT, shocks, vib)
  - Typical failure mechanisms: dielectric charging, self-actuation, material transfer and dielectric formation on the ohmic contacts)

MEMS peculiarities

Electronic products	MEMS devices
Processes well established, yield	Processed still been tuned
Gap between the designers and the process teams	The designers must know about the process (impact on the material prop., interactions between structures)
The package aims at separating the operating part from the exterior (except electrical connections)	The package needs to allow the sensing / actuation of the mobile parts and to transmit the signals (elec, optical, chemical)
Reliability issues are well-known	Reliability issues are numerous (product dependant) and involve many physical domains
Accelerated aging (quite) easy to setup	May be difficult to run multiple tests in parallel (MOEMS): expensive custom setup

Methodology

Preliminary study

- ✓ Bibliographic survey
- ✓ Synthesis of field experience
- ✓ Technological analyses on functional devices
- ✓ *Mission profiles*

Identification of (most probable) failure mechanisms
Definition of test plan (with critical stresses to accelerate failure mechanisms)

"Custom" Reliability test plan

- ✓ Realization of stress tests (one batch = one test), with in-situ integrity monitoring

Failed devices (failures due to stress tests)

Reliability evaluation synthesis

- ✓ Failure analysis
- ✓ FMEA building
- ✓ Lifetime & failure ratio in testing environments

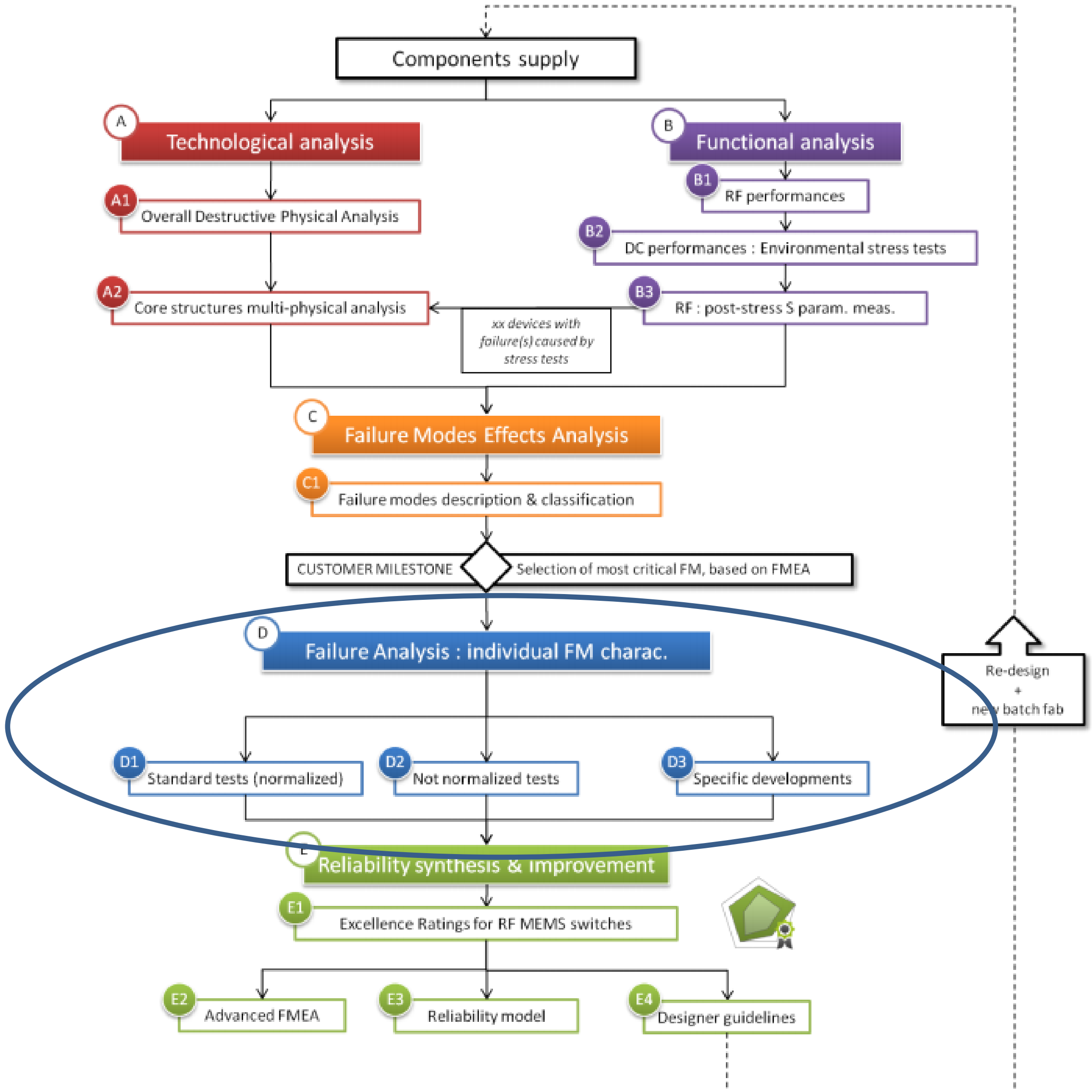
Failure mechanisms ranking and associated, accelerating stresses

Qualification plan definition

- ✓ Selection of safe operating area, according to device limits

"Product" dedicated qualification plan

The RF-MEMS case study



Et en pratique ?

Quels moyens de caractérisation des mécanismes de défaillance ?

The RF-MEMS case study

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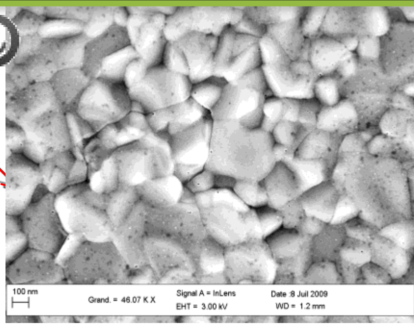
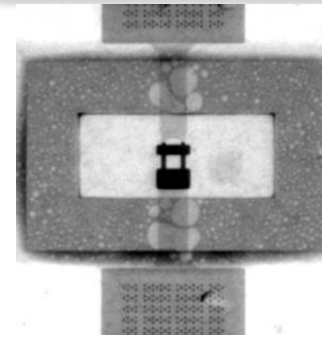
TESTS ANALYSES EXPERTISE

Fatigue & creep of movable parts

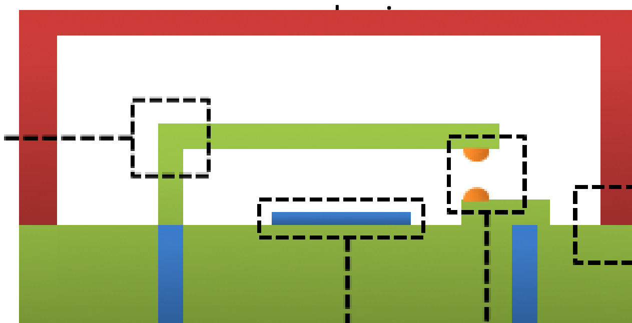


Decohesion of grain boundaries

Packaging hermeticity



MS sealing ring

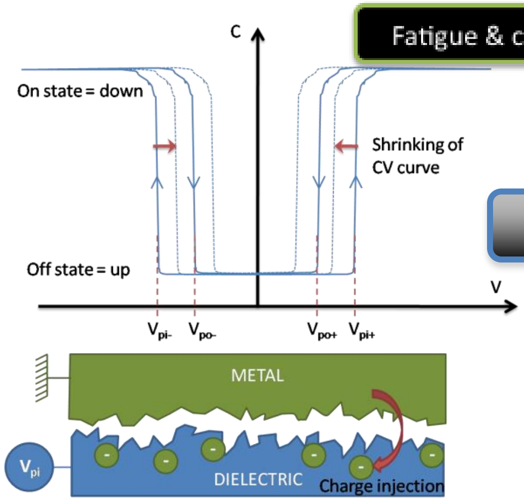


Fatigue & creep of movable parts

Charging effect

Packaging hermeticity

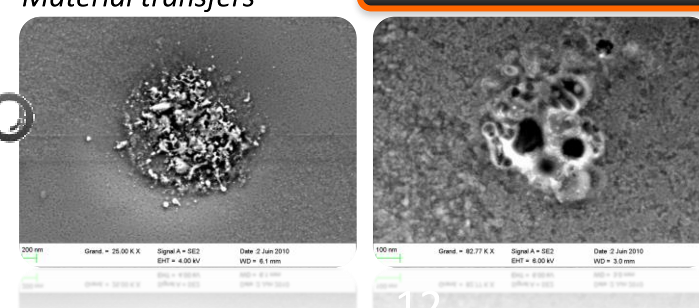
Contact degradation



Charging effect

Contact degradation

Material transfers



The RF MEMS case study

- Proposed test plan

Lifetime assessment

Operating tests under different environments
- HTOL, LTOL, DH, Radiation, Temp cycling, etc.
- Voltage cycling / DC stress

Robustness

- Die shear / wire pull
- Hermeticity measurement
- ESD
- Vibration / shocks
- Temperature step
- …

Qualification tests

Failure mechanisms

Dielectric charging assessment
- KPFM
- Cycling tests under different polarization conditions

Contact degradation
- Micro bending tests
- Cycling tests / Power handling ability

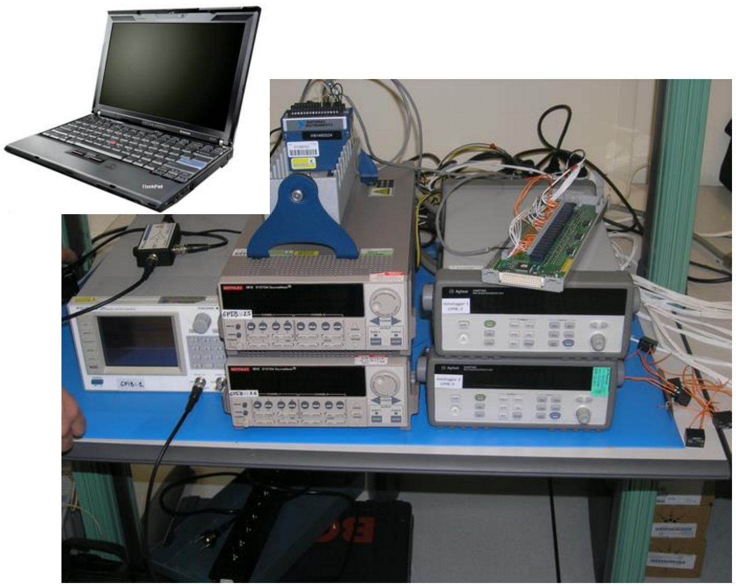
Packaging
- Sealing material inspection (SEM-EDX, EBSD)

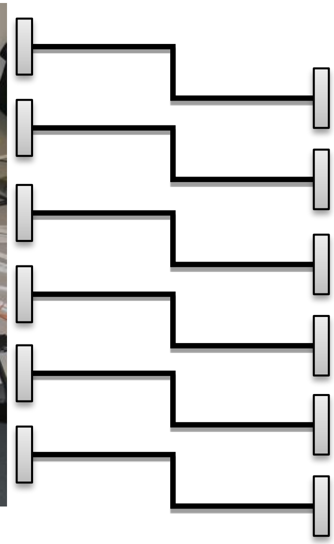
Creep / material fatigue
- Vpi / Vpo shift under permanent / cyclic actuation
- Crack propagation tests
- EBSD

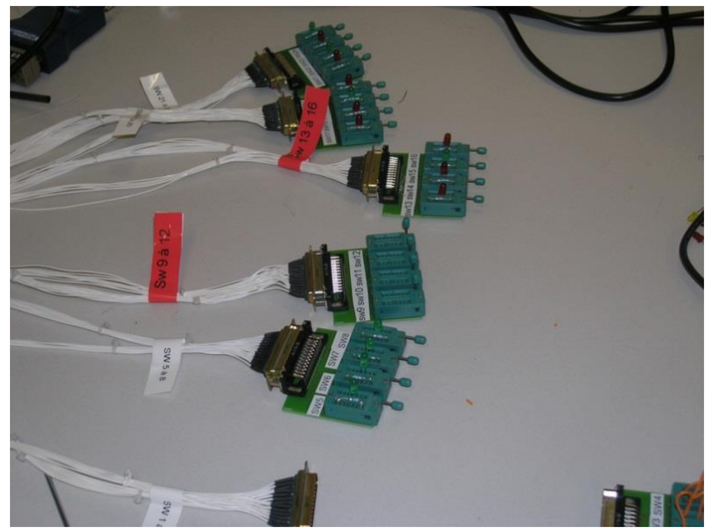
PoF / Acceleration factors

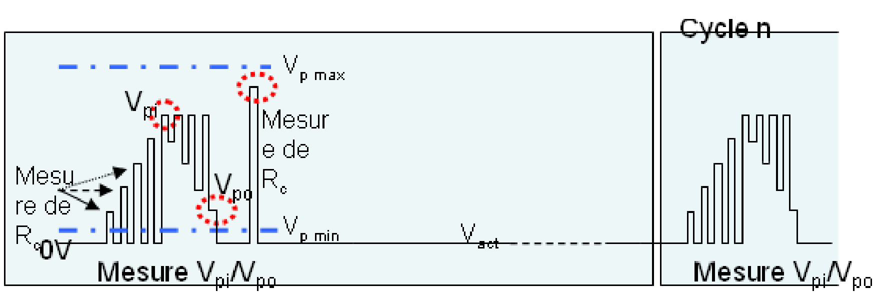
Environmental lifetest
MEMO project: CNES – TAS – LETI – XLIM

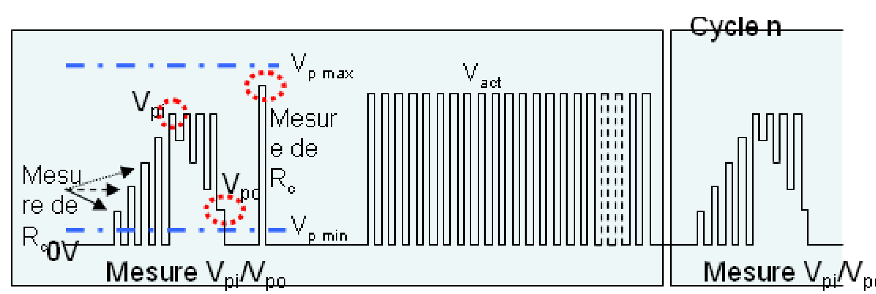
- 24 channels





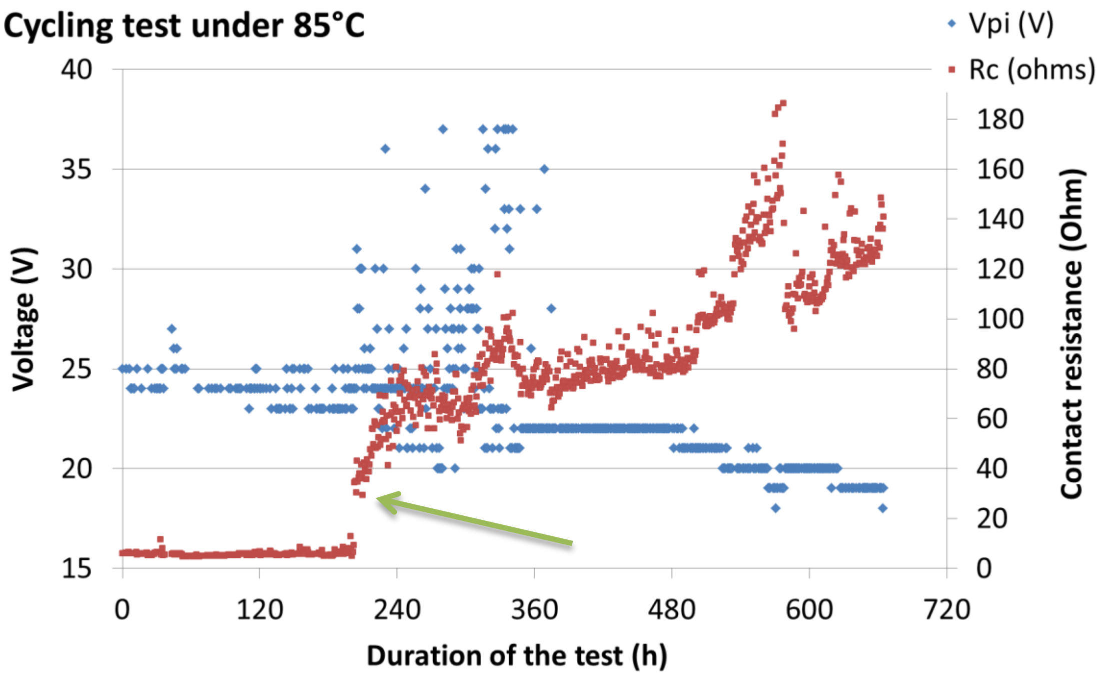






Environmental lifetest
MEMO project: CNES – TAS – LETI – XLIM

- HTOL



Cycling test at 1Hz

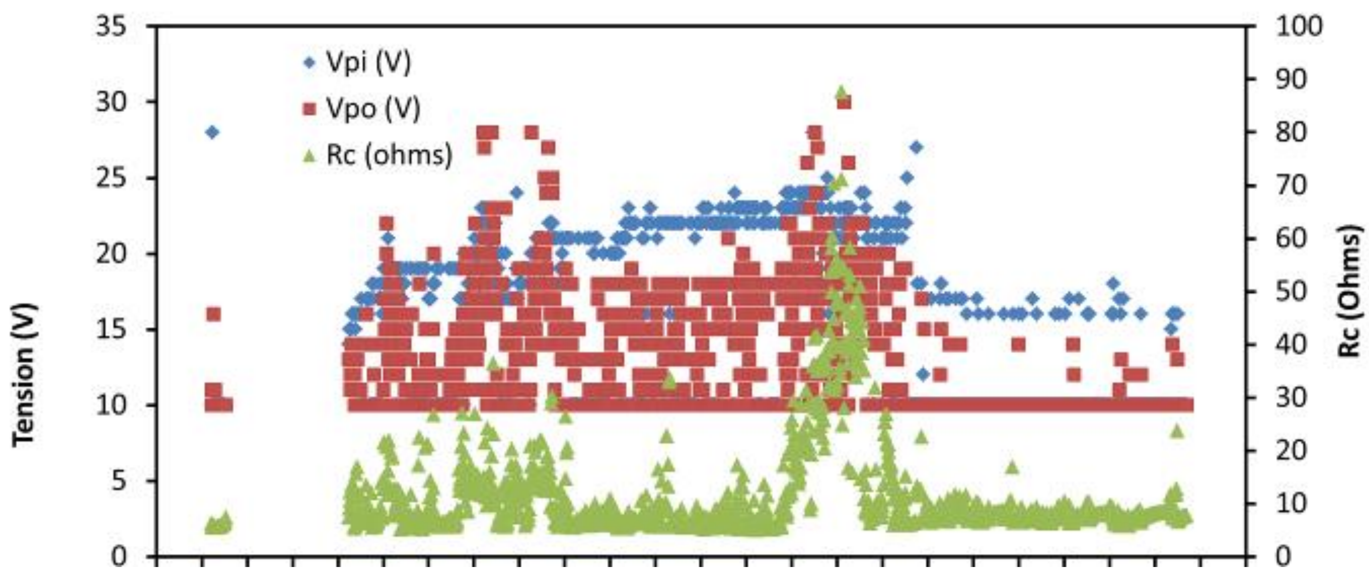
Contact resistance degradation

Mechanical relaxation?

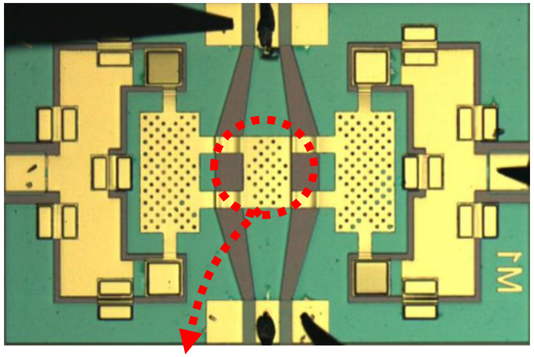
Environmental lifetest
MEMO project: CNES – TAS – LETI – XLIM

- Radiation test
  - 100 rad/h, 1000h
  - Vpi/Vpo/Rc measured every 30min

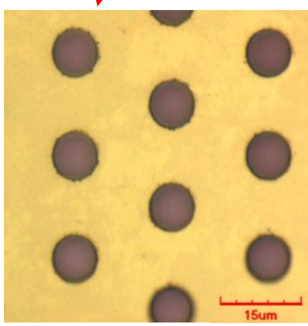
  - « DC stress » test



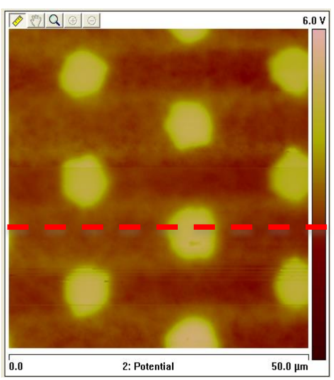
Experimental charging characterization: Kelvin Probe Force Microscopy techniques

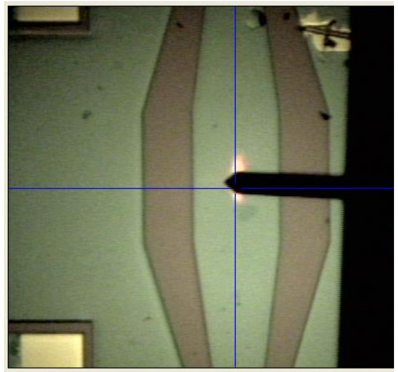


Microscope picture

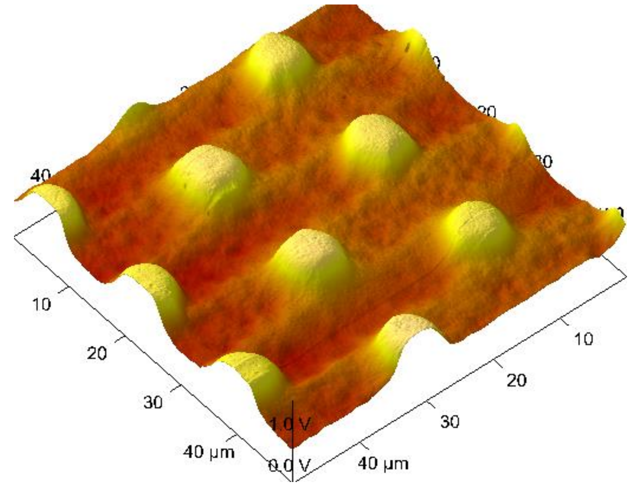


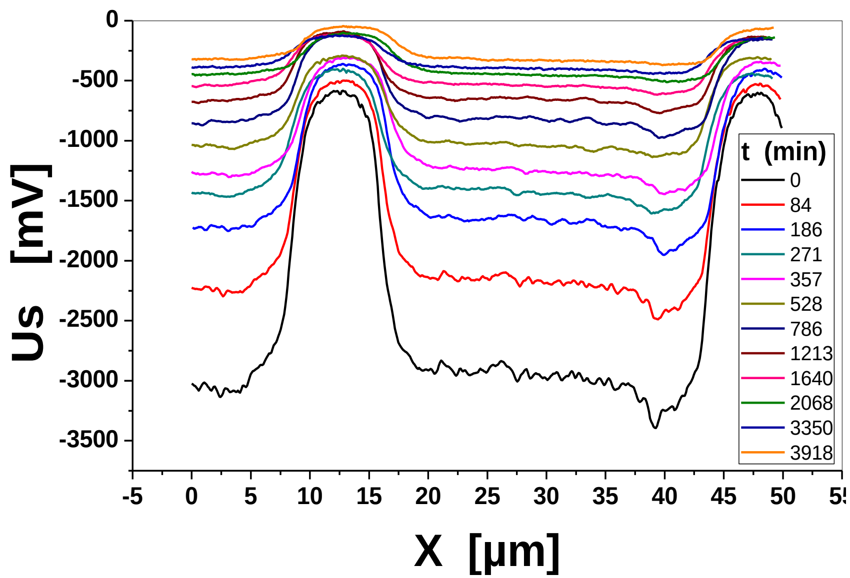
Surface potential





During KPFM scanning





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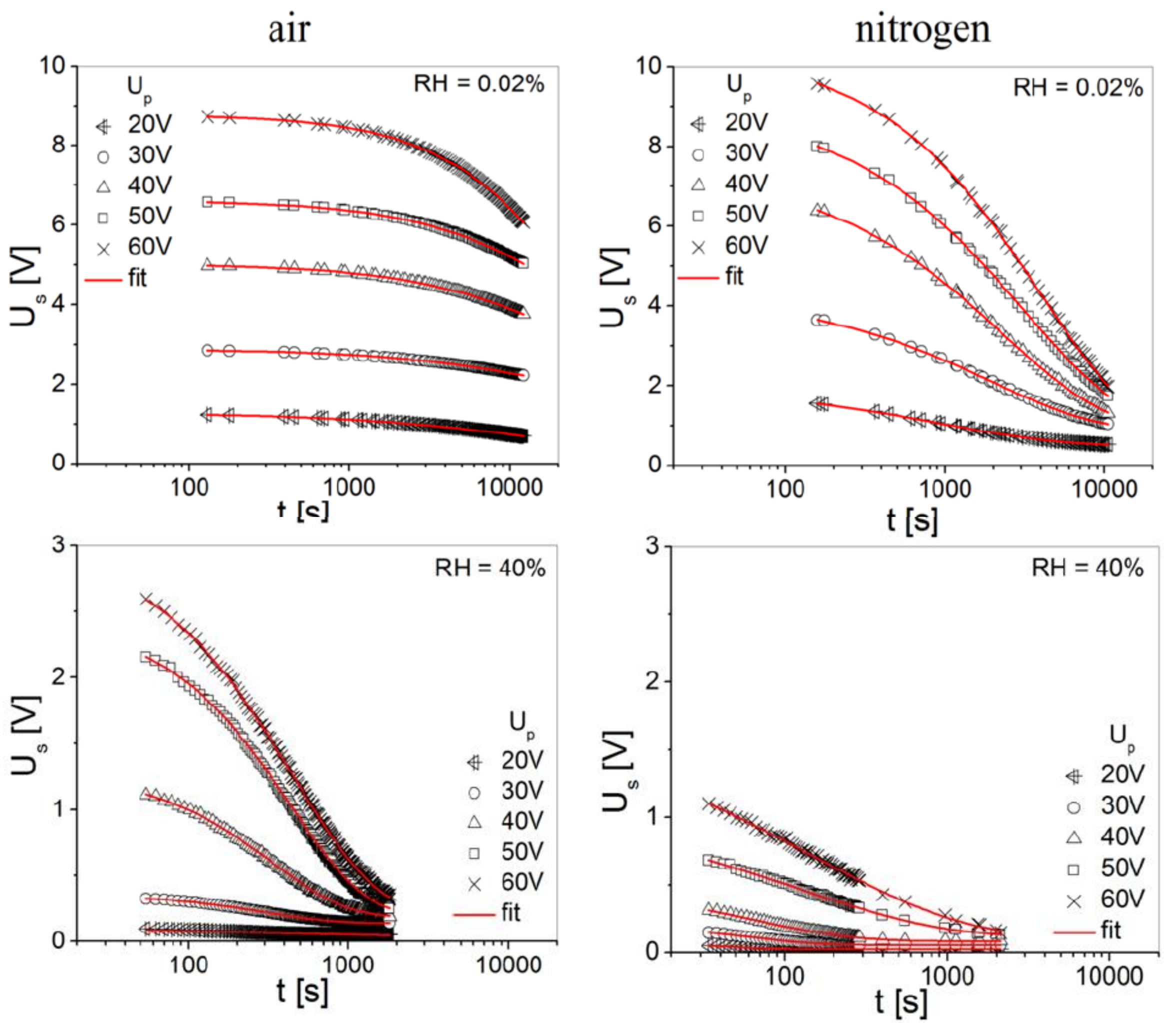

Vertical scales are different

Surface potential decay with time measured in air (left) and in nitrogen (right) under selected relative humidity levels for charges injected using different pulse amplitudes, *Up*.

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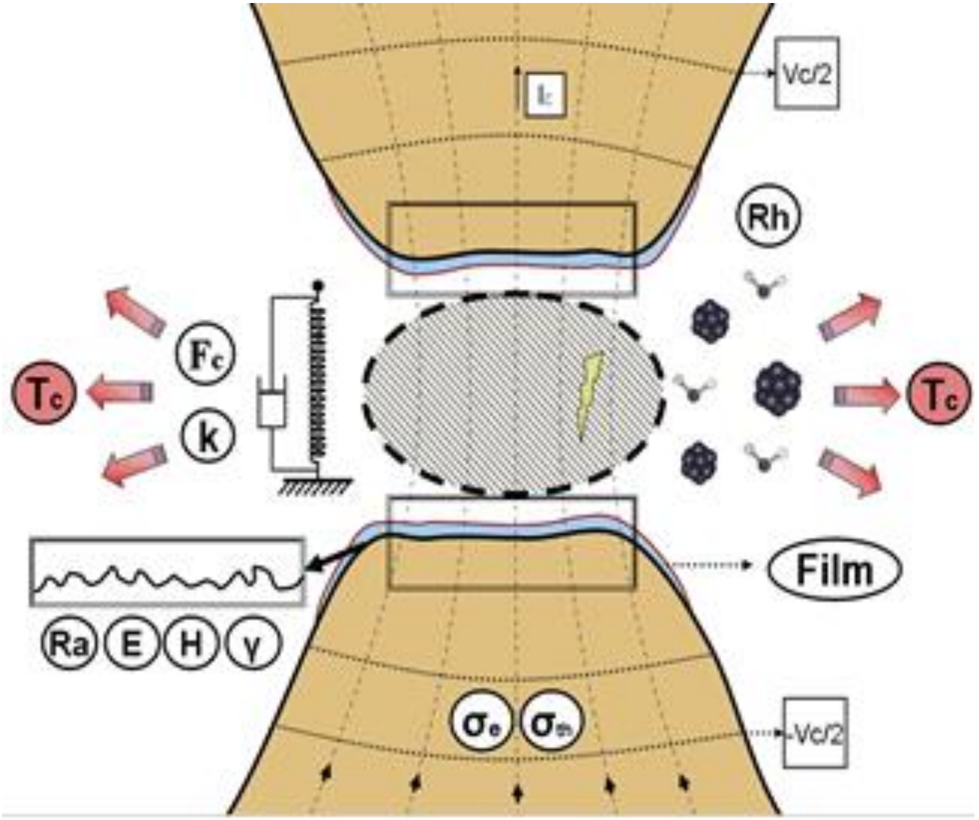
Electrical micro-contacts

- Problématique multiphysique
  - Mechanical effects
  - Electrical
  - Thermal
  - Chemical
- Ohm's law is not applicable anymore

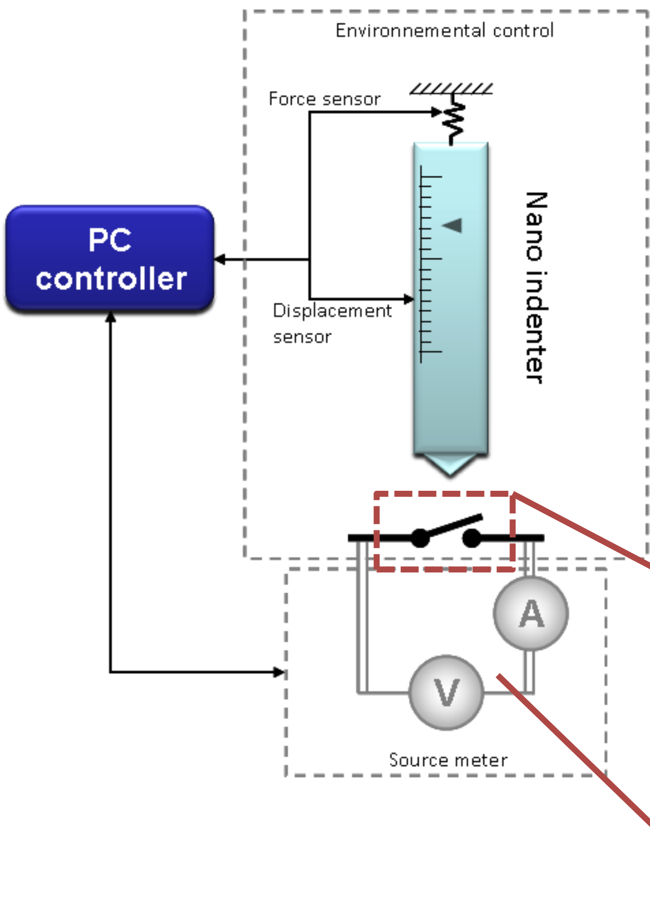
$$R_{Contact} = \Gamma(K) \underbrace{R_{Holm}}_{\text{Diffusive conduction mode}} + \underbrace{R_{Sharvin}}_{\text{Ballistic conduction mode}} \left(+R_{Film}?\right)$$

- The load applied by the actuator may vary with time (charging effect, creep)

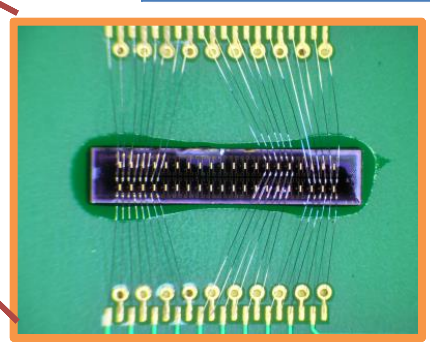


Description of the experimental set-up

Specific contact investigation:



Source Modes	Switching Modes
•Current source or voltage source	Hot switching Cold switching Mechanical switching
Input Parameters	**Range**
•Current level (Ic)	10^{-5} to 1A
•Maximum load applied (L_{max})	1µN to 6mN
•Contact voltage(Uc)	10^{-5} to 40V
•Holding plateau at load max t_{hold}	0 to several min
Environment	Dry nitrogen (< 5% RH)
Outputs	
•Voltage Drop (Vc) or current drop (Ic) [depending on the source mode]	•Contact stiffness (K)
•Tip Displacement (d)	•Contact resistance (Rc)

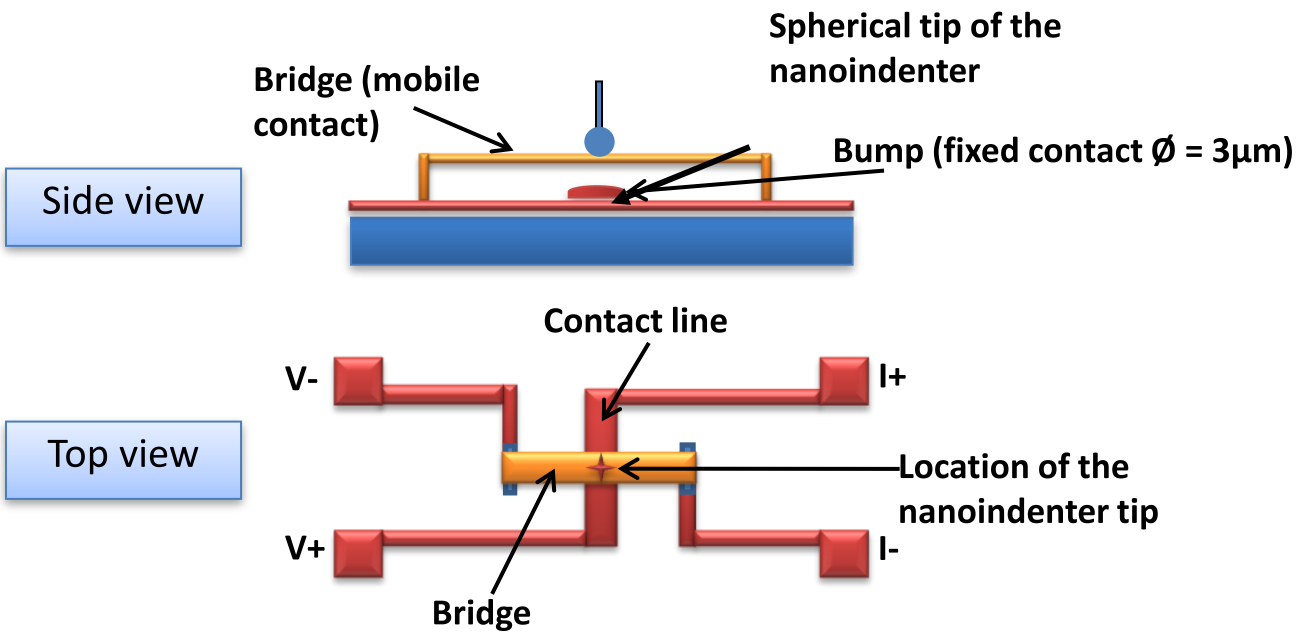


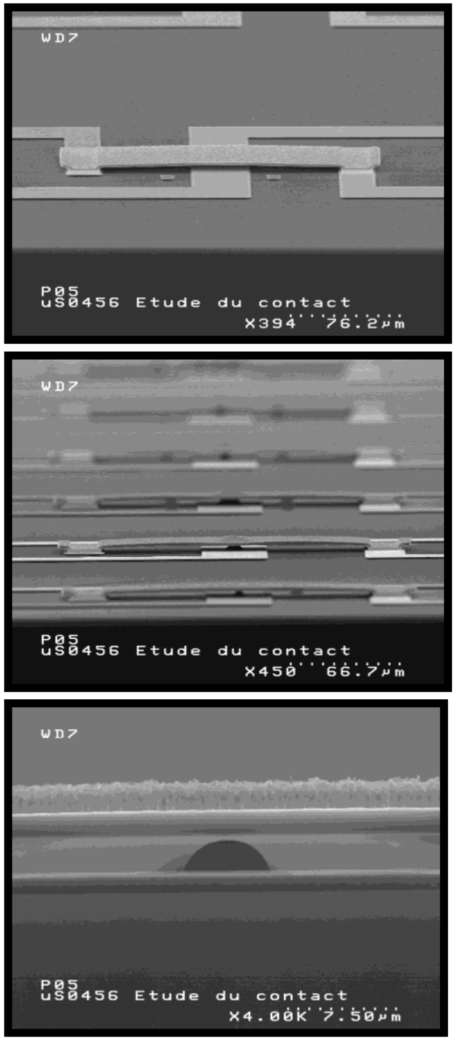
*Contact force resolution = 1µN
displacement resolution = 1nm

*test structures are reported and micro bonded on a PCB (Printed Circuit Board).

Test vehicles (LETI)

- Cross-rod experiment to compensate for the access resistances (from Holm)





Results: R_C VS F_C

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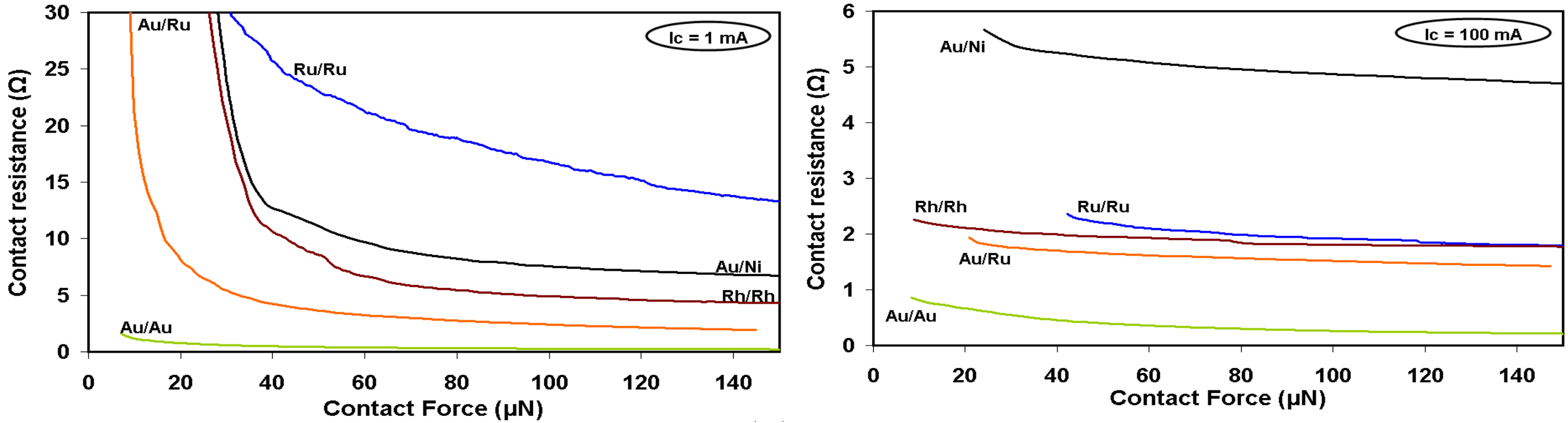
TESTS ANALYSES EXPERTISE



Contact resistance versus contact force as a function of the current flowing through the contact for Au/Ru, Au/Au, Ru/Ru, Rh/Rh and Au/Ni contacts at 1mA and 100mA ($V_{compliance}$ = 1V)

- **Au/Au contact** shows the more stable and the lowest contact resistance beyond contact force about 40µN from 1mA (R_c = 0.49Ω) to 100mA (R_c = 0.45Ω)
- **Rh/Rh contact** reaches a lower contact resistance at 140µN compared to the **Ru/Ru contact** at 1mA. This result could be attributed to the low resistivity of the rhodium compared to the ruthenium.
- **Au/Ru bimetallic contact** is relatively stable at the maximum contact load. From 1mA to 100mA, the contact resistance at 145µN decreases from 1.9Ω to 1.4Ω.

Conclusion

- MEMS components are now bridging the gap between development and successful integration in high-rel applications
- Need for standards, tuned for each family of MEMS
- Coupled approach environmental testing + failure mechanism identification and modelization (for acceleration factors determination)