IV Giornata IU.NET

Perugia - 21-22 settembre 2017

Francesco Pieri - UniPI

Sensors and MEMS @ IU.NET: status and perspectives

Where are we?

- More-than-Moore

- Already pervasive (and growing):
  - cellphones (already here): inertial, magnetic, resonators, ...
  - automotive (enabling for driverless cars): inertial sensors, LIDARs, ...
  - energy: thermoelectric/vibration energy harvesting
  - IoT (wearables, smart home, ...)
  - Biomedical for diagnostics and therapy (huge potential market, heavily regulated): biosensors, continuous drug delivery, ...
  - ....

- Sensors vs. MEMS?

- Access to technology is key:
  - tweak CMOS (inflexible)
  - In-house (limited in scope)
  - Partners with MEMS capabilities
  - Off-the-shelf (not-so-flexible; e.g. Europractice)

- MEMS Industry players: STMicroelectronics in Italy (and therefore Lab4MEMS I and II)

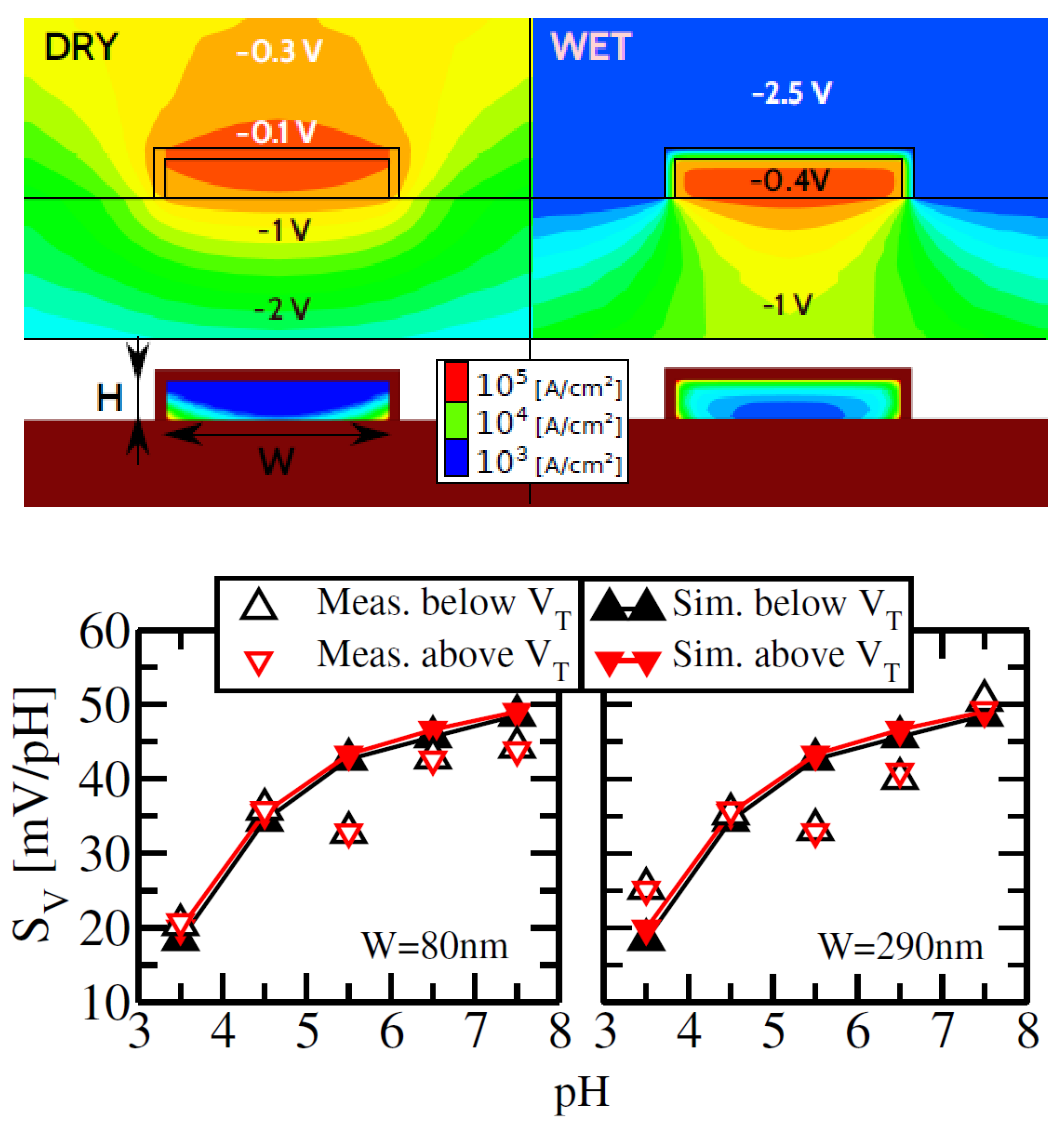
- MEMS/Sensors @ IU.NET

Sensors@UniUD: nano-electronic sensors

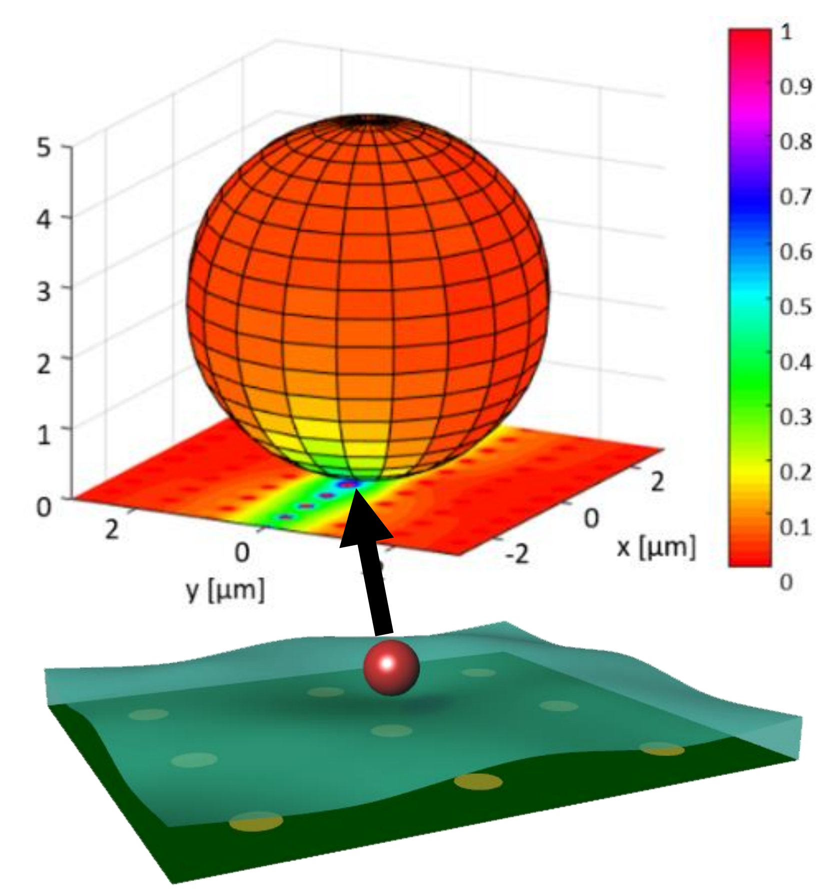
Nanoelectronics enables massively parallel sensors for pervasive monitoring and diagnostics.

- Based on Ion Sensitive FET arrays (mostly operated in DC), Micro- and Nanoelectrode arrays (Impedance spectroscopy in AC)
- Objective: optimization of the transduction chain, sensor design, interpretation of data
- Contents: multiscale, multiphysics numerical simulation tools, bridge to circuit design

Example: simulation of pH response of nanoribbon ISFETs



Example: high frequency impedance spectroscopy in nanocapacitor arrays



nature nanotechnology LETTERS

PUBLISHED ONLINE: 3 AUGUST 2015 | DOI: 10.1038/NNANO.2015.163

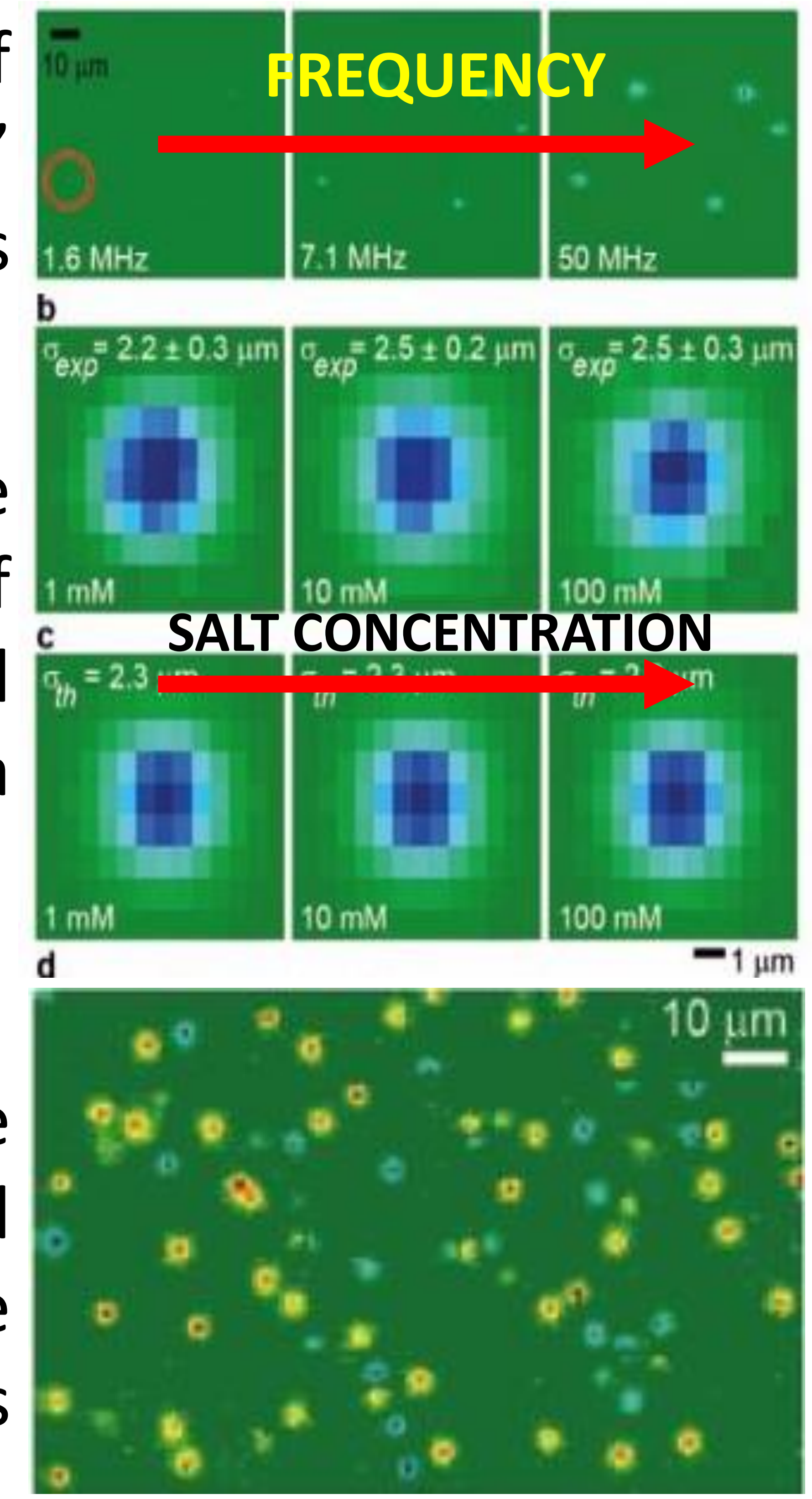
Real-time imaging of microparticles and living cells with CMOS nanocapacitor arrays

C. Laborde[1†], F. Pittino[2†], H. A. Verhoeven[3†], S. G. Lemay[1], L. Selmi[2], M. A. Jongsma[3] and F. P. Widdershoven[4*]

Sensing of "invisible" objects

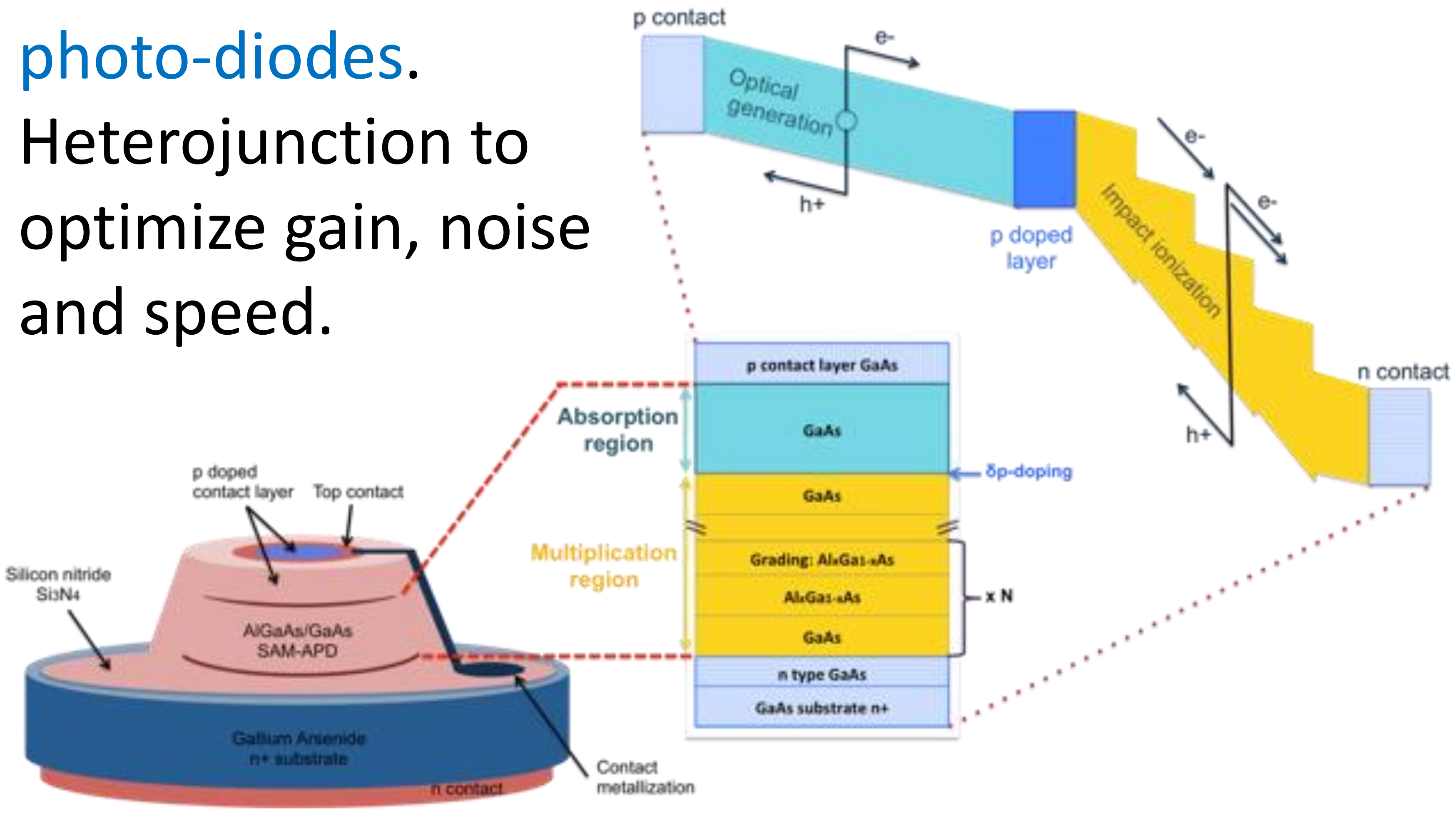
Quantitative prediction of experimental data

Discriminate dielectric and conductive particles

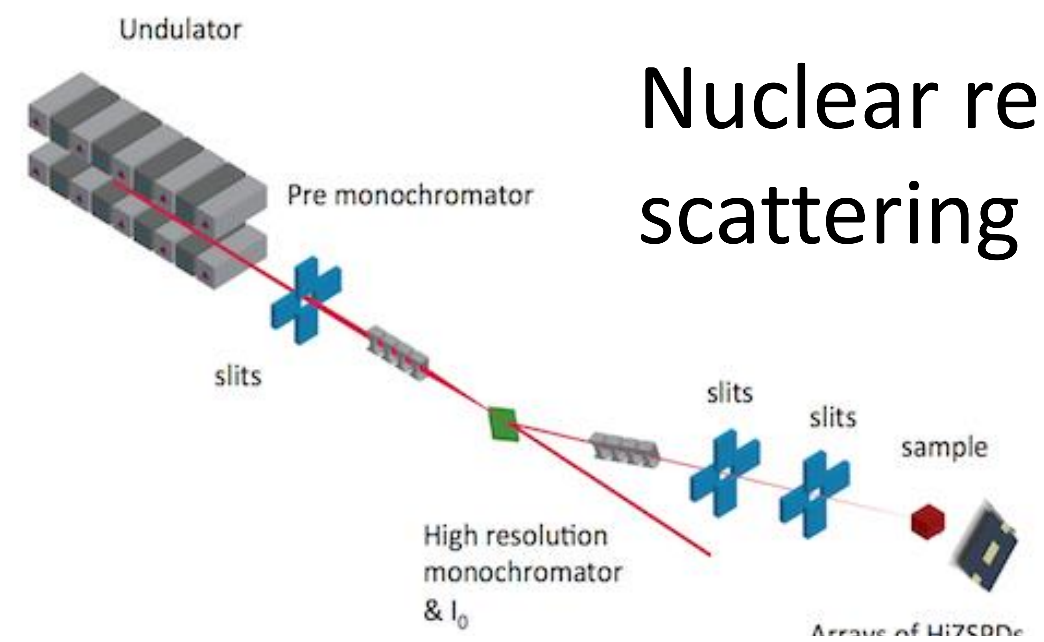


Sensors@UniUD: III-V x-ray detectors

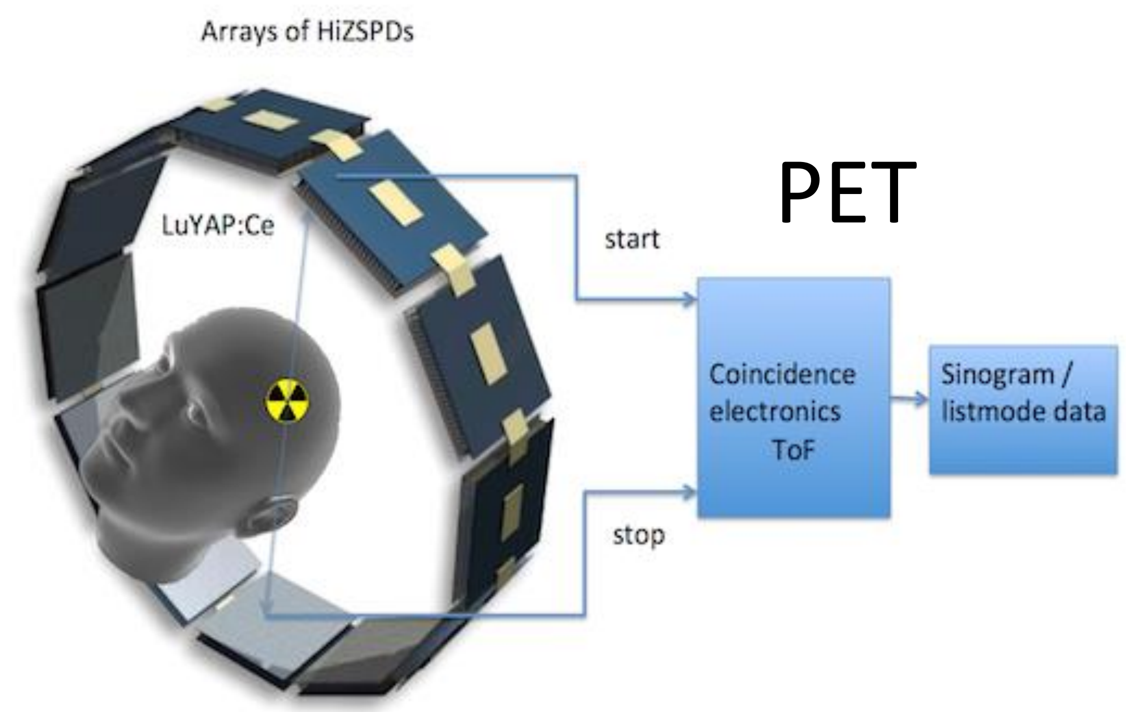
III-V avalanche photo-diodes. Heterojunction to optimize gain, noise and speed.



- Extension of existing concepts to innovative applications: X-ray detector for Synchrotron radiation, Free-Electron Laser or medical.
- Require very low-noise/low-jitter



Nuclear resonant scattering



PET

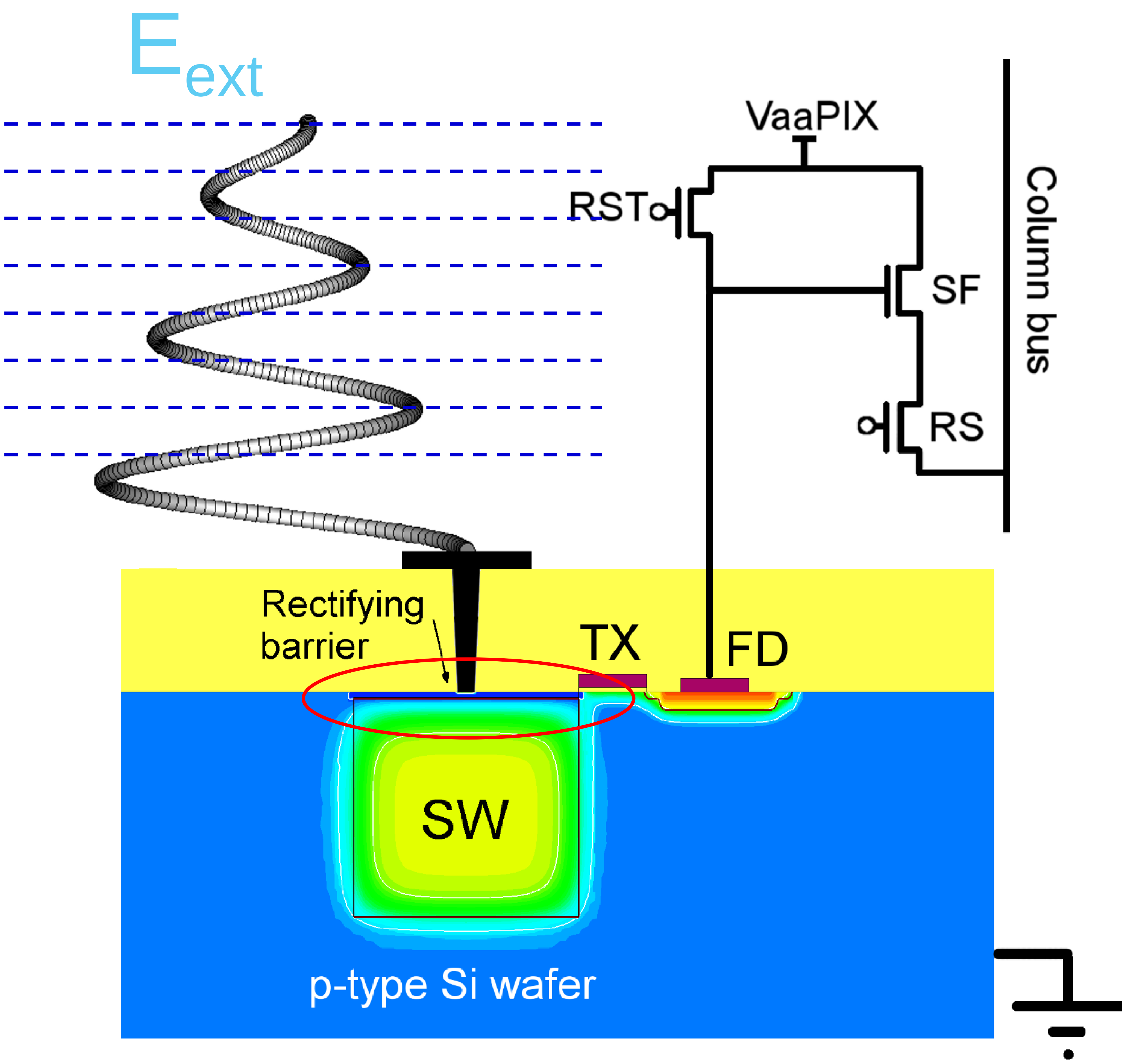
PRIN 2015

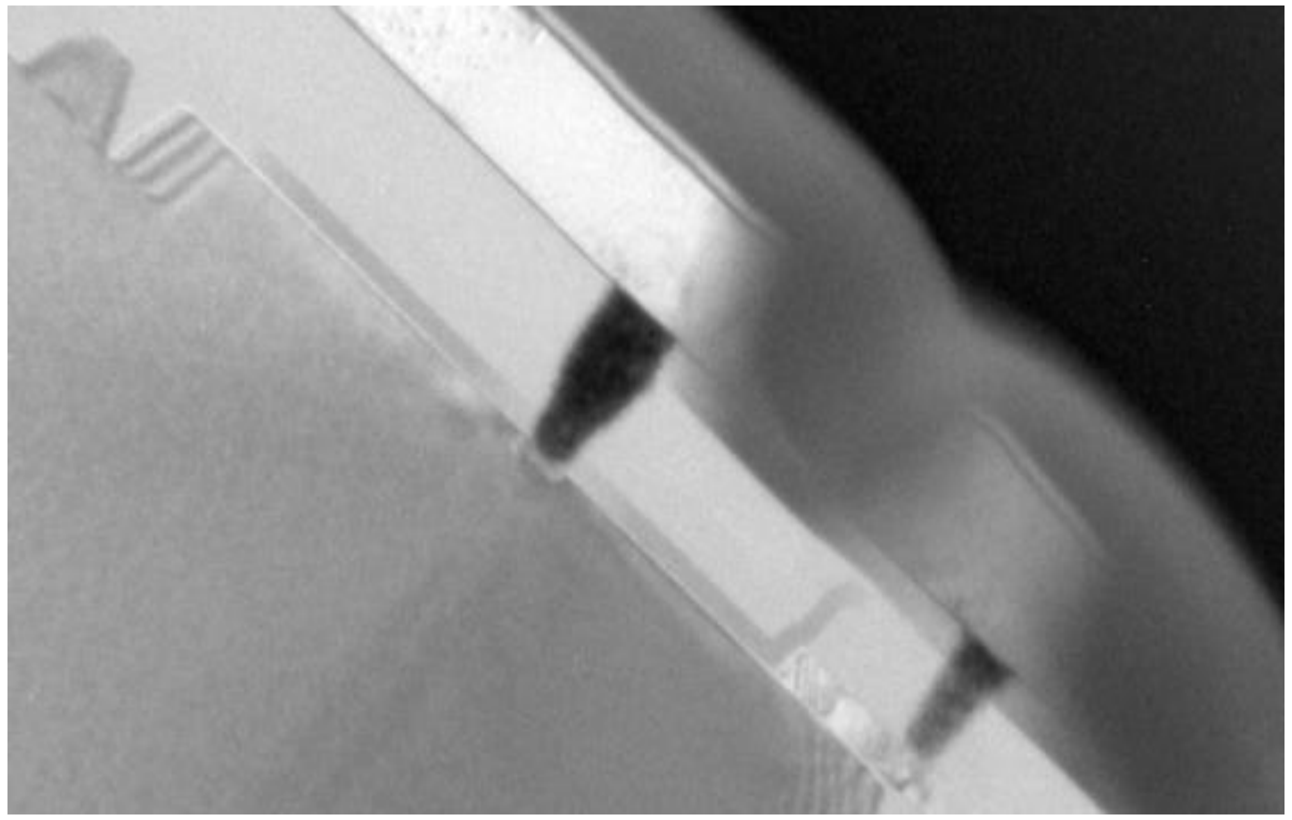
UniUD: modeling (MC+TCAD) of avalanche gain, noise and speed
UniTS + UniUD: experimental characterization
CNR-IOM: fabrication
ELETTRA Synchrotron: read-out electronics

- Partial exploitation of existing competences in MC simulation and III-V modeling
- Know-how then applicable to other optical detectors

IU.NET

Sensors@UniRM1: CMOS-based THz Rectifier



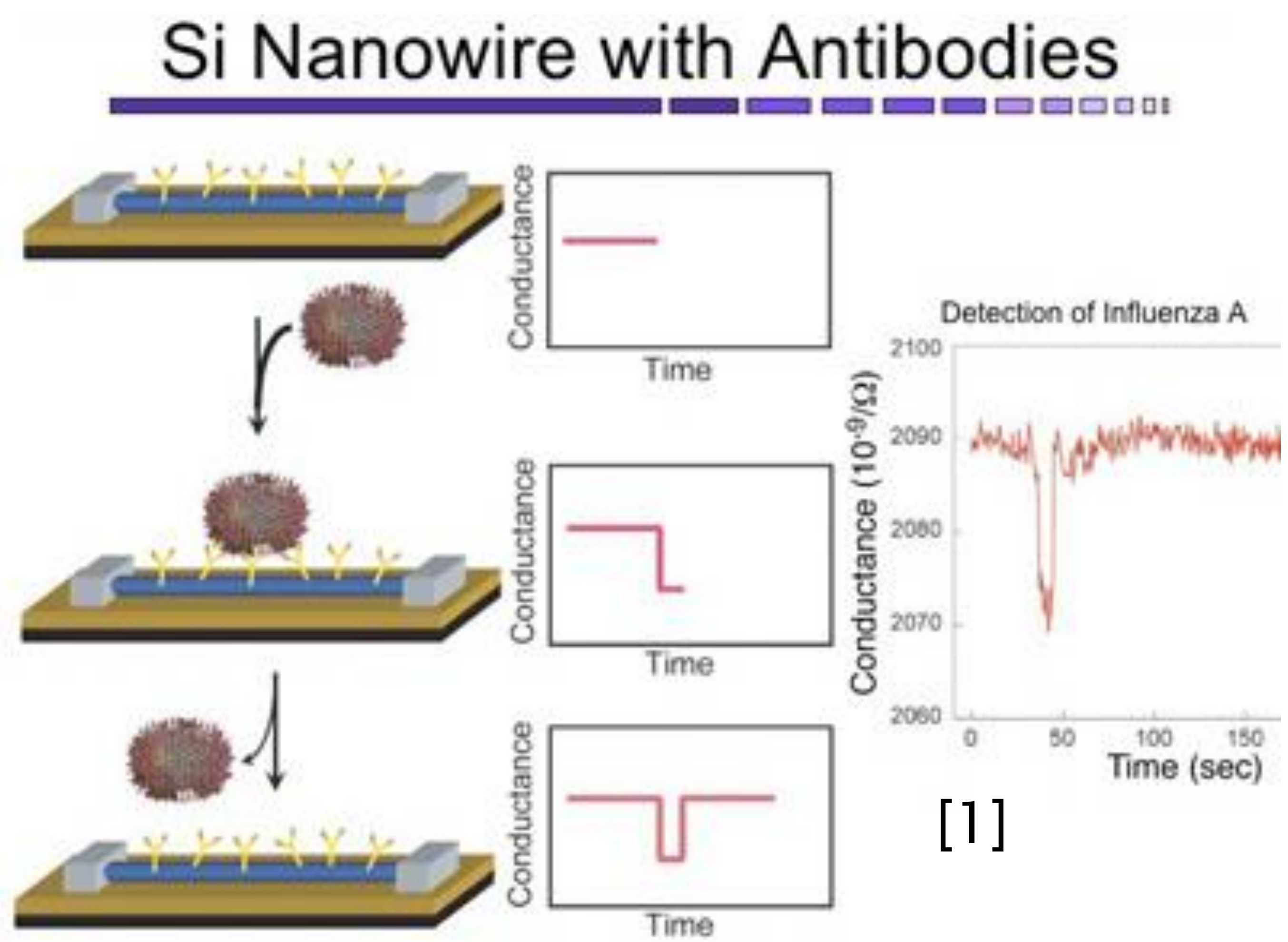


Evaluated NEP at 1 THz 0.6 pW/Hz^{0,5}

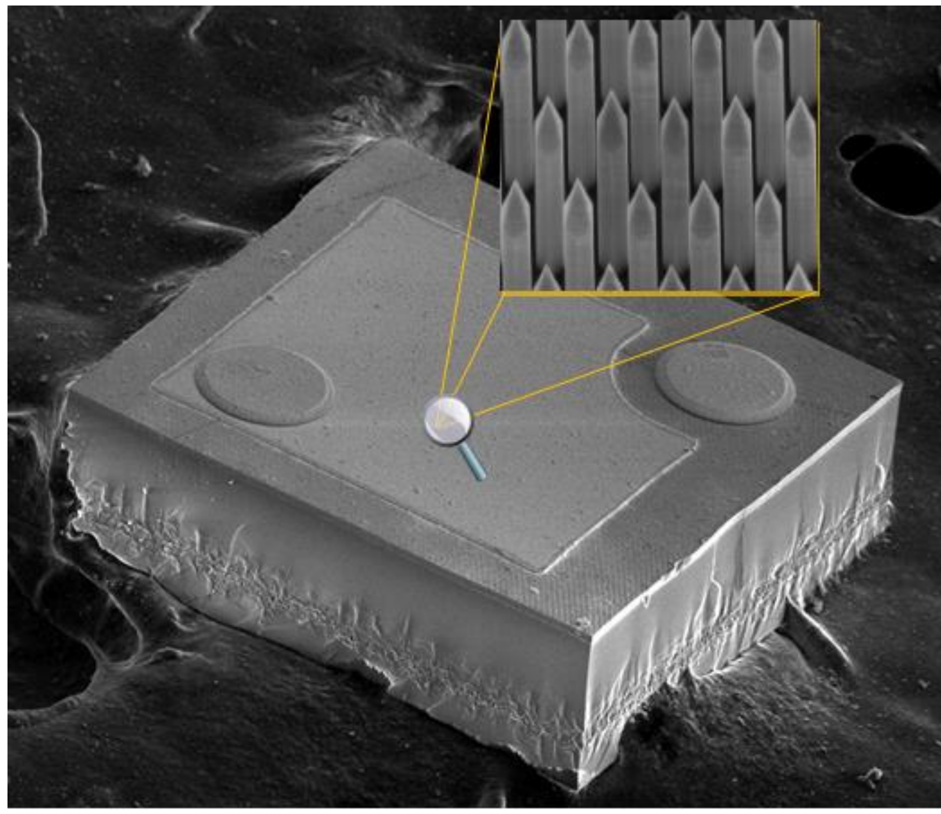
Proposed Architecture: principle of work

Sensors@UniRM1: Silicon nanostructures

- Sensori FET
- LED
- Celle solari
- Batterie



[1]



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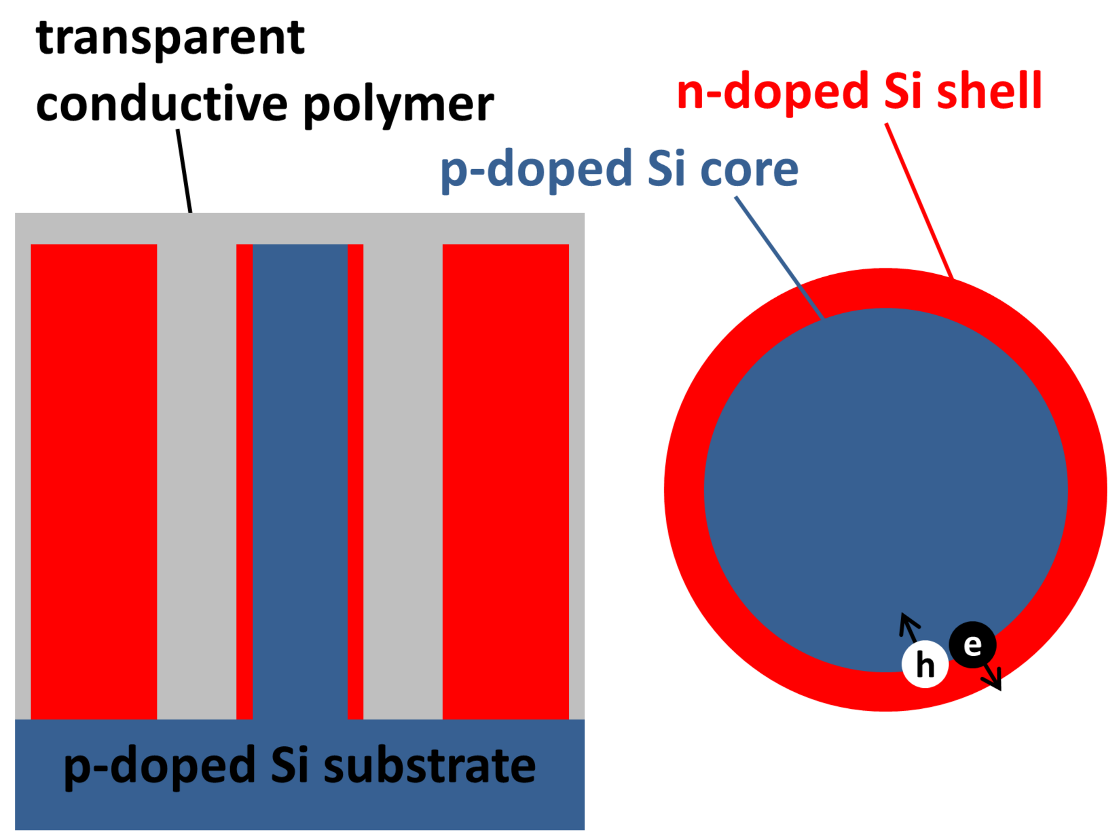
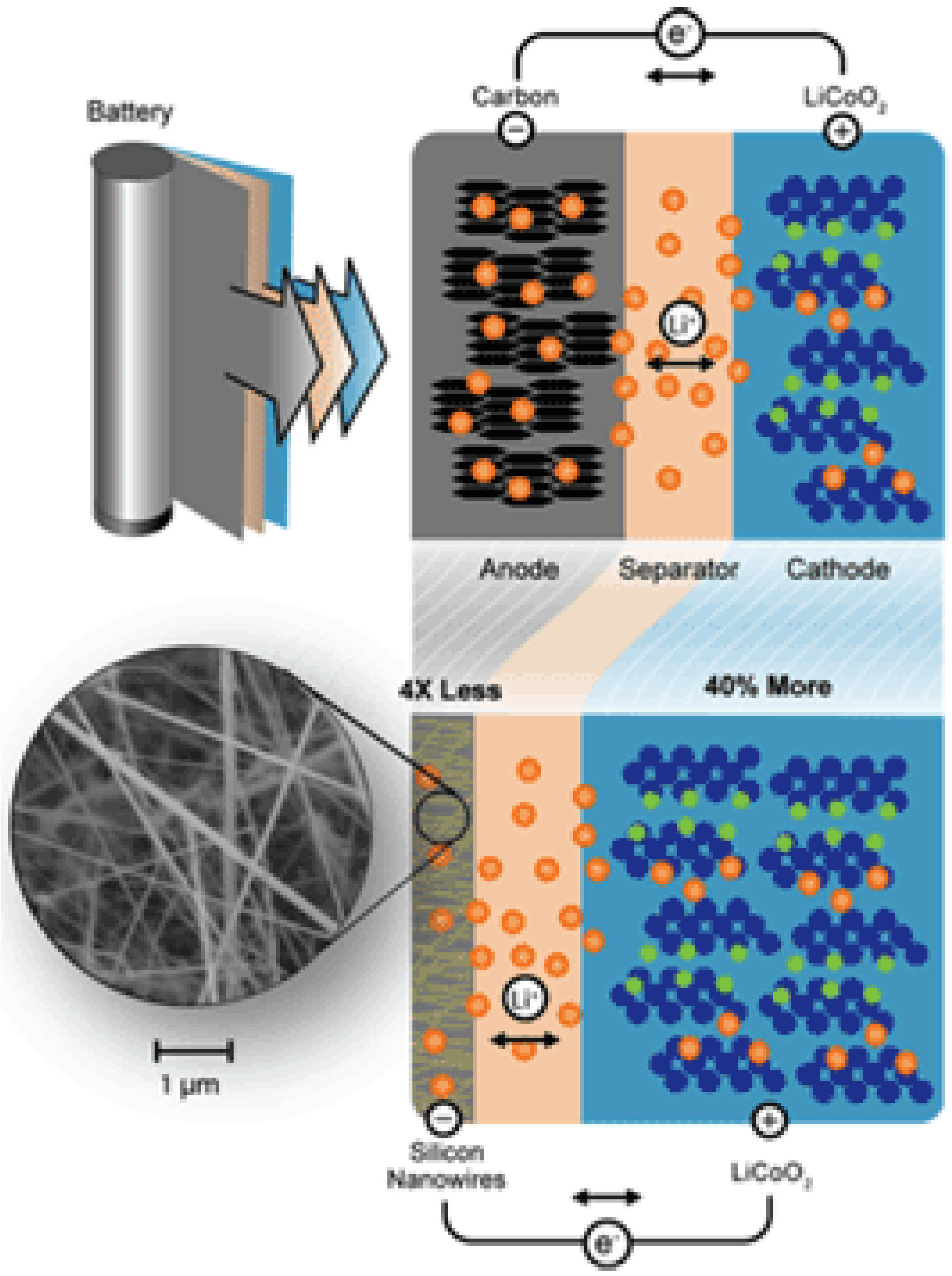
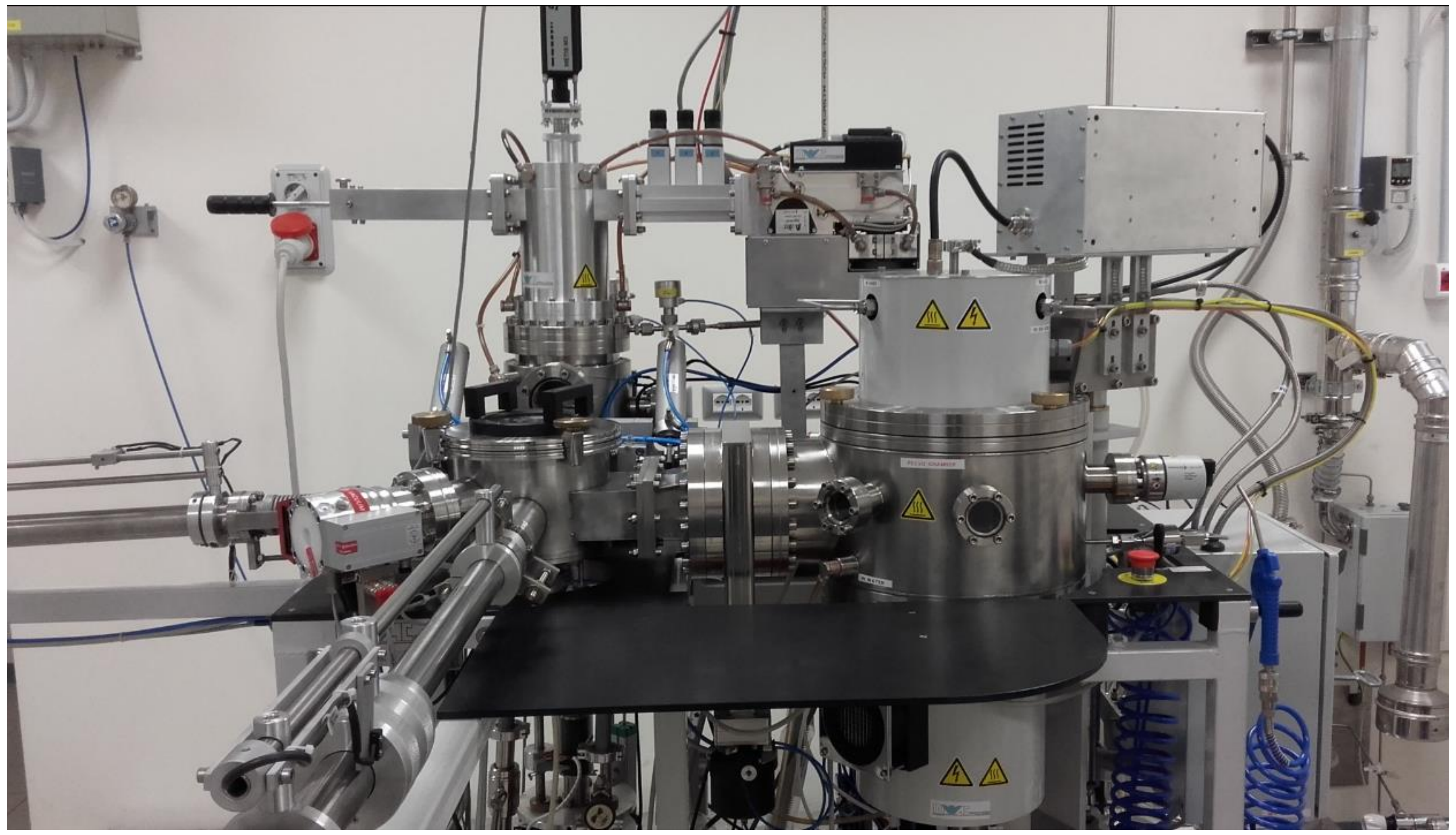
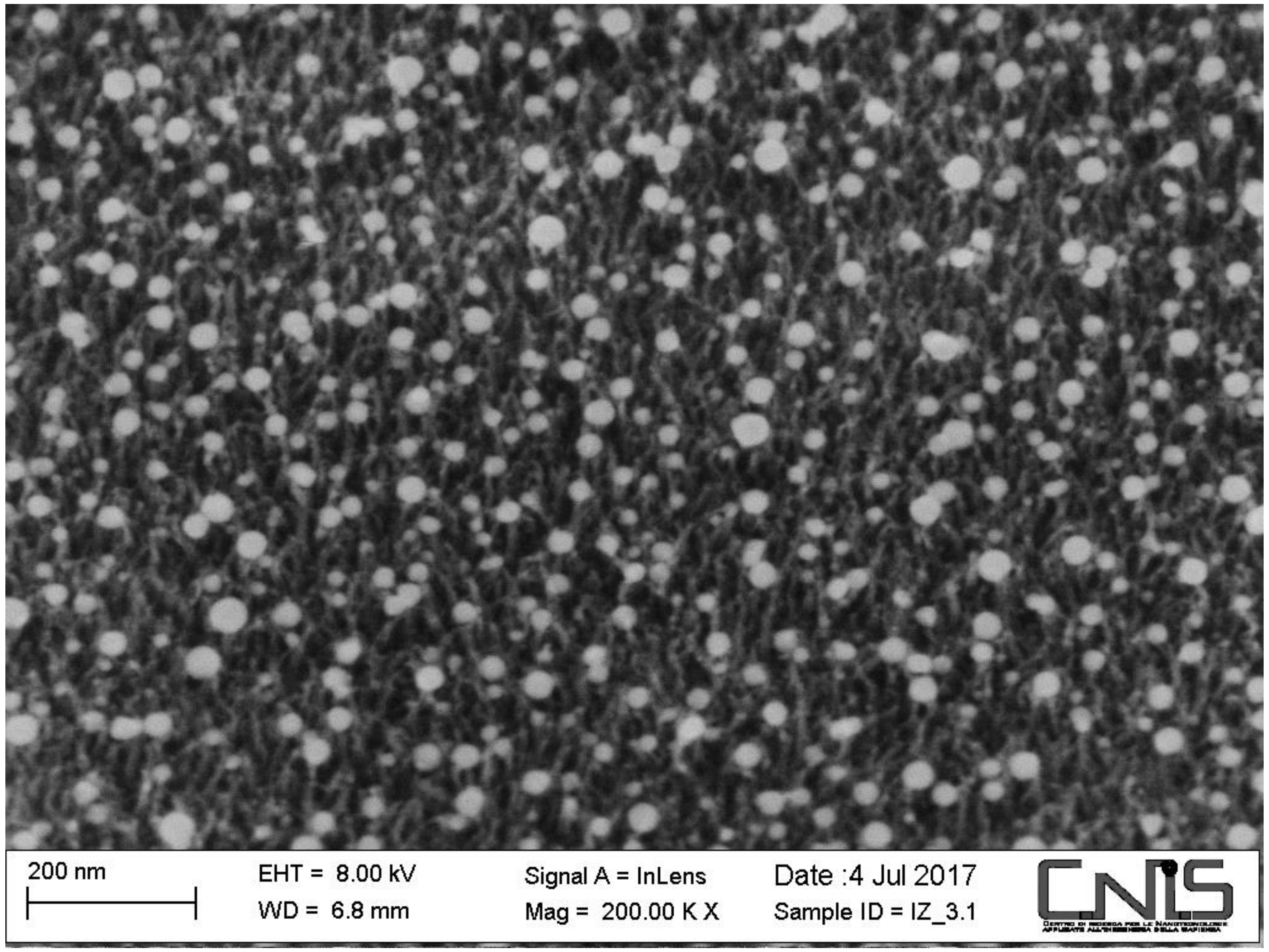




Sensors@UniRM1: Silicon nanostructures



Grown by MWCVD/PECVD



$T_{sub} = 200\ ^{\circ}C$

Lab4MEMS (I)

- ENIAC project, 2013-2016
- ST led
- Main goal:

  *"aims to establish a European Pilot Line for innovative technologies on advanced **piezoelectric** and **magnetic materials**, including advanced Packaging technologies to meet the ever evolving market needs."*

- IUNET involvement:

  PoliMI: 3-axis magnetometers, Lorentz magnetometers

  UniBO: piezoelectric energy scavengers

  UniPI: piezoelectric resonant sensors

MEMS@PoliMI: vision and tools

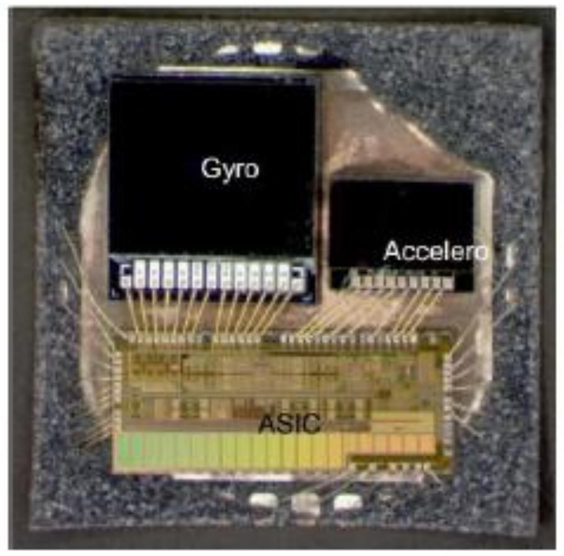
- Derive specifications at the sensor, electronics and package starting from application specifications.
- Predict trade-offs between these sub-specs, and take key decisions in the design phase with a system-level point of view.
- Predict effects of environmental changes and take them into account in the design for reliability & repeatability.

application specifications

sensor

electronics

packaging

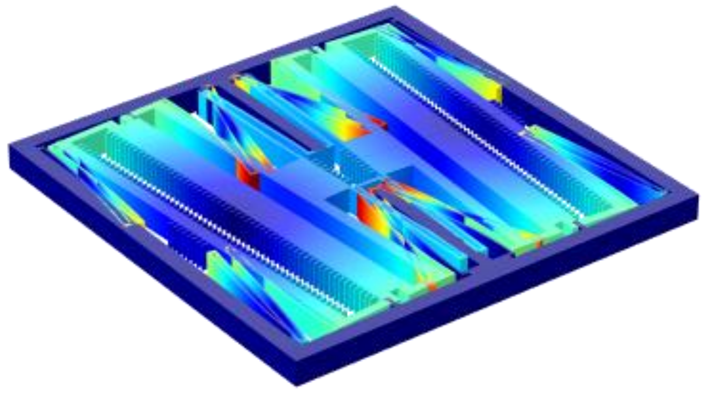


T, RH, ...

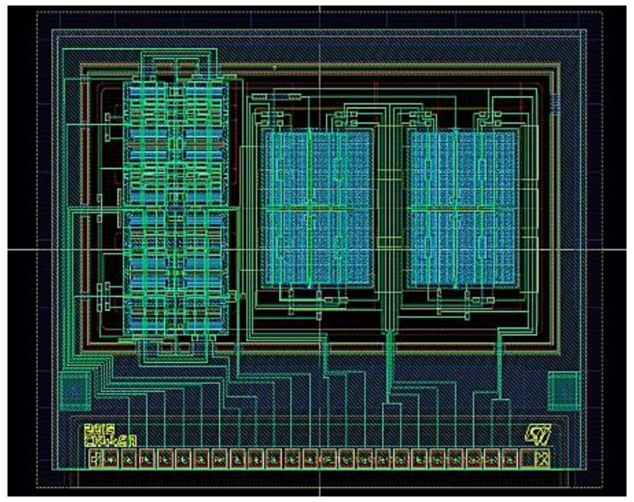
Vibrations, ...

MEMS Design

- Theory (Multiphysics coupled equations)
- Behavioral models (e.g. for nonlinearities, ...)

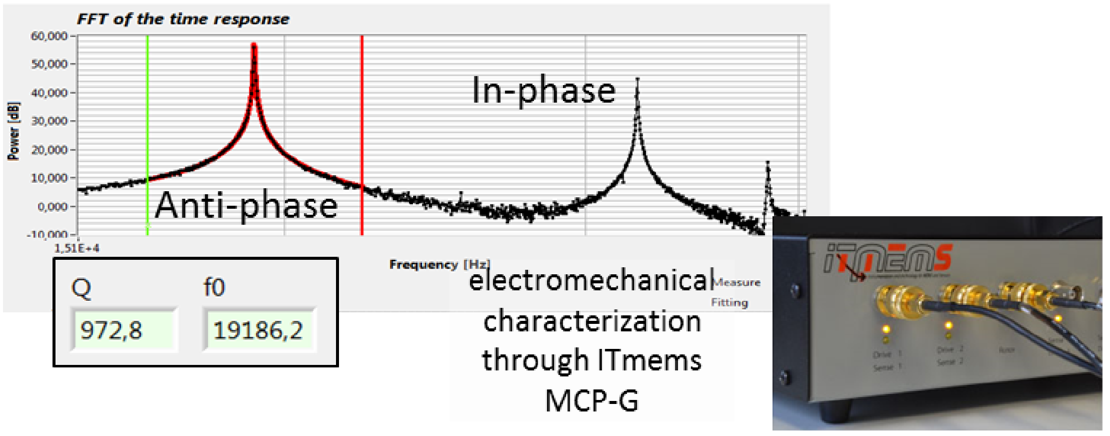


- FEM (2D-3D Modeling),
- CAD design (layout and final refinements)



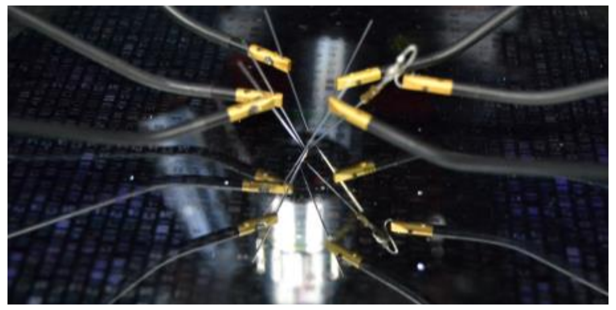
IC Design

(interfaces, oscillators)



Characterization

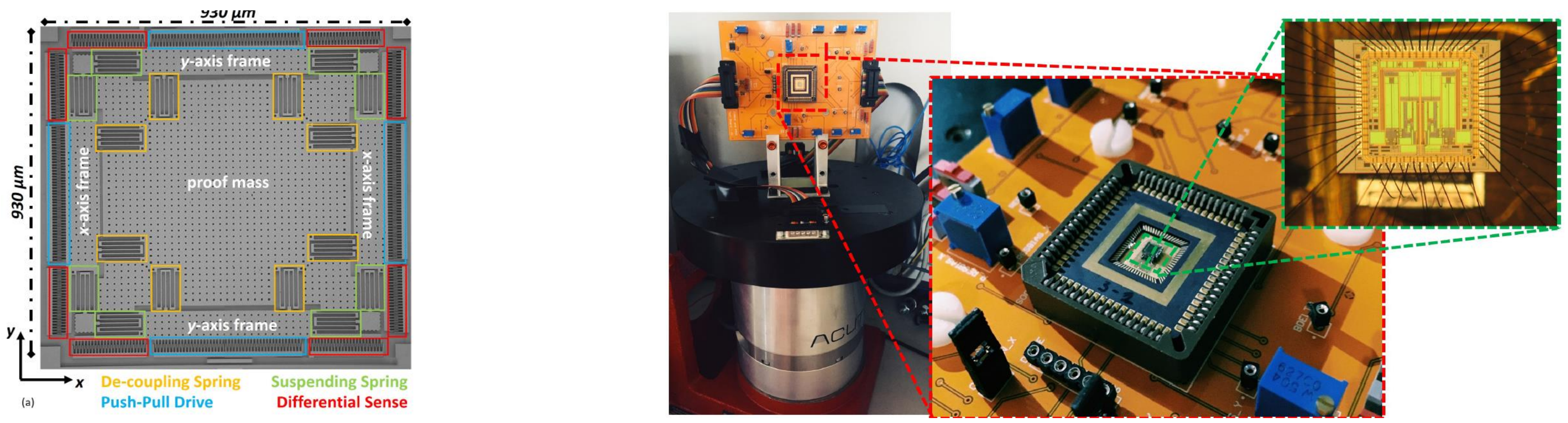
- Design validation (Q, resonance, C-V, ...)
- Performance validation (sensitivity, noise, TCS, ...)



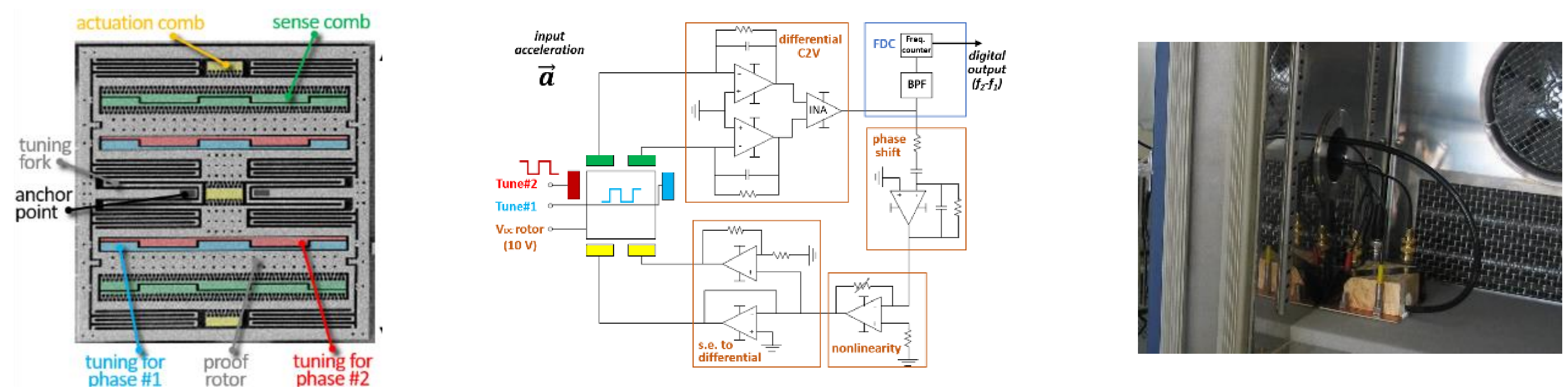
- Reliability

MEMS@PoliMI: Current activities

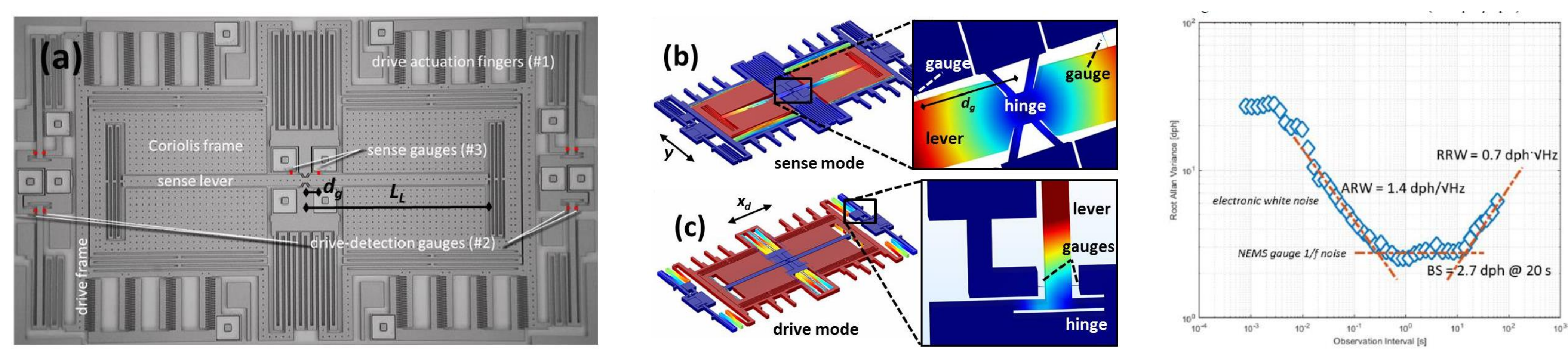
First 3-axis Frequency modulated Lissajous-mode gyroscopes



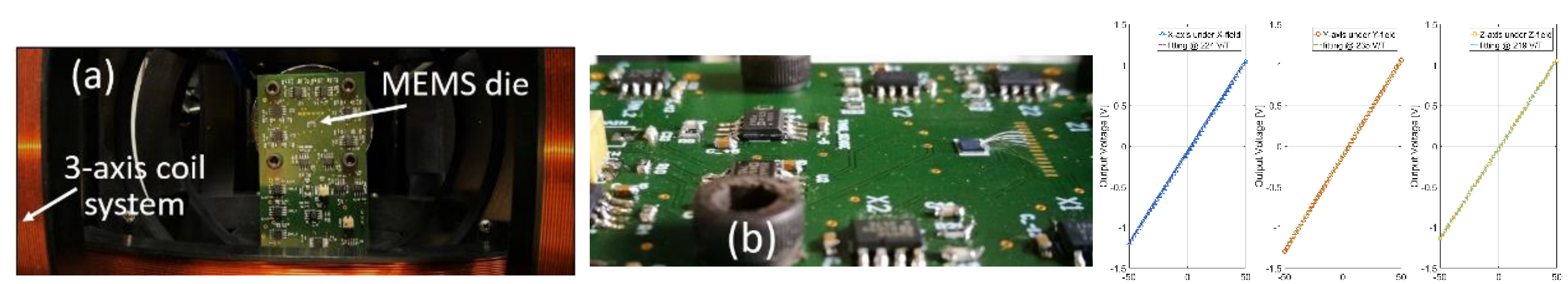
Novel modulated MEMS accelerometers for low offset drift



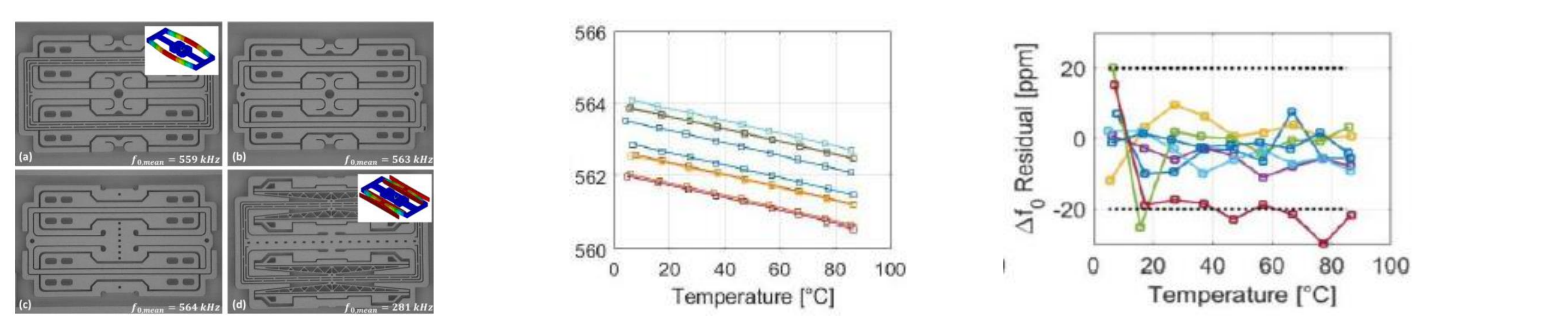
Piezoresistive-NEMS based compact, high-performance gyroscopes



Compact Lorentz-force MEMS magnetometers



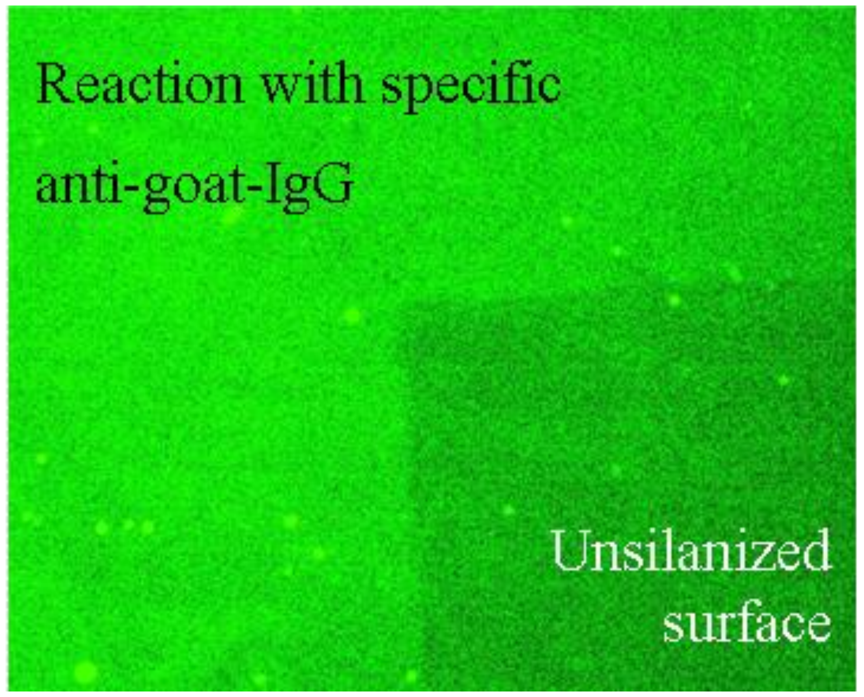
Real-time clocks based on MEMS resonators



MEMS@UniPI: resonant MEMS sensors

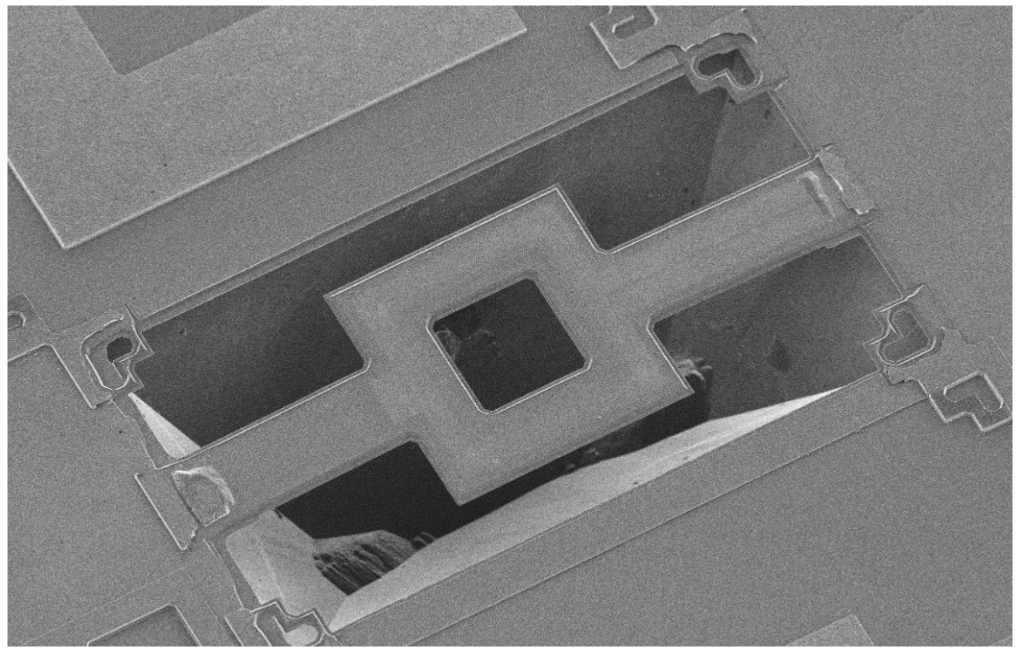
Expertise:

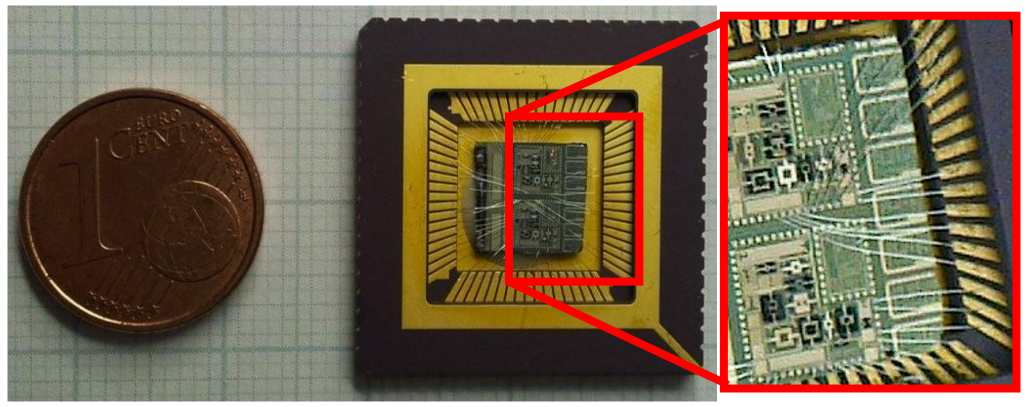
- MEMS Design and modeling (analytical and reduced models, FEM)
- CMOS-MEMS fabrication and characterization
- Resonant (bio)sensors

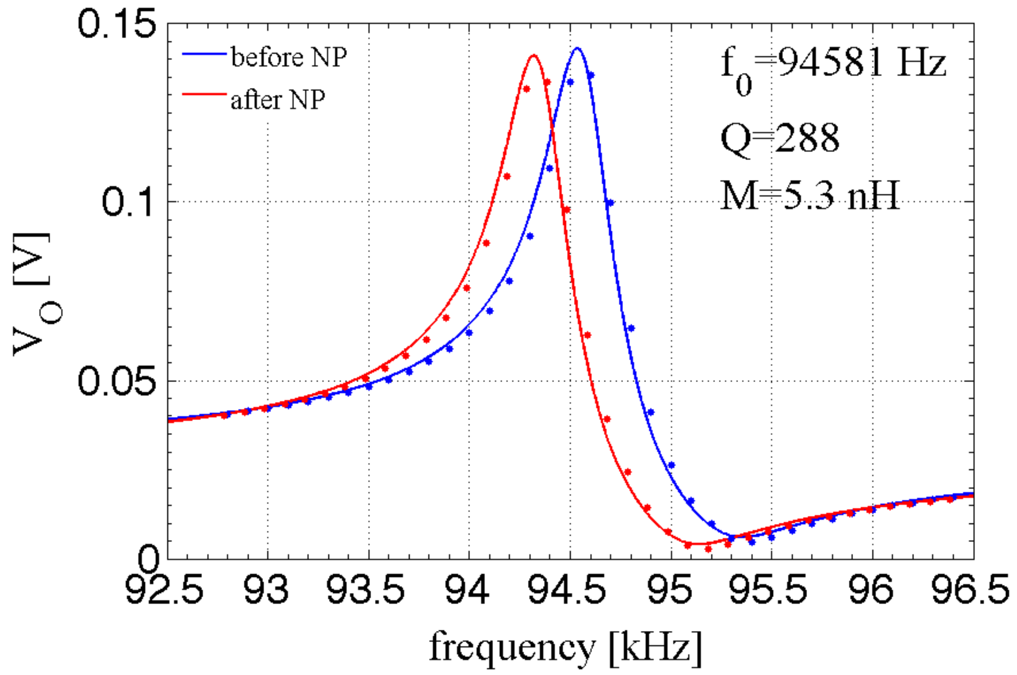


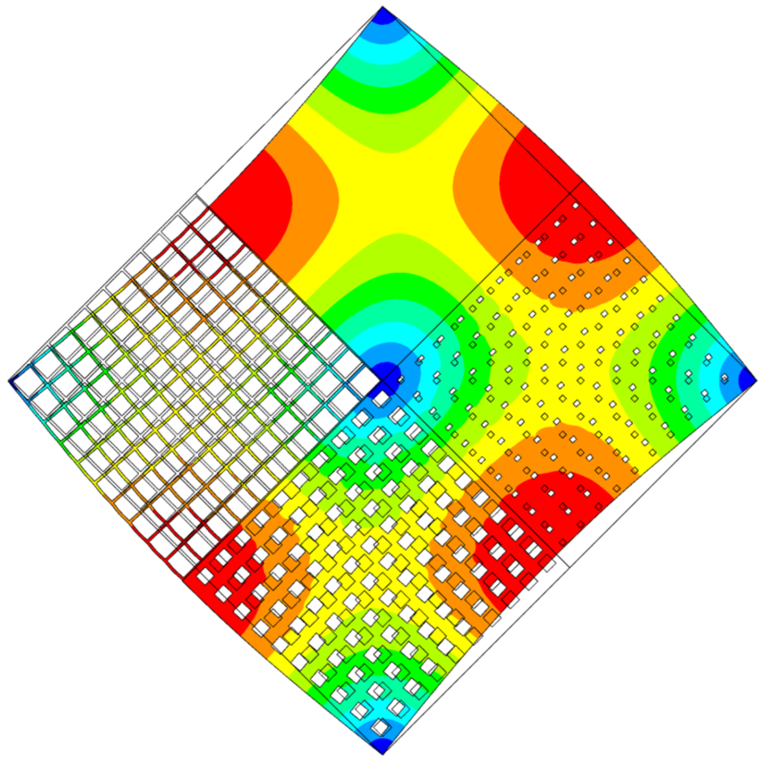
CMOS-compatible biofunctionalization

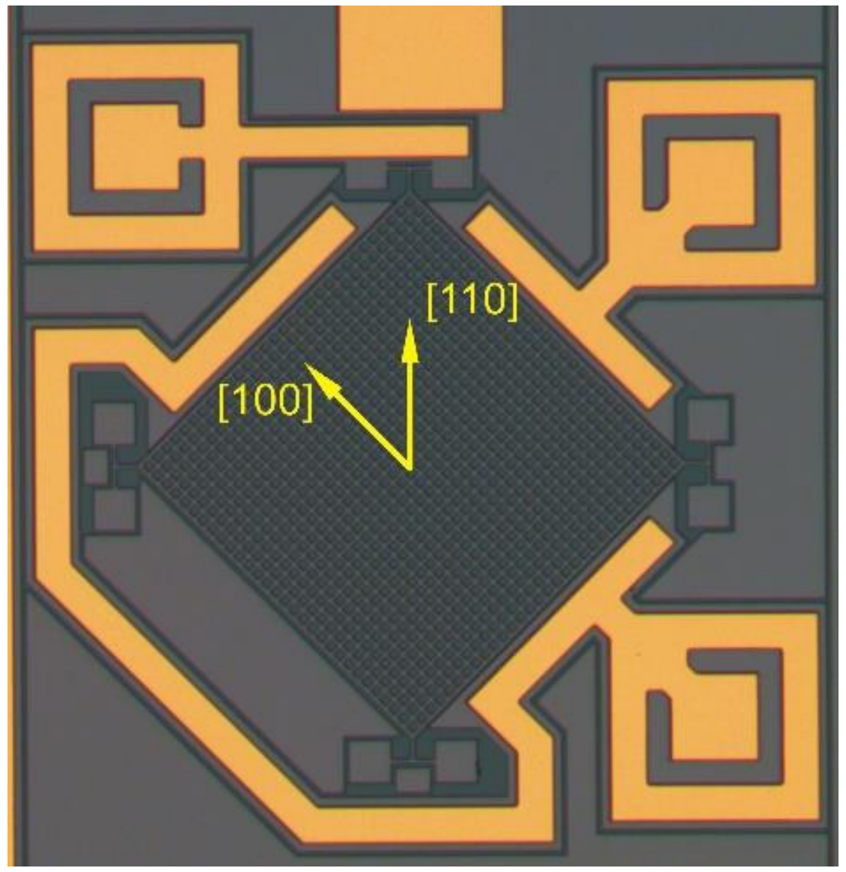
Example: CMOS-based resonant mass sensor









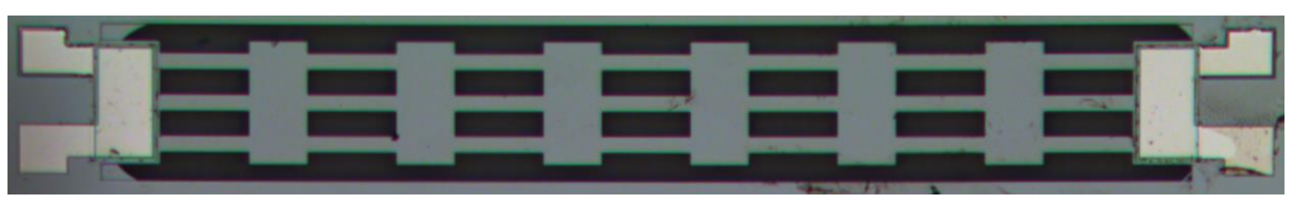


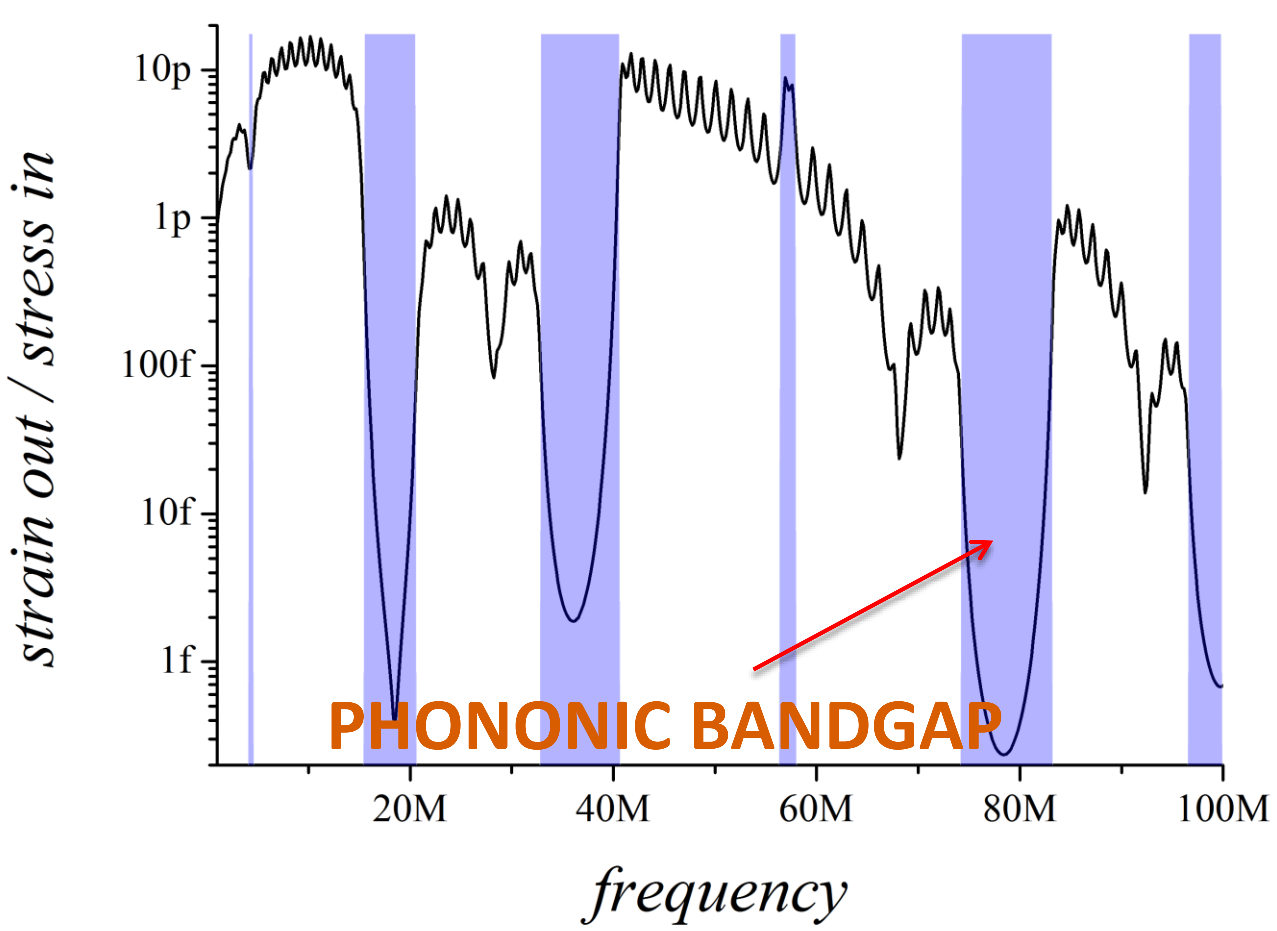
Example: c-Si Lamé resonators with enhanced sensitivity - TCF compensation by doping/perforations

MEMS@UniPI: resonant MEMS sensors

Phonic crystal resonators

Periodic modulation of mechanical properties (elasticity, density, cross-section, ...)

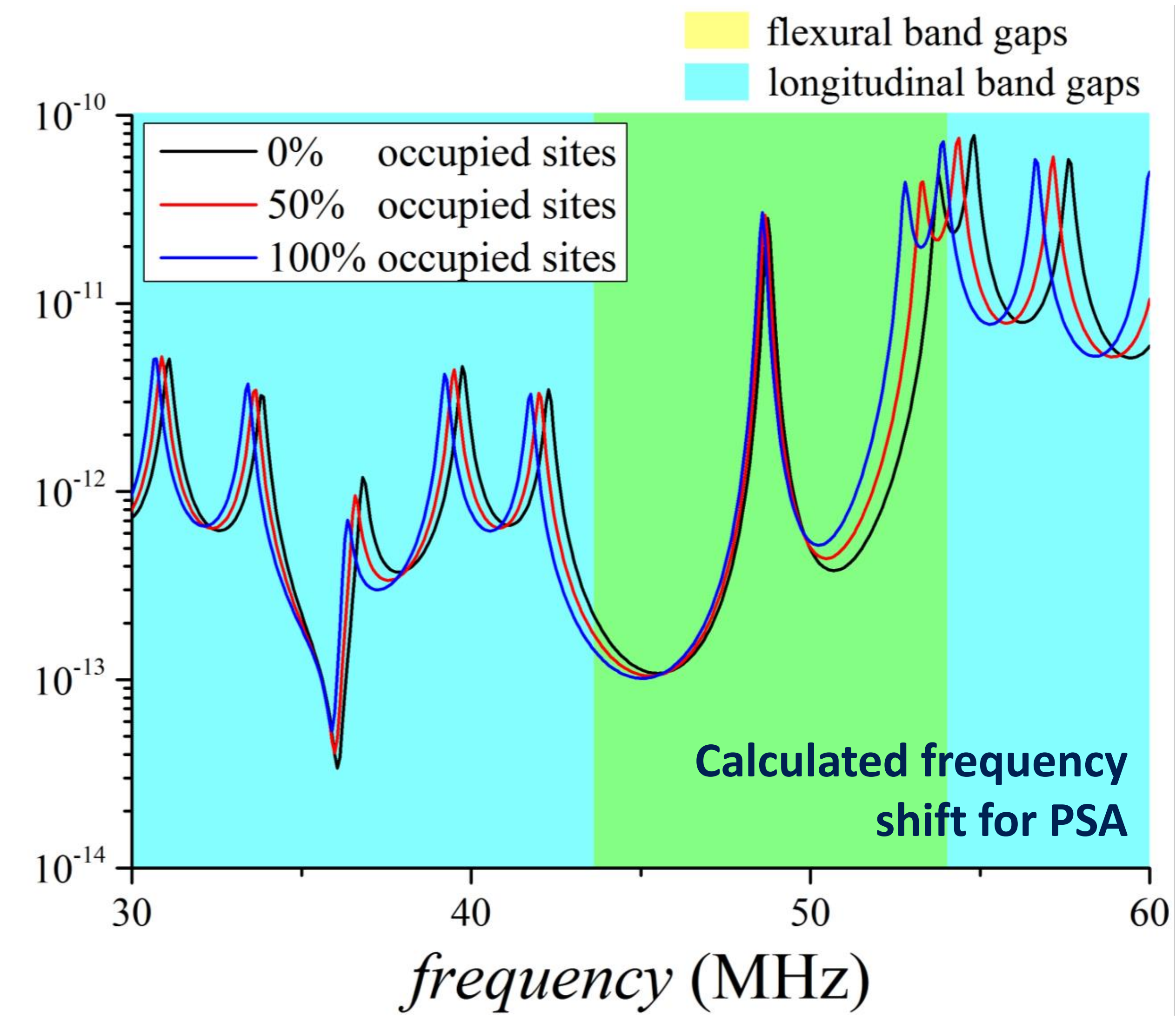


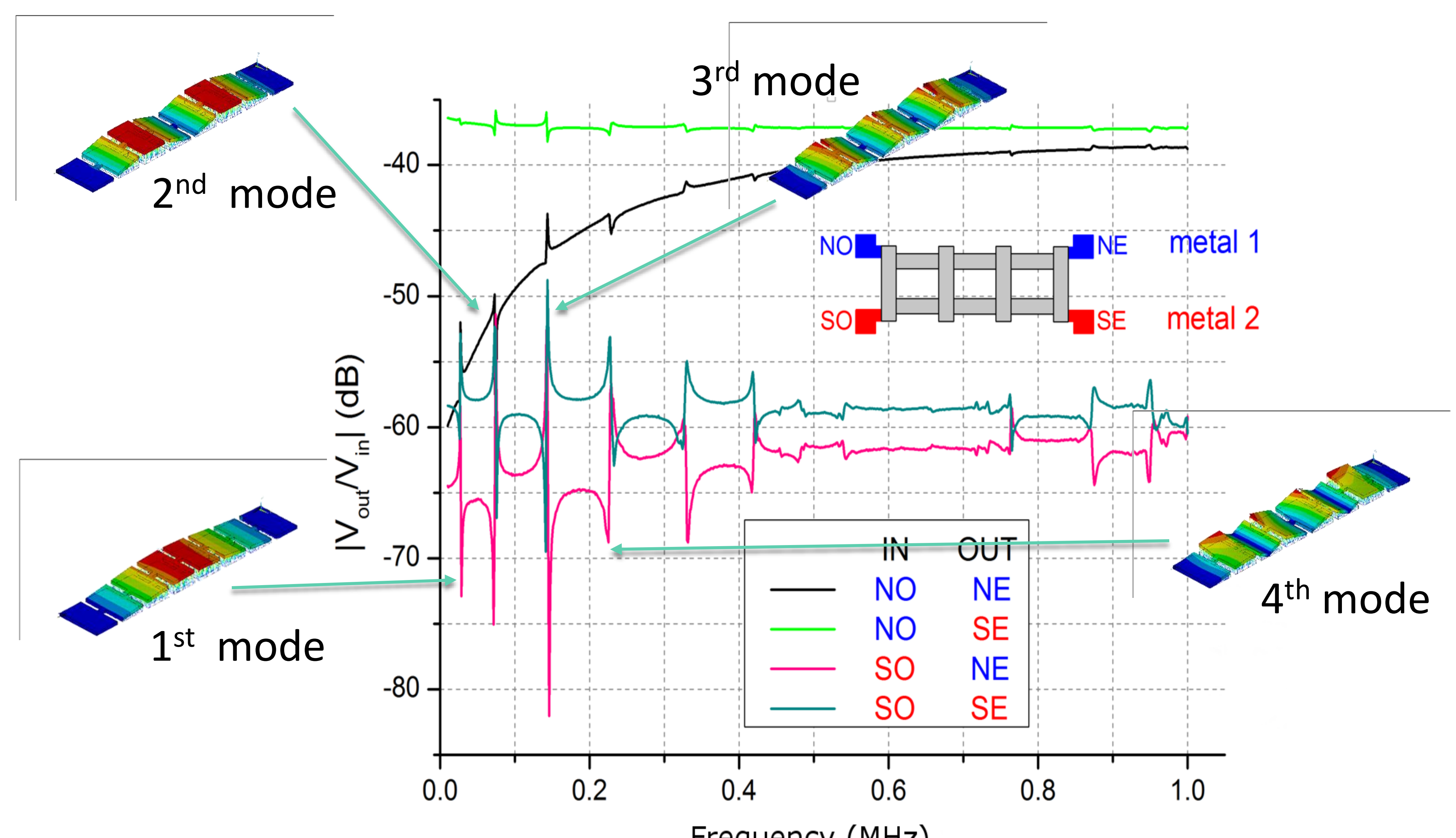


Fast modeling with acoustic transfer matrices

FEM validation

experimental validation

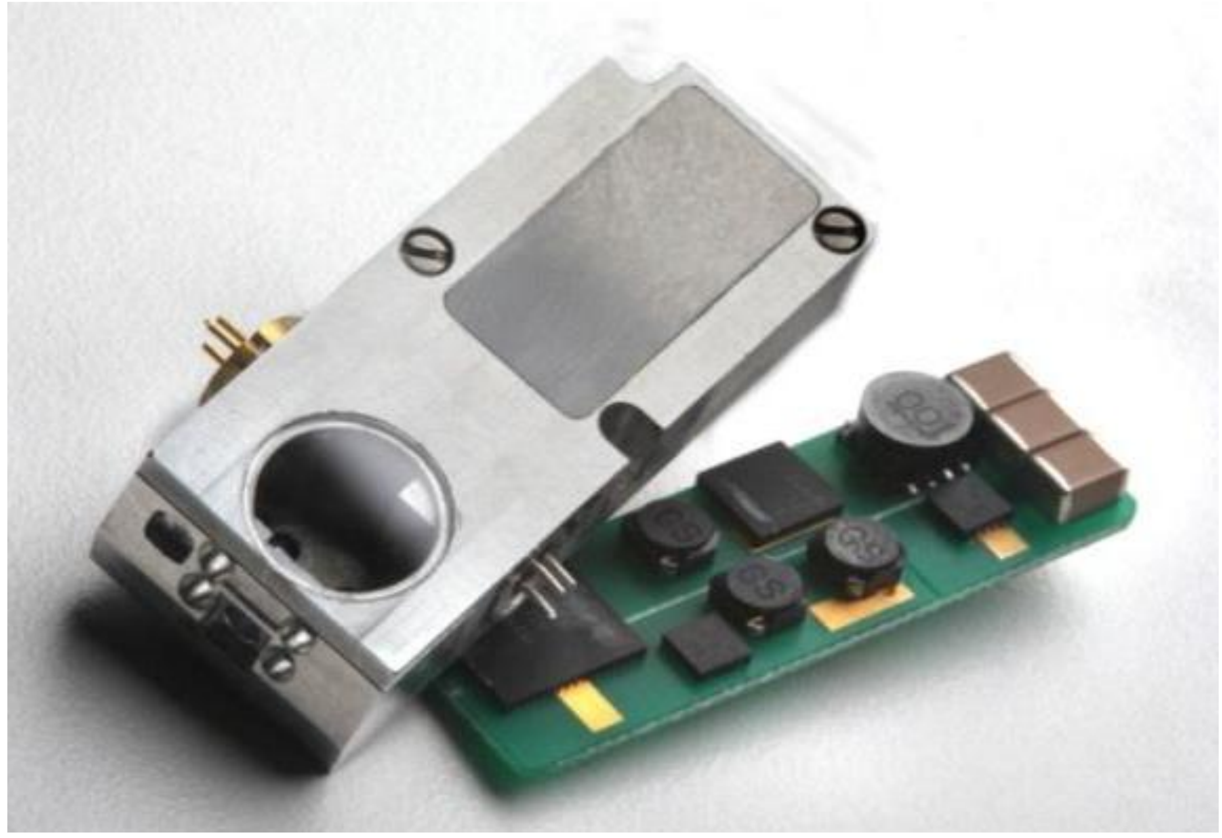




Lab4MEMS II

- ENIAC project, 2015-2018
- ST led (again)
- Main goal:

  "L4M2 will feature the Pilot Line for innovative technologies on advanced ***Micro-Opto-Electro-Mechanical Systems (MOEMS)****."*



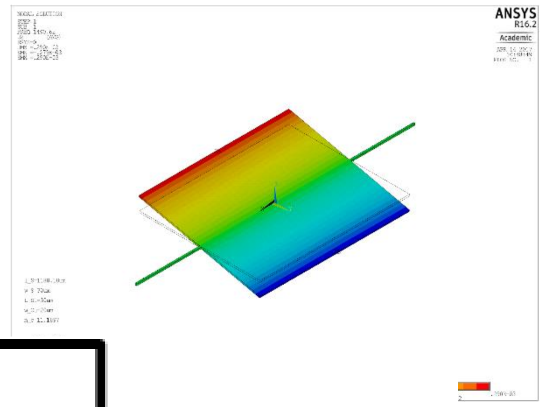
MOEMS pico-projector

IUNET involvement:

UniPI: mirror design
UniMoRe: IC design (mirror drivers, laser drivers)
UniBO: optical simulation of mirror reflectivity
UniPD: mirror characterization, mirror reliability

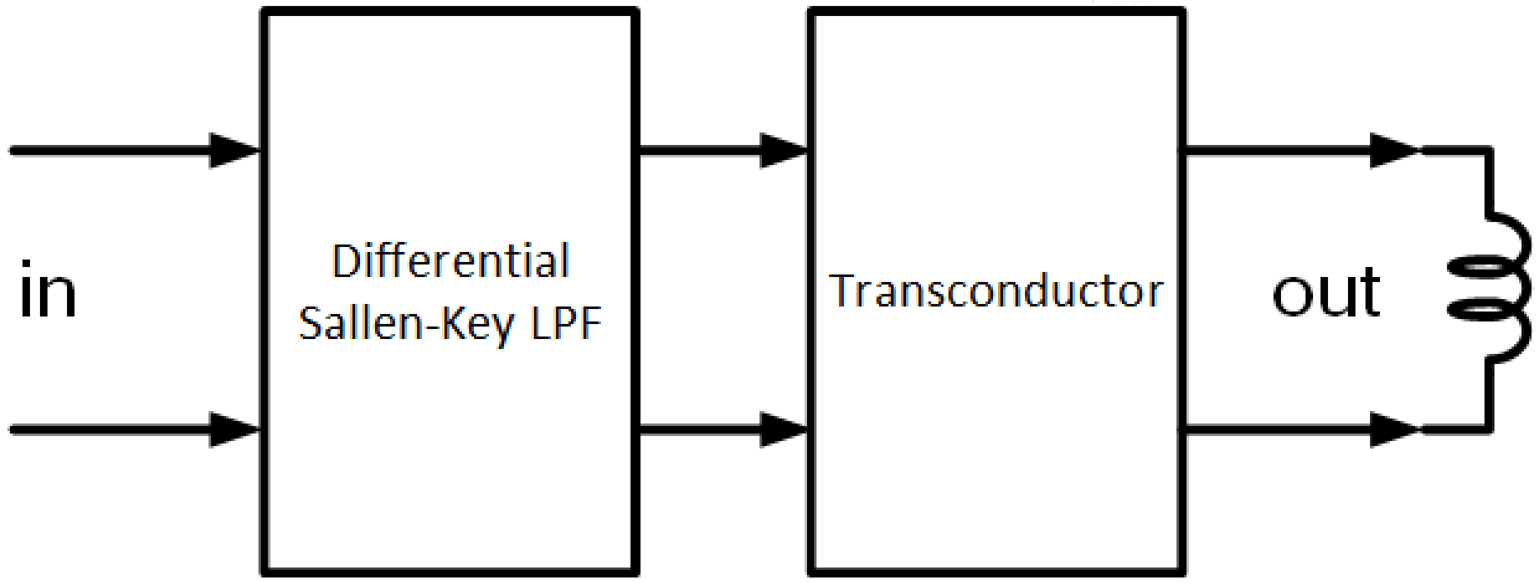
MEMS@UniMoRe: Circuit design for MOEMS

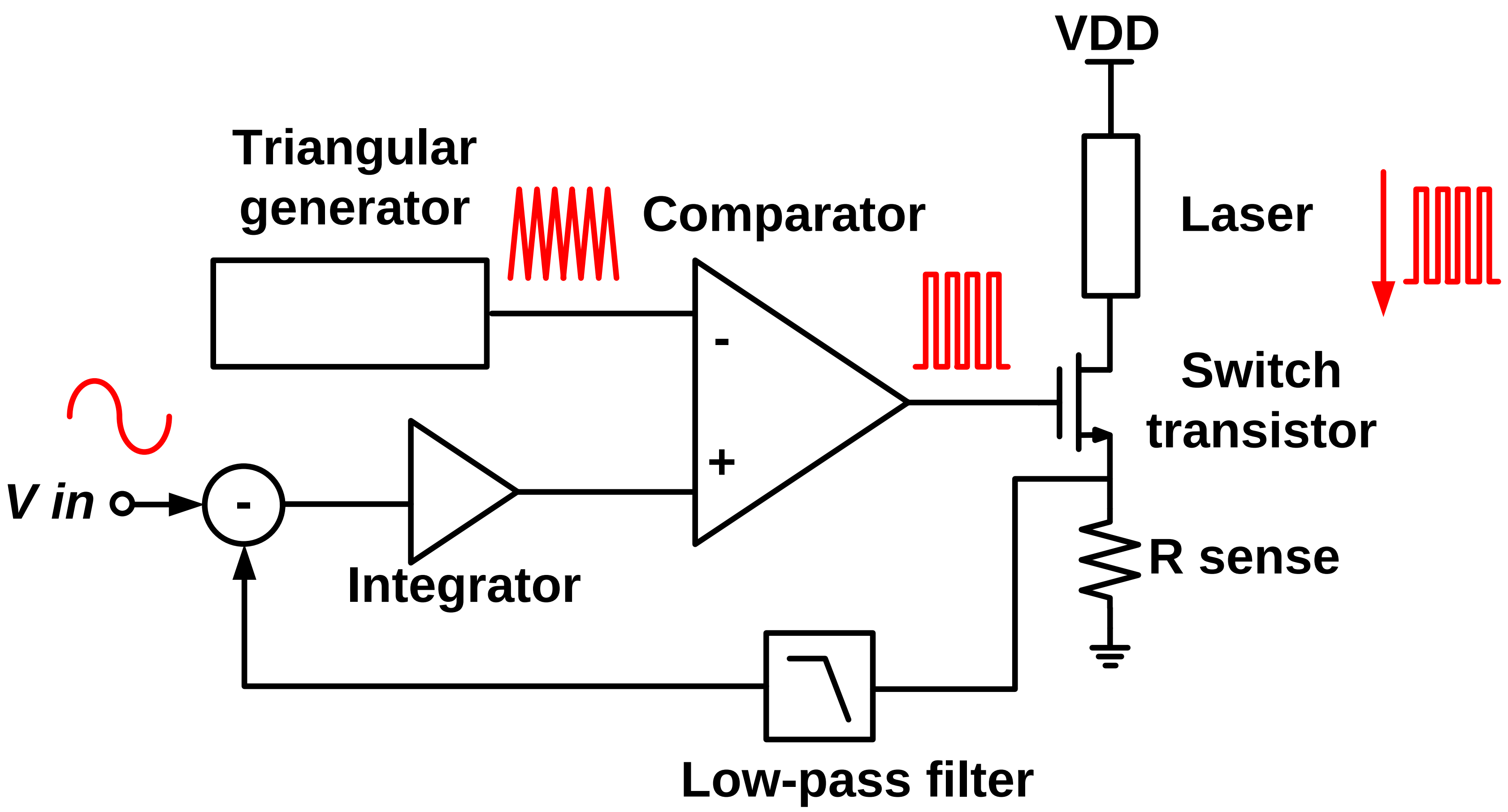
Technology: 65 and 55nm by STMicroelectronics



Current driver for micromirrors

- Transconductor stage: able to provide current > 75 mA
- Differential Sallen-Key 2nd order low pass filter: reduce gain at MEMS resonance (>300 Hz)





Laser driver for Speckle noise reduction

- “Class-D” amplifier where width of output pulse is modulated by the amplitude of the input signal

UNIMORE
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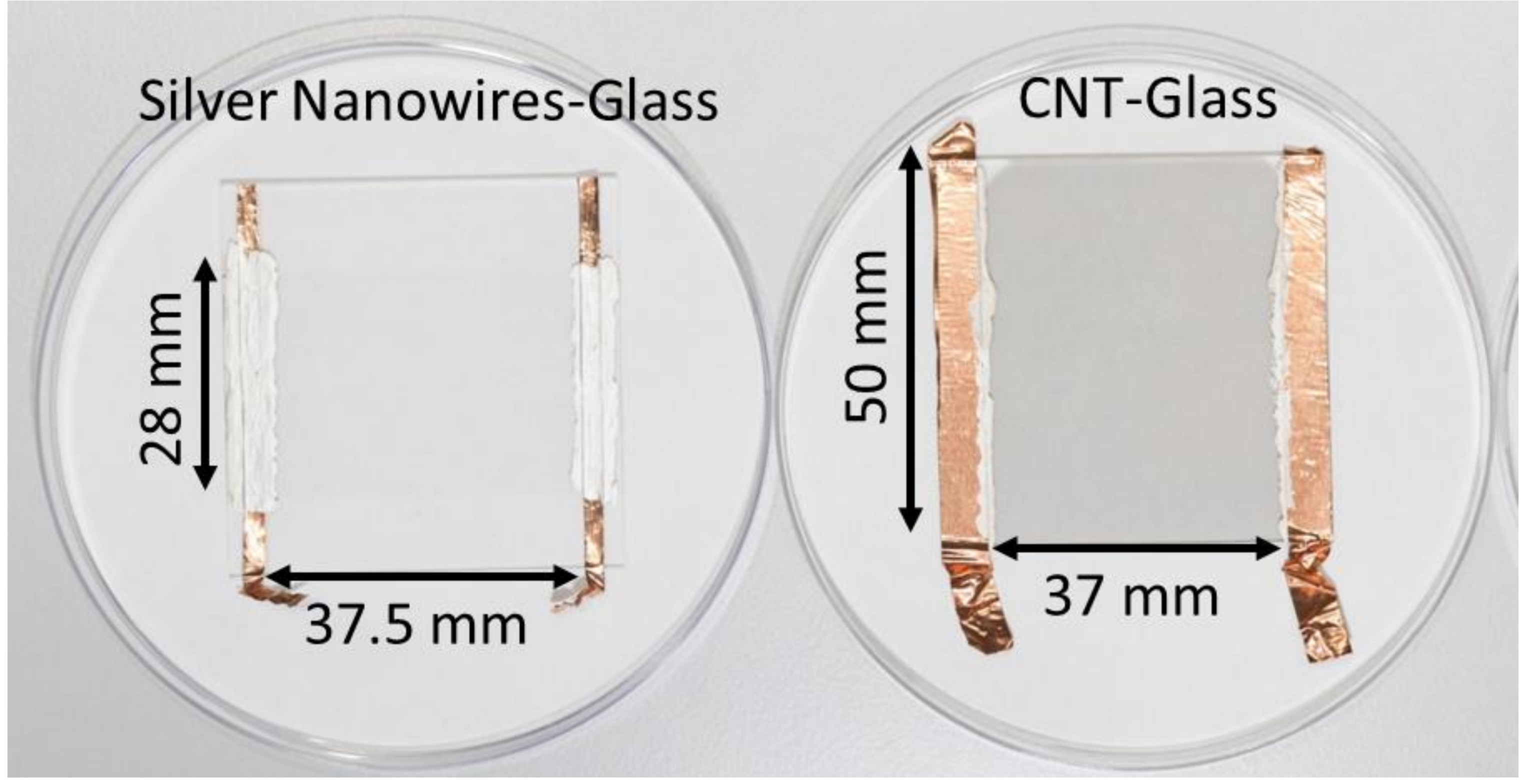
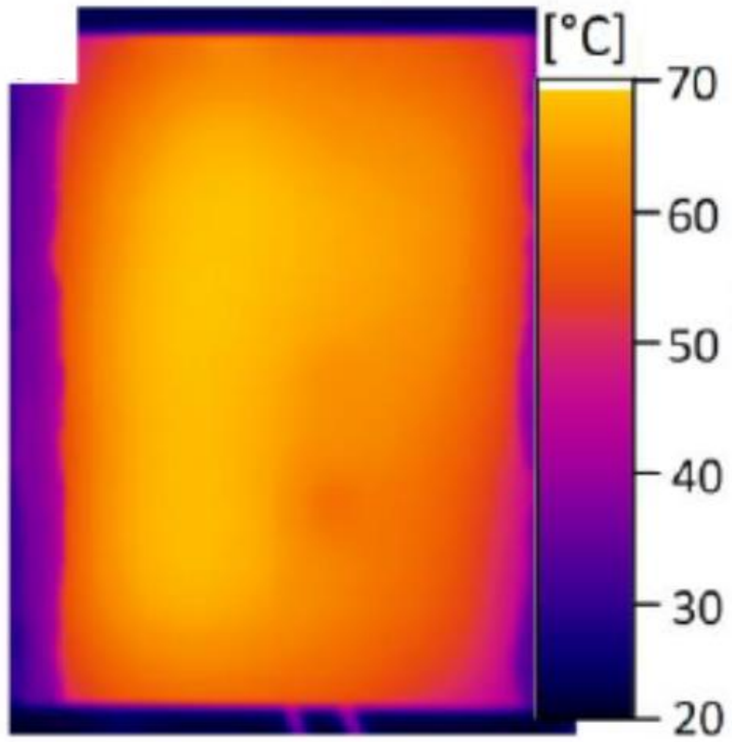
Sensors@UniMoRe: NW technology solutions

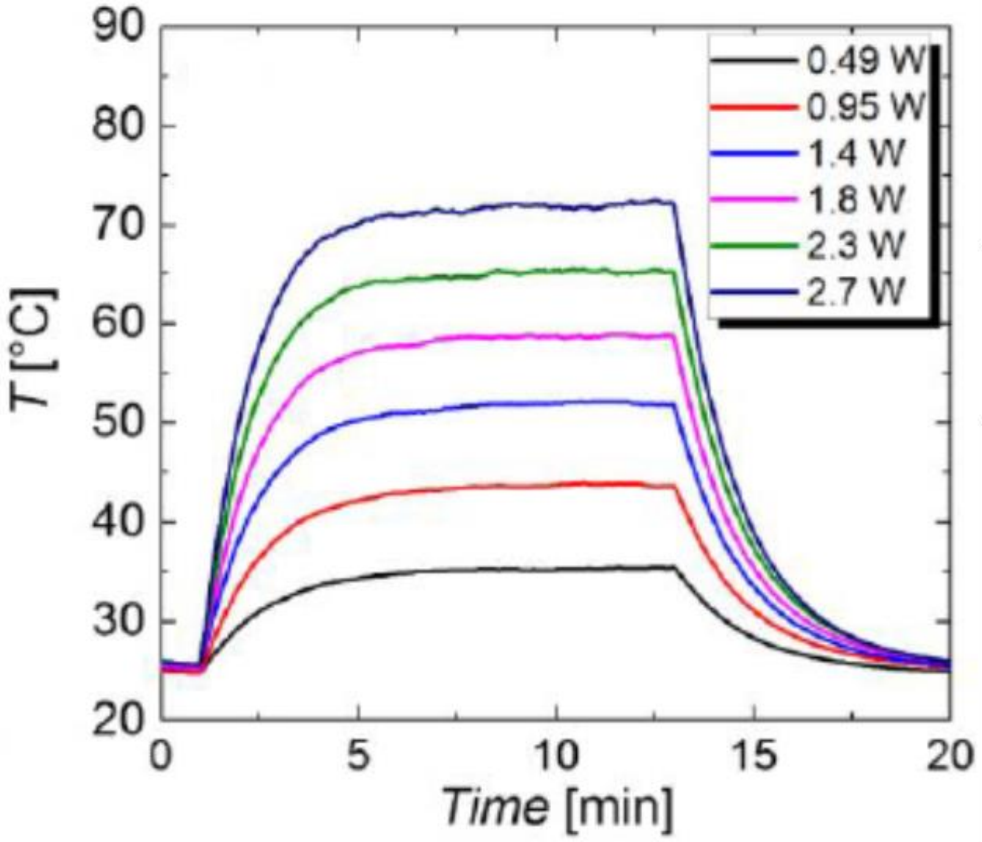
Printed NanoWires on transparent and/or flexible layers featuring tuned electrical and optical properties

Applications:

- Thermocouples
- Heaters
- Antennas
- Thermo-acoustic loudspeaker
- Piezo-electric mics & strain gauges





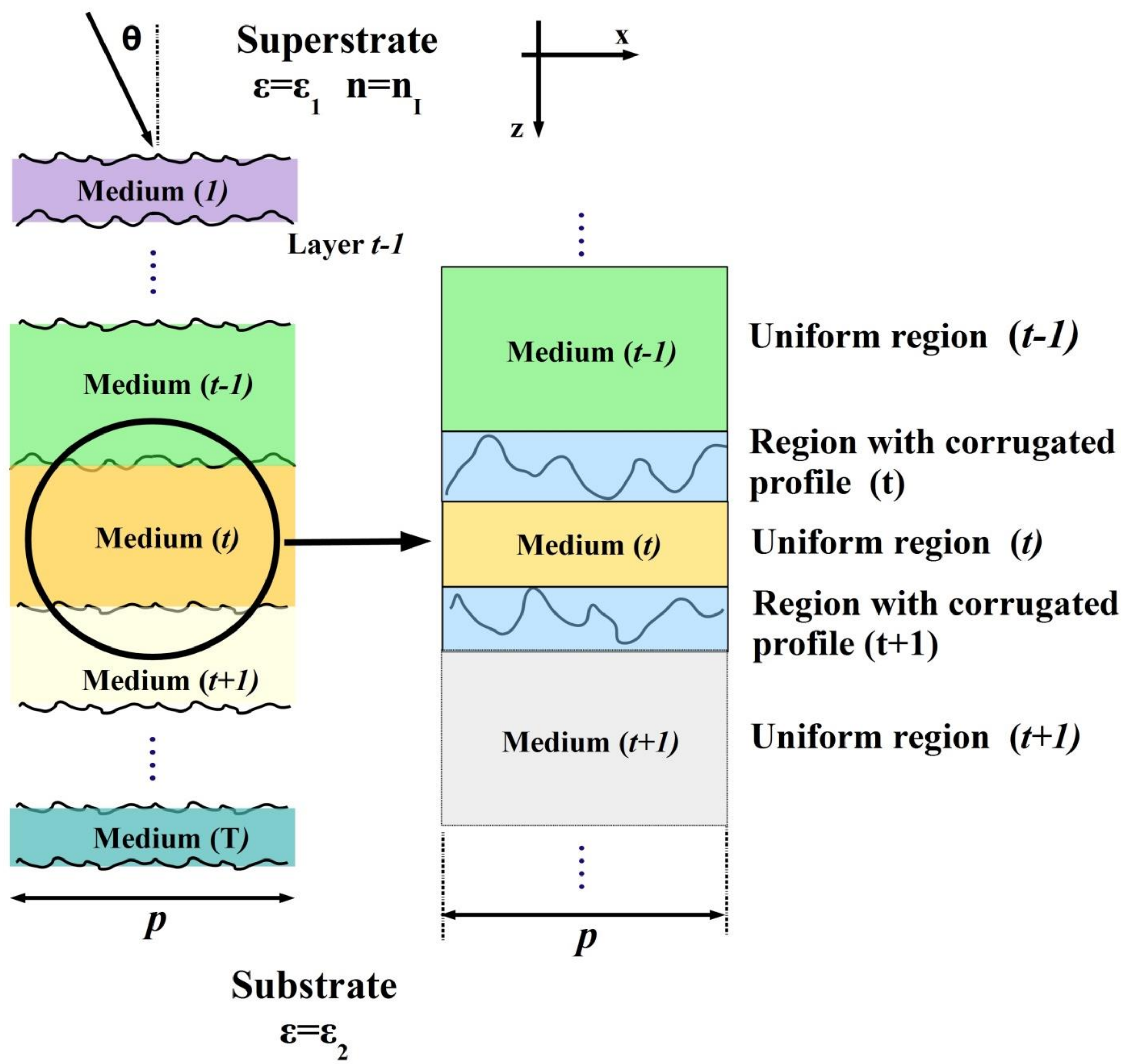


MOEMS@UniBO: optical simulations

- Expertise in the field of 2-D/3-D optical simulation (Finite Difference Time Domain – FDTD, Rigorous Coupled-Wave Analysis – RCWA) applied to optical reflectivity of micro-mirrors.

- Objective: optimize the geometry by taking into account for process-dependent interface morphologies.

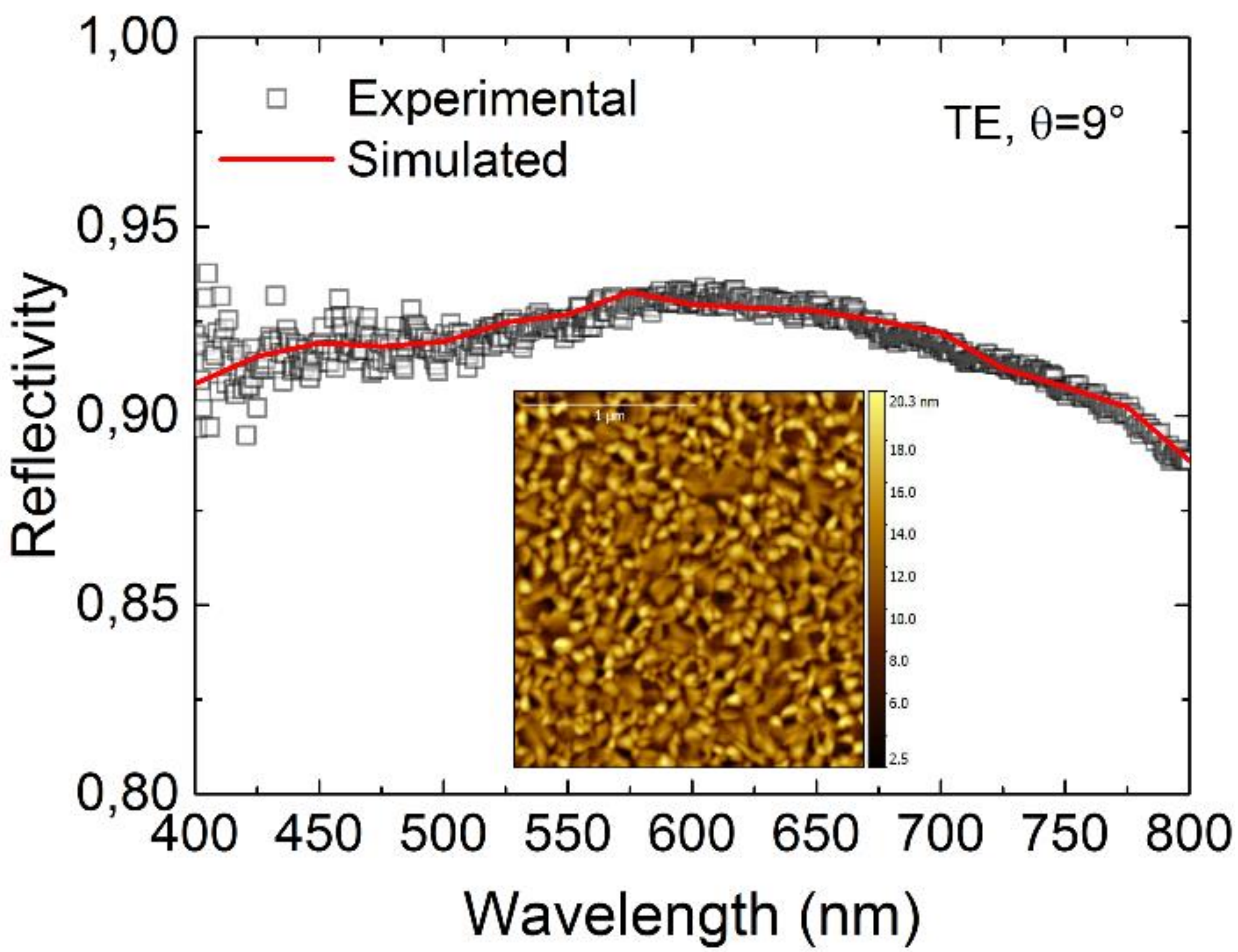
- Tool requirement: adequate simulation of light scattering with features smaller than the wavelength (rules out ray tracing. scalar scattering models)



Enhanced RCWA (eRCWA)

- 2D multi-layer stack.
- Inter-layer corrucated profiles
- structure is divided into uniform regions and corrugated interfaces (with non uniform permittivity).

MOEMS@UniBO: optical simulations

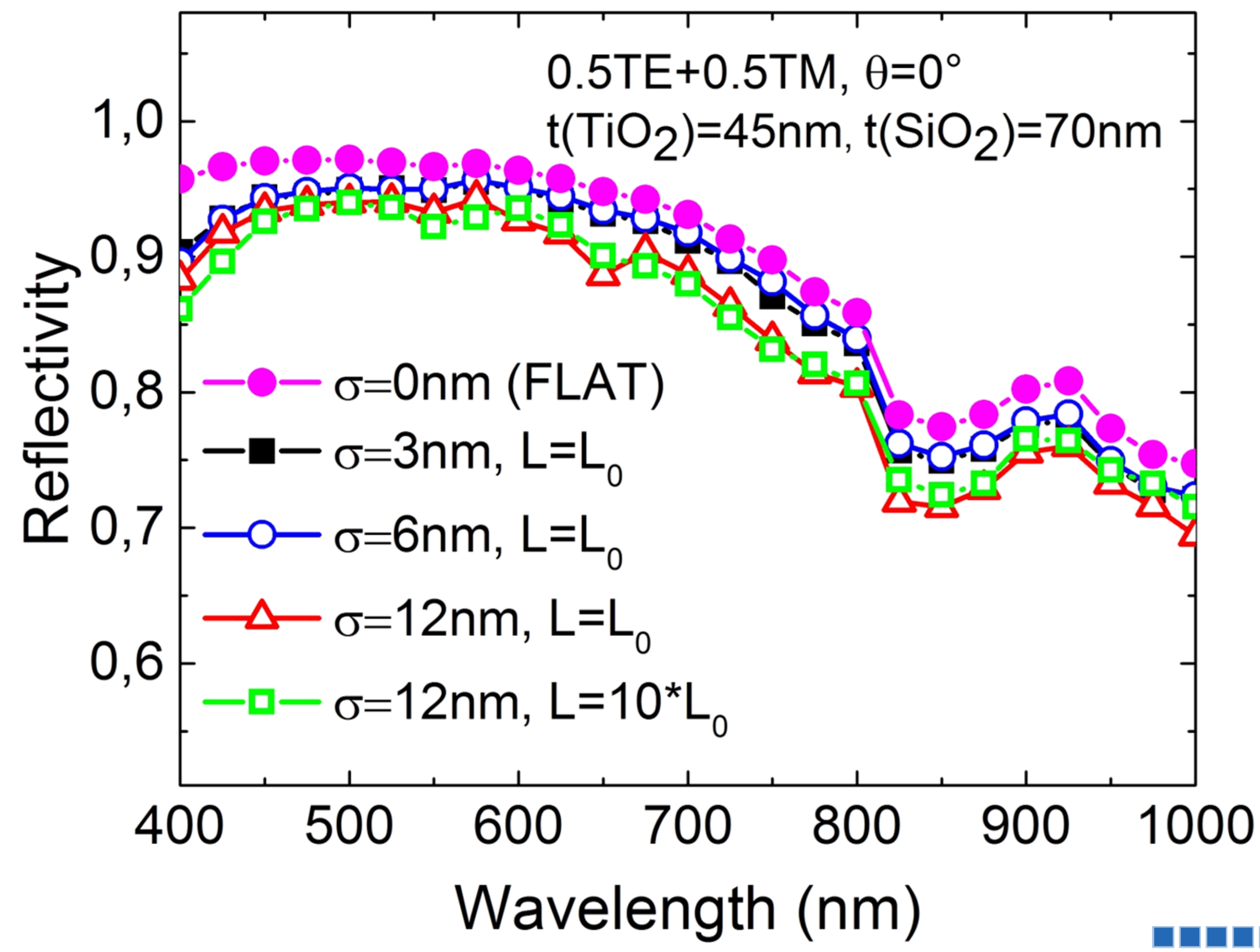


Experimental validation

- Uncoated 100nm AlCu mirror (100nm thick) on Silicon.
- Inset: AFM surface morphology images of the bare 100-nm-thick-AlCu layer on Si.

Parametric sensitivity

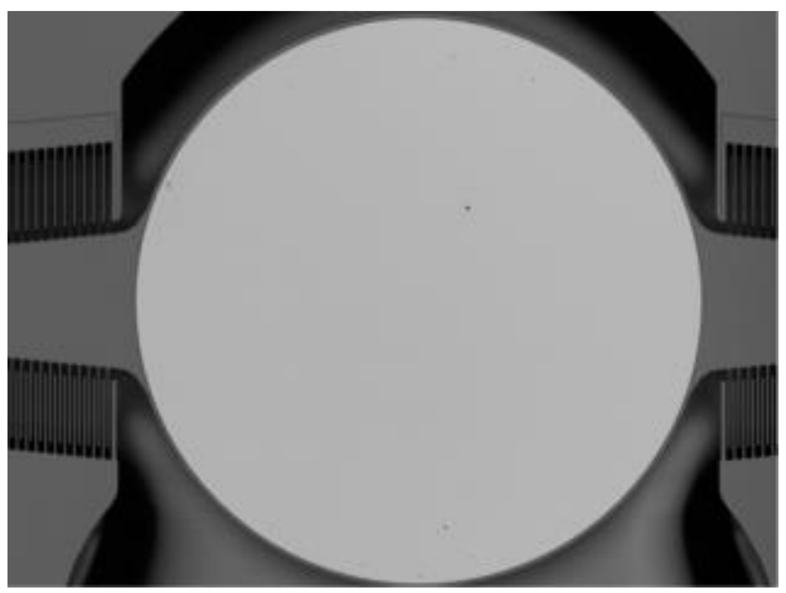
- Simulated reflectivity of a dual layer TiO_2/SiO_2 coated mirrors w/r to interface roughness σ and correlation length *L*.
- Comparison with ideal flat-interface assumption

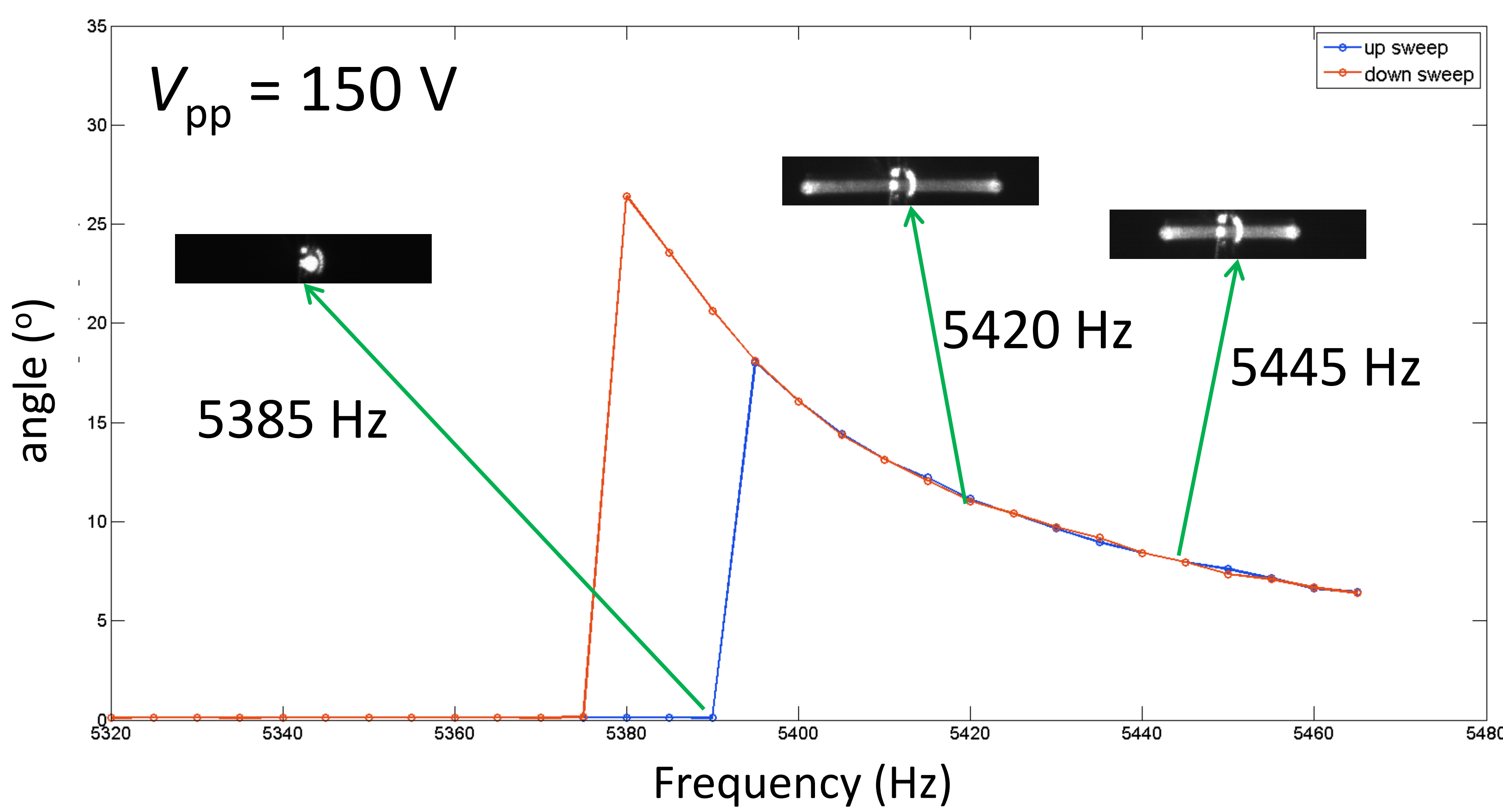


MEMS@UniPD: characterization

Characterization of static and dynamic performance of MEMS micromirrors

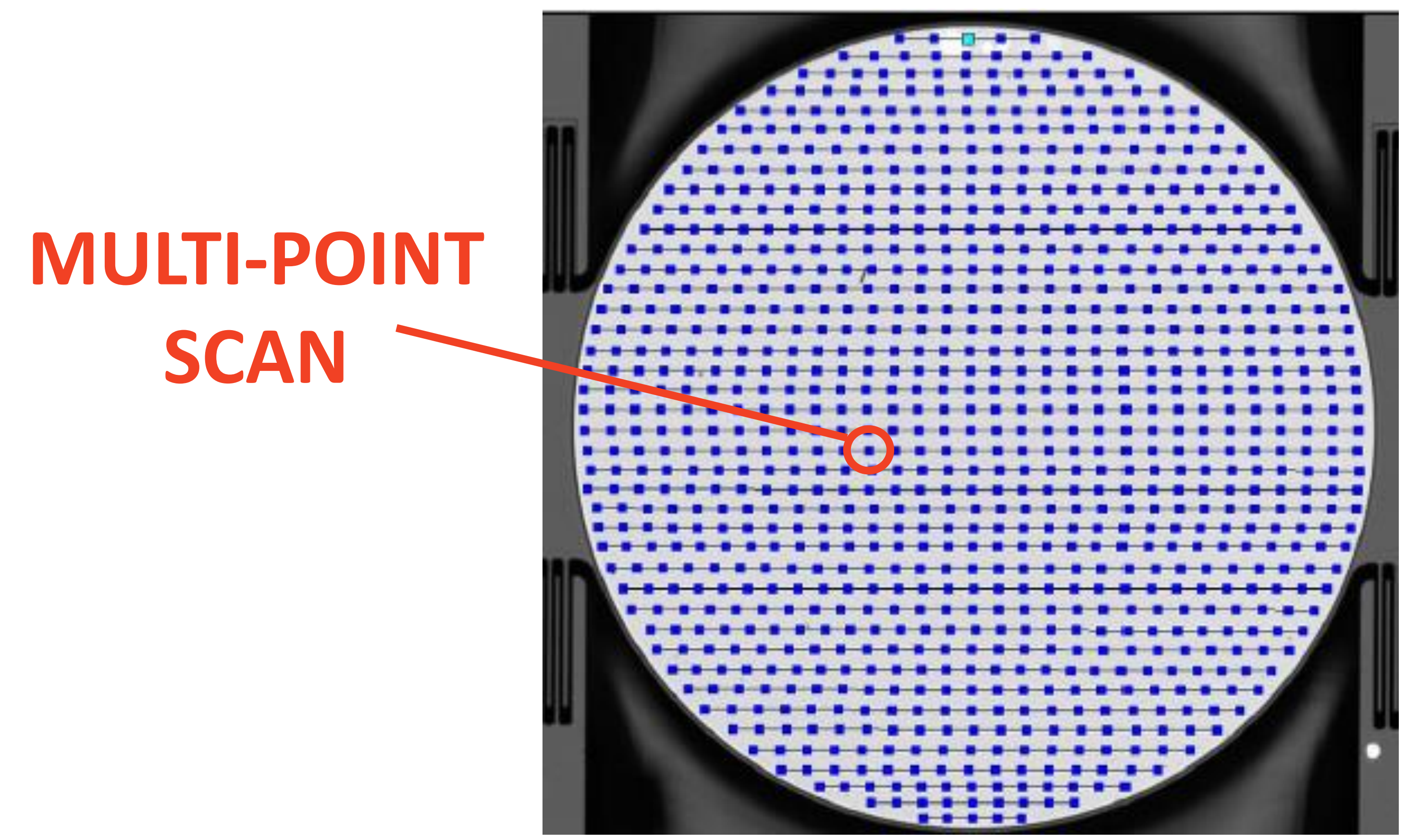
Frequency laser tracking of angular deflection in electrostatic torsional mirrors

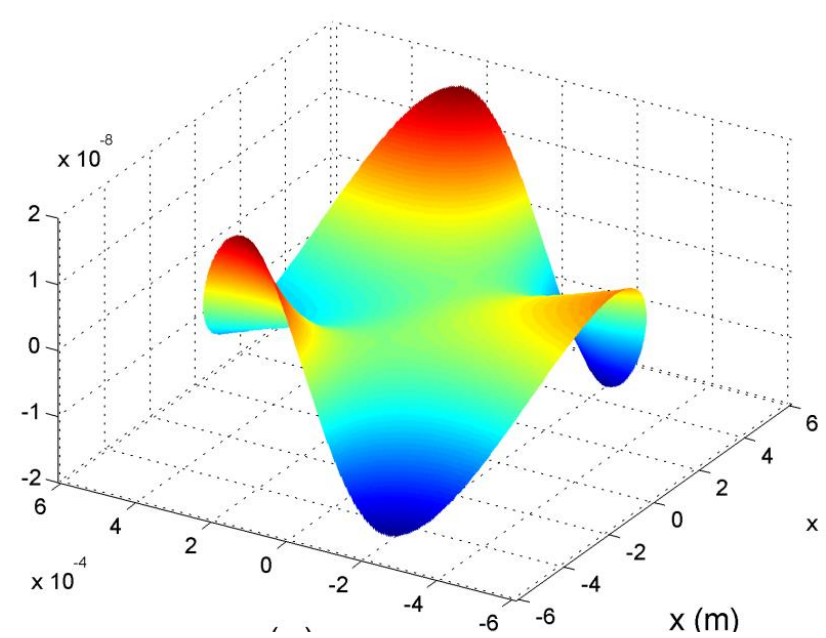




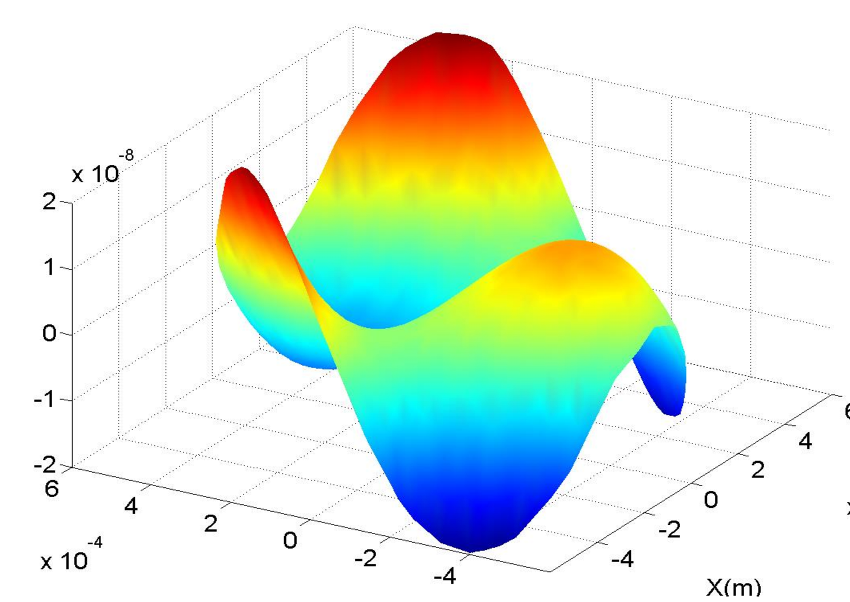
Hysteresis caused by mechanical non-linearities

Dynamic mirror deformation by laser Doppler vibrometry





FEM simulation

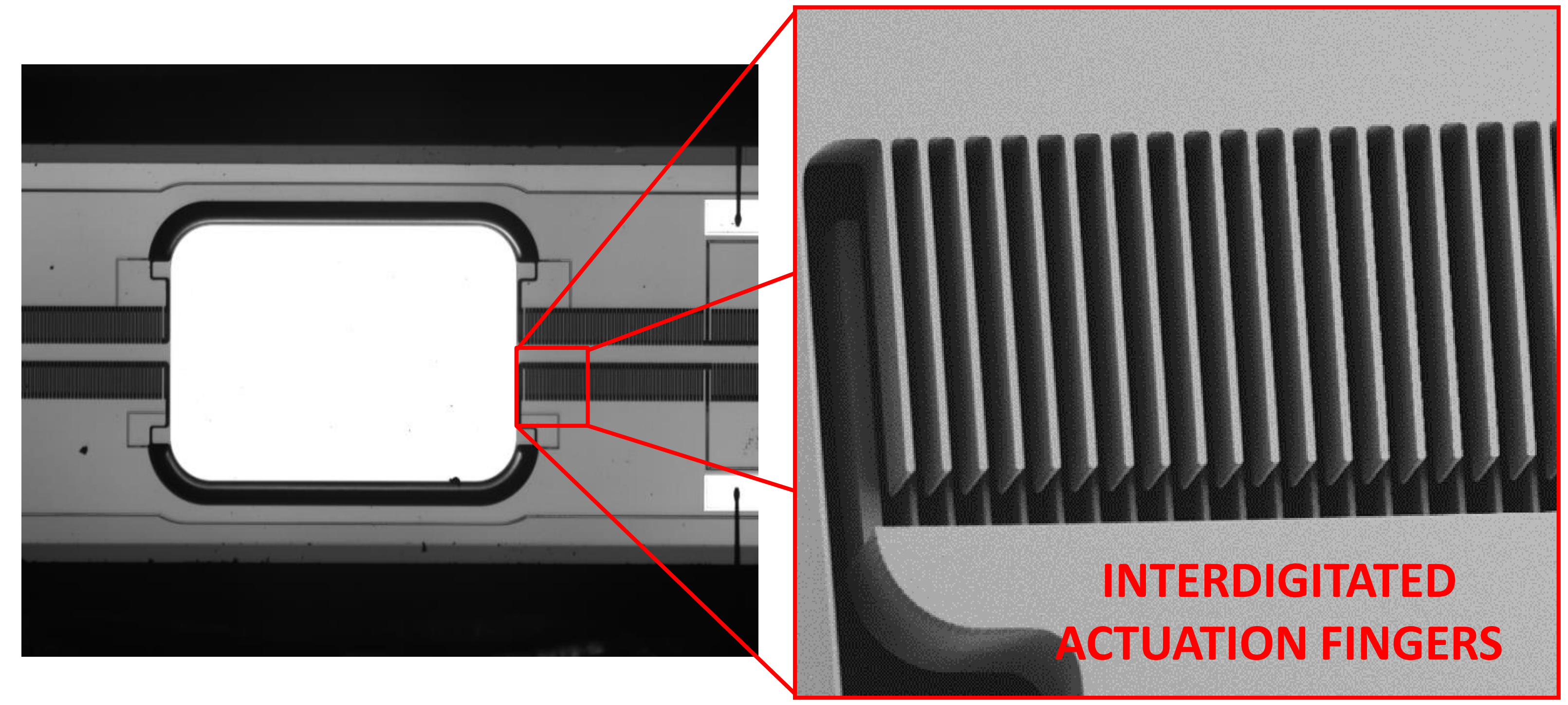


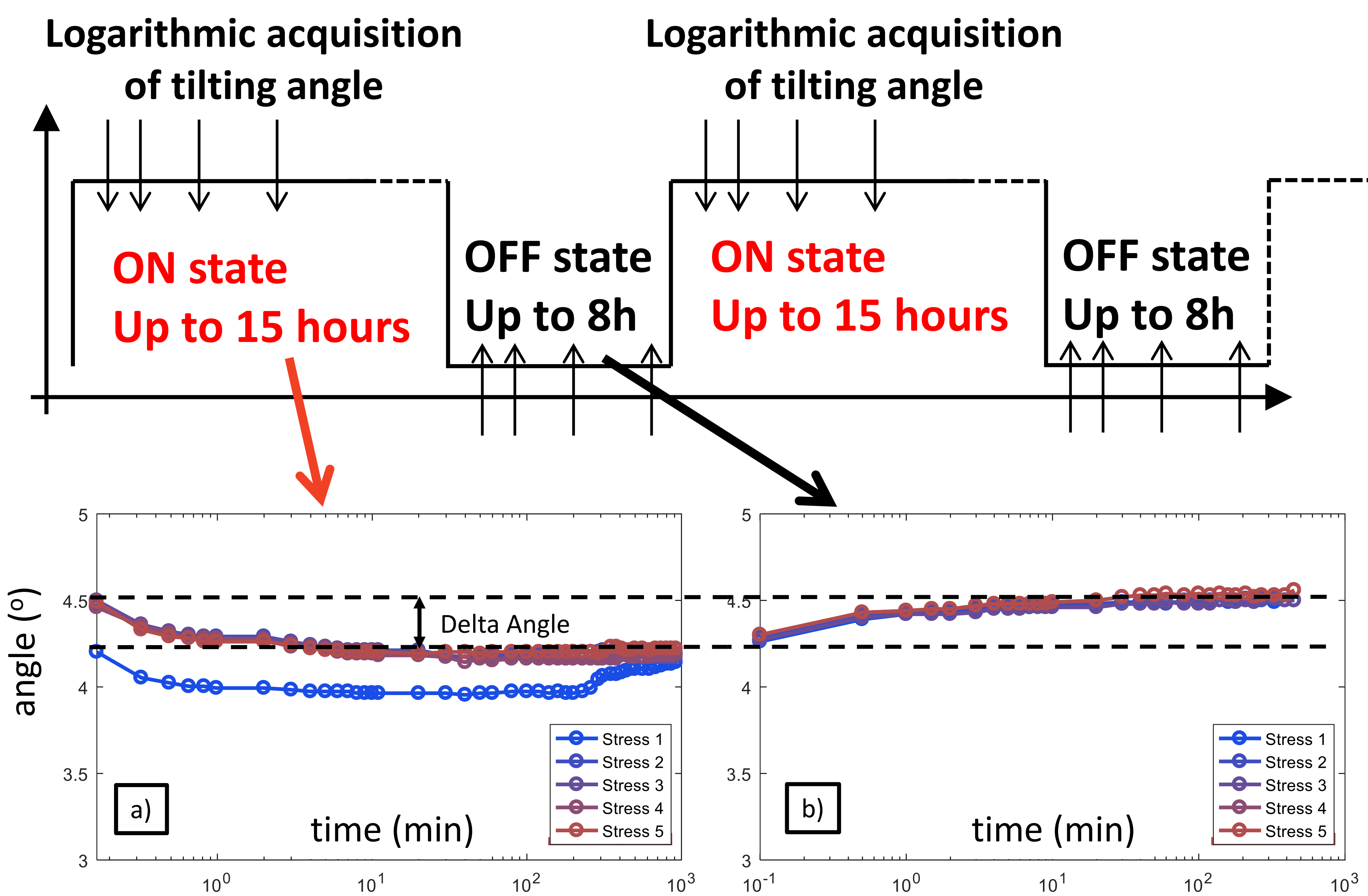
Vibrometry data

MEMS@UniPD: reliability

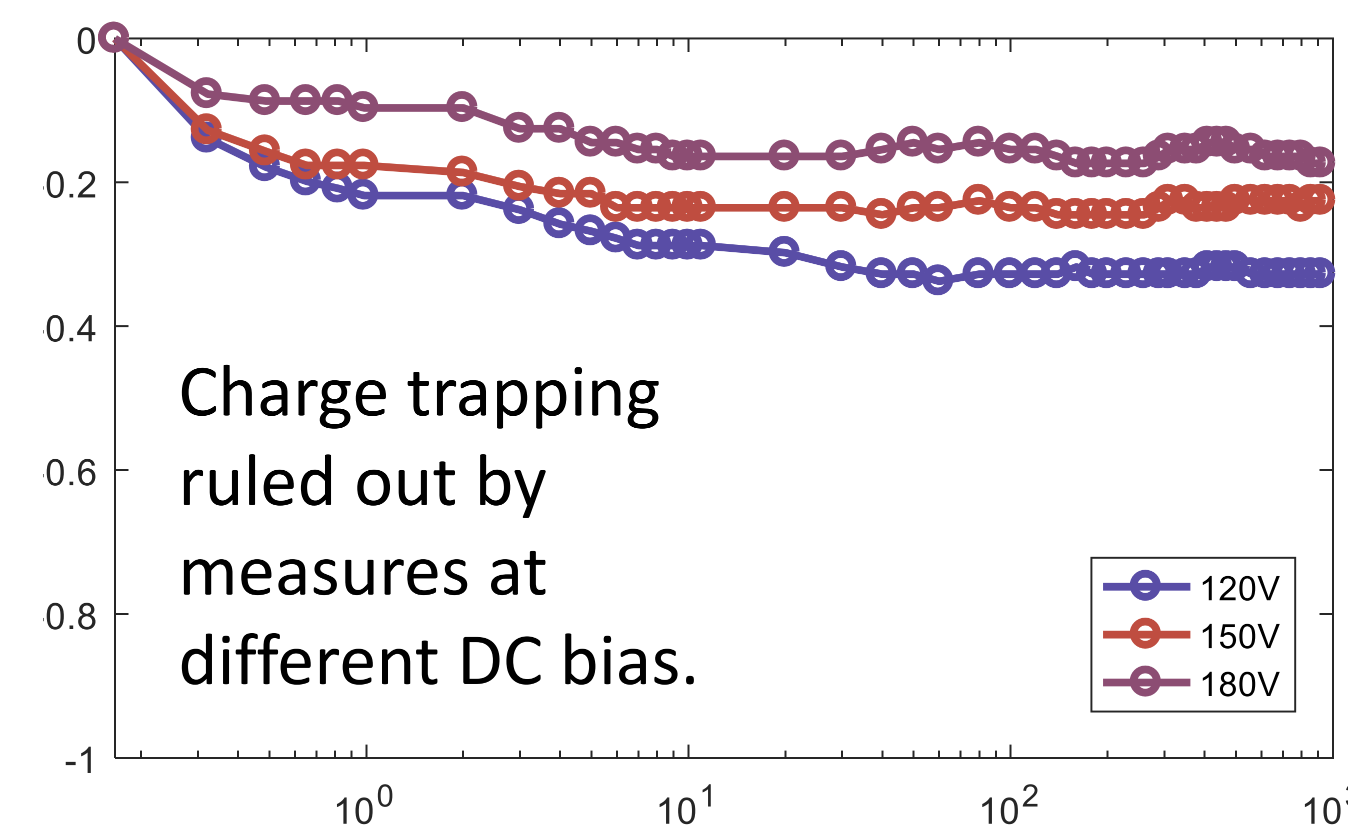
Evaluation of long-term stresses in linear electrostatic mirrors

- The mirror is alternatively **biased in DC (15 hours)** and **turned off (8 hours).**
- The tilting angle is acquired at logarithmic times during both phases.





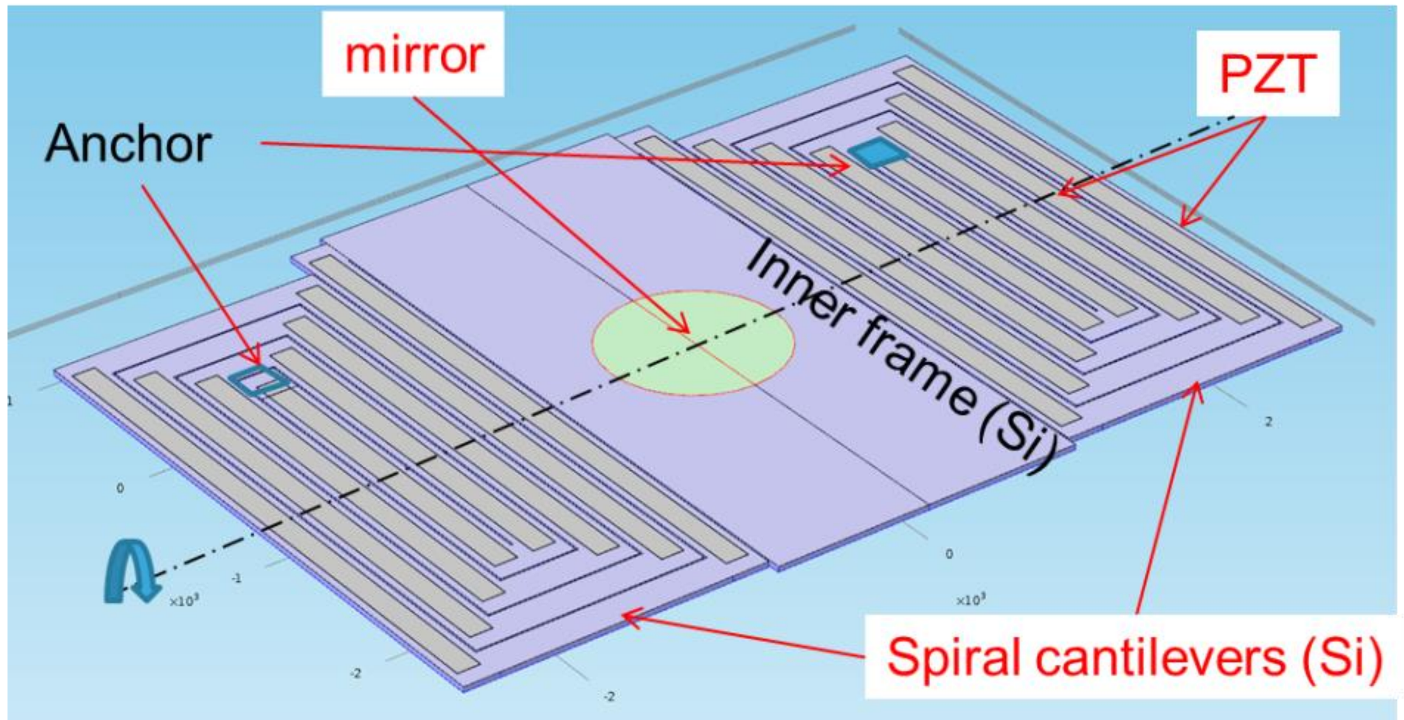
- Permanent angle change (blue curve, 300 min) → permanent stiffness variation.
- Recoverable angle change → change in the mechanical properties of the torsion bars.



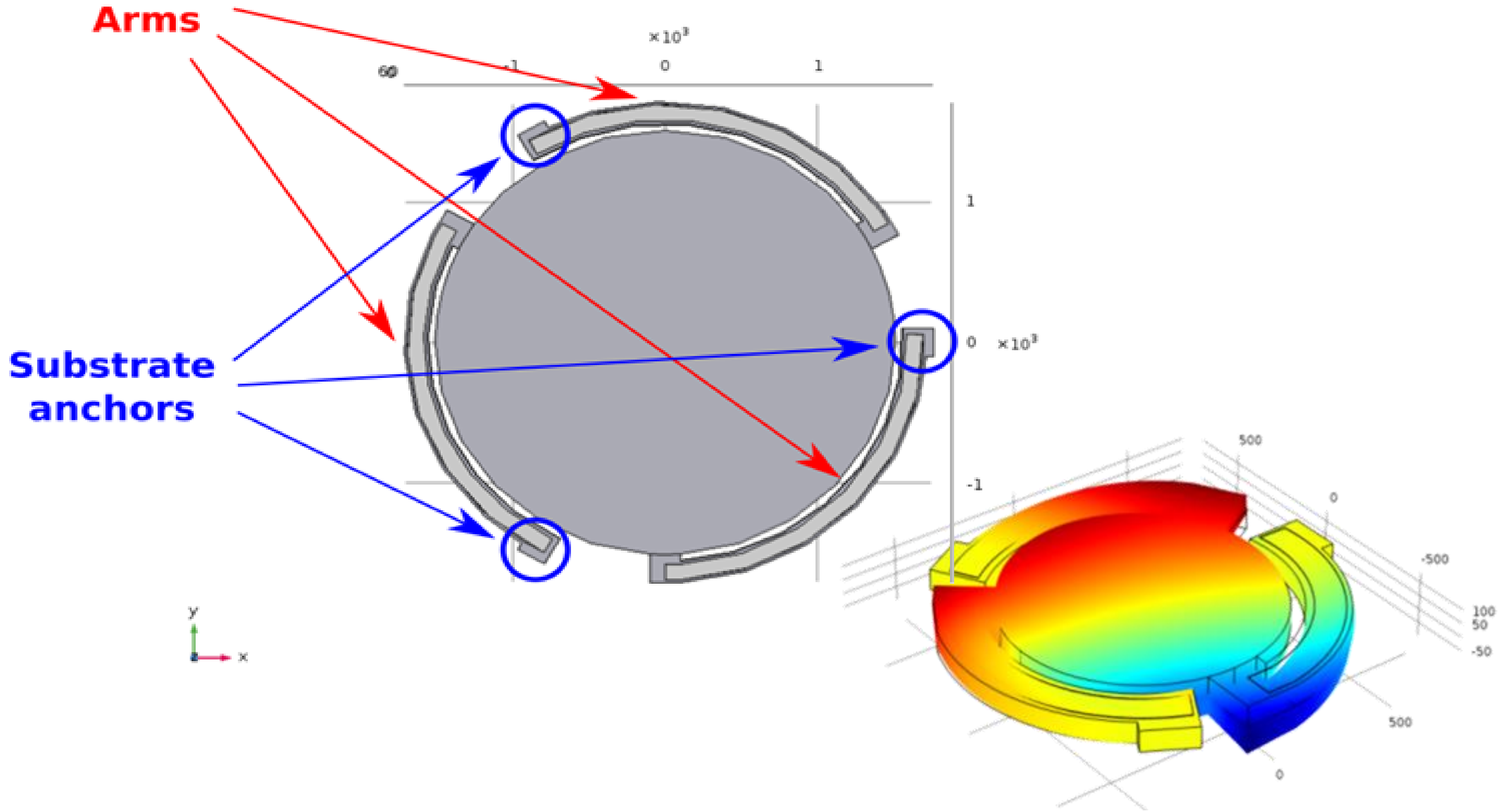
MEMS@PoliTO: MOEMS design

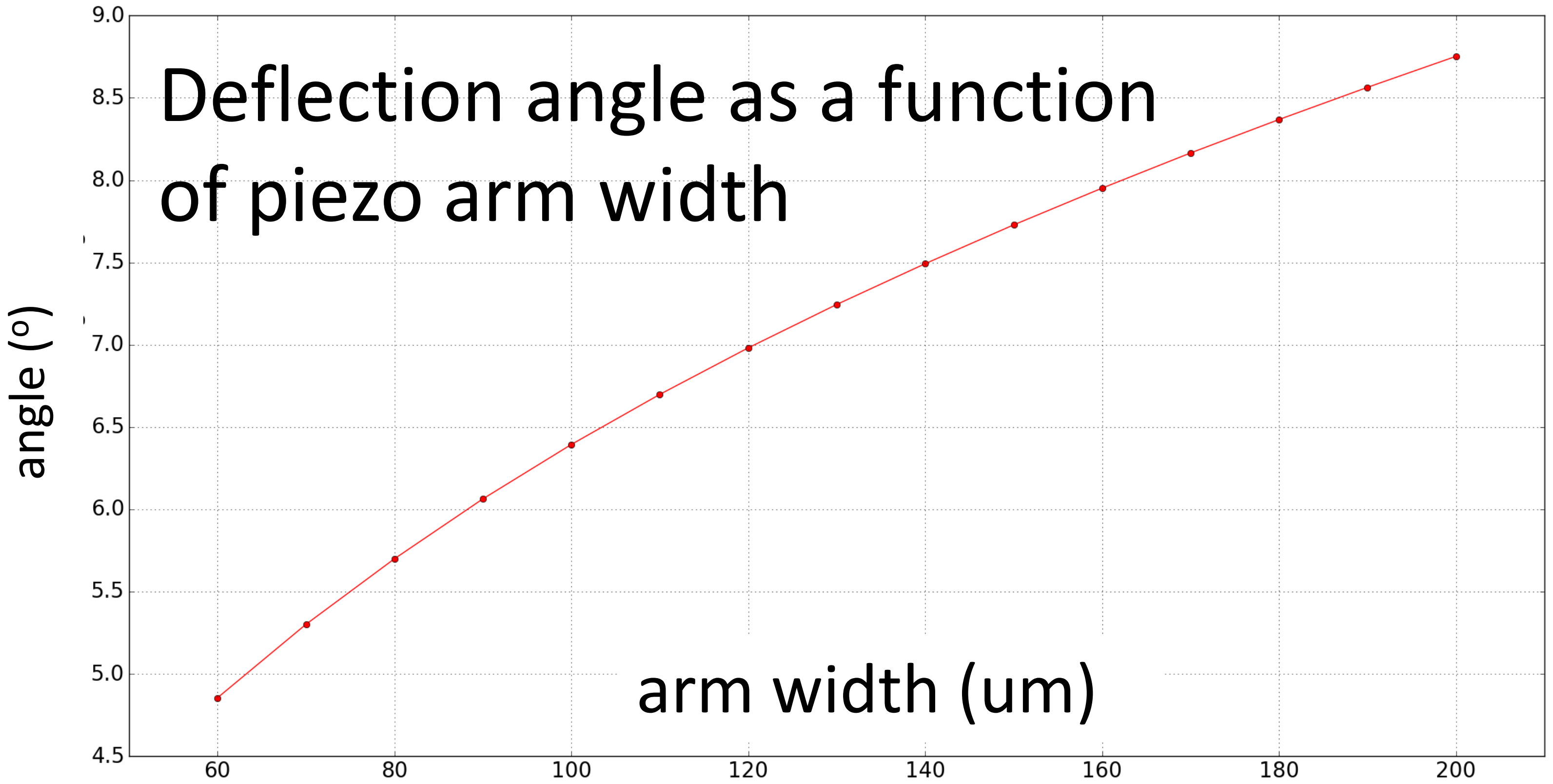
Design and FEM simulation of piezoelectric MEMS micromirrors

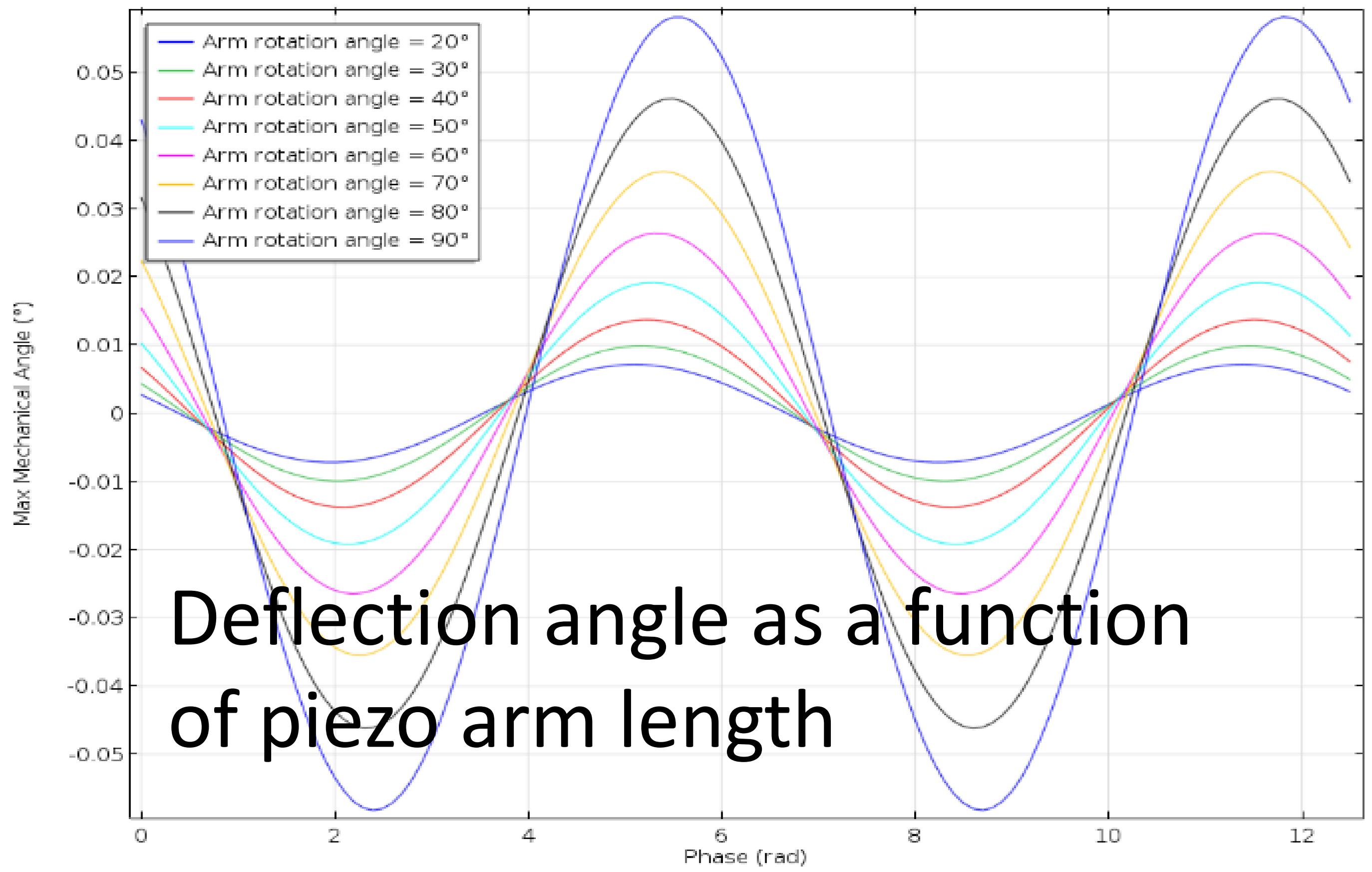
Tilting mirror with mechanical angle amplification



circular mirror with multiphase actuation







Where from here?

- Few traditional big players (Bosch, STM, HP, TI) but mature applications (inertial, pressure, etc.) are quickly commoditized

- new players can enter the market with the right application (e.g. Knowles with microphones, Avago with MEMS filters)

- Next trends:
  - Sensor is still the core, but
  - around the sensor, applications will be smart, pervasive, connected

- Role of IU.NET?

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