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
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

**Sensing of “invisible” objects**

**Quantitative prediction of experimental data**

**Discriminate dielectric and conductive particles**

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**Sensors@UniUD: nano-electronic sensors**
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

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
Sensors@UniRM1: CMOS-based THz Rectifier

Proposed Architecture: principle of work

Evaluated NEP at 1 THz 0.6 pW/Hz$^{0.5}$
Sensors@UniRM1: Silicon nanostructures

- Sensori FET
- LED
- Celle solari
- Batterie
Sensors@UniRM1: Silicon nanostructures

Grown by MWCVD/PECVD

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

• 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**.

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

Example: CMOS-based resonant mass sensor

Example: c-Si Lamé resonators with enhanced sensitivity - TCF compensation by doping/perforations
Phononic crystal resonators
Periodic modulation of mechanical properties (elasticity, density, cross-section, ...)

Fast modeling with acoustic transfer matrices
FEM validation
Experimental validation

MEMS@UniPI: resonant MEMS sensors
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)."

IUNET involvement:
- UniPI: mirror design
- UniMoRe: IC design (mirror drivers, laser drivers)
- UniBO: optical simulation of mirror reflectivity
- UniPD: mirror characterization, mirror reliability
Technology: 65 and 55nm by STMicroelectronics

**Current driver for micromirrors**
- Transconductor stage: able to provide current > 75 mA
- Differential Sallen-Key 2\textsuperscript{nd} 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
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
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 corrugated 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 $\sigma$ and correlation length $L$.
- Comparison with ideal flat-interface assumption.
Characterization of static and dynamic performance of MEMS micromirrors

Frequency laser tracking of angular deflection in electrostatic torsional mirrors

Dynamic mirror deformation by laser Doppler vibrometry

Hysteresis caused by mechanical non-linearities

FEM simulation

Vibrometry data

$V_{pp} = 150 \text{ V}$

5385 Hz

5420 Hz

5445 Hz
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.

Charge trapping ruled out by measures at different DC bias.
Design and FEM simulation of piezoelectric MEMS micromirrors

**Tilting mirror with mechanical angle amplification**

![Tilting mirror diagram](image)

**Circular mirror with multiphase actuation**

![Circular mirror diagram](image)

**Deflection angle as a function of piezo arm width**

![Graph](image)

**Deflection angle as a function of piezo arm length**

![Graph](image)
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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