FLEXTEG Workshop

June 25th, 2015
Dresden, GE

Mechanical Energy Harvesting at SiNERGY

Gonzalo Murillo, IMB-CNM (CSIC), Spain
Martijn Goedbloed, IMEC-NL, Netherlands

Mechanical energy harvesting: vibrations to electrical energy

- Electrostatic → **Holst Centre, Eindhoven (NL)**
  Martijn Goedbloed
  - Charged variable capacitor
- Piezoelectric → **IMB-CNM, Barcelona (ES)**
  Gonzalo Murillo
  - Electric charge due to applied stress in piezoelectric material
- ~~Electromagnetic~~
  - Induction by variable magnetic field

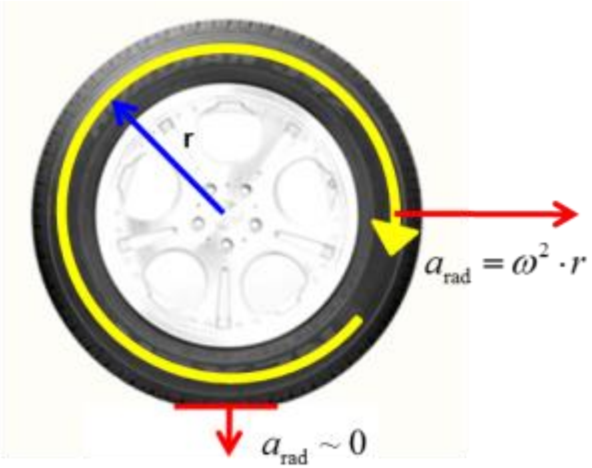
- Electrostatic Energy Harvesters

  M. Goedbloed at IMEC-NL

- Piezoelectric Energy Harvesters

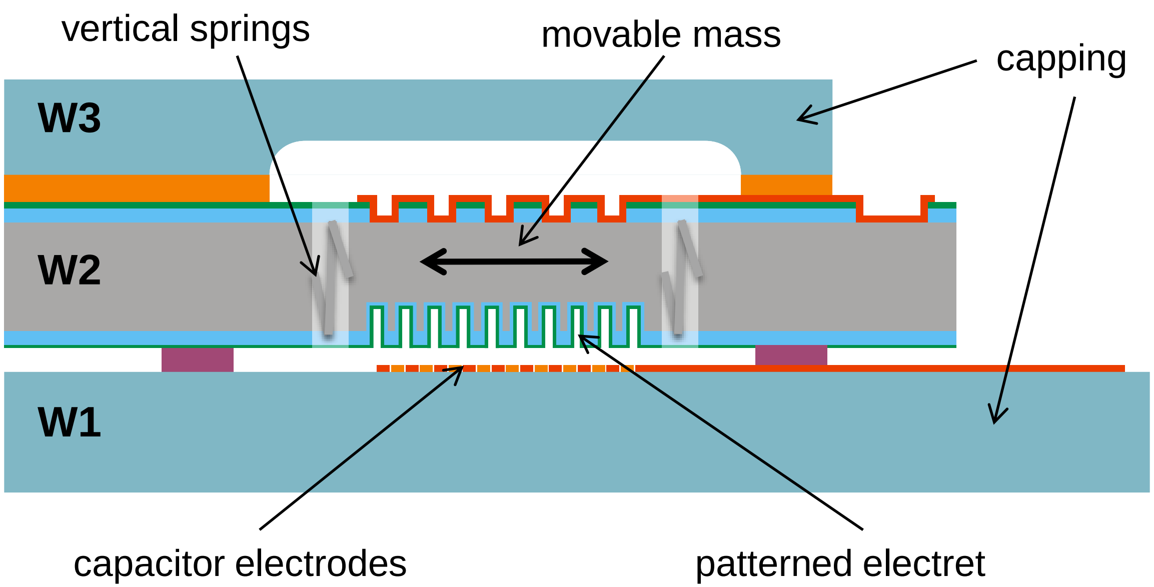
  G. Murillo at Microelectronic Institute of Barcelona

- Electrostatic Energy Harvesters
- Application goal: in-tire TPMS
  - Harvest energy from shocks and vibrations
  - Power requirements ~10µW
  - 2000 g shock resistance

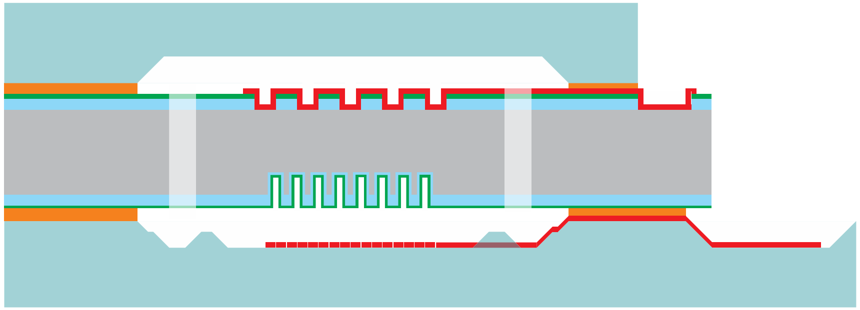


Device design, materials, fabrication process

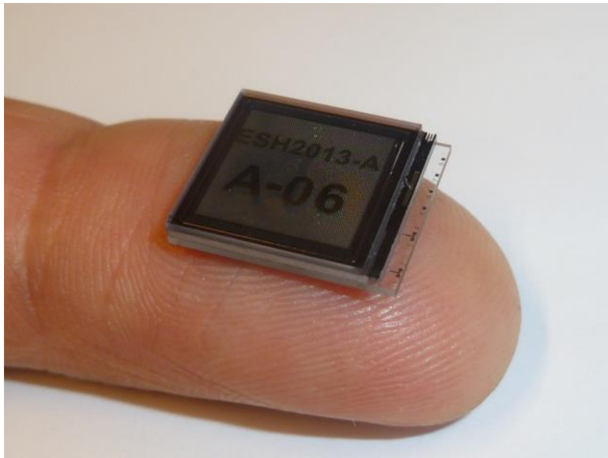
- Si mass on DRIE etched vertical springs
- Corrugated DRIE etched Si with SiO_2/Si_3N_4 electret
- Glass cappings with cavities and electrodes
- BCB or SU-8 polymer waferbond
- Stepped dicing for access to electrodes

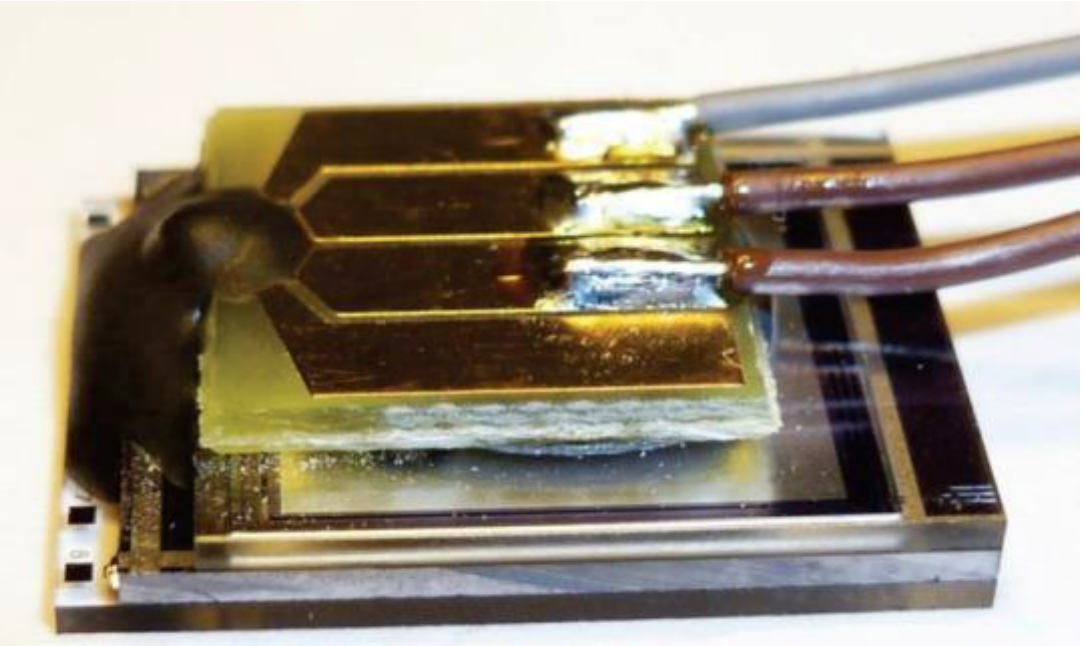


- Fabrication 1st generation harvesters
- First batch
  - Low electret voltage (equipment malfunctioning)
  - Low mechanical quality factor (air damping)
- Second batch with small improvements
  - Successful devices have been fabricated
  - W3 cavity 100µm deep to reduce air damping

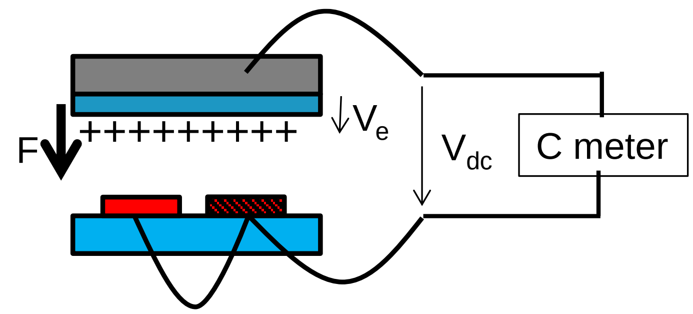


- Devices delivered to STE for application in TPMS
  - Mounted on PCB

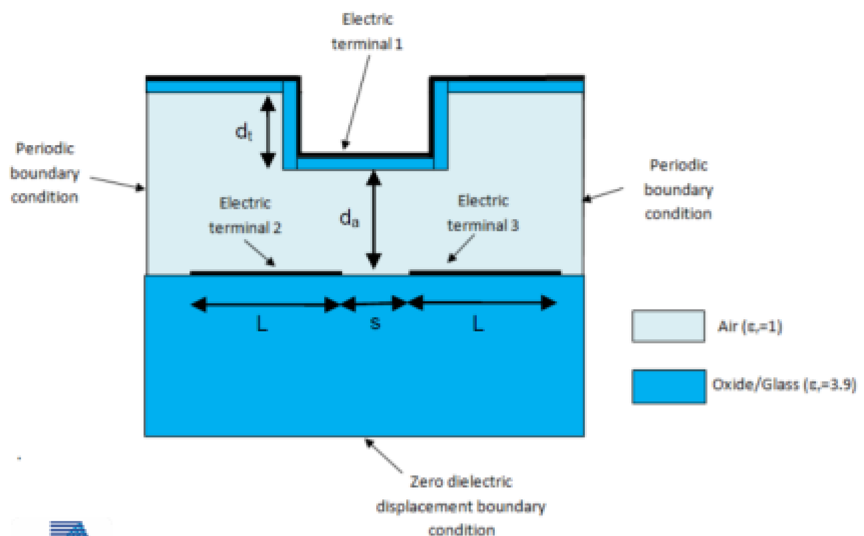


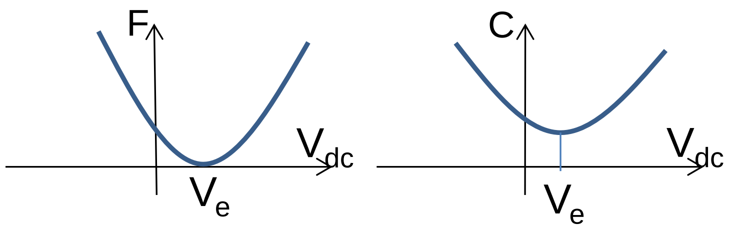


- Device characterisation
- Impedance analyser
  - Capacitance measurement
  - Capacitive electret voltage measurement
  - Capacitances and voltages were as expected



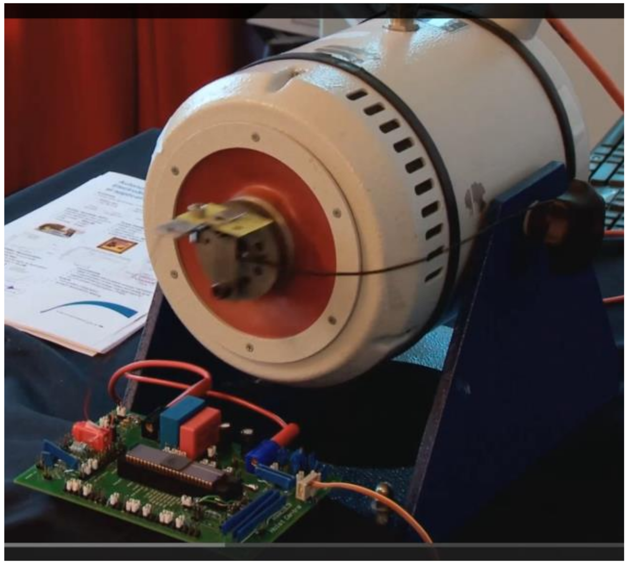
F proportional to $(V_{dc}-V_e)^2$

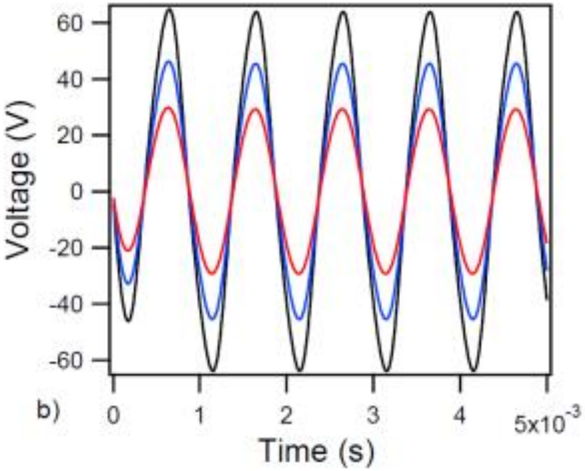


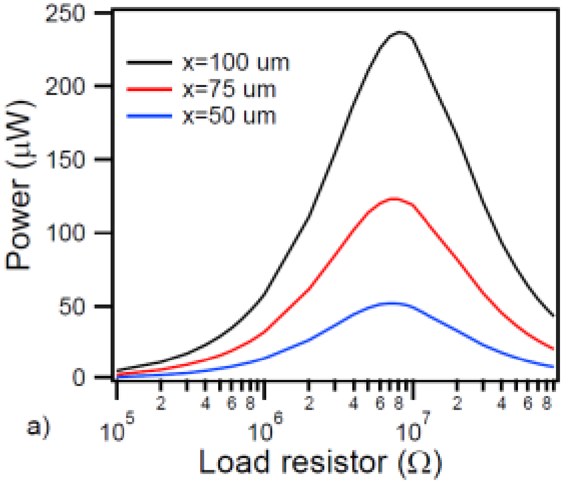


Minimum at $V_{dc}=V_e$

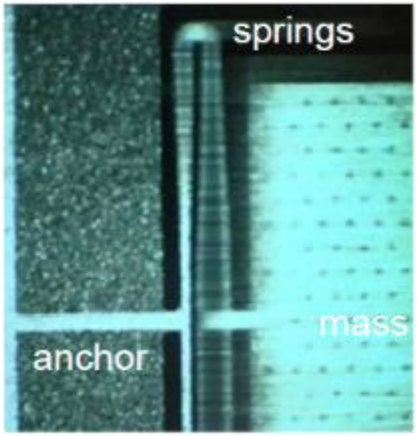
- Device characterisation
- Shaker setup
  - Sinusoidal input vibration
  - Frequency sweep
  - Load resistor optimisation

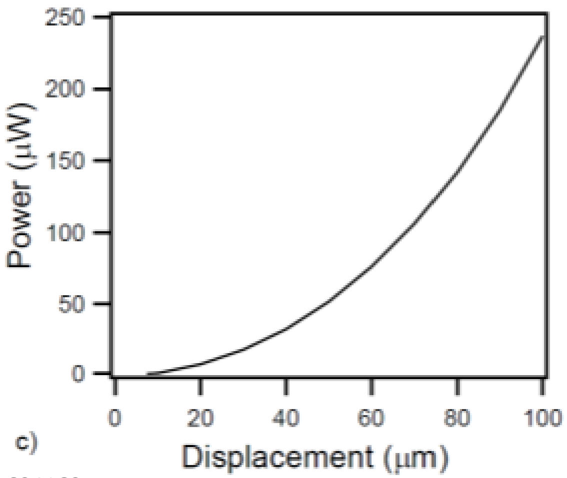






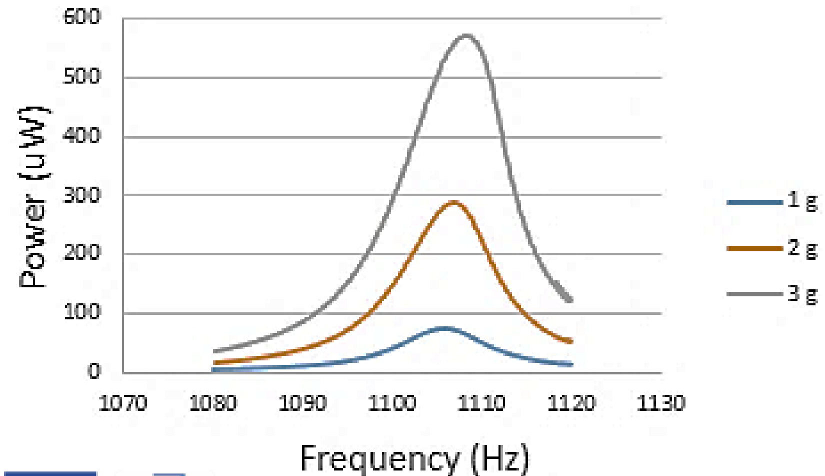
- Device characterisation
- Shaker setup
  - Sinusoidal input vibration
  - Observation of mass movement (amplitude) → quality factor Q
    - Normal Q measured for 2^{nd} batch of devices

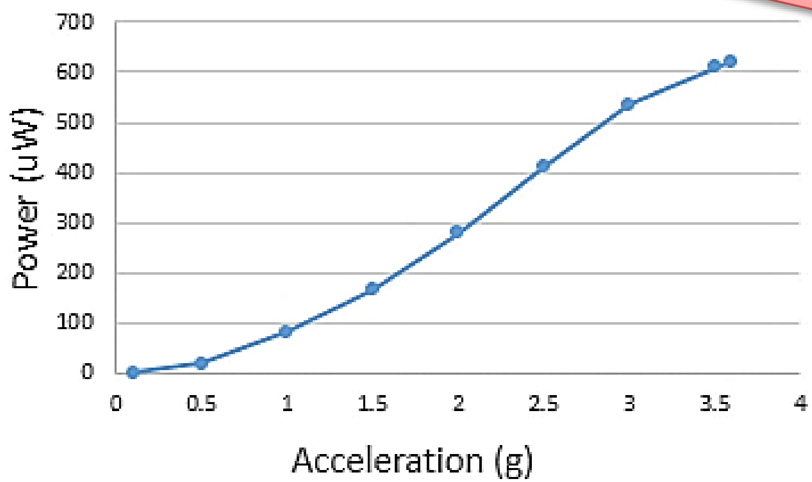




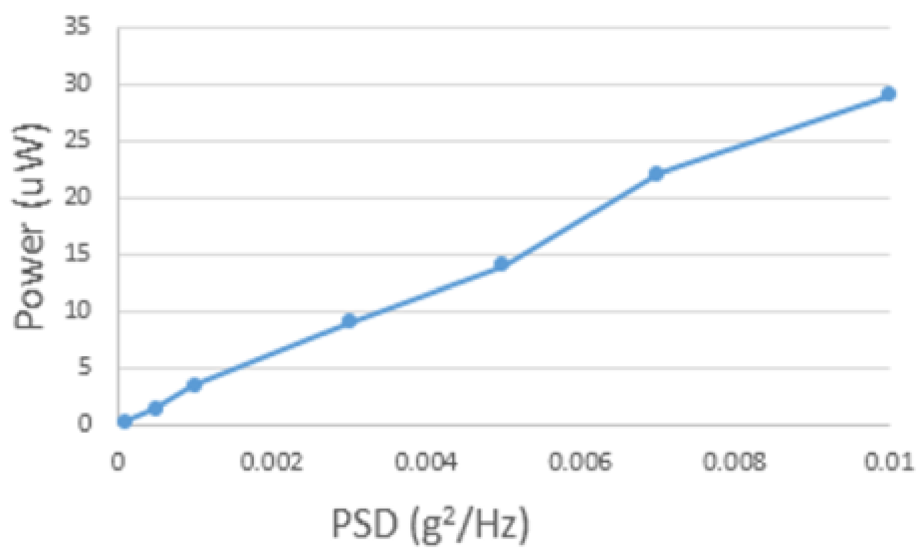
- Device characterisation
- Shaker setup
  - Sinusoidal input vibration
  - Frequency sweep at optimised load resistance
  - **600 µW output power** at full mass displacement
    - **More than predicted in model**

World Record for MEMS-based electrostatic harvesters





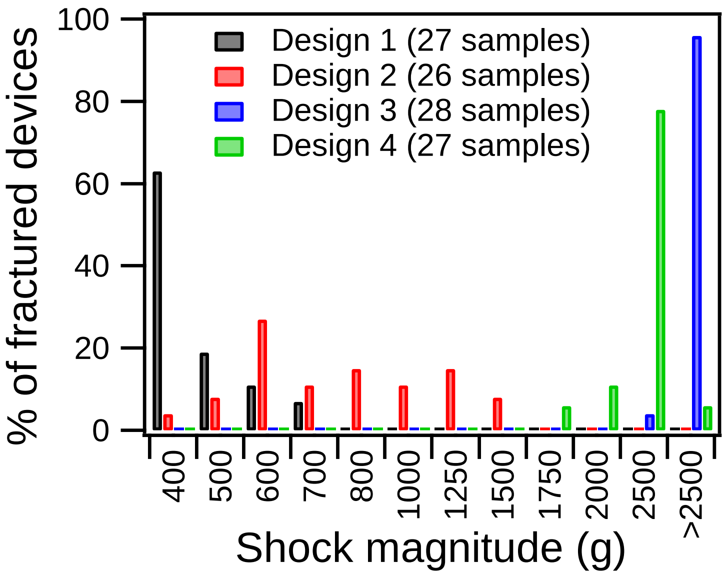
- Device characterisation
- Shaker setup
  - White noise excitation
  - Realistic output power value for application scenario
  - 30 µW enough to power a TPMS

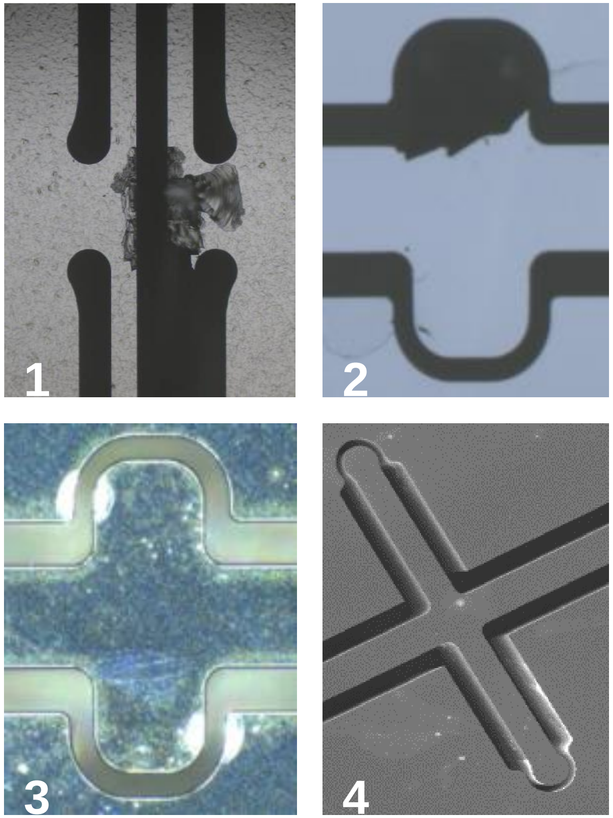


- Towards a 2nd generation improved devices
- Output power improvement
  - Higher electret voltage
- Lifetime improvement
  - Electret charge retention
- Reliability improvement
  - Confine the mass movement (stoppers)

• Reliability improvement

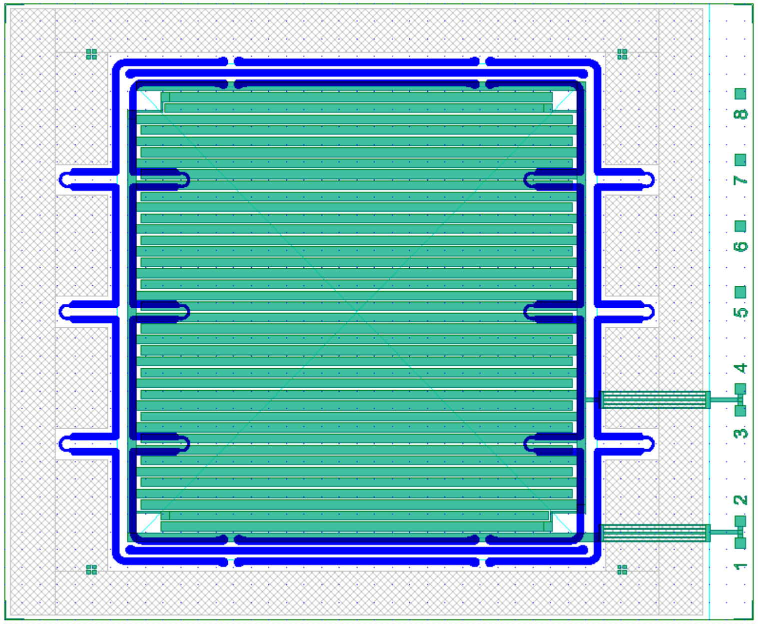
1. Original
2. Rigid stoppers
3. Rigid stoppers with soft coating
4. Flexible stoppers





M.Renaud *et al*, PowerMEMS 2014
M.Renaud *et al*, J Micromech Microeng, 2015, accepted

- Next months actions
- Mask redesign
  - Flexible stoppers
  - Deep W3 cavities with dimples
  - Increased waferbond area
- Process step optimization
  - SU-8 bond
  - Flex stopper etch on electret wafer



- Electrostatic Energy Harvesters

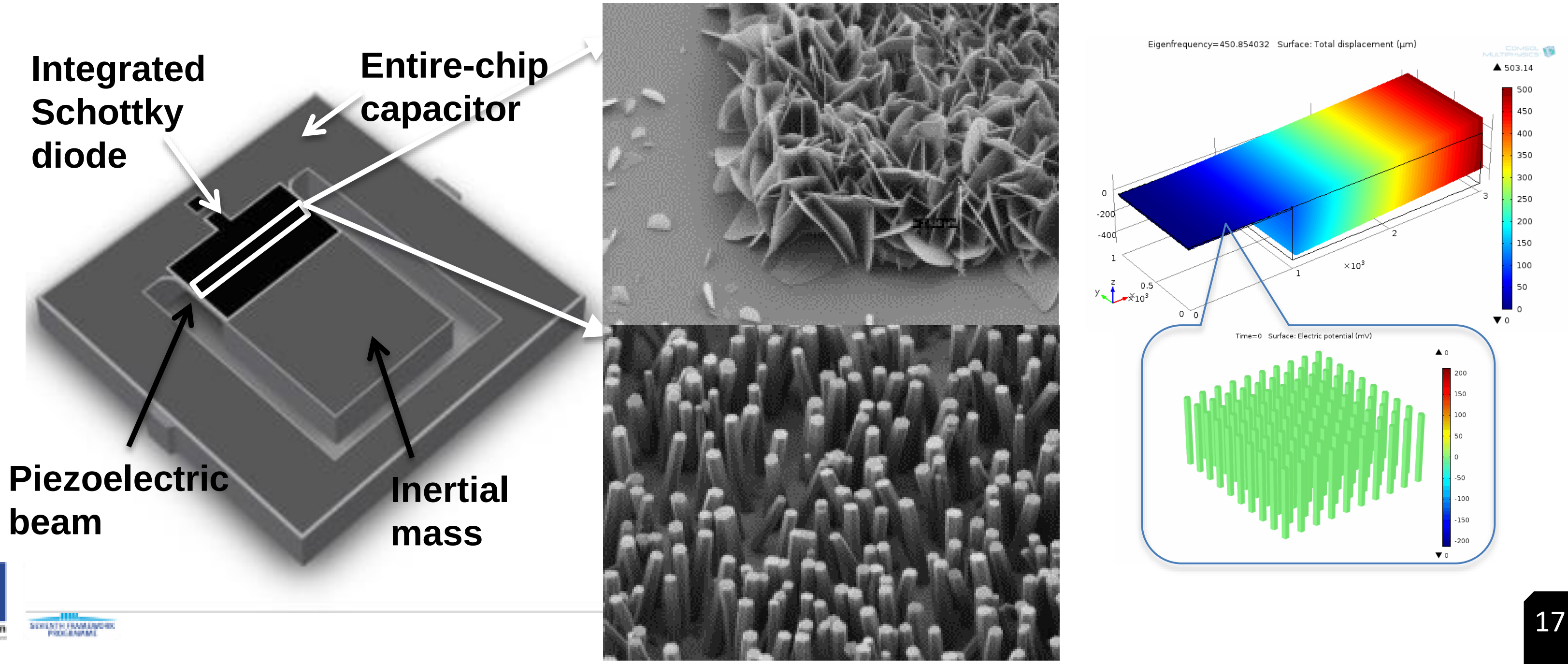
  M. Goedbloed at IMEC-NL

- Piezoelectric Energy Harvesters

  G. Murillo at Microelectronics Institute of Barcelona

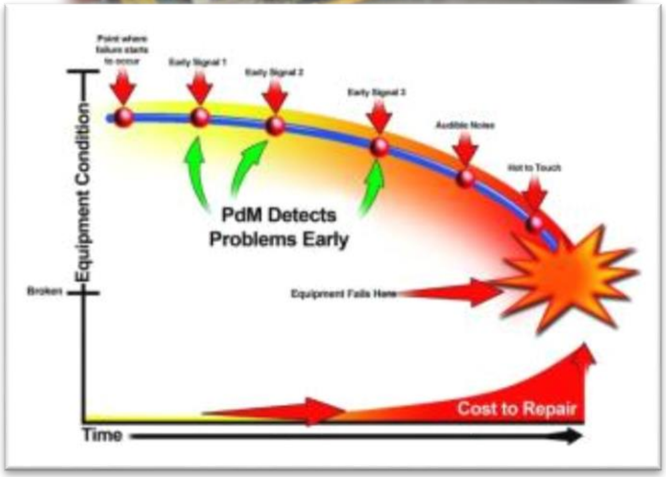
NMP3-SL-2013-604169

- Piezoelectric Energy Harvesters
  - Silicon mass and cantilever beam based on DRIE of an SOI wafer
  - **ZnO nanostructures** (NW and NS) arrays growth on top of beam
  - SU-8 polymer encapsulation of NW array
  - **Monolithically integrated Schottky diode and capacitor**



Applications scenario selected:

- Predictive maintenance

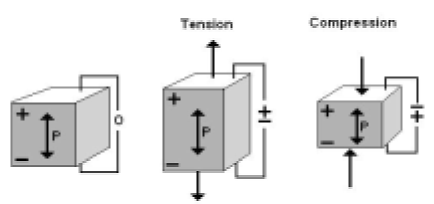


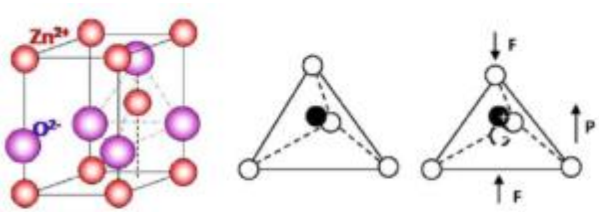
- *High number of nodes*
- *Difficult servicing*
- *Ambient vibrations available*

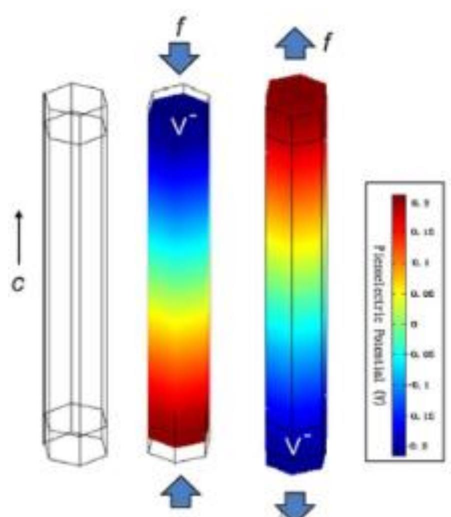
- *Perfect Test-bed for piezoelectric energy harvesting*
- ***Defined resonance frequencies***
- ***Low to moderate acceleration values***

Why ZnO nanostructures?

- ZnO is a semiconductor that presents a piezoelectric behavior and direct band-gap
- ZnO nanostructures are easy to grow and integrate with silicon
- More flexible and robust than thin-films
- Compatible with VLS silicon technologies
- ZnO NW & NS growth is also a low-cost solution and a hot-topic
- Collaboration with the inventor of the NANOGENERATOR and NANOPIEZOTRONICS: **Prof. Zhong Lin Wang** (H-index = 127)

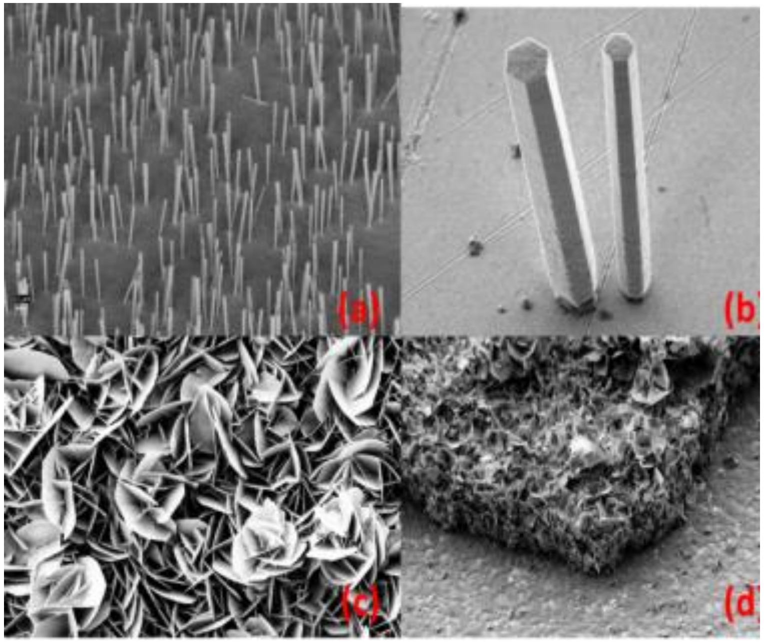






- Piezoelectric materials - ZnO nanostructures

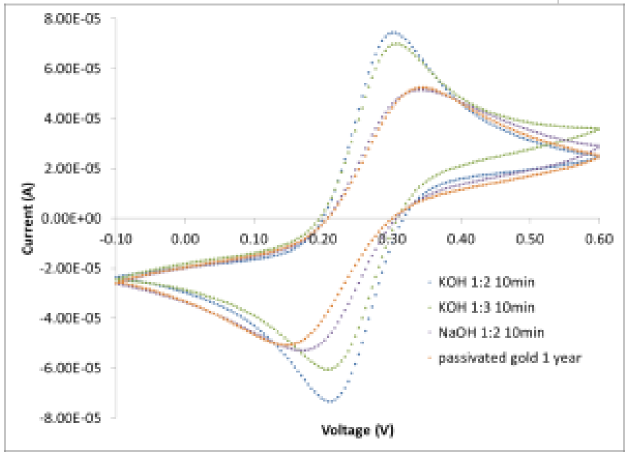
- **ZnO nanowires & ZnO nanosheets:**
  - Low temperature synthesis (<80 ^{o}C)
  - Easy to grow and integrate with silicon, low-cost solution at wafer-level
  - Inherent piezoelectric behavior of ZnO
  - High novelty provided by ZnO nanosheets
- Standard **AlN thin-film** approach has been used as a benchmark

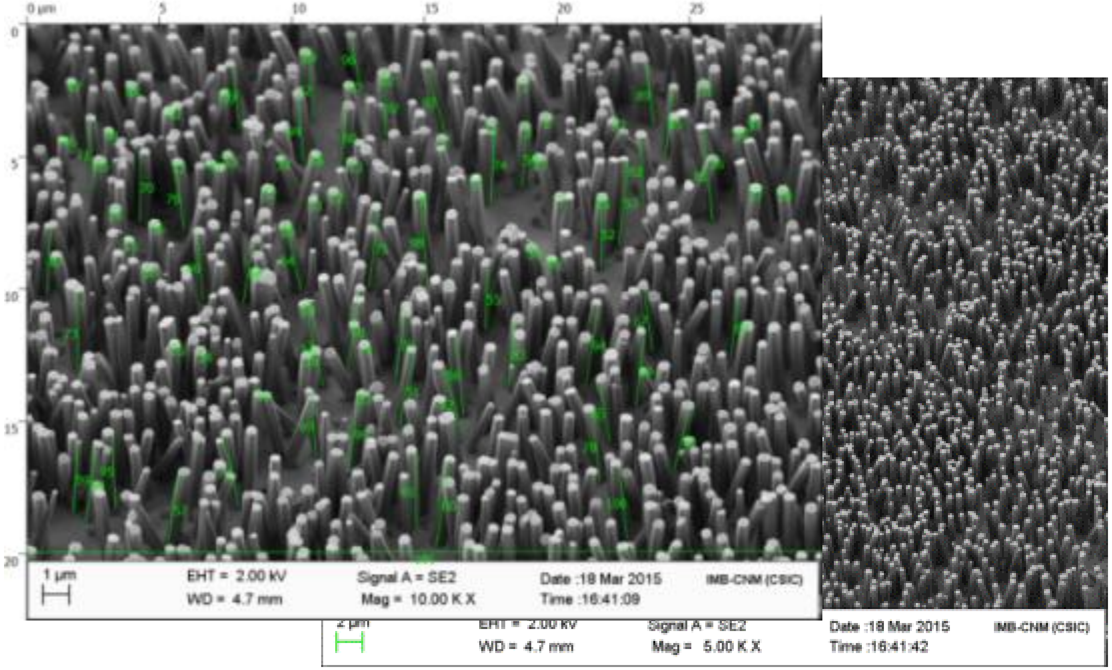


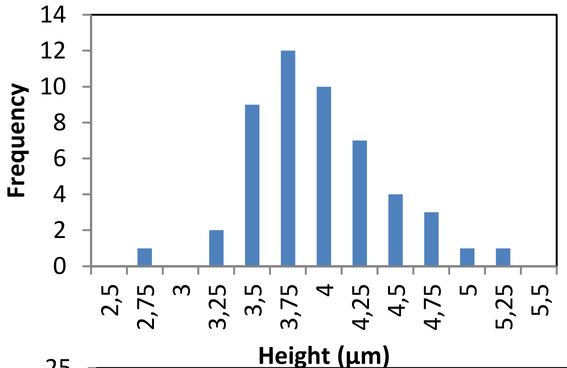
ZnO nanowires (overall view (a) and detailed view (b)), and nanosheets (top view (c) and tilted view (d)). NW lengths rate from 2 to 5 µm and thicknesses from 100 nm to 900 nm.

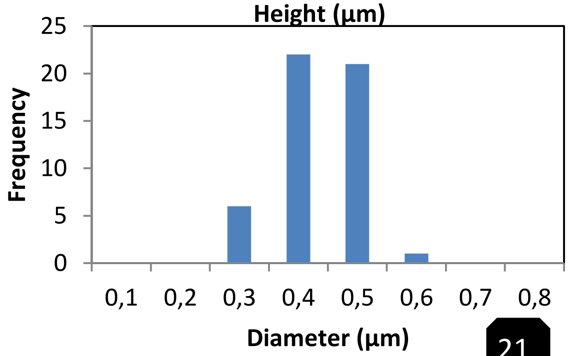
Growth Characterization of NW over gold seed layer

- Novel seed layer activation process proponed.
- Relationship between cyclic voltammetry and surface cleanness and quality









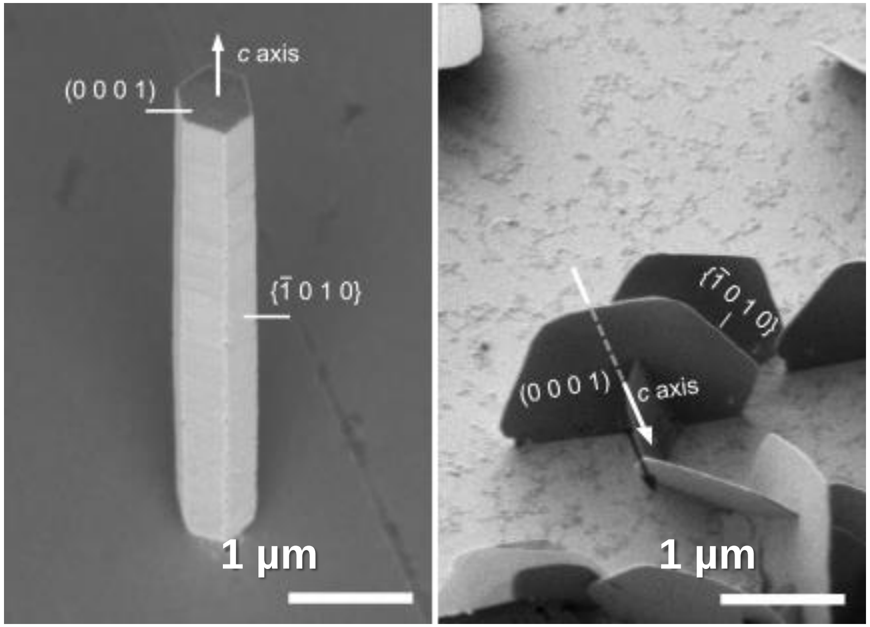
Density = 124 NW/100µm^2

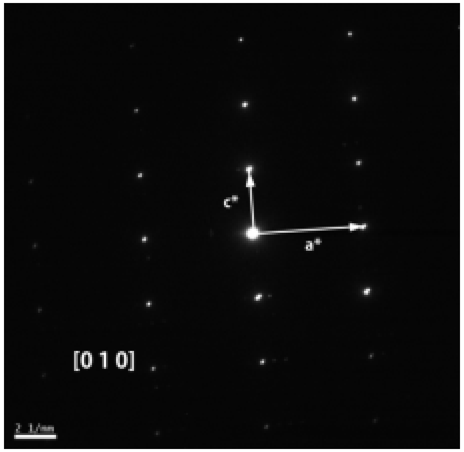
PATENT PENDING

- # Material Characterization

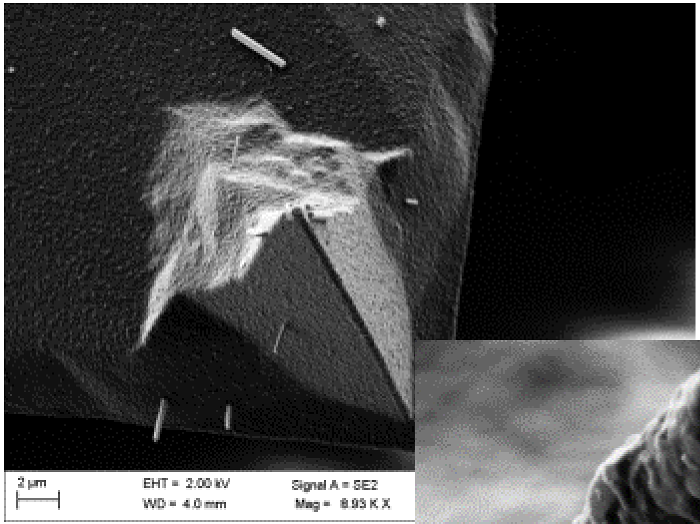
ZnO NS material characterization by TEM, SEM and XRD:

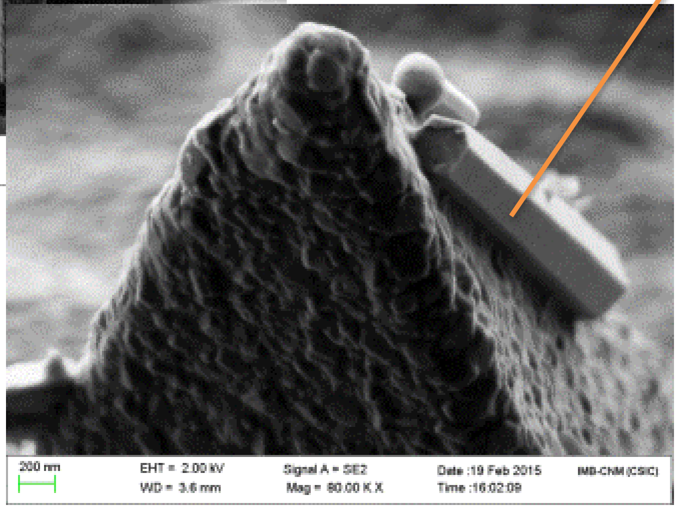
- ZnO NSs show a good crystalline structure.
- Expected high piezoelectric coefficient
- Thickness < 20 nm
- Extremely high-density
- Rapid and low-cost growth

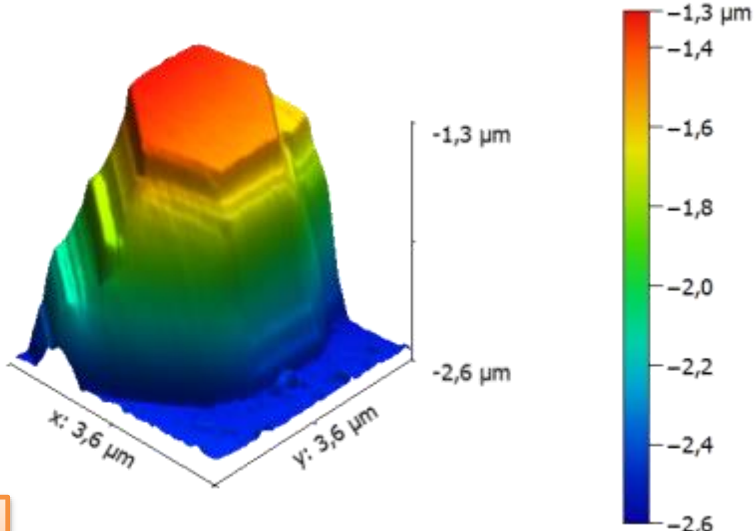


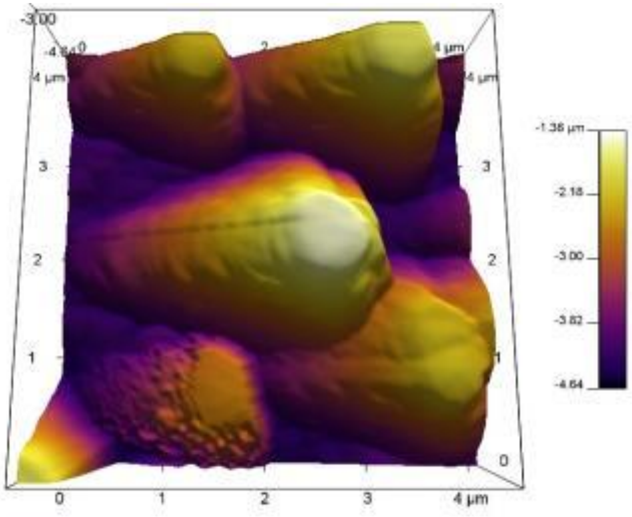


- Material Characterization
  - NW AFM measurement

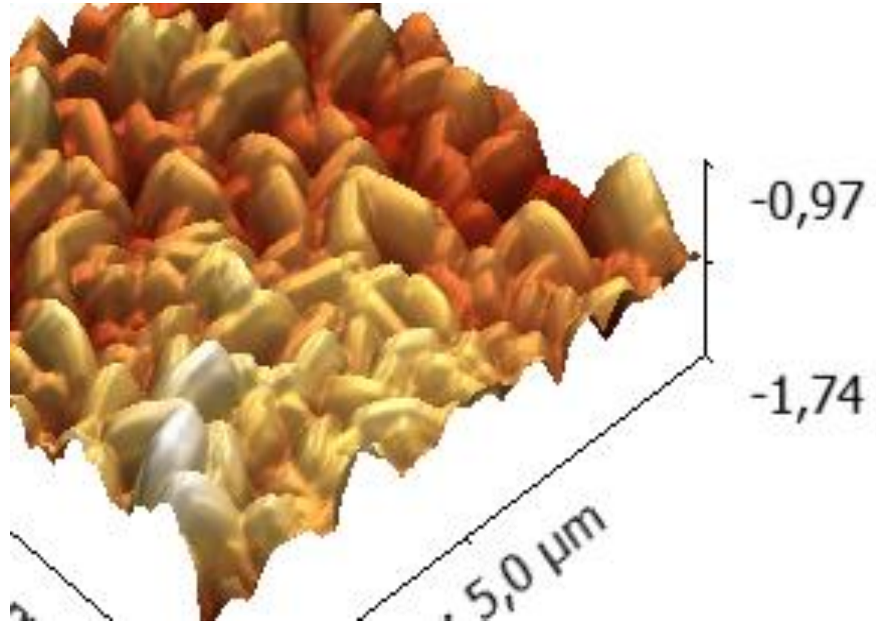


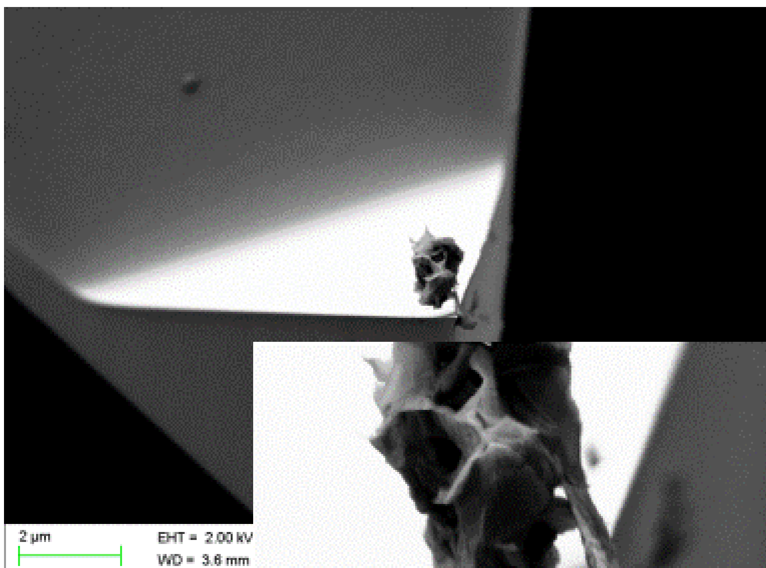


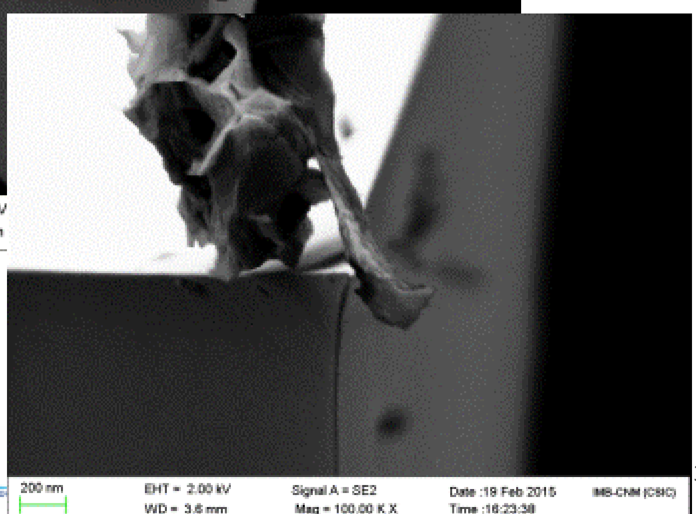


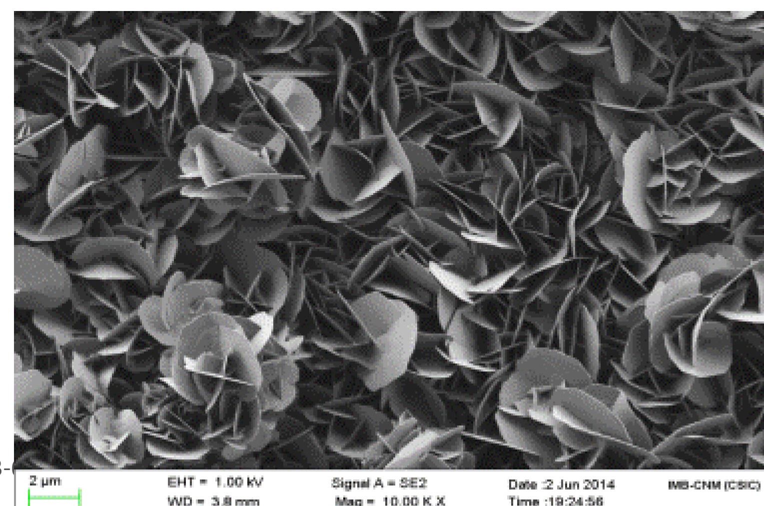


- Material Characterization
  - NS AFM measurements





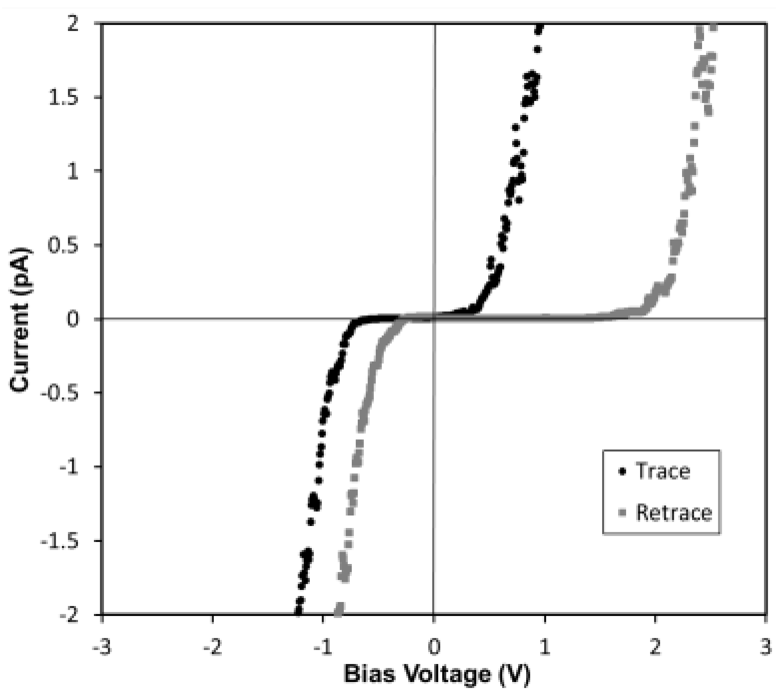


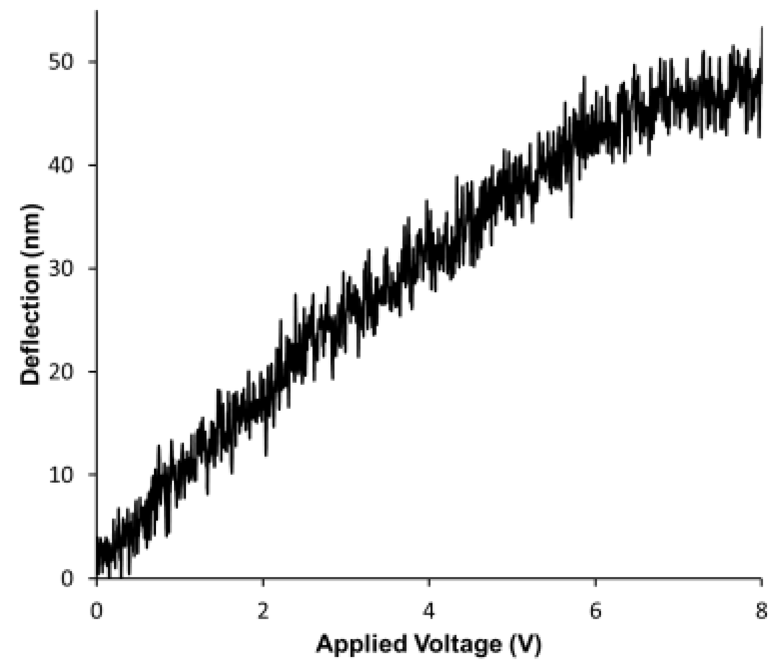


- Material Characterization
  - Piezoresponse AFM (PFM) measurement of ZnO nanowires and nanosheets at 37kHz.

ZnO nanowire: d33 ≈ 8.6pm/V

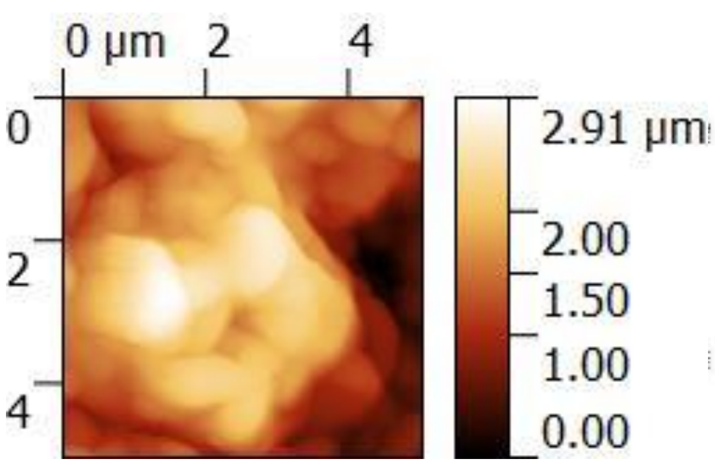
AlN: d33 ≈ 2.85pm/V



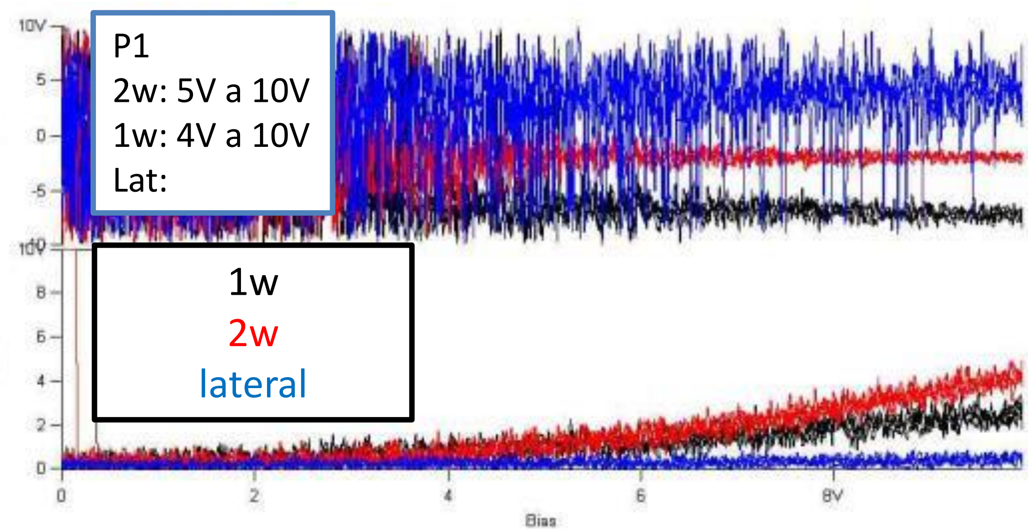


- # Material Characterization
  - Piezoelectric AFM (PFM) measurement of ZnO nanowires and nanosheets at 37kHz.

ZnO nanosheet: d31 ≈ 6pm/V

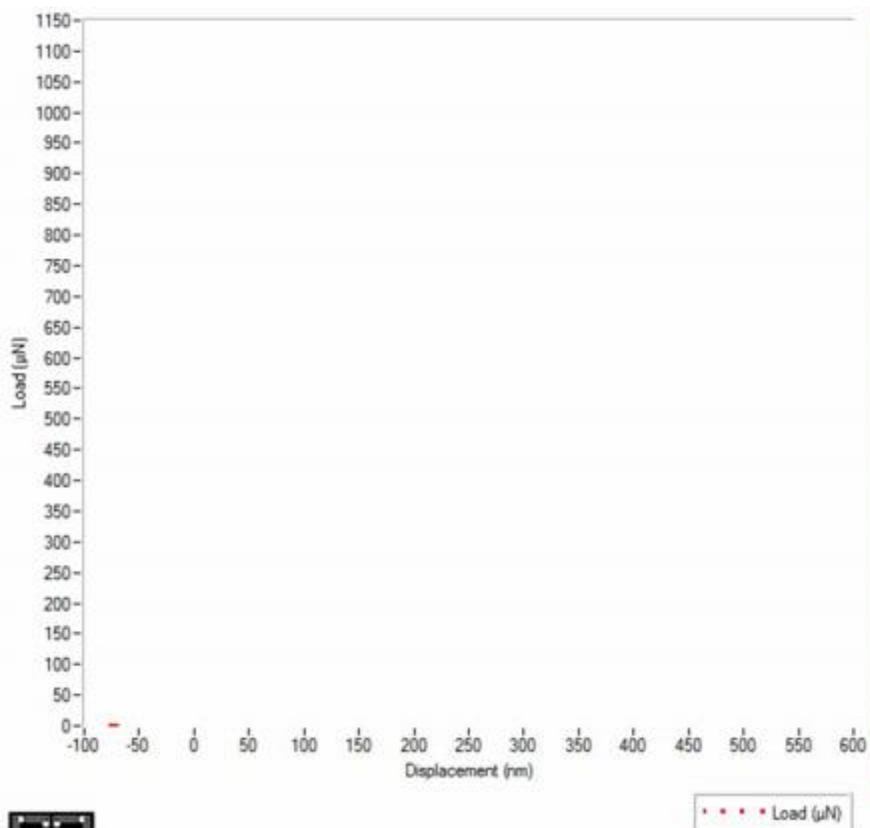


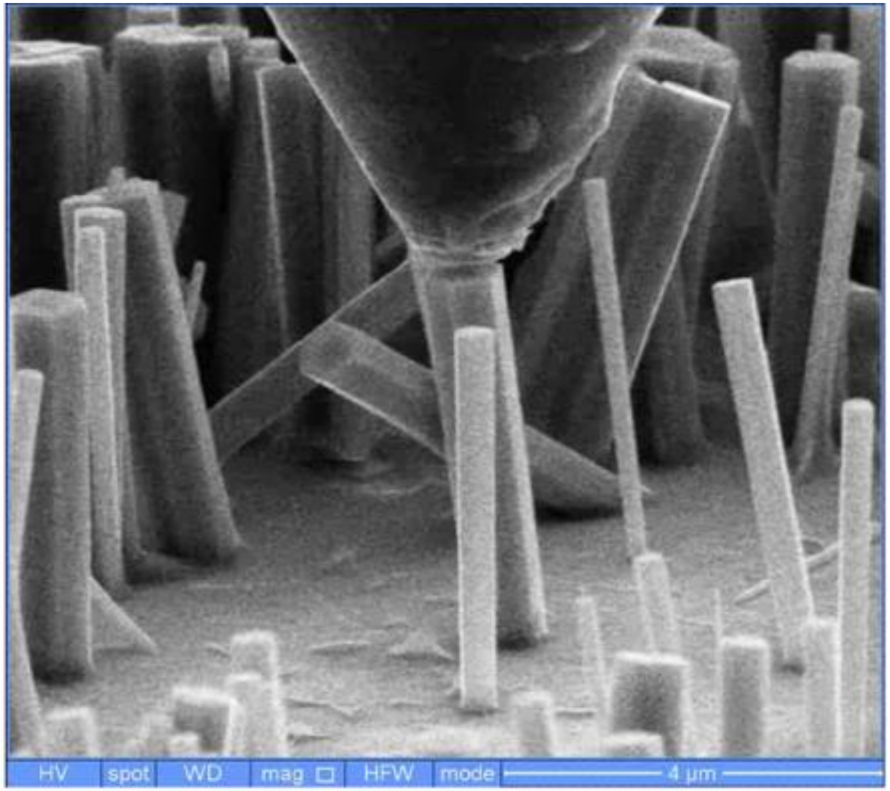
ZnO_ns_16hAlN100_0009.ibw



Material Characterization:

- ZnO nanostructures allow higher compression without fracture.
- It has been demonstrated that a single ZnO NW can stand for a compressing force of more than 1mN!





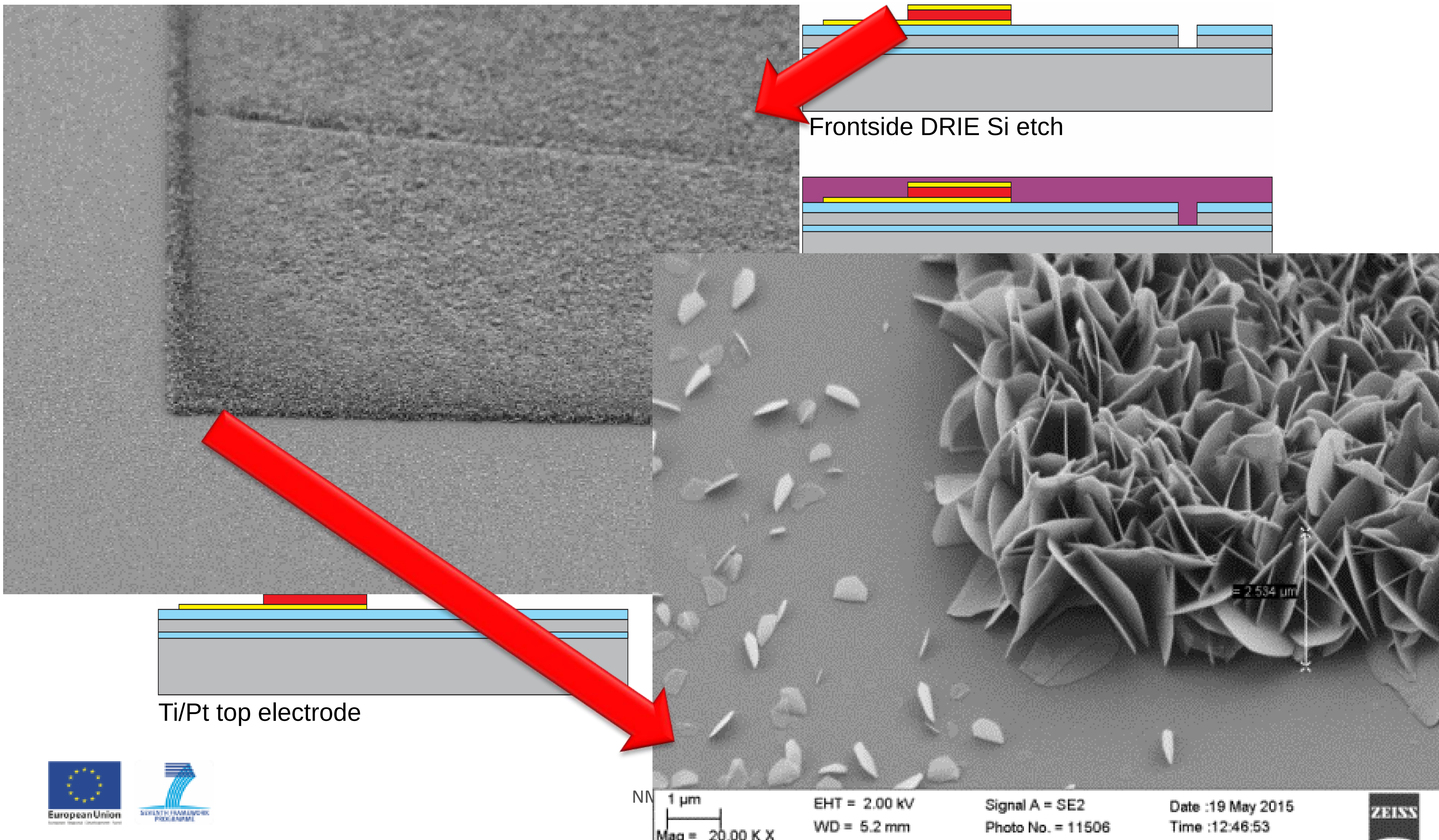
HYSITRON™

- Fabrication of 1st generation harvesters
- Piezoelectric ZnO nanostructures is used as main transduction method
- First batch is in progress with some issues
  - CVD has been down for 3 months (equipment malfunctioning)
  - Poor resist adherence during photolithography
  - Detachment of some part of Pt/AlN layer due to residual stress

PATENT PENDING

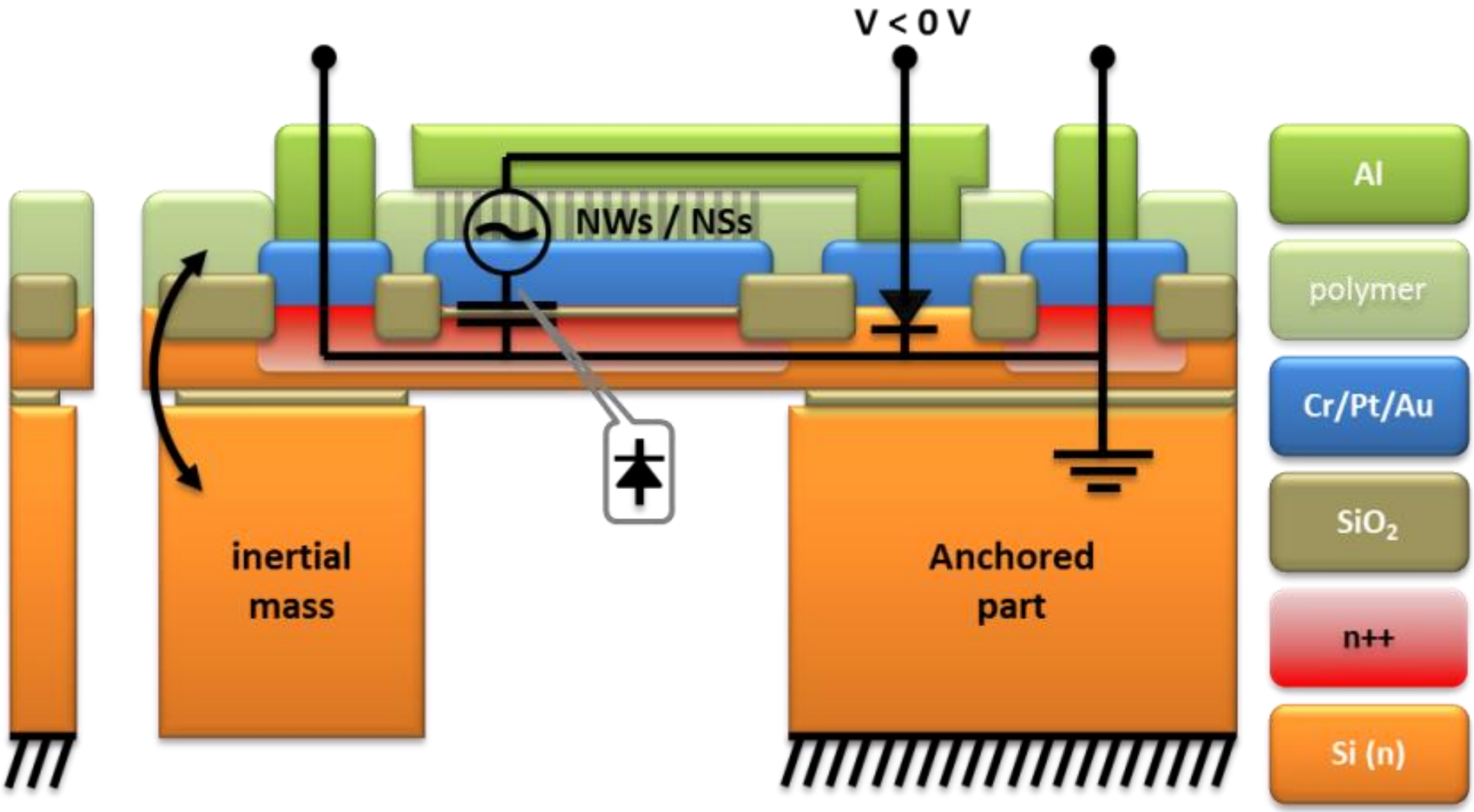
Piezoelectric Energy Harvesting
Silicon Friendly Materials and Device Solutions
for Microenergy Applications

- Fabrication process: 1st generation



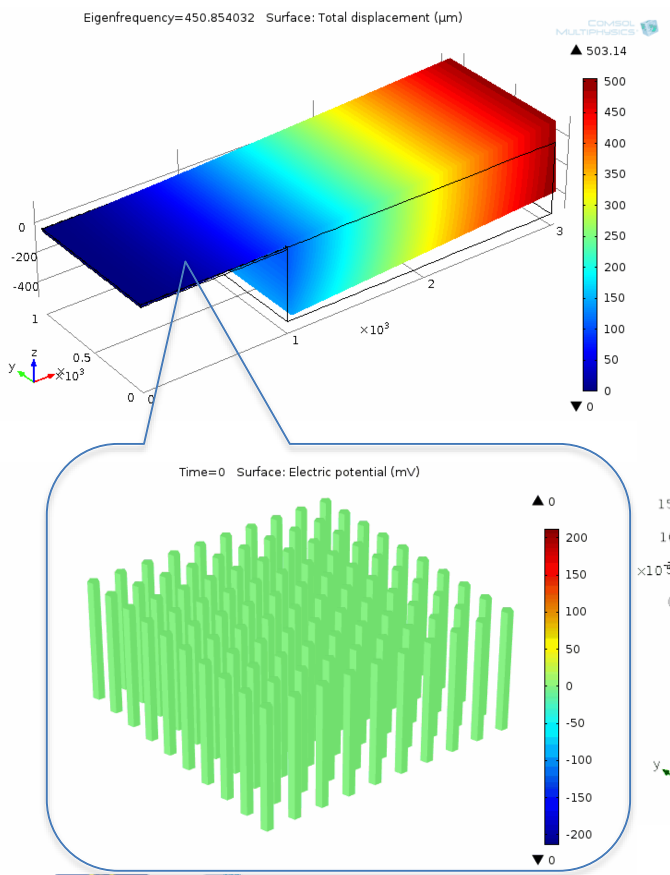
- Fabrication of 2nd generation harvesters
- Second batch with integrated diodes and capacitors have been launched
  - Entire chip surface is used as capacitor
  - Diode arrays integrated in every chip
  - Test structures included
  - Based on ZnO NS, ZnO NW and AlN thin film
- RIE etch of AlN (instead of wet etch) and wafer-scale NS and NW growth explored

- 2nd generation Fabrication Process



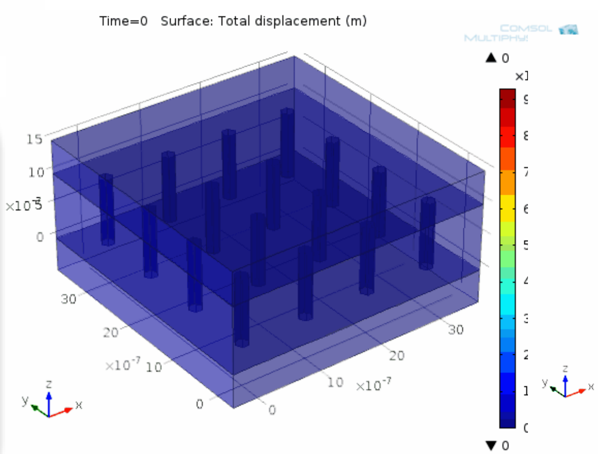
Predicted output power

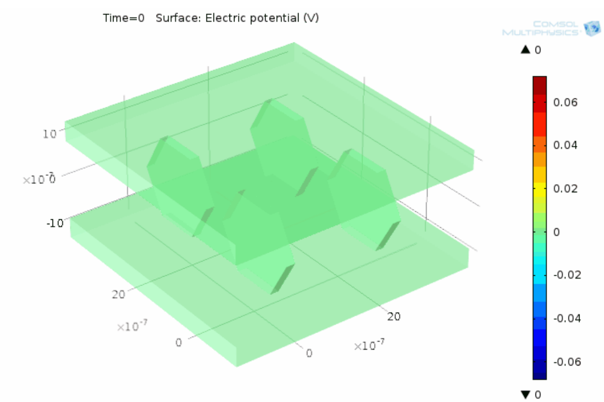
– Based on ZnO NWs and NSs: **Target: 400 µW/cm²**



For FEM simulations a **power density of 47 µW/cm²** at 447 Hz (Q = 50) for 1 g has been calculated.

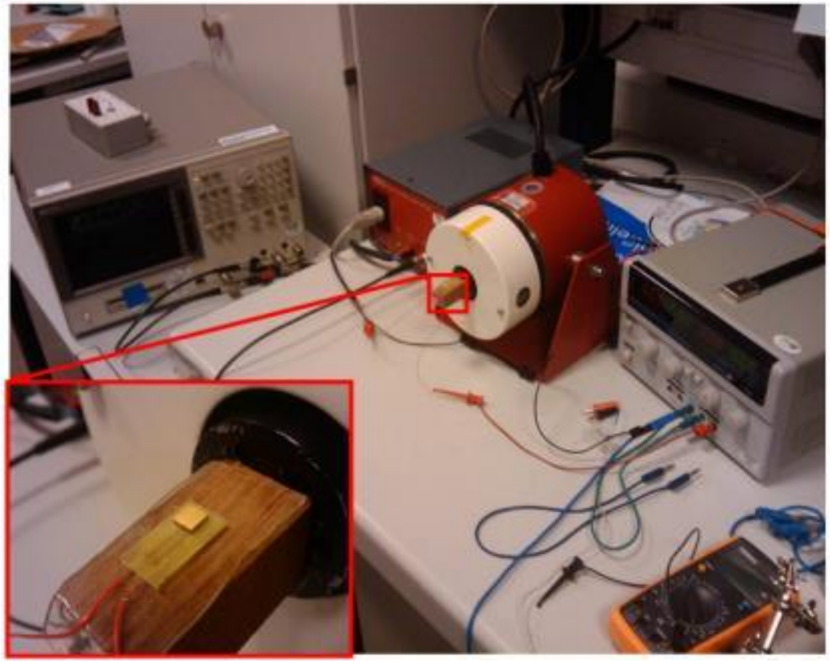
An expected power density of around **400 µW/cm²** for an acceleration of 10 g has been set as **target.**





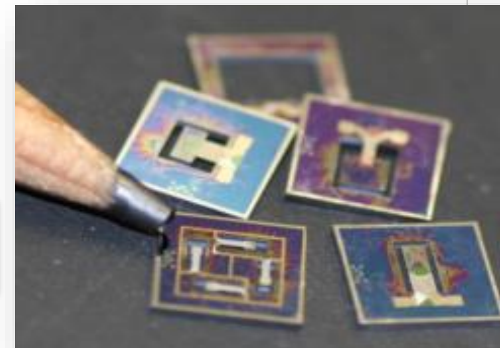
- Device characterisation
- Shaker + controller + accelerometer acquired
  - Sinusoidal input vibration
  - Frequency sweep
  - Arbitrary signal reproduction
  - Load resistor sweep controlled by PC

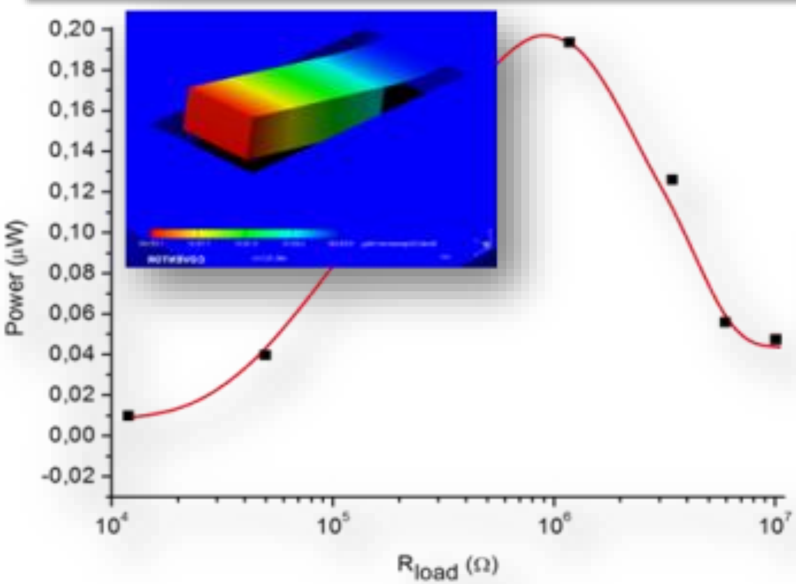
    - Shaker: VR5200HF
    - Controller: VR9502
    - Accelerometer

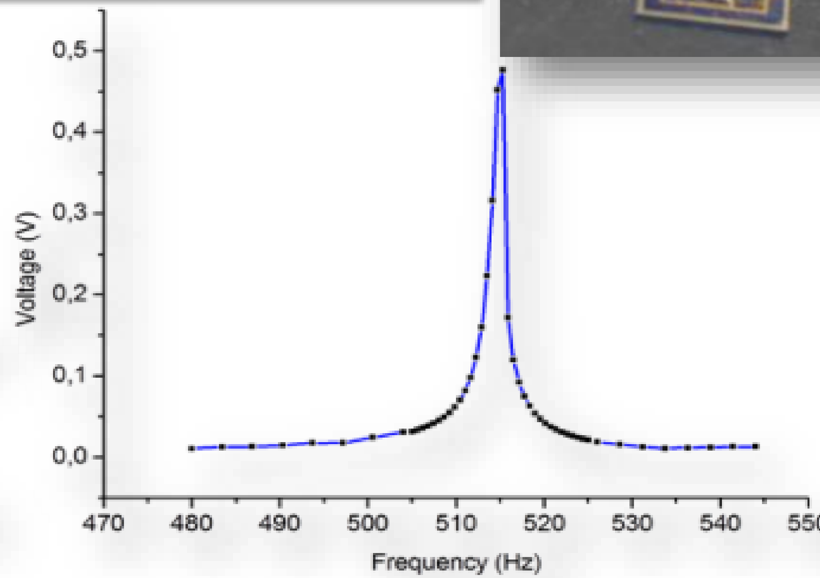


- Current output power for AlN-based version
  - Measured AlN-based devices: **6.67 µW/cm²**

0.2 µW @ 515 Hz, 0.64 m/s², R_{load} of 1.17 MΩ, Q of 350

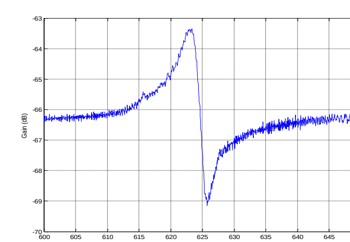






Characterization with Network Analyzer of the vibration-driven piezoelectric energy scavenger compatible with AlN-based FBAR technology

Device name	Beam length (µm)	Beam width (µm)	Mass length (µm)	Mass width (µm)	Resonance Frequency
K3	1000	500	500	500	2.17 kHz
L5	1000	1000	2000	1000	515 Hz
C5	1000	1000	1000	3000	622 Hz
J8	1000	1000	1000	3000	625 Hz
K8	1000	1000	1000	4000	530 Hz



- Next months actions
- Characterization of 1st and 2nd generation devices
- Mask redesign
  - Combination of device arrays
  - Piezopotential enhancement
  - Full-wave rectification
- Process optimization
  - Material configuration optimization
- PCB design and fabrication for device integration

This work was supported by FP7-NMP-2013-SMALL-7, SiNERGY (Silicon Friendly Materials and Device Solutions for Microenergy Applications), Contract n. 604169

Thank you! Any question?

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