UNIVERSITÀ DEGLI STUDI
DI PERUGIA

Micro e Nano Sistemi di Energy Harvesting per l'Internet delle Cose

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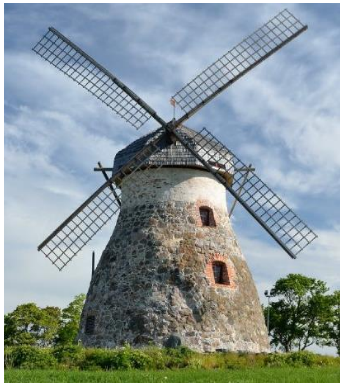
Dipartimento di Fisica, Università di Perugia

Physics Highlight Perugia
24 Novermbre 2020

Outline

- Energy Harvesting and IoT
- Research activities at Physics Dip./UNIPG
- Micro generators and electrets materials
- 3D printed energy harvesting systems
- Conclusions and perspectives

Energy Harvesting



Wind mill (Origin: Persia, 3000 years BC)

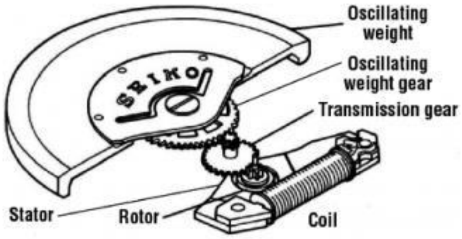
Sailing ship (XVI-XVII century)

Some of the earliest innovations in using water power were conceived in China during the Han Dynasty between 202 BC

Crystal radio – 1906
Self-powered by radio waves

First automatic wristwatch, Harwood, c. 1929 (Deutsches Uhrenmuseum, Inv. 47-3543)

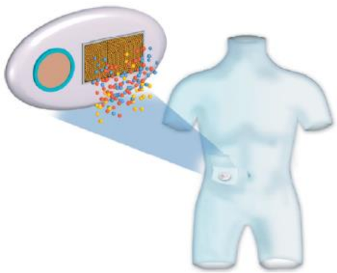
First automatic watch. Abraham-Louis Perrelet, Le Locle. 1776



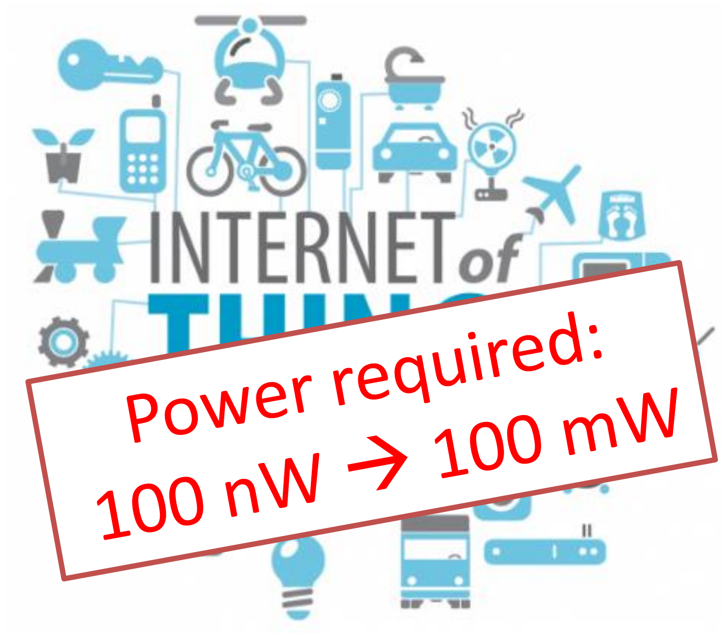
Self-charging Seiko wristwatch 1988

Energy Harvesting and IoT

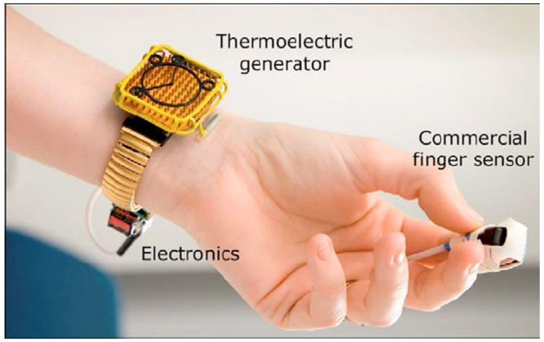
MEMS-based drug delivery systems



Bohm S. et al. 2000

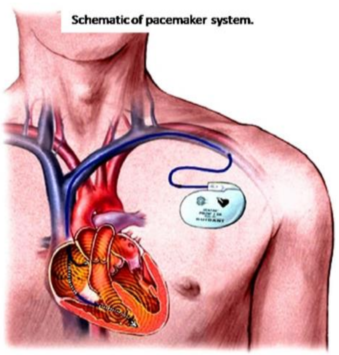


Body-powered oximeter



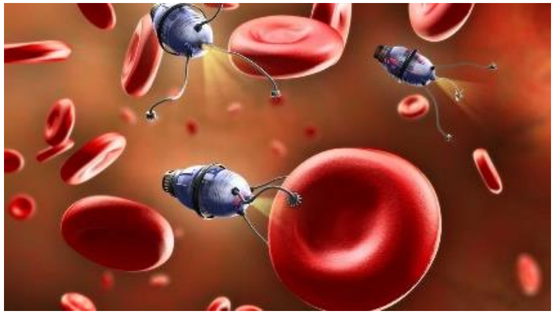
Leonov, V., & Vullers, R. J. (2009).

Heart powered pacemaker



D. Tran, Stanford Univ. 2007

Micro-robot for surgery

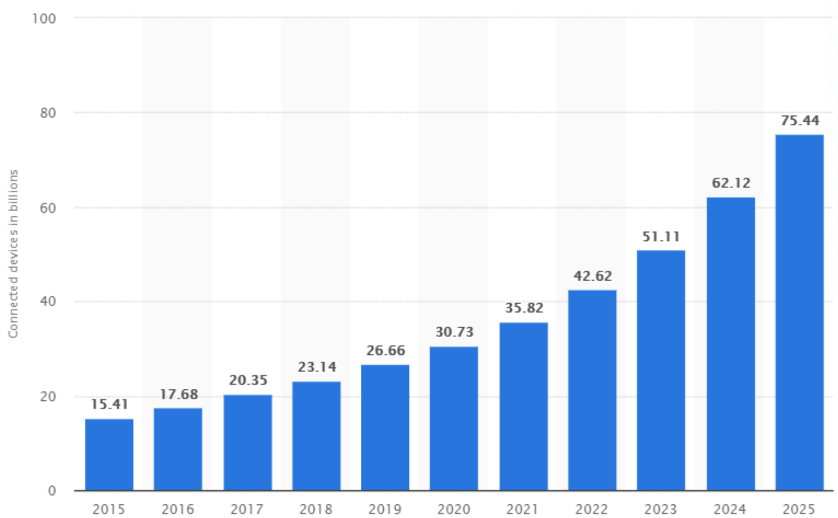


Remote monitoring

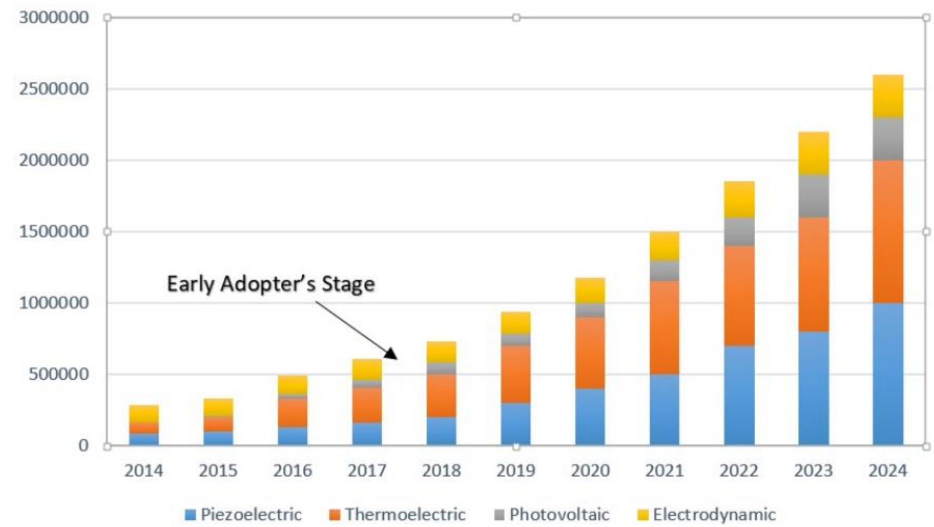
A. Freitas Jr., Nanomedicine, Landes Bioscience, 1999

Energy Harvesting and IoT

Internet of Things (IoT) connected devices installed base worldwide from 2015 to 2025 (in billions) – (Statista 2019)

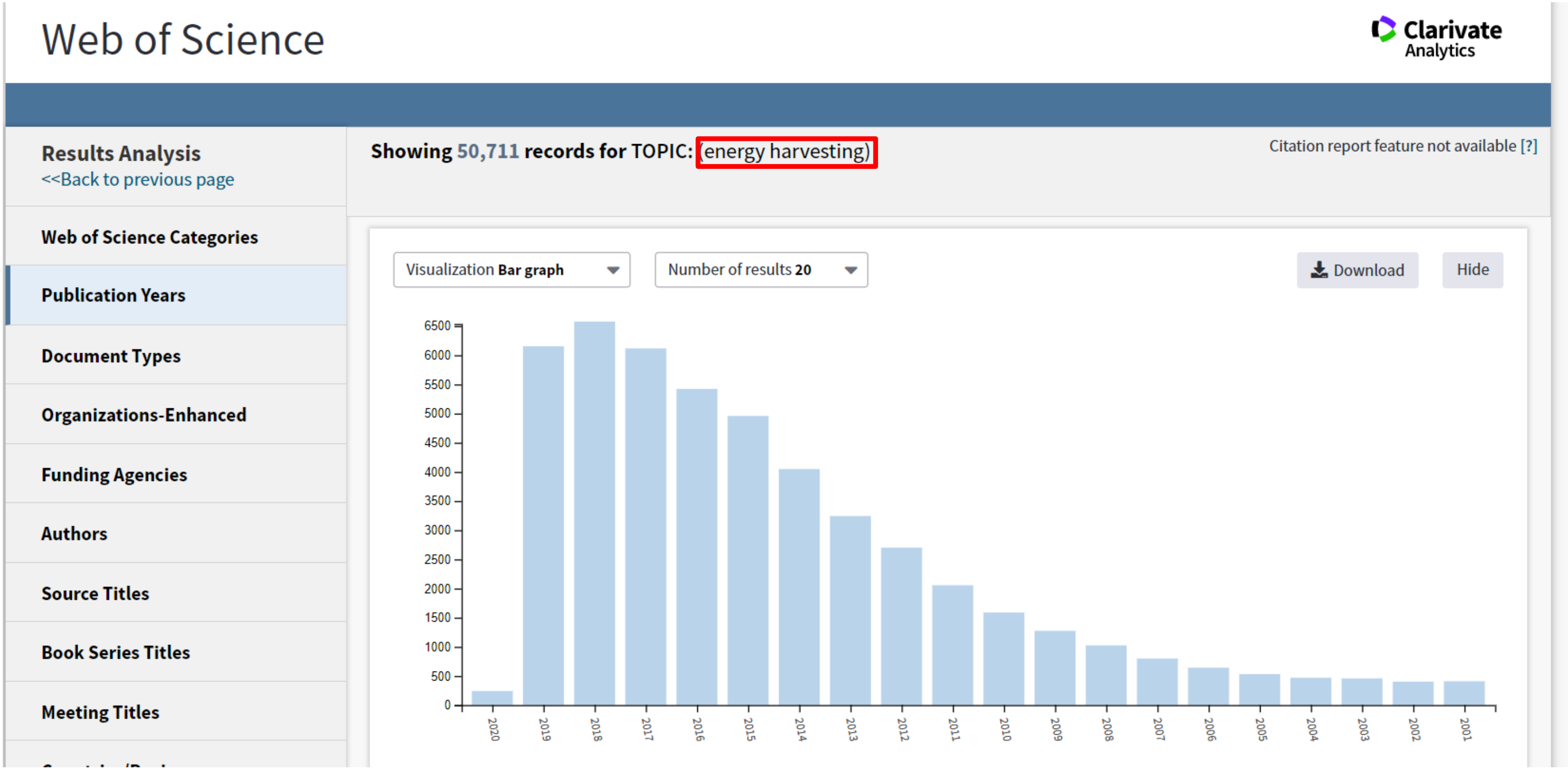


Global **energy harvesting** market (IDTechEx 2019)



75 Billions of IoT devices in 2025 need tech for energy autonomy

Energy Harvesting and IoT



Time

Vibration powered wireless sensor node

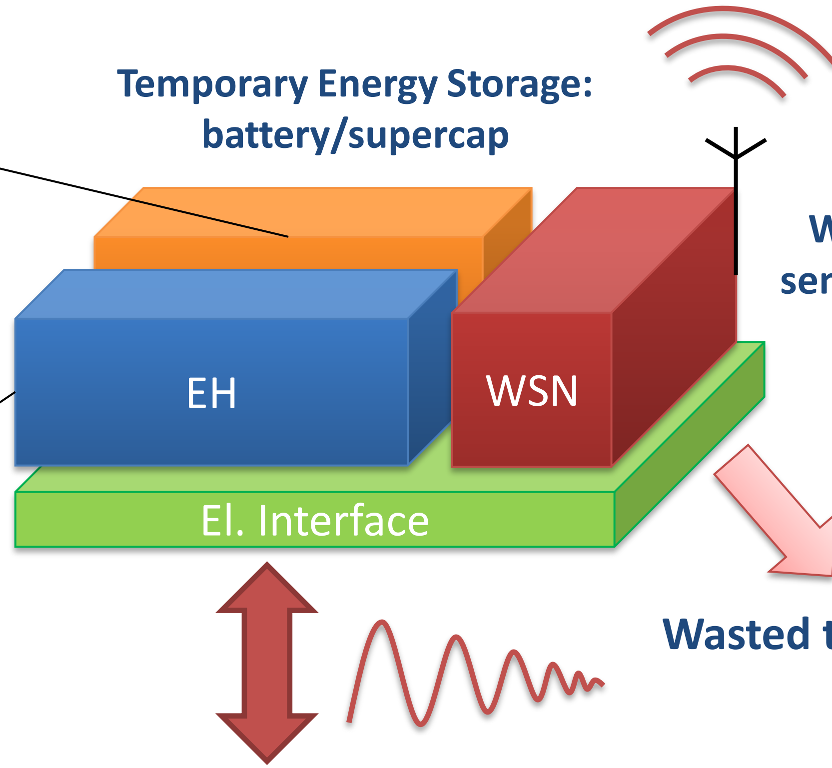
Power density objective for EH:
> 100 μW/cm^3

Transmitted
EM energy

Temporary storage
and conditioning electrinics:

- *Ultra capacitors*
- *Rechargeable Batteries*

Temporary Energy Storage:
battery/supercap



Wireless
sensor node

Wasted thermal energy

Vibration energy harvester:

- *piezoelectric,*
- *electromagentic,*
- *electrostatic,*
- *magnetostrictive*

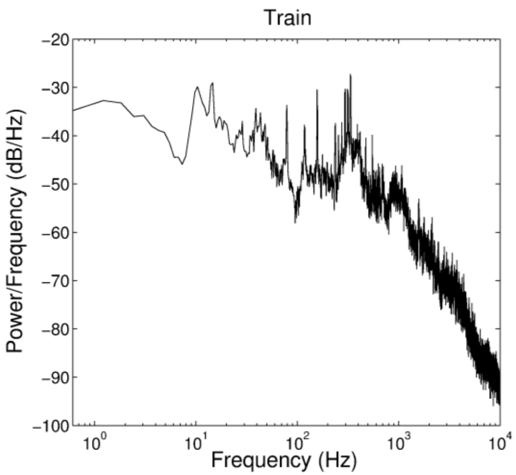
Mechanical vibrations

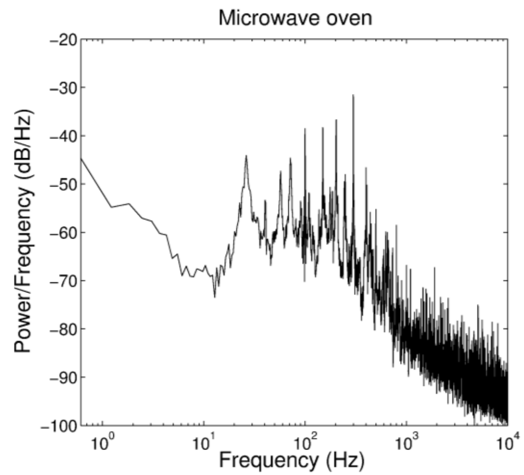
Vibration sources

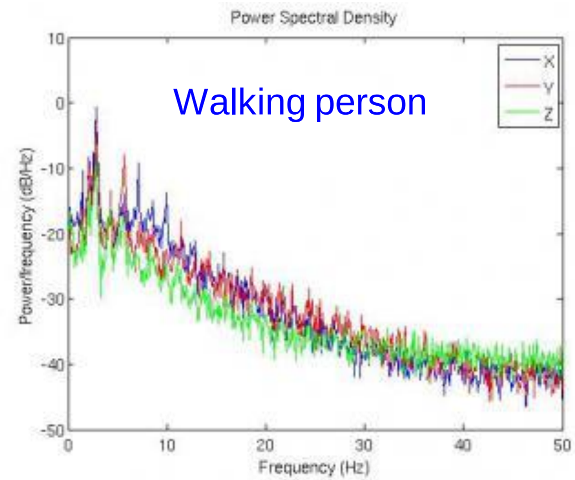
Energy Source	Characteristics	Efficiency	Harvested Power
Light	Outdoor Indoor	10~24%	100 mW/cm^2 100 μW/cm^2
Thermal	Human Industrial	~0.1% ~3%	60 μW/cm^2 ~1-10 mW/cm^2
Vibration	~Hz–human ~kHz–machines	25~50%	~4 μW/cm^3 ~800 μW/cm^3
RF	GSM 900 MHz WiFi	~50%	0.1 μW/cm^2 0.001 μW/cm^2

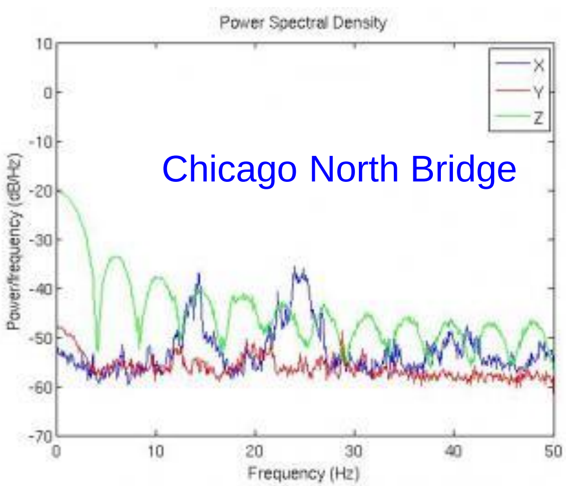
Source: Texas Instruments 2009

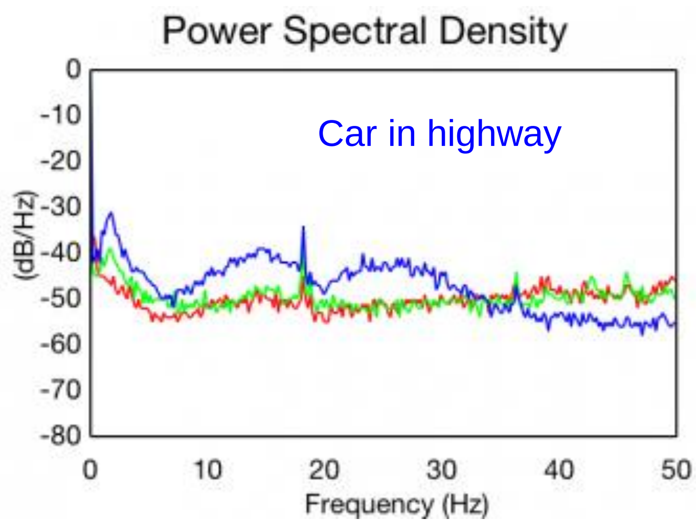
Vibration sources





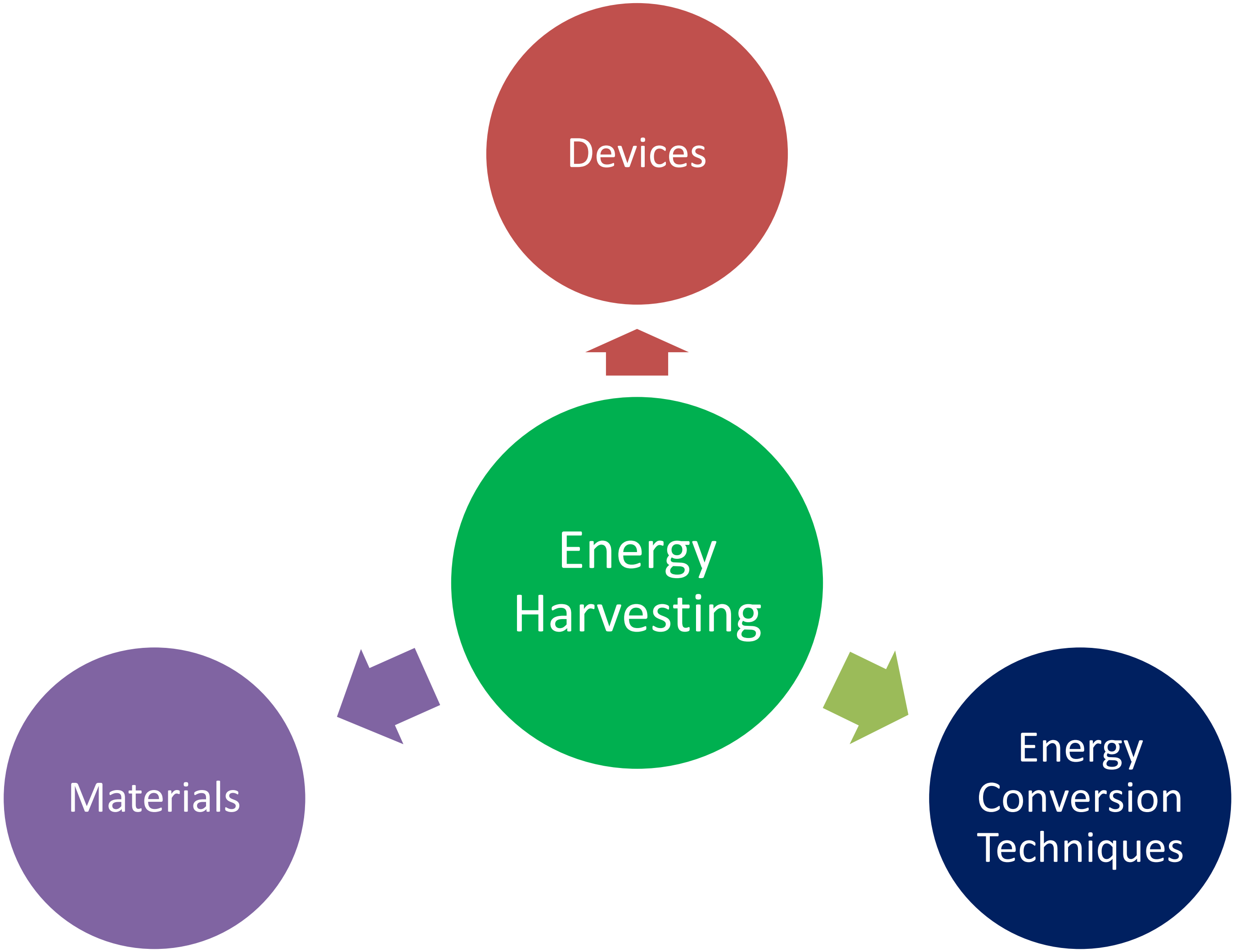






http://www.enables-project.eu/offer/virtual-access/

Research activities @ UNIPG



Research activities @ UNIPG

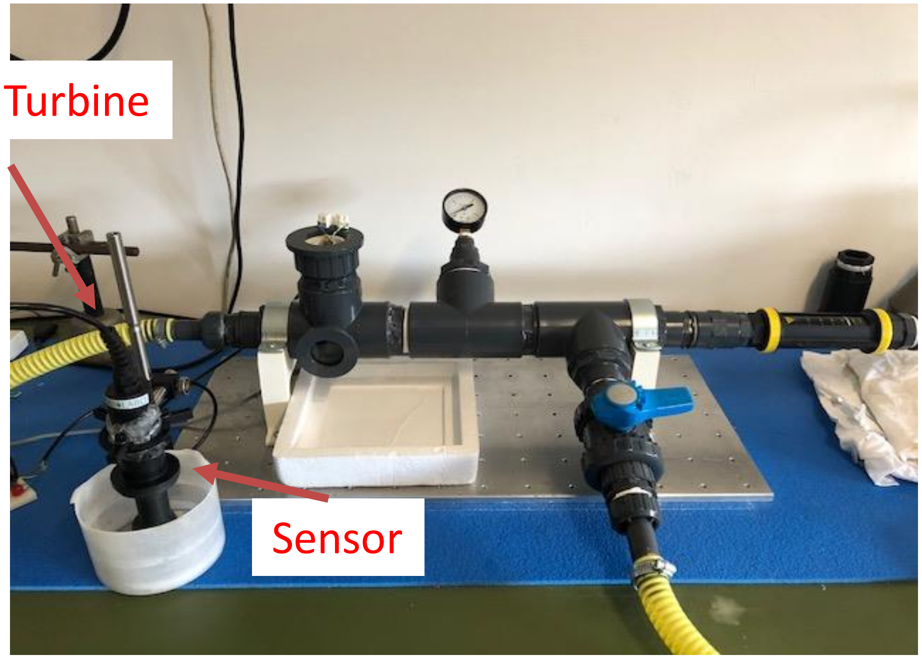
- **ENERGY HARVESTING PER APPLICAZIONI TECNOLOGICHE**
  - Sistemi autonomi per monitoraggio H2O/CO2 (ex-**PROTEUS**) (**Dr. Paola Tinivelli**)
  - Sistemi di monitoraggio sismico (progetto **SEISMO-NOLI** – in collaborazione con i geologi M. Porreca e M. Ercoli)
  - **Progetto EnABLES** - EC H2020 project. Vibration energy harvesting JRAs

- **MICRO GENERATORI E MATERIALI ELETTRO-ATTIVI**
  - Silicon MEMS Electrostatic Vibration Energy Harvesters (**JRA EnaBLES**)
    - In atto collaborazione Università di Southampton, ESIEE Paris
  - Micro Elettreti
  - Micro Risonatori Piezoelettrici
  - Micro Risonatori Piezo-magnetici (SPAWAR)

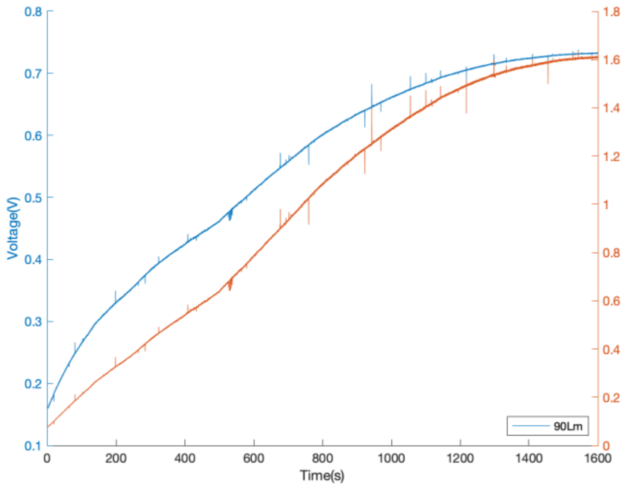
- **ENERGY HARVESTING da CELLULE** (collab. dip. Di Biotecnologia)

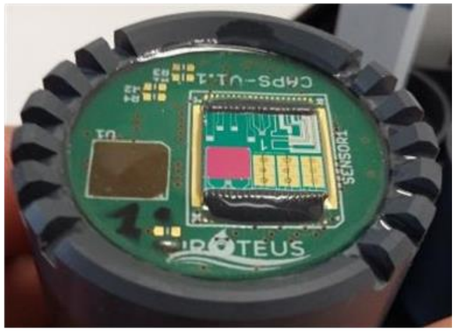
Water Self-powered Monitoring Systems

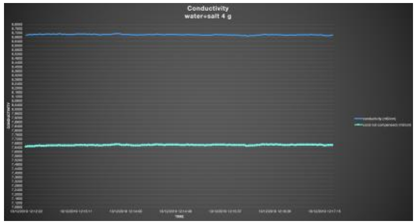
PROTESU project

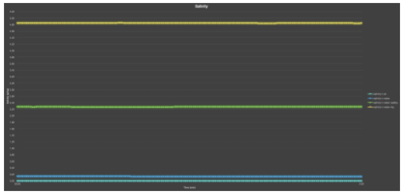


Paola Tinivelli – lavoro di dottorato



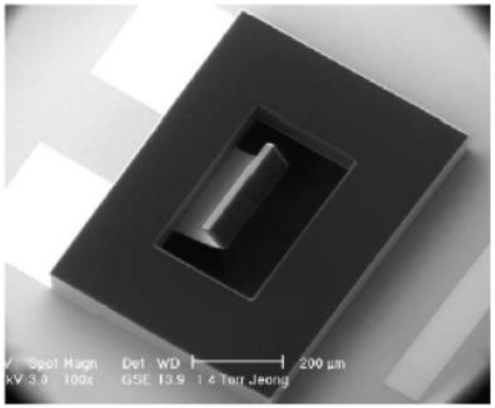




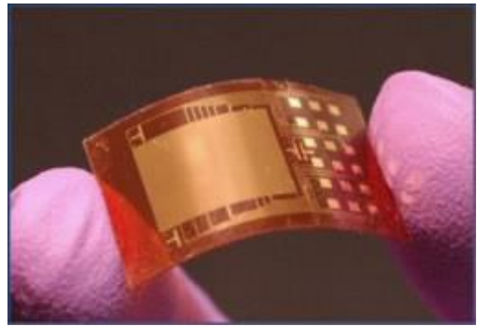


Microscale vibration energy harvesters

Piezoelectric

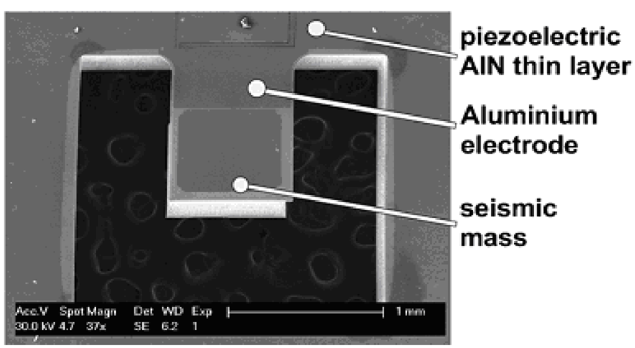


Jeon et al. 2005

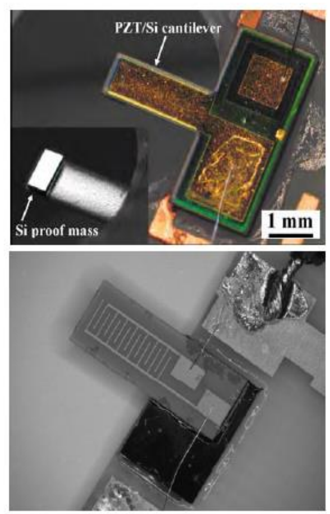


ZnO nanowires
Wang, Georgia Tech (2005)

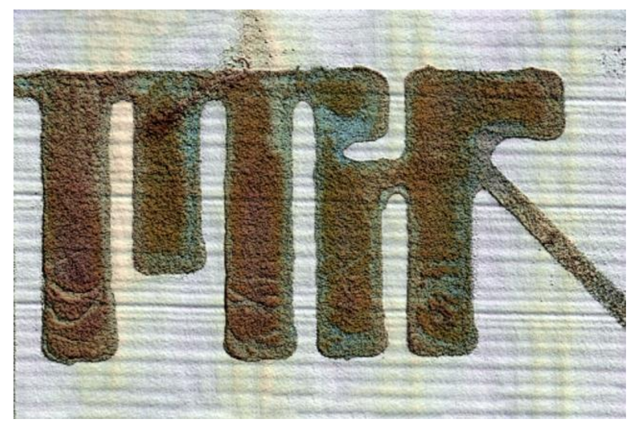
Chang. MIT 2013



M. Marzencki 2008 – TIMA Lab (France)



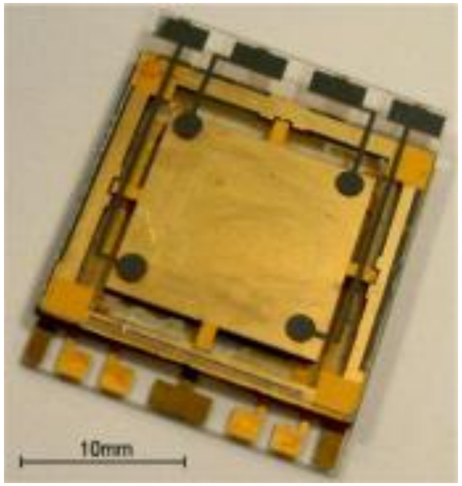
D. Briand, EPFL 2010



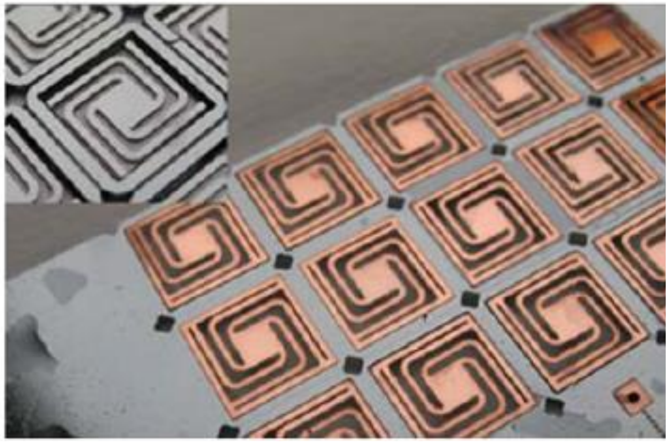
Ultrathin 3-D-printed films convert energy of one form into another (credit: MIT Aug. 2019)

Microscale vibration energy harvesters

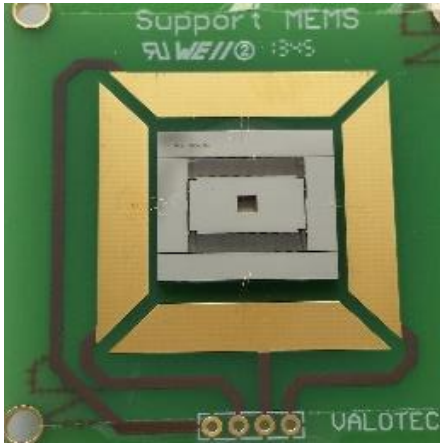
Electrostatic and electromagnetic



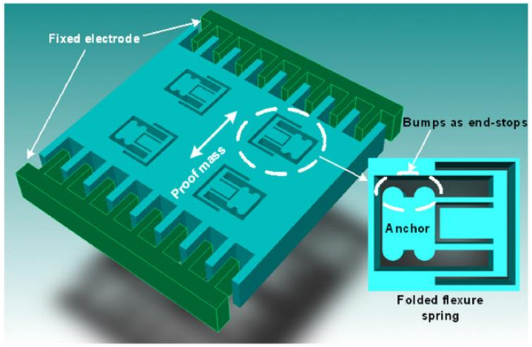
Mitcheson 2005 (UK)
Electrostatic generator 20Hz
2.5uW @ 1g



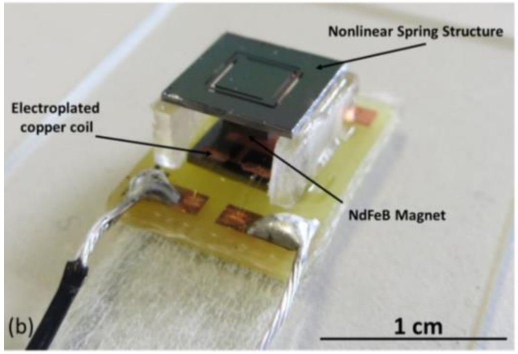
EM generator, Miao et al. 2006



Cottone F., Basset P. ESIEE Paris 2013



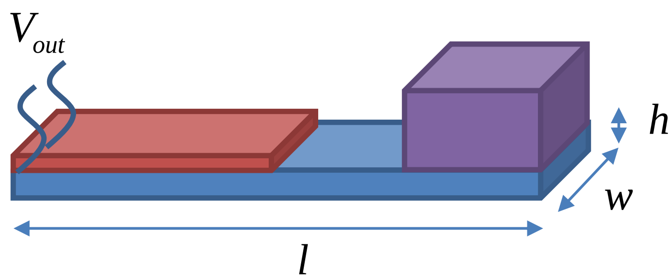
Le and Halvorsen, 2012



Mallick D. and Roy S., 2015

Microscale energy harvesters: scaling issues

First order power calculus with William and Yates model



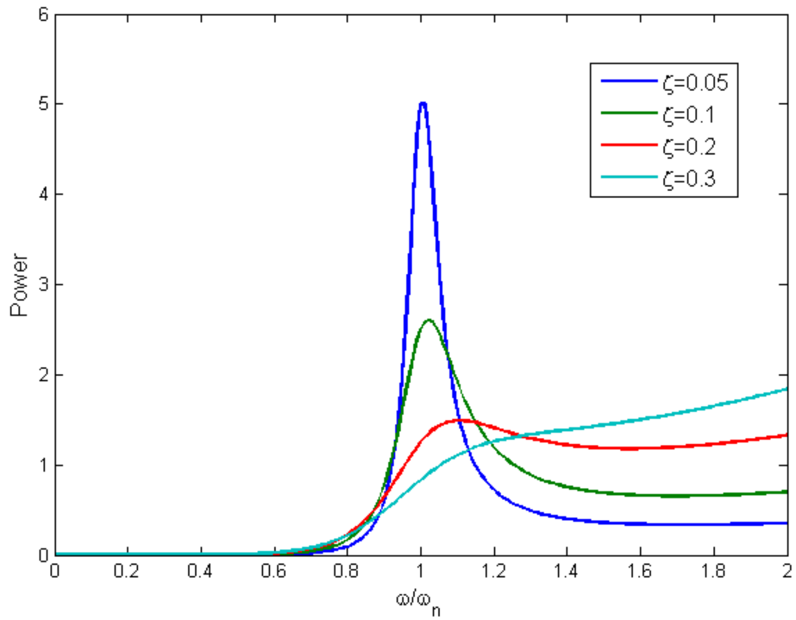
$$\omega_n = 2\pi C_n \sqrt{\frac{E}{\rho}} \frac{h}{l^2}$$

Boudary conditions	C1
doubly clamped	1,03
cantilever	0,162

$$k = \xi \frac{Ewh^3}{l^3}$$

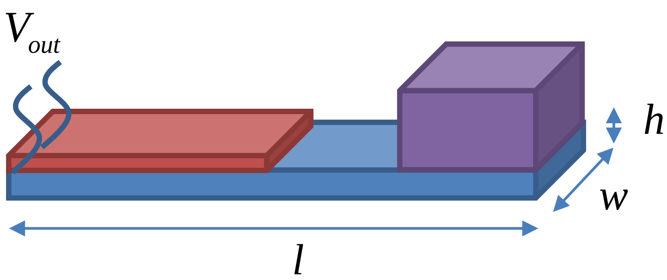
Boudary conditions	Uniform load ξ	Point load ξ
doubly clamped	32	16
cantilever	0,67	0,25

- Low efficiency off resonance
- High resonant frequency at miniature scales
- Power → $A^2 l^4$ where A is the acceleration and *l* the linear dimension



Microscale energy harvesters: scaling issues

First order power calculus with William and Yates model



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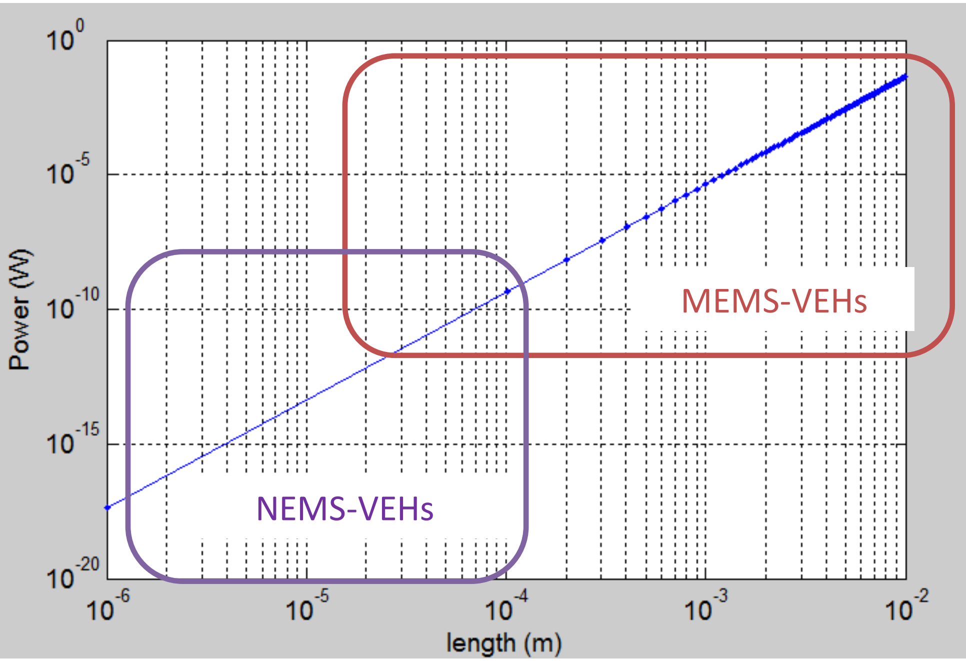
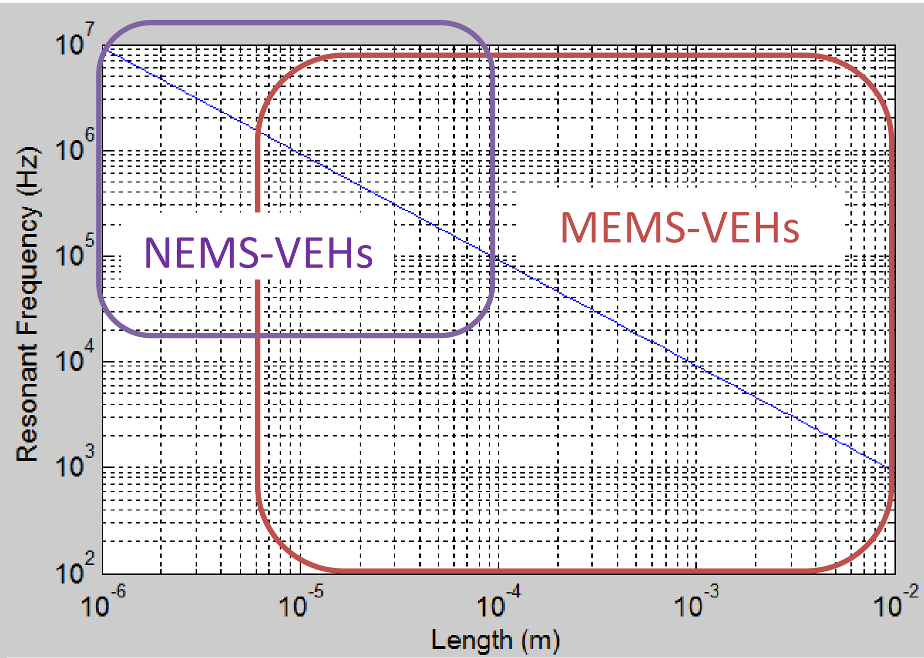
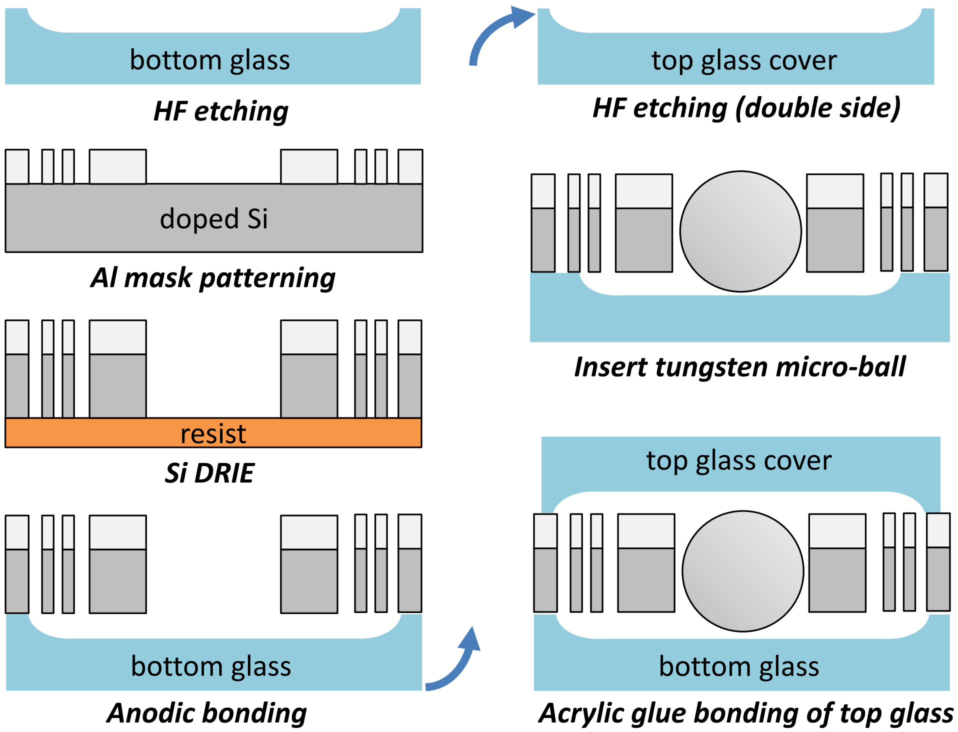




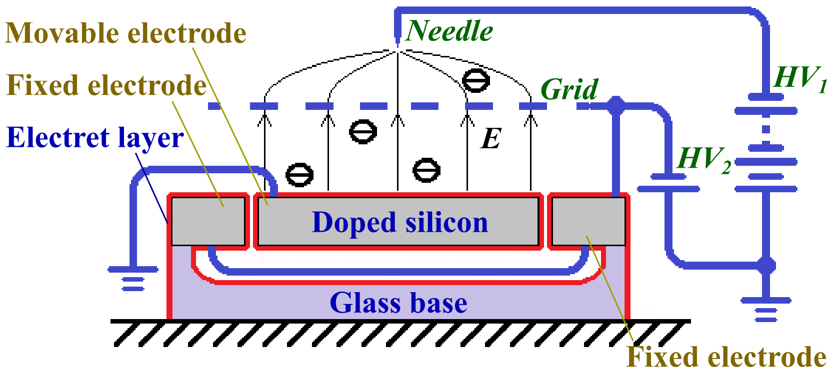
Low-frequency MEMS electrostatic VEH

Prototype fabrication process

Silicon DRIE etching process



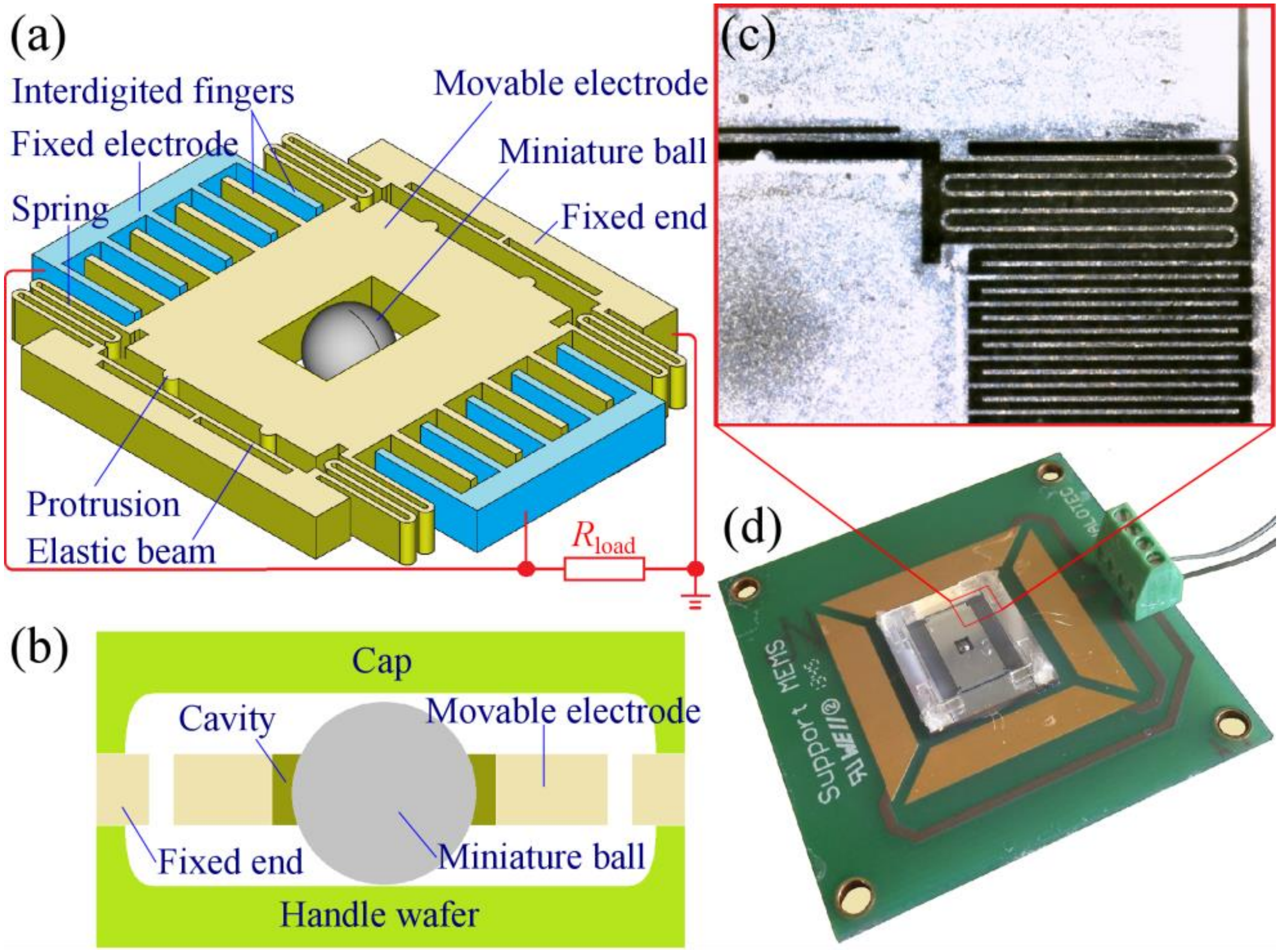
2nd Version with ELECTRETS: experimental set-up of the corona charging on the parylene electret layer



Fabricated at ESIEE Paris, Université de Paris-Est

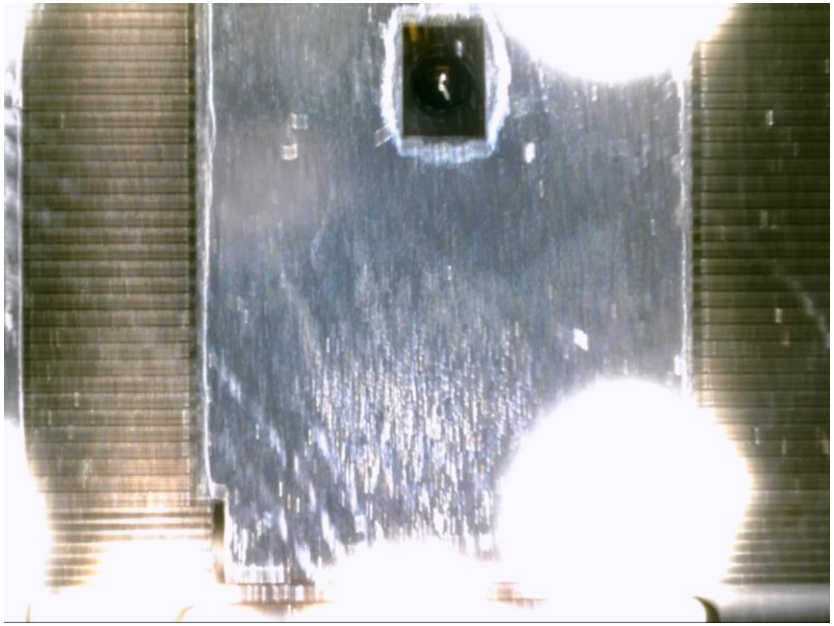
Low-frequency MEMS electrostatic VEH

Prototype fabrication process

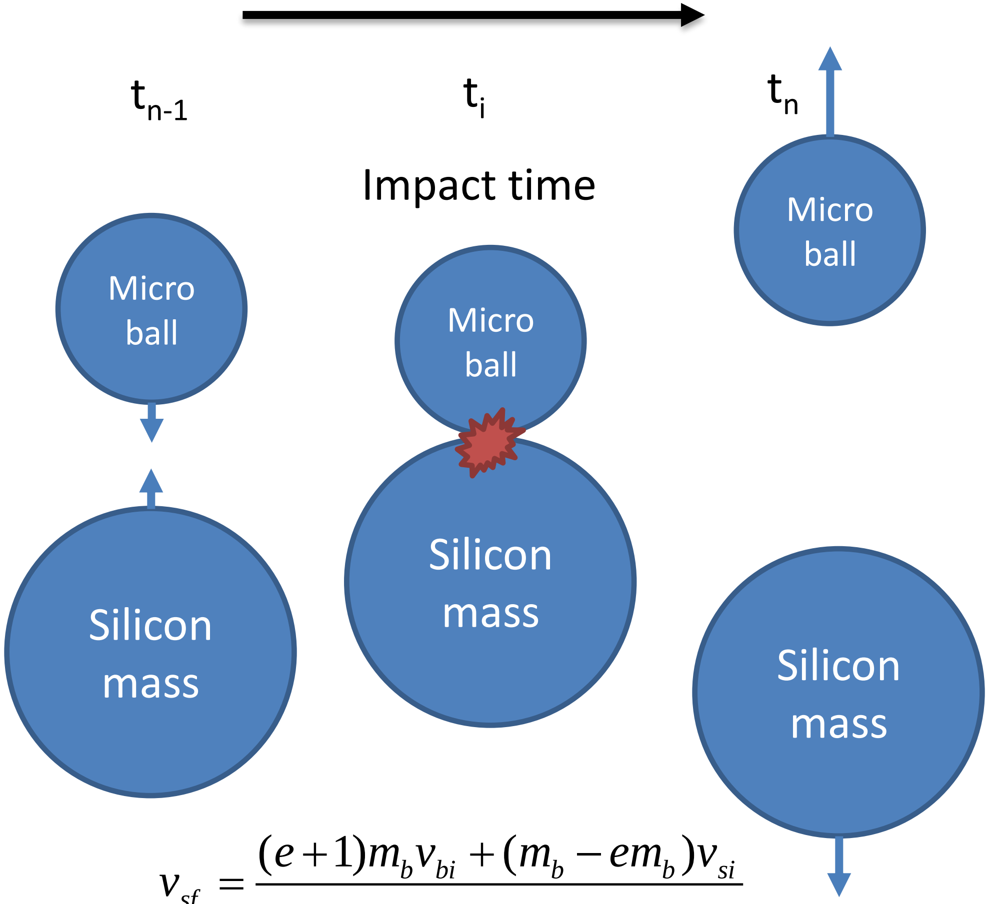


MEMS e-VEH at work

Experimental test



Working principle

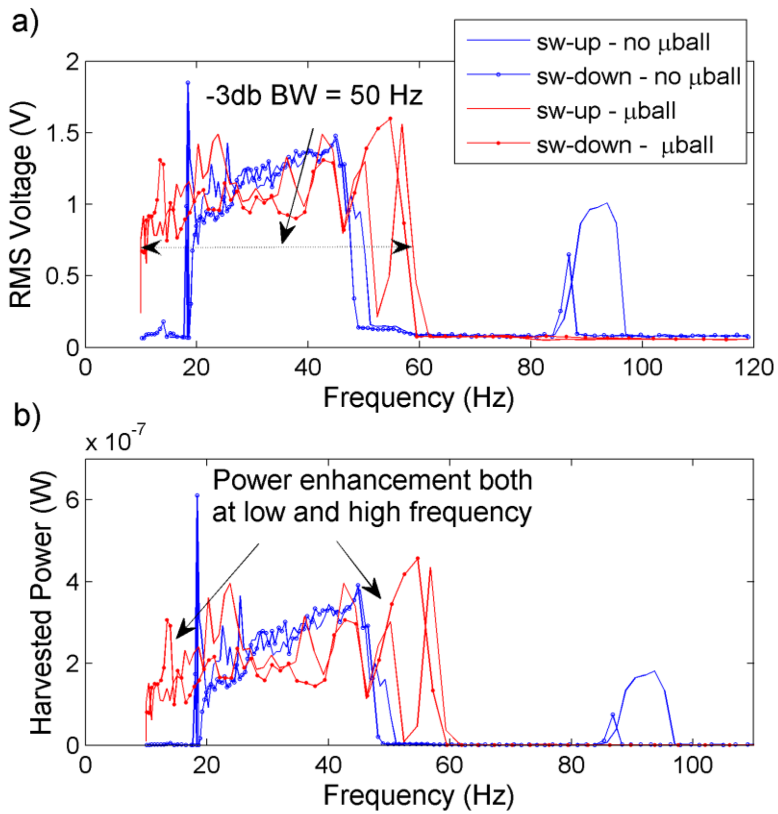


$$v_{sf} = \frac{(e+1)m_b v_{bi} + (m_b - e m_b) v_{si}}{m_b + m_s}$$

Velocity Amplified Energy Harvester
At Stoke Institute, University of Limerick, Ireland

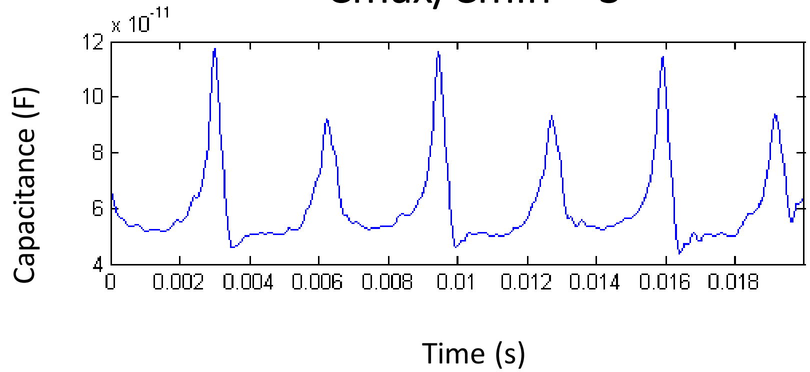
Experimental results

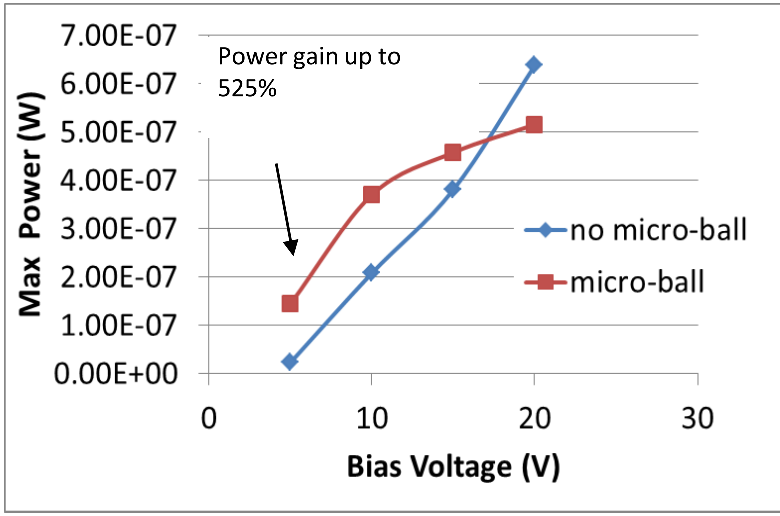
Experimental: Sine sweeping 10 – 120 Hz @ 0.3 g / R_L = 5 MOhm



F. Cottone et al., *2014 IEEE 27th Int. Conf. MEMS,* 2014.

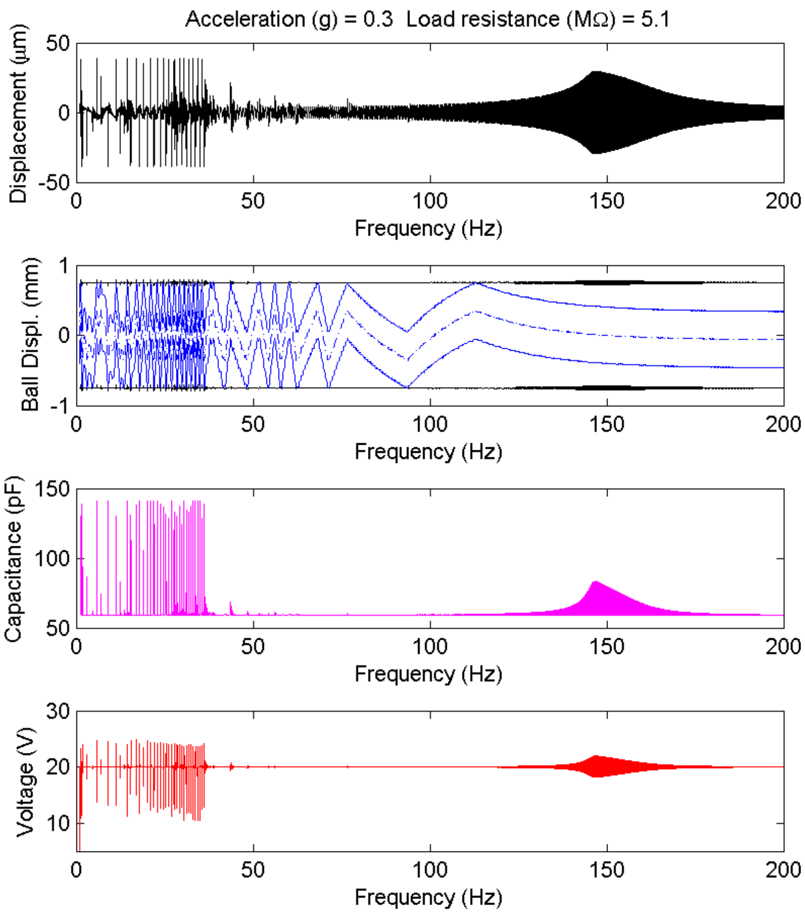
Cmax/Cmin = 3

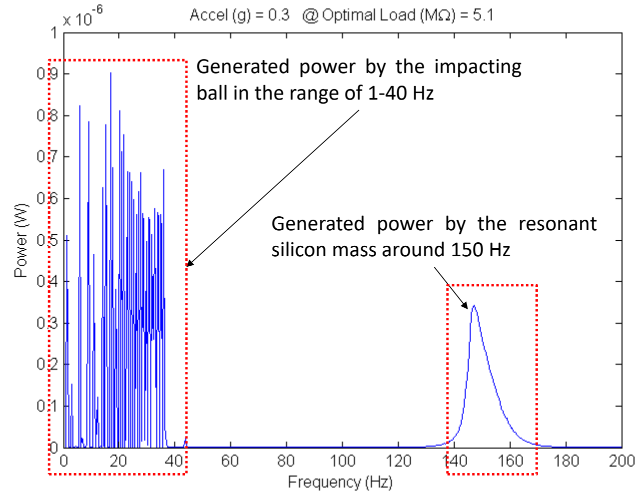


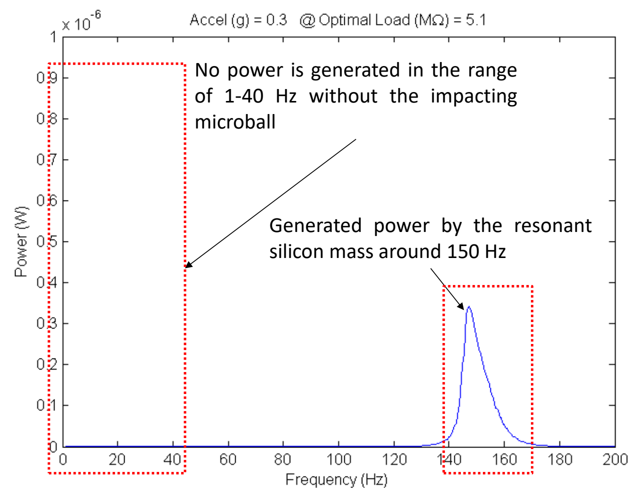


Numerical simulations

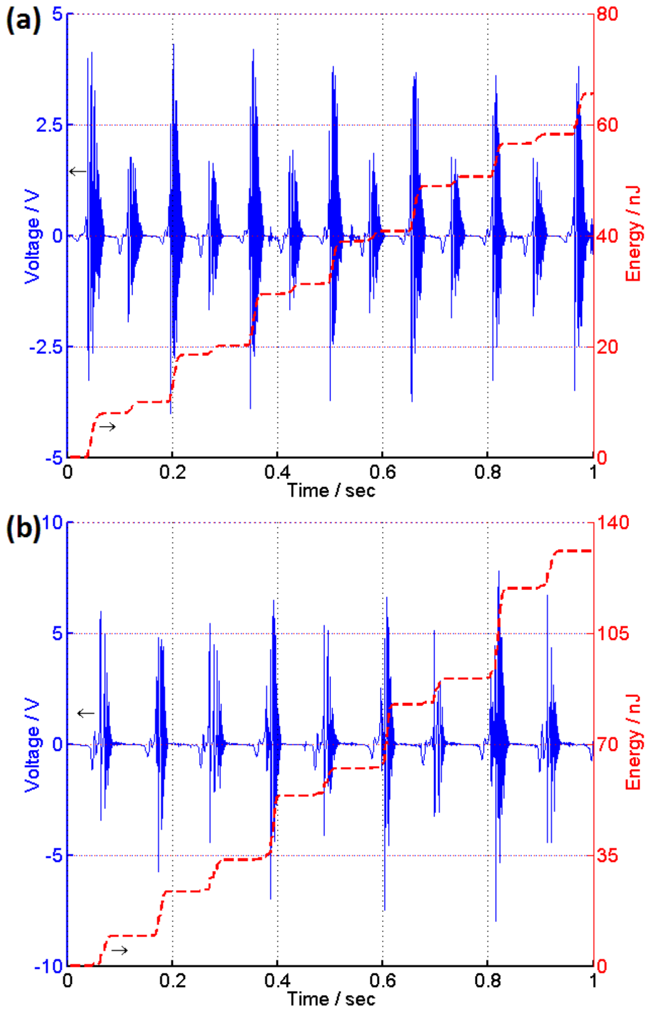
Numerical: sine sweeping 10 – 120 Hz @ 0.3 g / R_L = 5 MOhm







Experimental results of e-VEH with electrets



TEST with hand shaking of the transient output voltage and extracted energy.

(a) Vbias=21 V, a=2.0 grms, f=6.5 Hz;
(b) Vbias=46 V, a=2.0 grms, f=4.7 Hz

A 47-µF capacitor has been also charged through a bridge diode rectifier to 3.5 V to supply a **wireless temperature sensor node**.

Power Density 142 uW/cm^3

Y. Lu, F. Cottone, S. Boisseau, F. Marty, D. Galayko, and P. Basset, Appl. Phys. Lett. 2015.

Micro and nano generators

IOP Publishing Smart Materials and Structures
Smart Mater. Struct. 27 (2018) 075052 (9pp) https://doi.org/10.1088/1361-665X/aaca55

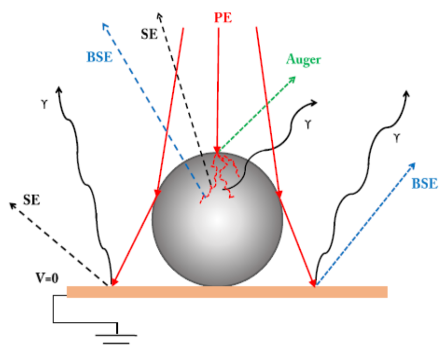
High charge density silica micro-electrets fabricated by electron beam

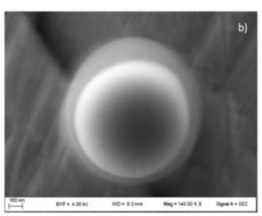
Francesco Bonacci[1], Alessandro Di Michele[2], Silvia Caponi[3], Francesco Cottone[2] and Maurizio Mattarelli[2]

Electrostatic

200 V surface potential

Charge concentration
0.1 C m^-3





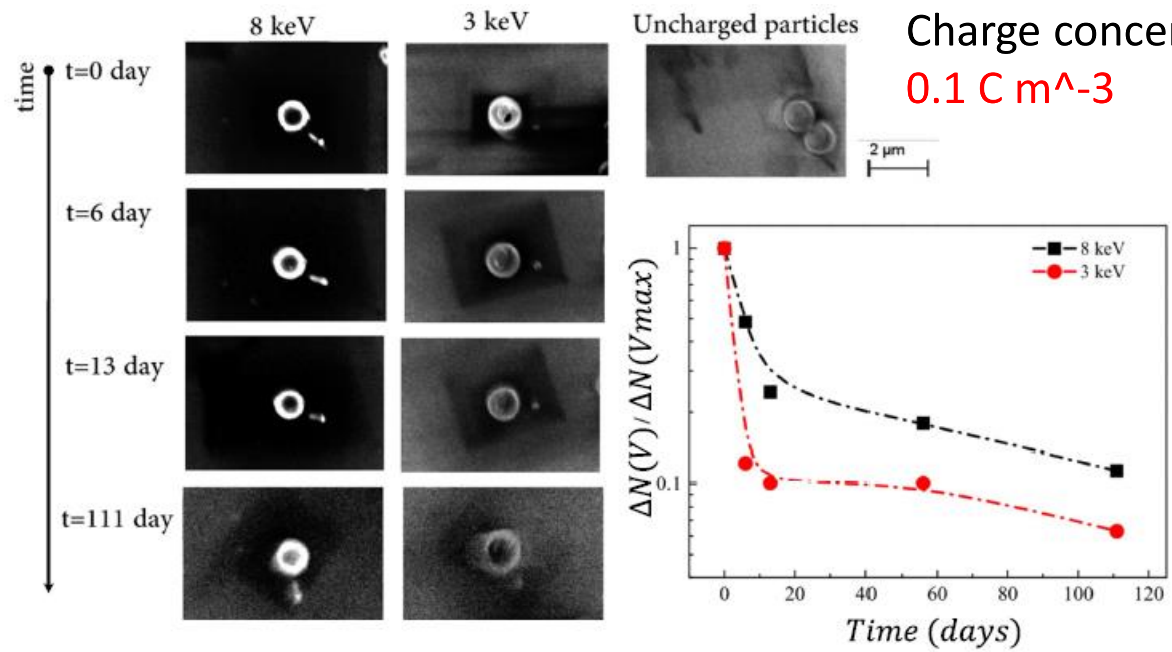
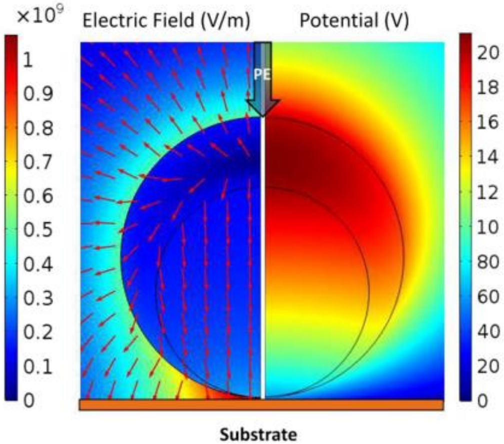


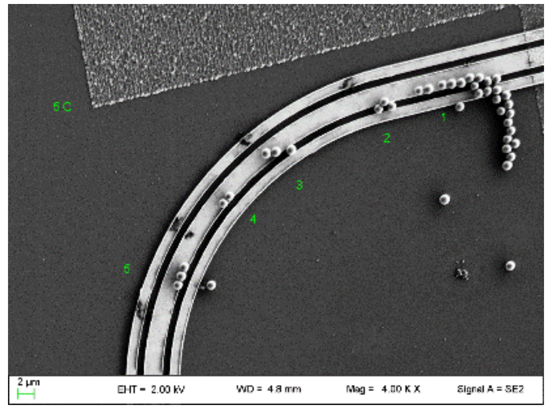
Figure 7. Images from the in-lens detector of the charged (first line, 8 keV and second line, 3 keV) and control particles (third line) at different times from the charging. In the graph: time behaviour of the emitted electrons difference between a charged and a non-charged particle.

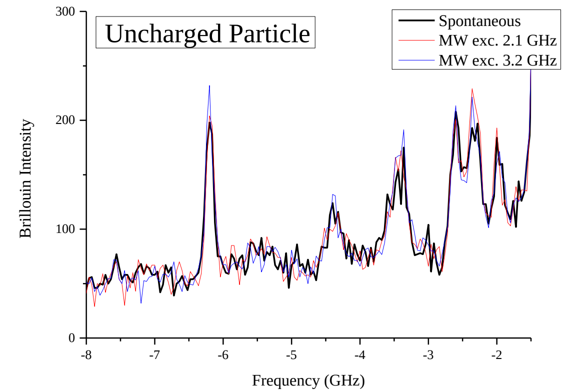
M. Mattarelli, A. Di Michele, S. Caponi, F. Cottone, F. Bonacci

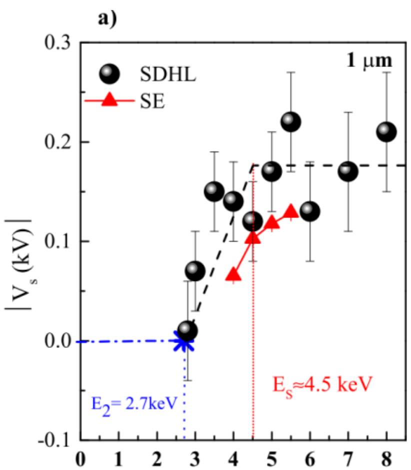
Micro and nano generators

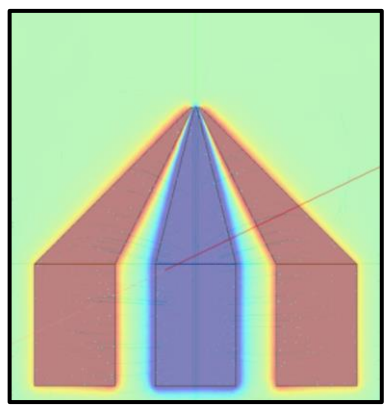
Electrostatic

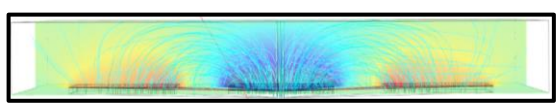


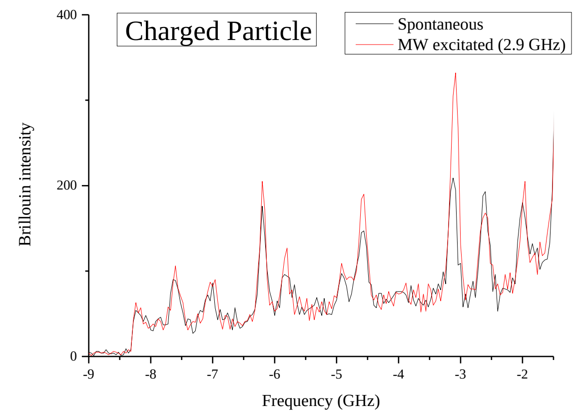












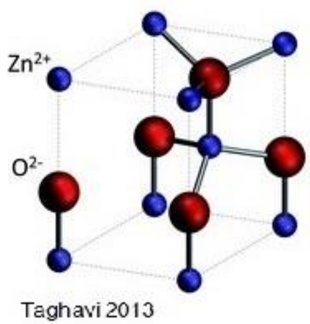
Transversal excitation of the modes on a MW antenna

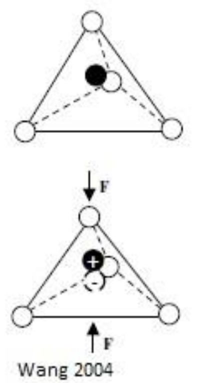
SiO2 particles charged by electron injection

M. Mattarelli, M. Madami, A. Di Michele, F. Cottone

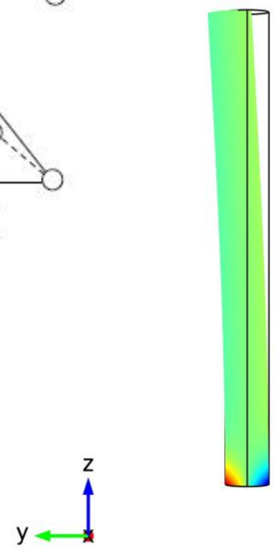
Micro and nano generators

Piezoelectric

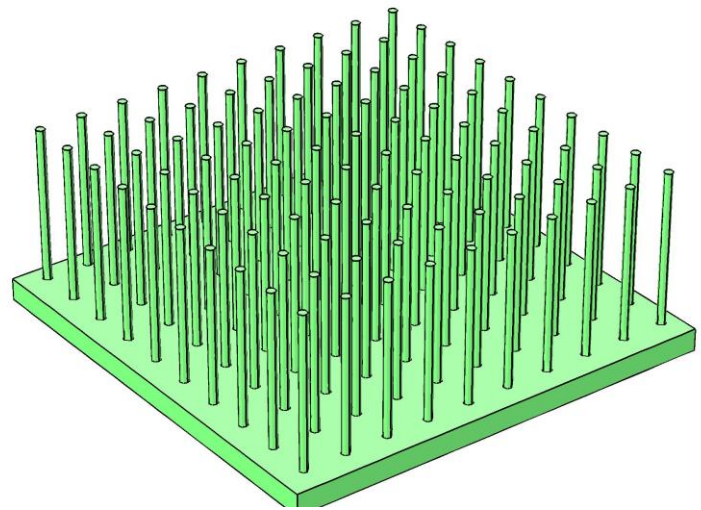


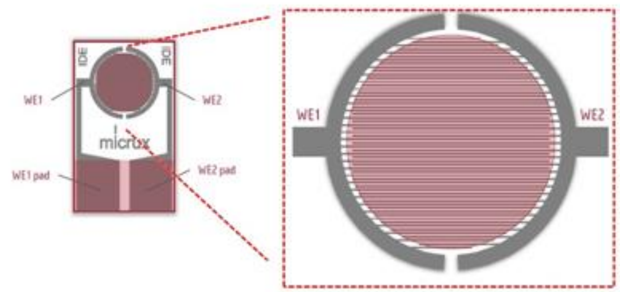


ZnO Pillar



ZnO forest



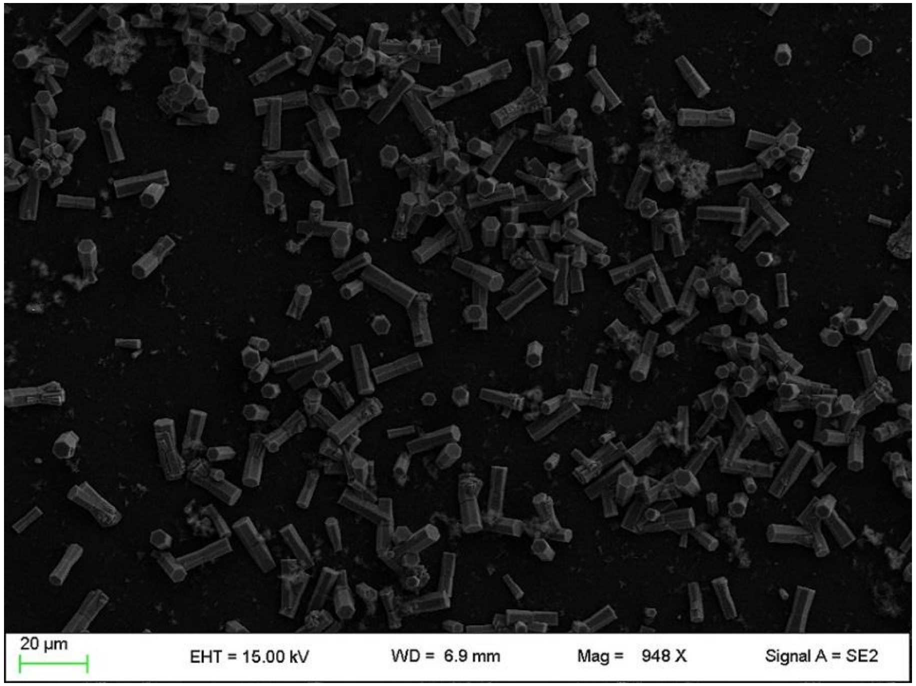


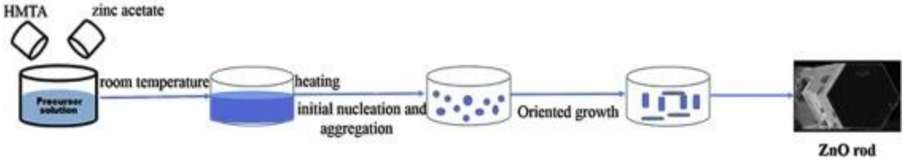
Why ZnO

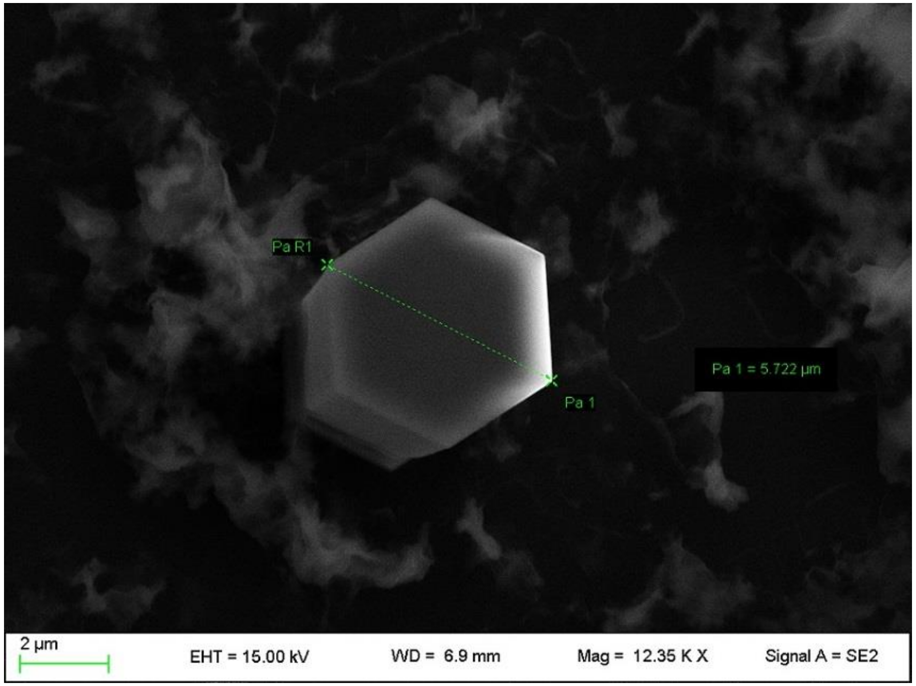
- Non-toxic → bio-compatible
- Wurzite structure
- Easy and cheap to fabricate
- Vast morfology

Micro and nano generators

Piezoelectric





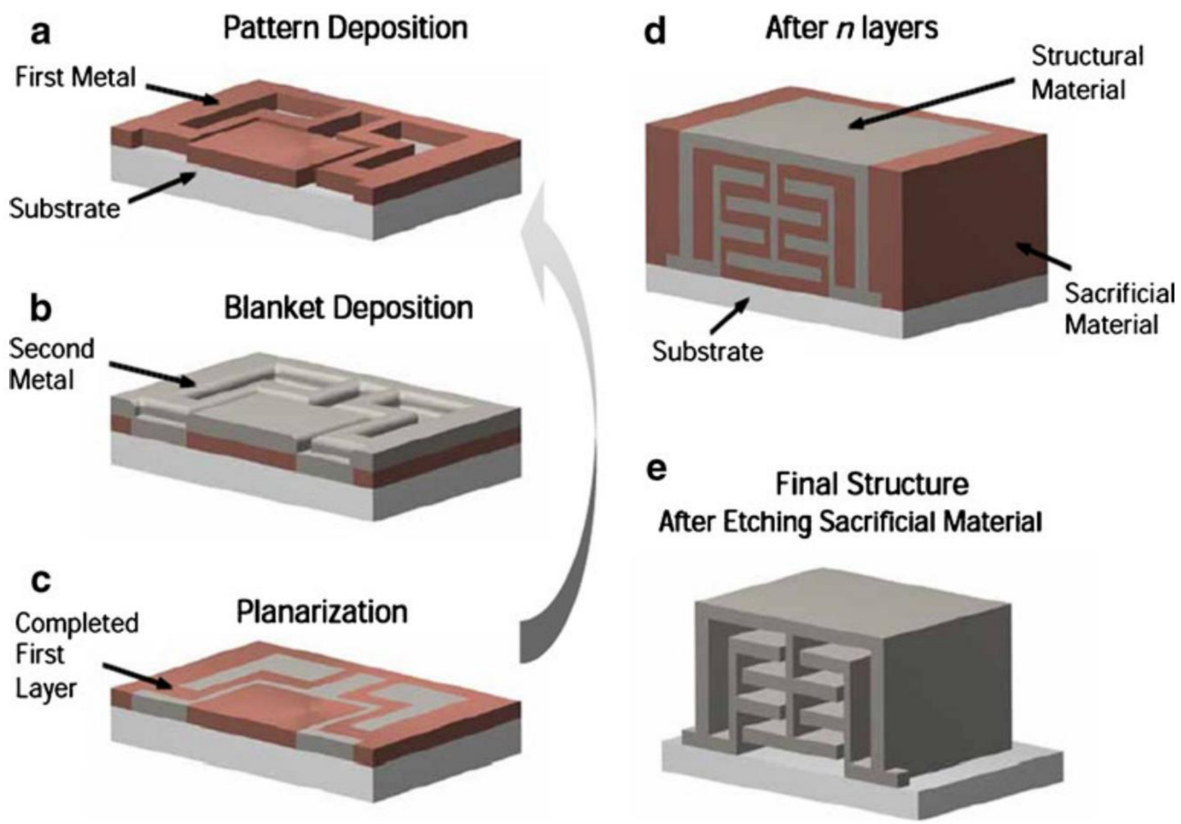


Hydrotermal synthesis
Length: 15 μm
Thickness: 4 – 6 um

A. Di Michele, G. Clementi, M. Mattarelli, F. Cottone

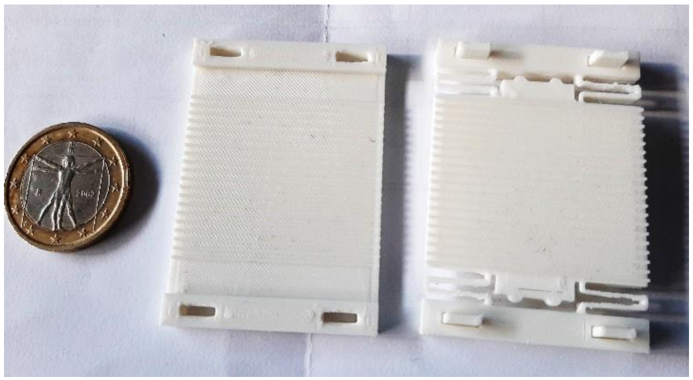
3D printed generators

Hybrid 3D printing techniques

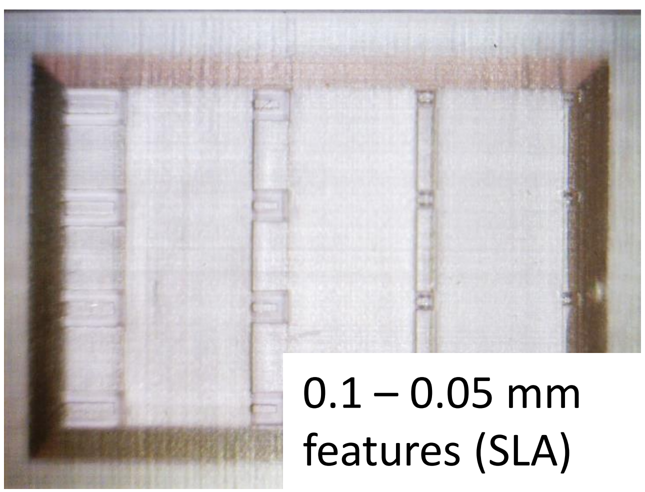


3D printed generators

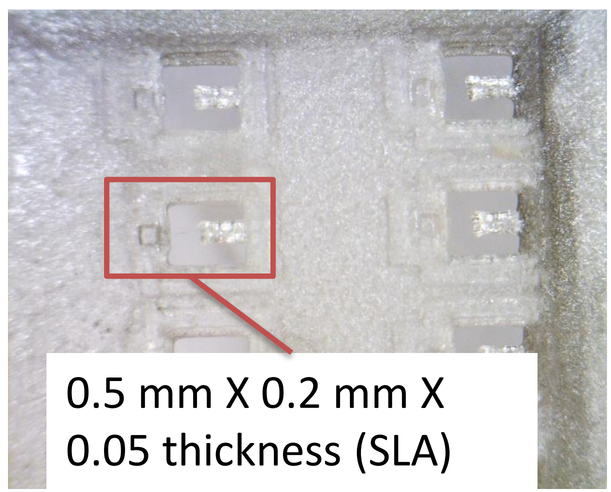
Low-cost rapid prototyping



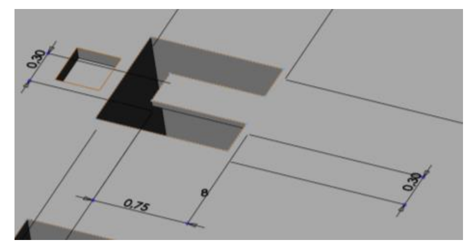
PLA electrostatic capacitive vibration energy harvester (FDM)

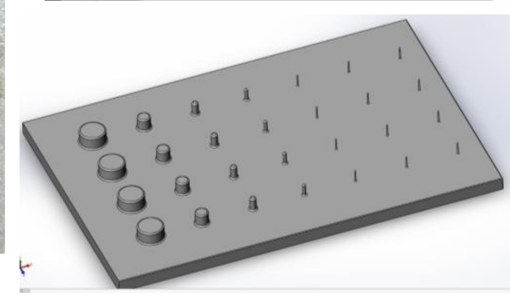


0.1 – 0.05 mm features (SLA)



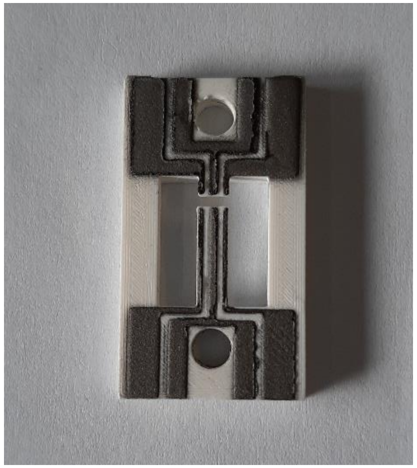
0.5 mm X 0.2 mm X 0.05 thickness (SLA)



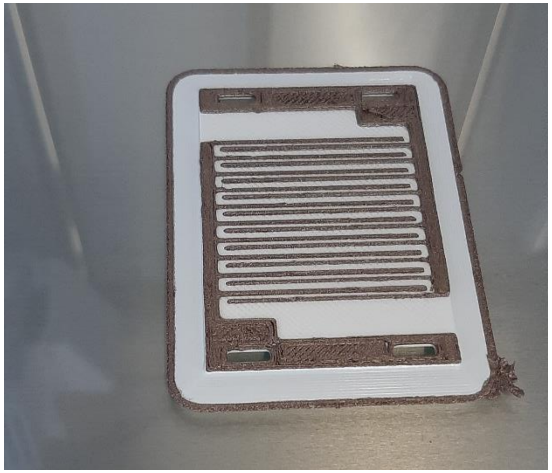


3D printed generators

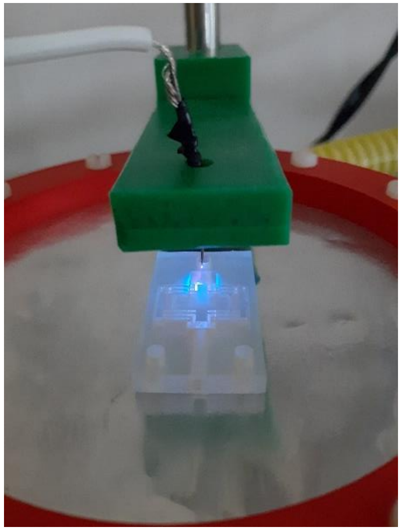
Low-cost rapid prototyping



Electrostatic bi-stable energy harvester



Interdigitated capacitive sensor



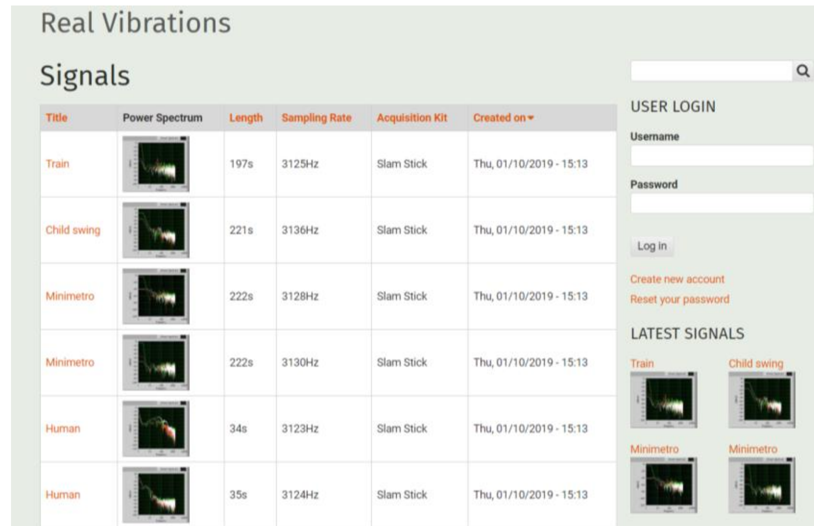
Corona discharge for electrets production

Polyvinylpyrrolidone for pharmaceutical application

Project EnABLES – Powering Internet of Things

European Infrastructure Powering the Internet of Things

https://realvibrations.nipslab.org/



Free of charge rapid access to undertake feasibility studies at EnABLES partner sites

https://www.enables-project.eu/

Access Centers

- Tyndall National Institute, Ireland
- Commisariat a L'energie Atomique et aux Energies
- Alternatives (CEA-Leti, CEA-Liten), France
- Fraunhofer IIS, Fraunhofer IMS, Germany
- Stichting IMEC Nederland, Netherlands

Knowledge Hubs

- Karlsruher Institute of Technology, Germany
- Politecnico Di Torino, Italy
- Alma Mater Studiorum – Universita di Bologna, Italy
- **Università degli Studi di Perugia, Italy**
- University of Southampton, UK

Conclusions

- Energy harvesting reaserch is expanding fast and represent a fundamental enabling technology for the development of the Internet of Things

- There still are many challenges both at macro and nano-scales: new device concept and materials are necessary to enahnce the energy efficiency

- Electrostatic and piezoelectric generators are very promising at micro/nano scale, but low cost process is needed to make the technology mature

- 3D printing techniques are very promising alternative to high cost facilities for the rapid prototyping of sensors and energy harvesting systems

Thank you!

Acknowledgments