Vibrational energy harvesting microgenerators based on piezoelectric thick films and MEMS

Erling Ringgaard, Tomasz Zawada, Michele Guizzetti, Karsten Hansen
CTS | Ferroperm, Kvistgaard, Denmark

Ruixao Xu, Anders Lei, Karen Birkelund, Erik V. Thomsen
DTU Nanotech - Department of Micro and Nanotechnology, Technical University of Denmark, Lyngby, Denmark

EMF2011, 28 June 2011, Bordeaux, France

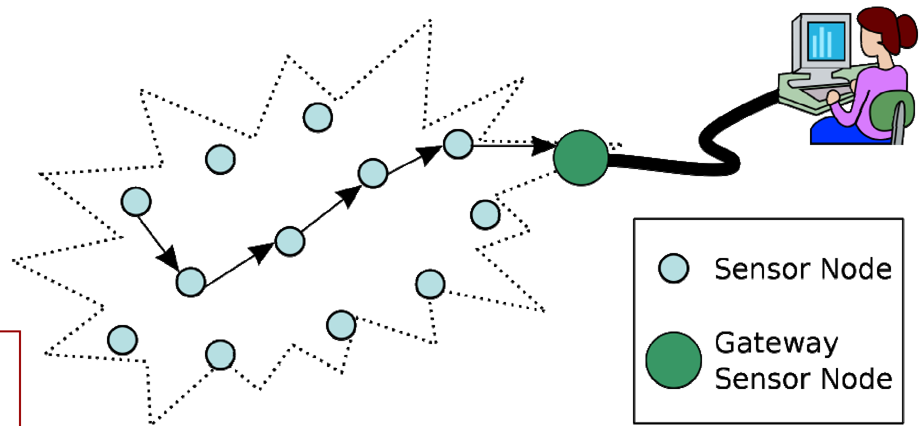
Outline

- Background of energy harvesting
- Introduction to InSensor® PZT thick film technology:
  - deposition and patterning techniques
  - available substrates and applications
- PZT thick film material for energy harvesting
- Experimental setup, test structures
- Wireless sensors
- Conclusions and summary

Introduction to energy harvesting

Background: Sensors everywhere!

- Smart House
- Smart Dust
- Distributed Wireless Sensor Networks



Wikimedia Commons

Integrate components:

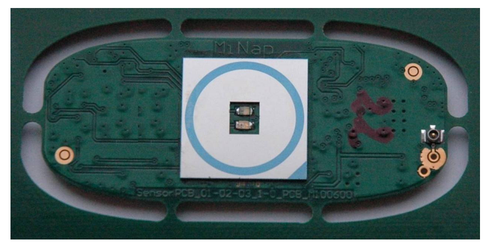
Sensors

Energy source

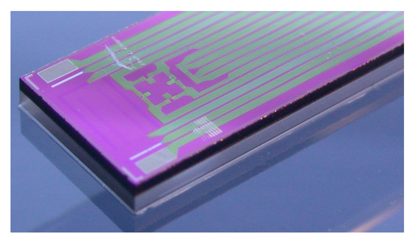
Microcontroller

Radio

Ultralow power!



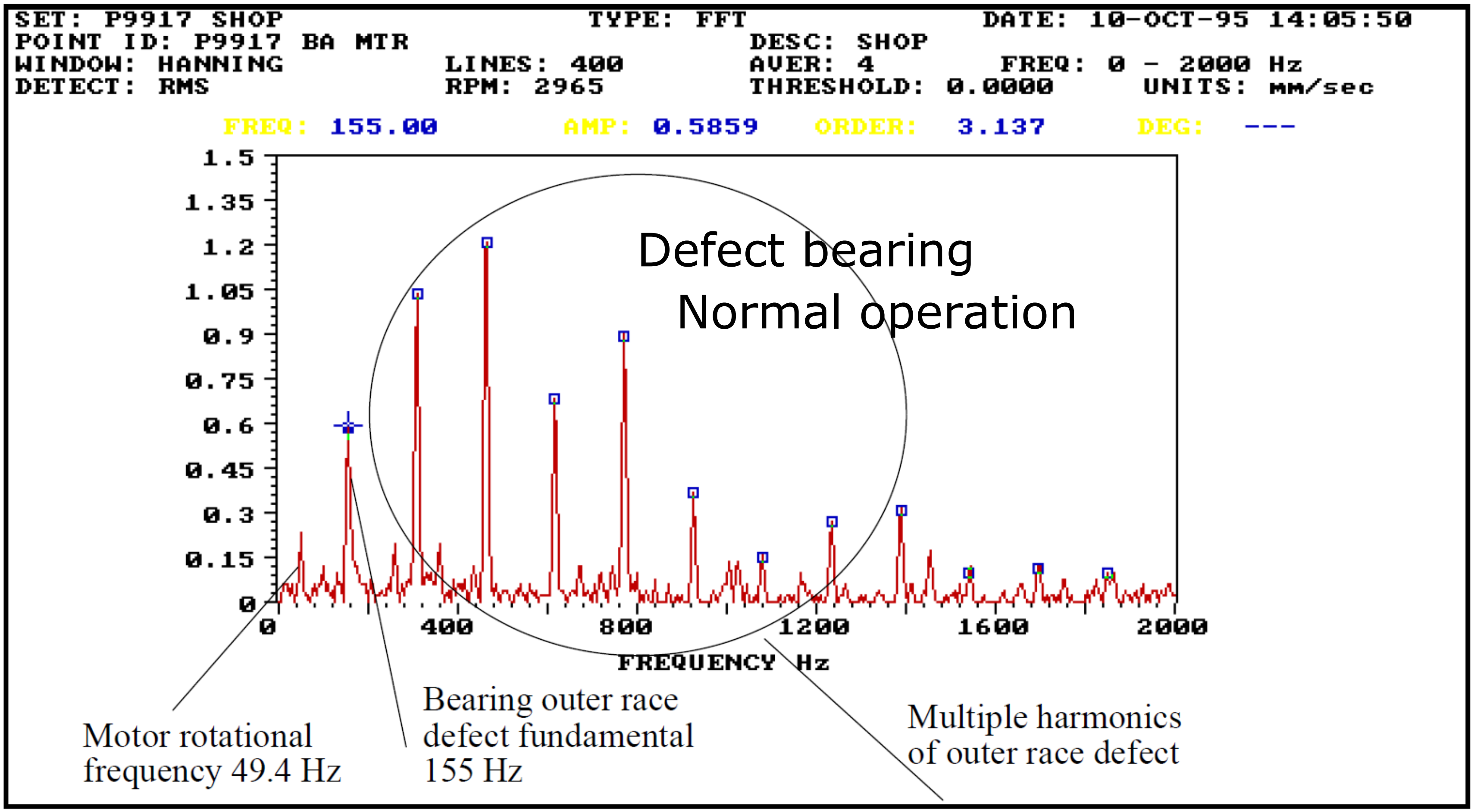
On humans:
An electronic patch



On fish:
Sensor system

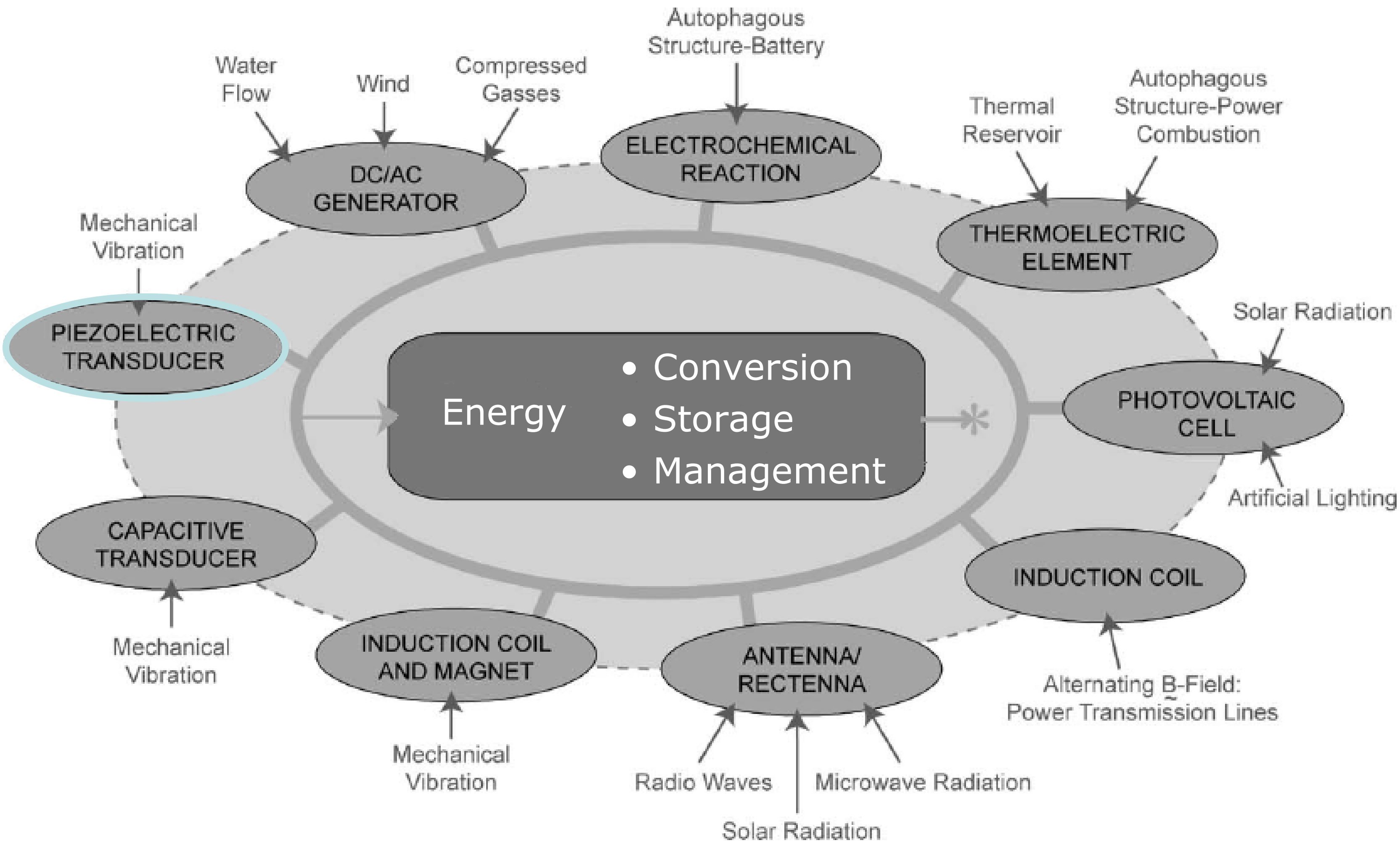
Example: Condition monitoring

Challenge: Measure vibrations on expensive machinery



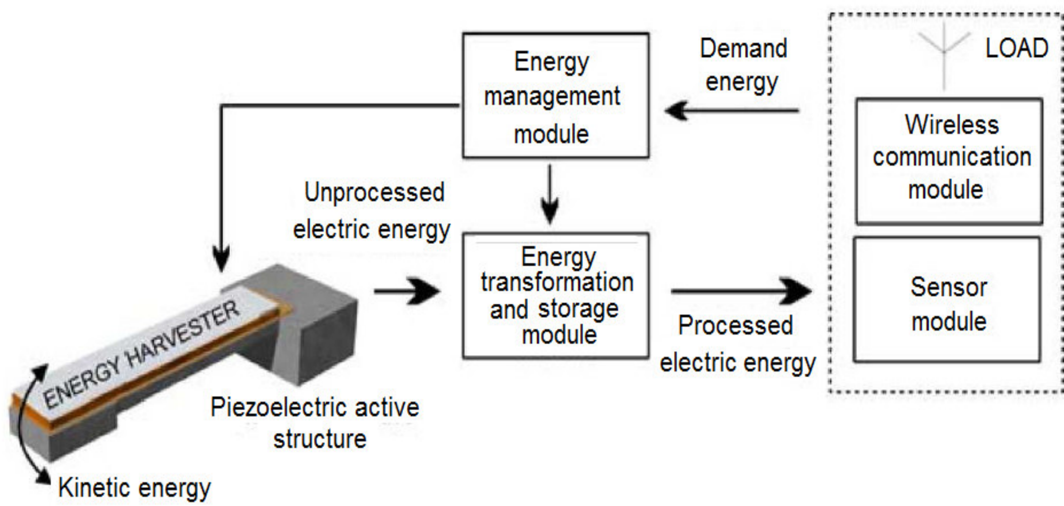
Source: www.vibanalysis.co.uk

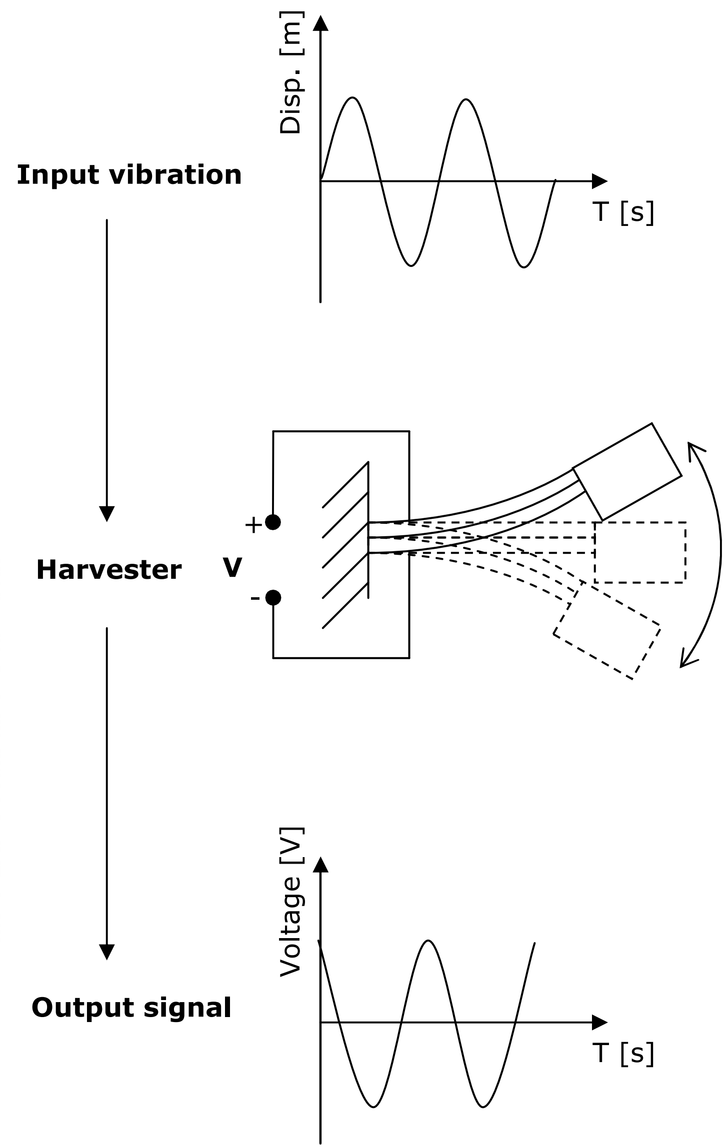
Powering Distributed Systems



Harvesting energy from vibrations

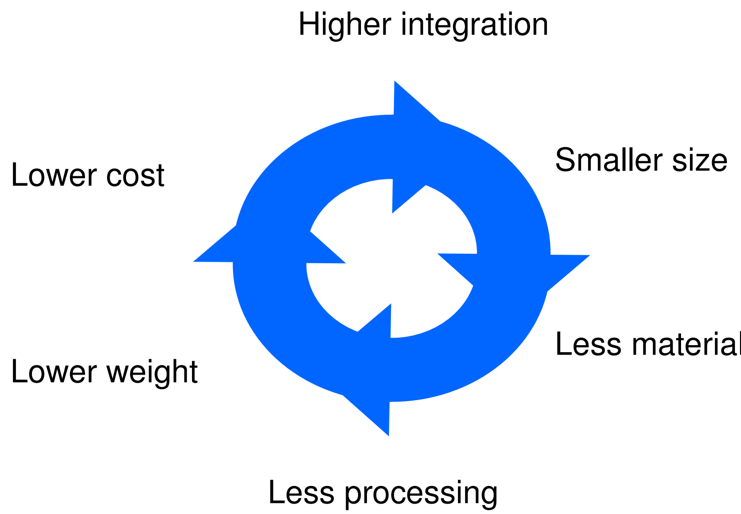
- **Vision:** Eliminate batteries by introducing energy harvesters enabling a new generation of distributed wireless sensing and control systems
- **Approach:** Harvest ambient vibrational energy using a ***piezoelectric*** transduction mechanism

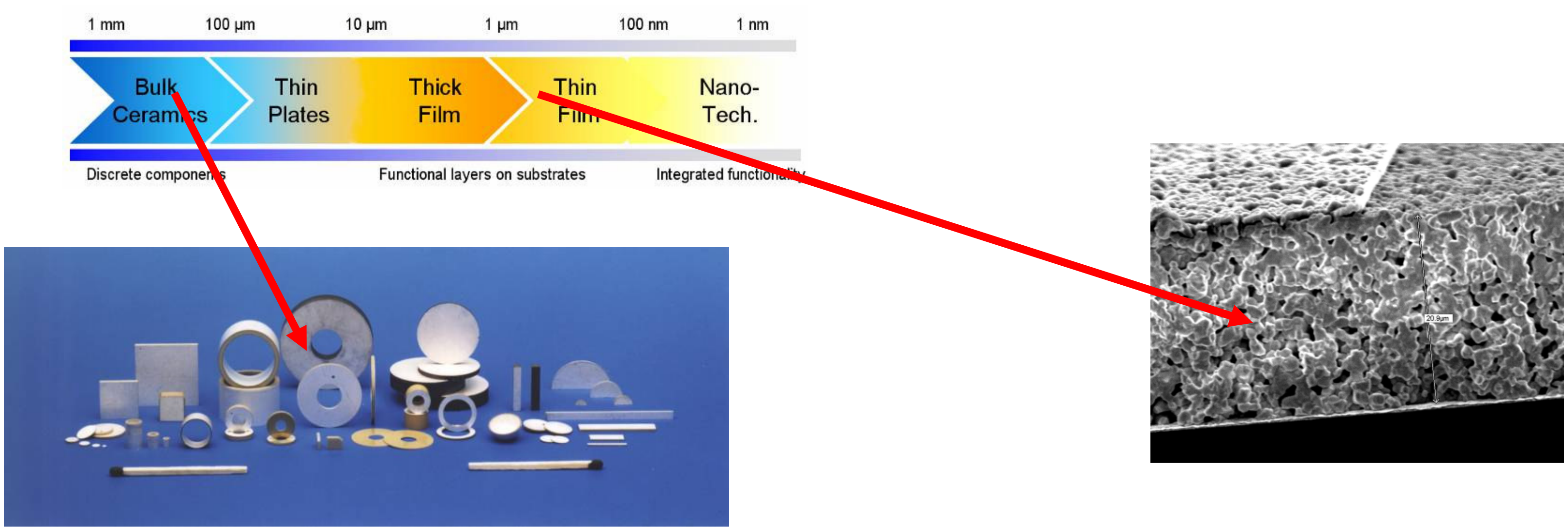




PZT thick films – technology and applications

Integrated piezoelectric materials



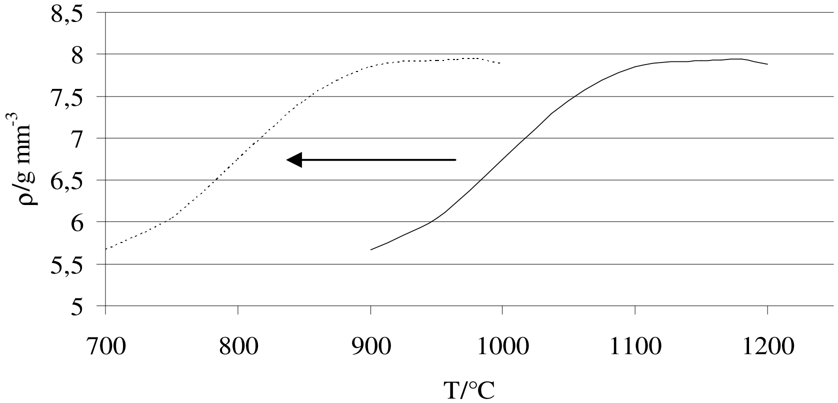


Challenges and the solution

- Compatibility challenges
  - Bulk ceramic is sintered at 1250 - 1300 ^{o}C
  - At these temperatures PZT will react with the substrate
  - Mismatch between thermal expansion coefficients causes delamination

Delamination effects

- Solution:
  - By introducing a sintering aid, the sintering temperature can be reduced significantly

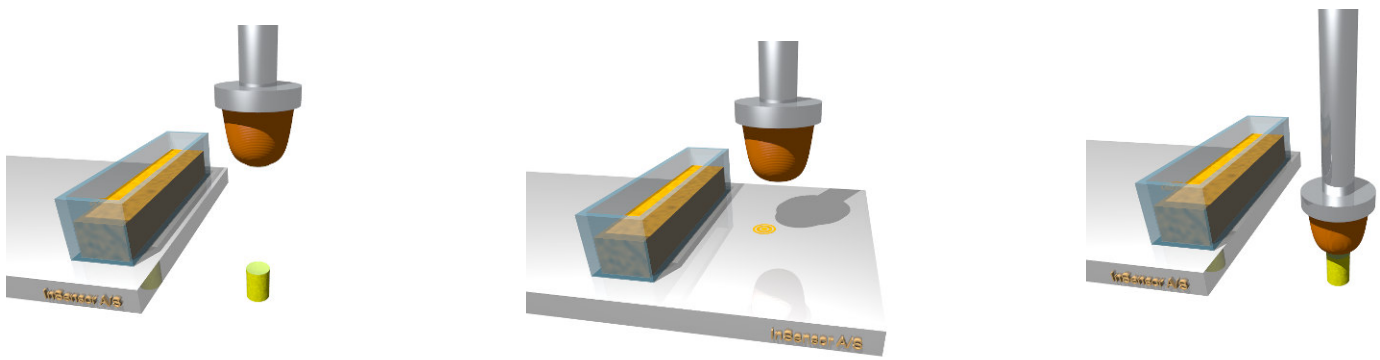


Densification at lower temperatures

Deposition techniques

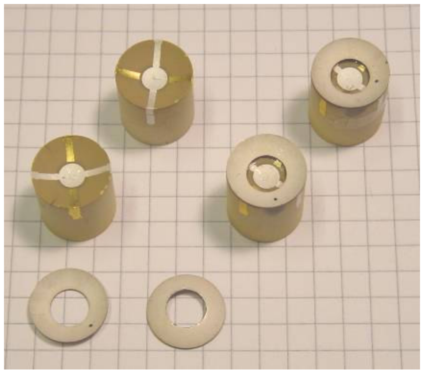
Screen printing

Pad printing

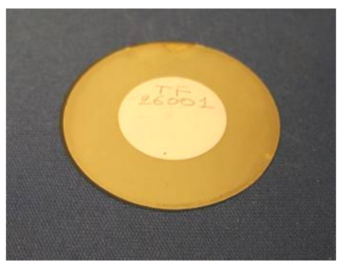


PZT thick film compatibility

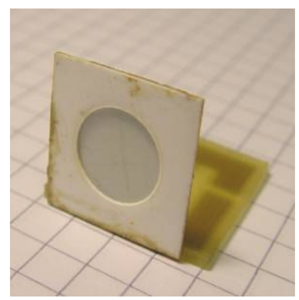
SUBSTRATES



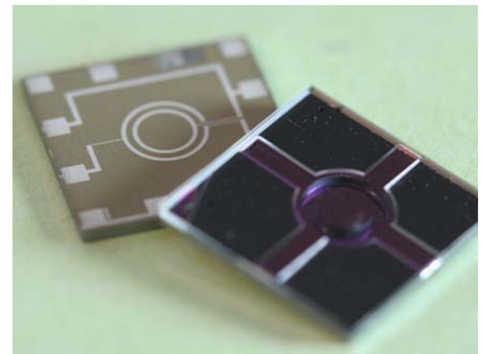
Ceramics



Stainless steel



LTCC*



Silicon/MEMS**

*) in cooperation with Thick Film Microsystems Lab, Wroclaw Univ. of Tech., Wroclaw, Poland

**) in cooperation with DTU Nanotech, Lungby, Denmark

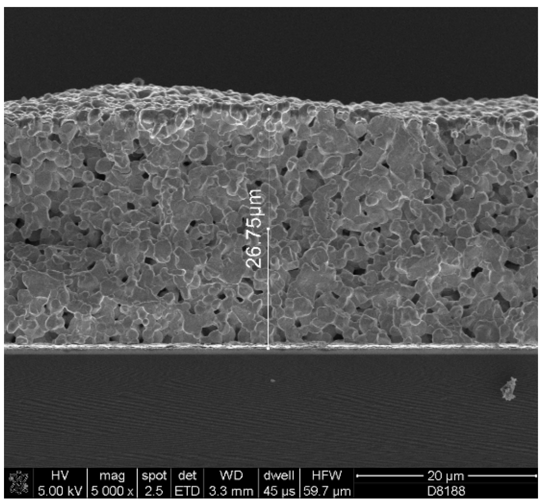
PZT thick films – areas of application

- Transducers
  - Medical imaging (high frequency, high resolution)
  - p-MUTs
- Actuators
  - Micro-valves
  - Micro-pumps
  - Micro-mirror positioning
  - Linear or angular positioning
- Sensors
  - Accelerometers
  - Strain gauges
  - Knock sensors
  - Pressure sensors
  - Hydrophones
  - Viscosity sensors
- Energy harvesting

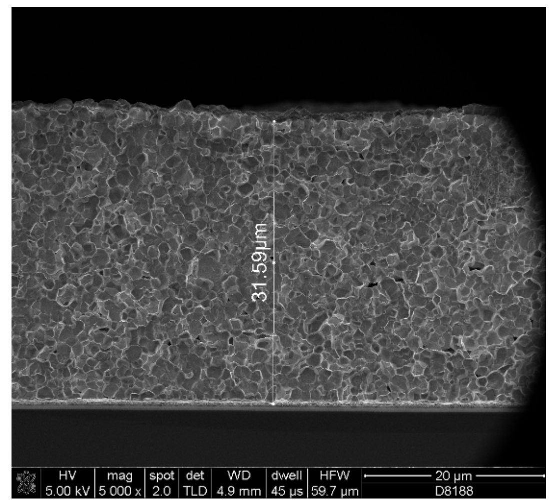
High-performance PZT thick film for energy harvesting

High performance PZT thick films

- The piezoelectric properties of the PZT thick film can be improved by using an additional processing of the green films in high pressure



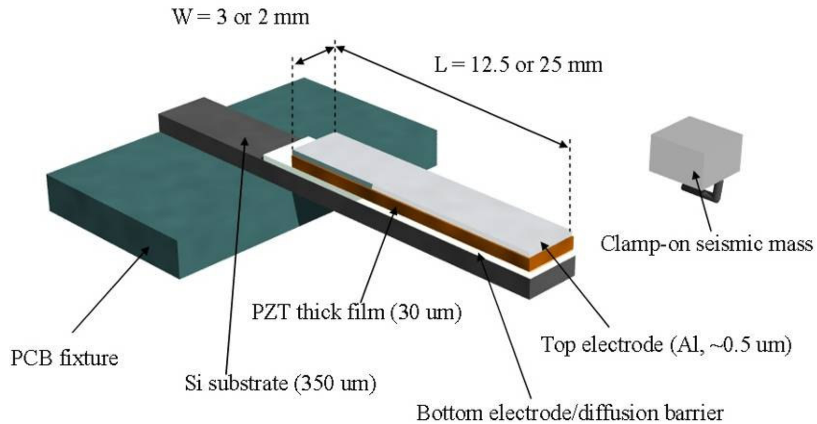
Micrograph of standard PZT thick film (on silicon)

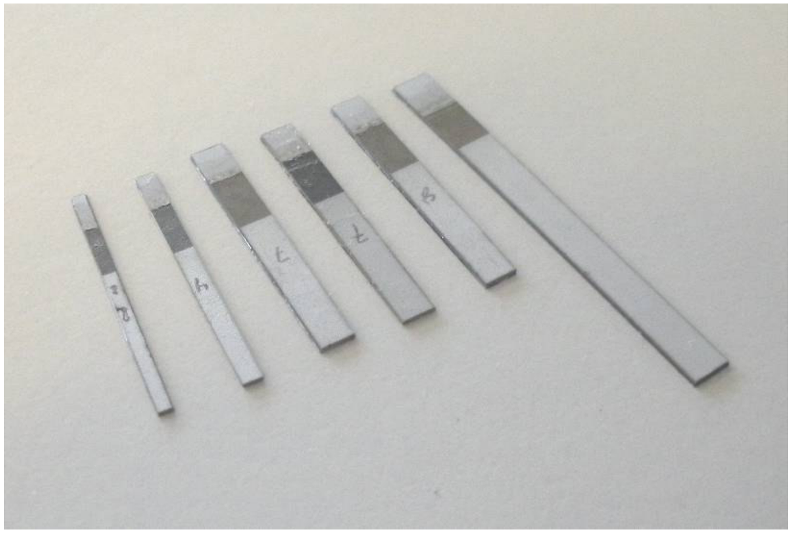


Micrograph of PZT thick film (on silicon) modified using high pressure processing

Test structures

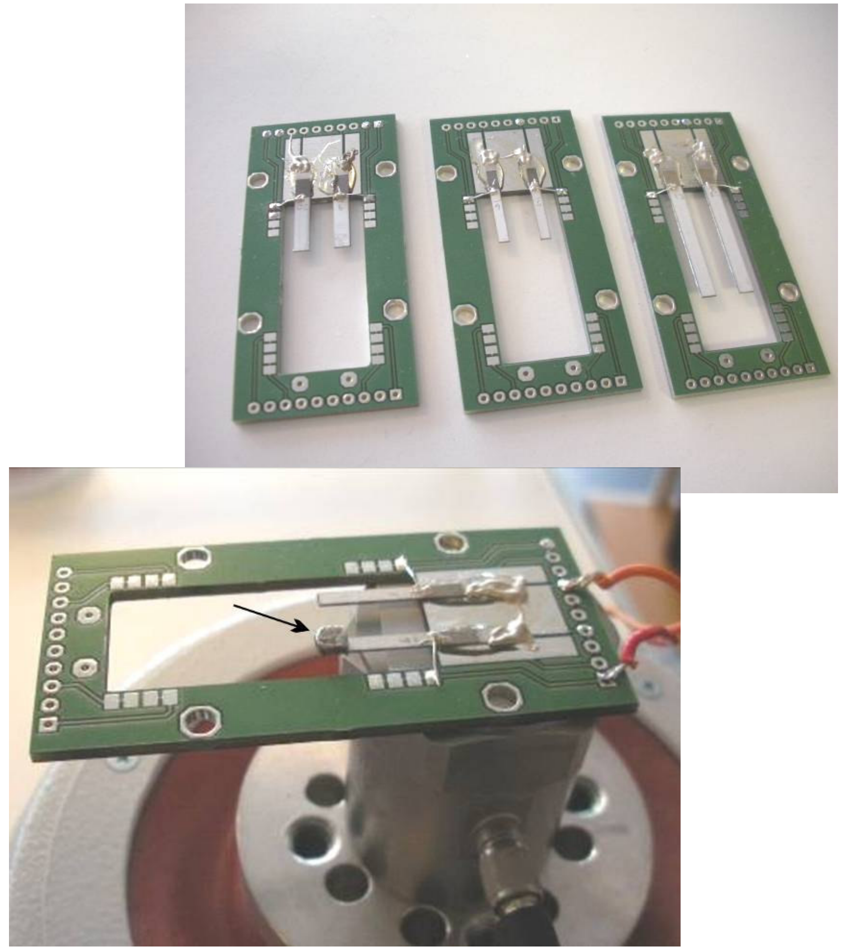
- Test structures, have been manufactured using InSensor® PZT thick films
  - Standard (STD) TF2100 (hard PZT based)
  - Modified (MOD) TF2100 (hard PZT based, high pressure treated)
- 30 µm thick film (both STD and MOD) has been deposited on 360 µm thick silicon substrate with dimensions equal to
  - 12.5x2 mm^2
  - 12.5x3 mm^2
  - 25x3 mm^2
- Pt based bottom electrode served also as diffusion barrier layer during the PZT sintering process
- Top electrode has been deposited using evaporation technique (0.5 µm thick)





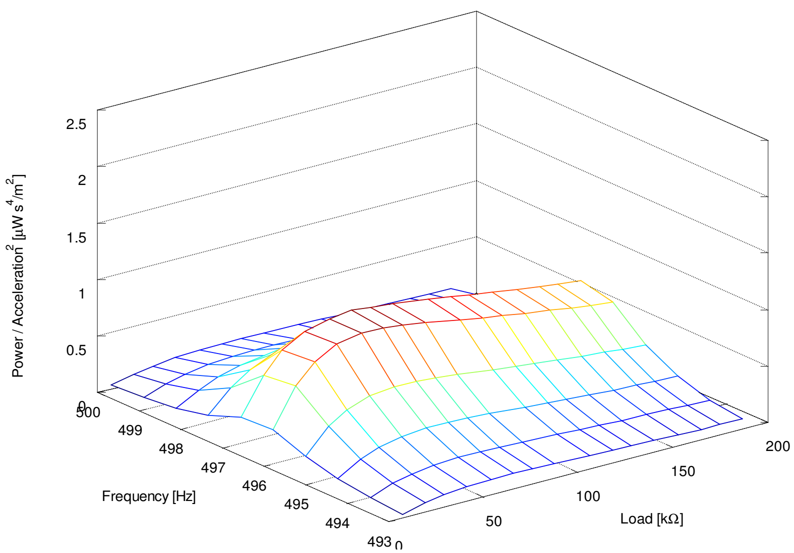
Experimental setup

- Before the measurements the devices were glued to PCB fixtures
- The whole fixture was mounted on a shaker, imposing a sinusoidal acceleration at the base of the cantilever
- A reference accelerometer was fixed to the vertical axis of the shaker, in order to measure the vertical acceleration
- Three different values of seismic mass have been used in the experiments (125 mg, 191 mg, 286 mg)
- The measurements were performed at around 1 m/s^2 acceleration



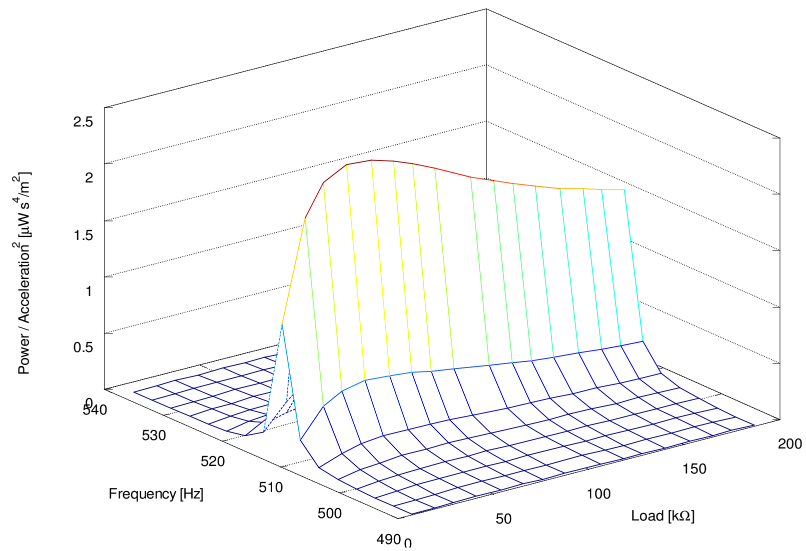
Test structures, bonded to PCB fixture (top), on the shaker with clamped-on seismic mass (bottom)

Measurement results – direct comparison



Standard PZT thick film

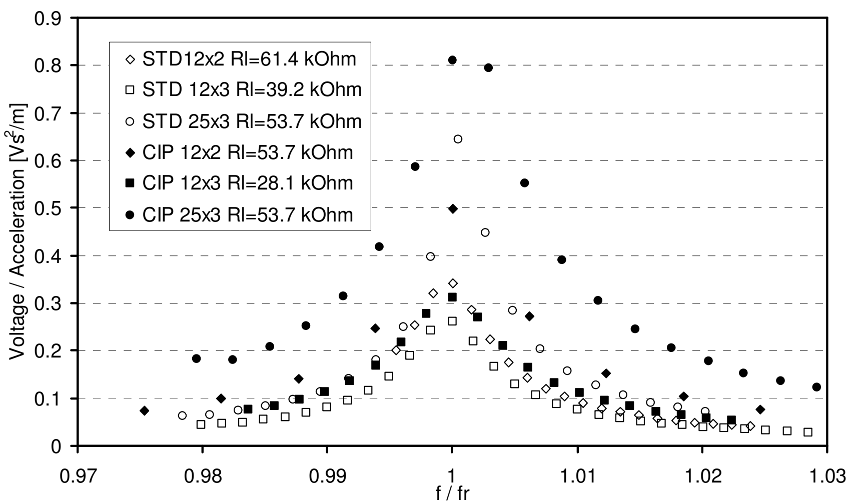
InSensor® TF2100



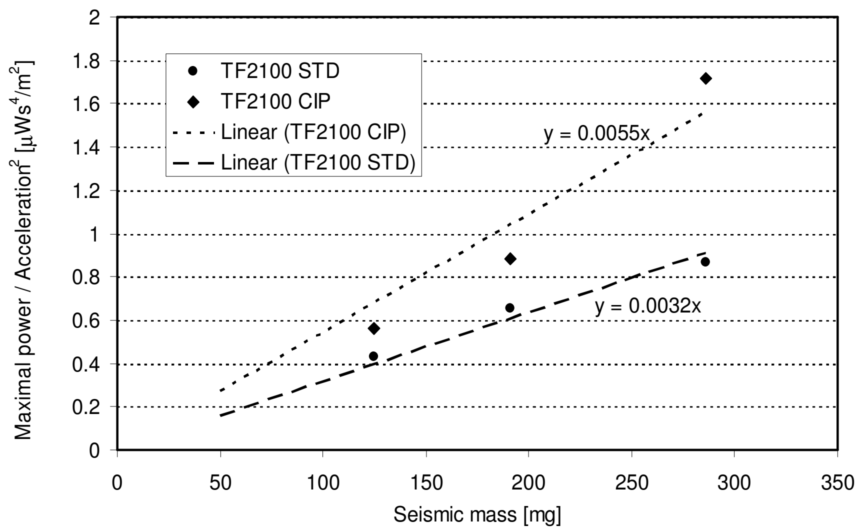
High performance PZT thick film

InSensor® TF2100

Results - continued



Normalised output voltage on sub-optimal resistive load



Output power at 1 m/s^2

Structures on 12.5x3 mm^2 substrates

Summary of results

- Output power P_{max} of a vibration energy harvesting generator with a seismic mass m can be expressed in the following way:

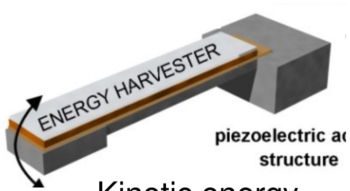
$$P_{max} \sim m\, a^2 / f_r \quad \Rightarrow \quad \mathrm{FoM} = P_{max}\, f_r / (m\, a^2) = \{P_{max}/a^2\}\, f_r / m$$

Planar dimensions [mm x mm]	Piezoelectric thick film	Resonance frequency; f_r [Hz]	Maximal measured output power, normalized; P_{max}/a^2 [μW s^4/m^2]	FoM
12.5 x 2	TF2100 STD	493.2	0.95	1.6
	TF2100 CIP	512.1	2.46	4.4
12.5 x 3	TF2100 STD	617.4	0.87	1.9
	TF2100 CIP	612.6	1.71	3.9
25 x 3	TF2100 STD	191.2	4.18	2.8
	TF2100 CIP	205.0	7.56	5.4

*) All values have been measured for seismic mass of 286 mg at matching resistive load

Complete wireless sensor system

From single harvester to a system



Kinetic energy

Electrical energy →

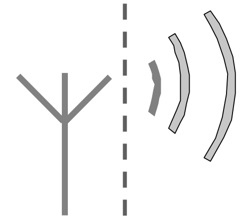
Energy management and storage module →

LOAD

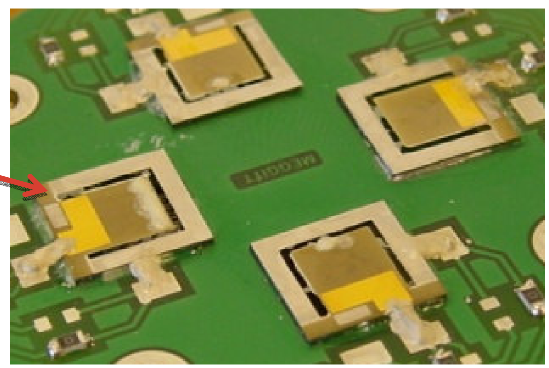
Microcontroller module

Acceleration sensor

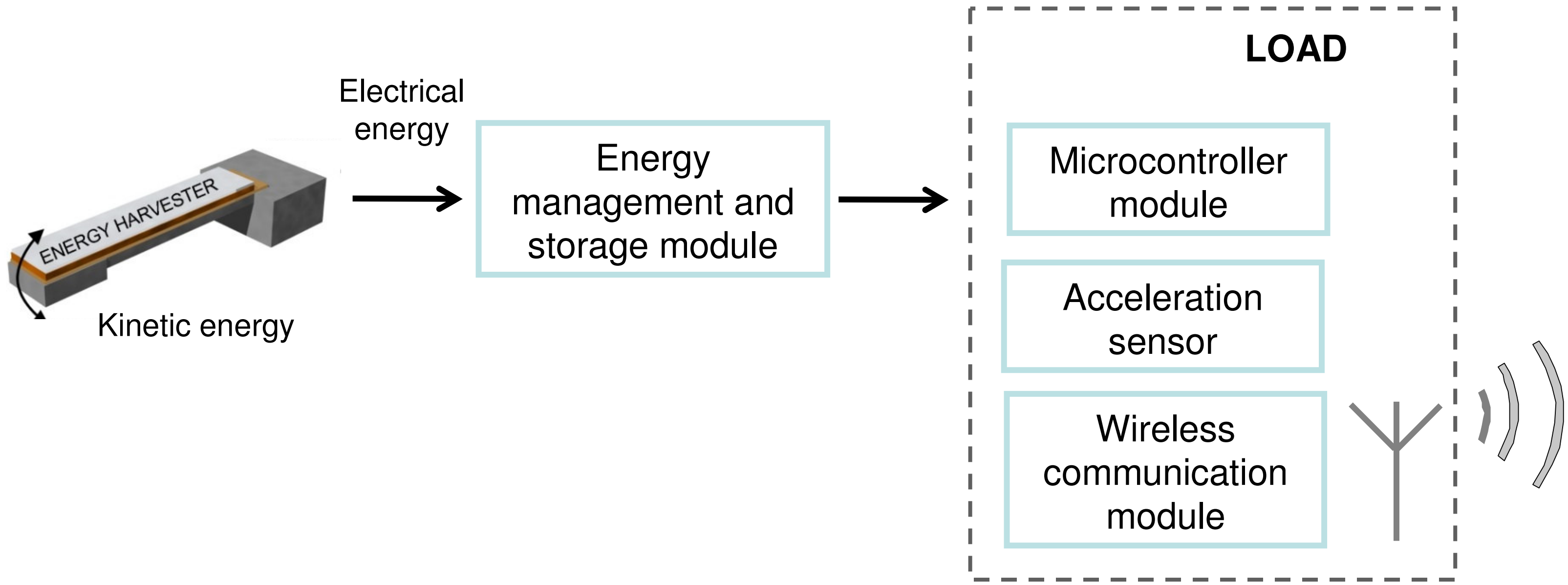
Wireless communication module



Energy harvester



Practical implementation of wireless sensor

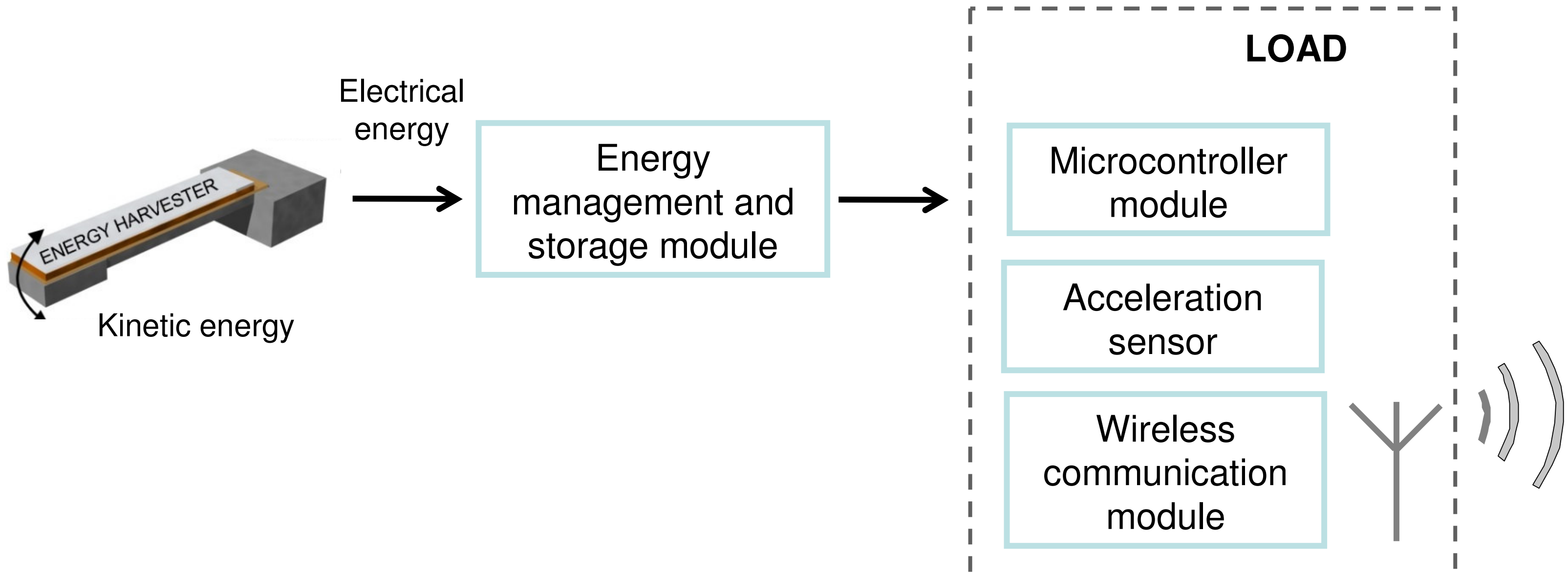


- Harvesters convert kinetic energy into electrical energy
- Electrical energy is stored and conditioned
- When sufficient electrical energy is available, the load is powered
- Microcontroller repeats acceleration measurement and performs intermittent data transmission

Characteristics of acceleration measurement

- 3D acceleration measurement performed
- Sampling frequency: 1600 Hz
- Resolution: 13 bits (38 mm/s^2 per LSB)
- Number of acquired samples for each axis: 60
- Acquisition time: 37.5 ms

Early prototype characteristics



- 3-4 harvesters excited at the same resonance frequency
- Resonance tuned adding extra mass (f_{res} = 167 Hz)
- Minimum RMS acceleration: 5 m/s^2
- Wireless data transmission demonstrated above 1 m distance

Conclusions (1): PZT thick films

- The properties of the PZT thick film can be substantially improved by high pressure processing
- Modified PZT thick films show superior performance over the standard ones and allow to significantly increase the output power of energy harvesting devices
- Figure of merit of the high performance based devices is approximately two times as high as one for the standard PZT thick film based devices
- The presented technology is a very promising candidate for fabrication of integrated and miniaturized devices on silicon (MEMS) comprising both sensors and energy harvesting micro-generators
- The high-performance InSensor® PZT thick films based MEMS devices can be manufactured at wafer-scale making it very attractive for high volume production

Conclusions (2): energy harvester

- Power harvesters realised with silicon micromachining technology and screen-printed PZT thick films
  - Open-circuit voltage up to 4 V @ 5 m/s^2 peak
  - Maximum power range up to 14 µW @ 5 m/s^2 peak
- Self-powered wireless sensor prototype
  - Harvester resonance frequency tuned by adding mass (f_{res} = 167 Hz)
  - Intermittent data transmission
  - 3D acceleration measurement
  - Radio frequency data transmission demonstrated
- More work will be put in harvesting at lower frequencies

Acknowledgement

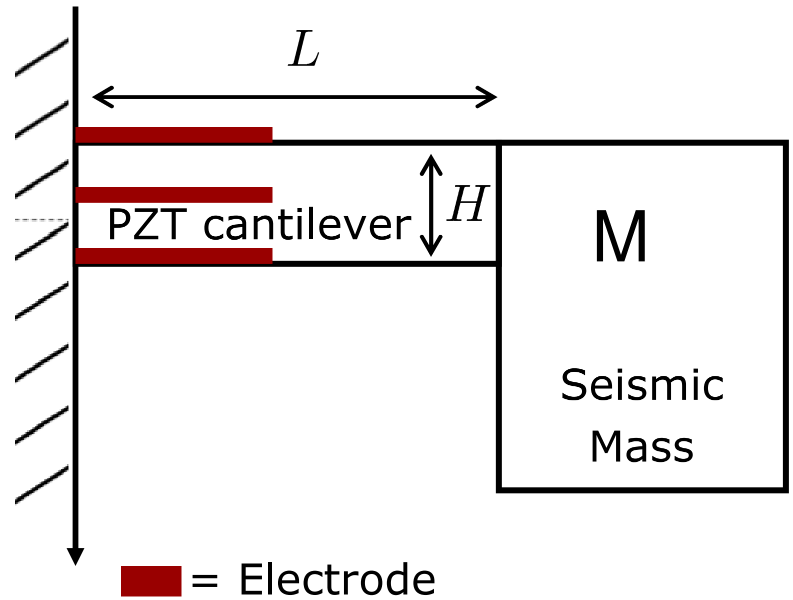
Danish National Advanced Technology Foundation through the ELBA project [**EL**iminating **BA**tteries – energy harvesters for integrated systems]

contract no. 036-2009-1

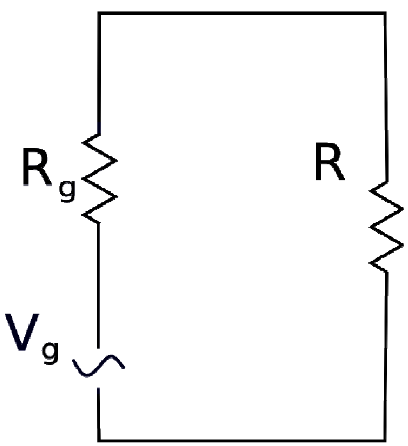
ELBA

Working principle

- Ambient mechanical vibrations accelerates the seismic mass which strains the piezoelectric cantilever beam.
- Energy is harvested by electrodes on the sides of the strained piezoelectric layer.
- Most effective at resonance:



$$P = \frac{R}{(R+R_g)^2} V_g^2$$



Power output:

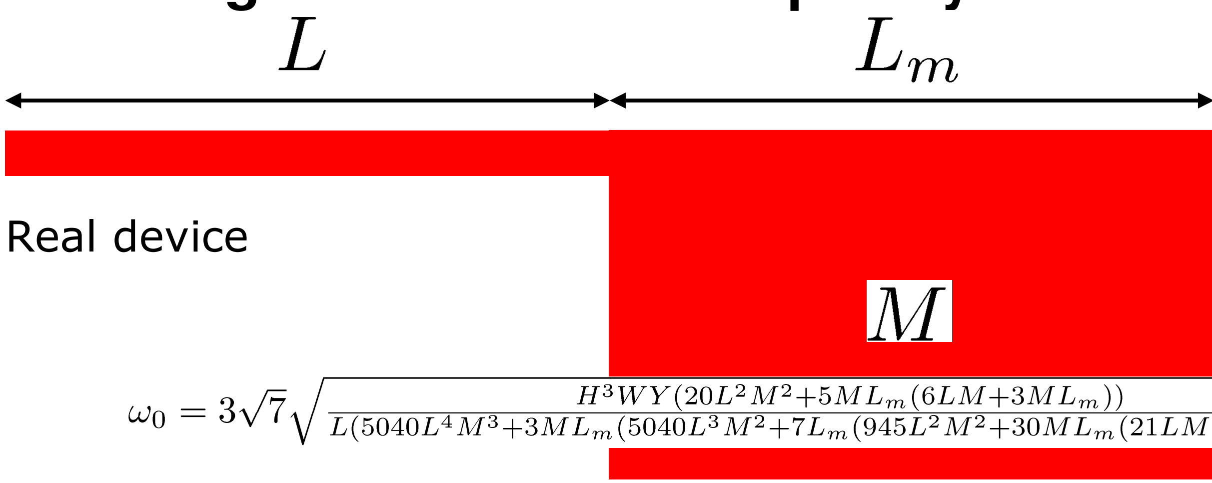
$$P \sim f(d_{31}, \varepsilon_{33}) g(Y, \nu) h(L, H, \ldots) \frac{Ma^2}{\omega}$$

Electrical parameters

Mechanical parameters

Geometrical parameters

Modelling the resonance frequency

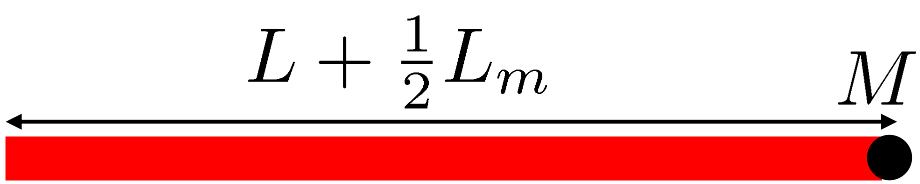


Real device

$$\omega_0 = 3\sqrt{7}\sqrt{\frac{H^3WY(20L^2M^2+5ML_m(6LM+3ML_m))}{L(5040L^4M^3+3ML_m(5040L^3M^2+7L_m(945L^2M^2+30ML_m(21LM+6ML_m))))}}$$

$$\omega_0 = \frac{1}{2}\sqrt{\frac{H^3WY}{L^3M}}$$

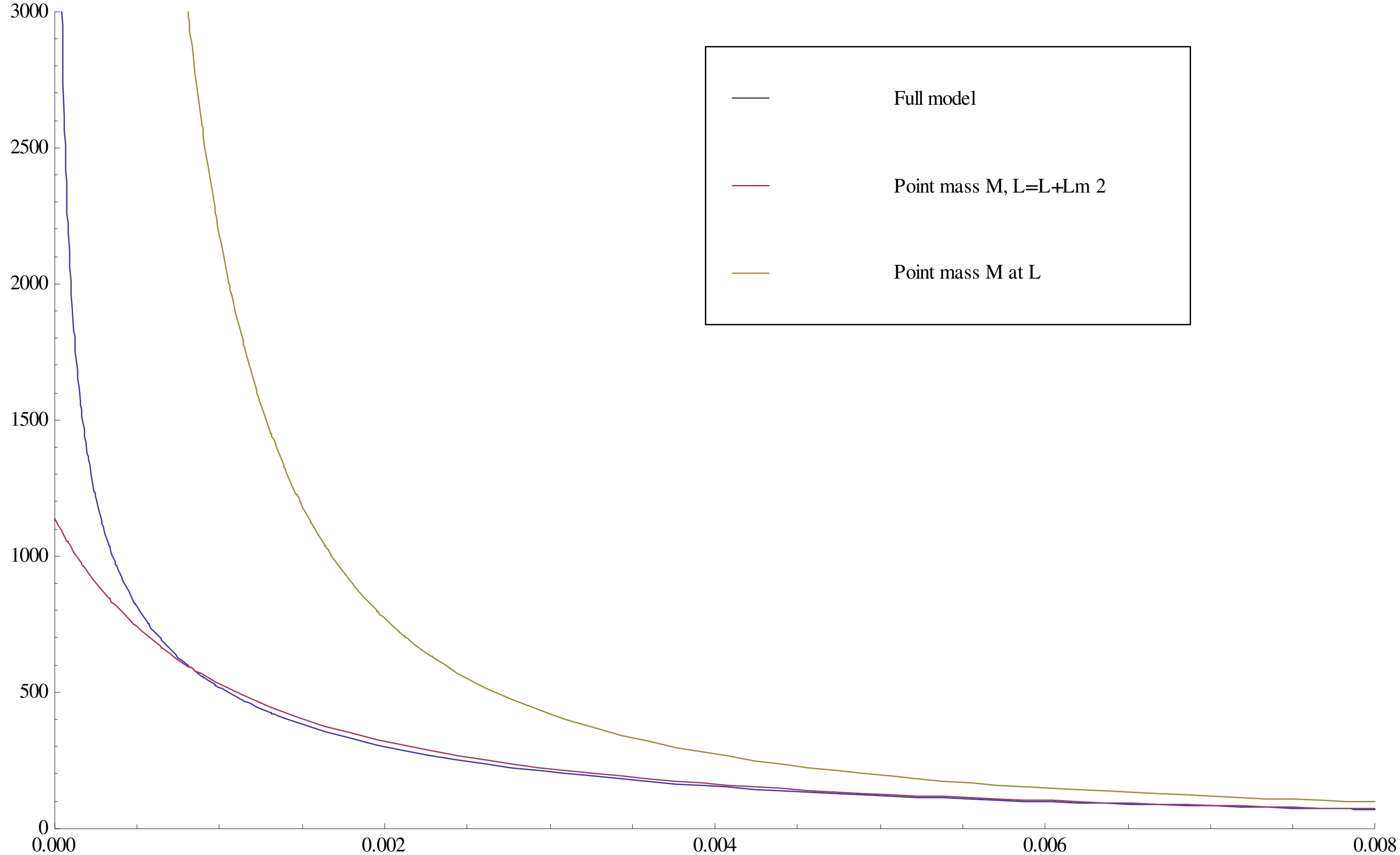
Too naive ☹



$$\omega_0 = \frac{1}{2}\sqrt{\frac{H^3WY}{\left(L+\frac{L_m}{2}\right)^3 M}}$$

Good approximation ☺

Modelling the resonance frequency



Resonance frequency

$$\omega_0 = \frac{1}{2}\sqrt{\frac{H^3WY}{\left(L+\frac{L_m}{2}\right)^3 M}}$$

$$= \sqrt{2}\sqrt{\frac{H^3Y}{L_m(2L+L_m)^3(H\rho_{\mathrm{PZT}}+h_m\rho_{\mathrm{Si}})}}$$

Does not depend on the width of the beam!