NiPS Laboratory
Noise in Physical Systems

UNIVERSITÀ DEGLI STUDI
DI PERUGIA

Kinetic Energy Harvesting

NiPS Summer School 2017

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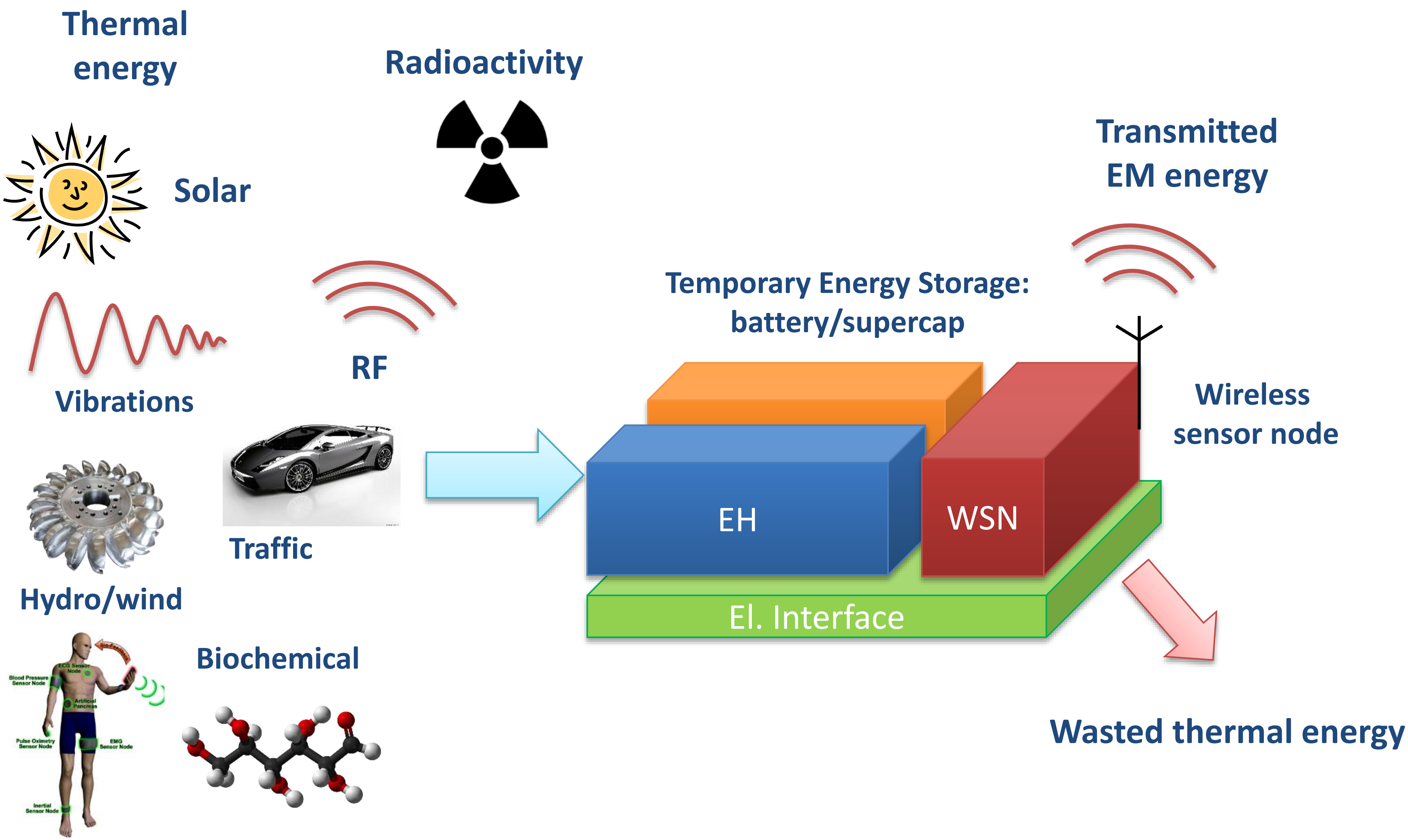
Outline

- Motivations of energy harvesting
- Introduction to Kinetic Energy Harvesting
- Theoretical model
- Macro to micro/nano Kinetic Energy Harvesting: scaling problems and examples
- Final considerations

What is an energy harvester ?



Power budget

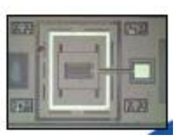
10 – 40W

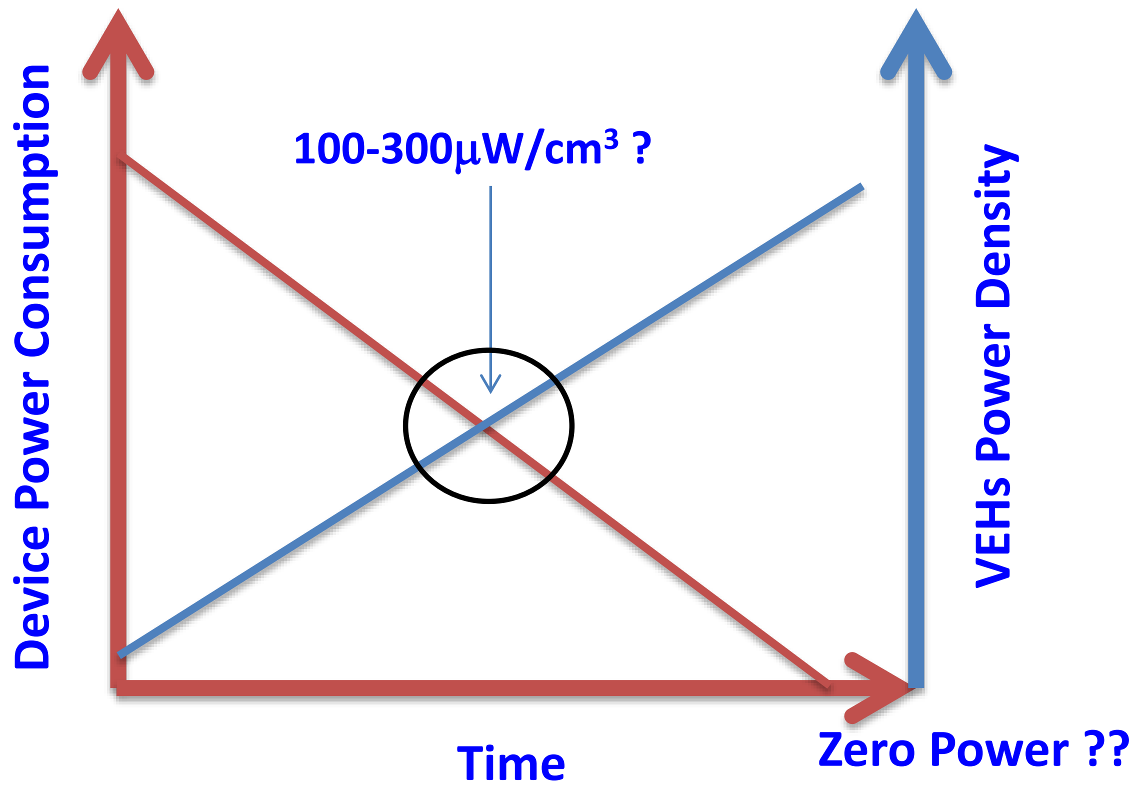
100 mW – 2 W

1 mW – 100 mW

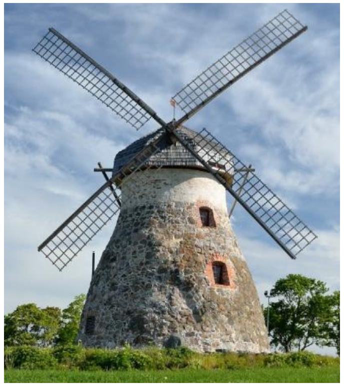
1 – 10 μW

< 10μW





Historical human-made energy harvesters



Wind mill (Origin: Persia, 3000 years BC)

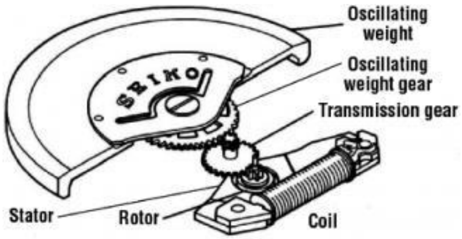
Sailing ship (XVI-XVII century)

Crystal radio - 1906

SELF-powered by Radio Frequencies !!!

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

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

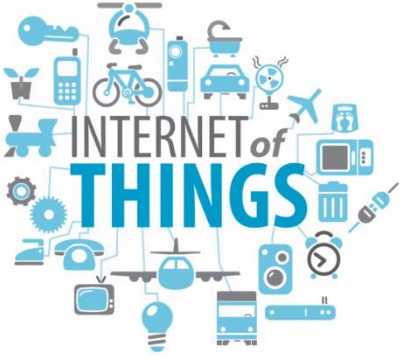


Self-charging Seiko wristwatch 1988

Energy havesting applications

Structural Monitoring

02/07/2014 - Belo Horizonte (Brazil)
(birdge collapse at FIAT factory)

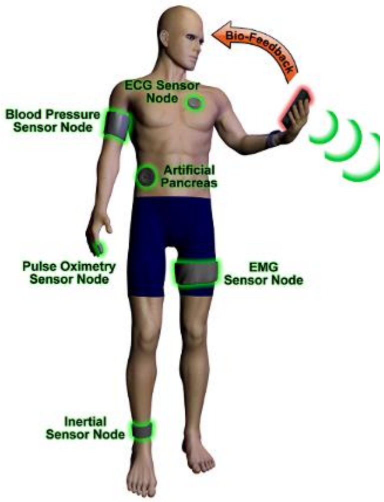


Environmental Monitoring

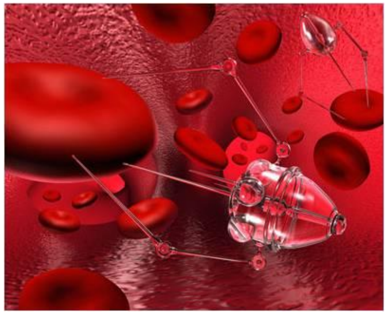
Military applications

Healthcare sensors

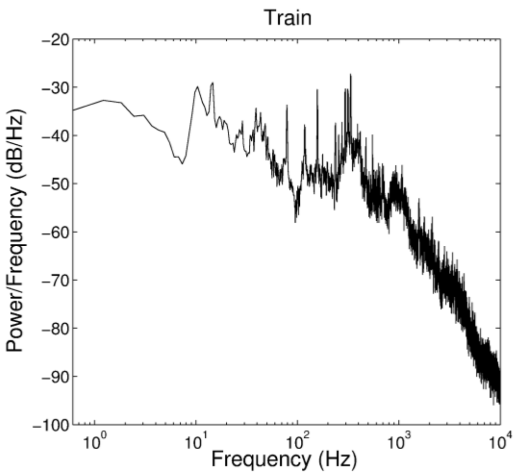
Emergency medical response
Monitoring, pacemaker, defibrillators

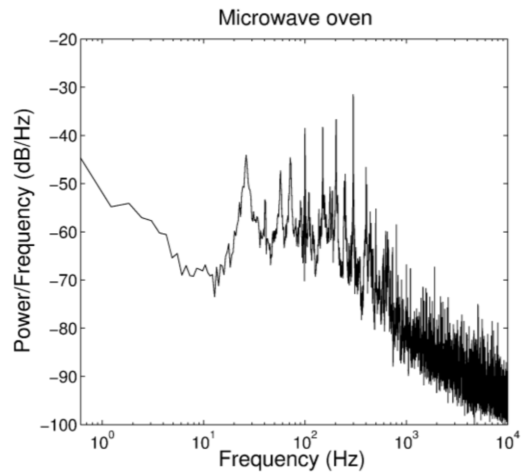


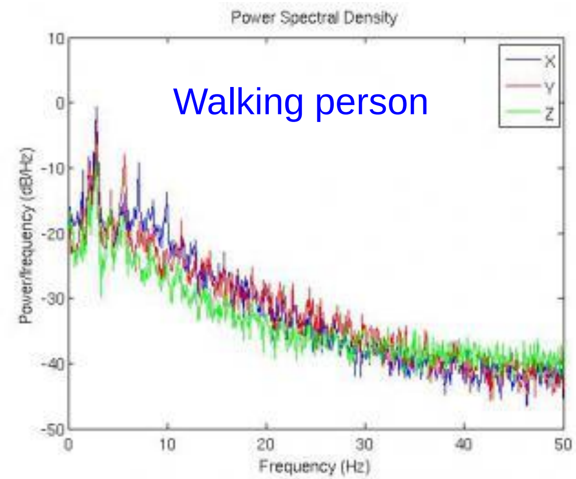
Nanomedicine

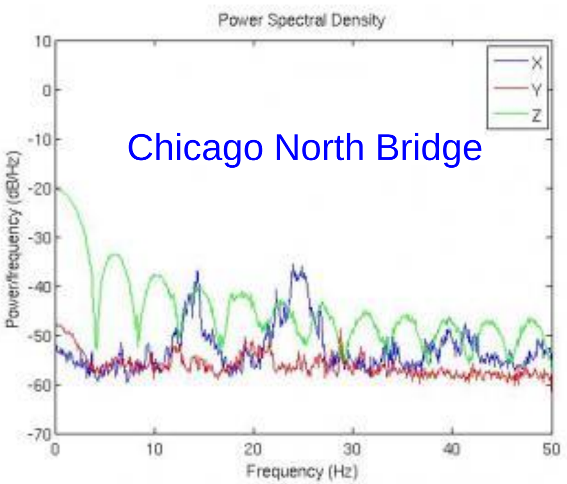


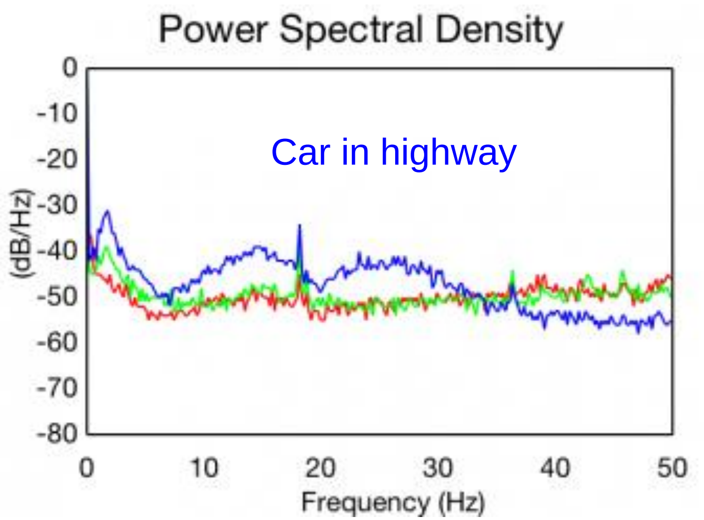
Vibration sources











http://realvibration.nipslab.org

Vibration sources

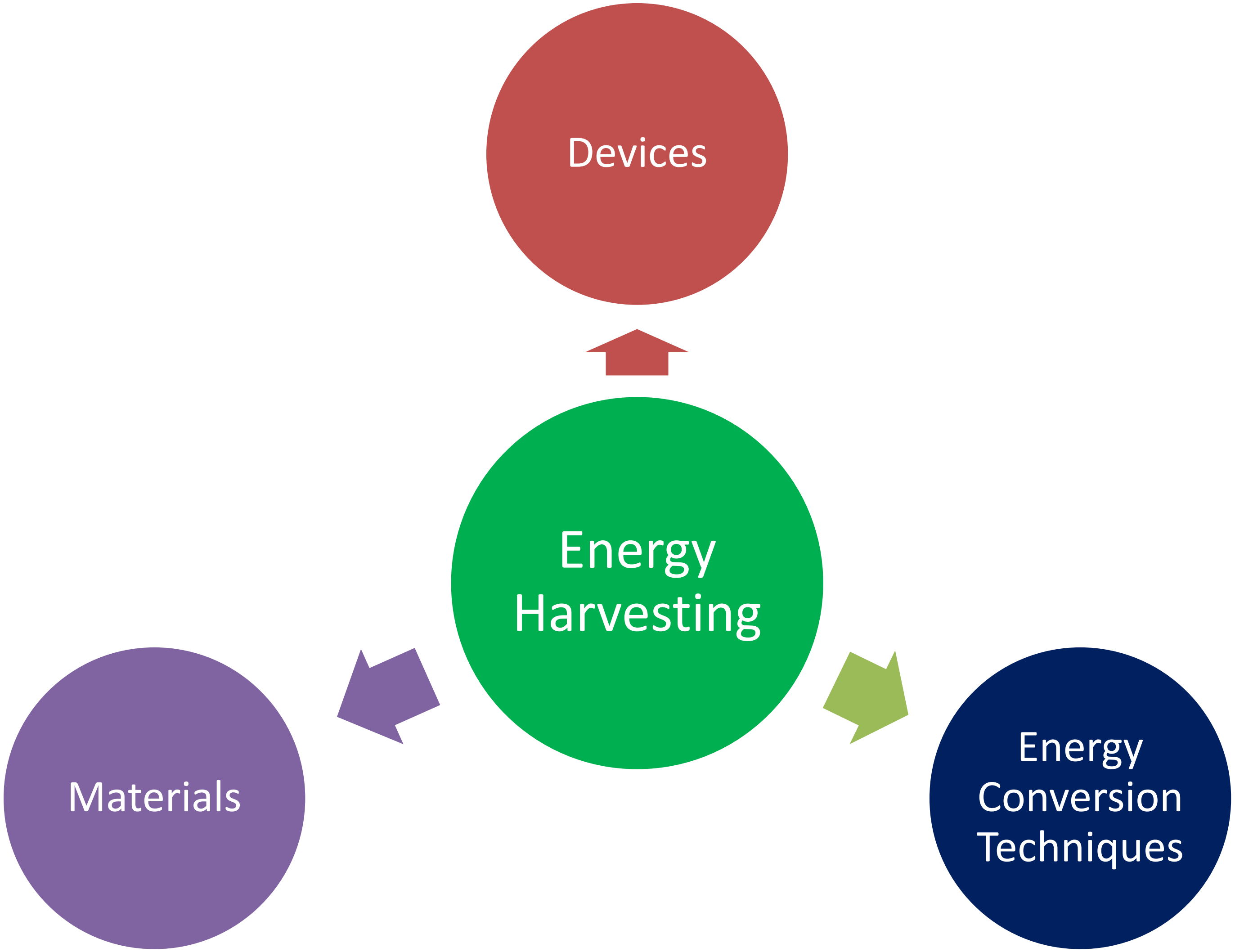
Energy Source	Characteristics	Efficiency	Harvested Power
Light	Outdoor Indoor	10~24%	100 mW/cm^2 100 µW/cm^2
Thermal	Human Industrial	~0.1% ~3%	60 µW/cm^2 ~1-10 mW/cm^2
Vibration	~Hz–human ~kHz–machines	25~50%	~4 µW/cm^3 ~800 µW/cm^3
RF	GSM 900 MHz WiFi	~50%	0.1 µW/cm^2 0.001 µW/cm^2

Source: White Paper - Texas Instruments 2005

An average human walking up a mountain expends around 200 Watts of power.

The most amount of power your iPhone accepts when charging is 2.5 Watts.

Vibration Energy Harvesting: research

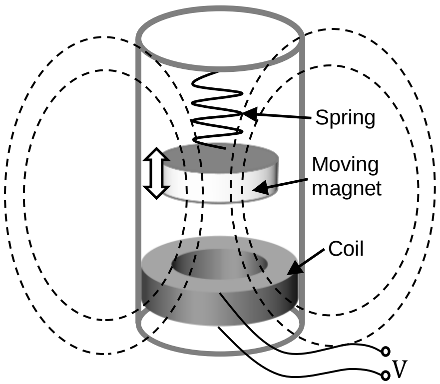


Vibration Energy Harvesting: scale

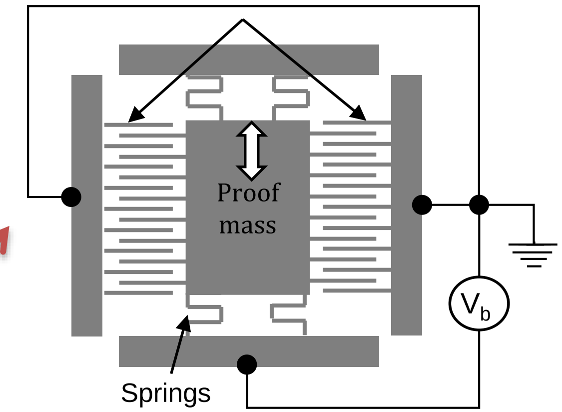
- **Macro**
  - Magnetic energy harvesters
  - Piezoelectric devices
  - Vibrational Structures with Magnetic Shape Memory Alloy (NiMnGa)
- **Micro**
  - Electrostatic Generators
  - Piezo Micro beams of stripes ZnO, BaTiO3
  - Electrets SiO2, Parylene, Teflon base
- **Nano**
  - Piezoelectric nanopillars, nanoribbons etc.
  - Triboelectric generators
  - Electrets nano-spheres

Vibration energy harvesting

Electromagnetic

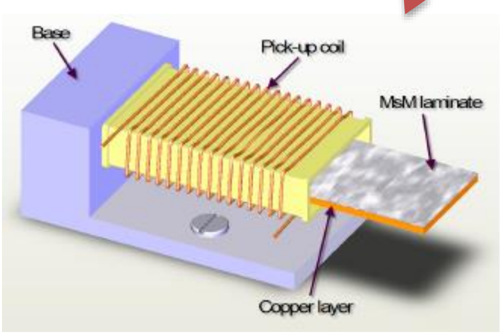


Electrostatic/Capacitive

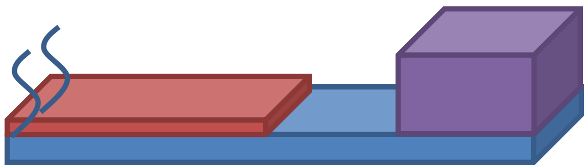


Kinetic to electricity conversion techniques

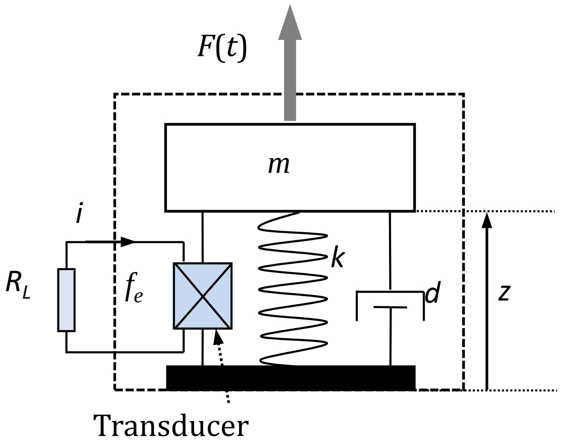
Magnetostrictive

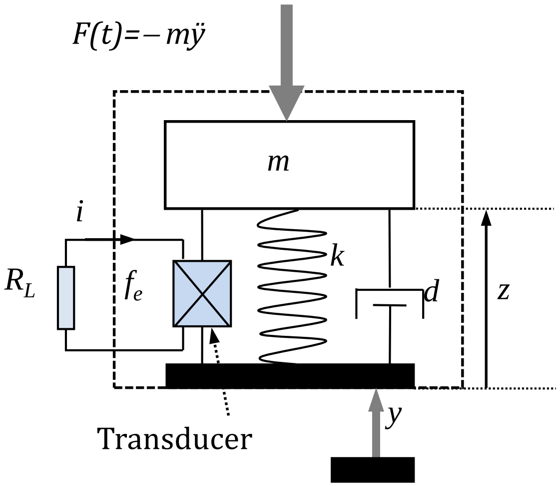


Piezoelectric



Dynamical model of VEH





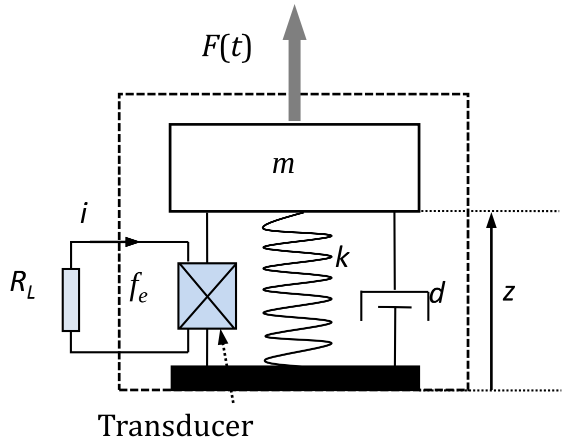
Inertial generators requires only one point of attachment to a moving structure, allowing a greater degree of miniaturization.

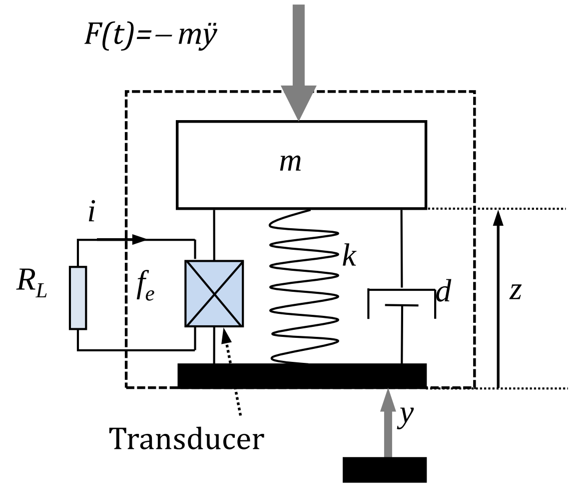
At micro/nano scale direct force generators are much more efficient because not limited by the inertial mass!!!

$$\begin{cases} m\ddot{z} + d\dot{z} + \dfrac{dU(z)}{dz} + \alpha V_L = F(t) \\ \dot{V}_L + (\omega_c + \omega_i)V_L = \lambda \omega_c \dot{z} \end{cases}$$

$$\begin{cases} m\ddot{z} + d\dot{z} + \dfrac{dU(z)}{dz} + \alpha V_L = -m\ddot{y} \\ \dot{V}_L + (\omega_c + \omega_i)V_L = \lambda \omega_c \dot{z} \end{cases}$$

Dynamical model of VEH





Inertial generators requires only one point of attachment to a moving structure, allowing a greater degree of miniaturization.

Power fluxes

$$\boxed{m\ddot{z}\dot{z} + d\dot{z}^2 + \frac{dU(z)}{dz}\dot{z} + \alpha V_L \dot{z} = F(t)\dot{z}}$$

$$P_m(t) = F(t)\cdot\dot{z}(t)$$

$$P_m(t) = -m\ddot{y}\cdot\dot{z} = -\rho l^3 \cdot \dot{z}$$

Dynamical model of VEH

$$\begin{cases} m\ddot{z} + d\dot{z} + \dfrac{dU(z)}{dz} + \alpha V_L = -m\ddot{y} \\ \dot{V}_L + (\omega_c + \omega_i)V_L = \lambda\omega_c \dot{z} \end{cases}$$

$\Rightarrow$ $\alpha, \lambda, \omega_c, \omega_i$ Parameters that depends only on the transduction technique!

For LINEAR mechanical oscillators with elastic potential well $\Rightarrow$

$$\begin{cases} m\ddot{z} + d\dot{z} + kz + \alpha V_L = -m\ddot{y} \\ \dot{V}_L + (\omega_c + \omega_i)V_L = \lambda\omega_c \dot{z} \end{cases}$$

Laplace transform

$$\ddot{y} = Y_0 e^{j\omega t} \Rightarrow \begin{pmatrix} ms^2 + ds + k & \alpha \\ -\lambda\omega_c s & s + \omega_c \end{pmatrix} \begin{pmatrix} Z \\ V \end{pmatrix} = \begin{pmatrix} -mY \\ 0 \end{pmatrix}$$

$\Rightarrow$

$$Z = \frac{-mY}{\det A}(s+\omega_c) = \frac{-mY \cdot (s+\omega_c)}{ms^3 + (m\omega_c + d)s^2 + (k + \alpha\lambda\omega_c + d\omega_c)s + k\omega_c},$$

$$V = \frac{-mY}{\det A}\lambda\omega_c s = \frac{-mY \cdot \lambda\omega_c s}{ms^3 + (m\omega_c + d)s^2 + (k + \alpha\lambda\omega_c + d\omega_c)s + k\omega_c}.$$

Dynamical model of VEH

For LINEAR mechanical oscillators

$$\begin{cases} m\ddot{z} + d\dot{z} + kz + \alpha V_L = -m\ddot{y} \\ \dot{V}_L + (\omega_c + \omega_i)V_L = \lambda\omega_c\dot{z} \end{cases}$$

By substituting s=jω in , we can calculate the electrical **power dissipated across the resistive load**

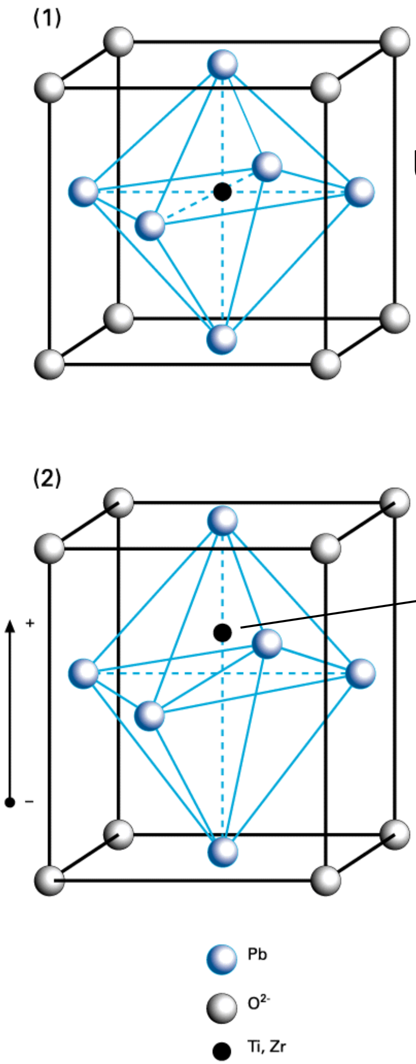
$$P_e(\omega) = \frac{|V|^2}{R_L} = \frac{Y_0^2}{2R_L}\left|\frac{m\lambda\omega_c j\omega}{(\omega_c + j\omega)(-m\omega^2 + dj\omega + k) + \alpha\lambda\omega_c j\omega}\right|^2$$

In the approximate version, at resonance $\omega=\omega_n$, (William et al.)

$$P_e = \frac{m\zeta_e\omega_n^3 Y_0^2}{4(\zeta_e + \zeta_m)^2} = \frac{m^2 d_e \omega_n^4 Y^2}{2(d_e + d_m)^2}$$

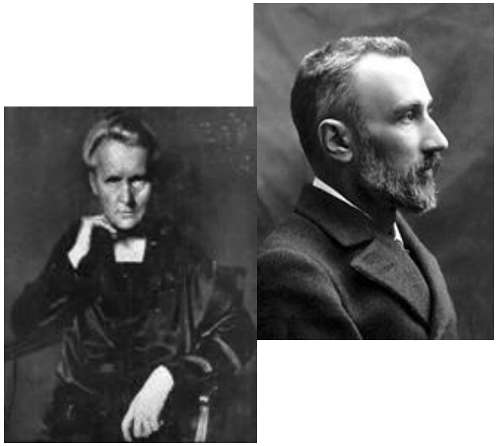
Where ω_c, λ and α are included in the electrical damping **factor d_e**

Piezoelectric conversion



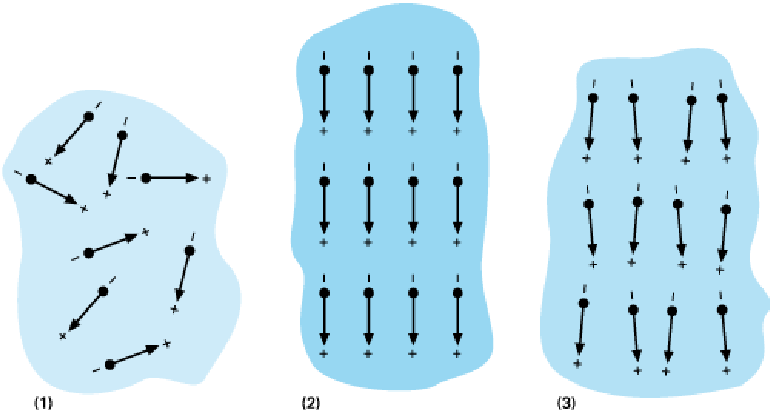
Unpolarized Crystal

Polarized Crystal



Pioneering work on the direct piezoelectric effect (stress-charge) in this material was presented by Jacques and Pierre Curie in 1880

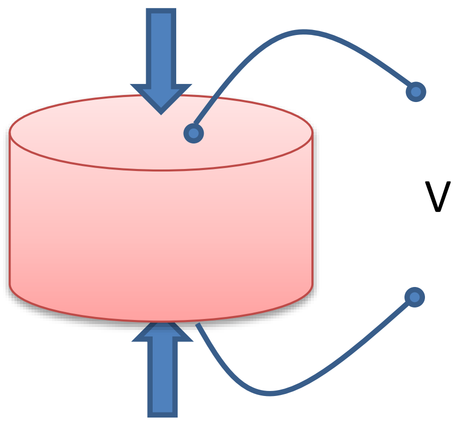
In 1903 Pierre received the Nobel Prize in Physics with his wife, Marie Skłodowska-Curieand and Henri Becquerel, for the research on the radiation phenomena discovered by Professor Henri Becquerel.



After poling the zirconate-titanate atoms are off center. The molecule becomes elongated and polarized

Piezoelectric conversion

Stress-to-charge conversion



direct piezoelectric effect

Biological

- Bones
- DNA !!!

Naturally-occurring crystals

- Berlinite ($AlPO_4$), a rare phosphate mineral that is structurally identical to quartz
- Cane sugar
- Quartz (SiO_2)
- Rochelle salt

Man-made ceramics

- Barium titanate ($BaTiO_3$)—Barium titanate was the first piezoelectric ceramic discovered.
- Lead titanate ($PbTiO_3$)
- Lead zirconate titanate ($Pb[Zr_xTi_{1-x}]O_3$ $0 \le x \le 1$)—more commonly known as ***PZT***, lead zirconate titanate is the most common piezoelectric ceramic in use today.
- Lithium niobate ($LiNbO_3$)

Polymers

- Polyvinylidene fluoride (PVDF): exhibits piezoelectricity several times greater than quartz. Unlike ceramics, long-chain molecules attract and repel each other when an electric field is applied.

Piezoelectric conversion

$$S = [s_E]T + [d^t]E$$
$$D = [d]T + [\varepsilon_T]E$$

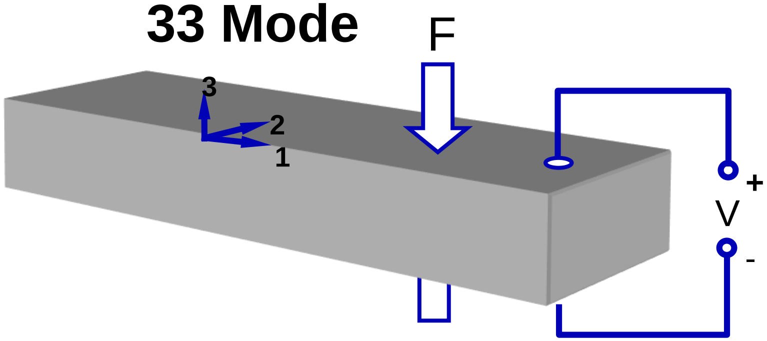
Strain-charge

$$T = [c^E]S - [e^t]E$$
$$D = [e]S + [\varepsilon^S]E$$

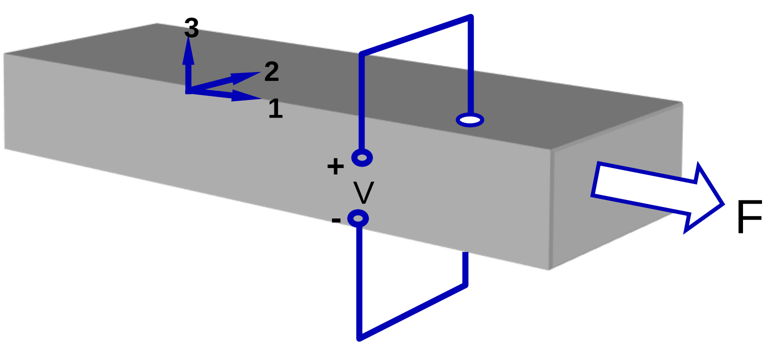
Stress-charge

- S = strain vector (6x1) in Voigt notation
- T = stress vector (6x1) [N/m^2]
- s_E = compliance matrix (6x6) [m^2/N]
- c^E = stifness matrix (6x6) [N/m^2]
- d = piezoelectric coupling matrix (3x6) in Strain-Charge [C/N]
- D = electrical displacement (3x1) [C/m^2]
- e = piezoelectric coupling matrix (3x6) in Stress-Charge [C/m^2]
- ε = electric permittivity (3x3) [F/m]
- E = electric field vector (3x1) [N/C] or [V/m]

33 Mode



31 Mode



Piezoelectric conversion

converse piezoelectric effect

$$\begin{bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{bmatrix} = \begin{bmatrix} s_{11}^E & s_{12}^E & s_{13}^E & 0 & 0 & 0 \\ s_{21}^E & s_{22}^E & s_{23}^E & 0 & 0 & 0 \\ s_{31}^E & s_{32}^E & s_{33}^E & 0 & 0 & 0 \\ 0 & 0 & 0 & s_{44}^E & 0 & 0 \\ 0 & 0 & 0 & 0 & s_{55}^E & 0 \\ 0 & 0 & 0 & 0 & 0 & s_{66}^E = 2\left(s_{11}^E - s_{12}^E\right) \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{32} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

direct piezoelectric effect

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} + \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix}$$

Depending on the independent variable choice 4 piezoelectric coefficients are defined:

$$d_{ij} = \left(\frac{\partial D_i}{\partial T_j}\right)^E = \left(\frac{\partial S_j}{\partial E_i}\right)^T$$

$$e_{ij} = \left(\frac{\partial D_i}{\partial S_j}\right)^E = -\left(\frac{\partial T_j}{\partial E_i}\right)^S$$

$$g_{ij} = -\left(\frac{\partial E_i}{\partial T_j}\right)^D = \left(\frac{\partial S_j}{\partial D_i}\right)^T$$

$$h_{ij} = -\left(\frac{\partial E_i}{\partial S_j}\right)^D = -\left(\frac{\partial T_j}{\partial D_i}\right)^S$$

Voigt notation is used to represent a symmetric tensor by reducing its order.
Due to the symmetry of the stress tensor, strain tensor, and stiffness tensor, only 21 elastic coefficients are independent. *S* and *T* appear to have the "vector form" of 6 components. Consequently, *s* appears to be a 6 by 6 matrix instead of rank-4 tensor.

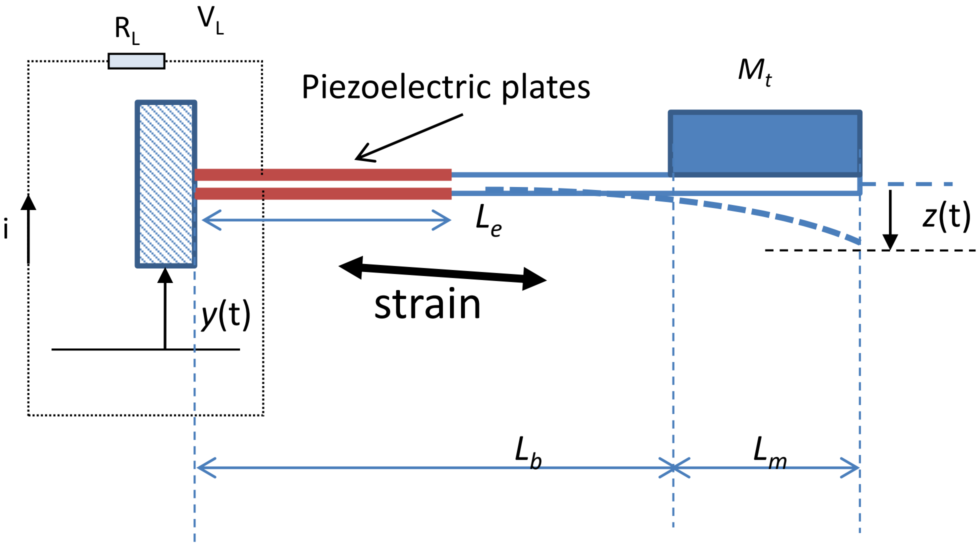
Piezoelectric conversion

Characteristic	PZT-5H	BaTiO3	PVDF	AlN (thin film)
d_{33} (10^{-10} C/N)	593	149	-33	5,1
d_{31} (10^{-10} C/N)	-274	78	23	-3,41
k_{33}	0,75	0,48	0,15	0,3
k_{31}	0,39	0,21	0,12	0,23
ε_r	3400	1700	12	10,5

$$k_{31}^2 = \frac{El.energy}{Mech.energy} = \frac{d_{31}^2}{s_{11}^E \varepsilon_{33}^T}$$

Electromechanical Coupling is an adimensional factor that provides the effectiveness of a piezoelectric material. It is defined as the ratio between the mechanical energy converted and the electric energy input or the electric energy converted per mechanical energy input

Piezoelectric conversion

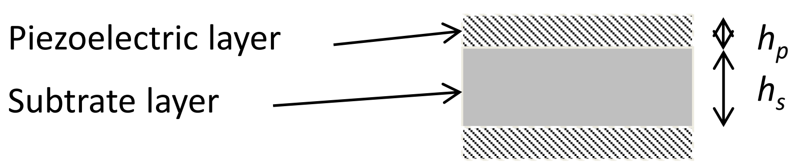


Governing equations

$$\begin{cases} m\ddot{z} + d\dot{z} + kz + \alpha V_L = -m\ddot{y} \\ \dot{V}_L + (\omega_c + \omega_i)V_L = \lambda\omega_c \dot{z} \end{cases}$$

$$\alpha = kd_{31} / h_p k_2, \qquad \lambda = \alpha R_L,$$

$$\omega_c = 1/R_L C_p, \qquad \omega_i = 1/R_i C_p,$$



Ep and *Es* are the Young's modulus of piezo layer and steel substrate respectively

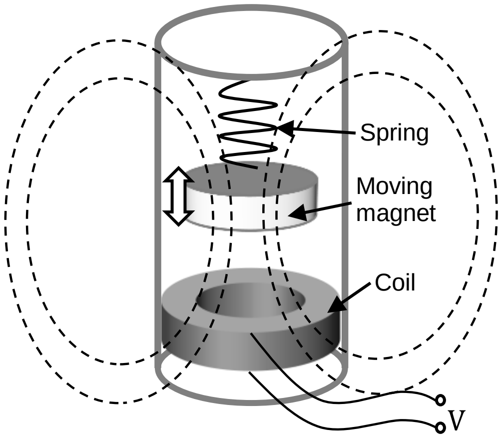
$$k = k_1 k_2 E_p,$$

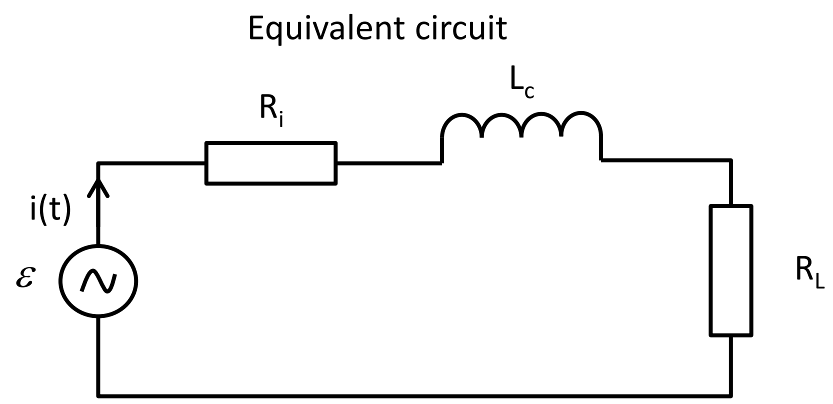
$$k_1 = \frac{2I}{b(2l_b + l_m - l_e)}, \qquad k_2 = \frac{3b(2l_b + l_m - l_e)}{l_b^2\left(2l_b + \frac{3}{2}l_m\right)},$$

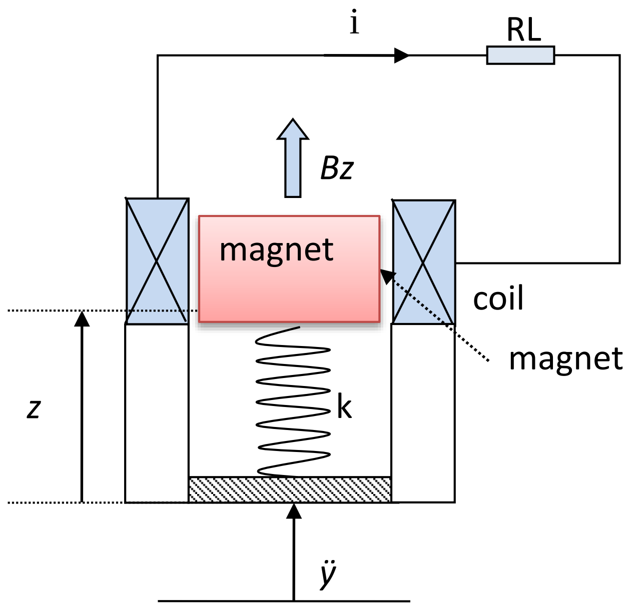
$$b = \frac{h_s + h_p}{2}, \qquad I = 2\left[\frac{w_b h_p^3}{12} + w_b h_p b^2\right] + \frac{E_s / E_p w_b h_s^3}{12},$$

Inertia area moment of the beam

Electromagnetic conversion





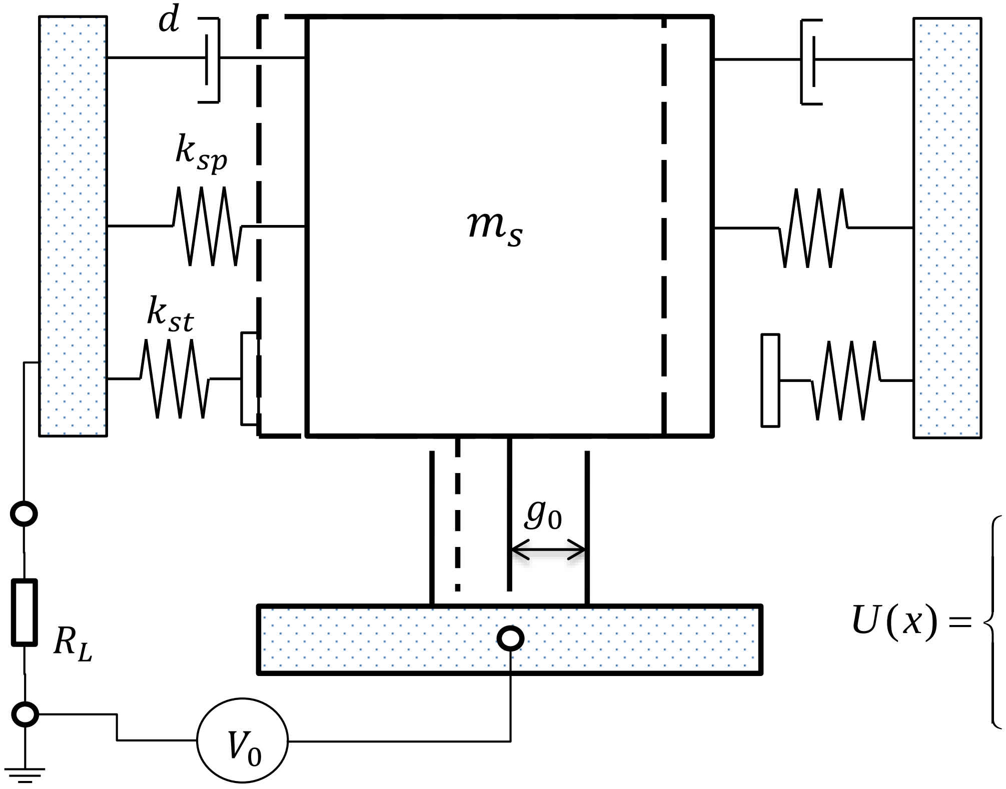


Governing equations

$$\begin{cases} m\ddot{z} + d\dot{z} + kz + \alpha V_L = -m\ddot{y} \\ \dot{V}_L + (\omega_c + \omega_i) V_L = \lambda \omega_c \dot{z} \end{cases}$$

$$\alpha = Bl / R_L, \qquad \lambda = Bl = \alpha R_L,$$
$$\omega_c = R_L / L_c, \qquad \omega_i = R_i / L_c,$$

Electrostatic conversion



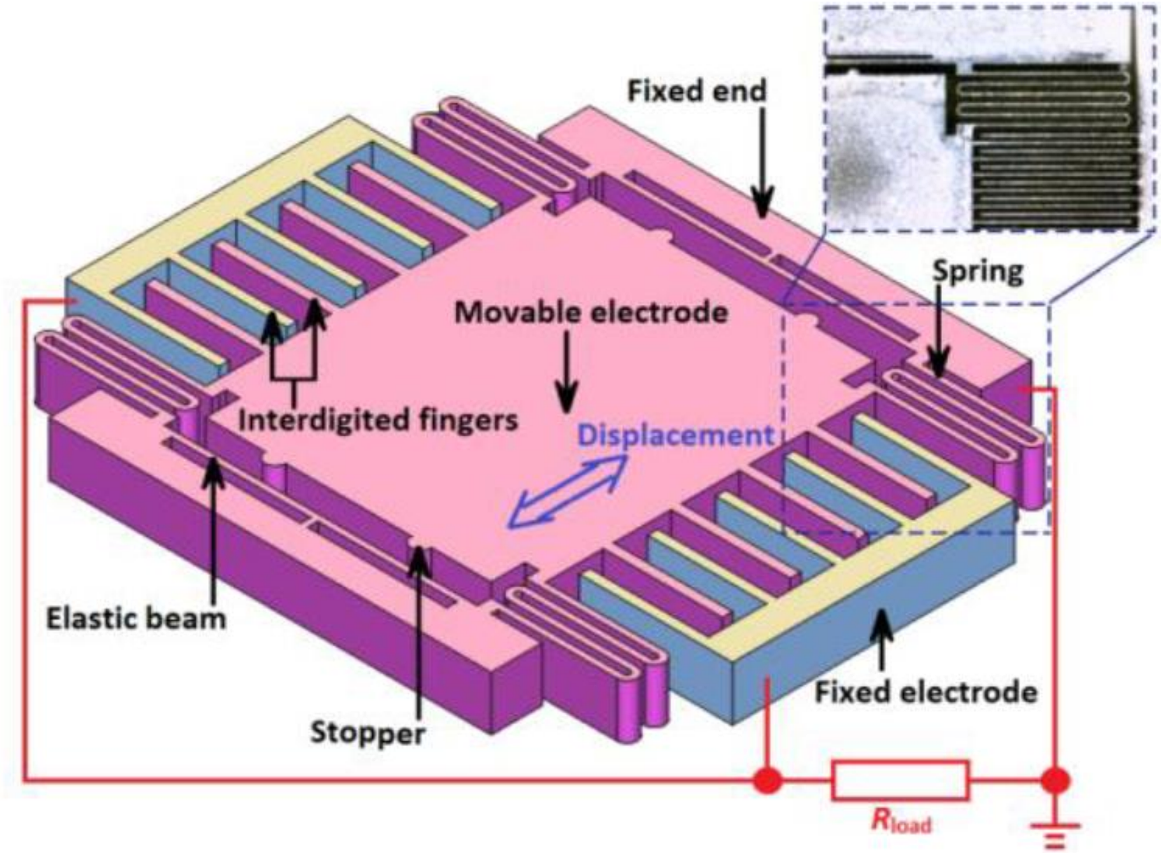
Governing equations

$$m\frac{d^2x}{dt^2}+(c_a+c_i)\frac{dx}{dt}+\frac{dU(x)}{dx}=-m\frac{d^2y}{dt^2},$$

$$R_L\frac{d}{dt}(C\cdot V)+V=U_0,$$

$$U(x)=\begin{cases}\frac{1}{2}k_{sp}x^2-\frac{1}{2}C(x)U_0^2, & \text{for } |x|<x_{\lim}\\ \frac{1}{2}(k_{sp}+k_{st})x^2-\frac{1}{2}C(x)U_0^2, & \text{for } |x|\geq x_{\lim}\end{cases}$$

Electrostatic conversion



Y. Lu, F. Cottone, S. Boisseau, F. Marty, D. Galayko, and P. Basset, *Applied Physics Letters* 2015.

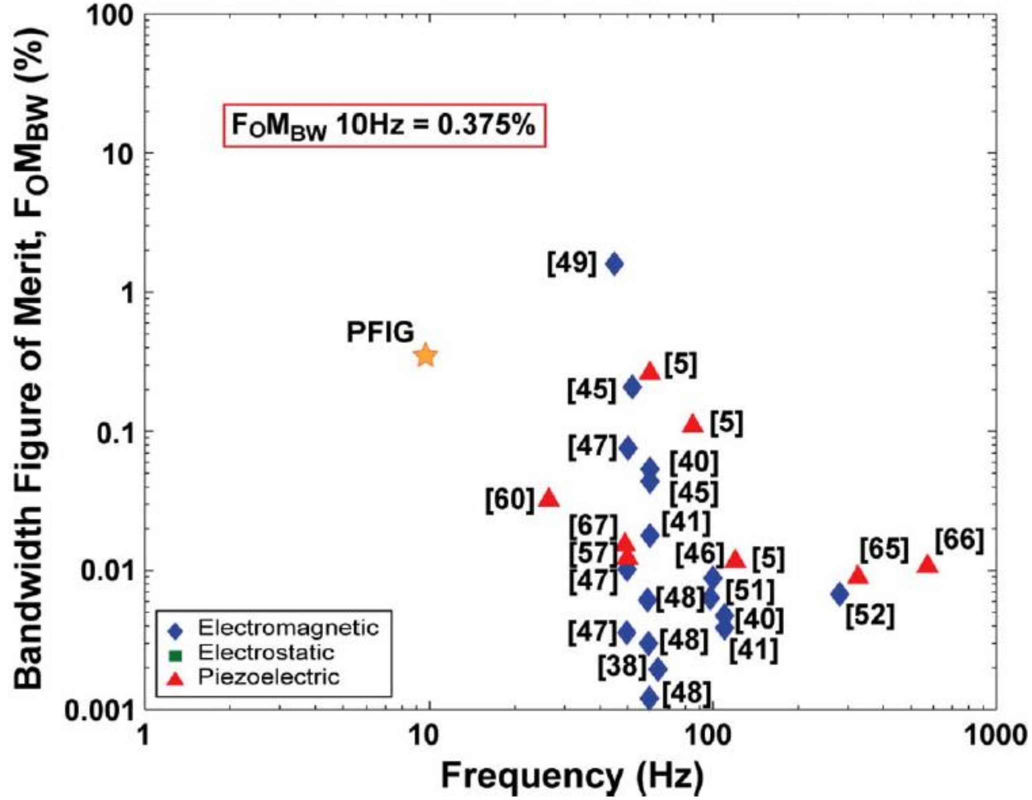
Figure of merit

$$\mathrm{FoM_V} = \frac{\text{Useful Power Output}}{\frac{1}{16} Y_0 \rho_{Au} Vol^{\frac{4}{3}} \omega^3}$$

Bandwidth figure of merit

$$\mathrm{FoM_{BW}} = \mathrm{FoM_V} \times \frac{\delta\omega_{1\ \mathrm{dB}}}{\omega}$$

Frequency range within which the output power is less than 1 dB below its maximum value



Galchev et al. (2011)

Mitcheson, P. D., E. M. Yeatman, et al. (2008).

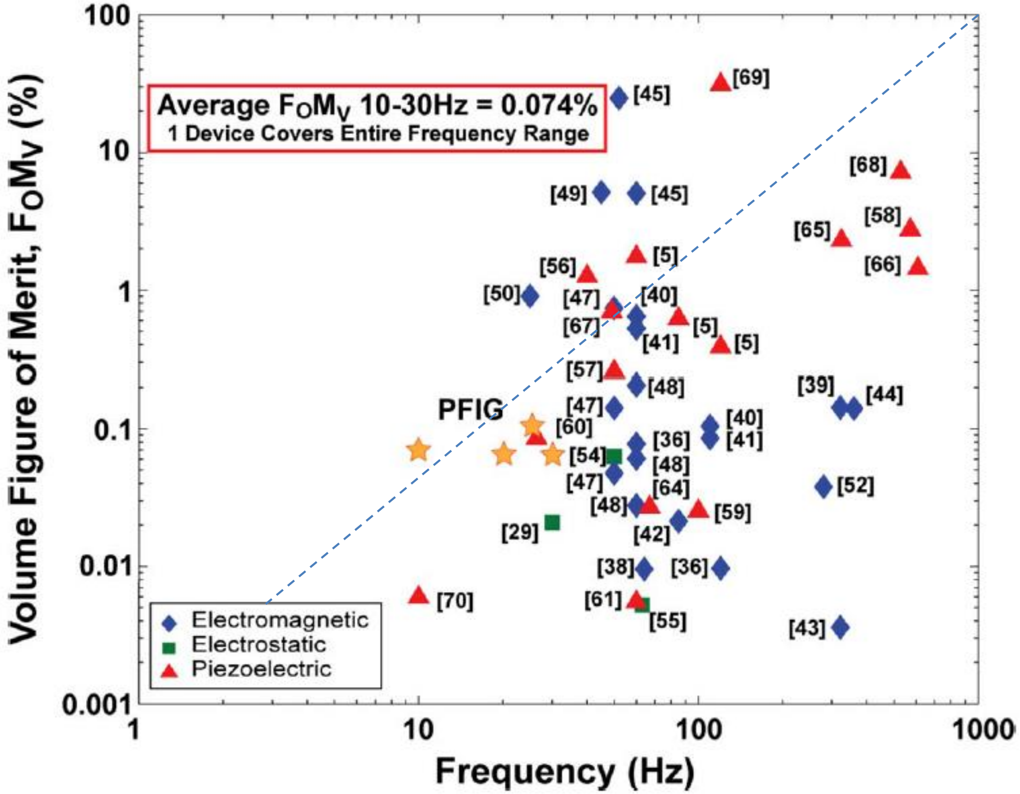
Figure of merit

$$\mathrm{FoM_V} = \frac{\text{Useful Power Output}}{\frac{1}{16} Y_0 \rho_{Au} Vol^{\frac{4}{3}} \omega^3}$$

Bandwidth figure of merit

$$\mathrm{FoM_{BW}} = \mathrm{FoM_V} \times \frac{\delta\omega_{1\ \mathrm{dB}}}{\omega}$$

Frequency range within which the output power is less than 1 dB
below its maximum value



Galchev et al. (2011)

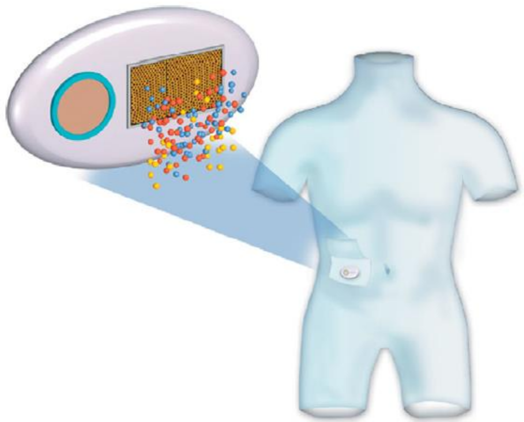
Mitcheson, P. D., E. M. Yeatman, et al. (2008).

Comparison of conversion techniques

Technique	Advantages	Drawbacks
Piezoelectric	• high output voltages • well adapted for miniaturization • high coupling in single crystal • no external voltage source needed	• expensive • small coupling for piezoelectric thin films • large load optimal impedance required (MΩ) • Fatigue effect
Electrostatic	• suited for MEMS integration • good output voltage (2-10V) • possiblity of tuning electromechanical coupling • Long-lasting	• need of external bias voltage • relatively low power density at small scale
Electromagnetic	• good for low frequencies (5-100Hz) • no external voltage source needed • suitable to drive low impedances	• inefficient at MEMS scales: low magnetic field, micro-magnets manufacturing issues • large mass displacement required.

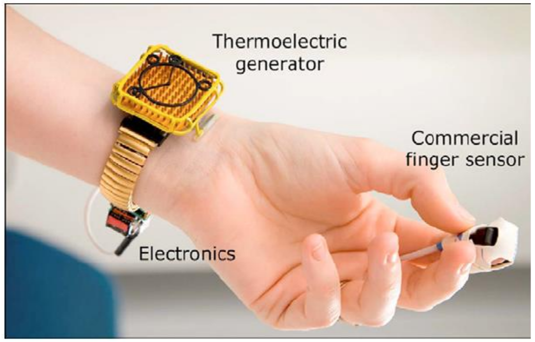
Microscale energy harvesters

MEMS-based drug delivery systems



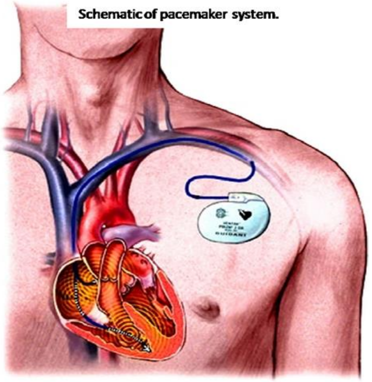
Bohm S. et al. 2000

Body-powered oximeter



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

Heart powered pacemaker



D. Tran, Stanford Univ. 2007

Pacemaker consumption is **40uW**.

Beating heart could produce **200uW** of power

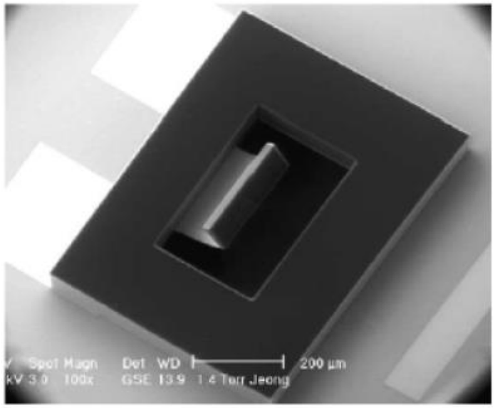
Micro-robot for remote monitoring

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

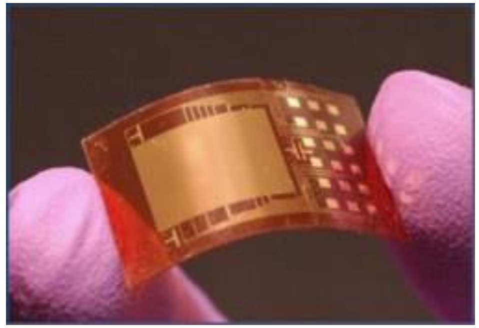
The input power a 20 mg robotic fly is **10 – 100 uW**

Microscale energy harvesters

Piezoelectric

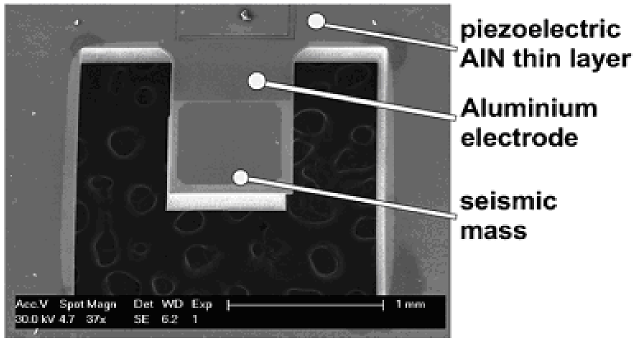


Jeon et al. 2005

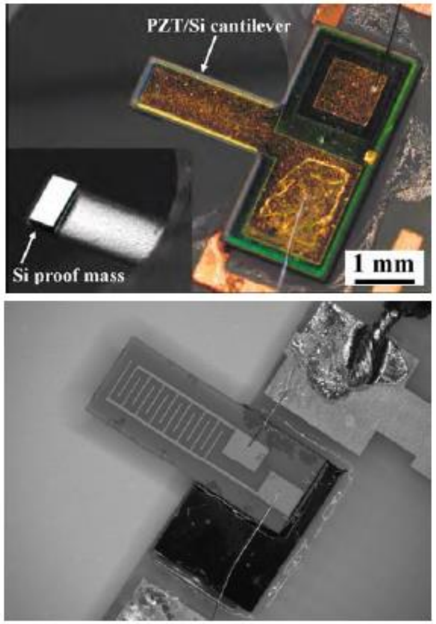


ZnO nanowires
Wang, Georgia Tech (2005)

Chang. MIT 2013



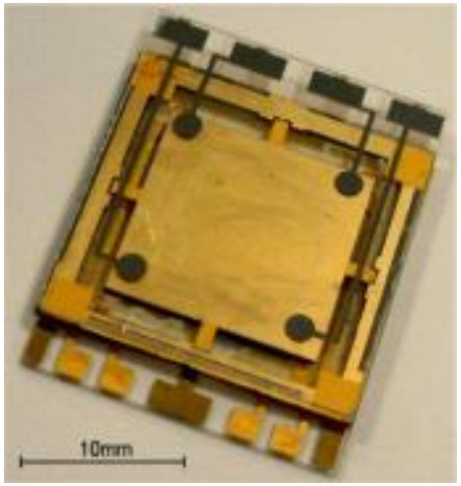
M. Marzencki 2008 – TIMA Lab (France)



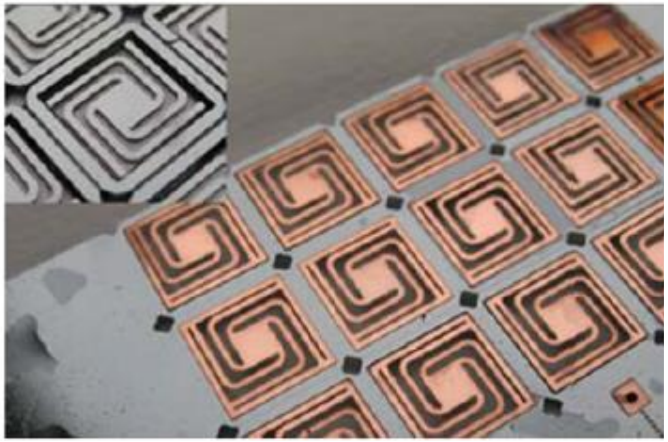
D. Briand, EPFL 2010

Microscale energy harvesters

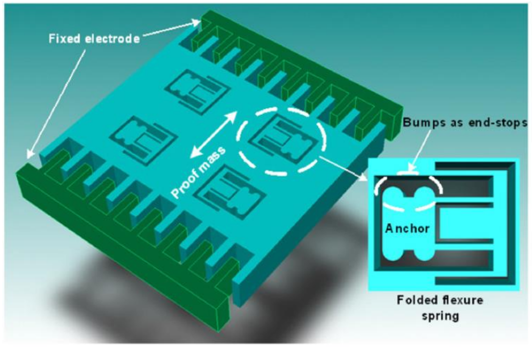
Electrostatic and electromagnetic



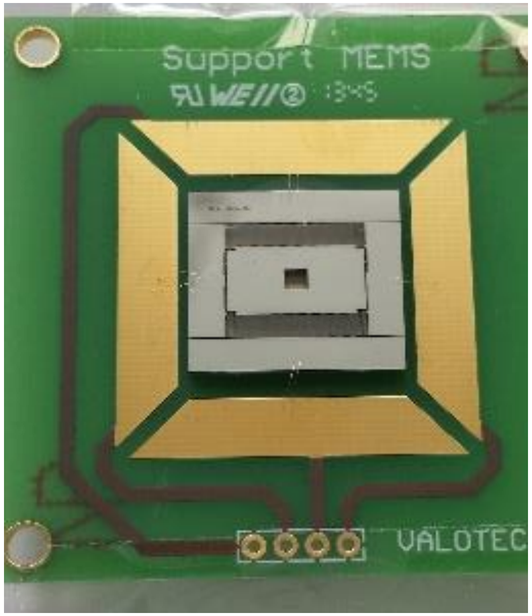
Mitcheson 2005 (UK)
Electrostatic generator 20Hz
2.5uW @ 1g



EM generator, Miao et al. 2006



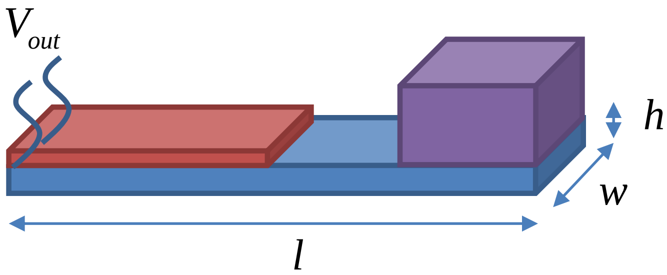
Le and Halvorsen, 2012



Cottone F., Basset P. ESIEE Paris 2013

Microscale energy harvesters: scaling issues

First order power calculus with William and Yates model



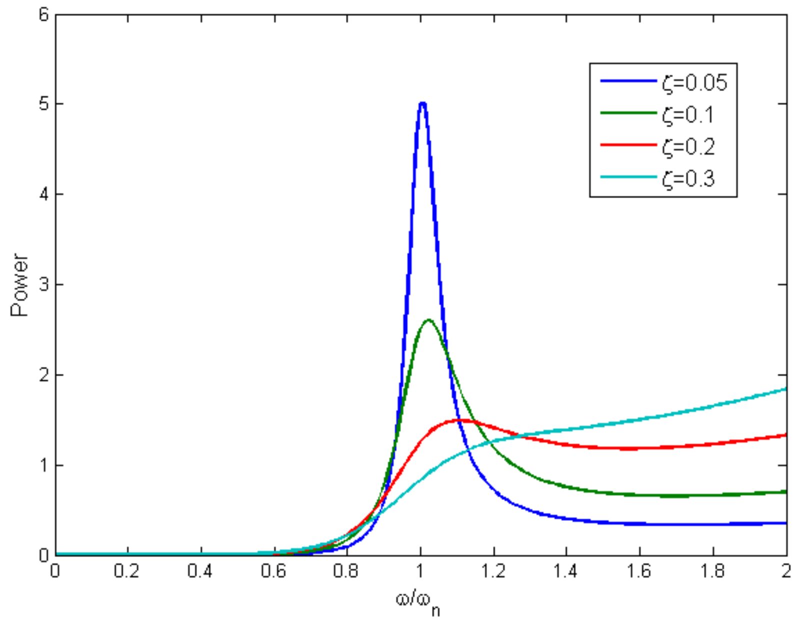
$$\omega_n = 2\pi C_n \sqrt{\frac{E}{\rho}} \frac{h}{l^2}$$

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

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

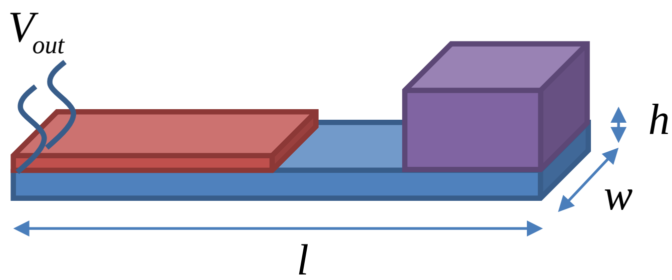
Boudary conditions	Uniform load ξ	Point load ξ
doubly clamped	32	16
cantilever	0,67	0,25

- 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



The instantaneous dissipated power by electrical damping is given by

$$P(t) = \frac{d}{dt}\int_0^x F(t)dx = \frac{1}{2}d_T\dot{x}^2$$

The velocity is obtained by the first derivative of steady state amplitude

$$\dot{X} = \frac{\omega r^2 Y_0}{\sqrt{(1-r^2)^2 + (2(\zeta_e + \zeta_m)r)^2}},$$

that is

$$\boxed{P_e = \frac{m\zeta_e\left(\frac{\omega}{\omega_n}\right)^3 \omega^3 Y_0^{\ 2}}{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2(\zeta_e+\zeta_m)\frac{\omega}{\omega_n}\right]^2}}$$

At resonance, that is $\omega=\omega_n$, the maximum power is given by

$$\boxed{P_e = \frac{m\zeta_e\omega_n^3 Y_0^{\ 2}}{4(\zeta_e+\zeta_m)^2} = \frac{m^2 d_e \omega_n^4 Y^2}{2(d_e+d_m)^2}}$$

or with acceleration amplitude $A_0=\omega_n^{\ 2}Y_0$.

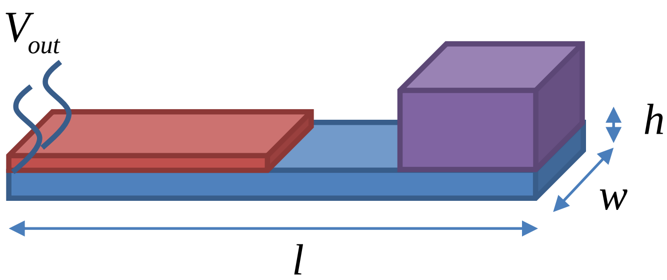
$$\boxed{P_{el} = \frac{m\zeta_e A^2}{4\omega_n(\zeta_m+\zeta_e)^2}}$$

for a particular transduction mechanism forced at natural frequency ω_n, the power can be maximized from the equation

Max power when the condition $\zeta_e=\zeta_m$ is verified

Microscale energy harvesters: scaling issues

First order power calculus with William and Yates model



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

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

$$m_{eff} = m_{beam} + 0.32 m_{tip} = lwh\rho_{si} + 0.32(l/4)^3 \rho_{si}$$

$$P_{el} = \frac{m\zeta_e A^2}{4\omega_n(\zeta_m + \zeta_e)^2} = \frac{\left(lwh\rho_{si} + 0.32(l/4)^3\rho_{mo}\right)}{8\omega_n\zeta_m}A^2 = \frac{\left(lwh\rho_{si} + 0.32(l/4)^3\rho_{mo}\right)}{16\pi C_n\sqrt{\frac{E}{\rho_{si}}}\frac{h}{l^2}\zeta_m}A^2$$

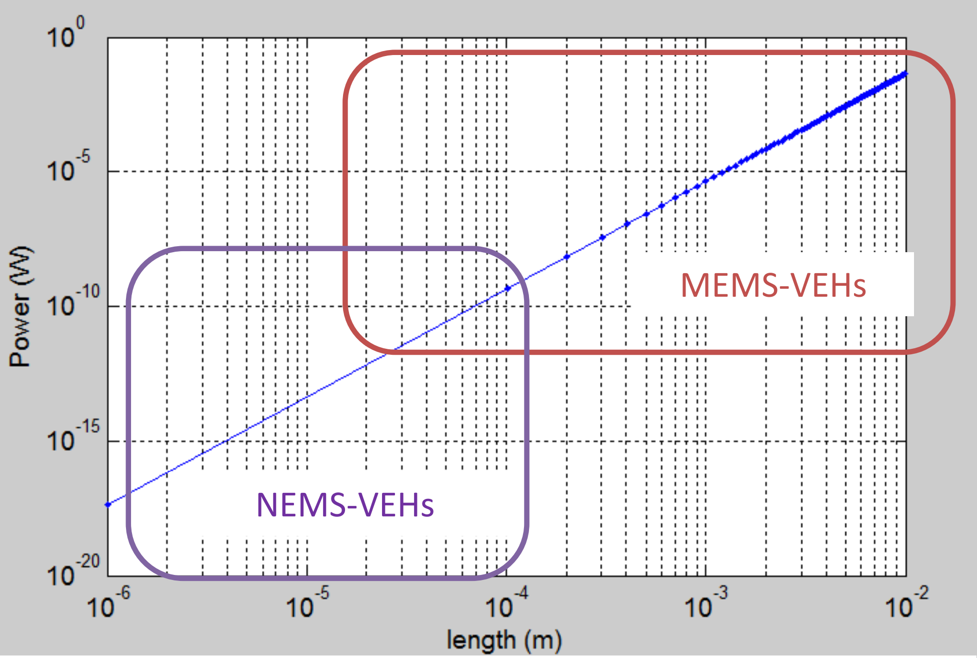
At max power condition $\zeta_e=\zeta_m$

By assuming

$$A = 1g$$
$$\zeta_m = 0.01$$
$$h = l/200$$
$$w = l/4$$

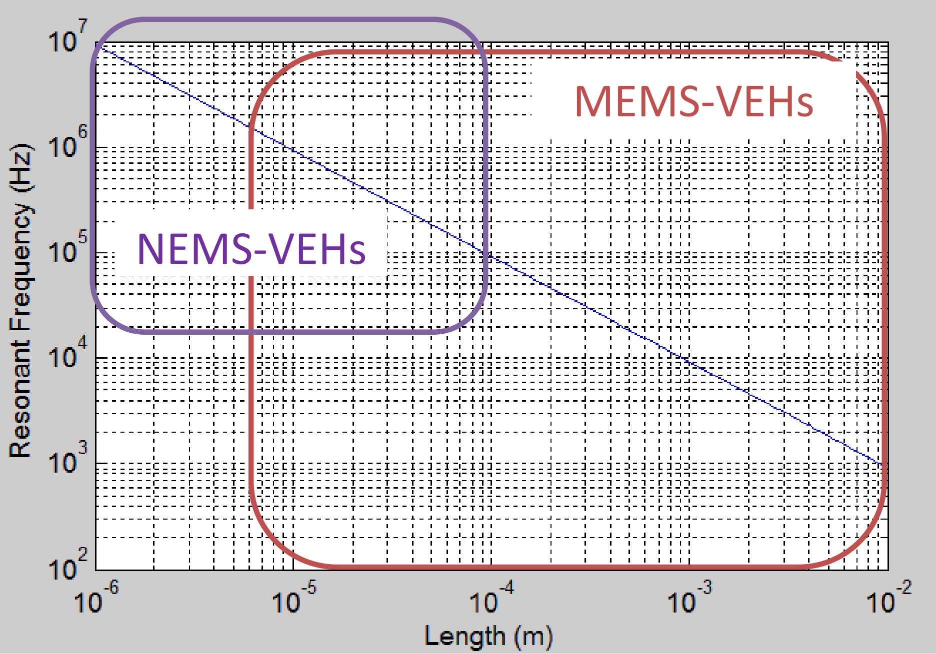
$$\boxed{P_{el} = \frac{\rho_{si}/800 + 0.32\cdot 64\rho_{mo}}{\frac{16}{200}\pi C_n\sqrt{\frac{E}{\rho_{si}}}\zeta_m}A^2 l^4}$$

Microscale energy harvesters: scaling issues

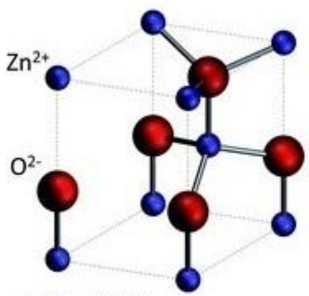


By assuming

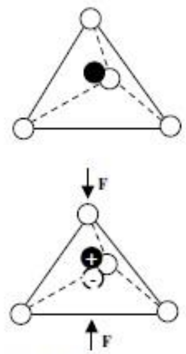
$$A = 1g$$
$$\zeta_m = 0.01$$
$$h = l / 200$$
$$w = l / 4$$



Piezoelectric micro-pillars

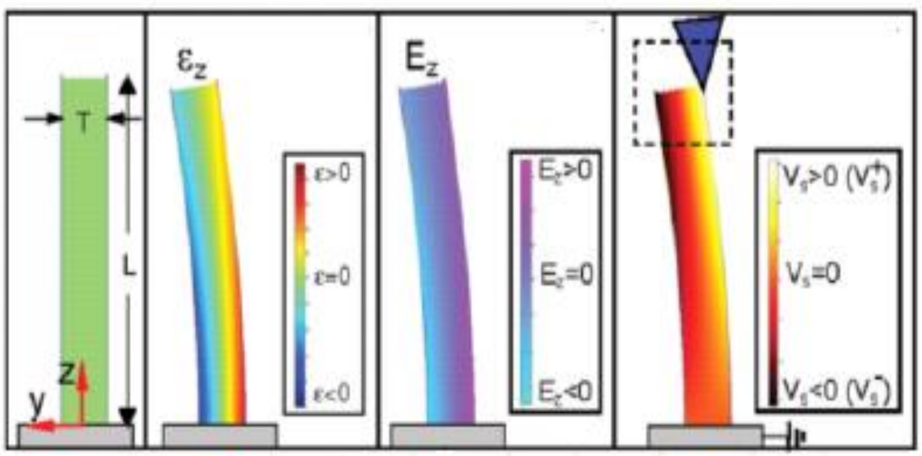


Taghavi 2013



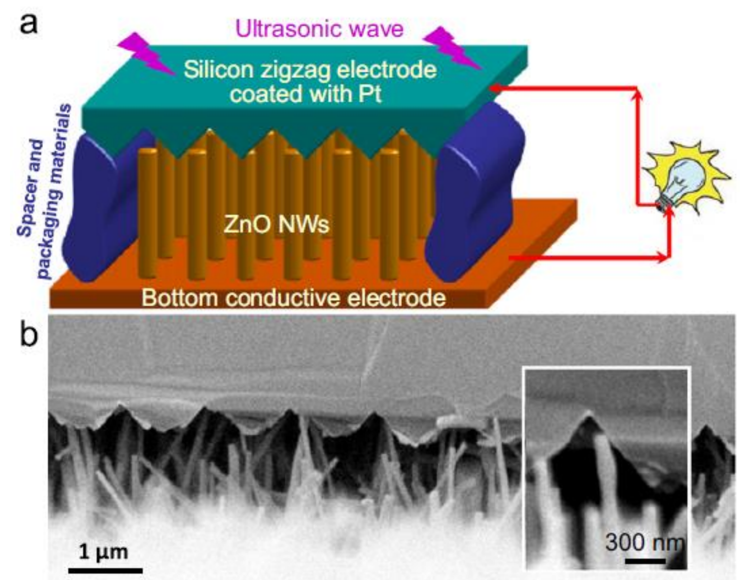
Wang 2004

ZnO Pillar



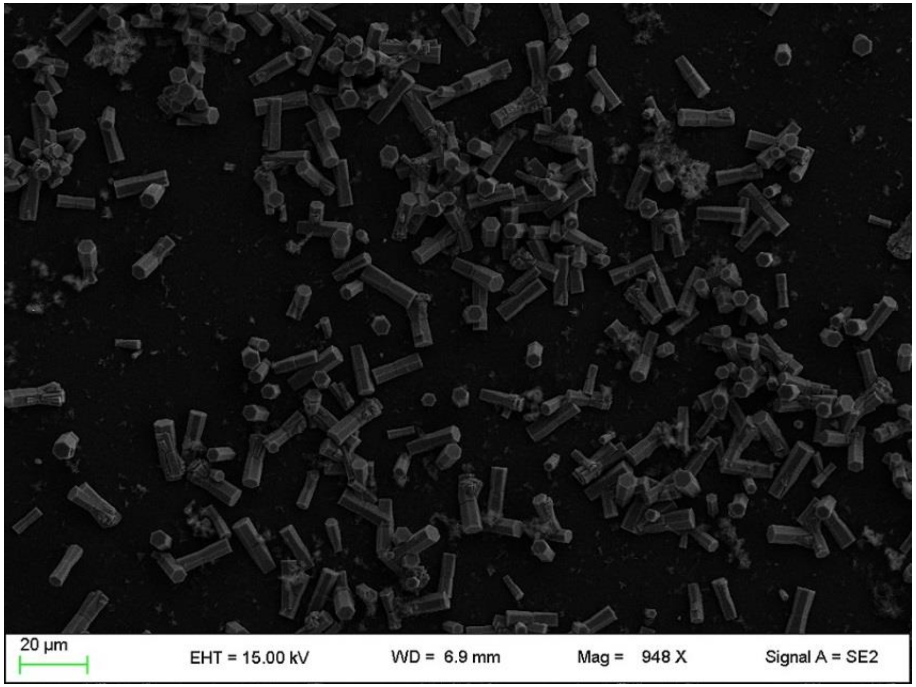
Wang 2004

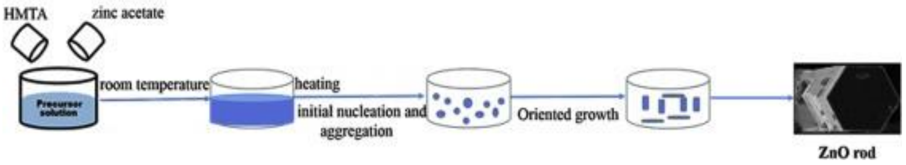
ZnO nanowires forest

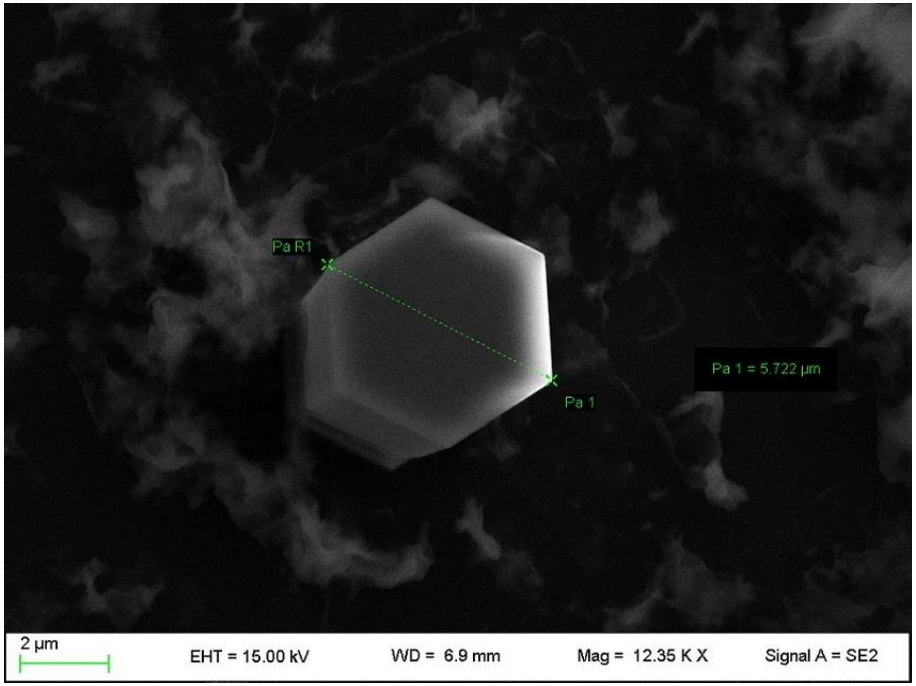


X. Wang 2011

Piezoelectric micro-pillars



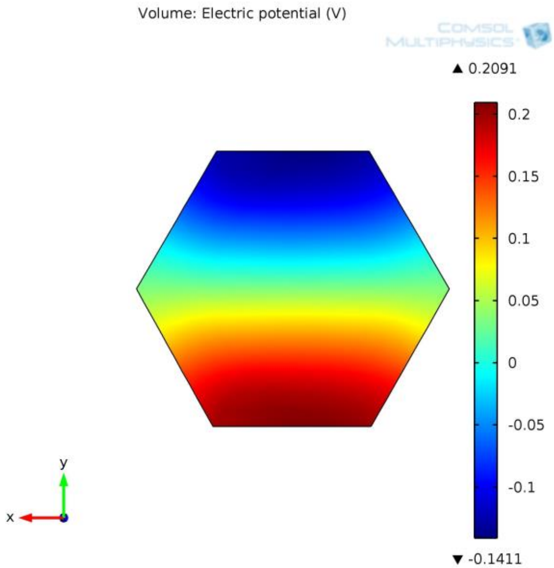


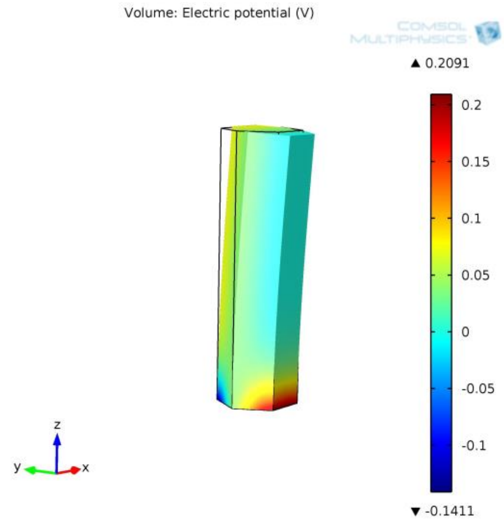


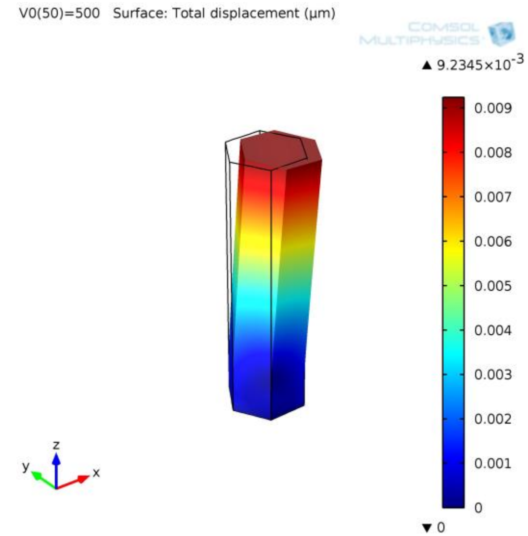
Hydrotermal synthesis
Length: 15 μm
Thickness: 4 – 6 um

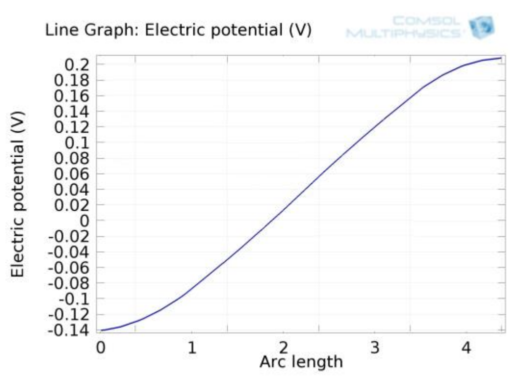
A. Di Michele, G. Clementi, M. Mattarelli, F. Cottone

Piezoelectric micro-pillars









Stress-strain equations

$$S = [s_E]T + [d^t]E$$

$$D = [d]T + [\varepsilon_T]E$$

Strain-charge form

$$\omega_1 = \beta_1^2 \sqrt{\frac{EI}{\mu}} = \frac{3.515}{L^2}\sqrt{\frac{EI}{\mu}}$$

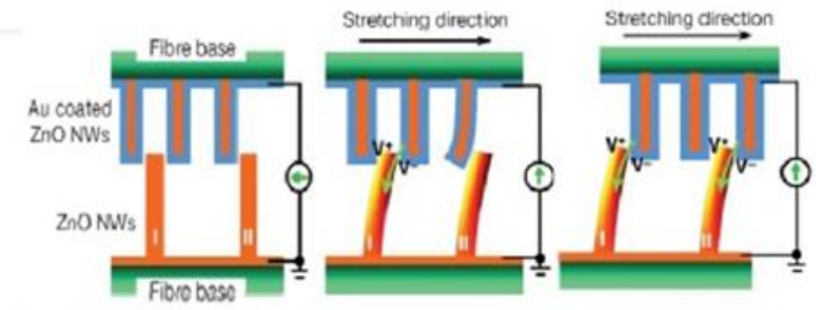
Length: 17 μm
Thickness: 5um
First mode: 10.9 Mhz

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

Piezoelectric micro-pillars, ribbons, nano-wires

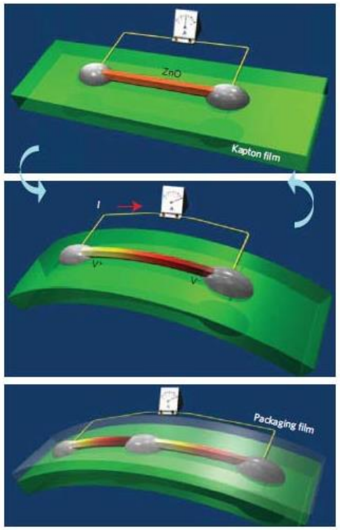
- Implementation of vertically-aligned ZnO micropillars on IDE and other geometry (e.g. horionzontal)
- Use of the devive as VEH and vibration sensor
- Fabrication of same device with BaTiO3
- Use of the piezo pillars as micro electro-mechanical antenna

Microfibre-Nanowire:



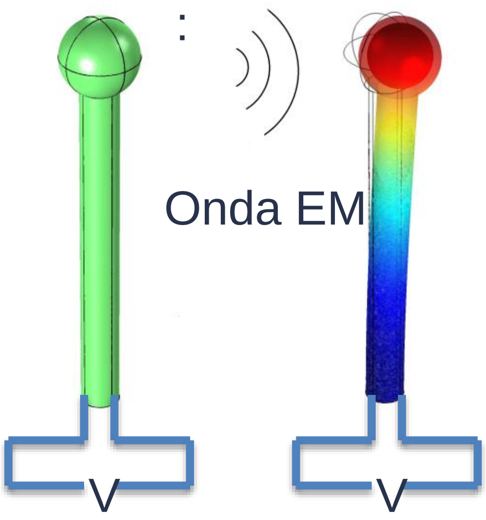
Wang(2008)

Piezoelectric ribbon:



Yang(2009)

Microantenna :



Final considerations

- **Kinetic energy harvesting systems** are promising technology to enable autonomous low-power wireless devices

- **Main transduction techniques are piezoelectric, inductive and electrostatic:** large research is beign carried out for both materials and device fabrication

- Theoretical model is complete for linear oscillator based VEH

- Reducing the size to micro and nano is challenging → The application decide wether it si convenient reone macro-scale VEH

- **Inertial vibration energy harvesters** are very limited at small scale $P \sim l^3$ → direct force piezoelectric/electrostatic devices are more efficient at nanoscale.