Funded by the
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Micro scale
Energy Harvesting Systems

ERASMUS + IESRES
INNOVATIVE EUROPEAN STUDIES on RENEWABLE ENERGY SYSTEMS

Teaching Activity
8th – 13th May 2017 - Klaipeda, Lithuania

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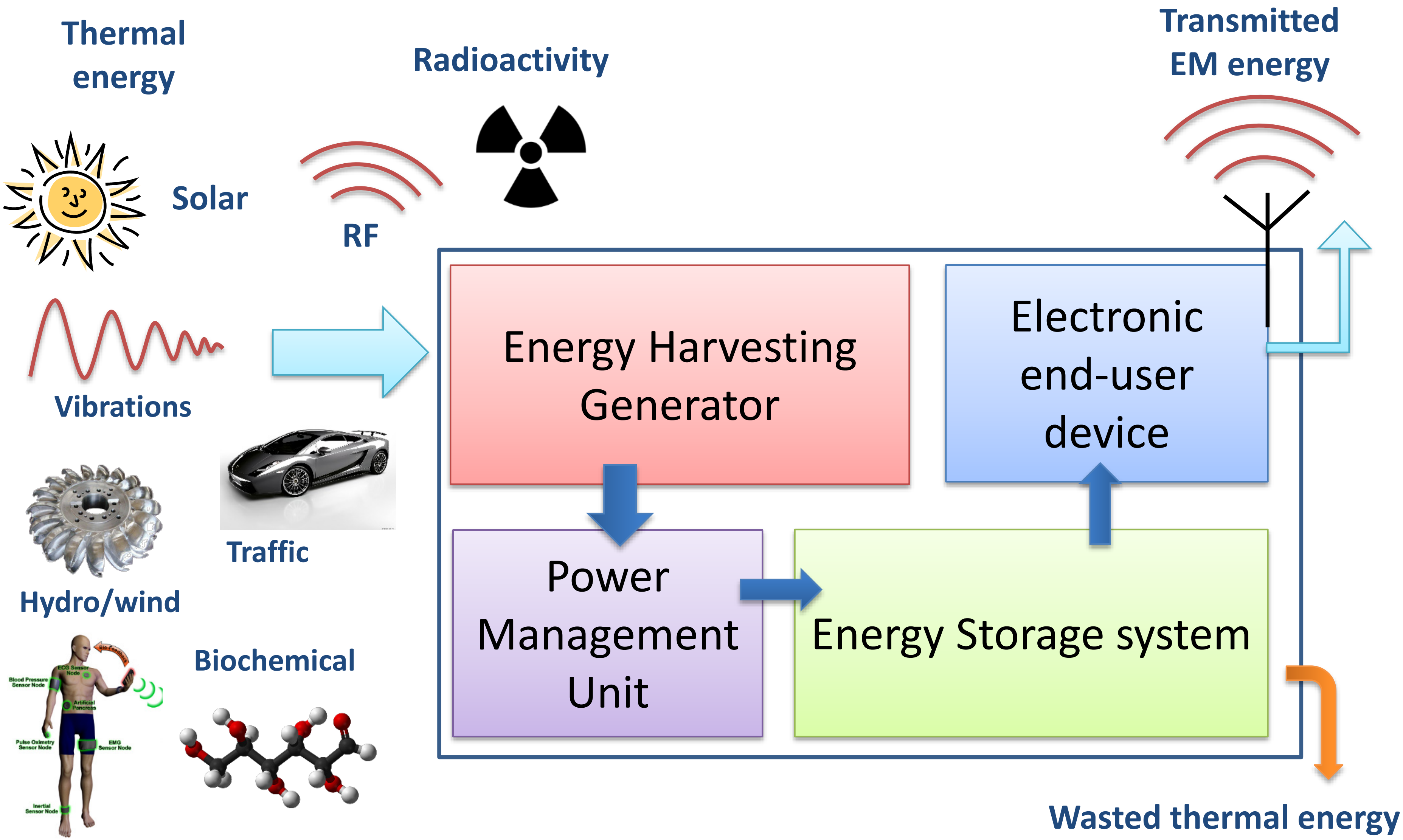
Outline

- Energy harvesting fundamentals
- Micro- to nano-scale vibrational energy harvesters
- Piezoelectric micro-structures for EH
- MEMS electrostatic systems for EH
- Final considerations

What is an energy harvester ?



Historical human-made energy harvesters

Wind mill (Origin: Persia, 3000 years BC)

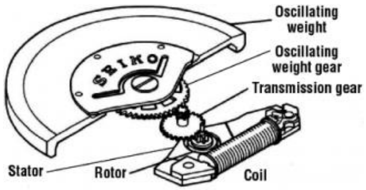
Sailing ship (XVI-XVII century)

Crystal radio - 1906

SELF-powered by Radio Frequencies !!!

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

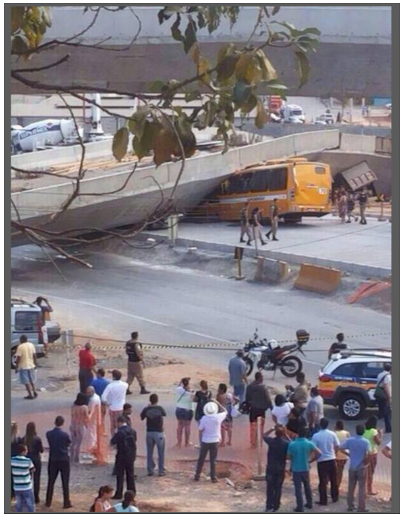
First automatic watch. Abraham-Louis Perrelet, Le Locle. 1776



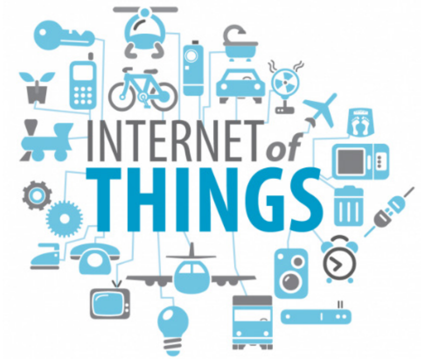
Self-charging Seiko wristwatch

Energy havesting applications

Structural Monitoring



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

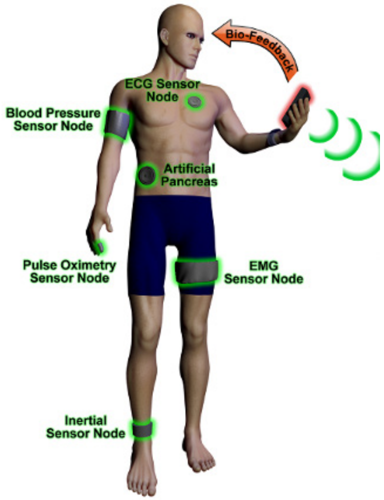


Environmental Monitoring

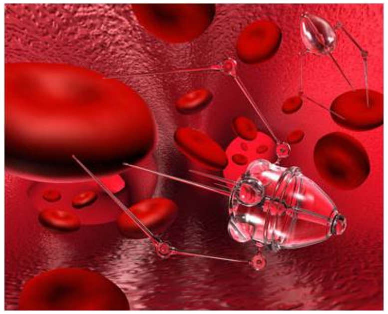
Military applications

Healthcare sensors

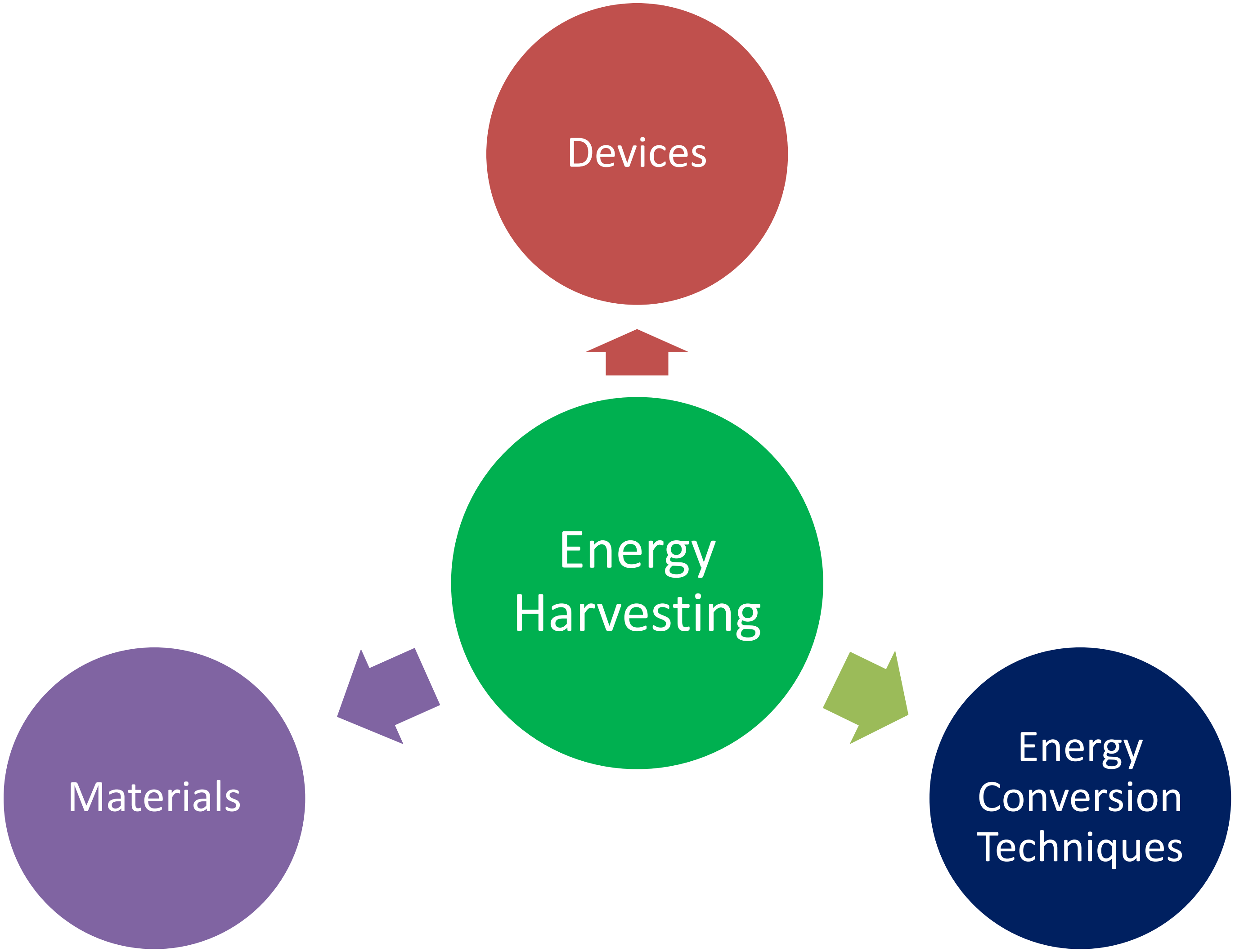
Emergency medical response
Monitoring, pacemaker, defibrillators



Nanomedicine



Energy Harvesting research



Vibration Energy Harvesting research

Macro

- Vibrational EM devices
- Vibrational Piezo Cantilevers
- Vibrational Structures with Magnetic Shape Memory Alloy (NiMnGa)

Micro

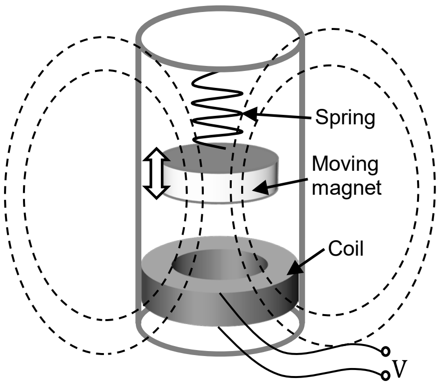
- Electrostatic Generators
- Piezo Micro beams of stripes ZnO, BaTiO3
- Electrets SiO2, Parylene, Teflon base

Nano

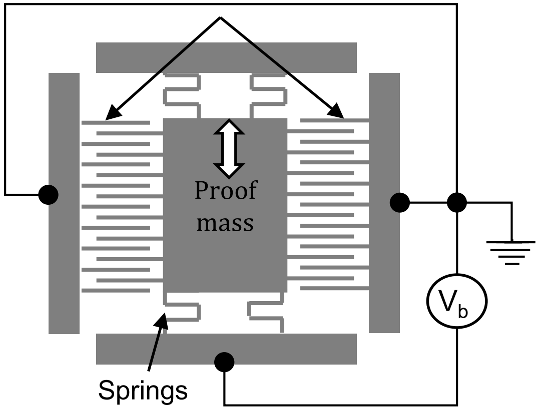
- Piezoelectric nanopillars, nanoribbons etc.
- Triboelectric generators
- Electrets nano-spheres

Vibration energy harvesting

Electromagnetic

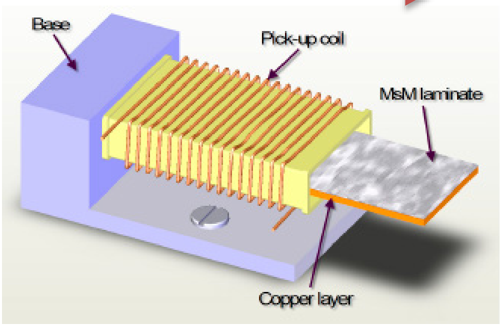


Electrostatic/Capacitive

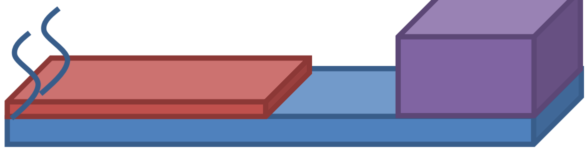


Vibration to electricity energy conversion techniques

Magnetostrictive



Piezoelectric



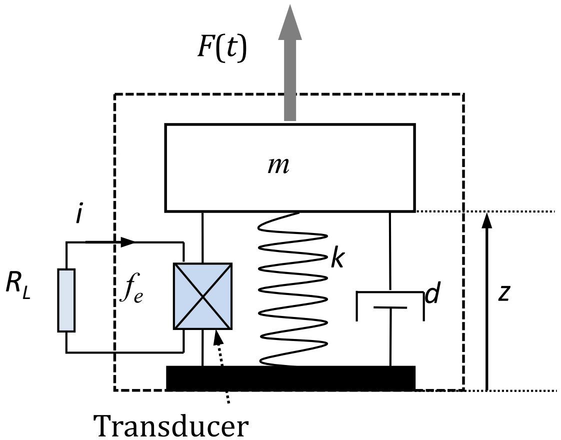
Piezoelectric conversion

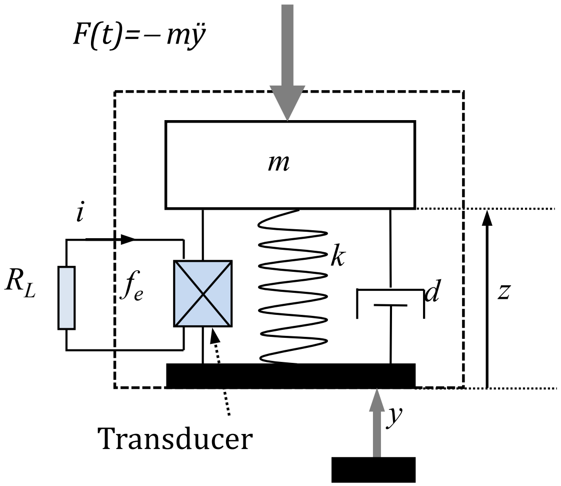
Characteristic	PZT-5H	BaTiO3	PVDF	AlN (thin film)
d_{33} (10^{-10} C/N)	593	149	-33	5,1
d_{31} (10^{-10} C/N)	-274	78	23	-3,41
k_{33}	0,75	0,48	0,15	0,3
k_{31}	0,39	0,21	0,12	0,23
ε_r	3400	1700	12	10,5

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

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

Dynamical model of VEH





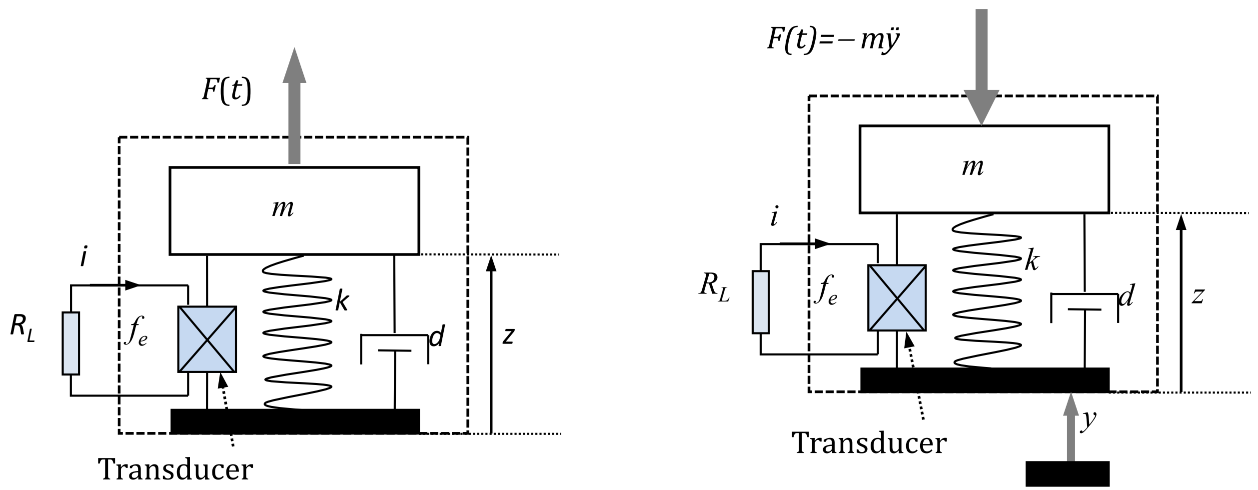
Inertial generators requires only one point of attachment to a moving structure, allowing a greater degree of miniaturization.

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

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

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

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

Dynamical model of VEH

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

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

For LINEAR mechanical oscillators with elastic potential well

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

Laplace transform

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

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

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

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**

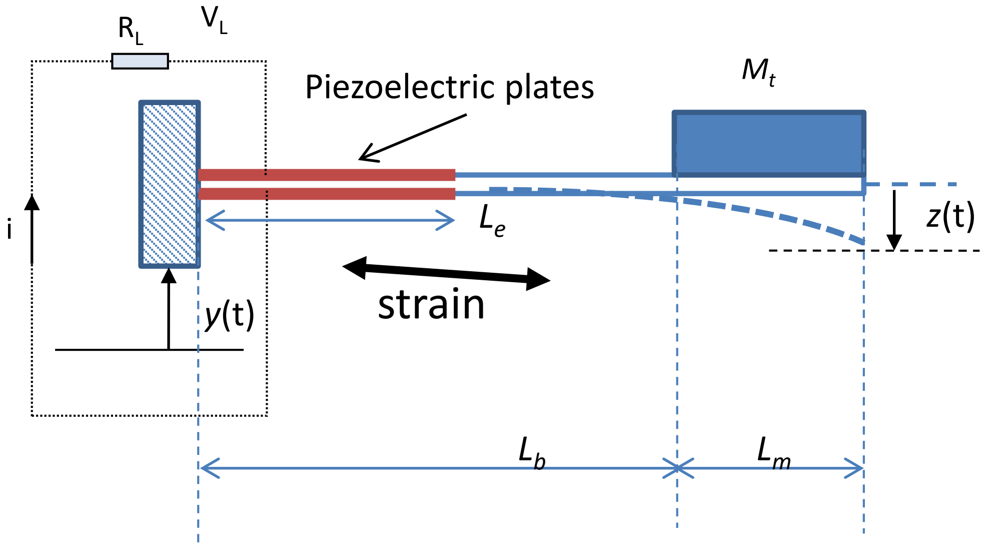
$$P_e(\omega) = \frac{|V|^2}{R_L} = \frac{Y_0^2}{2R_L}\left|\frac{m\lambda\omega_c j\omega}{(\omega_c + j\omega)(-m\omega^2 + dj\omega + k) + \alpha\lambda\omega_c j\omega}\right|^2$$

In 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

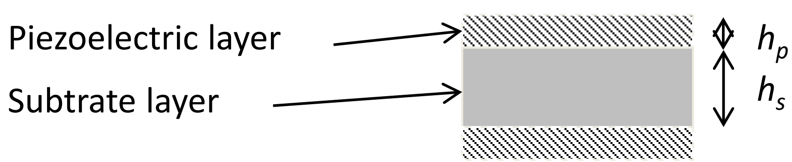


Governing equations

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

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

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



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

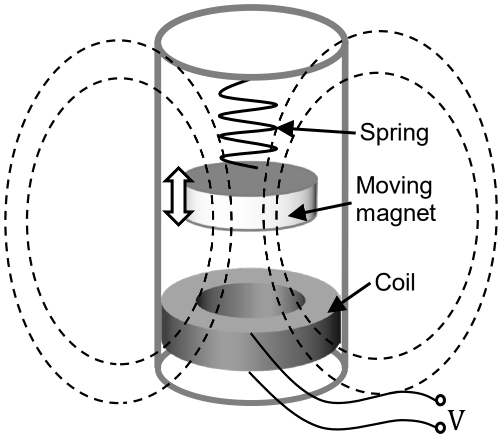
$$k = k_1 k_2 E_p,$$

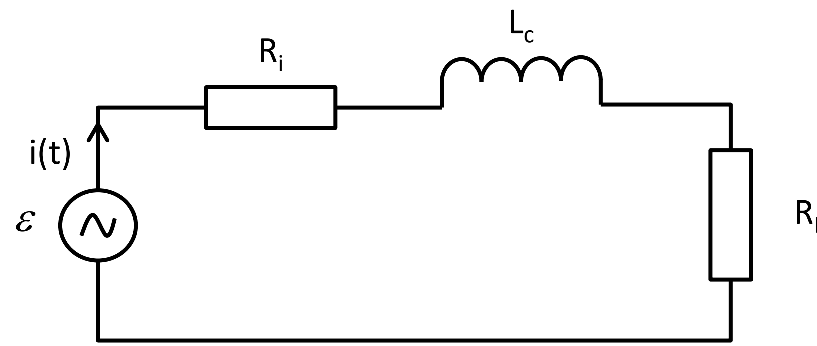
$$k_1 = \frac{2I}{b(2l_b + l_m - l_e)}, \qquad k_2 = \frac{3b(2l_b + l_m - l_e)}{l_b^2\left(2l_b + \frac{3}{2}l_m\right)},$$

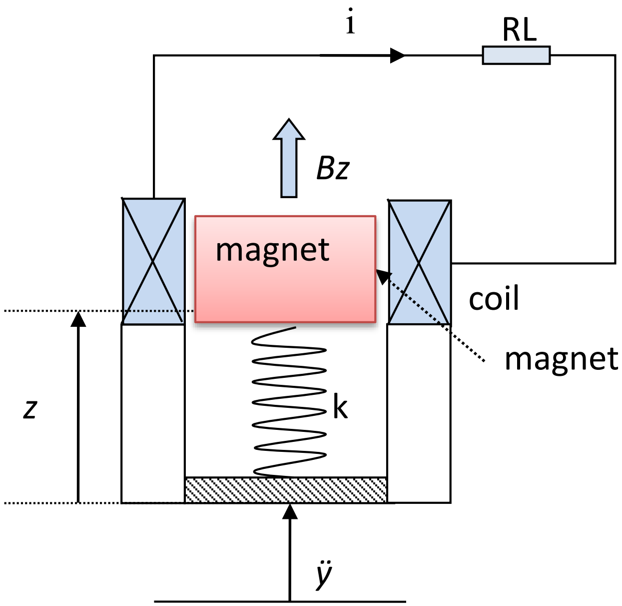
$$b = \frac{h_s + h_p}{2}, \qquad I = 2\left[\frac{w_b h_p^3}{12} + w_b h_p b^2\right] + \frac{E_s/E_p w_b h_s^3}{12},$$

Inertia area moment of the beam

Electromagnetic conversion







Governing equations

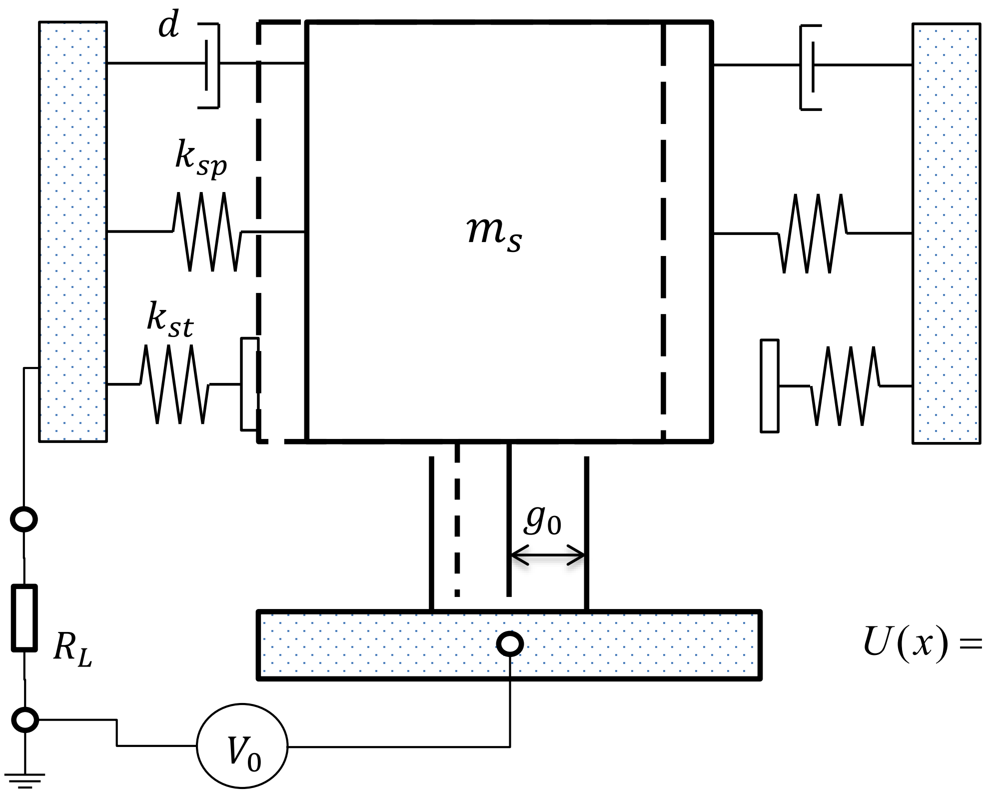
$$\begin{cases} m\ddot{z} + d\dot{z} + kz + \alpha V_L = -m\ddot{y} \\ \dot{V}_L + (\omega_c + \omega_i)V_L = \lambda \omega_c \dot{z} \end{cases}$$

⇩

$$\alpha = Bl / R_L, \qquad \lambda = Bl = \alpha R_L,$$

$$\omega_c = R_L / L_c, \qquad \omega_i = R_i / L_c,$$

Electrostatic conversion



Governing equations

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

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

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

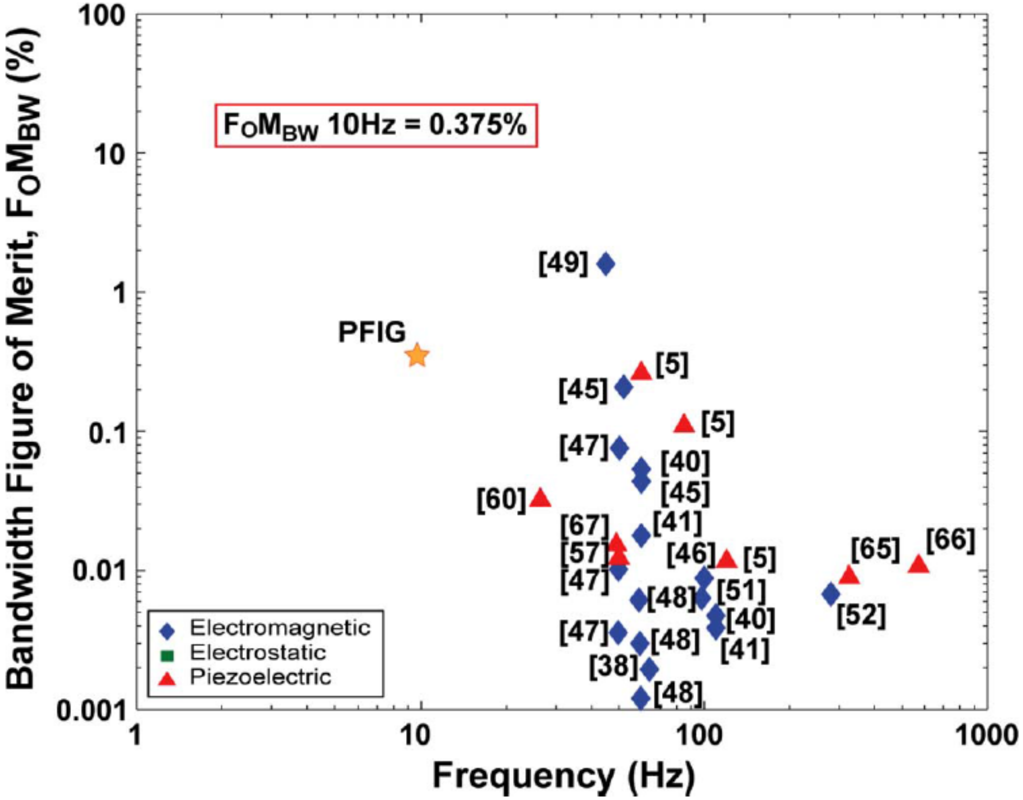
Figure of merit

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

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).

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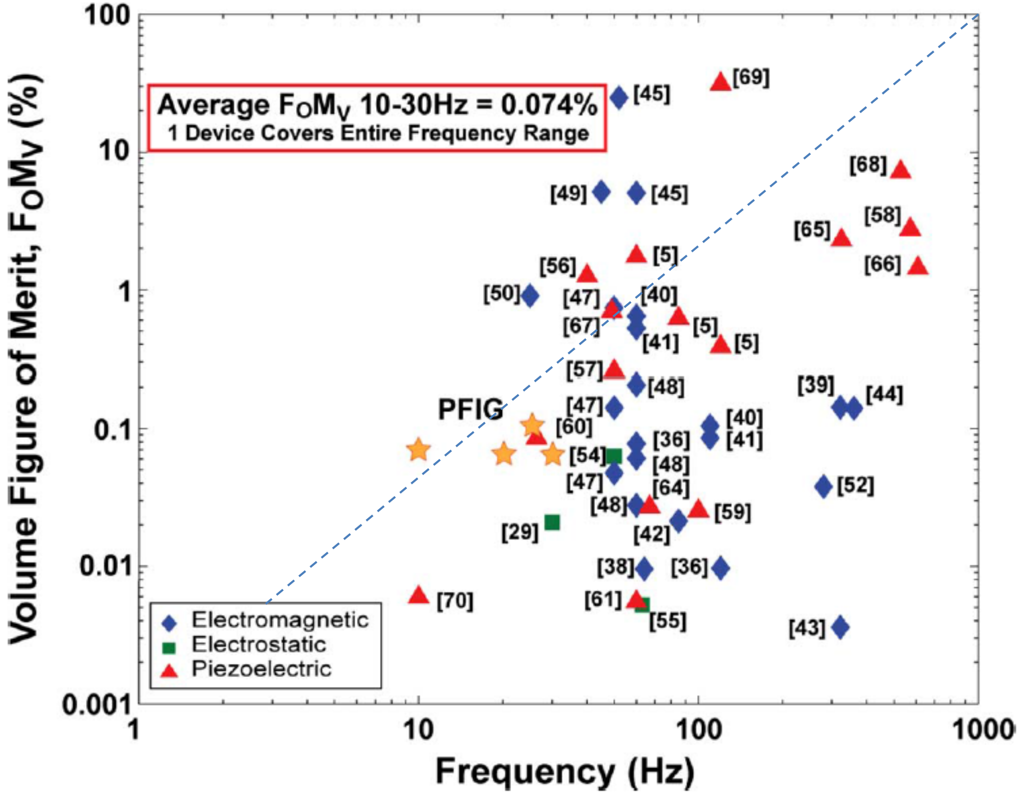


Galchev et al. (2011)

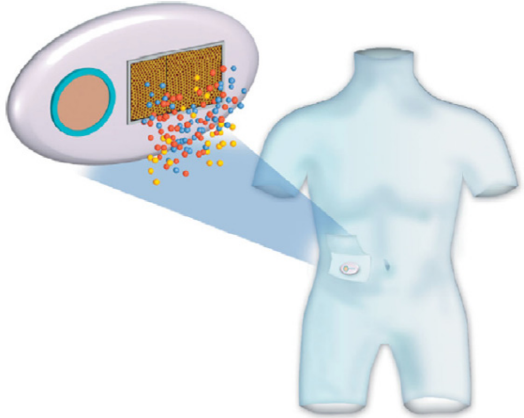
Mitcheson, P. D., E. M. Yeatman, et al. (2008).

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.

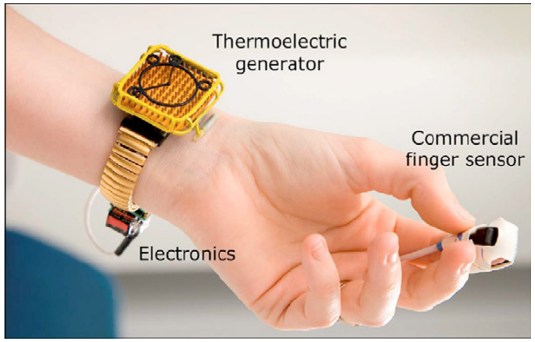
Microscale energy harvesters

MEMS-based drug delivery systems



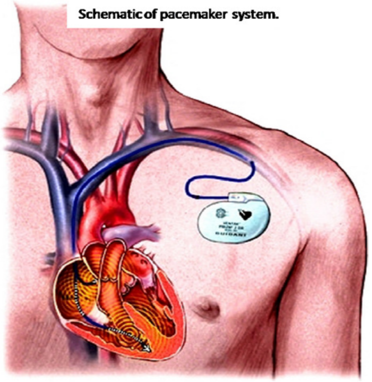
Bohm S. et al. 2000

Body-powered oximeter



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

Heart powered pacemaker

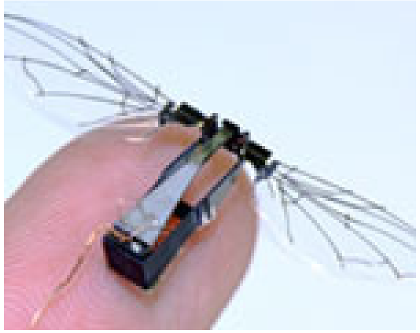


D. Tran, Stanford Univ. 2007

Pacemaker consumption is **40uW**.

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

Micro-robot for remote monitoring

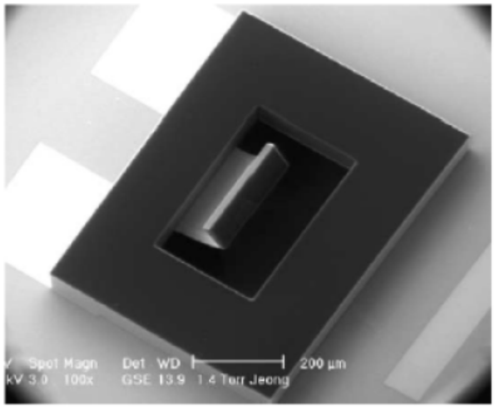


A. Freitas Jr., Nanomedicine, Landes Bioscience, 1999

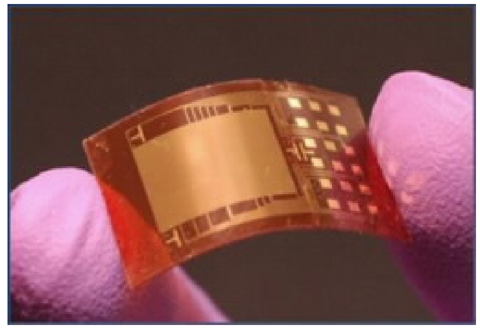
The input power a 20 mg robotic fly is **10 – 100 uW**

Microscale energy harvesters

Piezoelectric

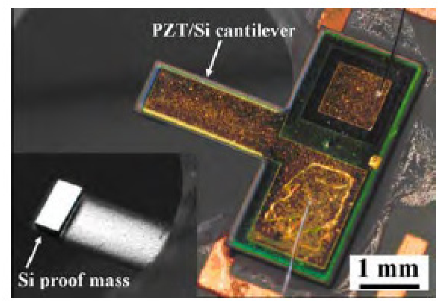


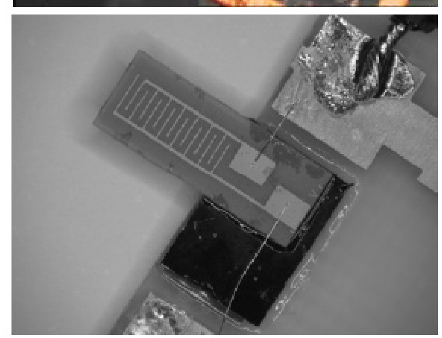
Jeon et al. 2005



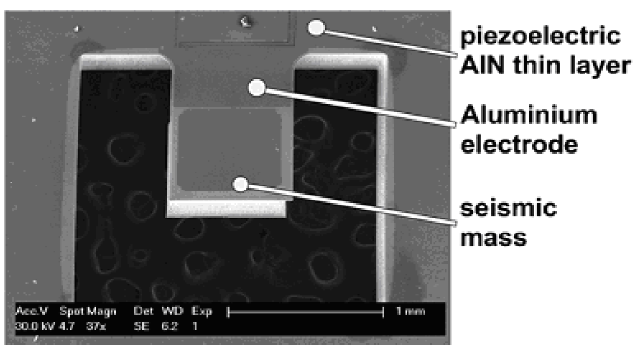
ZnO nanowires
Wang, Georgia Tech (2005)

Chang. MIT 2013





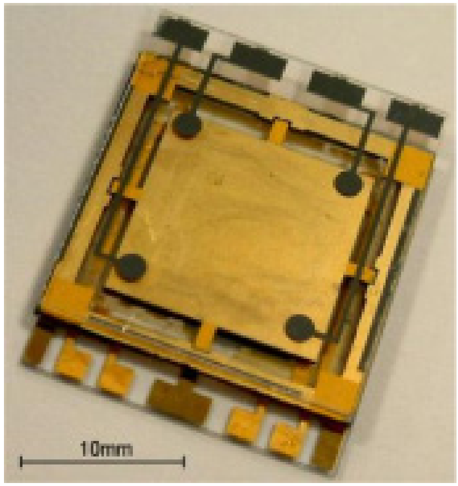
D. Briand, EPFL 2010



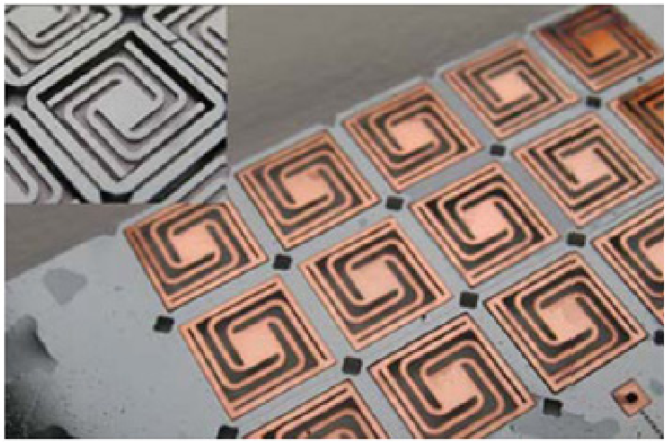
M. Marzencki 2008 – TIMA Lab (France)

Microscale energy harvesters

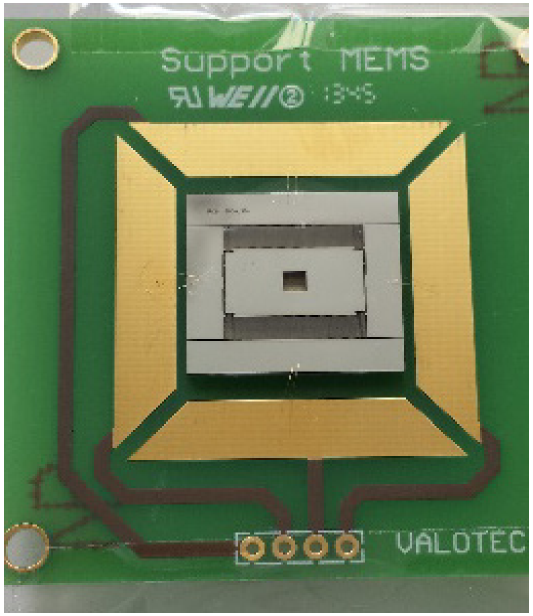
Electrostatic and electromagnetic



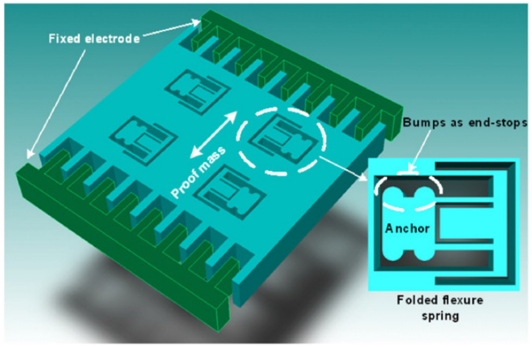
Mitcheson 2005 (UK)
Electrostatic generator 20Hz
2.5uW @ 1g



EM generator, Miao et al. 2006



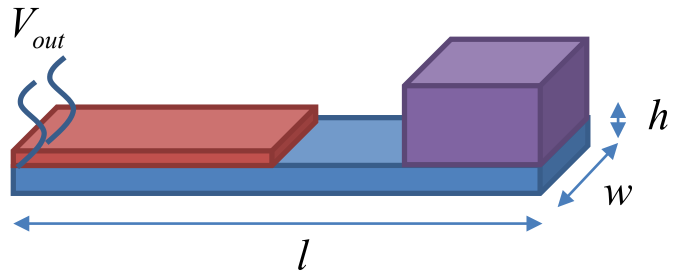
Cottone F., Basset P. ESIEE Paris 2013



Le and Halvorsen, 2012

Microscale energy harvesters: scaling issues

First order power calculus with William and Yates model



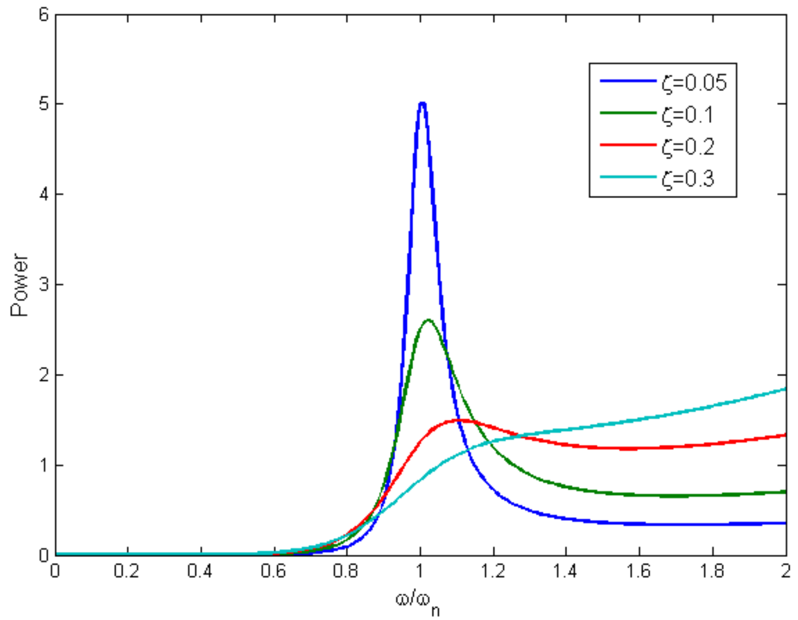
$$\omega_n = 2\pi C_n \sqrt{\frac{E}{\rho}} \frac{h}{l^2}$$

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

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

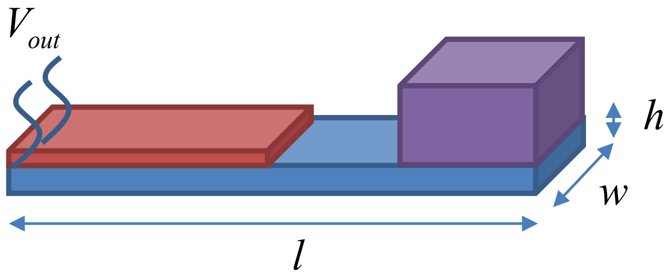
Boudary conditions	Uniform load ξ	Point load ξ
doubly clamped	32	16
cantilever	0,67	0,25

- 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



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

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

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

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

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

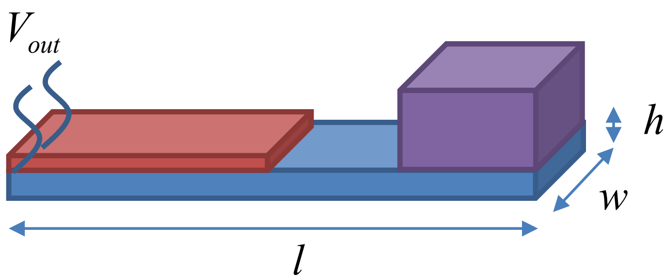
$$P_{el} = \frac{m\zeta_e A^2}{4\omega_n(\zeta_m + \zeta_e)^2}$$

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



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

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

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

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

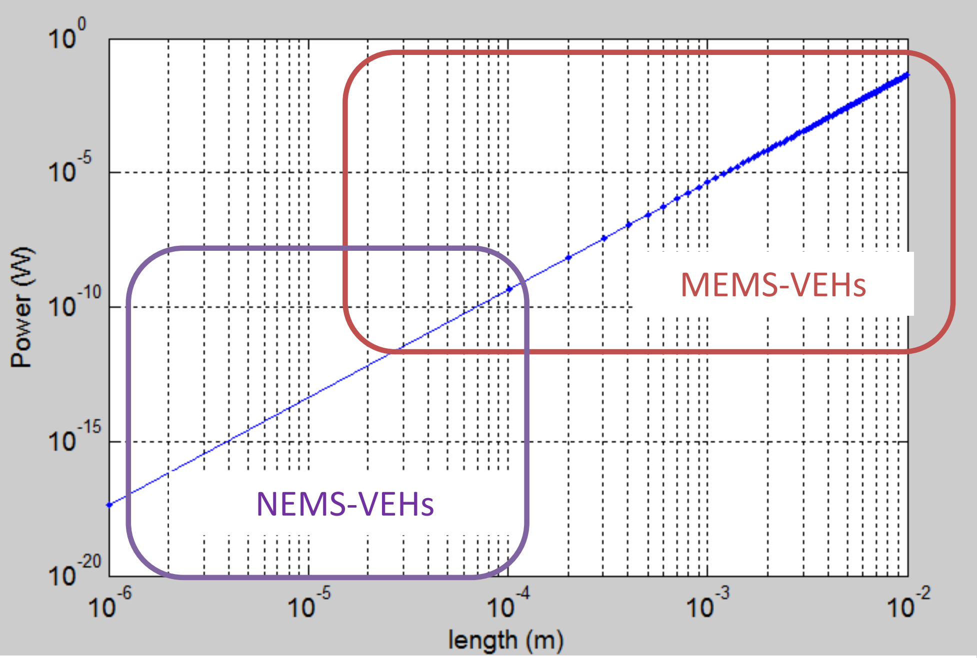
At max power condition $\zeta_e = \zeta_m$

By assuming

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

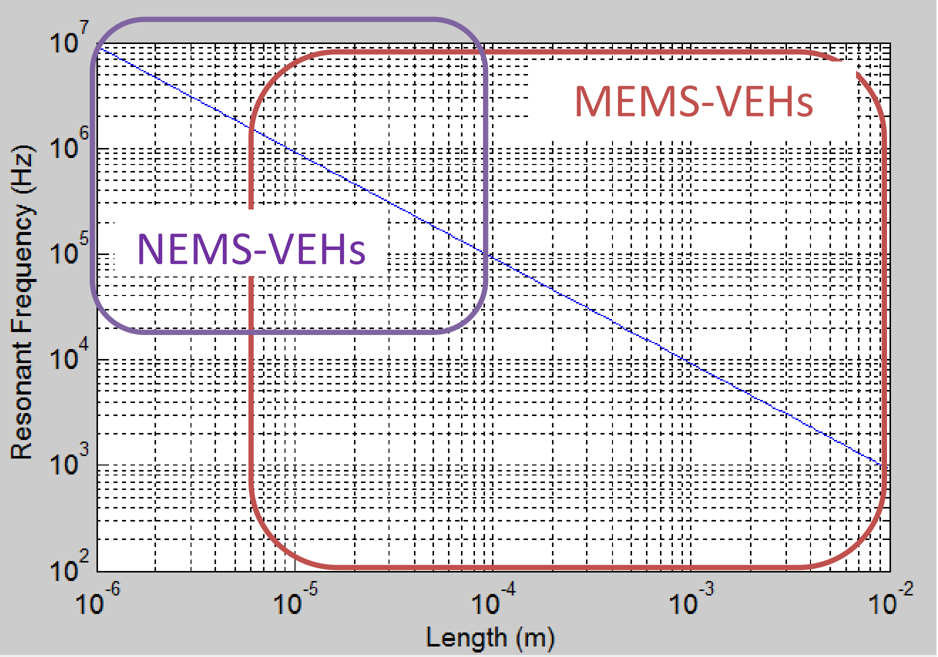
$$P_{el} = \frac{\rho_{si}/800 + 0.32 \cdot 64 \rho_{mo}}{\frac{16}{200}\pi C_n \sqrt{\frac{E}{\rho_{si}}}\zeta_m} A^2 l^4$$

Microscale energy harvesters: scaling issues

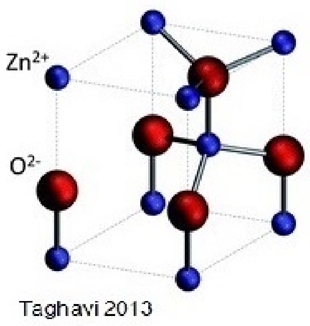


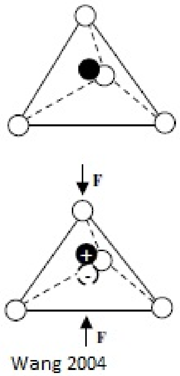
By assuming

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

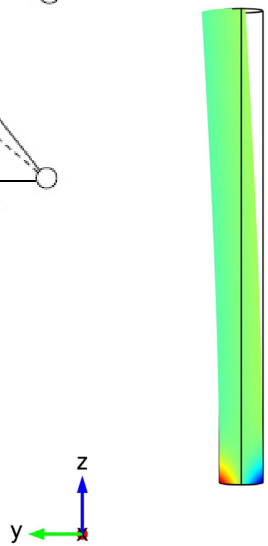


Piezoelectric micro-pillars

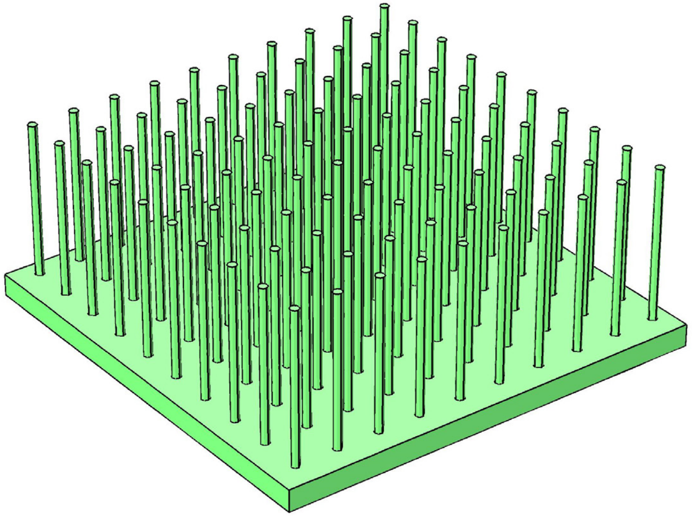


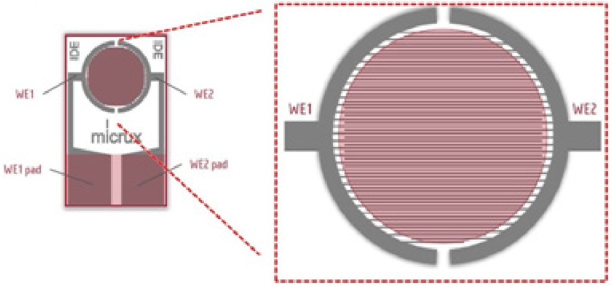


ZnO Pillar



ZnO forest

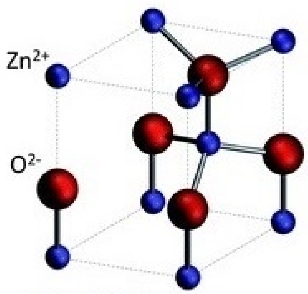




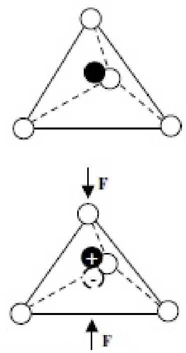
Why ZnO

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

Piezoelectric micro-pillars



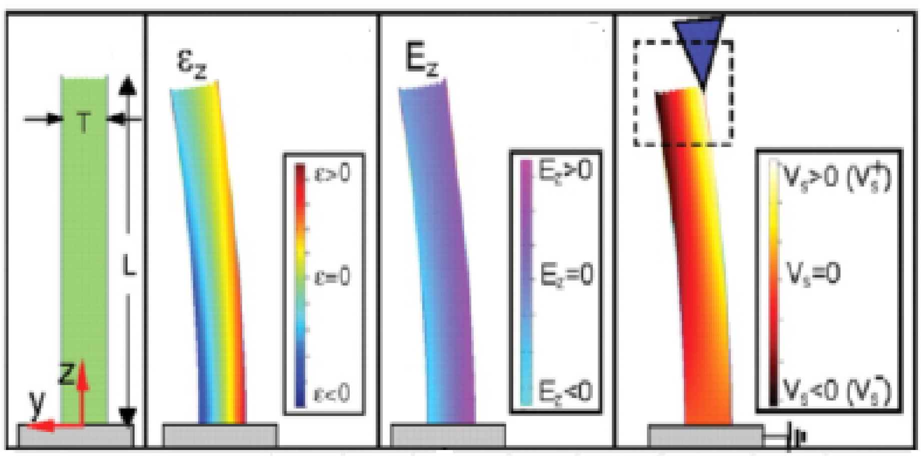
Taghavi 2013



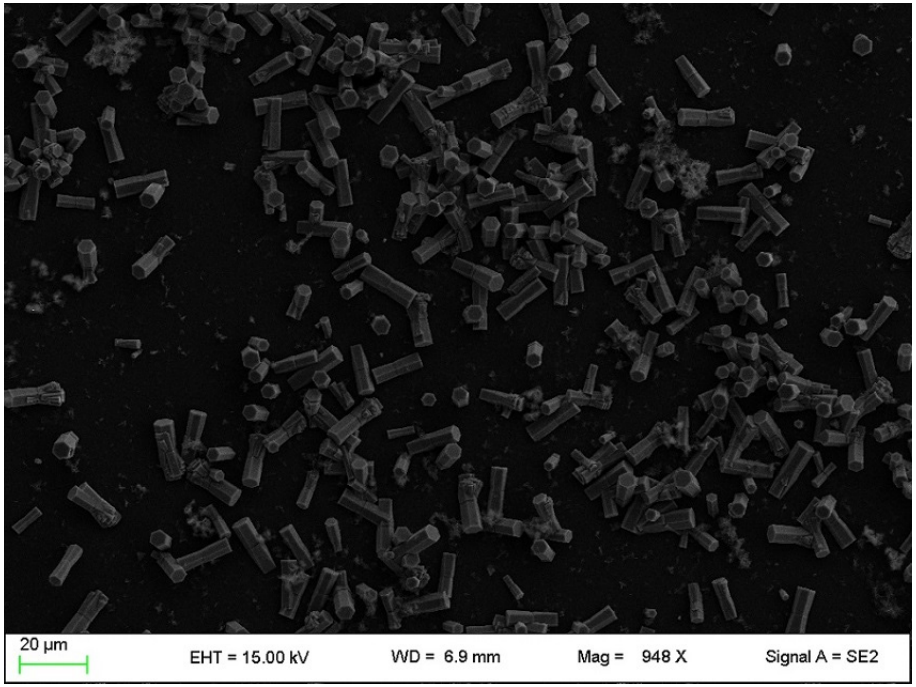
Wang 2004

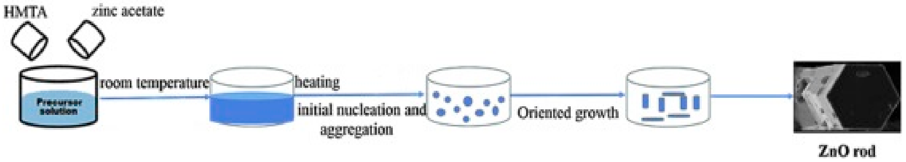
ZnO Pillar

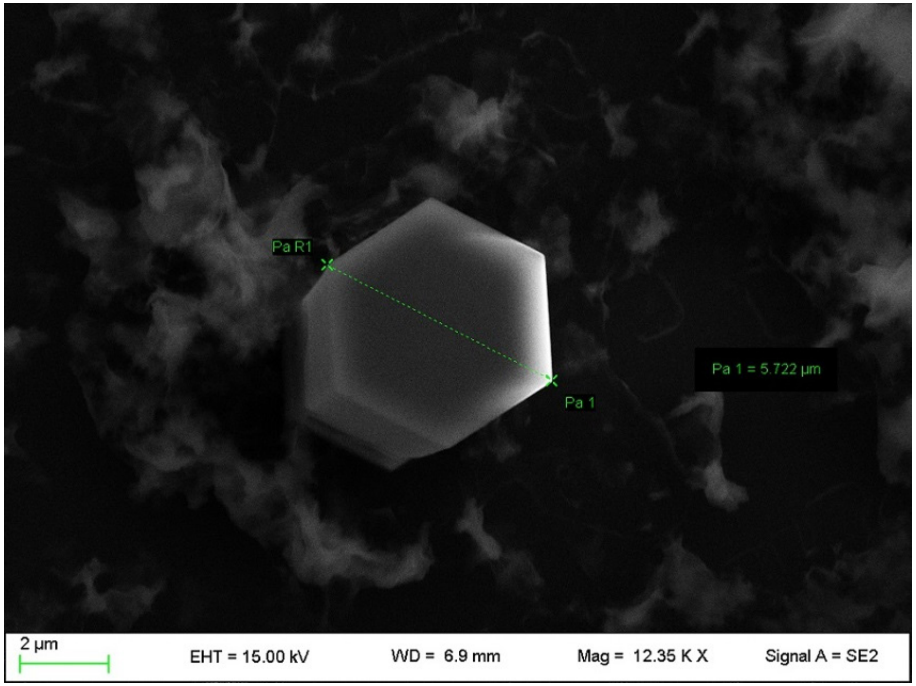
ZnO forest



Piezoelectric micro-pillars

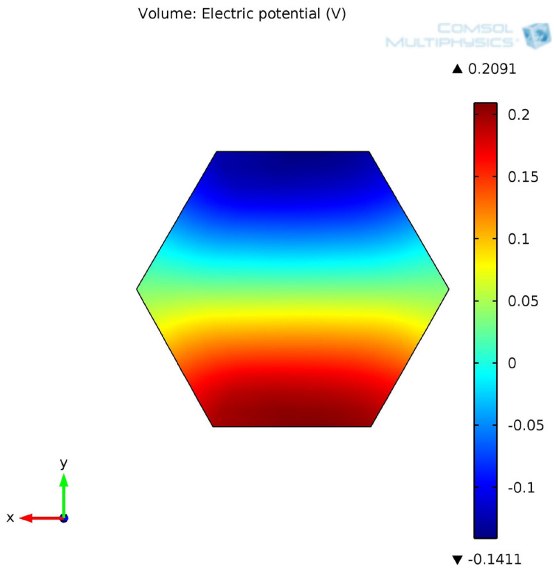


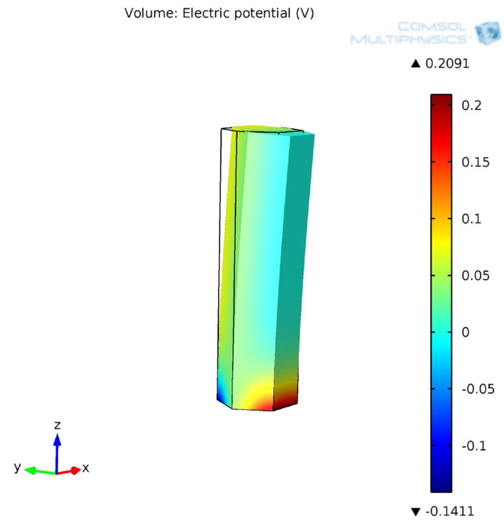


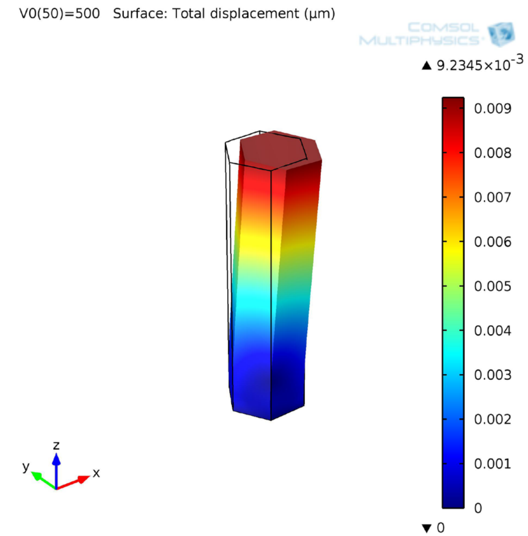


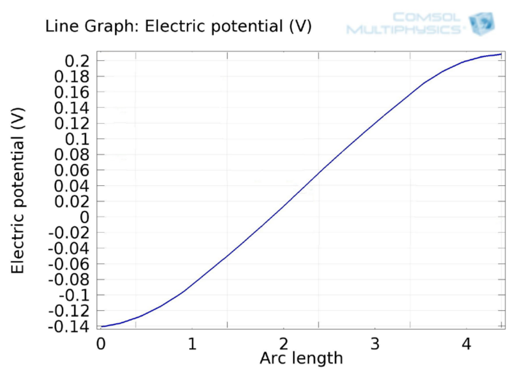
Hydrotermal synthesis
Length: 15 µm
Thickness: 4 – 6 um

Piezoelectric micro-pillars









Stress-strain equations

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

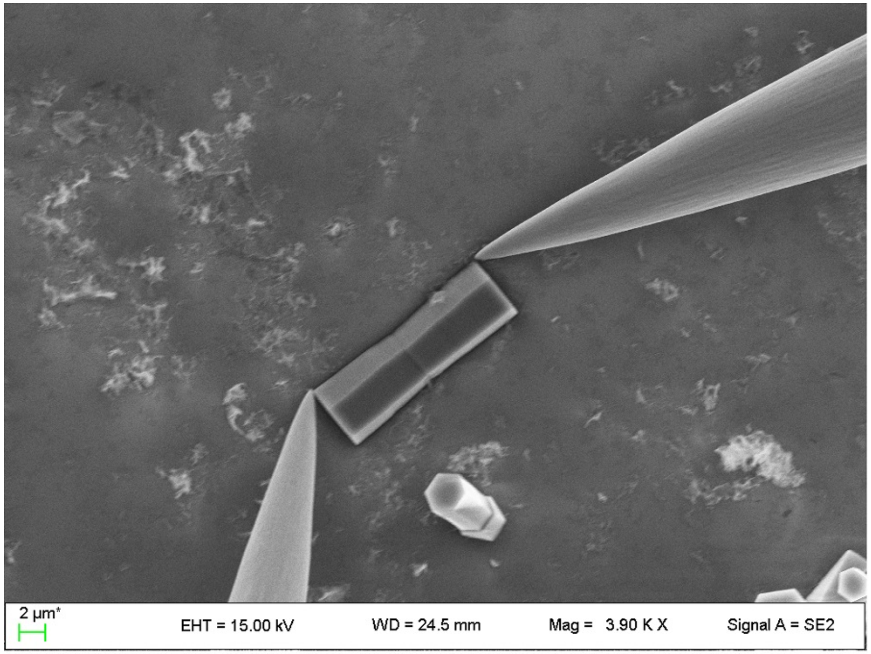
$$D = [d]T + [\varepsilon_T]E$$

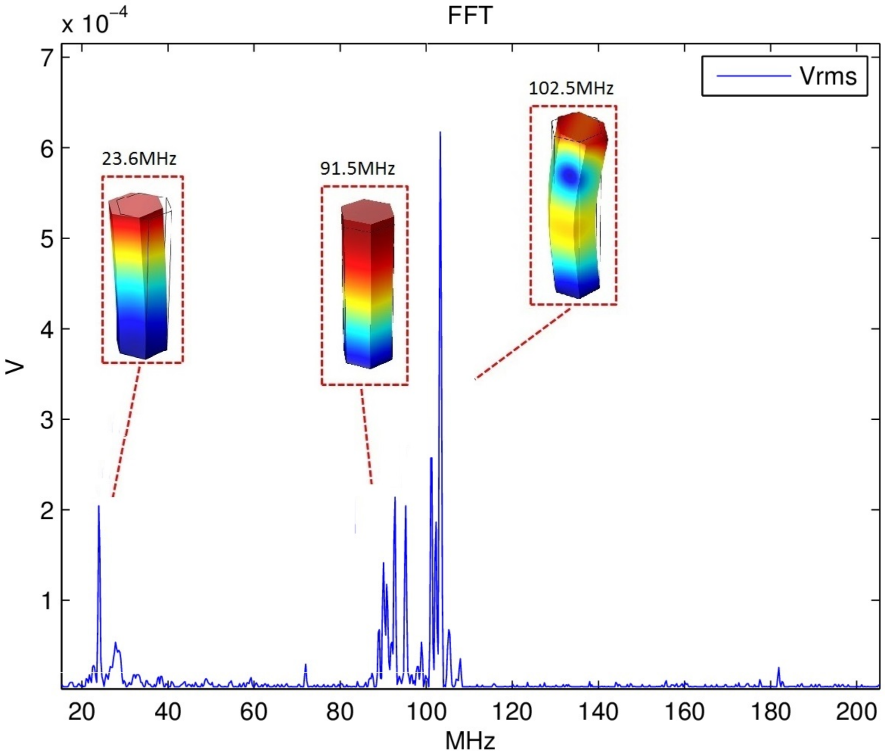
Strain-charge form

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

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

Piezoelectric micro-pillars



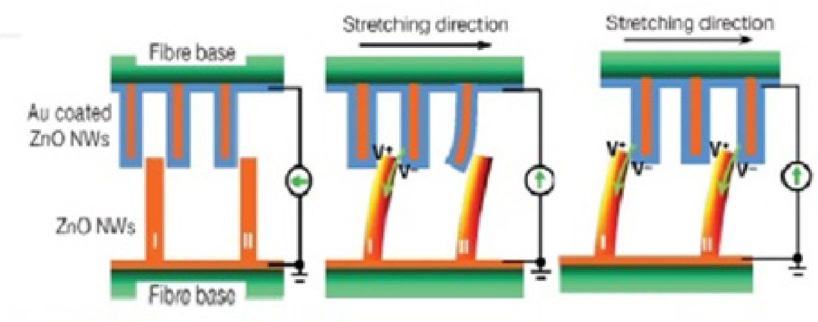


- SEM with metal probes (100nm) on a single ZnO crystal for frequency mode investigation

Piezoelectric micro-pillars: future development

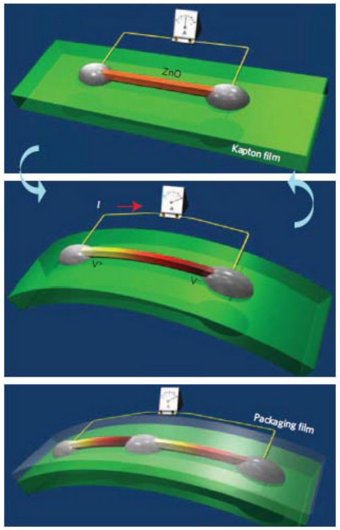
- Implementation of vertically-aligned ZnO micropillars on IDE and other geometry (e.g. horionzontal)
- Use of the devive as VEH and vibration sensor
- Fabrication of same device with BaTiO3
- Use of the piezo pillars as micro electro-mechanical antenna

Microfibre-Nanowire:



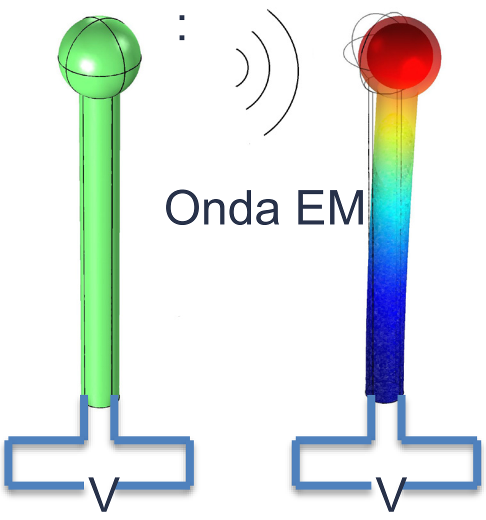
Wang(2008)

Piezoelectric ribbon:



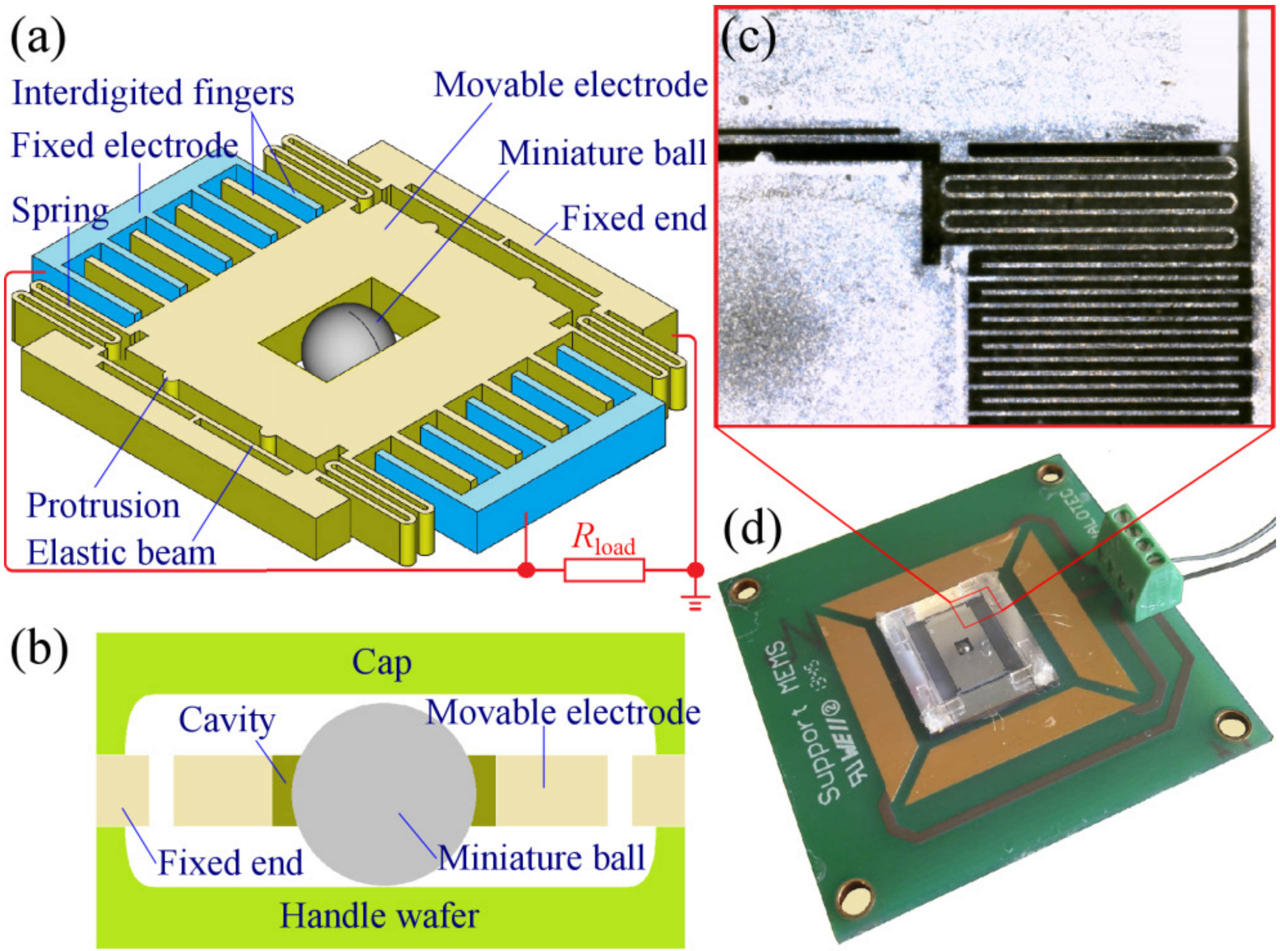
Yang(2009)

Microantenna



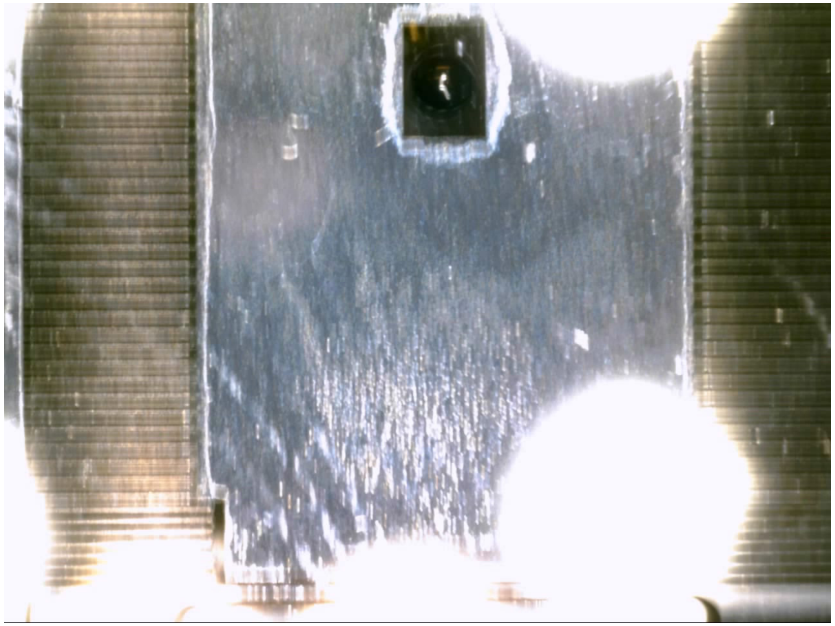
Low-frequency MEMS electrostatic VEH

Prototype fabrication process

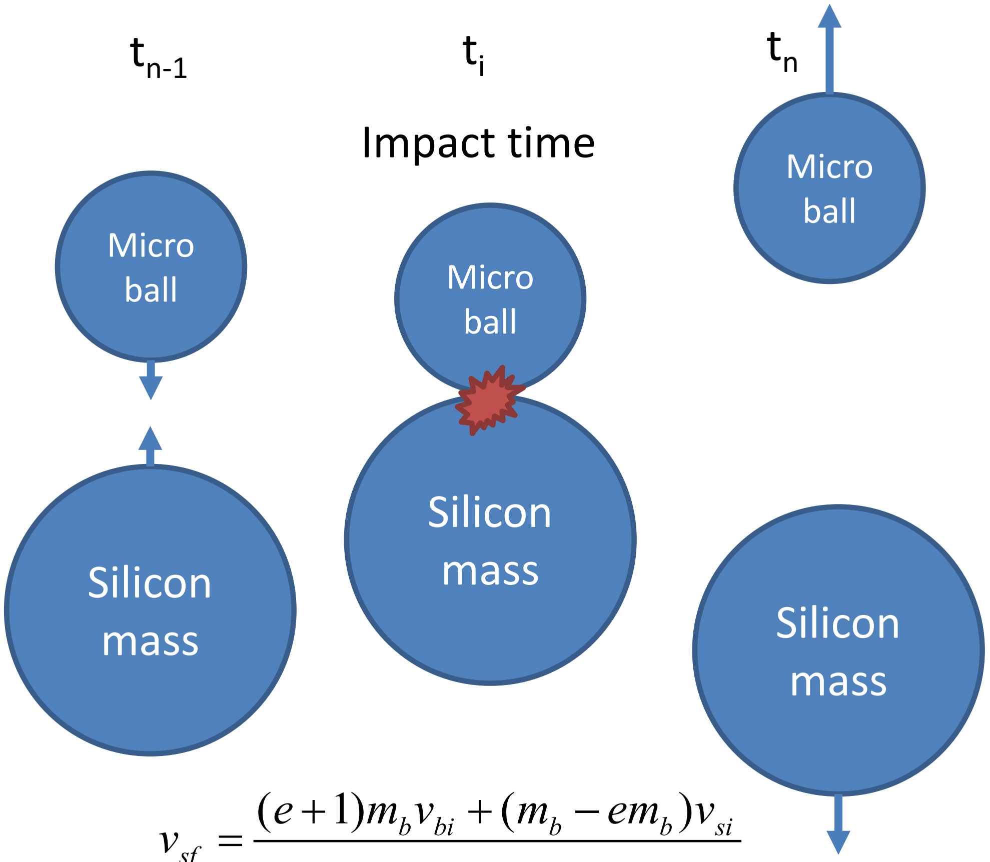


Low-frequency MEMS electrostatic VEH

Experimental test



Working principle

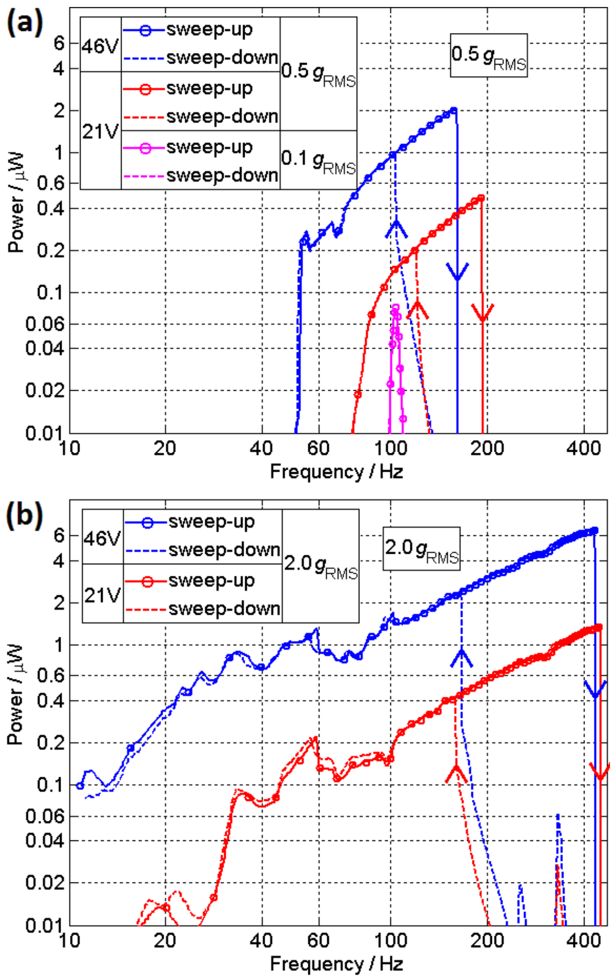


$$v_{sf} = \frac{(e+1)m_b v_{bi} + (m_b - e m_b) v_{si}}{m_b + m_s}$$

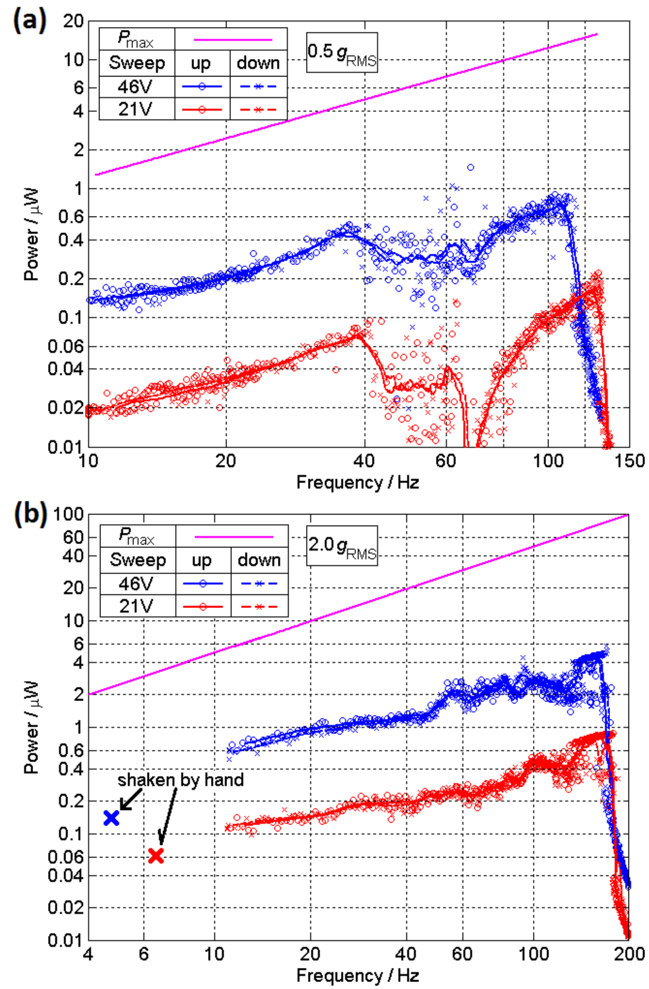
Velocity Amplified Energy Harvester
At Stoke Institute, University of Limerick, Ireland

Low-frequency MEMS electrostatic VEH

without micro-ball

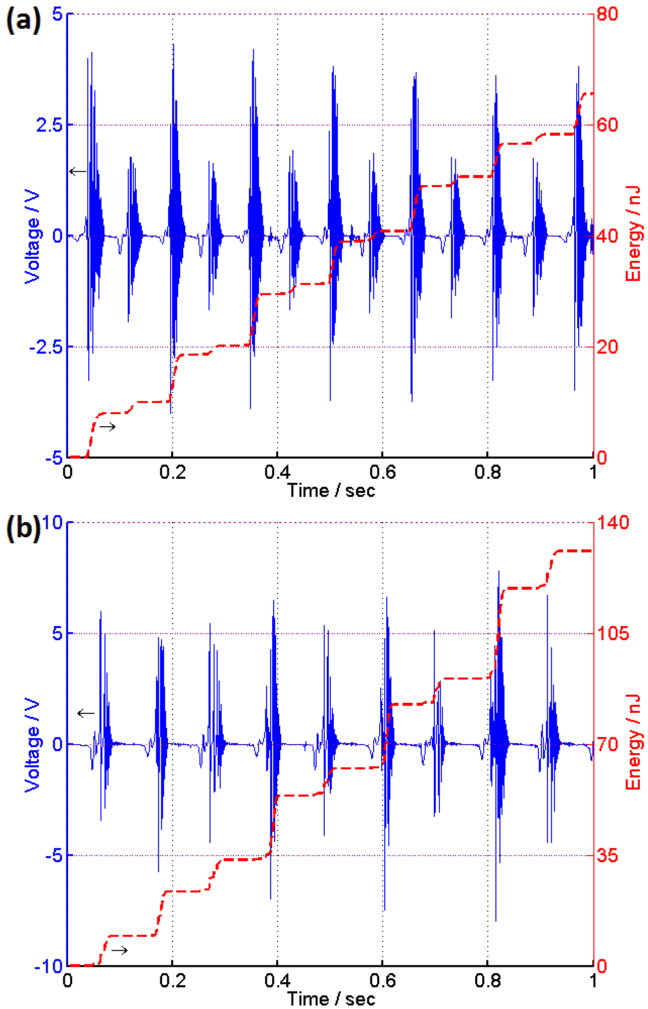


with micro-ball



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

Low-frequency MEMS electrostatic VEH



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.

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

Performance comparison

Vibration type	MEMS Direction	Accel. (gRMS)	Main input Freq. (Hz)	Vbias (V)	Power (uW)	Power Density (uW/cm3)
Man walking	X	0.39	4.15	20	1.34	13.40
Man walking	Y	0.27	2.1	20	0.793	7.93
Man walking	Z	0.41	2.44	20	1.15	11.50
Man running	Z	1.20	3.3	20	14.9	142.00

Table 2 Comparison of Effectiveness of Published Electrostatic Motion Harvesters

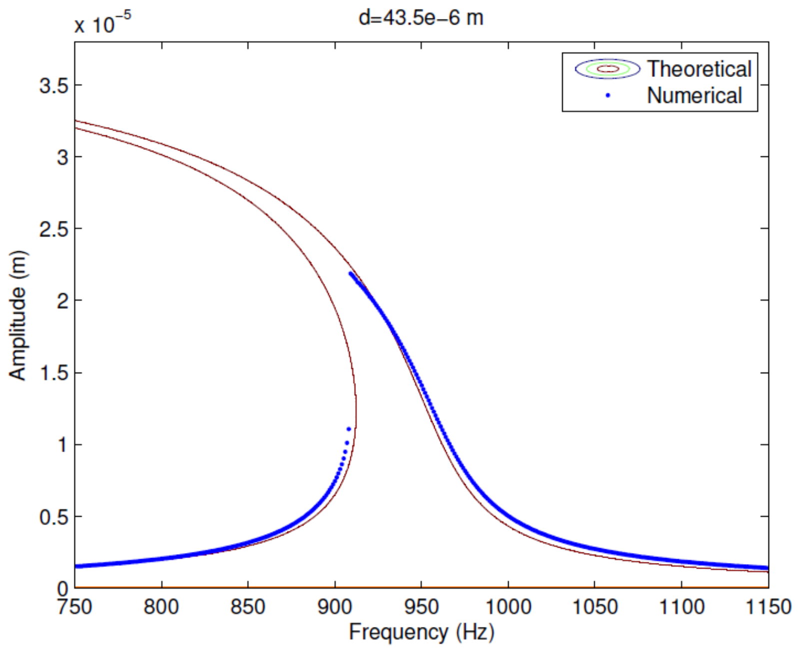
Author	Reference	Generator Volume [cm^3]	Proof Mass [g]	Input Amplitude [μm]	Input Frequency [Hz]	Z_l [μm]	Power (unprocessed) [μW]	Power (processed) [μW]	Power Density [$\mu W/cm^3$]	Harvester Effectiveness [%]	Volume Figure of Merit [%]
Tashiro	[104]		640	380	4.76	19000		58		0.09	
Tashiro	[142]	15	780	9000	6		36		2.42		0.02
Mizuno	[108]	0.6	0.7	0.64	743	4.9	7.4×10^{-6}		1.23×10^{-3}	6.6×10^{-6}	1.86×10^{-9}
Miyazaki	[143]		5	1	45	30		0.21		12.4	
Arakawa	[144]	0.4	0.65	1000	10	1000	6		15	7.42	0.68
Despesse	[145]	18	104	90	50	90	1760	1000	56	7.66	0.06
Yen	[146]				1500			1.8			
Tsutsumino	[147]			600	20	600	278				
Tsutsumino	[148]			1000	20	1000	6.4				
Mitcheson	[109]	0.6	0.12	1130	20	100	2.4		4	17.9	0.02

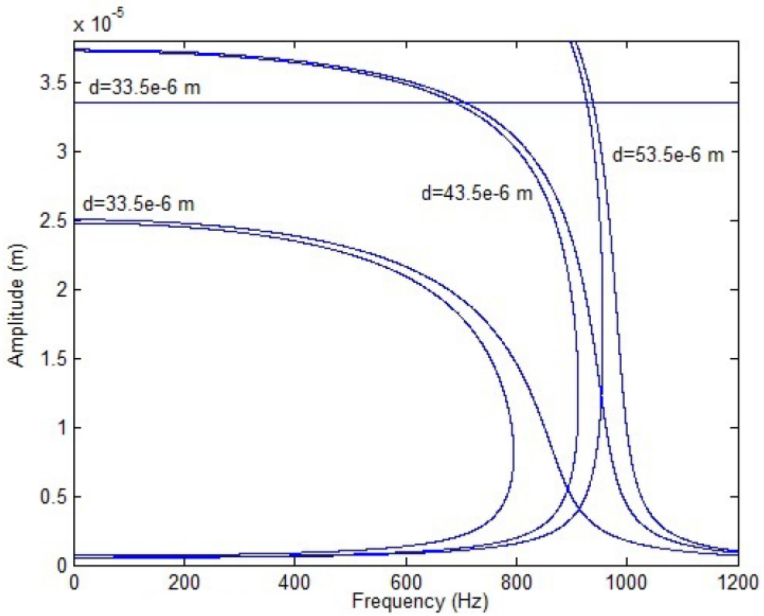
Almost 1 order of magnitude higher than average power density of previous works

P. D. Mitcheson, et al, *Proceedings of the IEEE,* vol. 96, pp. 1457-1486, 2008.

Modeling of e-VEH

With Homotopy Perturbation Method





Dr. Riccardo Marcaccioli - unpublished

Final considerations

- **MEMS/NEMS Energy harvesting systems** are becoming a promising technology to enable autonomous low-power wireless devices

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

- **Power efficiency** can be improved by:
  - Innovative electro-active materials (electrets, lead-free piezo)
  - innovative micro and nanostructures
  - Nonlinear dynamical approach: bistable systems, freqeuncy-up converters, impacting masses, electrostatic softening

- Specific **application** decides if one or many micro-VEH are the best choice with respect to one macro-scale VEH
- Micro- to nano-structures of piezoelectric materials have wide applications as **sensors**