MEMS/NEMS scale vibration energy harvesting

NiPS Summer School
July 14-18th, 2014
Perugia, Italy

Francesco Cottone

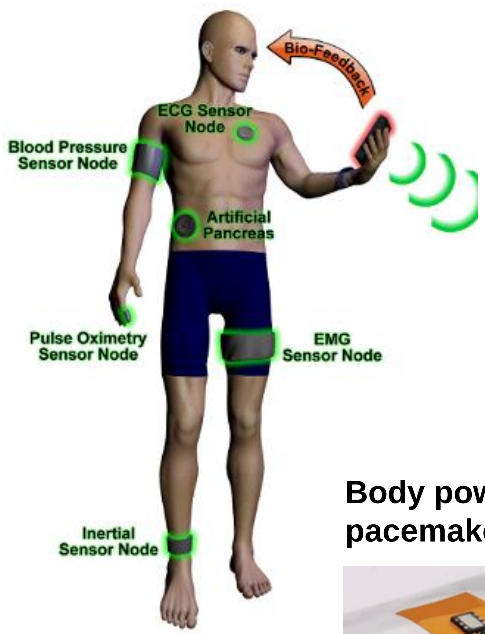
NiPS lab, Physics Dep., Università di Perugia
francesco.cottone at unipg.it

Outline

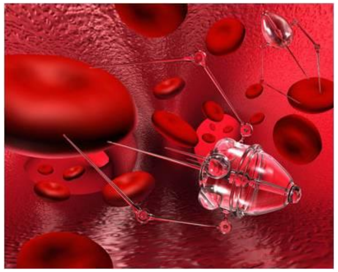
- MEMS- to NEMS-based energy harvesters and potential applications
- Micro/nanoscale energy harvesters: scaling issues
- Nonlinear and frequency-up conversion approaches
- Conclusions

MEMS- to NEMS-based harvesting devices and potential applications

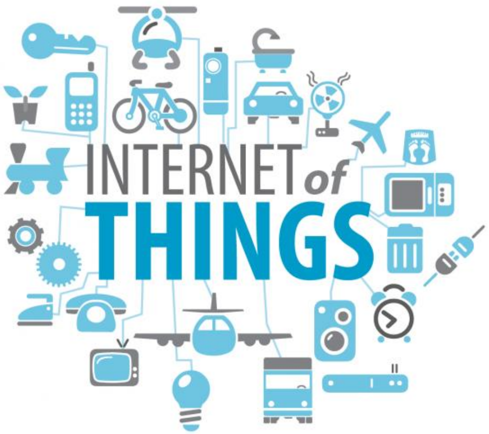
Medical applications



Nanomedicine



Internet of Things (IoT)



source: www.google.com

Body powered pacemaker

University of Illinois and University of Arizona.

https://www.youtube.com/watch?v=F11M7978n7c

Structural Monitoring

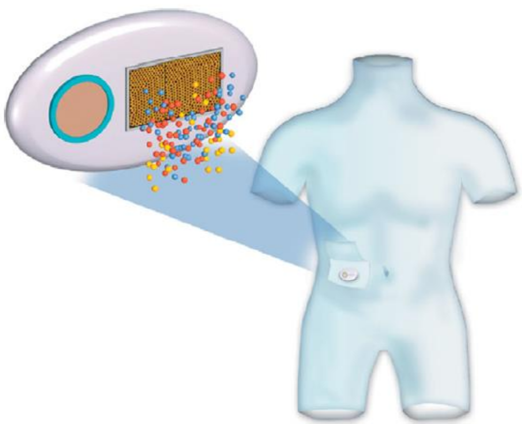
02/07/2014 - bridge collapse at FIAT factory @ Belo Horizonte (Brazil) (source: Corriere della sera)

Military/Aerospace

source: microstrain

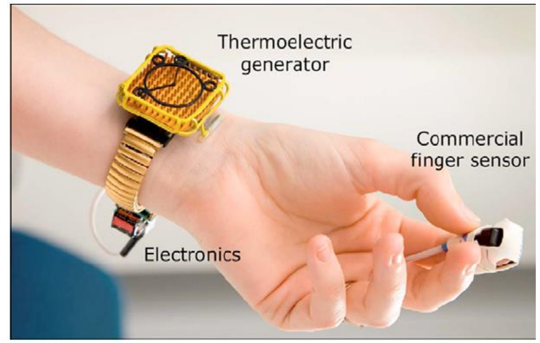
MEMS- to NEMS-based harvesting devices and potential applications

MEMS-based drug delivery systems



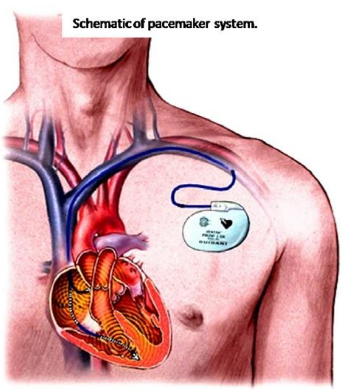
Bohm S. et al. 2000

Body-powered oximeter



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

Heart powered pacemaker

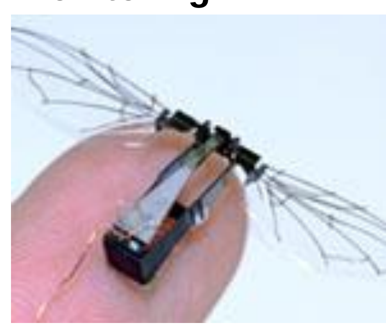


D. Tran, Stanford Univ. 2007

Pacemaker consumption is around **40uW**.

Beating heart could produce **200uW** of power from heat differentials, physiological pressures, and flows and movements, such as blood flow

Micro-robot for remote monitoring



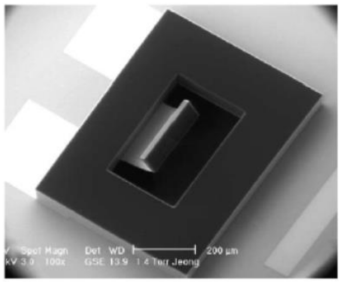
A. Freitas Jr., Nanomedicine, Landes Bioscience, 1999

A 1mm-20mg nanorobot flying at 1 m/s requires F ~ 4 microN and **P ~ 41 uW.**

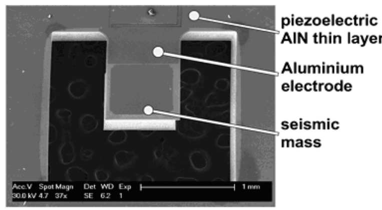
The input power for a 20mg robotic fly is **10 – 100 uW** depending on many factors: air friction, aerodynamic efficiency etc.

MEMS- to NEMS-based harvesting devices and potential applications

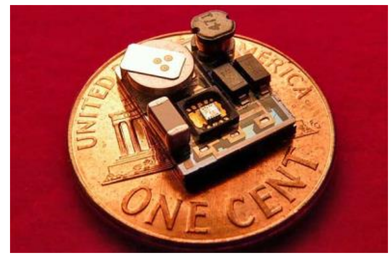
MEMS-based energy harvesting devices



Jeon et al. 2005

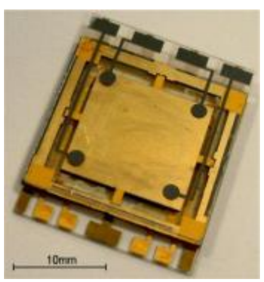


M. Marzencki 2008 – TIMA Lab (France)

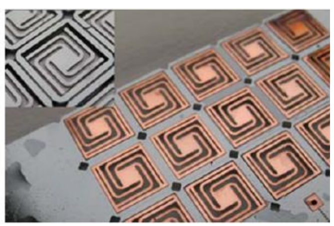


Khalil Najafi 2011 Univ. Michigan

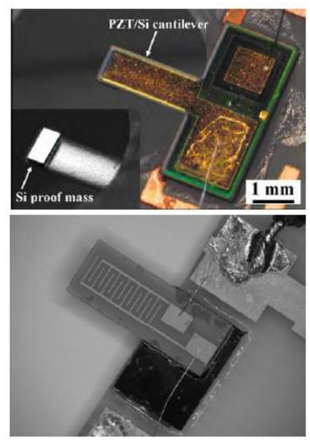
Chang. MIT 2013



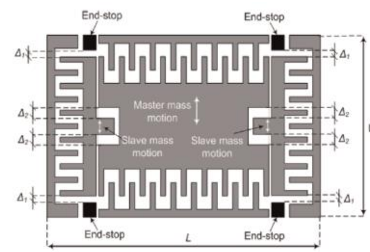
Mitcheson 2005 (UK)
Electrostatic generator 20Hz
2.5uW @ 1g



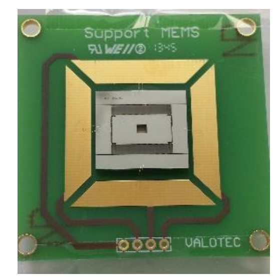
EM generator, Miao et al. 2006



D. Briand, EPFL 2010



Le, C. P., Halvorsen 2012



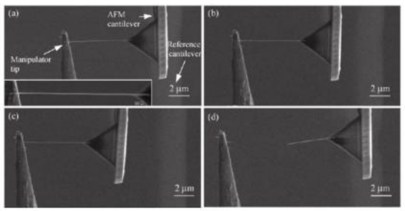
Cottone F., Basset P.
ESIEE Paris 2013-14

2005 → 2015

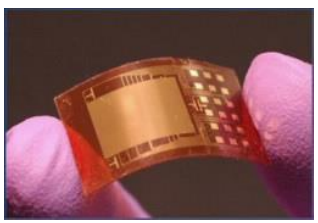
Time

MEMS- to NEMS-based harvesting devices and potential applications

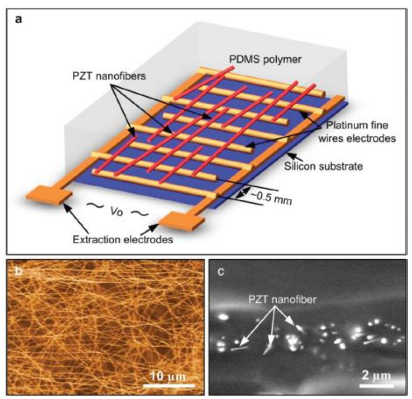
NEMS-based energy harvesting devices



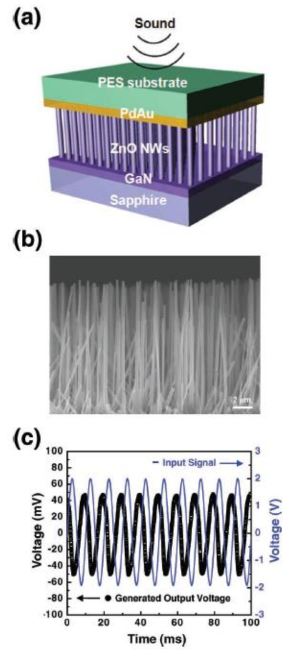
ZnO nanowires –Xu F. (2010)
tensile stress test



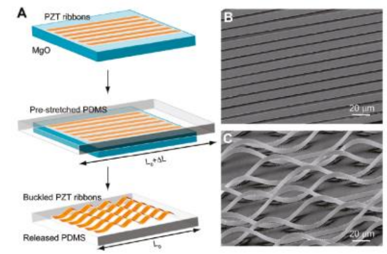
ZnO nanowires
Wang, Georgia Tech (2005)



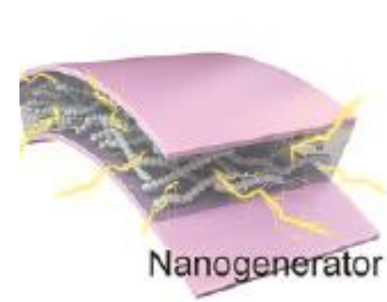
Chen, X. et al (2010) Nano letters
0,6 V – 30nW



Cha, S. (2010). Sound-driven piezoelectric nanowire-based nanogenerators. Advanced materials



Qi, Yi, 2011 Nano Letters
PZT Nanoribbons



Virus-directed BaTiO3 nanogenerator
Jeong, C. et al (2013). ACS nano,

2005 → 2015

Time

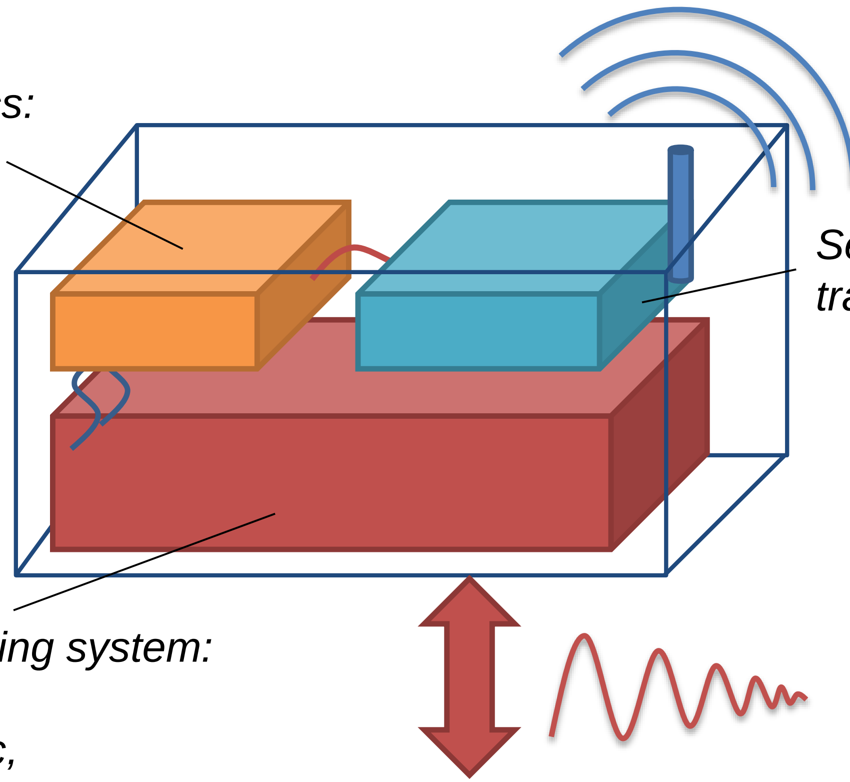
Microscale kinetic harvesters: scaling issues

Objective :

100 µW/cm³ of power density

Temporary storage
and conditioning electrinics:

- *Ultra capacitors*
- *Rechargeable Batteries*



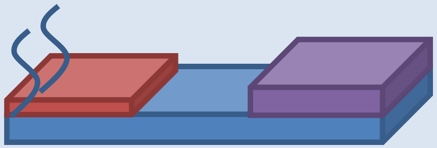
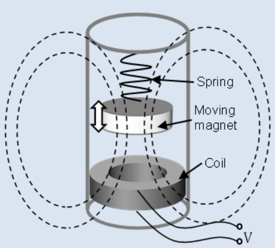
Sensor node and transceiver

Energy harvesting system:

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

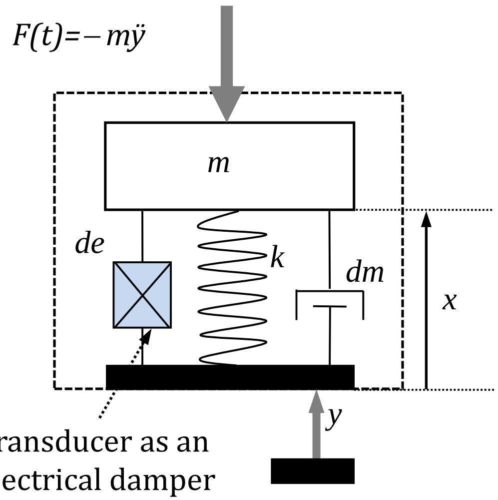
Mechanical vibrations

Who's the best for MEMS/NEMS ?

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 kinetic harvesters: scaling issues

First order power calculus with William and Yates model



Motion equation

$$m\ddot{x}(t) + (d_m + d_e)\dot{x}(t) + kx(t) = -m\ddot{y}(t)$$

Inertial force

$$f(t) = -m\ddot{y} = Y_0 \sin(\omega t)$$

$$x(t) = \frac{\omega^2}{\sqrt{\left(\frac{k}{m} - \omega^2\right)^2 + \left(\frac{(d_e + d_m)\omega}{m}\right)^2}} Y_0 \sin(\omega t - \phi)$$

Steady state solution

setting $d_T = d_m + d_e$ the total damping coefficient, the phase angle ϕ is given by

$$\phi = \tan^{-1}\left(\frac{d_T \omega}{k - \omega^2 m}\right)$$

and the natural frequency $\omega_n = \sqrt{k/m}$

By introducing the damping ratio, namely $\zeta_T = (\zeta_e + \zeta_m) = d_T / 2m\omega_n$, the position transfer fuction is expressed by

$$H_{xf}(\omega) = \frac{X(\omega)}{Y(\omega)} = \frac{\omega^2}{-\omega^2 + 2i\omega(\zeta_e + \zeta_m)\omega_n + \omega_n^2}$$

Microscale kinetic harvesters: scaling issues

First order power calculus with William and Yates model

The instantaneous dissipated power by electrical damping is given by

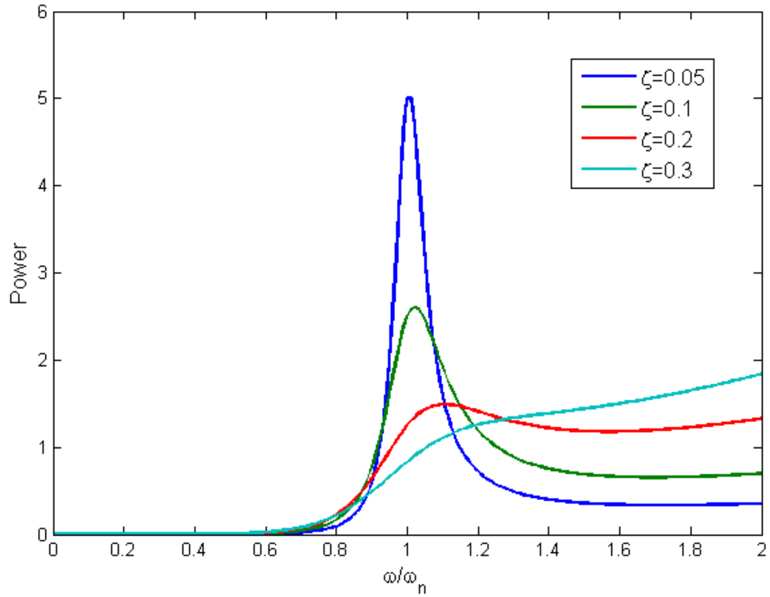
$$P(t) = \frac{d}{dt}\int_0^x F(t)dx = \frac{1}{2}d_T\dot{x}^2$$

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 $A_0=\omega_n^{\ 2}Y_0$.

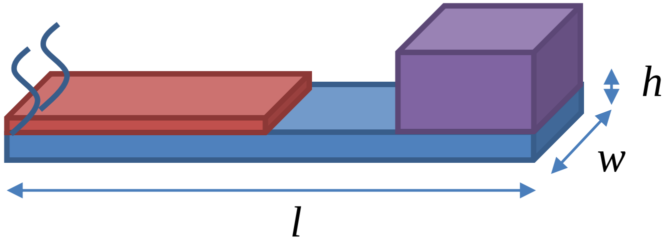
for a particular transduction mechanism forced at natural frequency ω_n, the power can be maximized from the equation

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

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

Microscale kinetic harvesters: scaling issues

PIEZOELECTRIC MATERIALS COMPARISON



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

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

$$k = \xi E w \frac{h^3}{l^3}$$

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

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

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

At max power condition $\zeta_e = \zeta_m$

By assuming

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

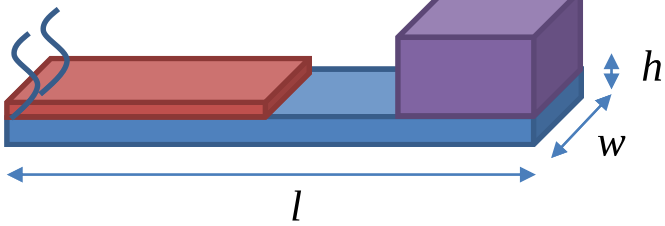
$$P_{el} = \frac{\rho_{si}/800 + 0.32 \cdot 64\rho_{mo}}{\frac{16}{200}\pi C_n \sqrt{\frac{E}{\rho_{si}}}\zeta_m} A^2 l^4$$

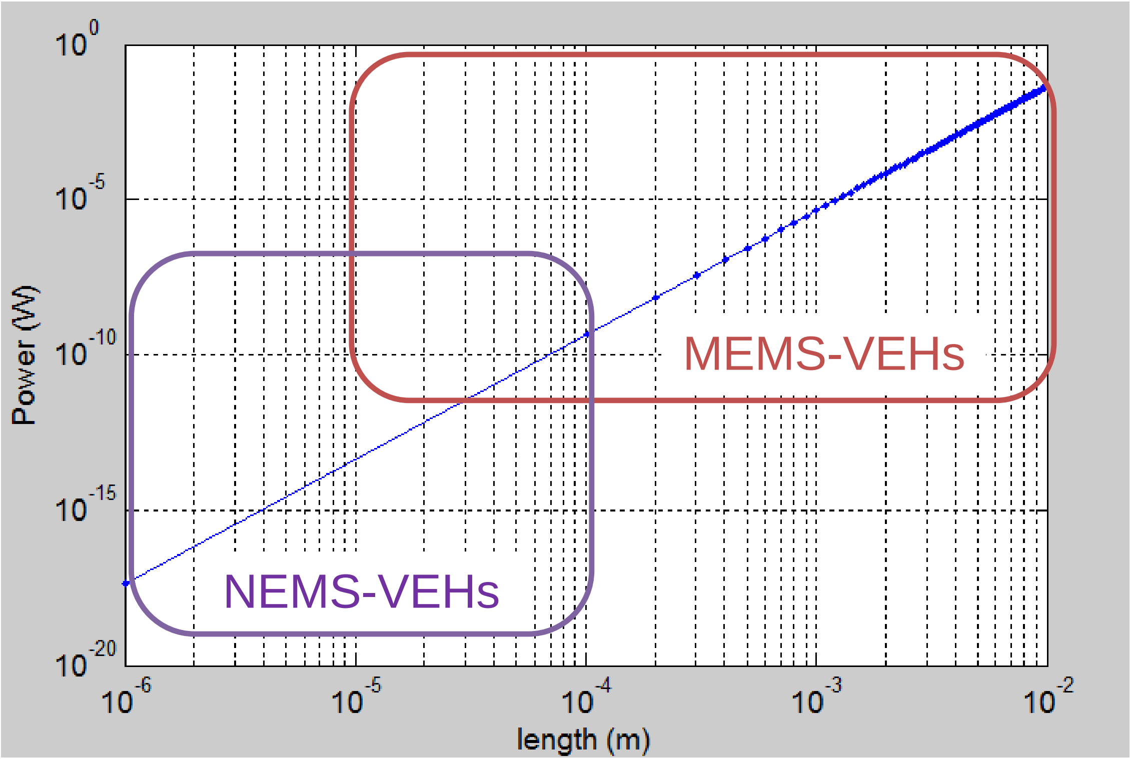
Microscale kinetic harvesters: scaling issues

PIEZOELECTRIC MATERIALS COMPARISON

By assuming

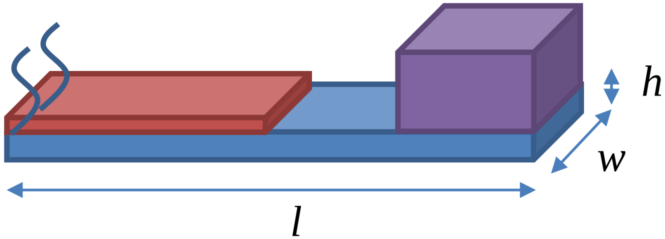
$$A = 1g$$
$$\zeta_m = 0.01$$
$$h = l/200$$
$$w = l/4$$





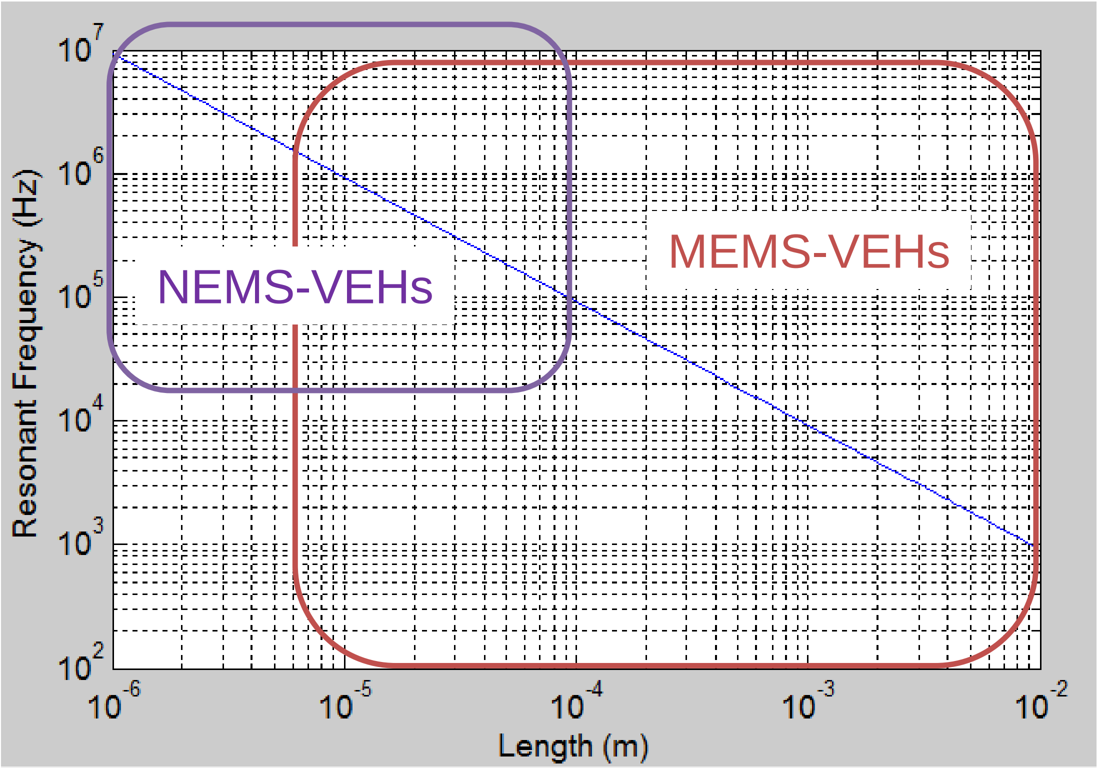
Microscale kinetic harvesters: scaling issues

PIEZOELECTRIC MATERIALS COMPARISON



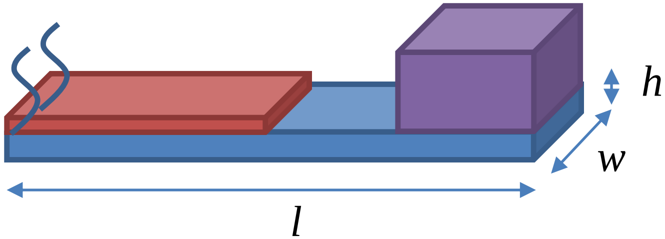
By assuming

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



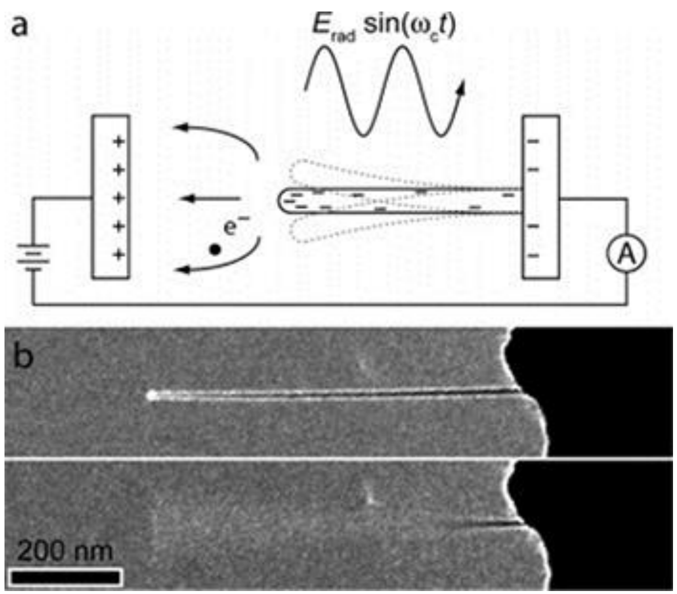
Microscale kinetic harvesters: scaling issues

PIEZOELECTRIC MATERIALS COMPARISON

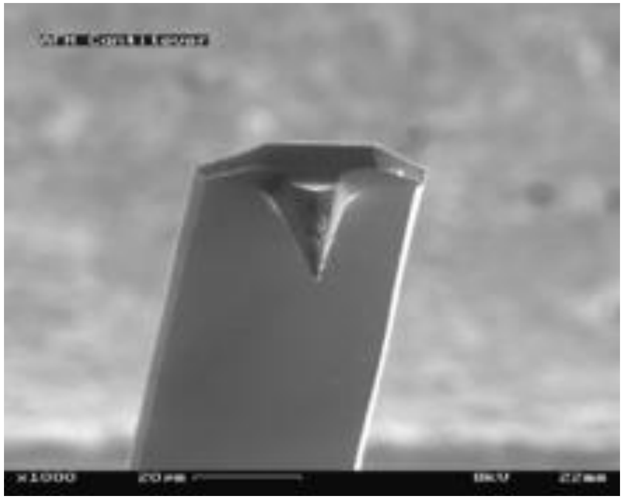


By assuming

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



Alex Zettl, California Univ. 2010



AFM cantilever

Piezoelectric conversion

Material properties example

Strain-charge

$$\mathbf{S} = \mathbf{s_E} \cdot \mathbf{T} + \mathbf{d}^t \cdot \mathbf{E}$$

$$\mathbf{D} = \mathbf{d} \cdot \mathbf{T} + \boldsymbol{\varepsilon}_\mathbf{T} \cdot \mathbf{E}$$

Stress-charge

$$\mathbf{T} = \mathbf{c_E} \cdot \mathbf{S} - \mathbf{e}^t \cdot \mathbf{E}$$

$$\mathbf{D} = \mathbf{e} \cdot \mathbf{S} + \boldsymbol{\varepsilon}_\mathbf{S} \cdot \mathbf{E}$$

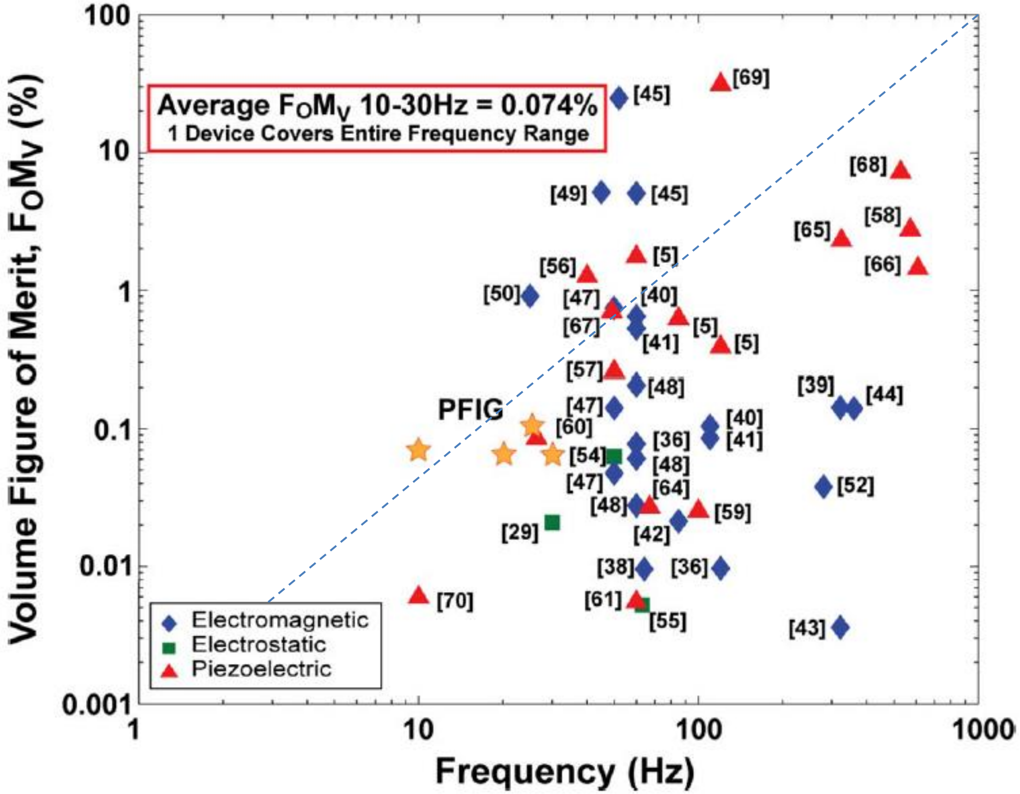
Characteristic	PZT-5H	BaTiO3	PVDF	AlN (thin film)
d_{33} (10^{-10} C/N)	593	149	-33	5,1
d_{31} (10^{-10} C/N)	-274	78	23	-3,41
k_{33}	0,75	0,48	0,15	0,3
k_{31}	0,39	0,21	0,12	0,23
ε_r	3400	1700	12	10,5

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

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

Microscale kinetic harvesters: scaling issues

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



Galchev et al. (2011)

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

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

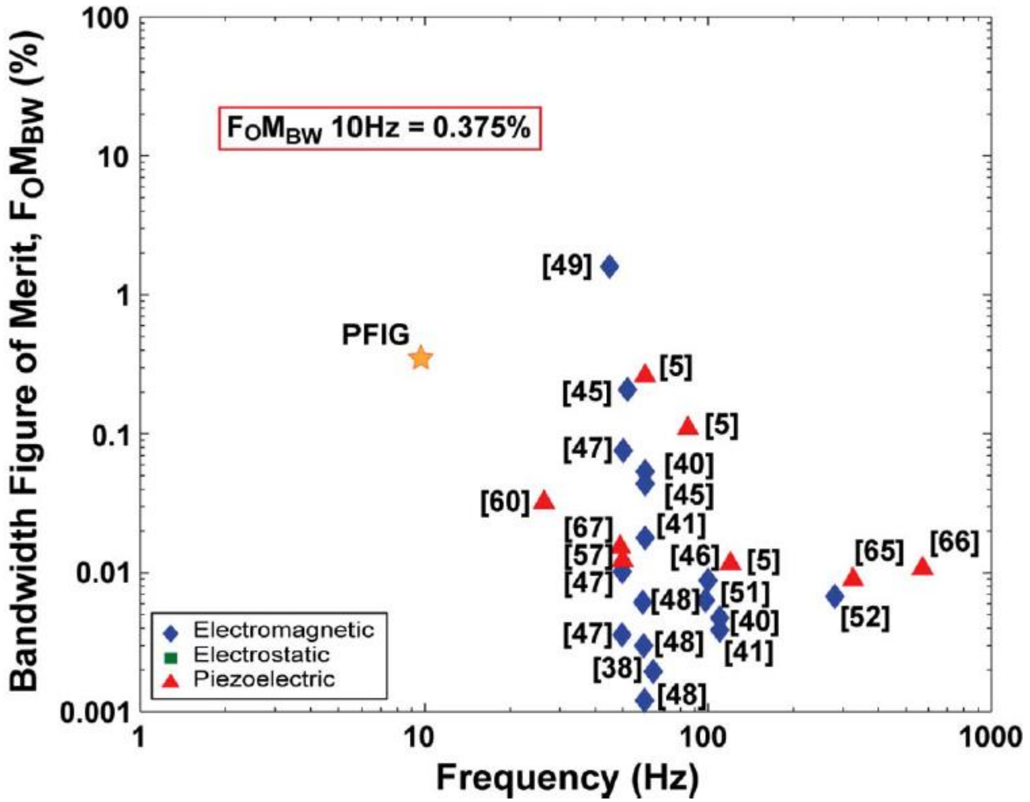
Microscale kinetic harvesters: scaling issues

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

Bandwidth figure of merit

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

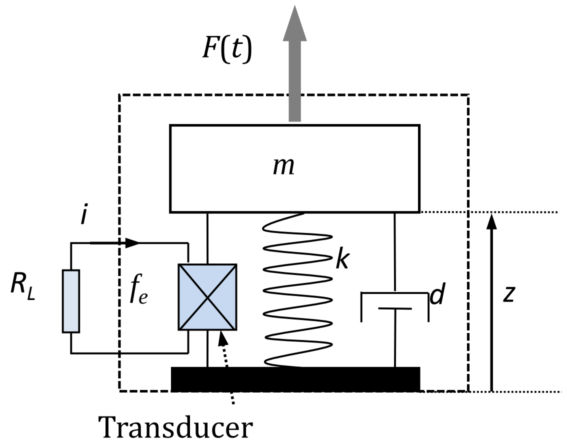
Frequency range within which the output power is less than 1 dB
below its maximum value

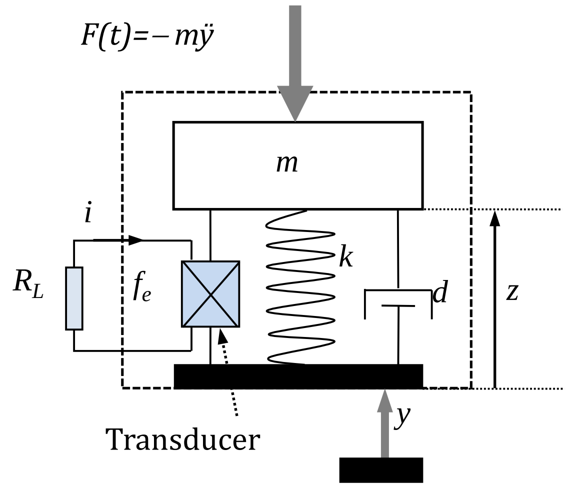


Galchev et al. (2011)

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

Microscale kinetic harvesters: scaling issues



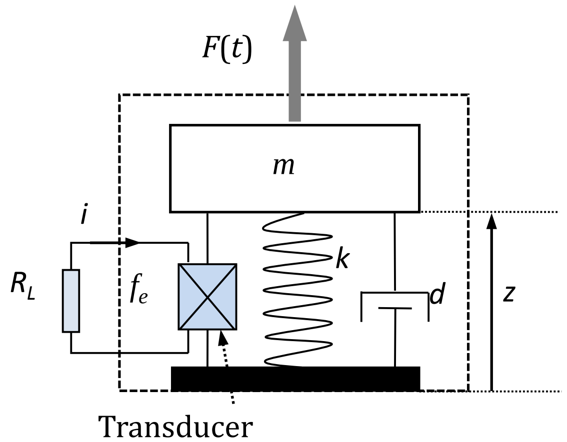


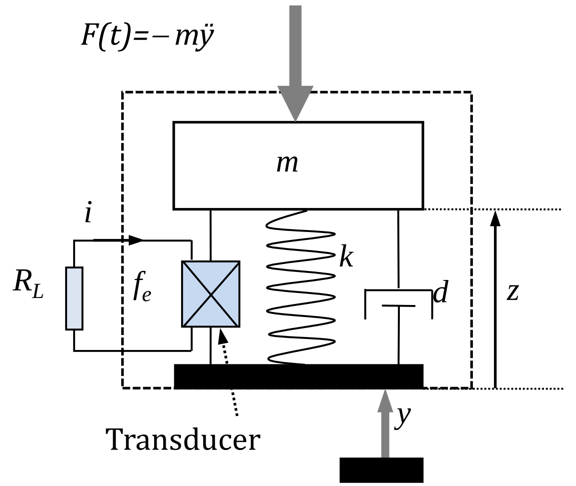
At micro/nano scale direct force generators are much more efficient because not limited by the inertial mass!!!

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

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

Microscale kinetic harvesters: scaling issues





Power fluxes

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

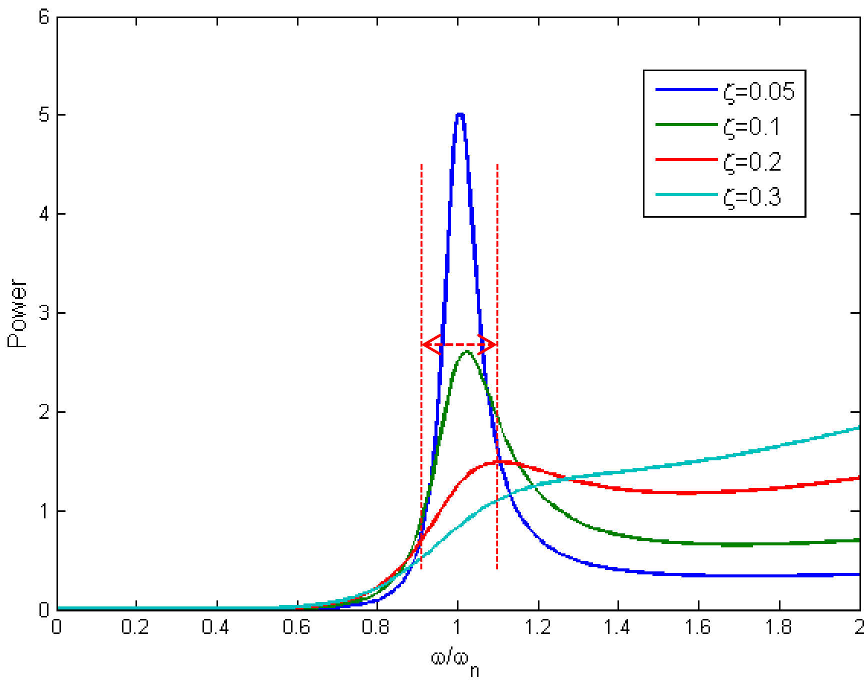
$$P_m(t) = F(t) \cdot \dot{z}(t)$$

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

Main limits of inertial resonant VEHs

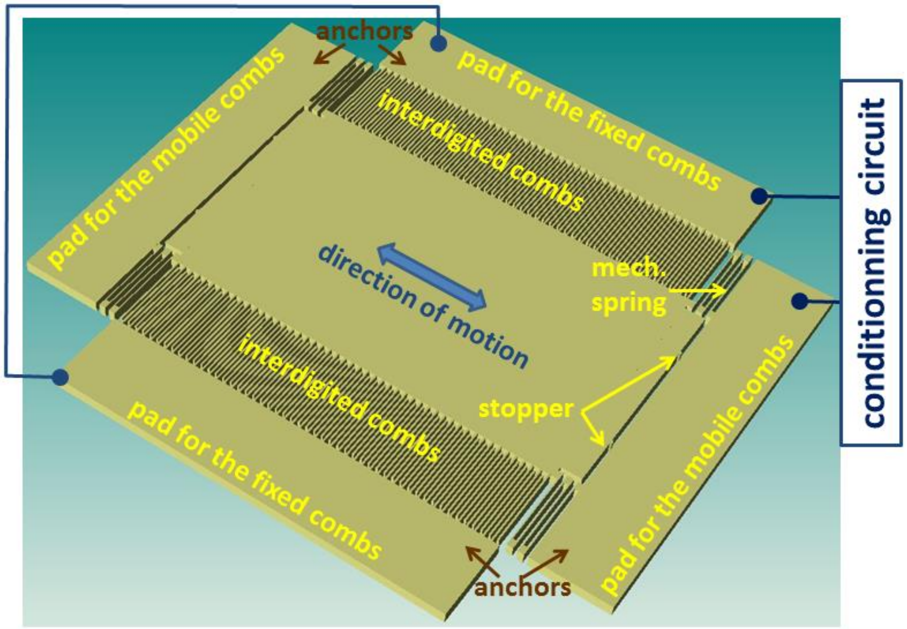
Problems at micro- to nano-scale

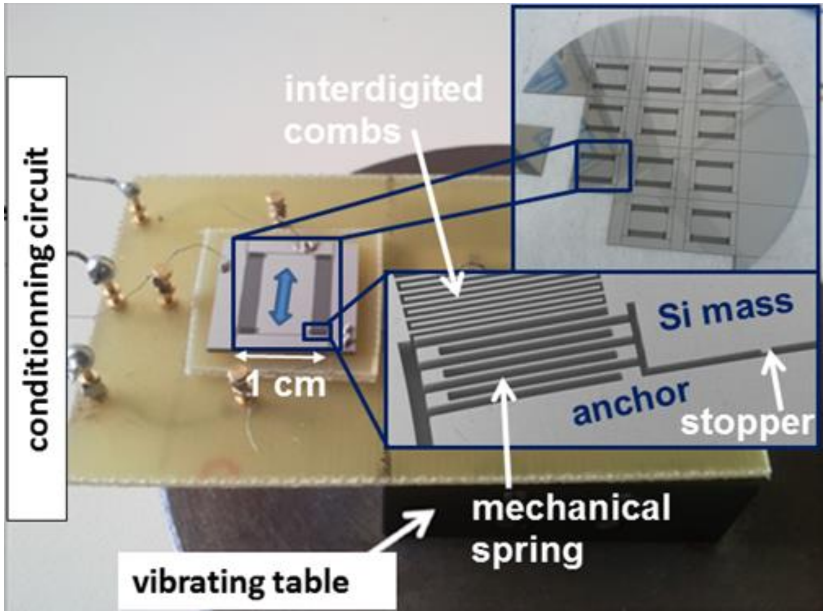
- Narrow bandwidth
- Non-adaptation to variable vibration sources
- High resonant frequency at micro/nano-scale
- Poor piezoelectric coefficient



At 20% off the resonance the power falls by 80-90%

Nonlinear MEMS electrostatic kinetic energy harvester





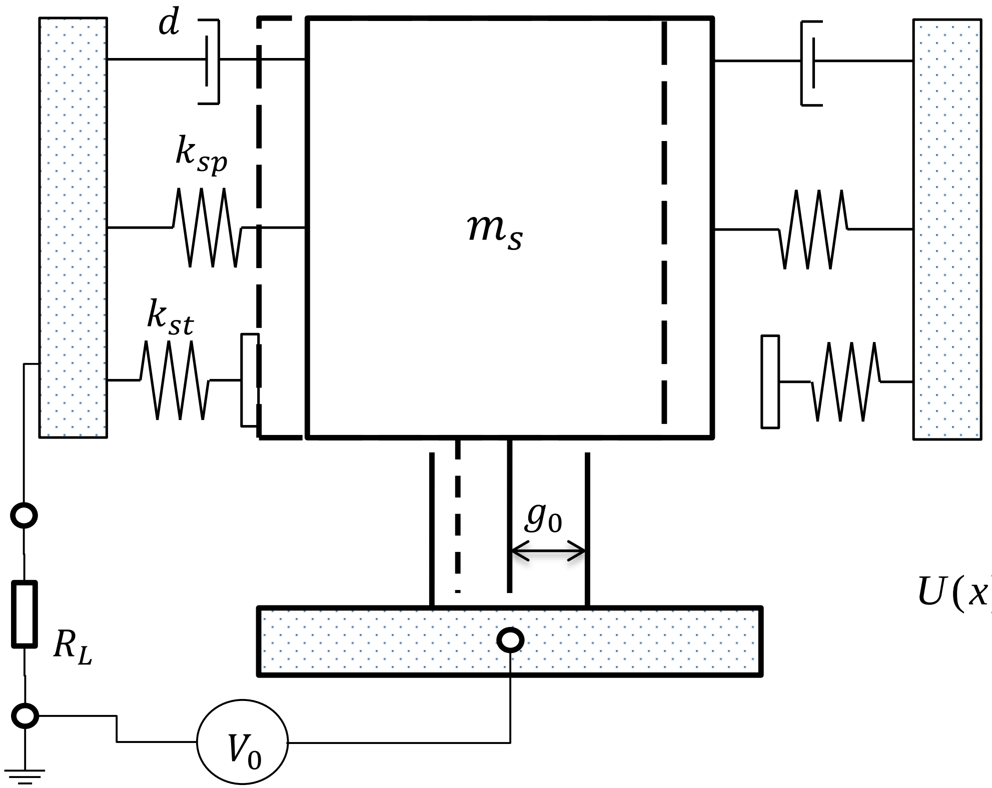
Guilllemet, R., Basset, P., Galayko, D., Cottone, F., Marty, F., & Bourouina, T. (2013).
Micro Electro Mechanical Systems (MEMS), 2013 IEEE 26th International Conference on (pp. 817-820): IEEE.

Cottone, F., Basset, P., Guillemet, R., Galayko, D., Marty, F., & Bourouina, T. (2013). *2013 Transducers & Eurosensors.*

Basset, P., Galayko, D., Cottone, F., Guillemet, R., Blokhina, E., Marty, F., & Bourouina, T. (2014). *Journal of Micromechanics and Microengineering 24(3), 035001*

Nonlinear MEMS electrostatic kinetic energy harvester

Mathematical modeling



Governing equations

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

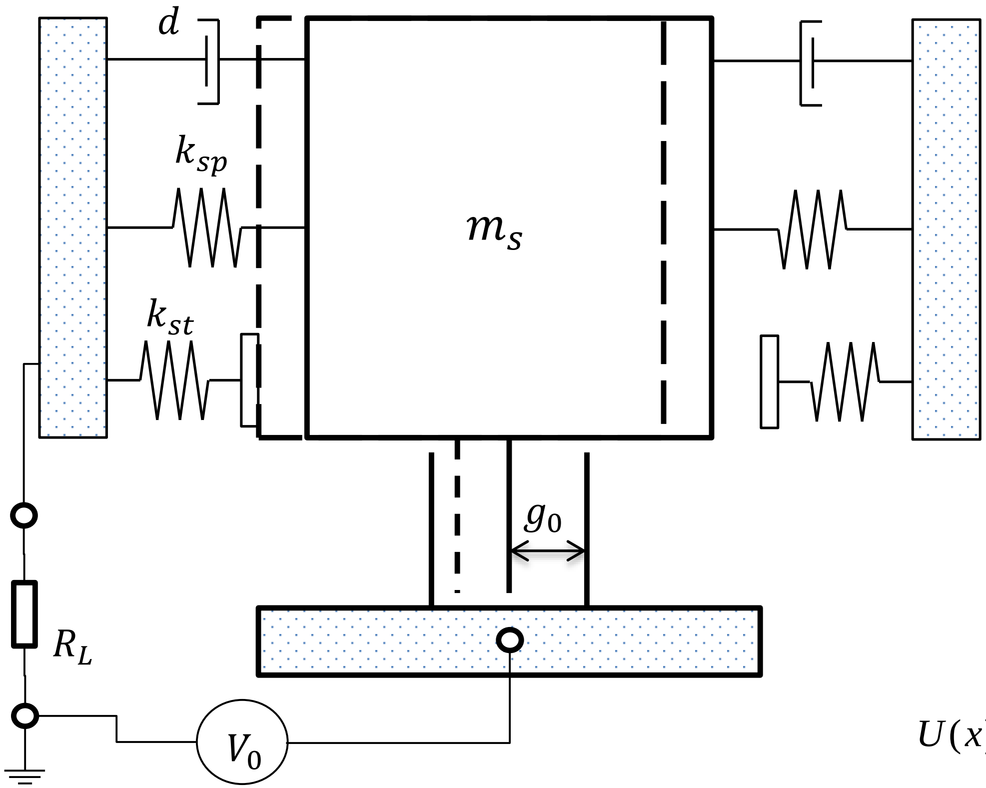
$$R_L\frac{d}{dt}(C\cdot V)+V=U_0,$$

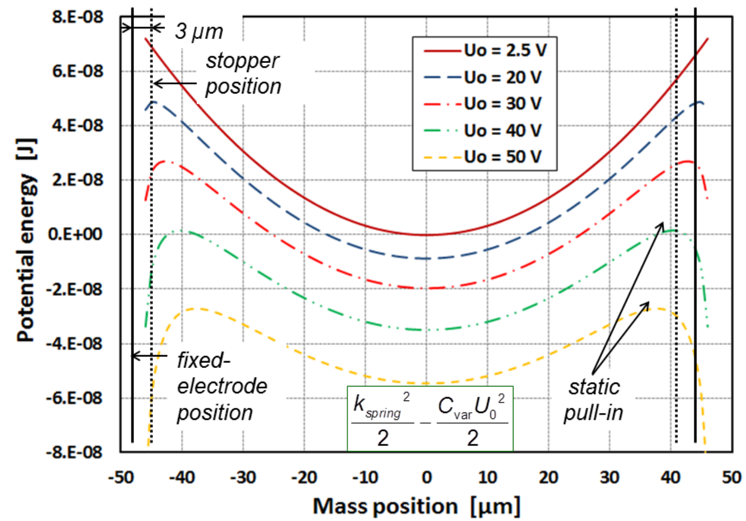
$$U(x)=\begin{cases}\frac{1}{2}k_{sp}x^2-\frac{1}{2}C(x)U_0^2, & \text{for } |x|<x_{\lim}\\ \frac{1}{2}(k_{sp}+k_{st})x^2-\frac{1}{2}C(x)U_0^2, & \text{for } |x|\geq x_{\lim}\end{cases}$$

$$C(x)=C_{par}+\varepsilon N_f l_f\frac{1}{2r}\left[\ln\left(\frac{d_0-x+2hr}{d_0-x}\right)+\ln\left(\frac{d_0+x+2hr}{d_0+x}\right)\right],$$

Nonlinear MEMS electrostatic kinetic energy harvester

Mathematical modeling

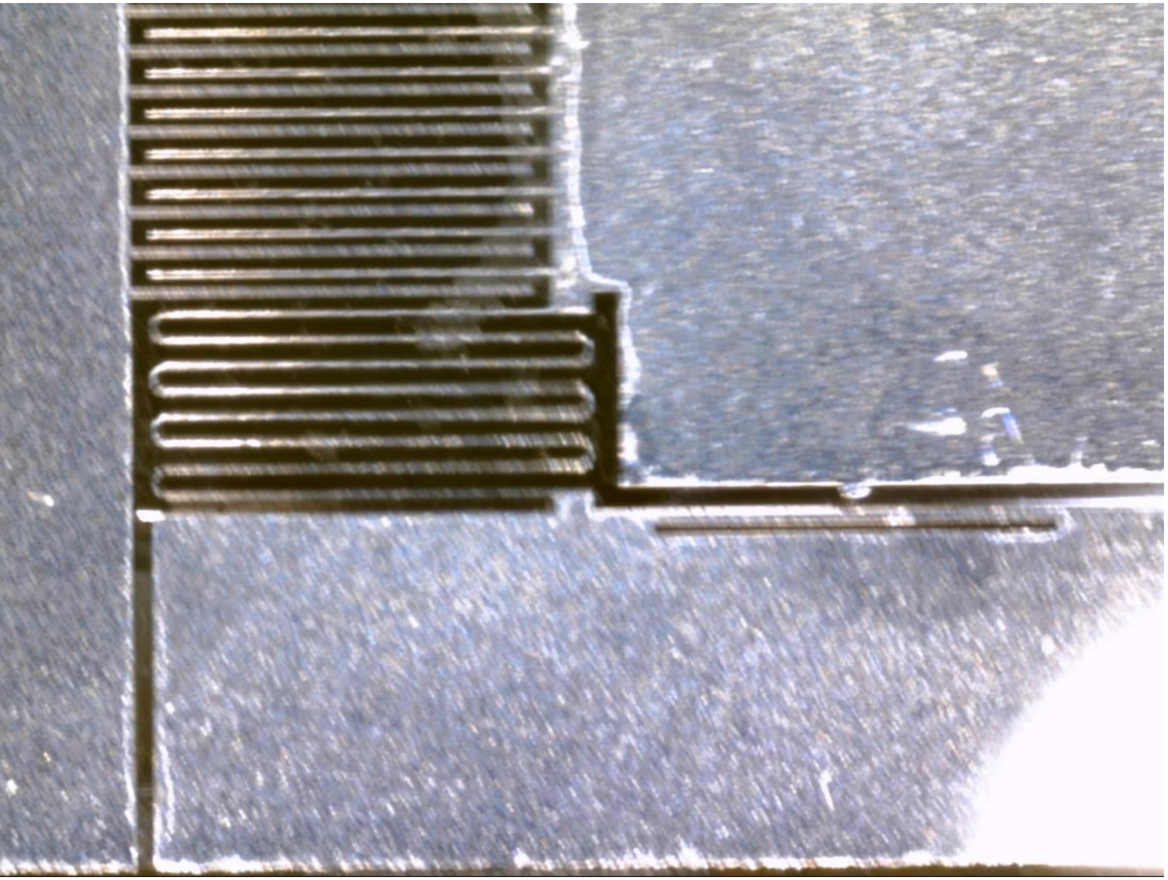


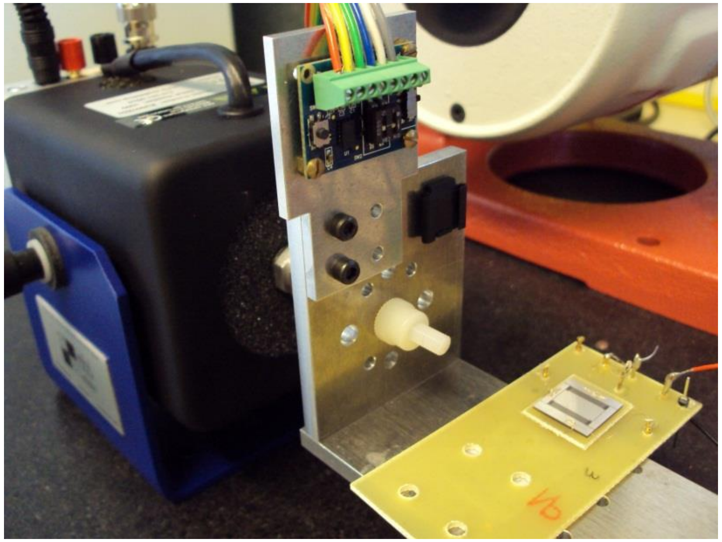


$$U(x) = \begin{cases} \frac{1}{2}k_{sp}x^2 - \frac{1}{2}C(x)U_0^2, & \text{for } |x| < x_{\lim} \\ \frac{1}{2}(k_{sp} + k_{st})x^2 - \frac{1}{2}C(x)U_0^2, & \text{for } |x| \geq x_{\lim} \end{cases}$$

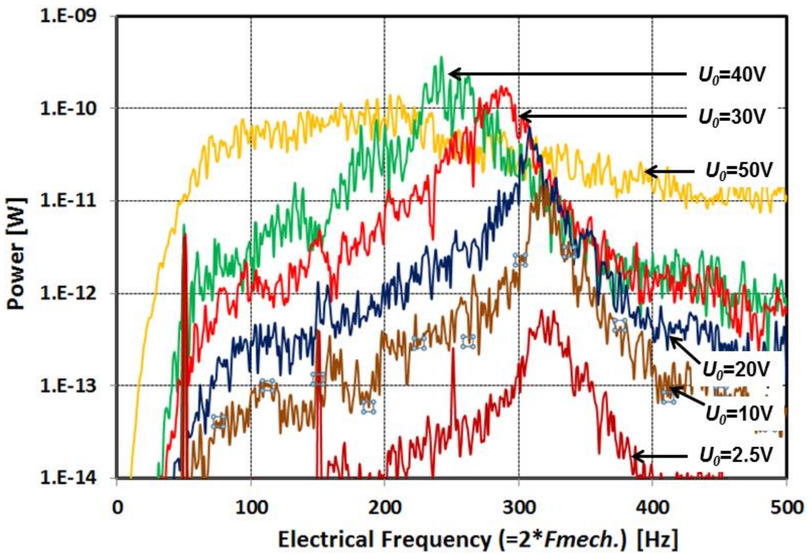
Electrostatic generators

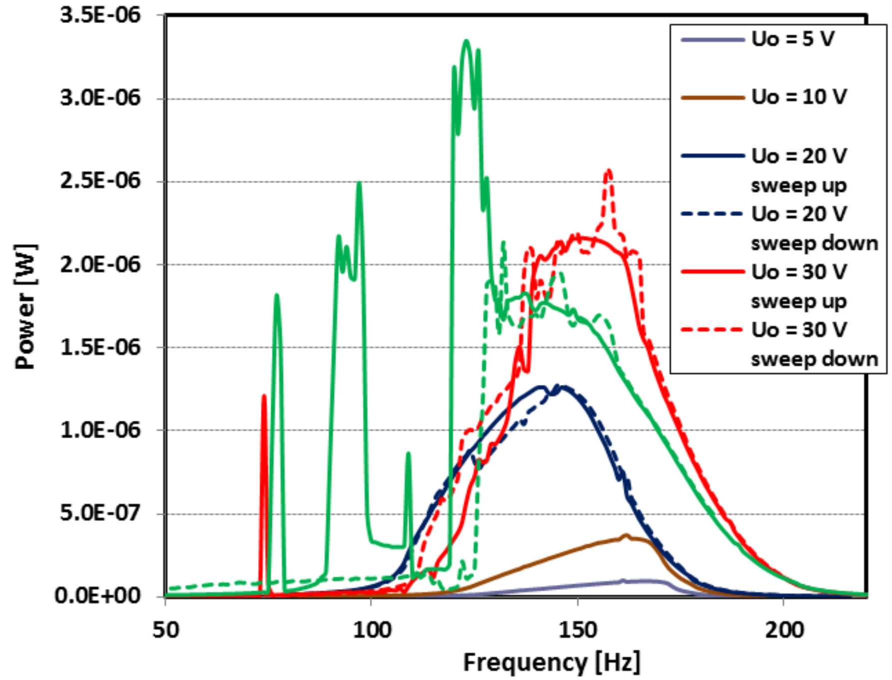
F. Cottone, P. Basset Université Paris-Est, ESIEE Paris,
Silicon MEMS-based electrostatic harvesters.





Nonlinear MEMS electrostatic kinetic energy harvester





Cottone, F., Basset, P., Guillemet, R., Galayko, D., Marty, F., & Bourouina, T. (2013). *Transducers & Eurosensors.*

Basset, P., Galayko, D., Cottone, F., Guillemet, R., Blokhina, E., Marty, F., & Bourouina, T. (2014). JMM *24*(3), 035001.

Conclusions

- Many potential applications are waiting for powerful MEMS/NEMS harvesting system to enable self-powering features
- Inertial vibration energy harvesters are very limited at small scale -> direct force piezoelectric/electrostatic devices are more efficient at nanoscale
- Design challenges
  - Materials with high electromechanical coupling,
  - Cheap miniaturization/fabrication processes
  - Very efficient conditioning electronics
- In general the specific application decides if one or many micro-VEH are the best choice with respect to one macro-scale VEH

Research activities done in collaboration with