Kinetic Energy Harvesting

NiPS Summer School 2017
June 30th - July 3rd - Gubbio (Italy)

Francesco Cottone
NiPS lab, Physics Dep., Università di Perugia, Italy
francesco.cottone at unipg.it
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?

- Thermal energy
- Solar
- Vibrations
- Hydro/wind
- Biochemical
- Radioactivity
- RF
- Traffic

Temporary Energy Storage: battery/supercap

Wireless sensor node

Wasted thermal energy

El. Interface

EH

WSN

Transmitted EM energy
Power budget

- 10 – 40W
- 100 mW – 2 W
- 1 mW – 100 mW
- 1 – 10 μW
- < 10μW

Device Power Consumption

VEHs Power Density

100-300μW/cm³ ?

Time

Zero Power ??
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 harvesting applications

Structural Monitoring

Environmental Monitoring

Military applications

Nanomedicine

Healthcare sensors
- Emergency medical response
- Monitoring, pacemaker, defibrillators

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

Train

Microwave oven

Walking person

Chicago North Bridge

Car in highway

http://realvibration.nipslab.org
Vibration sources

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Characteristics</th>
<th>Efficiency</th>
<th>Harvested Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>Outdoor/Indoor</td>
<td>10-24%</td>
<td>100 mW/cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>100 μW/cm²</td>
</tr>
<tr>
<td>Thermal</td>
<td>Human/Industrial</td>
<td>~0.1%</td>
<td>60 μW/cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td>~3%</td>
<td>~1-10 mW/cm²</td>
</tr>
<tr>
<td>Vibration</td>
<td>~Hz–human/~kHz–machines</td>
<td>25-50%</td>
<td>~4 μW/cm³</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~800 μW/cm³</td>
</tr>
<tr>
<td>RF</td>
<td>GSM 900 MHz/WiFi</td>
<td>~50%</td>
<td>0.1 μW/cm²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.001 μW/cm²</td>
</tr>
</tbody>
</table>


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**

- Moving magnet
- Spring
- Coil

**Magnetostrictive**

**Kinetic to electricity conversion techniques**

**Electrostatic/Capacitive**

- Proof mass
- Springs

**Piezoelectric**

- Base
- Pick-up coil
- MuM laminate
- Copper layer

NiPS Summer School 2017 – June 30th - July 3rd - Gubbio (Italy) – F. Cottone
Dynamical model of VEH

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

\[
\begin{align*}
    m \ddot{z} + d \dot{z} + \frac{dU(z)}{dz} + \alpha V_L &= F(t) \\
    \dot{V}_L + (\omega_c + \omega_i) V_L &= \lambda \omega_c \dot{z}
\end{align*}
\]

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

\[
\begin{align*}
    m \ddot{z} + d \dot{z} + \frac{dU(z)}{dz} + \alpha V_L &= -m \ddot{y} \\
    \dot{V}_L + (\omega_c + \omega_i) V_L &= \lambda \omega_c \dot{z}
\end{align*}
\]
Dynamical model of VEH

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

Power fluxes

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

\[ P_m(t) = F(t) \cdot \dot{z}(t) \quad P_m(t) = -m\ddot{y} \cdot \dot{z} = -\rho l^3 \cdot \dot{z} \]
Dynamical model of VEH

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

For LINEAR mechanical oscillators with elastic potential well

Laplace transform

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

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

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

Parameters that depends only on the transduction technique!
Dynamical model of VEH

For LINEAR mechanical oscillators

\[
\begin{align*}
  m\ddot{z} + d\dot{z} + kz + \alpha V_L &= -m\ddot{y} \\
  V_L + (\omega_c + \omega_i)V_L &= \lambda \omega_c \dot{z}
\end{align*}
\]

By substituting \( s=j\omega \) 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 \( \omega_c, \lambda \) and \( \alpha \) are included in the electrical damping factor \( d_e \)
Piezoelectric conversion

Unpolarized Crystal

Polarized Crystal

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

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-Curie and Henri Becquerel, for the research on the radiation phenomena discovered by Professor Henri Becquerel.
Piezoelectric conversion

Stress-to-charge conversion

Direct piezoelectric effect

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$_x$Ti$_{1-x}$]O$_3$, 0≤x≤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.

**Biological**

- Bones
- DNA
Piezoelectric conversion

\[ S = \begin{bmatrix} s_E \end{bmatrix} T + \begin{bmatrix} d^T \end{bmatrix} E \]
\[ D = \begin{bmatrix} d \end{bmatrix} T + \begin{bmatrix} \varepsilon_T \end{bmatrix} E \]

- \( S = \) strain vector (6x1) \text{ in Voigt notation} \\
- \( T = \) stress vector (6x1) [N/m²] \\
- \( s_E = \) compliance matrix (6x6) [m²/N] \\
- \( c^E = \) stiffness matrix (6x6) [N/m²] \\
- \( d = \) piezoelectric coupling matrix (3x6) in Strain-Charge [C/N] \\
- \( D = \) electrical displacement (3x1) [C/m²] \\
- \( e = \) piezoelectric coupling matrix (3x6) in Stress-Charge [C/m²] \\
- \( \varepsilon = \) electric permittivity (3x3) [F/m] \\
- \( E = \) electric field vector (3x1) [N/C] or [V/m]
Piezoelectric conversion

**converse piezoelectric effect**

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

**direct piezoelectric effect**

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

**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.

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

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

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

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

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

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>PZT-5H</th>
<th>BaTiO3</th>
<th>PVDF</th>
<th>AIN (thin film)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{33}$ (10^{-10} C/N)</td>
<td>593</td>
<td>149</td>
<td>-33</td>
<td>5,1</td>
</tr>
<tr>
<td>$d_{31}$ (10^{-10} C/N)</td>
<td>-274</td>
<td>78</td>
<td>23</td>
<td>-3,41</td>
</tr>
<tr>
<td>$k_{33}$</td>
<td>0,75</td>
<td>0,48</td>
<td>0,15</td>
<td>0,3</td>
</tr>
<tr>
<td>$k_{31}$</td>
<td>0,39</td>
<td>0,21</td>
<td>0,12</td>
<td>0,23</td>
</tr>
<tr>
<td>$\varepsilon_r$</td>
<td>3400</td>
<td>1700</td>
<td>12</td>
<td>10,5</td>
</tr>
</tbody>
</table>

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

\[
\begin{align*}
\frac{d^2 z}{dt^2} + \frac{d}{dt} k z + k_1 z + \alpha V_L &= -m \dot{y} \\
\dot{V}_L + (\omega_c + \omega_i)V_L &= \lambda \omega_c \dot{z}
\end{align*}
\]

\[
\alpha = k_d \frac{1}{h_p k_2}, \quad \lambda = \alpha R_L,
\]

\[
\omega_c = \frac{1}{R_L C_p}, \quad \omega_i = \frac{1}{R_i C_p},
\]

\[
k = k_1 k_2 E_p,
\]

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

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

Ep and Es are the Young’s modulus of piezo layer and steel substrate respectively.
Electromagnetic conversion

\[ m \ddot{z} + d \dot{z} + kz + \alpha V_L = -m \ddot{y} \]
\[ \dot{V}_L + (\omega_c + \omega_i)V_L = \lambda \omega_c \dot{z} \]

\[ \alpha = B_l / R_L, \quad \lambda = B_l = \alpha R_L, \]
\[ \omega_c = R_L / L_c, \quad \omega_i = R_i / L_c, \]
Electrostatic conversion

Governing equations

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

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

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

Figure of merit

\[ \text{FoM}_V = \frac{\text{Useful Power Output}}{\frac{1}{16} Y_0 \rho_{\text{Au}} V_0 \delta^2 \omega^3} \]

Bandwidth figure of merit

\[ \text{FoM}_{\text{BW}} = \text{FoM}_V \times \frac{\delta \omega_{1 \text{dB}}}{\omega} \]

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

Galchev et al. (2011)

Figure of merit

\[ \text{FoM}_V = \frac{\text{Useful Power Output}}{\frac{1}{16} Y_0 \rho_A V_0 \beta^2 \omega^3} \]

Bandwidth figure of merit

\[ \text{FoM}_{BW} = \text{FoM}_V \times \frac{\delta \omega_{1\ dB}}{\omega} \]

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

Galchev et al. (2011)

## Comparison of conversion techniques

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

---

**NiPS Summer School 2017 – June 30th - July 3rd - Gubbio (Italy) – F. Cottone**
Microscale energy harvesters

**MEMS-based drug delivery systems**

Bohm S. et al. 2000

**Heart powered pacemaker**

Pacemaker consumption is 40uW.

Beating heart could produce 200uW of power

D. Tran, Stanford Univ. 2007

**Body-powered oximeter**

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

**Micro-robot for remote monitoring**

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

A. Freitas Jr., Nanomedicine, Landes Bioscience, 1999
Microscale energy harvesters

Piezoelectric
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

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

\[ k = \xi \frac{Ewh^3}{l^3} \]

- Low efficiency off resonance
- High resonant frequency at miniature scales
- Power \( \rightarrow A^2/l^4 \) where A is the acceleration and l the linear dimension

<table>
<thead>
<tr>
<th>Boundary conditions</th>
<th>Uniform load ( \xi )</th>
<th>Point load ( \xi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>doubly clamped</td>
<td>32</td>
<td>16</td>
</tr>
<tr>
<td>cantilever</td>
<td>0.67</td>
<td>0.25</td>
</tr>
</tbody>
</table>

---

NiPS Summer School 2017 – June 30th - July 3rd - Gubbio (Italy) – F. Cottone
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

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

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

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

for a particular transduction mechanism forced at natural frequency \( \omega_n \), 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 energy harvesters: scaling issues

First order power calculus with William and Yates model

\[ V_{out} \]

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

\[ k = \xi \frac{Ewh^3}{l^3} \]

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

\[ P_{el} = \frac{m\xi A^2}{4\omega_n (\xi_m + \xi_e)^2} = \frac{(lwh\rho_{si} + 0.32(l/4)^3\rho_{mo})}{8\omega_n \xi_m} A^2 = \frac{(lwh\rho_{si} + 0.32(l/4)^3\rho_{mo})}{16\pi C_n \sqrt{\frac{E}{\rho_{si}}} \frac{h}{l^2} \xi_m} A^2 \]

At max power condition \( \xi_e = \xi_m \)

By assuming

\[ A = 1g \]

\[ \xi_m = 0.01 \]

\[ h = l/200 \]

\[ w = l/4 \]

\[ P_{el} = \frac{\rho_{si}}{800} + 0.32 \cdot 64\rho_{mo} \frac{A^2 l^4}{16} \]

\[ \frac{16}{200} \pi C_n \sqrt{\frac{E}{\rho_{si}}} \xi_m \]
Microscale energy harvesters: scaling issues

By assuming

\[
A = 1g \\
\zeta_m = 0.01 \\
h = l / 200 \\
w = l / 4
\]
Piezoelectric micro-pillars

ZnO nanowires forest

ZnO Pillar

Wang 2004

X. Wang 2011
Piezoelectric micro-pillars

Hydrothermal synthesis
Length: 15 μm
Thickness: 4 – 6 μm

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 \( \mu \)m
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. horizontal)
- Use of the device as VEH and vibration sensor
- Fabrication of same device with BaTiO3
- Use of the piezo pillars as micro electro-mechanical antenna

Microfibre-Nanowire:

Piezoelectric ribbon:

Microantenna:

Wang (2008)

Yang (2009)
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 being 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 decides whether it is convenient to use macro-scale VEH.

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