Advanced MEMS and Microsystems

Dr. Danick Briand, Prof. Guillermo Villanueva

Announcements

TODAY 20 May 2025

- **Lecture on PowerMEMS (2h)**
- **Seminar Melexis at 12h15**

NEXT WEEK 27 May 2025

- **Handle-in your answers for the seminar from Melexis**
- **NO CLASS: Quiz to be done at home**

Course content and schedule

Dates	Topics	Lecturers
18.02	Introduction Transducers review: pre-recorded lectures	D. Briand / G. Villanueva
25.02	Sensors part I Exercices	D. Briand
04.03	Sensors part II Industrial seminar #1	D. Briand
11.03	Students presentations	D. Briand / G. Villanueva
18.03	Actuators and Optical MEMS Industrial seminar #2	D. Briand
25.03	Acoustic and Ultrasonic MEMS Industrial seminar #3	G. Villanueva
01.04	RF-MEMS	G. Villanueva
08.04	NEMS	G. Villanueva
15.04	Interactive session	D. Briand / G. Villanueva
29.04	Thermal and gas sensors Industrial seminar #4	D. Briand
06.05	Packaging	D. Briand
13.05	Packaging Industrial seminar #5	D. Briand
20.05	PowerMEMS Industrial seminar #6	D. Briand
27.05	Quiz at home NO CLASS	All

LESSON 09 – PowerMEMS

Dr. Danick Briand

Maître d'Enseignement et de Recherche (MER)

Team leader MEMS & Printed Microsystems

EPFL-STI-LMTS

Content

1. Introduction to PowerMEMS
2. Micro energy harvesting
   - Thermal
   - Vibrations

MEMS devices

- **MEMS**
  - Mechanical sensors and actuators
- **MOEMS and Optical MEMS**
  - Sensing or manipulating optical signals at the micro-scale
- **RF-MEMS**
  - Refers to components of which moving sub-millimeter-sized parts provide RF functionality
- **BioMEMS**
  - Biological matter is manipulated to analyze and measure its activity / biological and biomedical analysis and measurements and micro total analysis systems
- **PowerMEMS**
  - Micro devices for power supply and energy scavening and harvesting

Energy storage

- Electrochemical batteries have been a dominant form of energy storage for the past 100 years
- Batteries are probably the easiest power solution for wireless electronics because of their versatility

The strongest competitor !

- *Primary* batteries irreversibly transform chemical energy to electrical energy
- *Secondary* batteries can be recharged;
  they can have their chemical reactions reversed by supplying electrical energy to the cell, restoring their original composition

Super capacitor, ultracapacitor, electrochemical capacitor

- Standard capacitors can provide significantly higher power densities than batteries, energy density lower by about 2 to 3 orders
- Supercapacitor: higher energy density than standard capacitor and retain long life and short charging time
- Supercapacitor store ionic charge in an electric double layer to increase their effective capacitance

CAP-XX offers a very low profile.

- Energy density 1 order of magnitude higher than standard capacitor and 1 to 2 orders of magnitude lower than rechargeable batteries

- Larger operating temperature range (-40 to 85 °C) than a battery

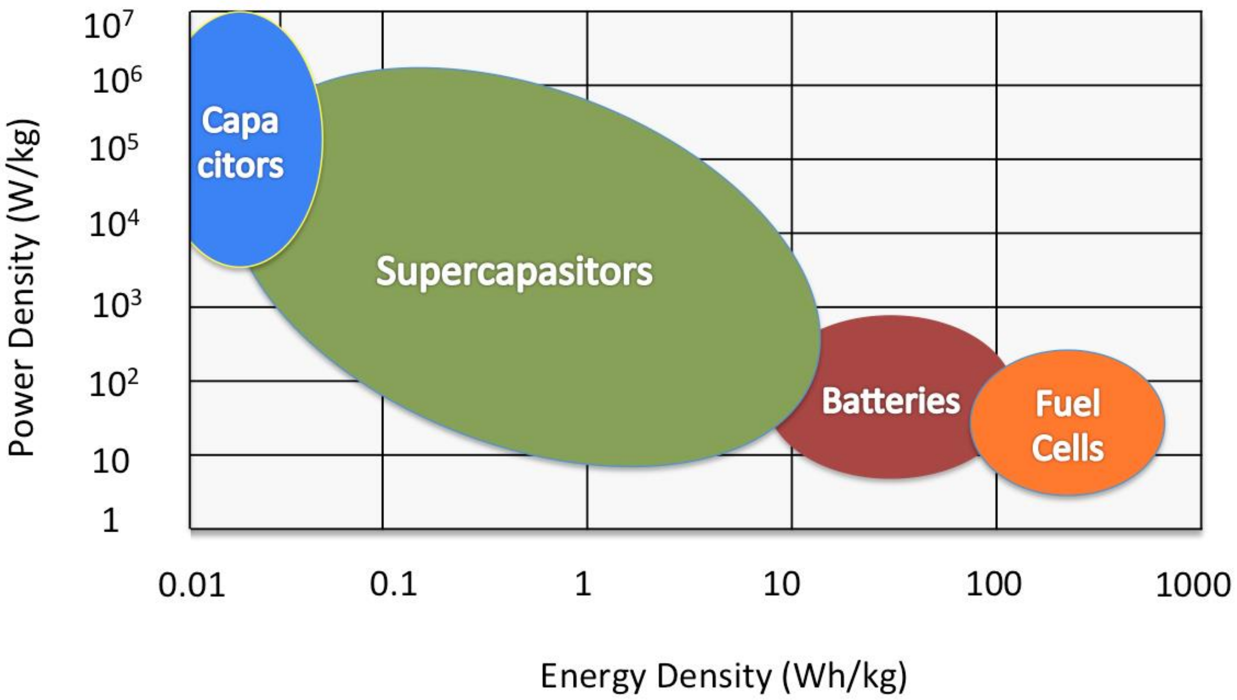
- Low impedance source for peak current loads (interesting for wireless communication)

- Several discharging and charging cycles (millions)

- However, supercaps exhibit relatively high self-discharge current

Battery vs. Supercapacitors

- **Comparison**



Why not stick to batteries ?




10W 1W 1mW 100μW 10μW 1μW

- ***Batteries***
  - Storage of energy but limited in power
  - Progresses are really small year by year
  - Lifetime limitation
  - Internal resistance variation
  - Limited temperature of operation
  - Volume
  - Maintenance
  - Environmental concerns

- ***Categories of devices to power***

– **Consumer goods eliminating the need to connect to the power grid (the W)**

– **Large scale distributed smart systems with no maintenance and reduced size (The mW and the μW)**

Potential solutions

- Improve energy density of storage systems
- Develop different methods to distribute the power to nodes
- Develop technologies that enable a system to generate or « harvest » its own power

Alternative energy sources and power devices

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-
-
-
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Physical energy sources

- *Nuclear*
- *Radioactivity*
- *Light*
- *Heat*
- *Wind*
- *Acoustics, vibrations*
- *Geothermal*
- *Tides*

Radio frequency power distribution

- *For electronics ID tags (RFID), smart tags*
  - More effective when focused on a specific location
  - Simple model neglecting reflections and interference: power received:

$$P_r = \frac{P_0 \lambda^2}{4\pi R^2}$$

Most likely in indoor environment: $1/R^4$

P_0: transmitted power, λ: wavelength, R is the distance between transmitter and receiver

  - Frequency in 2.4-2.485 GHz, 5 meters, 1 Watt transmitter, the power received at the node would be 50 µW

Light / Solar cells

- *Midday sunny day: incident sun light has a power density of roughly 100 mW/cm^2 at the surface of the earth*
  - *Single crystal silicon solar cells exhibit effiencies of 15 -20 % outdoor*
- *Light office: 100 $\mu W/cm^2$ at the surface of a desk*
  - *Thin film amorphous silicon or cadnium telluride cells indoor at 10% efficiency*
- *Power available from 15 mW/cm^2 outdoors to 10 $\mu W/cm^2$ indoors*

Power from a cadnium telluride solar cell at various distances from a 60 W incandescent bulb and under standard office lighting conditions.

Distance (cm)	20	30	45	Office light
Power ($\mu W/cm^2$)	503	236	111	7.2

Temperature gradients

- ***Maximum efficiency of power conversion from a temperature difference is equal to the Carnot efficiency:***

$$\eta = \frac{T_{high} - T_{low}}{T_{high}}$$

Room temperature of 20°C:
source 5°C above = 1.6%
source 10°C above = 3.3.%

- ***Amount of heat flow (power) is given by:***

$$q' = k\frac{\Delta T}{L}$$

Silicon at 140 W/mK, 5°C difference, 1 cm length:
Heat flow = 7 W/cm^2, at Carnot efficiency : 117 mW/cm^2

k: thermal conductivity of the material
L: length of the material

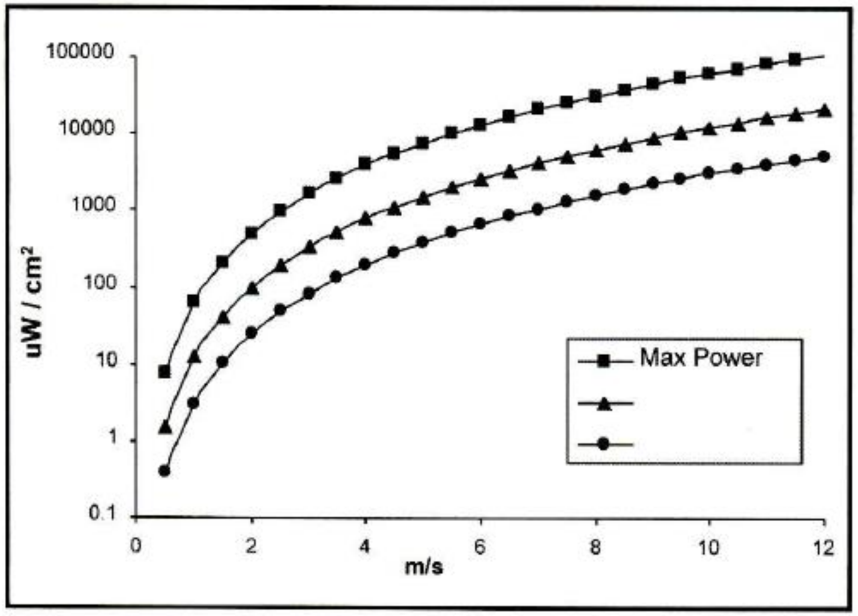
Acoustics, vibrations

- **Energy in the form of acoustic waves: a sound wave of 100 dB in sound level only has a power level of 0.96 µW/cm^2**
- **Low level vibrations occur in many environments:**
  - **Large commercial buildings, automobiles, aircrafts, ships, trains, industrial environments, machine tools…**
  - **Potential of 300 µW/cm^3 in such environments**

Wind / air flow

– *Potential power from moving air is:* $P = \frac{1}{2}\rho A v^3$

ρ: density of air
(1.22 kg/m3 at AtmPressure)
A: cross-sectional area
υ: air velocity



← 20%
← 5%

5 m/s = 18 km/hour

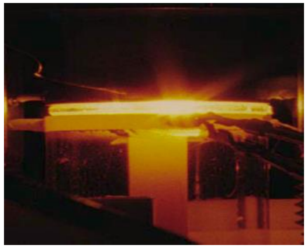
Maximum power density vs. air velocity. Power density assuming 20% and 5% conversion efficiencies are also shown [4].

Alternative power sources

Power Source	P/cm³ (µW/cm³)	E/cm³ (Whr/cm³)	P/cm³/yr (µW/cm³/Yr)	Secondary Storage Needed	Voltage Regulation	Comm. Available
Primary Battery	-	0,80	90	No	No	Yes
Secondary Battery	-	0,30	34	-	No	Yes
Micro-Fuel Cell	-	0,97	110	Maybe	Maybe	No
Ultra-capacitor	-	0,03	3.2	No	Yes	Yes
Heat engine	-	0,93	106	Yes	Yes	No
Radioactive(^{63}Ni)	0.52	0,46	0.52	Yes	Yes	No
Solar (outside)	15000 *	-	-	Usually	Maybe	Yes
Solar (inside)	10 *	-	-	Usually	Maybe	Yes
Temperature	40 *	-	-	Usually	Maybe	Limited
Human Power	330	-	-	Yes	Yes	No
Air flow	350	-	-	Yes	Yes	No
Pressure Variation	17	-	-	Yes	Yes	No
Vibrations	200	-	-	Yes	Yes	Limited
Strain induced	200	-	-	Yes	Yes	Limited

Micro power devices and systems

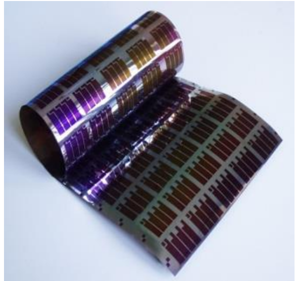
- **Two main categories:**
  - ➢ Generator (batteries, micro-heat engines, fuel-cells)



MIT Turbine

MTI fuel cell

  - ➢ Harvesters / scavengers (solar cells, mechanical, thermal)



VHF Technologies (CH)

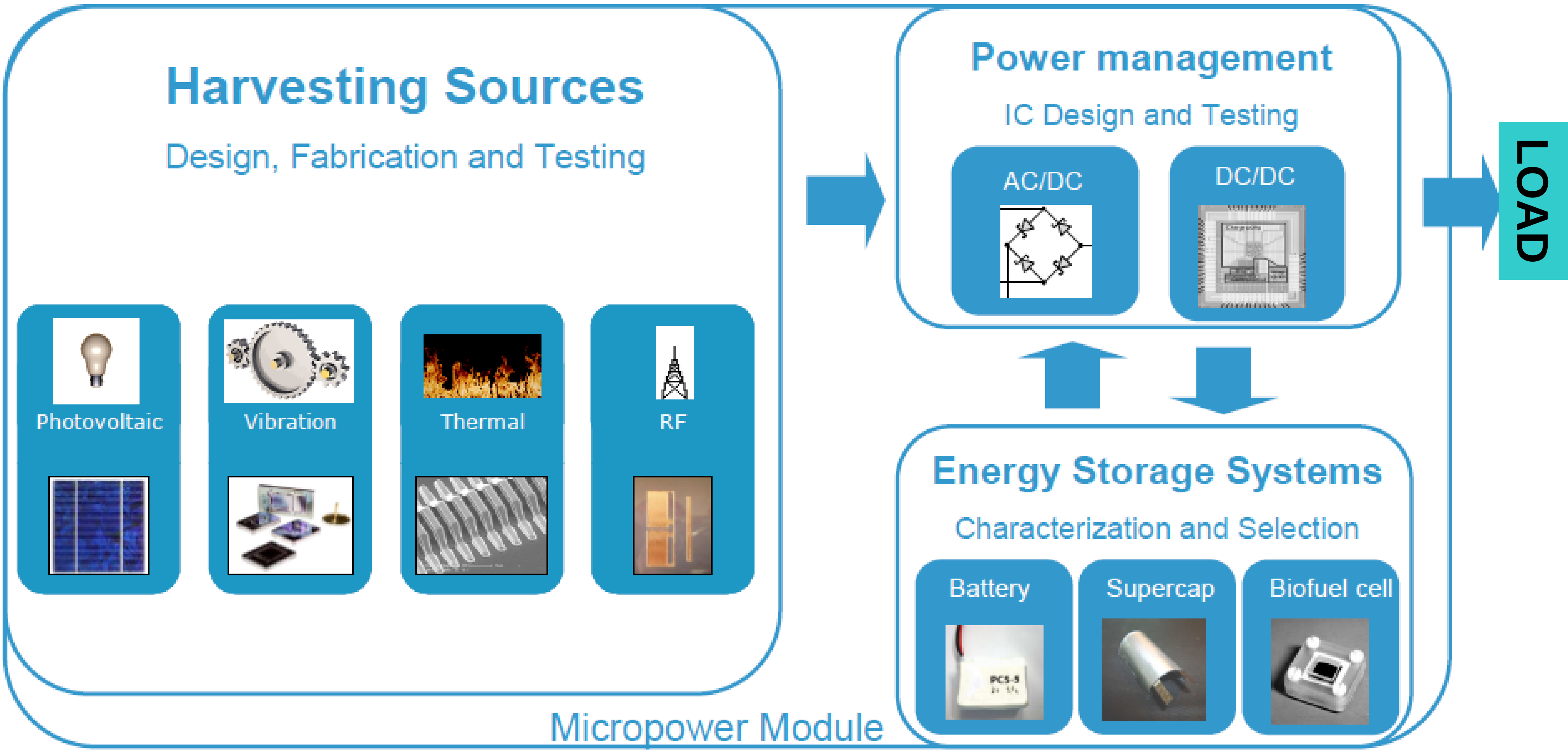
Perpetuum (UK)

Micropelt (DE)

Content Micro energy harvesting

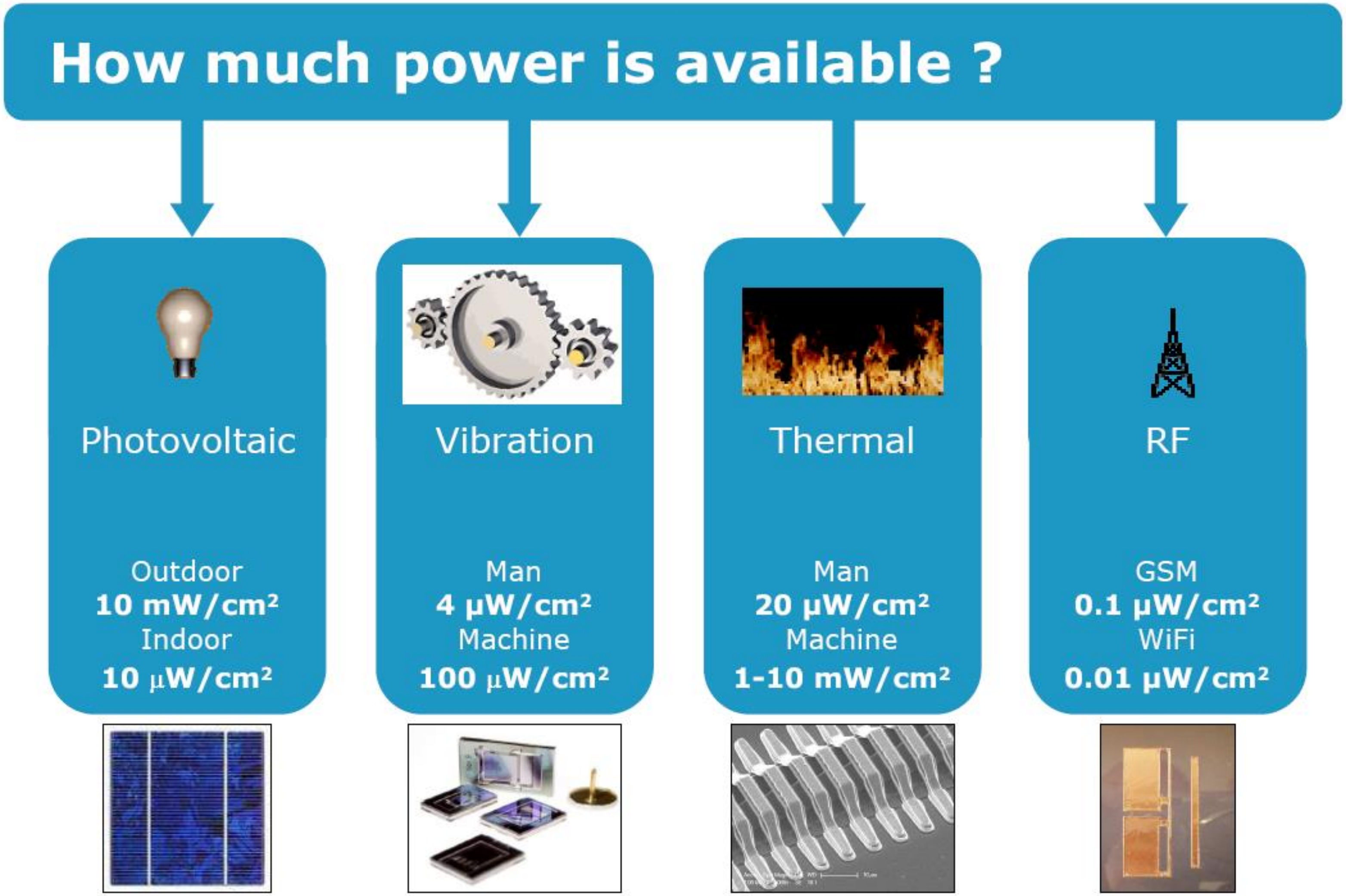
- **Sources of energy and harvesting approaches**
- **Thermal energy harvesting**
- **Vibration energy harvesting**
- **Some applications**
- **Conclusions and perspectives**

No practical power without power management



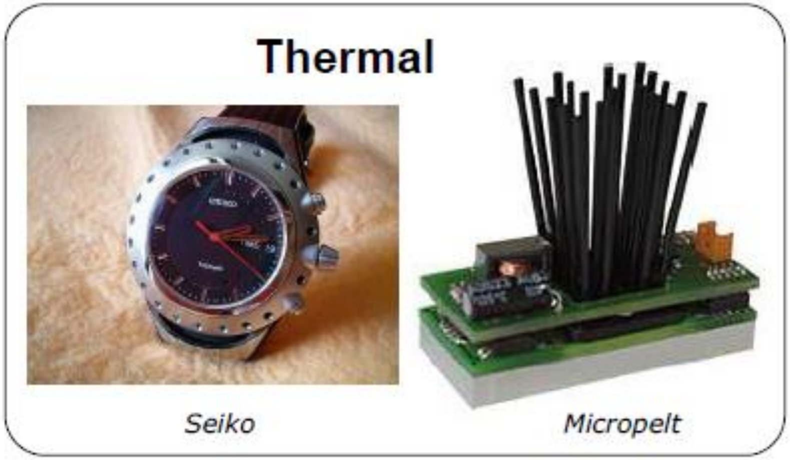
IMEC - Holst Center

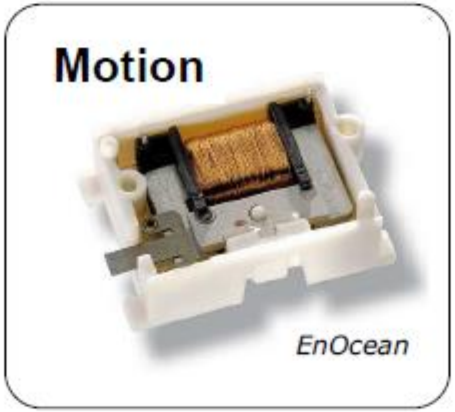
Power available



*Vullers et al, Micropower Energy Harvesting, Solid-State Electronics 53 (7) Pgs 684-693, DOI: 10.1016/j.sse.2008.12.011

Energy harvesters getting smaller





HOWEVER … today's systems are only addressing niche applications:

- too little power generated
- or too big/heavy
- too expensive

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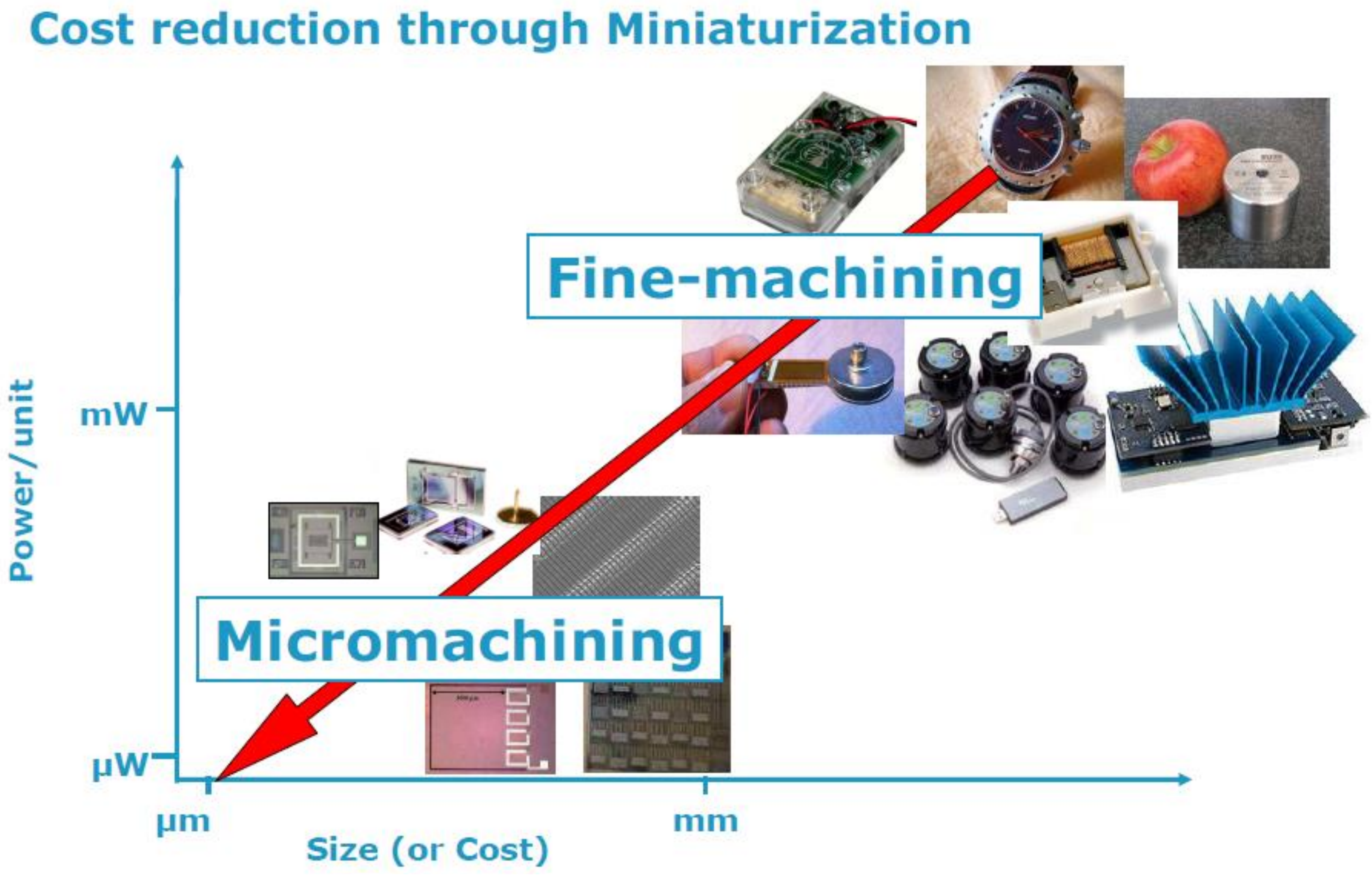
Towards miniaturization



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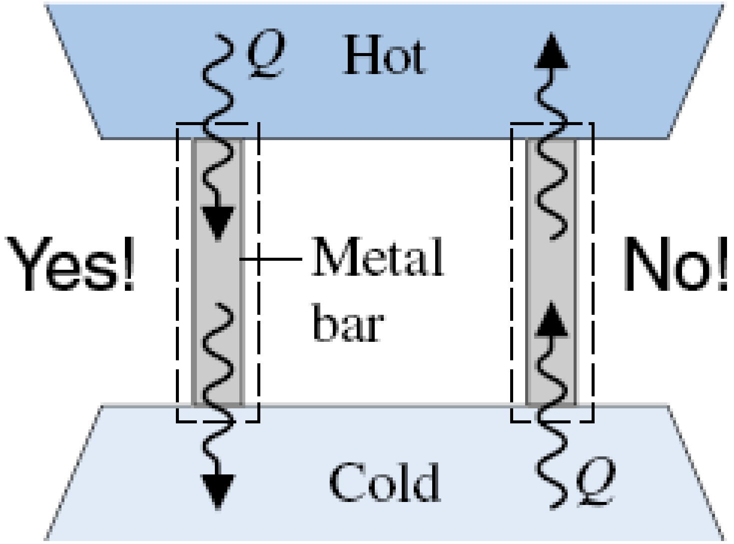
Principles and definitions

- ***Heat Transfer*: heat naturally flows from the hot to the cold region**

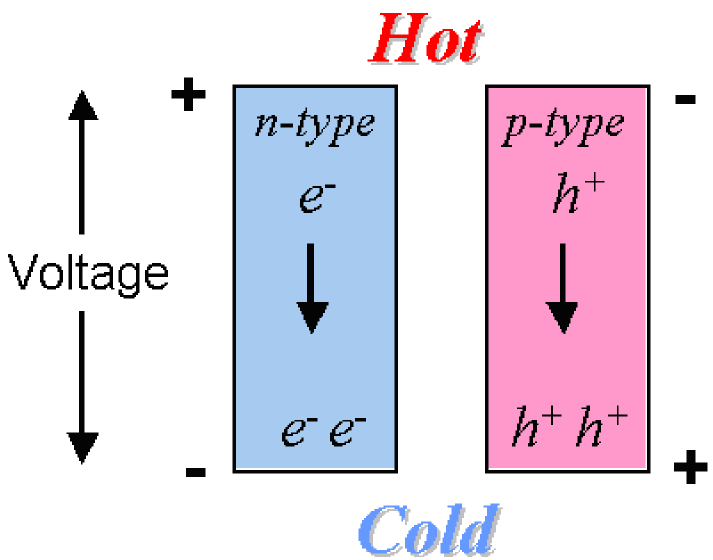
$$\dot{Q} = \Delta T / R_t$$

R_t **: Thermal Resistance**

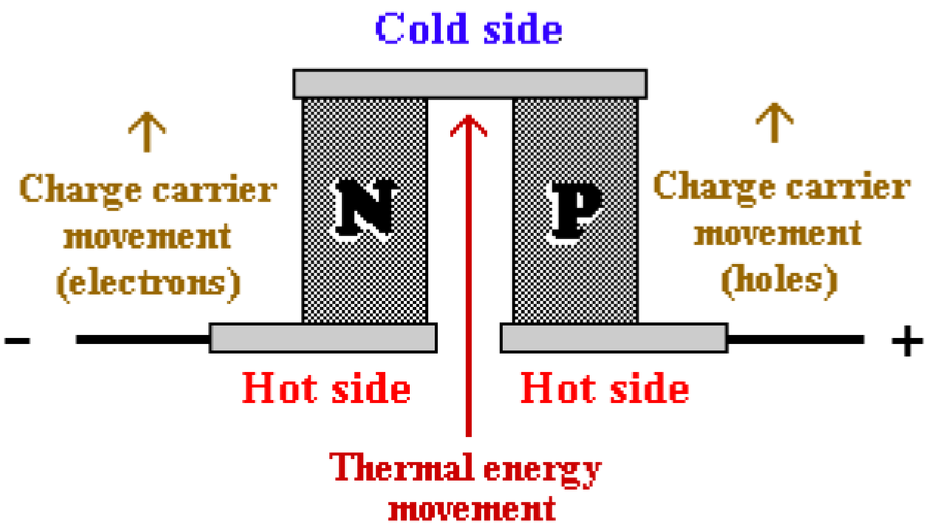


Basic principles

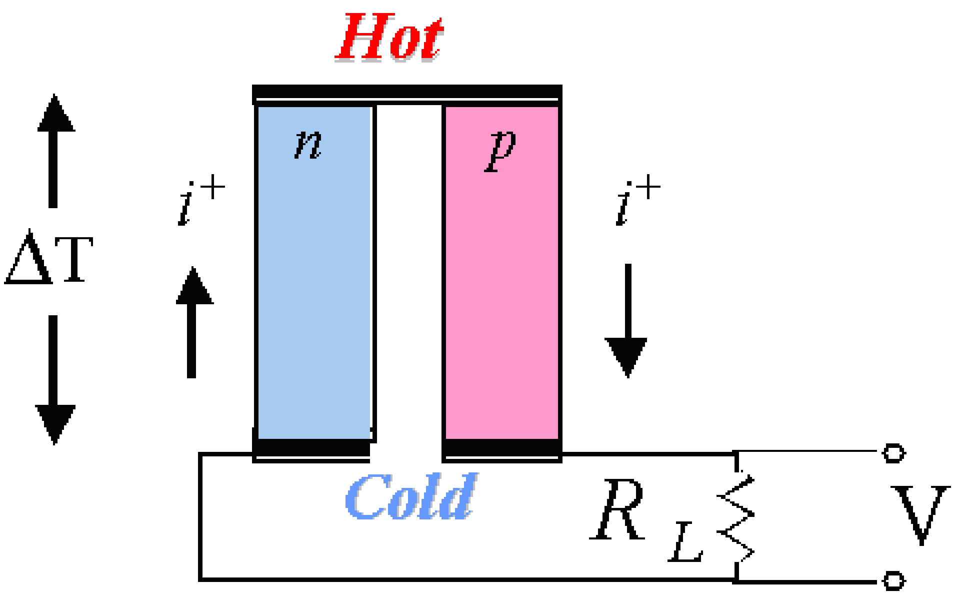
Seebeck Effect

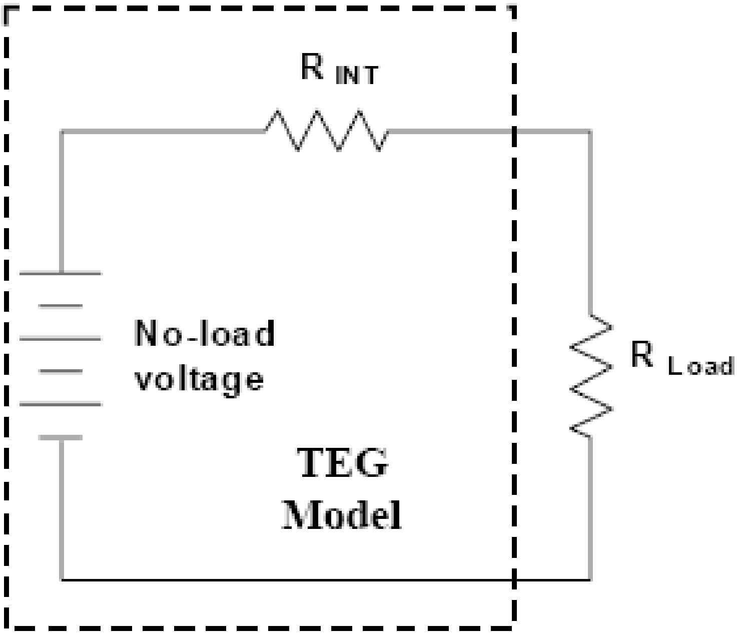


Series connections



$V = \alpha \Delta T$ where α : Seebeck coefficient (V/K)





- ***Optimum power generation when $R_L = R_{INT}$; where $R_{INT} = l / \sigma A$***

  σ = electrical conductivity

  ***A/l* = Cross sectional area to length ratio of TE elements**

- **Power = *IV* = V^2/R = $\alpha^2\sigma \Delta T^2$ *A/l*   with $V = \alpha\Delta T$**

- For efficient operation, high power must be produced with a minimum of heat (Q). The thermal conductivity, k, acts as a thermal short and reduces efficiency.

- Figure of Merit:

$$zT = \frac{\alpha^2 \sigma}{k} T$$

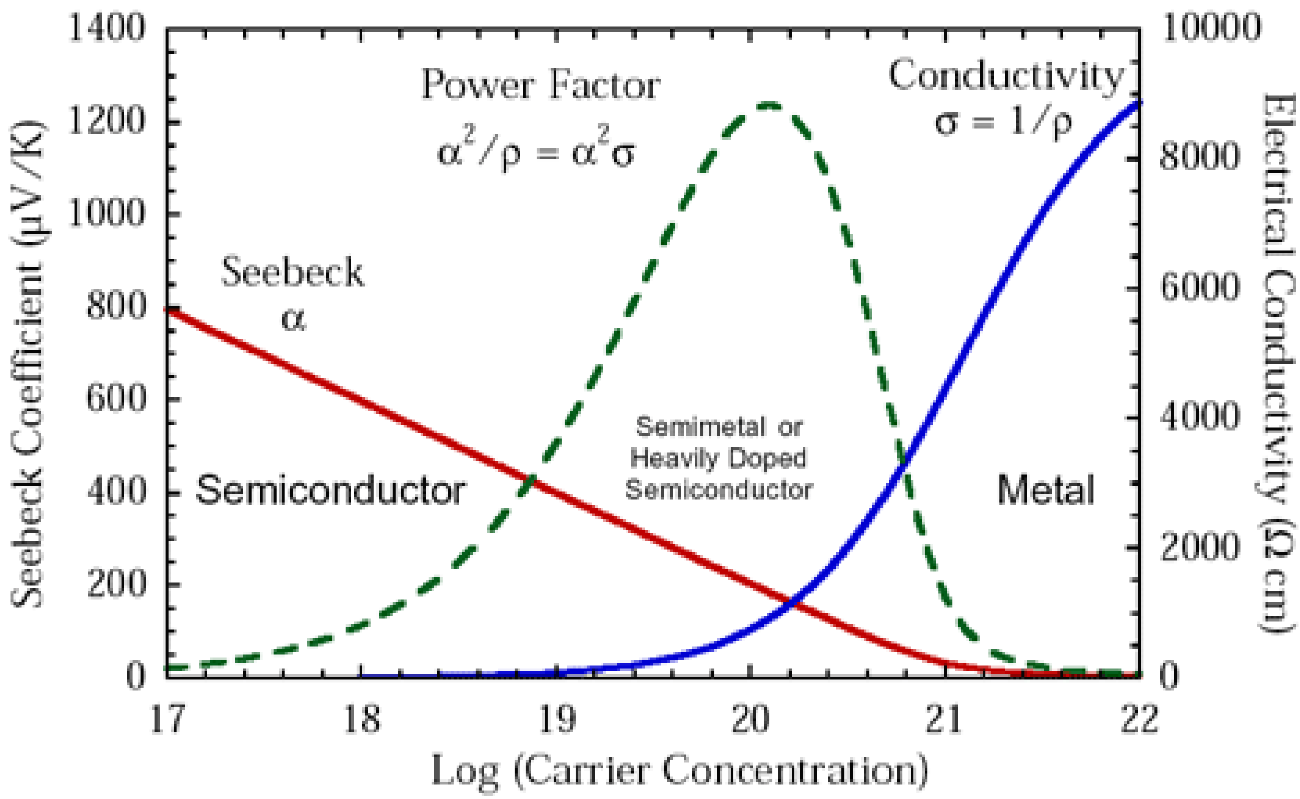
To maximize zT, want a material with:

- High power factor: $\alpha^2\sigma$

- Low thermal conductivity, k

CRC Handbook of Thermoelectrics, CRC Press, 1995

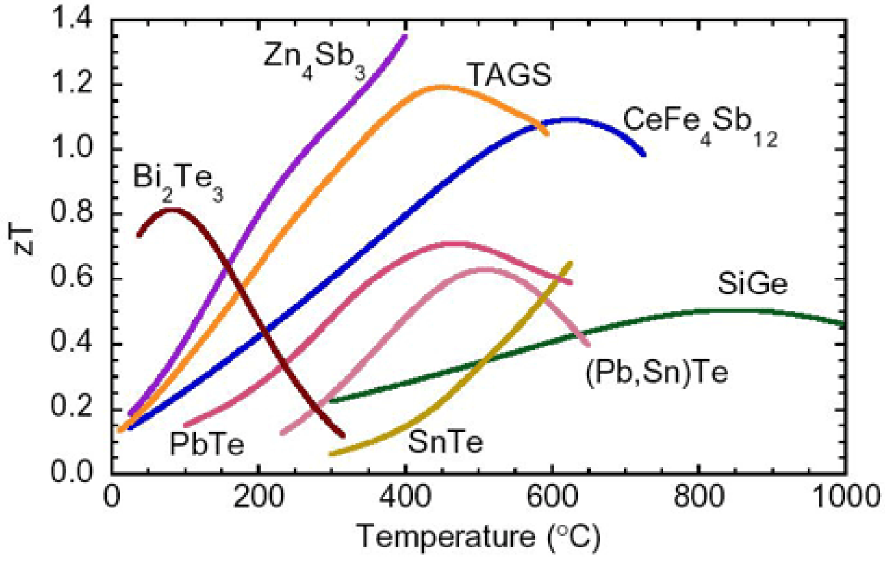
Materials selection



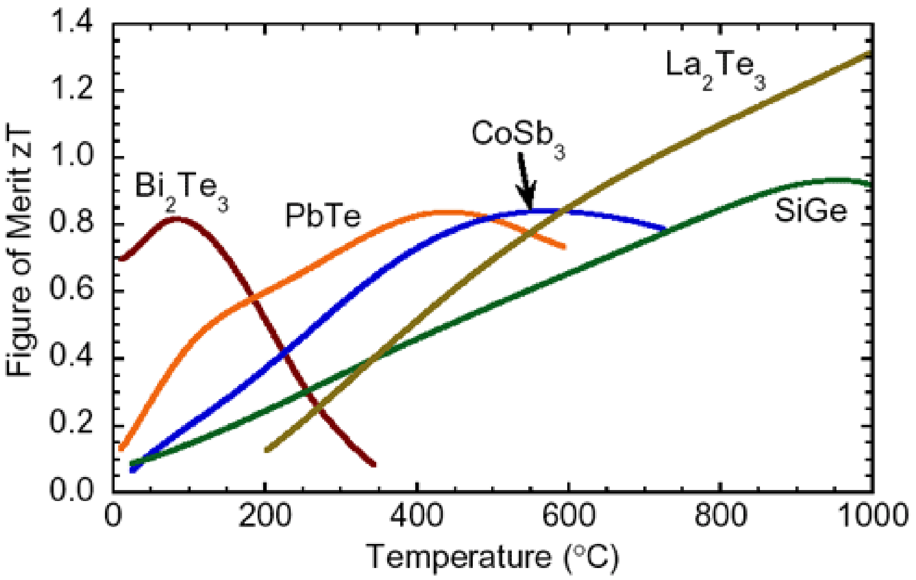
CRC Handbook of Thermoelectrics, CRC Press, 1995

Material properties

zT for p-type TE materials

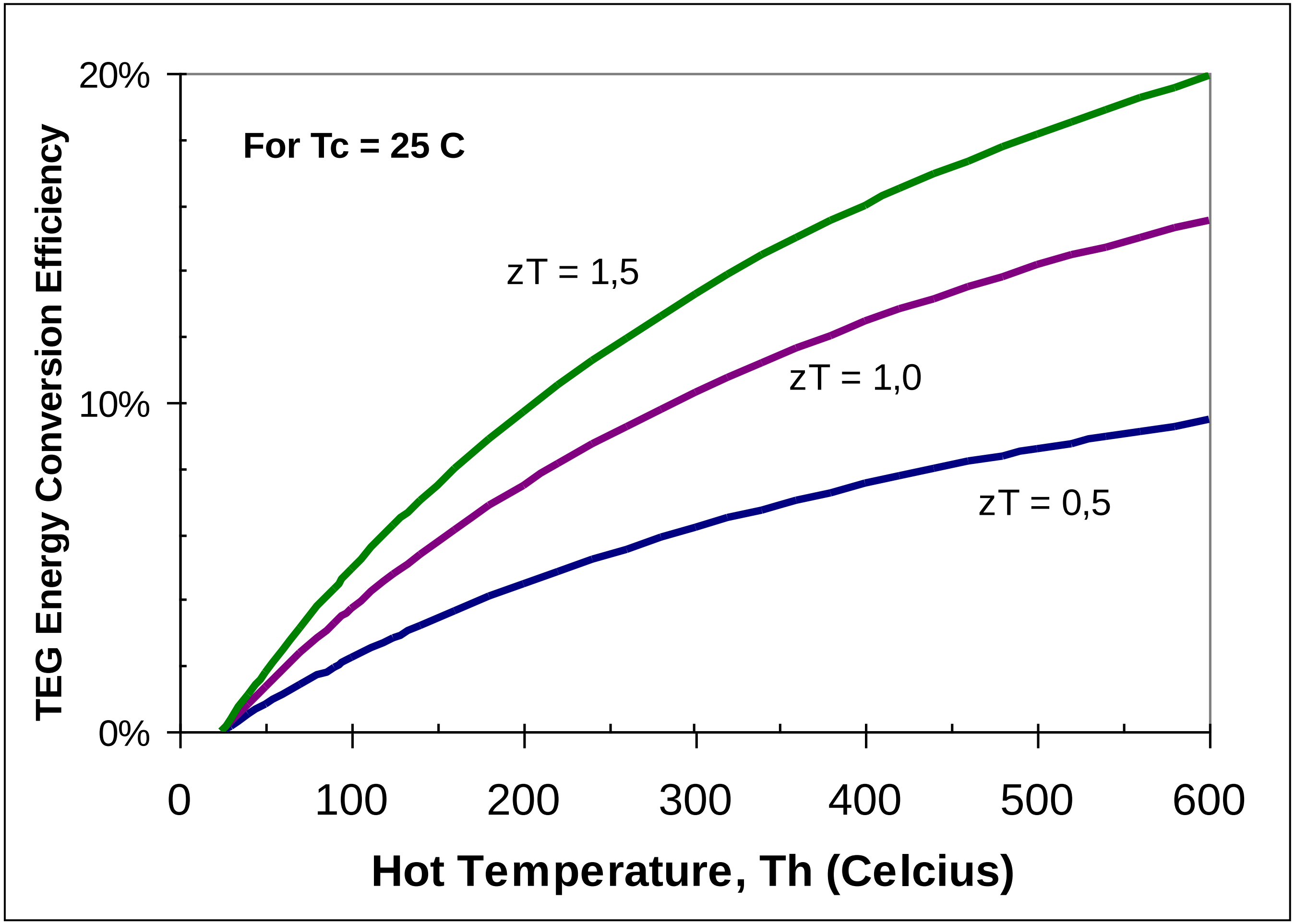


zT for n-type TE materials



CRC Handbook of Thermoelectrics, CRC Press, 1995

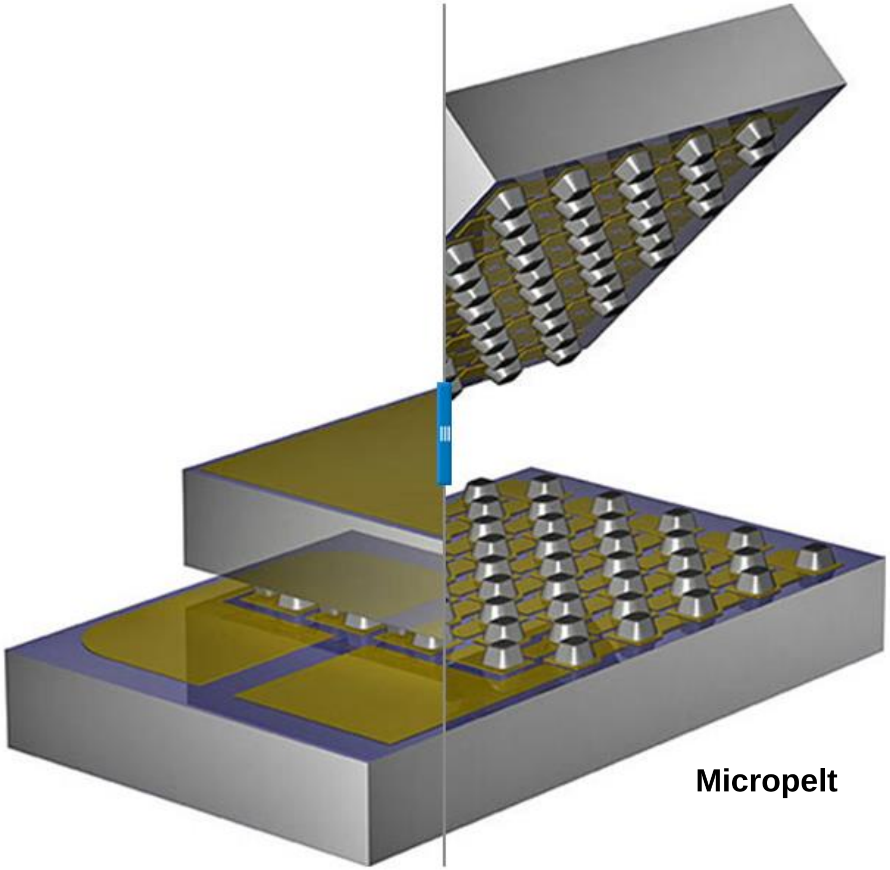
Efficiency


For Tc = 25 C
zT = 1,5
zT = 1,0
zT = 0,5
20%
10%
0%
TEG Energy Conversion Efficiency
0
100
200
300
400
500
600
Hot Temperature, Th (Celcius)

Microfabricated examples

- Thin film process with nearly a hundred leg pairs per mm² for a viable self-sustained energy source harvesting thermal energy

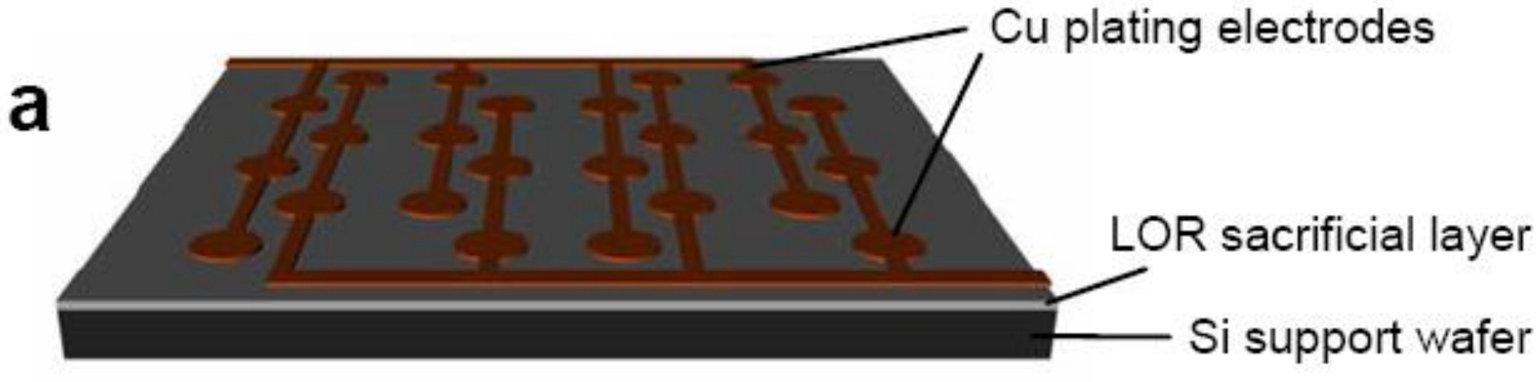
- 20 degrees over ambient can provide more than 2 V and 4 mW



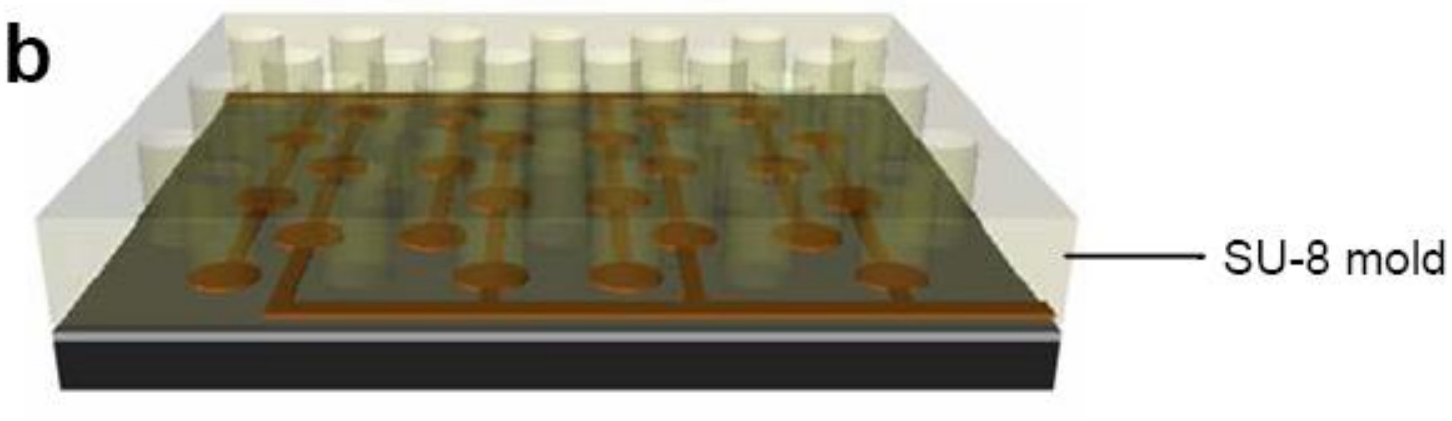
n and p type sputtered Bi_2Te_3 thick thermocouples

Assembly of the two wafers

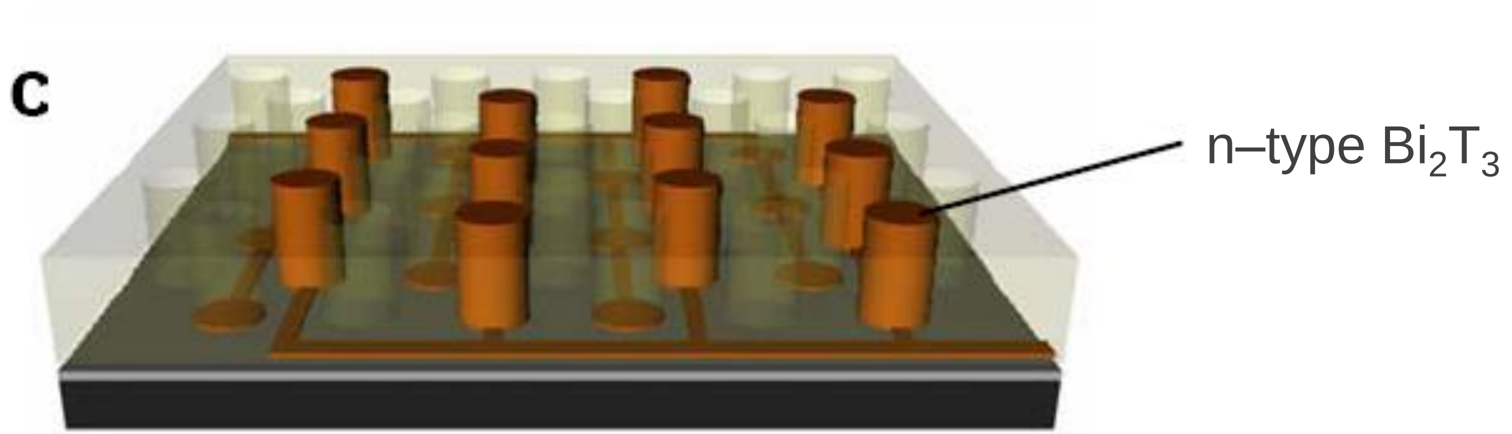
greenTEG technology



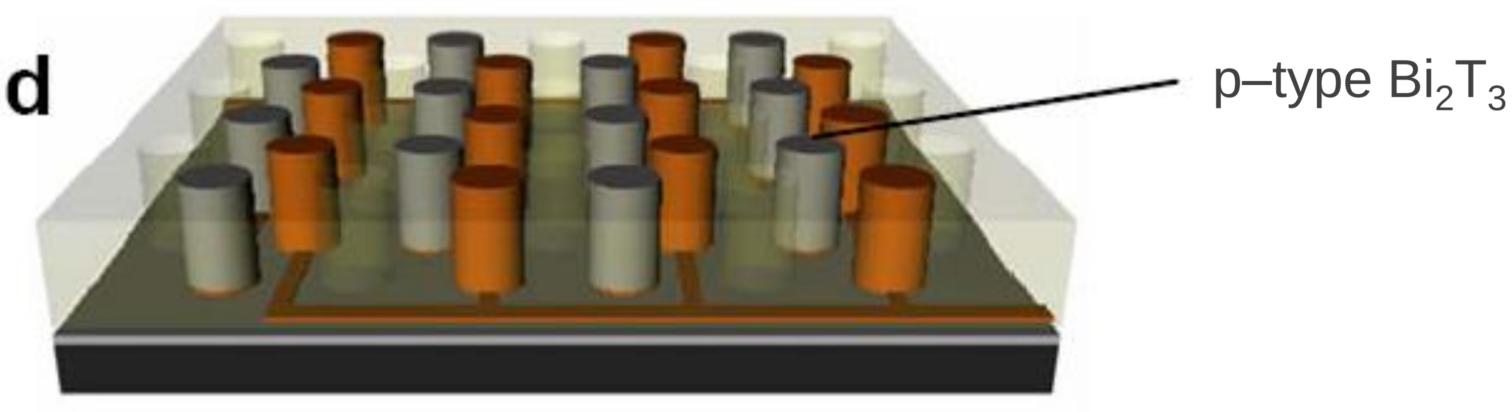
greenTEG technology



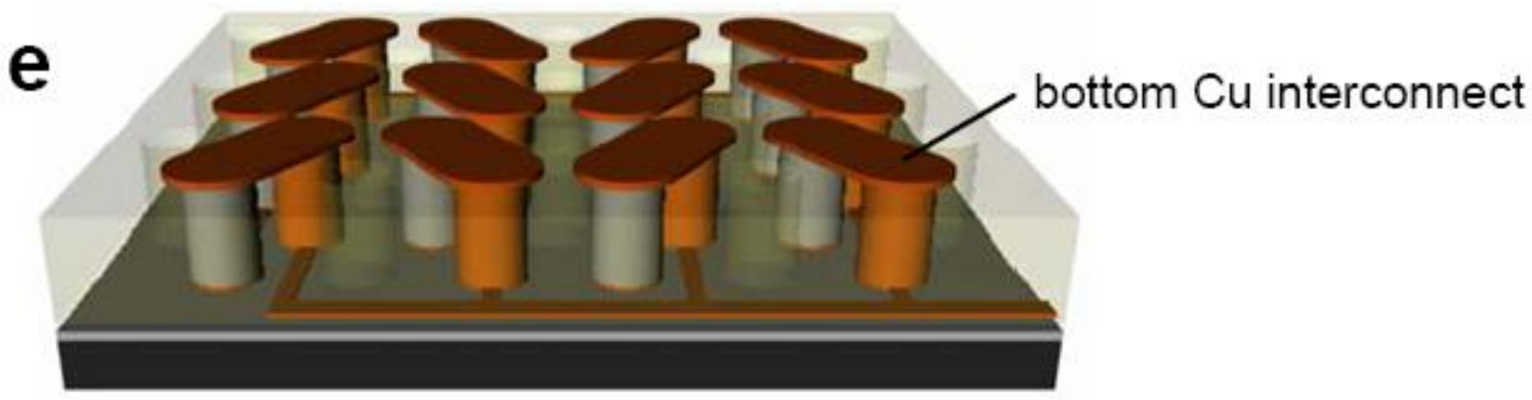
greenTEG technology



greenTEG technology



greenTEG technology



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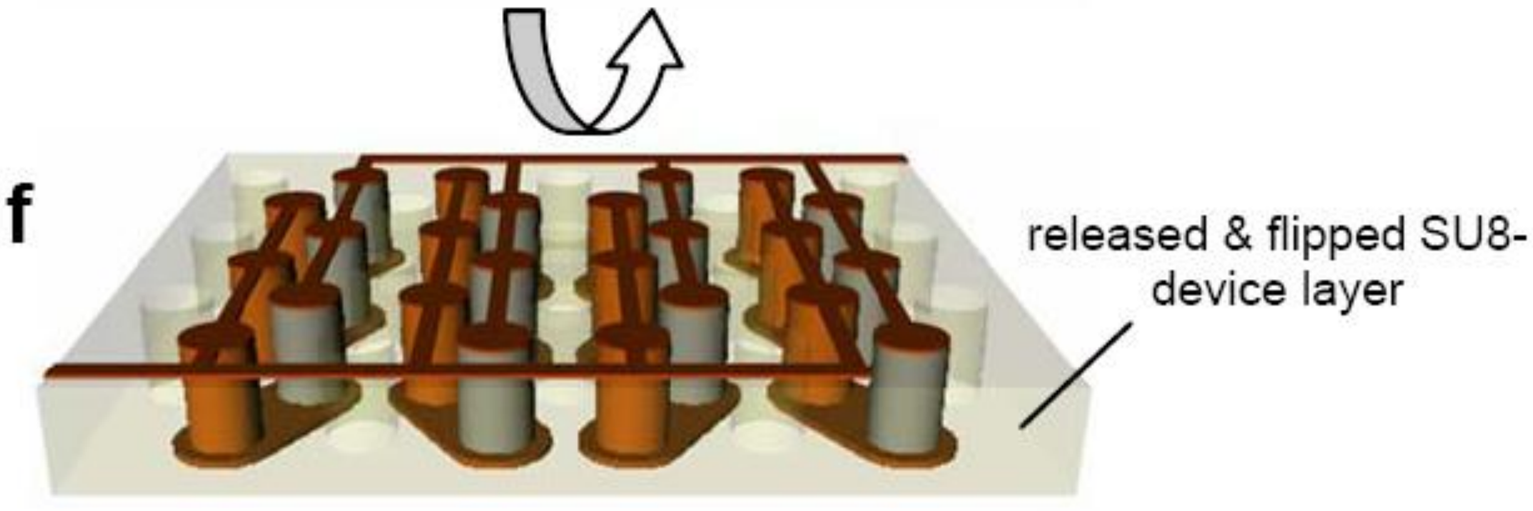
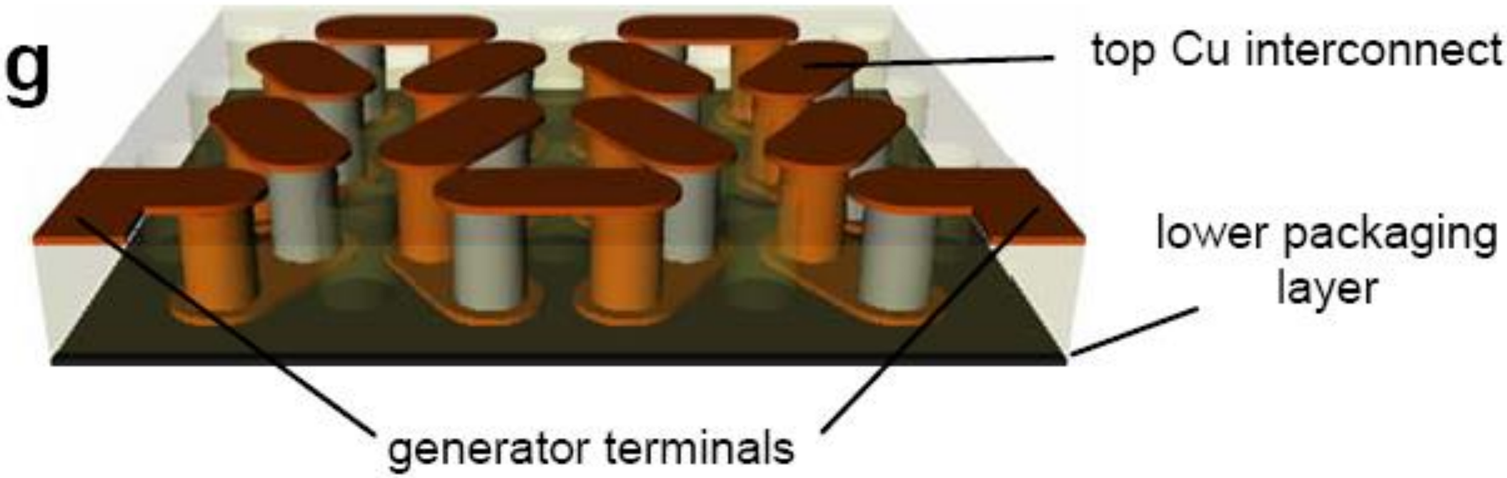
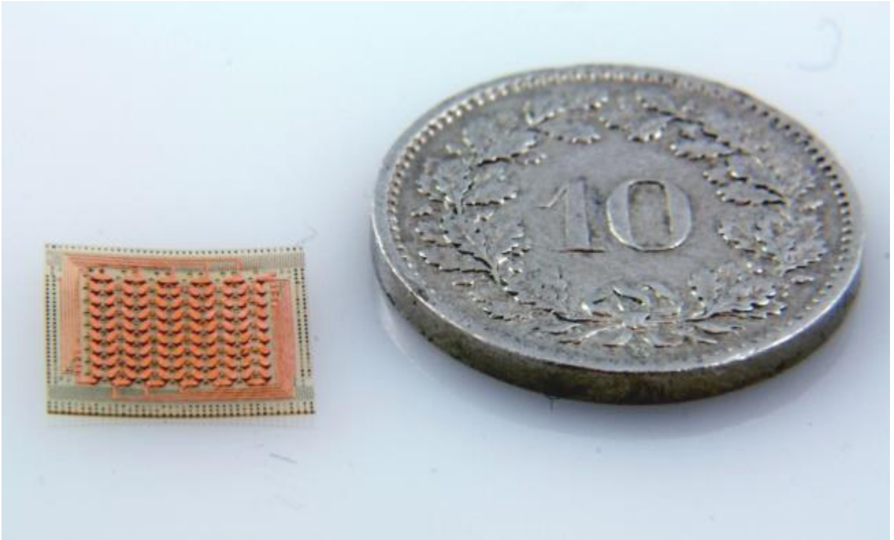
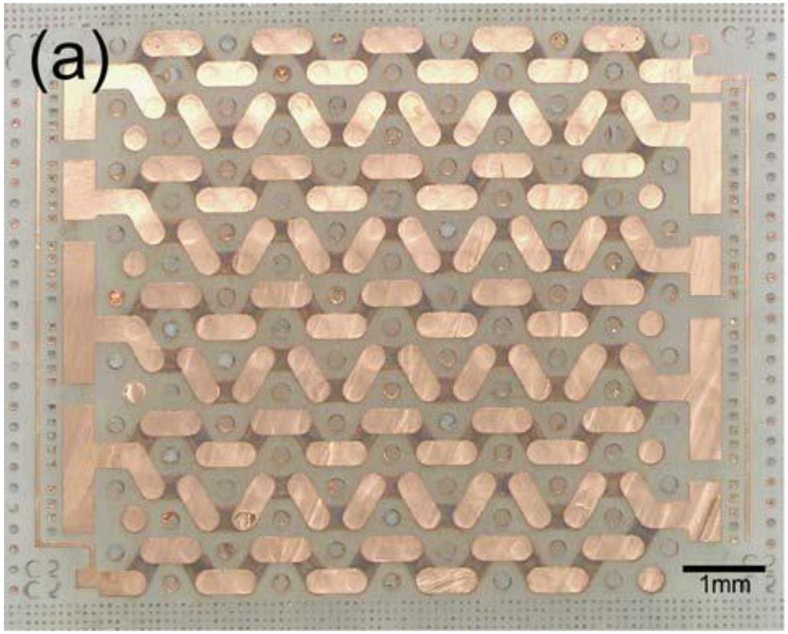


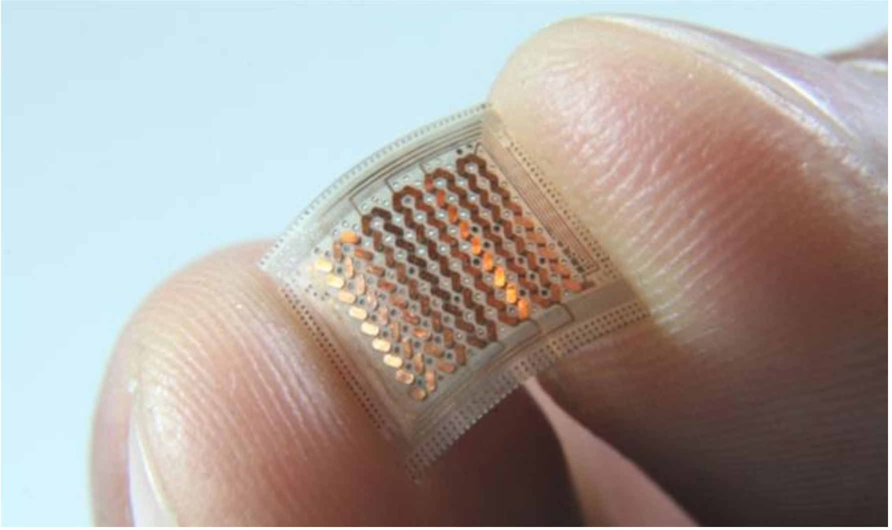
greenTEG technology



GreenTEG devices



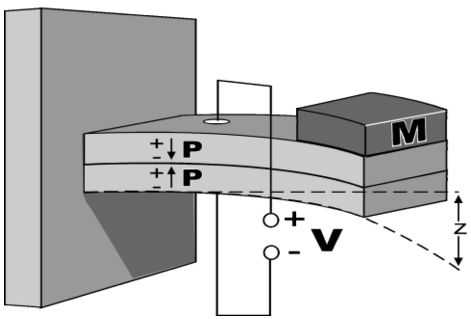




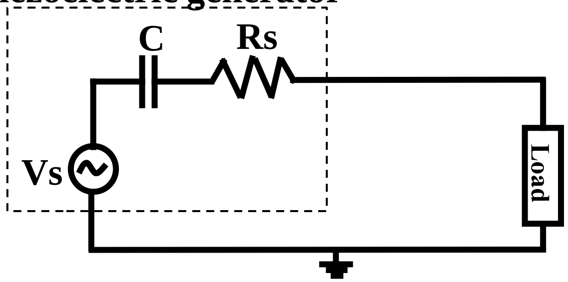
Three conversion principles to convert vibrations

Piezoelectric

Strain in piezoelectric material causes a charge separation (voltage across capacitor)

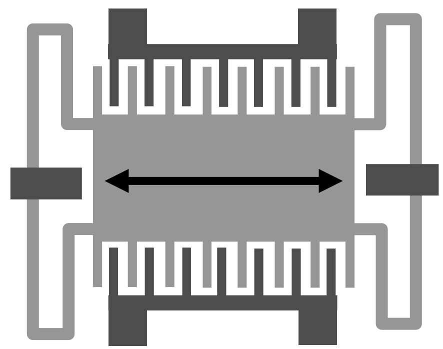


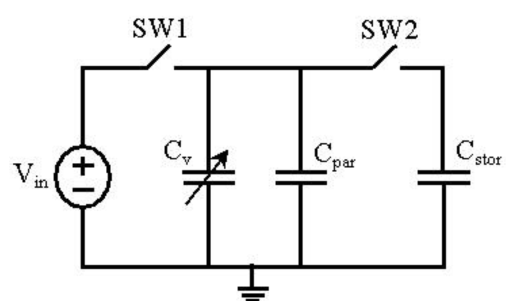
Piezoelectric generator



Capacitive

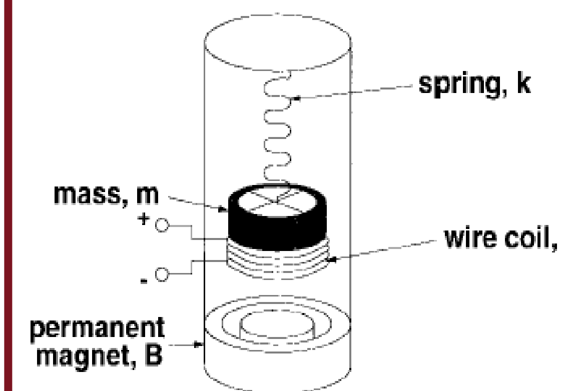
Change in capacitance causes either voltage or charge increase.





Inductive

Coil moves through magnetic field causing current in wire.



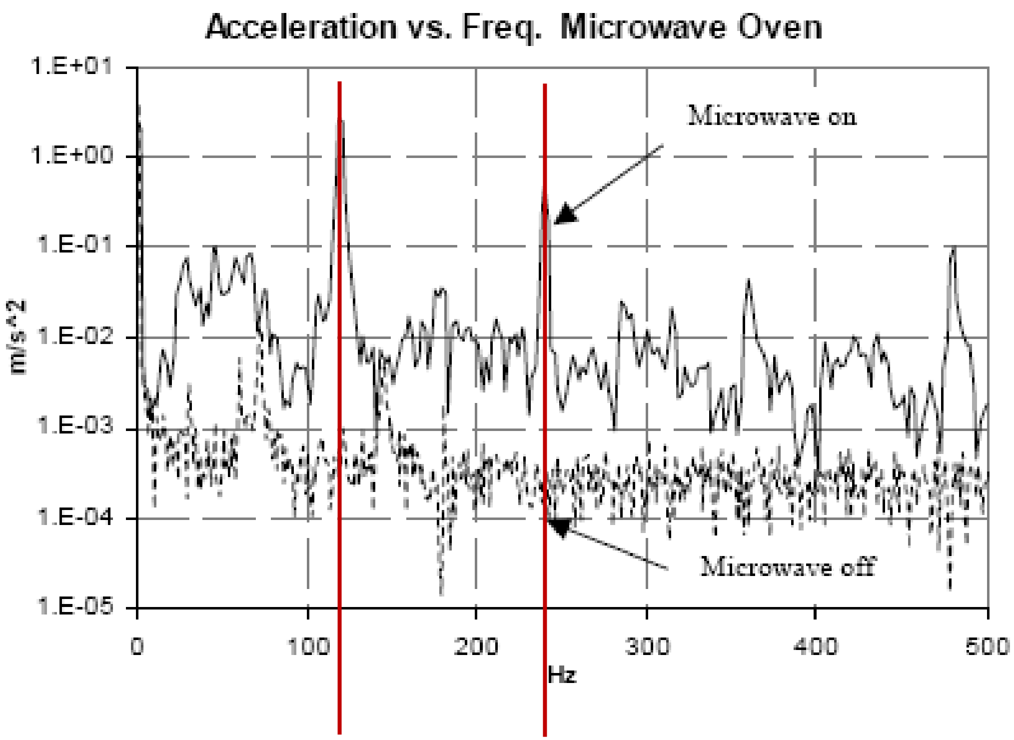
Amirtharajah et. al., 1998

Vibration energy harvesting

- **Structural vibrations often occur at specific frequencies, that of the source or the natural frequency of the structure itself**

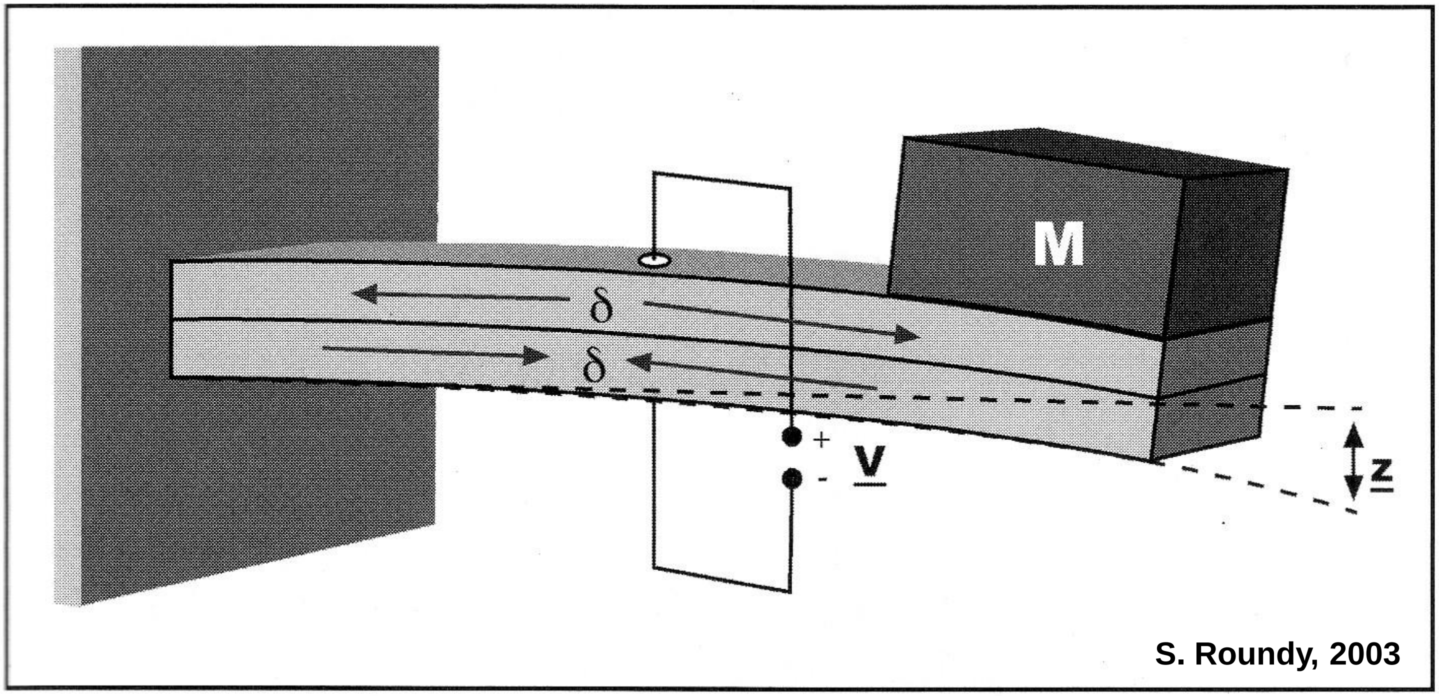
$$\ddot{y} = |A|\omega^2 \sin(\omega t)$$

- **Structural vibrations excite the energy harvester that is attached to it**
- **Mechanical energy is converted to electrical energy**
- **Electric power is provided to a collocated sensor or other distributed instrument**



Roundy, 2003

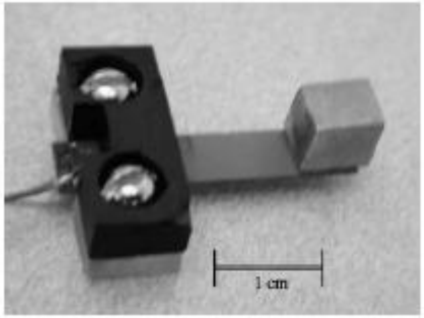
Piezoelectric principle



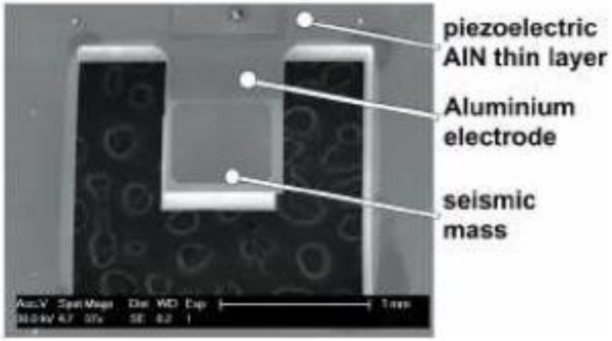
- Coupling of strain field with electric field
- Bending strain generates oscillating voltage
- Position of the neutral plane in the piezoelectric material is important to not have charges cancelation between region in compression and in tension

Piezoelectric micro-harvesters

- **Micromachined devices are resonant transducers**
- **PZT or AlN used (high d_{31} or low ε)**



Shad Roundy et al, Berkeley, 2003
70 μW, 2.25 m/s² @ 100Hz, 1cm³



M. Marzencki et al, Tima Labs, 2007
2 μW, 2g @ 840 Hz, 25mm³

Elfrink et al., 2008, IMEC
60 μW, 2g @ 572Hz, 0.2 cm²

- **Resonance frequency of device matching vibration frequency of the source in the environment**
- **Bilayer cantilever, piezoelectric on silicon beam, with neutral place as close as possible to the interface between the two materials**
- **Proof mass, high density metal (W) or silicon, included to increase stress (i.e. output power) and decrease resonance frequency**

Principle

- Structural vibrations excite the base, y(t), of a miniature spring-mass-damper system:

$$\ddot{y} = |Y|\omega^2 \sin(\omega t)$$

- Motion is imparted to the mass, m, through the spring of rigidity, k, with a force:

$$F_{spring} = k\ z(t)$$

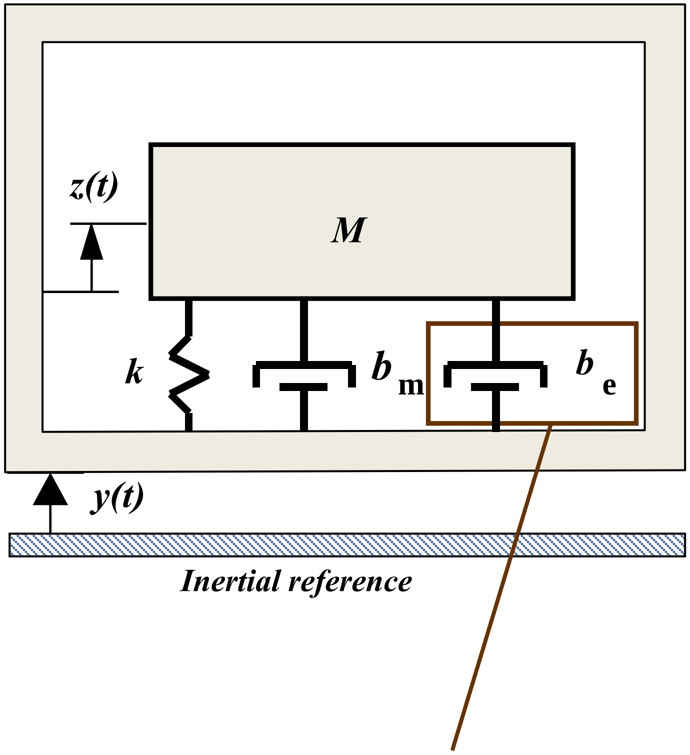
- Motion of the mass is damped by viscous and internal friction:

$$F_{mech.damp.} = b_m \dot{z}(t)$$

[1]

and the electromechanical force:

$$F_{electro\text{-}mech.damp.} = b_e \dot{z}(t)$$



Electro-mechanical conversion represented as damping term

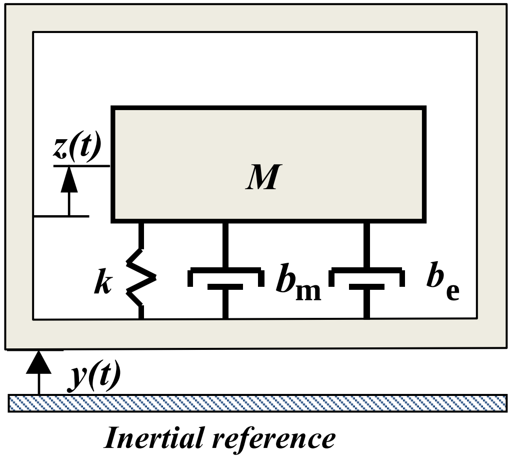
Roundy, Wright, Rabaey (2004)

Simple model: Linear second order system

Momentum conservation equation applied on the mass, M:

$$m(\ddot{z}+\ddot{y}) = \Sigma F$$
$$m(\ddot{z}+\ddot{y}) = -b_m\dot{z} - b_e\dot{z} - kz + F_{ext}(=0)$$
$$m\ddot{z} + (b_m + b_e)\dot{z} + kz = -m\ddot{y}$$

[2]



Defining the non-dimensional damping ratio:

$$\zeta_m = \frac{b_m}{2m\omega_n}; \zeta_e = \frac{b_e}{2m\omega_n}; \zeta_T = \zeta_m + \zeta_e$$

and natural frequency:

$$\omega_n = \sqrt{\frac{k}{m}}$$

[3]

z = relative mass displacement
y = input displacement

Williams and Yates, 1995

Simple model: Power estimation

Harvested power can be estimated as the <u>power dissipated in the electromechanical damper</u>. Since power is the product of force and velocity, the harvested power over one cycle can be expressed as:

$$\dot{W}_e = \int F_e d\dot{z}$$

Recalling that the electromechanical force is (Eqn 1):

$$F_e = b_e \dot{z}$$

then:

$$\dot{W}_e = b_e \int \dot{z} d\dot{z} = \tfrac{1}{2} b_e \dot{z} \quad [4]$$

Matching of resonant frequency with the input frequency (vibration):

$$\dot{W}_e(\omega_n) = \frac{m \zeta_e A^2}{4 \omega_n \zeta_T^{\,2}} \quad [5]$$

function of the amp[litude, $A=|Y|\omega^2$, of the input acceleration (often known) ***:***

For maximum power:

- **Increase mass**
  Larger displacement
  Larger stress in the piezo films
- **Minimize frequency (for fixed acceleration amplitude, A)**
  Ambient vibrations: 60 to 200 Hz
- **And damping … (next page)**

Williams and Yates, 1995

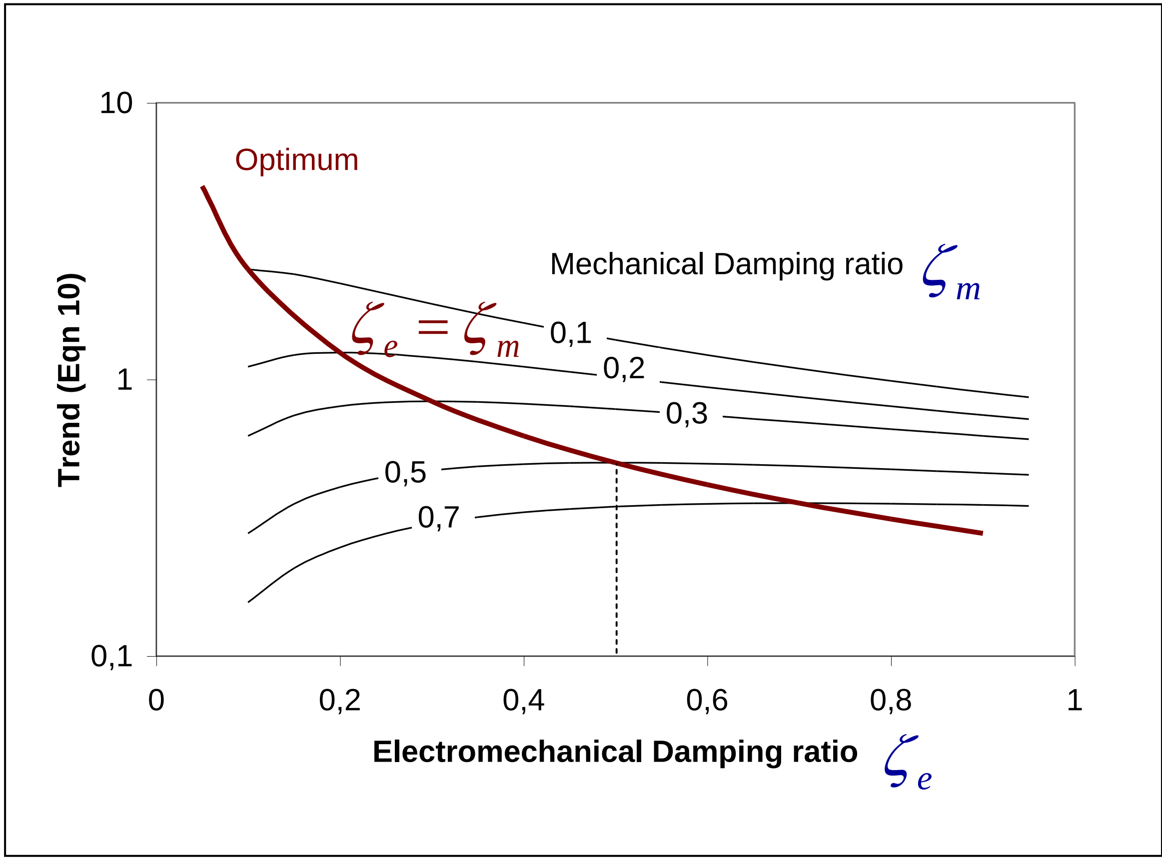
Impact of damping

The harvested power is a function of damping according to:

$$\dot{W}_e(\omega_n) \alpha \frac{\zeta_e}{\zeta_T^2} = \frac{\zeta_e}{(\zeta_e + \zeta_m)^2} \quad [10]$$

- **Since the *mechanical damping* appears in the denominator, it should be minimized.**
- **The figure shows that the power is maximized for:**

$$\zeta_e = \zeta_m$$



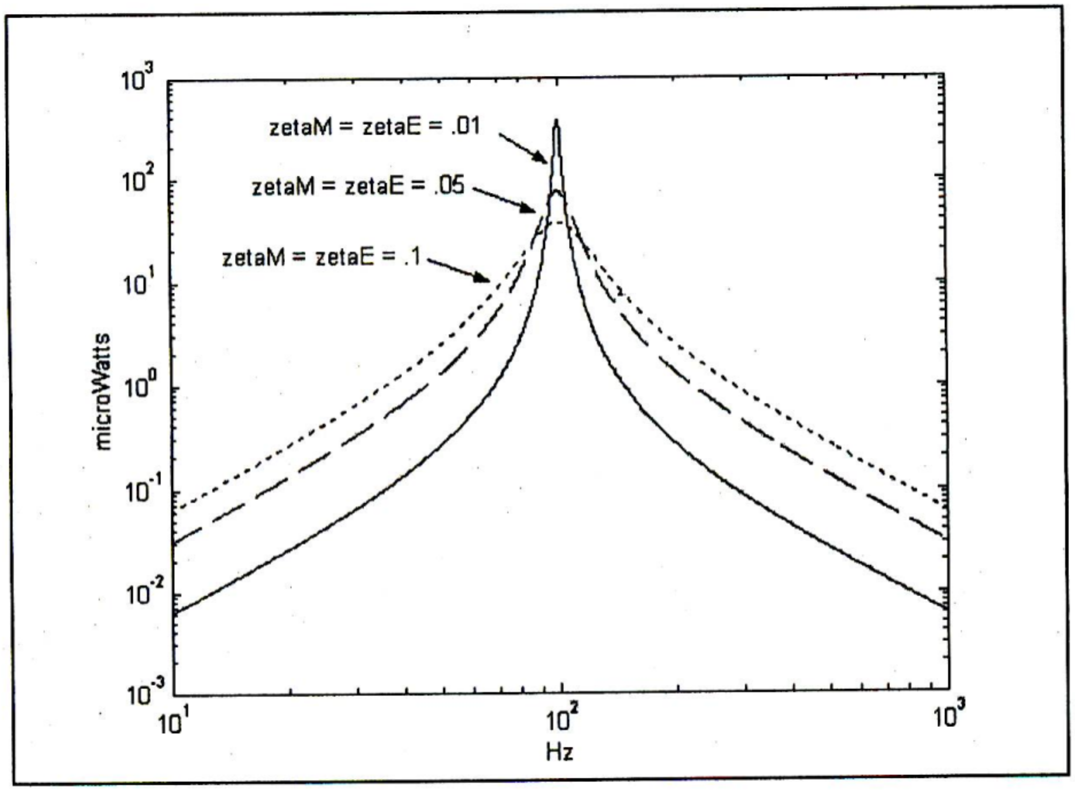
- **Low damping implies:**
  - **→ High Q**
  - **→ Large displacements at resonance (z)**

Fundamentally limited by stress in structures

Practically limited by the vacuum packaging

Impact of damping

- Lower damping = higher power output at resonant frequency
- But less when going away from the resonant frequency



Power output as a function of frequency for different damping levels

S. Roundy, 2003

Energy density

Yield strength

Energy density:

$$u_{Piezo} = \frac{\sigma_y^2 k^2}{2Y}$$

Coupling coefficient

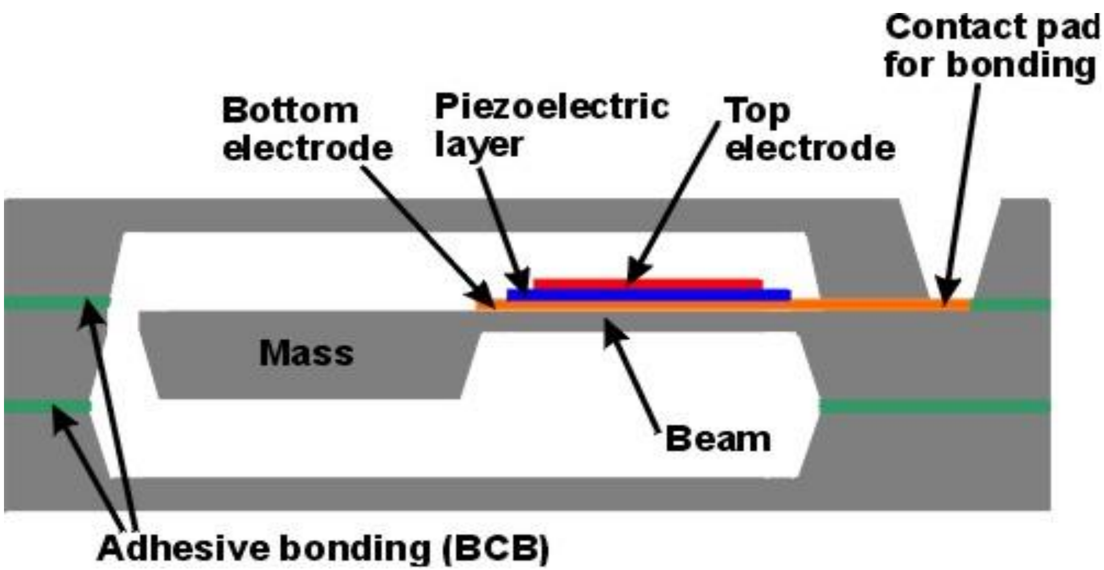
Young's modulus

Using values for PZT: energy density ~ 335 mJ/cm^3

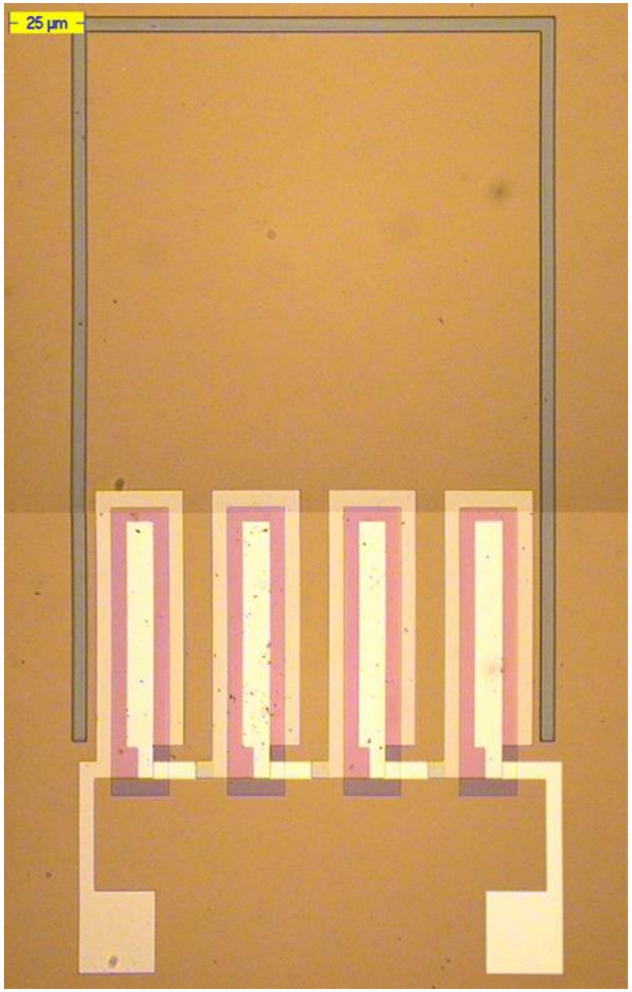
k^2: Electromechanical coupling coefficient is a numerical measure of the conversion efficiency between electrical and acoustic energy in piezoelectric materials

MEMS implementations

The piezoelectric effect converts mechanical strain into electrical current or voltage. Strain causes charge separation across the device, producing an electric field and, consequently, a voltage drop which producing an irregular ac signal.



Design of wafer-bonded vibrational scavenger



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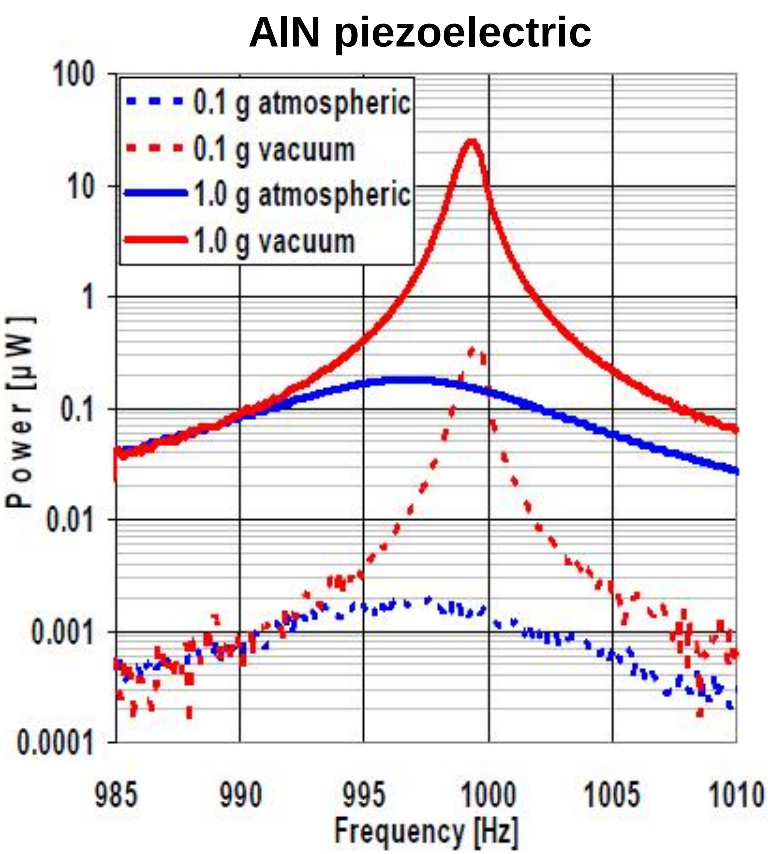
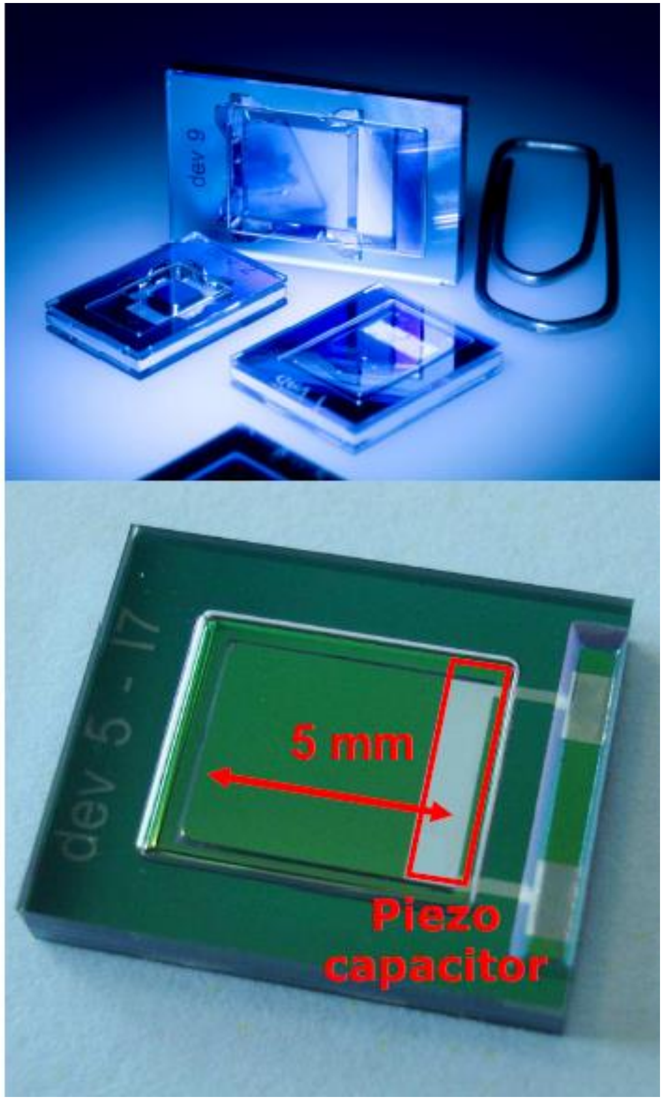
MEMS implementations

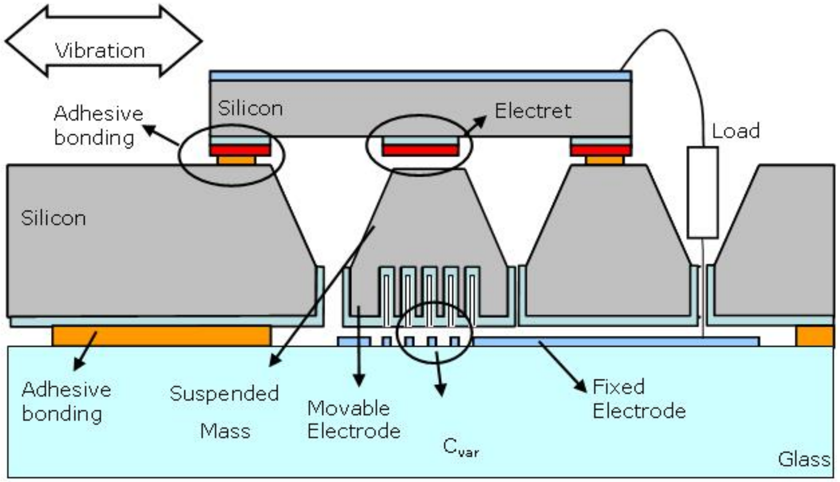
R. Elfrink @ HOLST/IMEC, IEDM2009





Electrostatic principle

- **Basic principle: charge and discharge of capacitor**
- **Charge or voltage constrained**
- **Miniaturization helps: larger capacitance variation**
- **First micromachined embodiment in 2003**



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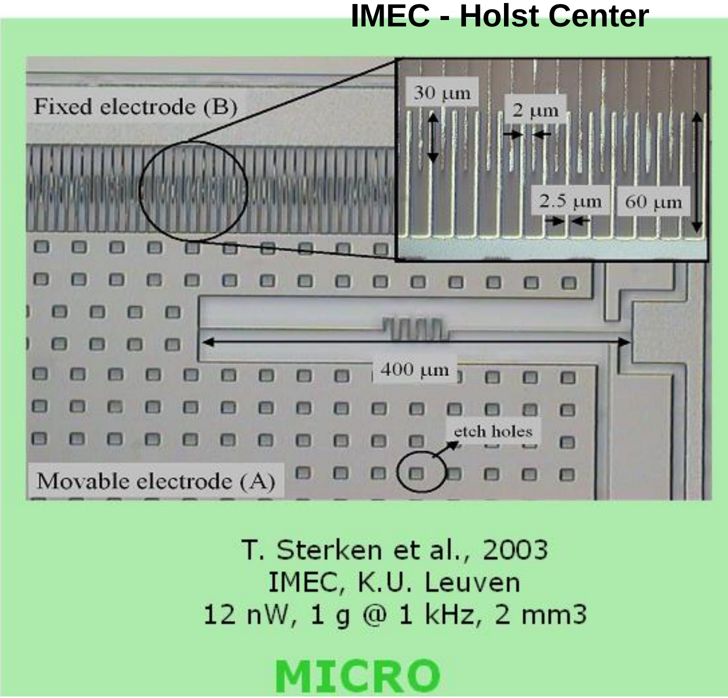

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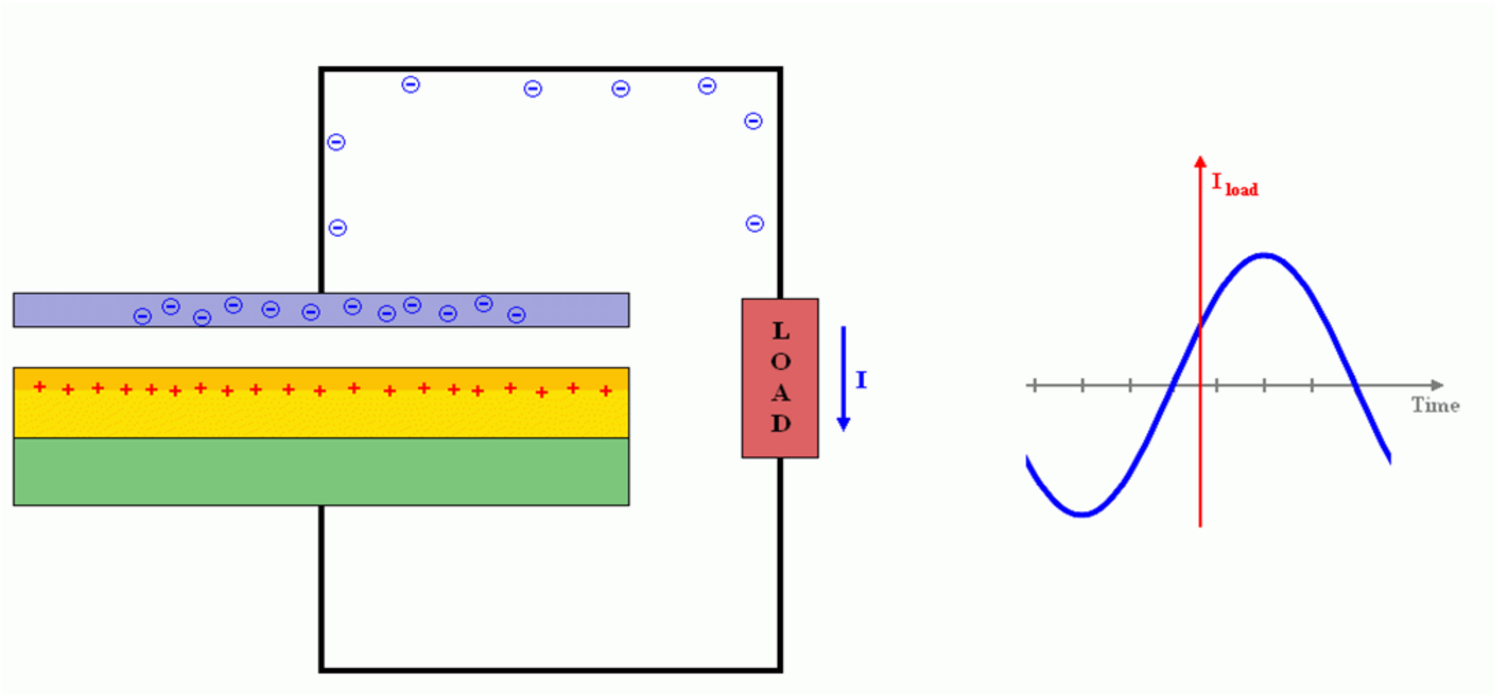

Electrostatic principle

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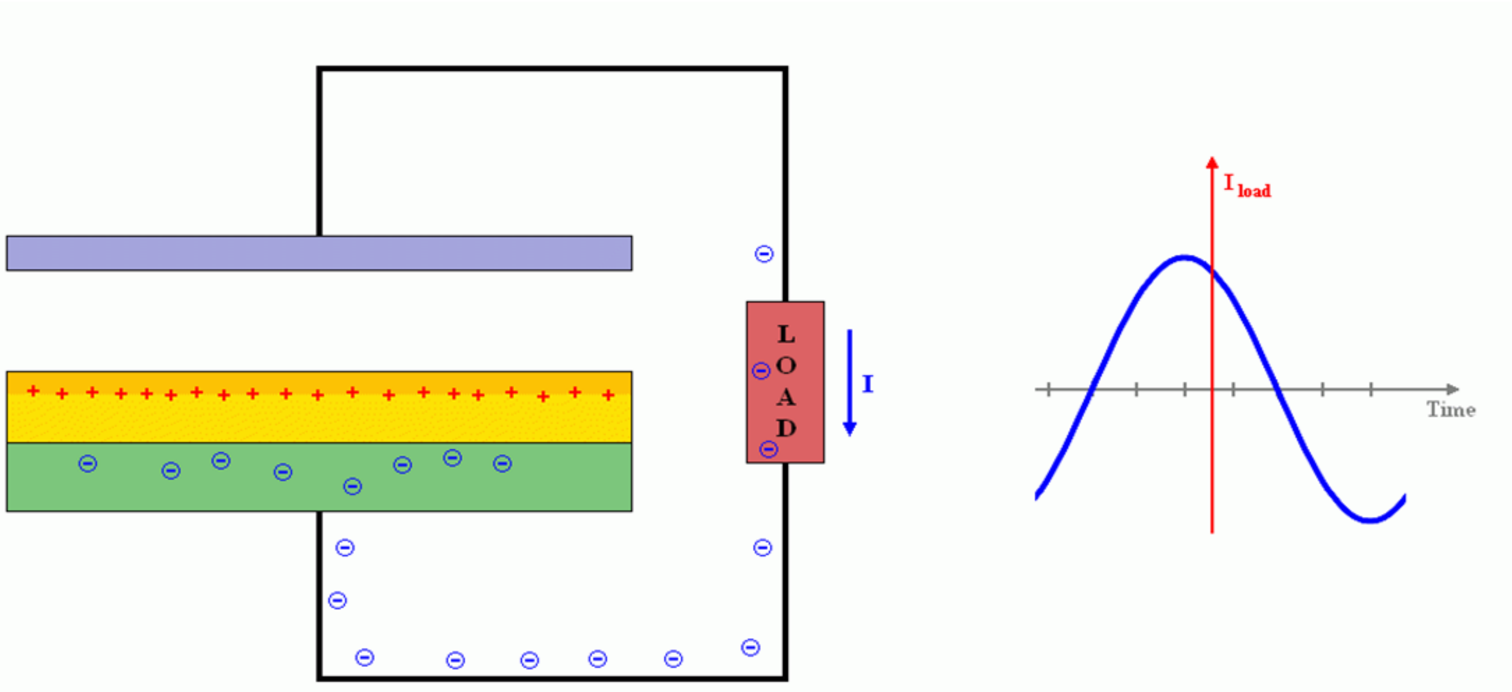
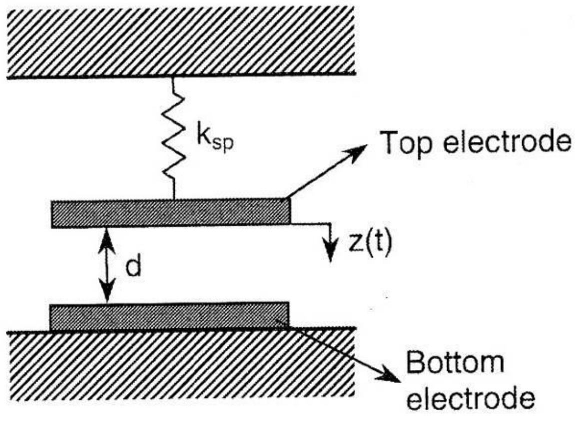


Principles

First, charge the device in the max. capacitance position

$$q = V_{in} C_{\max}$$



- **Capacitance changes with gap:** $C \propto \frac{1}{gap}$

- **Electrical energy stored:** $E_{elec} = \frac{q^2}{2C(z)}$

- **Energy density (Upper bound)** $u_{ES} = \frac{1}{2}\varepsilon_0 \mathbf{E}^2 \approx 5\ mJ/cm^3 = 1.4\ mWhr/cm^3$

for $\mathbf{E} = 30\ \mathrm{MV/m}$ **V = 60 V, gap = 2 µm**

Basic principle:

$$C = \frac{\varepsilon_o A}{d} \qquad V = \frac{Q}{C} \qquad E = \frac{1}{2} QV$$

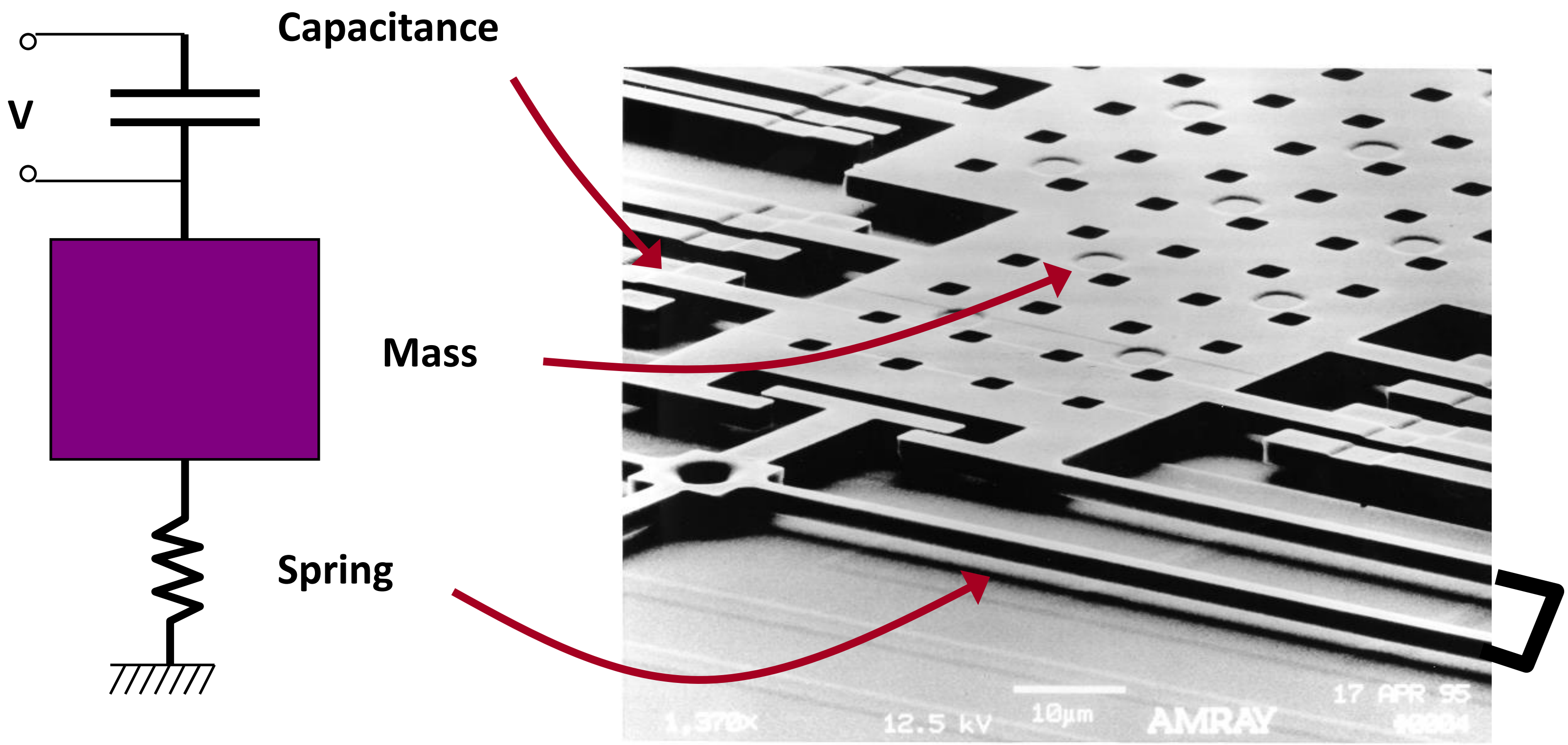
Design a variable capacitor in which A or d change when subjected to mechanical vibrations.

If Q is kept constant, V (and E) will increase according to:

$$\frac{V_{\max}}{V_{\min}} = \frac{C_{\max} + C_{par}}{C_{\min} + C_{par}}$$

S. Roundy, 2003

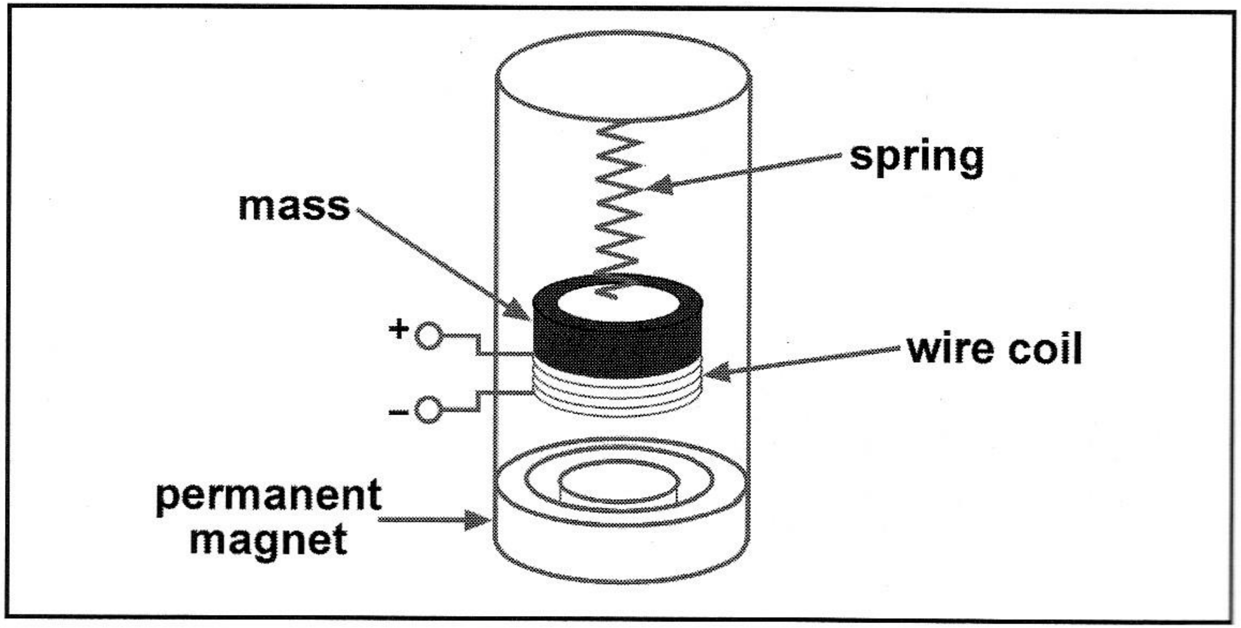
Capacitive oscillator (similar to accelerometer)



Acceleration → Force → Deflection → Capacitance → Voltage

Structure **Circuit**

Electromagnetic energy conversion



- **Moving coil in magnetic field induces current**

Faraday's law: $\varepsilon = - d\phi_b / dt$

Amritharajah & Chandrakasan (1998)

- **Energy density:** $u_{EM} = \dfrac{\mathbf{B}^2}{2\mu_0}$

For $\mathbf{B} = 1\ \mathrm{Tesla}$ $\quad u_{EM} \sim 400\ mJ/cm^3 = 111\ mWh/cm^3$

- **A.C. Voltage** $\quad V = N\,B\,l\,\dfrac{dz}{dt} \sim 30\,\mathrm{mV}$

  - **Low voltage**
  - **Voltage reduces with decreasing size**

Roundy, Wright, Rabaey (2004)

For vibrations

Table –3.2. Summary of maximum energy density of three types of transducers.

Type	Governing Equation	Practical Maximum	Theoretical Max.
Piezoelectric	$u = \sigma_y^2 k^2 / 2Y$	17.7 mJ/cm^3	335 mJ/cm^3
Electrostatic	$u = \frac{1}{2}\varepsilon E^2$	4 mJ/cm^3	44 mJ/cm^3
Electromagnetic	$u = B^2 / 2\mu_0$	4 mJ/cm^3	400 mJ/cm^3

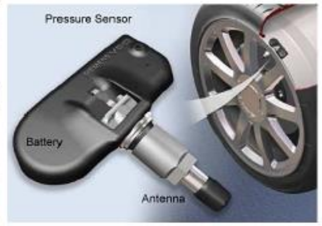
S. Roundy, 2003

Comparison conversion principles

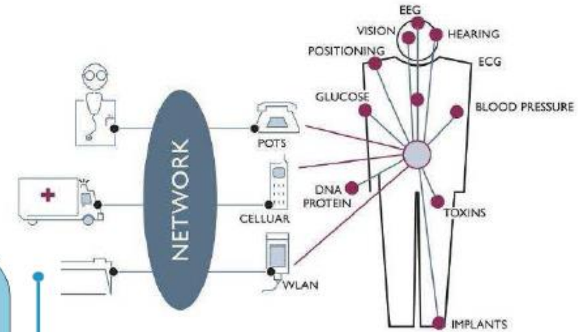
	Advantages	Limitations
Electromagnetic	No separate voltage source High energy density	Difficult to integrate Low voltages (<0.1 V)
Electrostatic	Easy to integrate Voltages of 2 – 10 V	Low energy density Need separate voltage source Mechanical stops needed
Piezoelectric	No separate voltage source Voltages of 2 –10 V High energy density	Challenge to integrate Piezo thin films with MEMS Reliability of piezoceramics

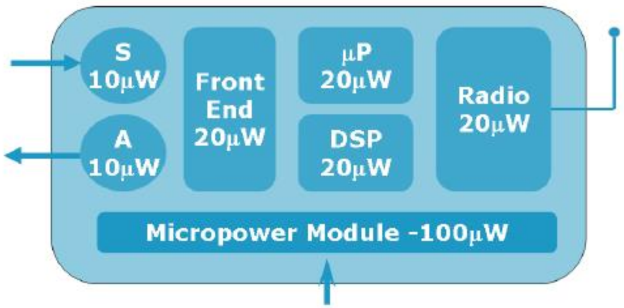
Some applications

TPMS: Tire Pressure Monitoring System



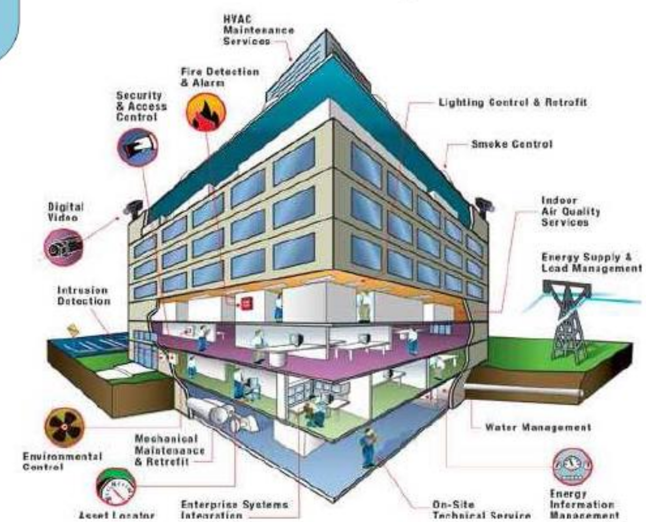
BAN: Body Area Network





Predictive Maintenance

Smart Buildings



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Conclusions

- **Miniaturising is of interest but its involves a decrease of the output power level**
  - **Need for better harvesters (converting materials) and less consuming devices and systems**

- **Thermoelectric devices can be « easily » micromachined but there is a need for efficiency improvement**

- **Micromachined vibrations energy converters can generate µWs (piezoelectric providing the highest energy density) but there still relatively large and robustness unproven**

- **Young field with a lot of opportunities in research**

Perspectives

- **Not one size fits all: list applications for each technology based on power level, energy sources, power density, environmental impact**
- **Reliability**
- **Challenges at the system level**
  - Electronics power management
  - Integration with electronics, sensors and other microsystems
- **List other approaches not discussed:**
  - Radioactive
  - Thermophotovoltaics
  - Biochemical
- **Role of nanotechnology (new materials)**

Questions

- Energy sources
  - The different energy sources to power microsystems
  - Energy sources available in our environment
  - Ranking in terms of power density and order of magnitudes

- Thermal energy harvesting
  - Basic principle and schematic configuration
  - How to optimize the power level generated linked to ZT factor
  - Microfabricated configuration
  - Type of materials involved

- Mechanical energy harvesting
  - Different principles to convert mechanical energy to electrical energy
  - Advantages and disadvantages of the different principles when implemented at the micro-scale
  - Principle of operation of resonant type vibration energy harvester
  - Narrow band vs wideband in relation to damping and quality factor
  - Criteria for optimum power generation
  - Implementation: architecture, materials and transducers using MEMS technologies