INTRODUCTION TO ENERGY HARVESTING AND LINEAR VIBRATION ENERGY HARVESTING

(ICT-ENERGY SUMMER SCHOOL 2016)

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Outline for Short Course

- **Introduction and Linear Energy Harvesting**
- Energy Harvesting Transducers
  - Electromagnetic
  - Piezoelectric
  - Electrostatic
- Wideband and Nonlinear Energy Harvesting
- Applications

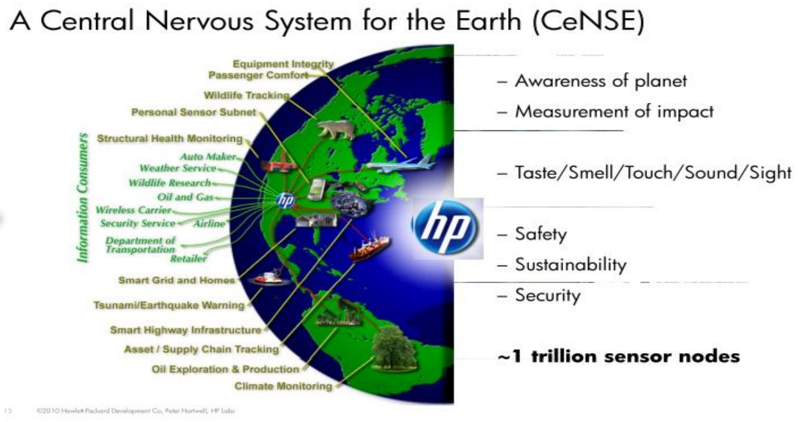
Outline for This Lecture

- What is energy harvesting? And, why?
- Types of energy harvesting
  - RF
  - Photovoltaic
  - Thermal
  - Wind
  - Vibrations
- Linear Vibration Energy Harvesting Theory
- Figures of Merit for Vibration Energy Harvesters

Billion Sensors

- Driven by mobile devices
- Can be regularly recharged
- Short lifetime
- Not dependent on energy harvesting

Trillion Sensors



A Central Nervous System for the Earth (CeNSE)

- Awareness of planet
- Measurement of impact
- Taste/Smell/Touch/Sound/Sight
- Safety
- Sustainability
- Security

~1 trillion sensor nodes

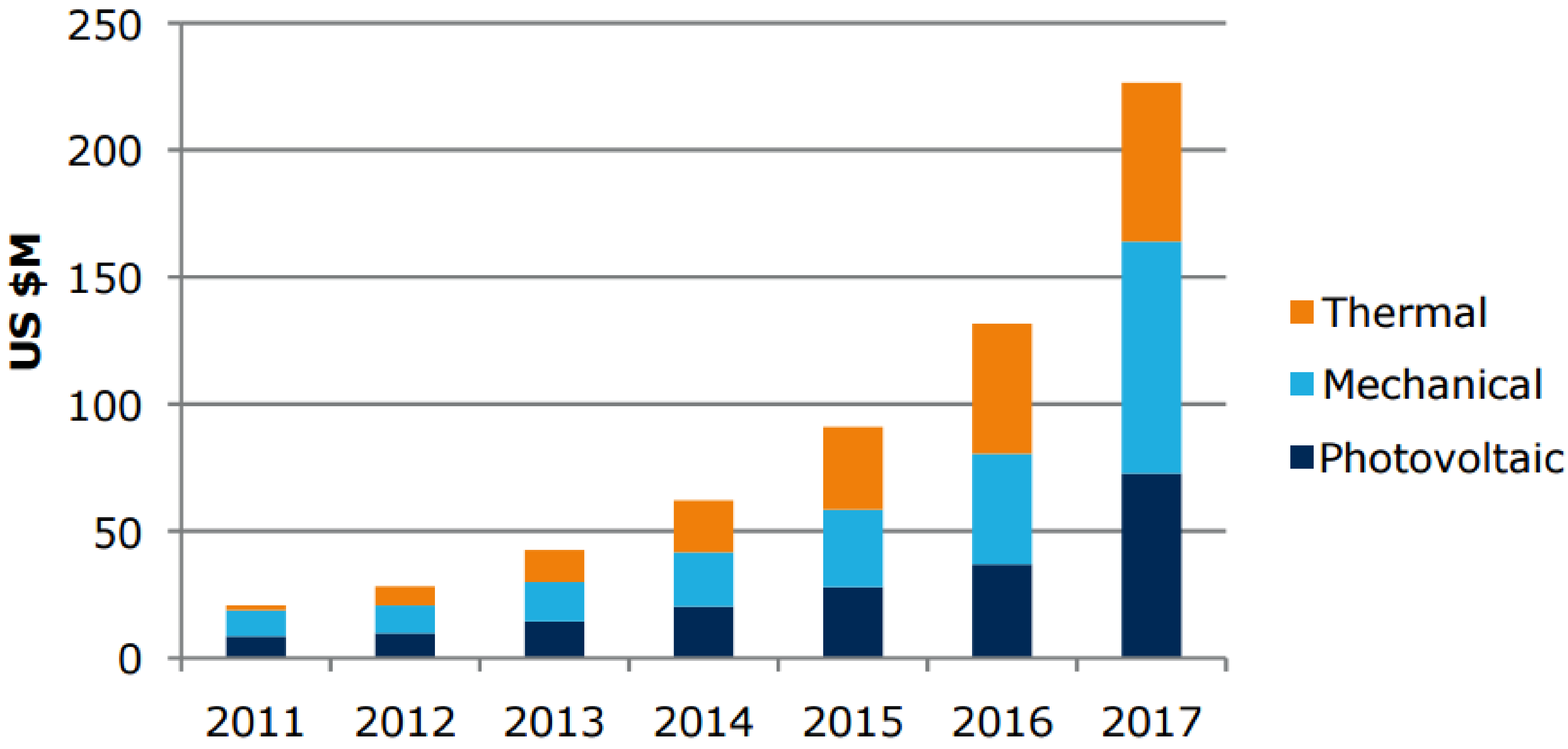
15 ©2010 Hewlett Packard Development Co, Peter Hartwell, HP Labs

Source: Peter Hartwell, HP Labs
http://www.hpl.hp.com/news/2009/oct-dec/cense.html

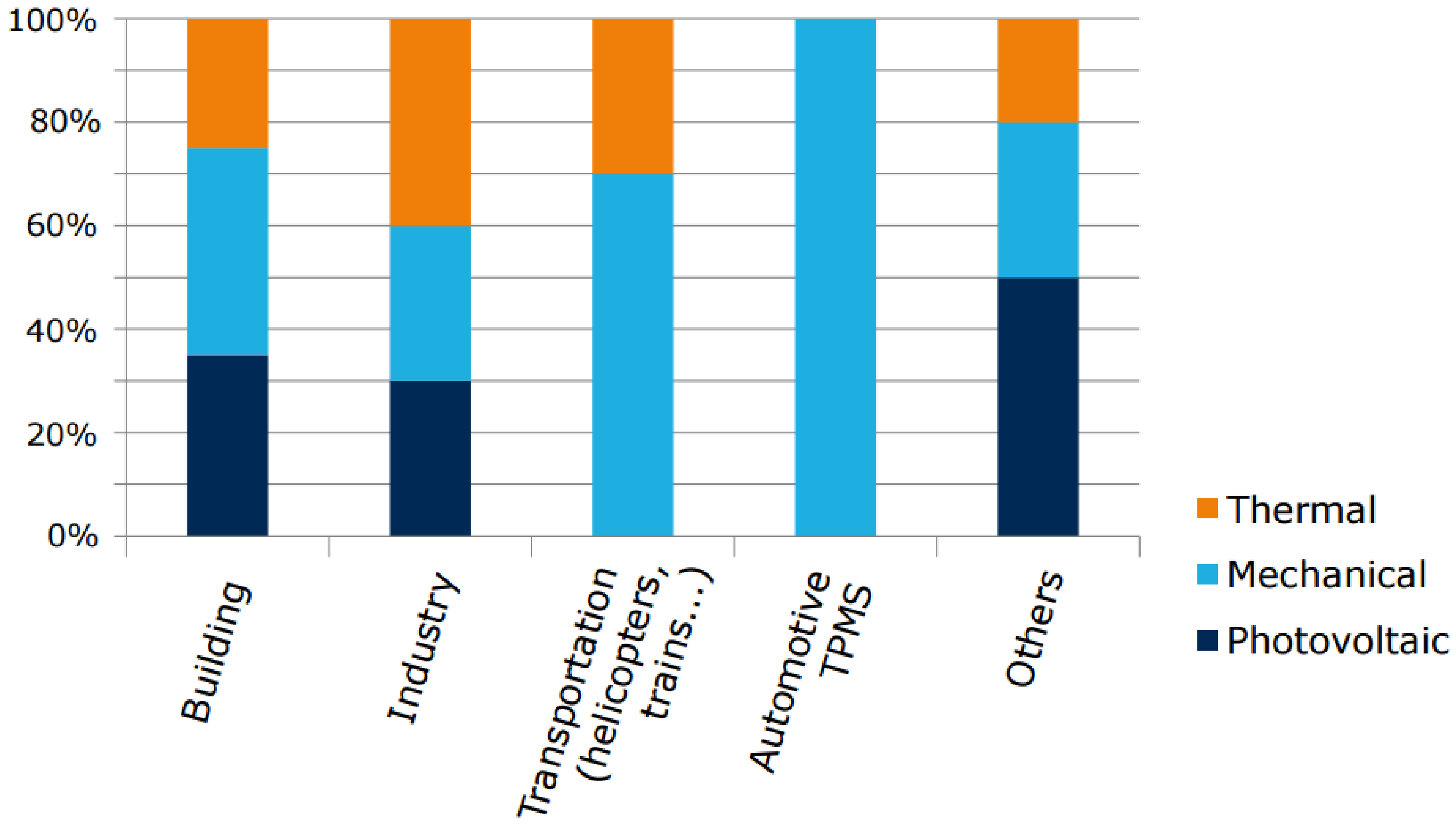
- Driven by autonomous wireless sensors
- Long lifetime (> 5 years)
- Battery recharging costly and/or infeasible

Market for modules

(Source: Energy Harvesting report, Yole Développement, to be released in November 2012)



http://www.yole.fr/iso_upload/Mag/ACMEMStrendsOct%202013.pdf



2017 energy harvesting transducer principle breakdown

(Source: Energy Harvesting report, Yole Développement, to be released in November 2012)

http://www.yole.fr/iso_upload/Mag/ACMEMStrendsOct%202013.pdf

IoT Device Taxonomy

(Courtesy of Vijay Raghunathan, Purdue Univ.)

Type-I

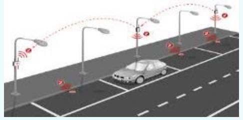
Wearable Devices

Type-II

Set-and-forget devices

Type-III

Infrastructure monitoring devices



Type-IV

Batteryless, transiently powered devices

Type-V

Wall-powered appliances

IoT Device Taxonomy

(Courtesy of Vijay Raghunathan, Purdue Univ.)

Type-I

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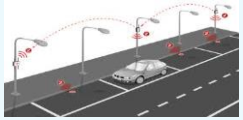

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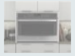
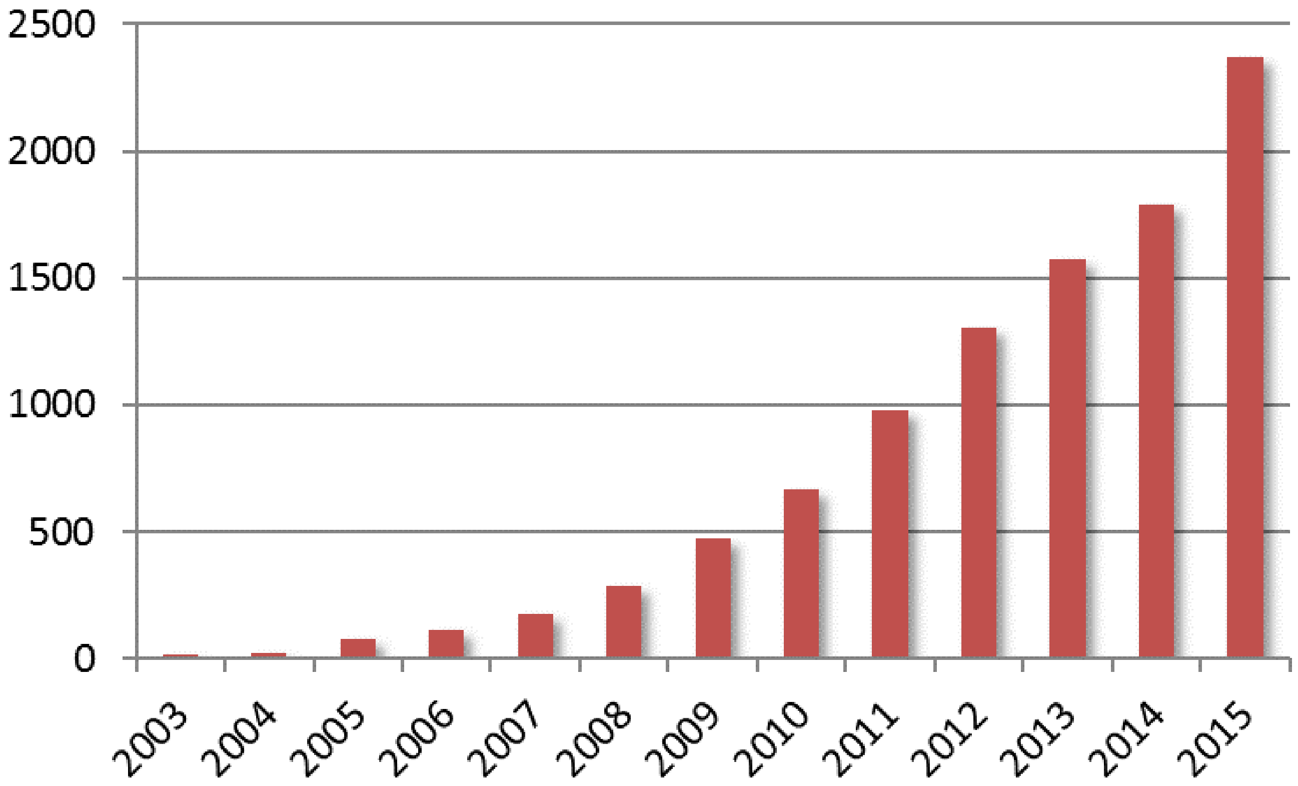
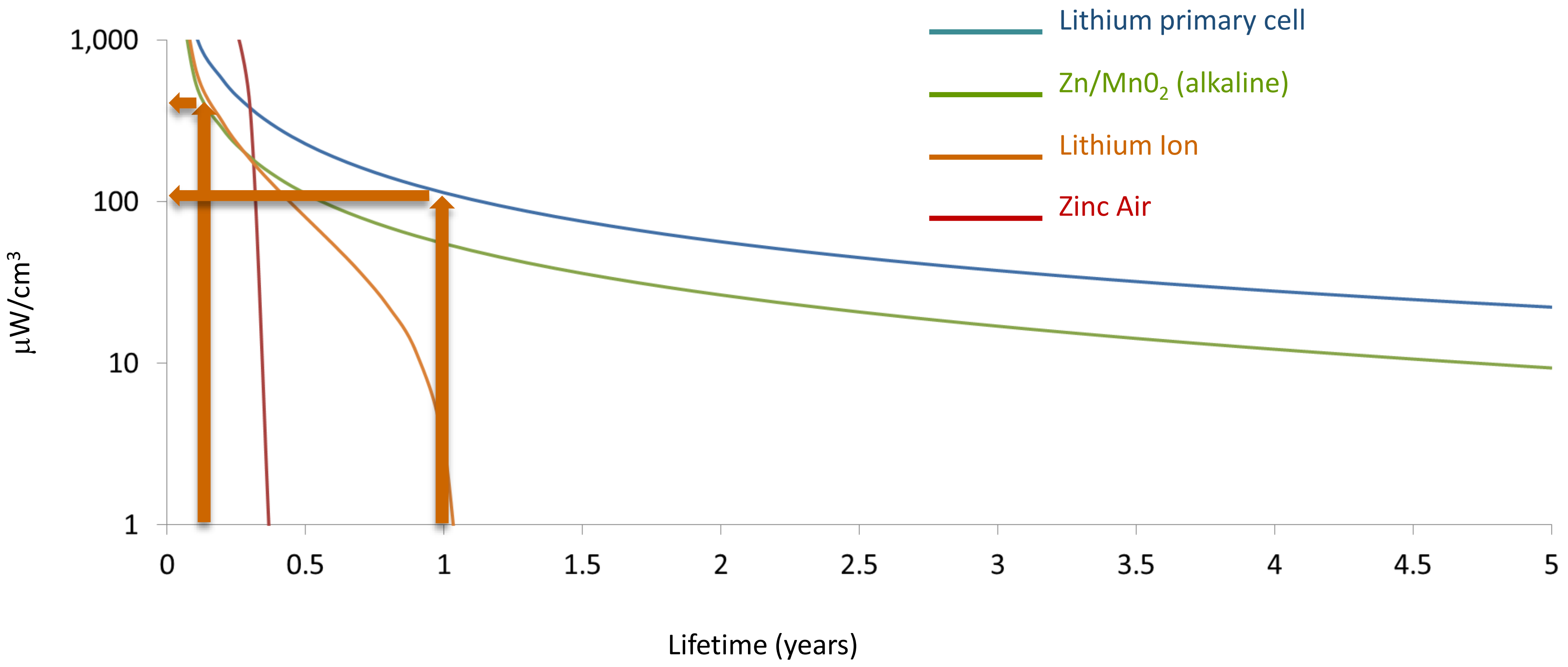


Energy Harvesting Publications by Year



From Google Scholar
“Energy Harv*” or “Energy Scav*” in title

Continuous Power / cm^3 vs. Lifetime



DIFFERENT TYPES OF ENERGY HARVESTING

RF Power

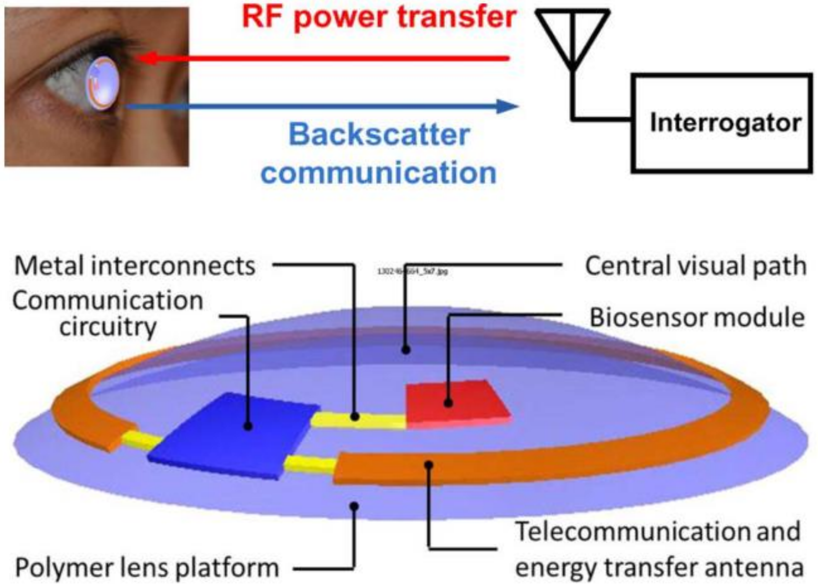


Fig. 1. Conceptual diagram of an active contact-lens system for wireless health monitoring.

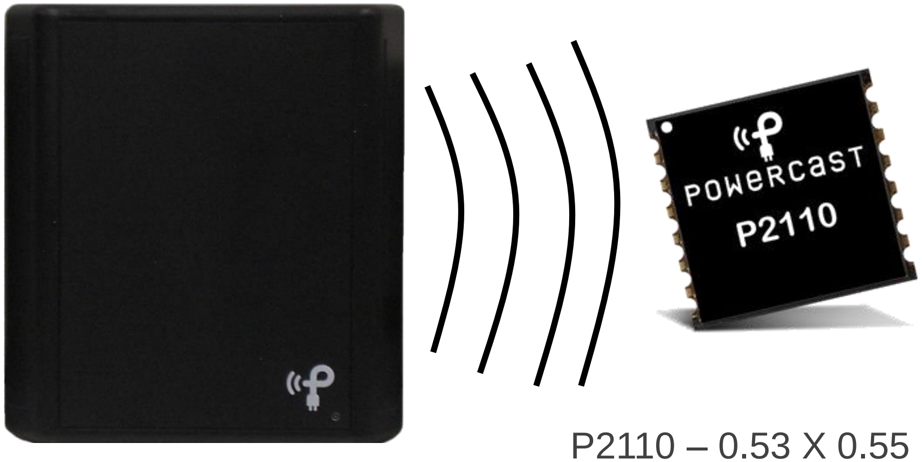
Liao et. al., IEEE Journal of Solid State Circuits, 2012
Univ. of Washington

- Glucose sensor on a contact lens
- Measures glucose in tear fluid
- RF powered
- Consumes 3 uW
- Google commercializing this (https://en.wikipedia.org/wiki/Google_Contact_Lens)

RF Power

Transmitter

Receiver



P2110 – 0.53 X 0.55 inches

http://www.powercastco.com/power-calculator/

- Powercast makes RF power harvesting products
- Microwatts to milliwatts
- Targeting things like high functionality RFID, ePaper labels, wireless sensors etc.

RF Power

- Example 1
  - Assume antenna gains of 1

$$P_r = P_0\left(\frac{\lambda}{4\pi R}\right)^2$$

P_0 = transmit power
P_r = power received
λ = wavelength
R = transmit distance

  - For 2.4 GHz, R = 5 meters, and P_0 = 1 watt

  - P_r = 4 uW

- Example 2
  - Use PowerCast Calculator

$$P_r = G_t G_r P_0\left(\frac{\lambda}{4\pi R}\right)^2$$

f = 915 MHz
$P_0 * G_t$ = 1 watt
G_r = 6.0 dBi (default value)
R = 5 meters

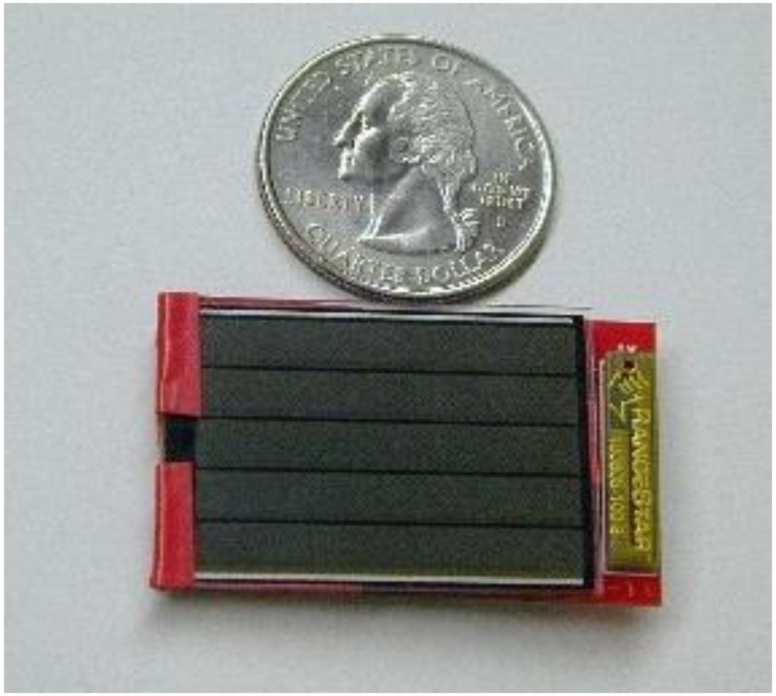
  - P_r = 108 uW

28 uw after conversion to DC

Photovoltaic

- ~ 15 mW/cm^2 outside in the Sun

Inside



Power Measured At Increasing Distances from a 60 watt Bulb

Distance	**Power (mW/cm^2)**
20 cm	503
30 cm	236
45 cm	111
Office Light	7.2

Thermal Gradients

Even with low efficiency, power output is attractive for some applications

Citizen Eco-Drive Thermo

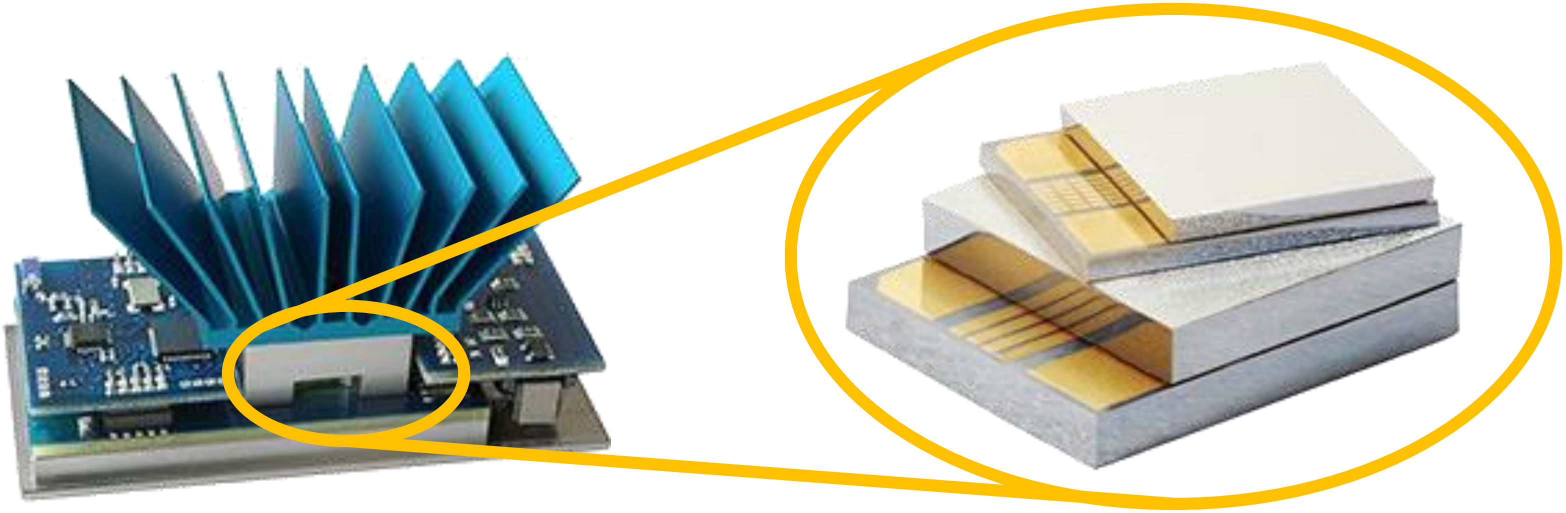
13.8 μW at ΔT of 1 °C

Size = 0.7cm X 0.7cm

Thermo Life

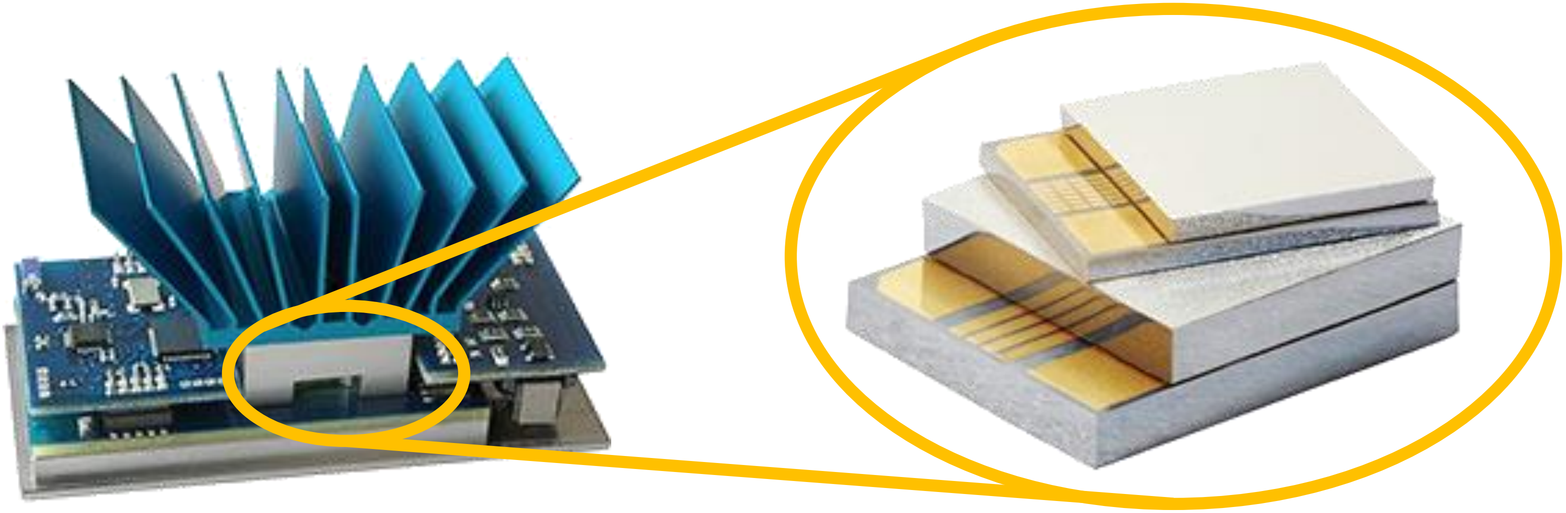
~ 25 μW at ΔT of 2 °C

Thermal Gradients



Micropelt GmbH

Thermal Gradients



Micropelt GmbH

- Example using http://www.micropelt.com/products/mypelt.php
  - $\Delta T = 5\ ^{o}C$, 25 rows in series
  - Output

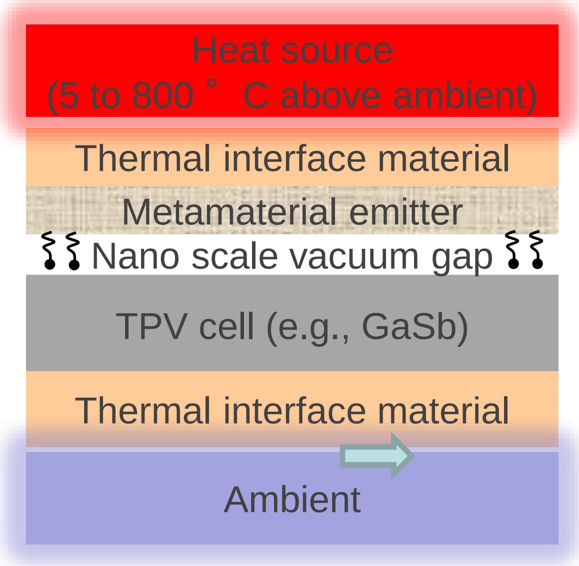
    88 mA, 0.75 V

    33 mW with matched load

University of Utah nano-TPV
(Courtesy of Prof. Mathieu Francoeur)

- Waste Heat Conversion
  - 58% of power generated in US is lost to heat
  - Potential heat recovery application spaces
    - Electronics (including data centers)
    - PV cells - passive cooling/heat recovery
    - Power generation (power plants)
    - Body heat powered electronics / sensors
    - Automotive applications

nano-TPV Stack



Heat source

(5 to 800 ° C above ambient)

Thermal interface material

Metamaterial emitter

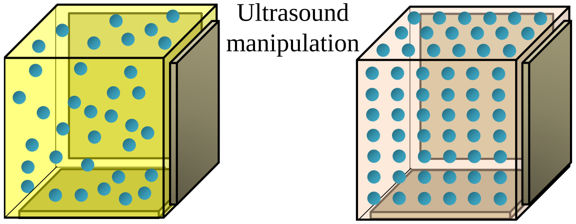
⌇⌇ Nano scale vacuum gap ⌇⌇

TPV cell (e.g., GaSb)

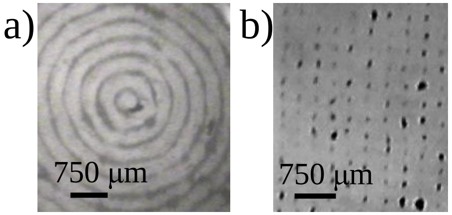
Thermal interface material

Ambient

Metamaterial manufacturing process: using bulk acoustic waves for directed self-assembly of dispersed dielectric inclusions in a dielectric matrix

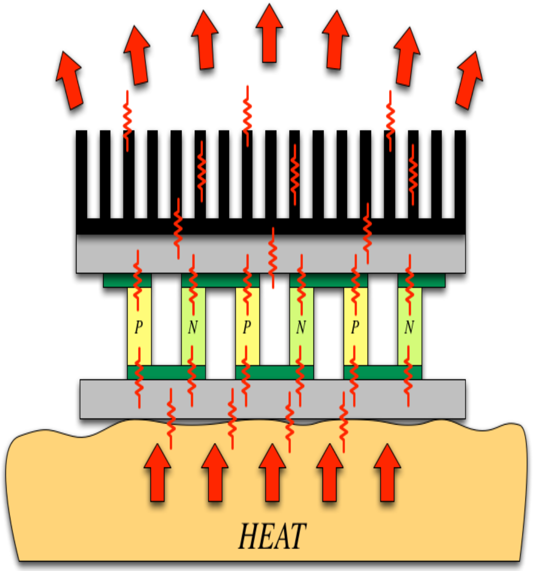


Directed self-assembly of 5 nm diamond particles using bulk acoustic waves

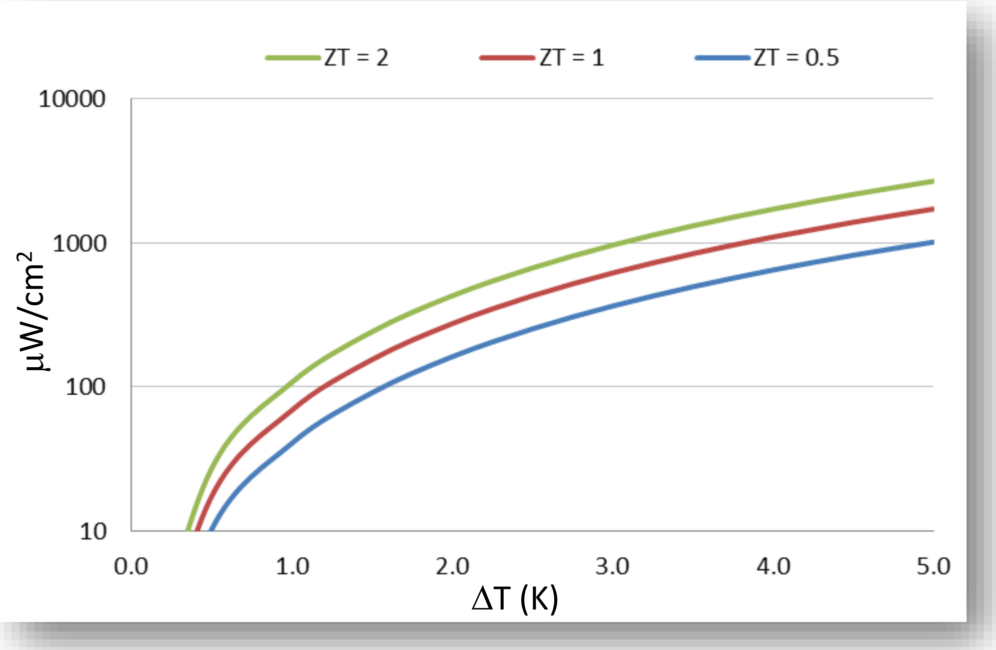


Raeymaekers et al., JAP, 2011

Thermal Energy Harvesting



Courtesy of Prof. Mehmet Ozturk, NC State



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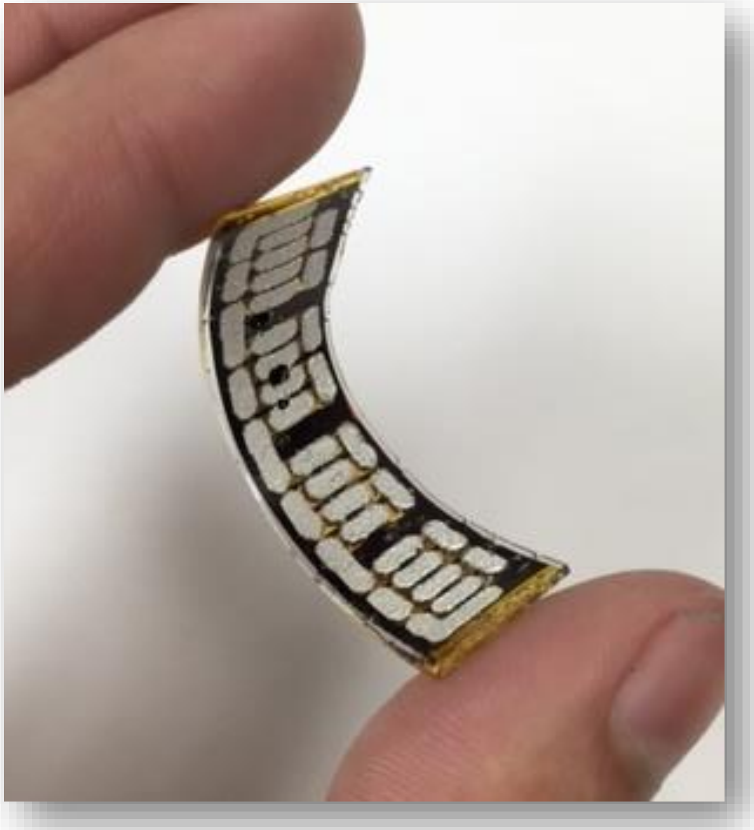
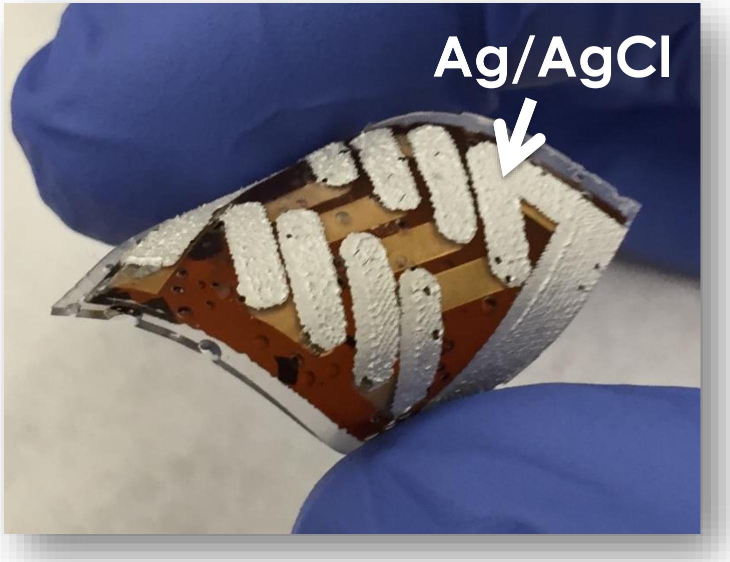
Advanced materials and processing





SSIST

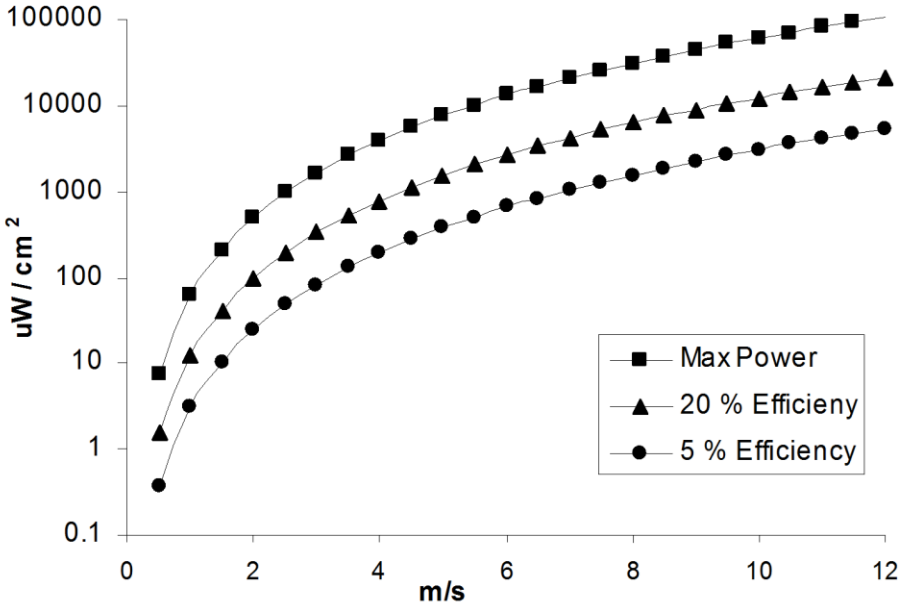
NC STATE UNIVERSITY

Courtesy of Prof.
Mehmet Ozturk,
NC State

Air / Fluid Flow

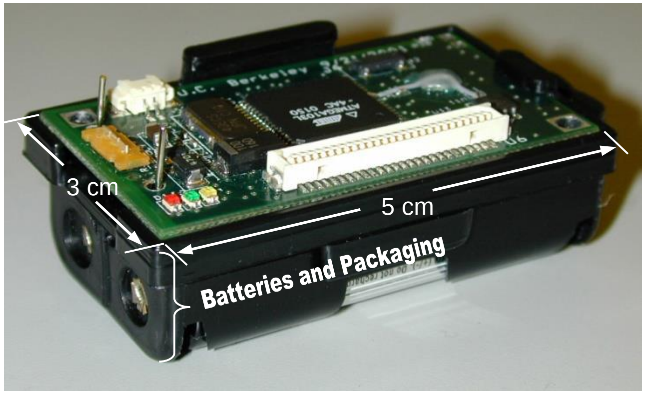
- Potential Power Given By:

$$P = \frac{1}{2}\rho A v^3$$



- Maximum Efficiency of Large Wind Turbines Generally About 40% (Limit Is 59%)
- Average Efficiency Generally About 20%
- Optimized for Wind Velocities of About 8 m/s

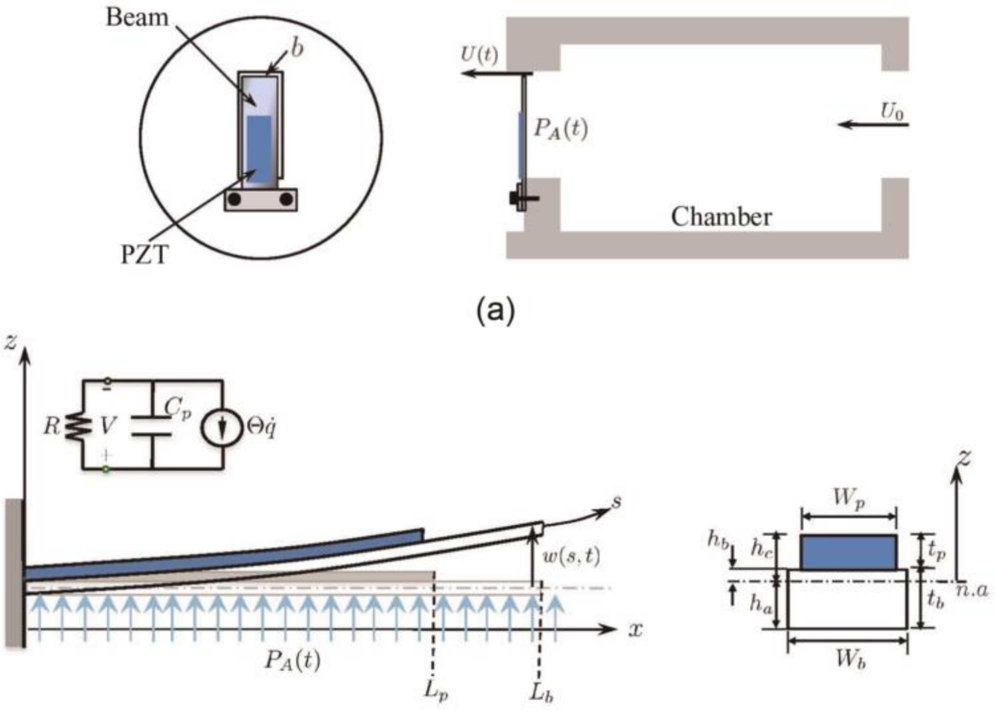
Air / Fluid Flow



Wind Velocity (m/s)	Power (uW/cm^2)	Efficiency
2.5	100	5 %
4	215	5.5 %
5	350	11 %

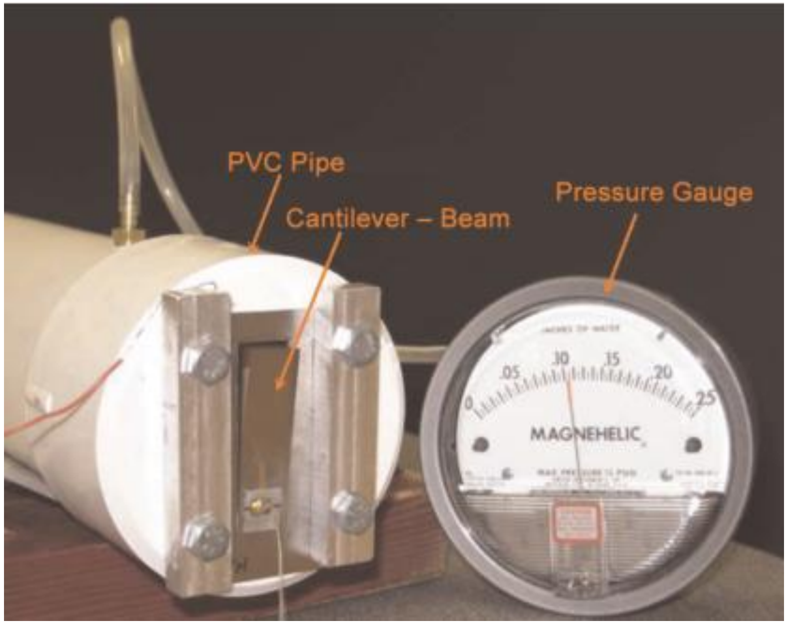
Experimental power output values reported by Federspiel and Chen, 2003

Aeroelastic Energy Harvesters



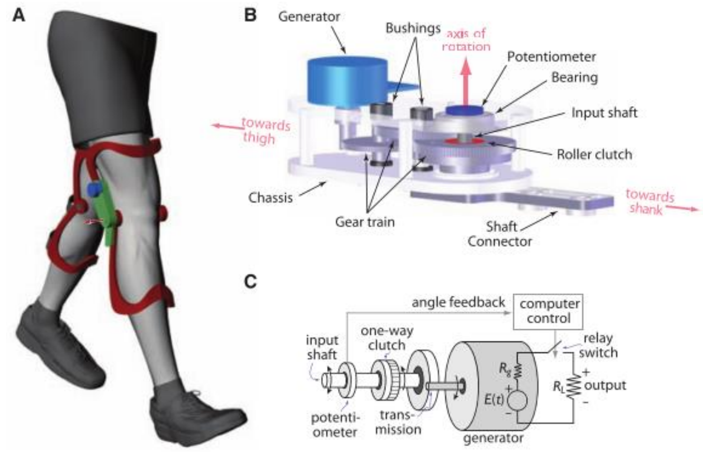
(a)

(b)

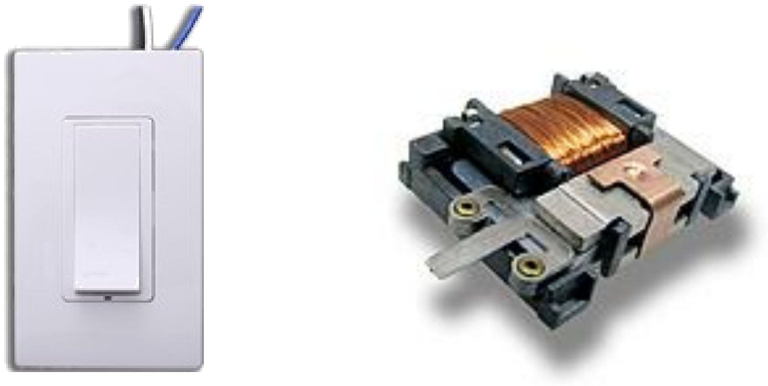


Bilbao, Liu, and Daqaq, JIMSS 2012

User Input

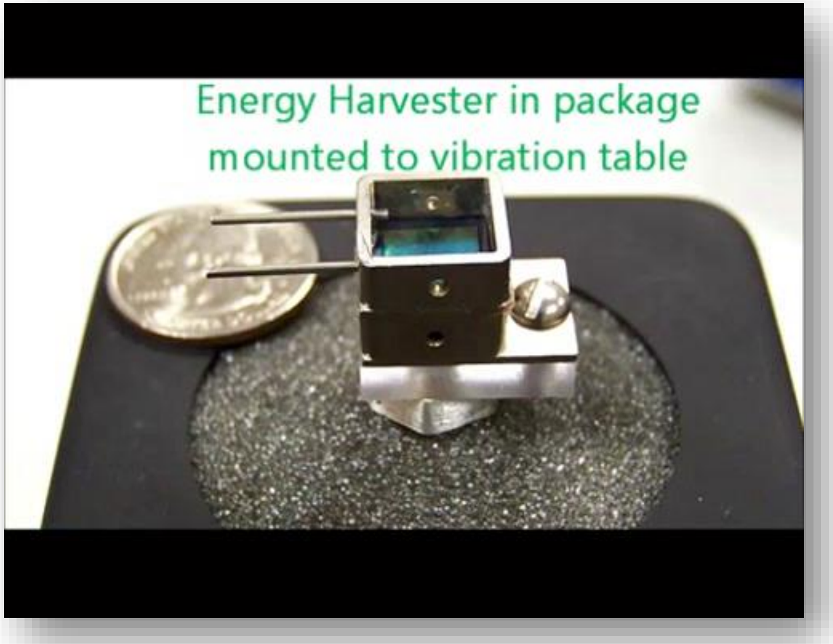


Donelan et. al. Science, 2008



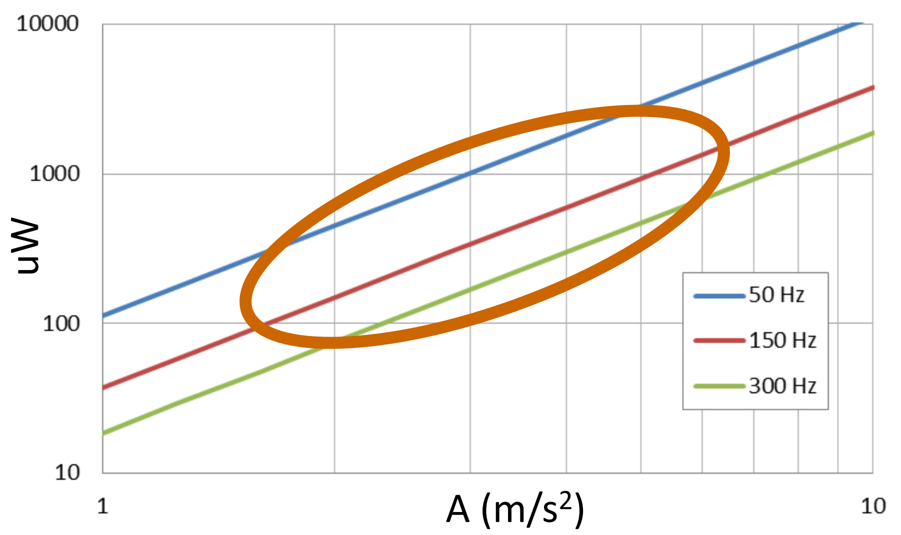
EnOcean, www.enocean.com

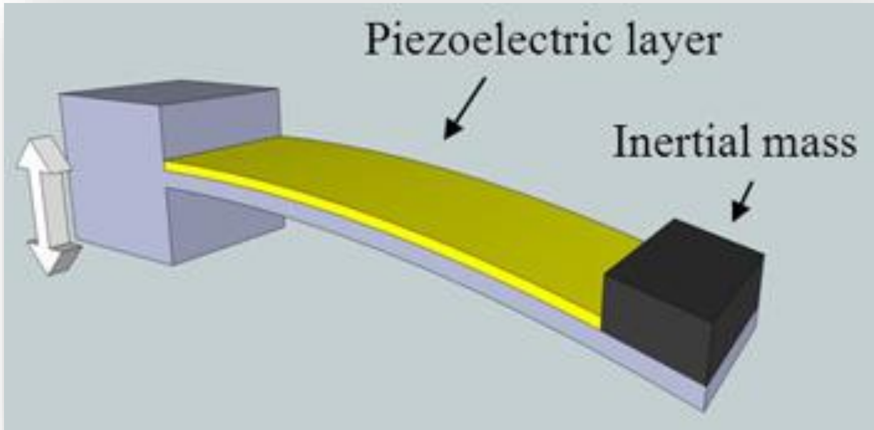
Vibrations



Microgen Systems Inc.

Courtesy of Robert Andosca

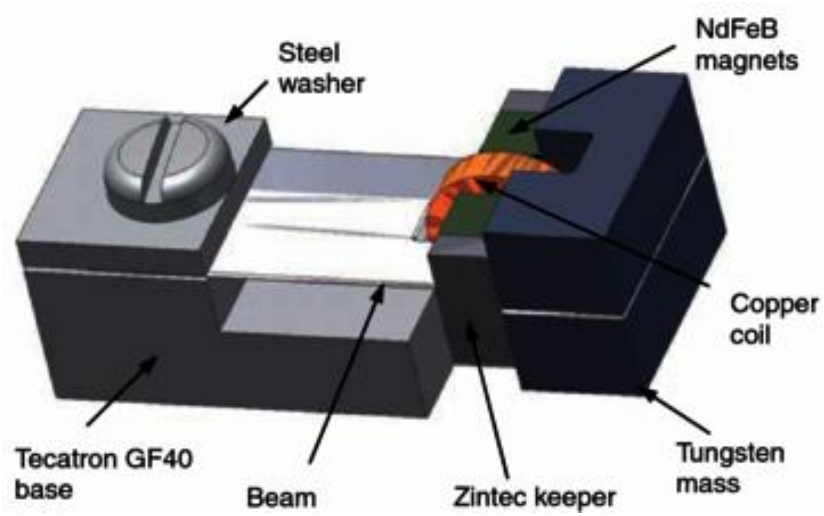




VIBRATION / MOTION BASED ENERGY HARVESTING

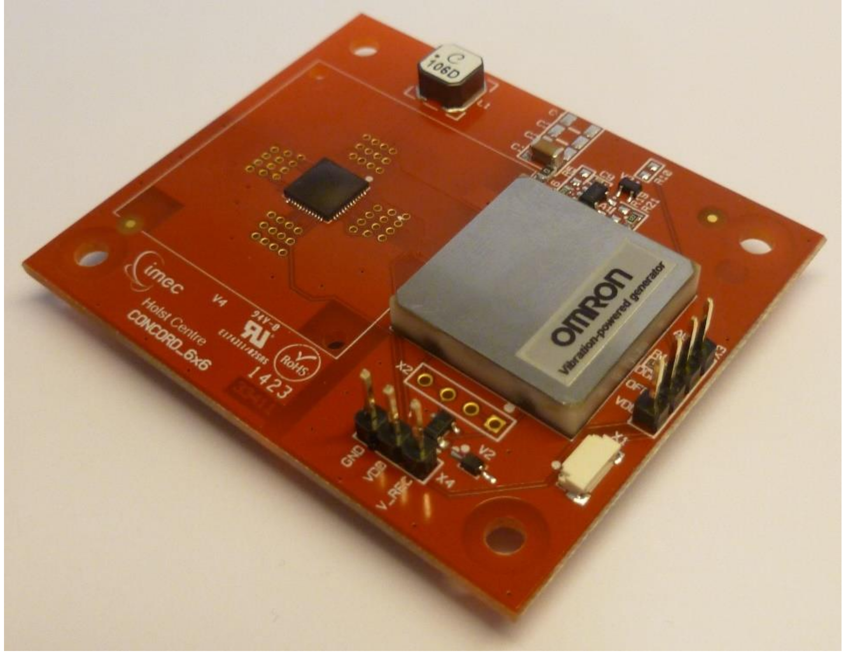
Perpetuum - Electromagnetic

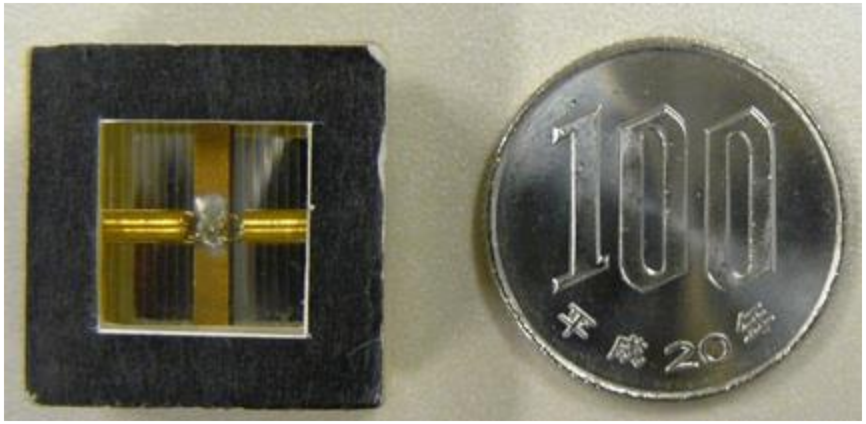
Perpetuum



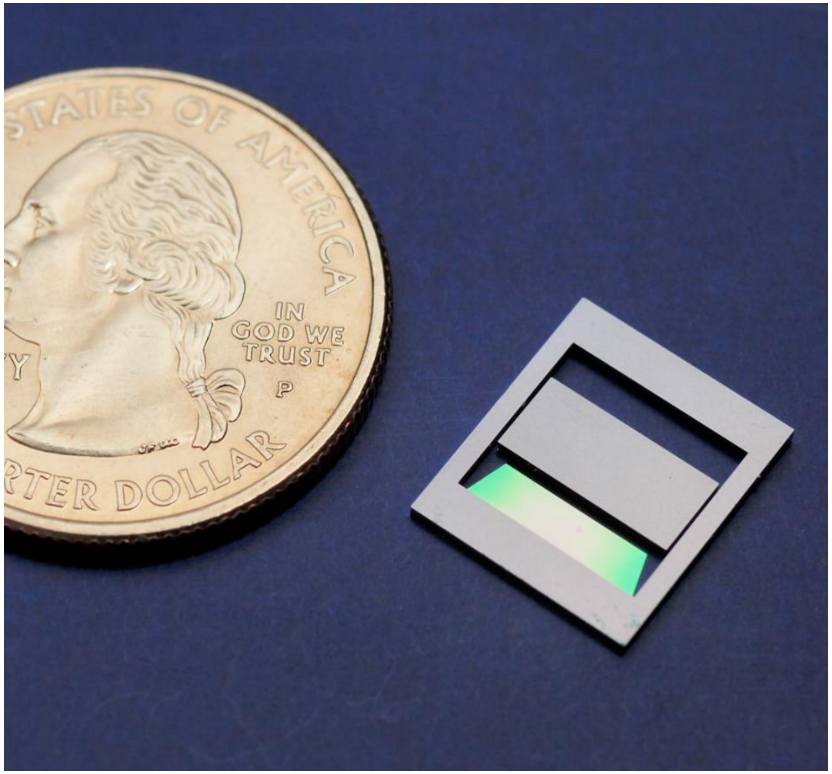
Beeby et. al, JMM, 2007

Omron - Electrostatic

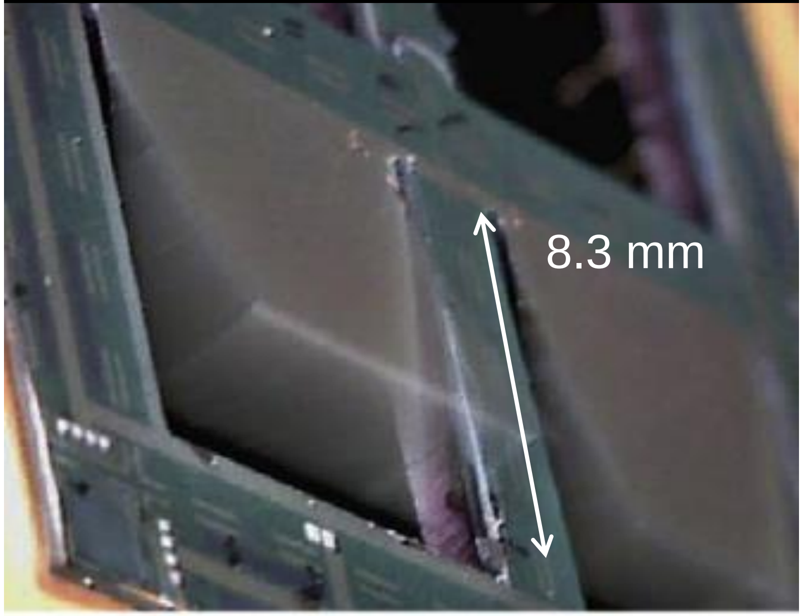




MicroGen Systems - Piezoelectric

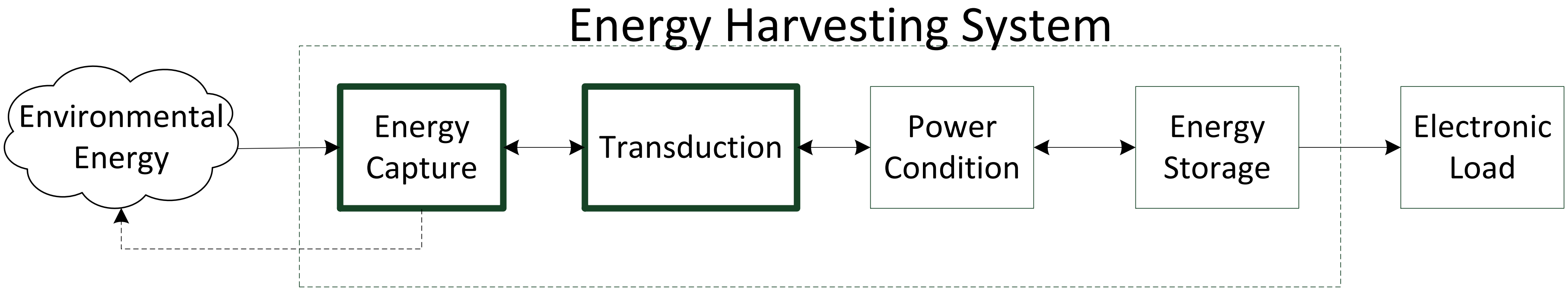


Andosca et al., Sensors and Actuators A, 178 **(2012)** 76



https://www.microgensystems.com/

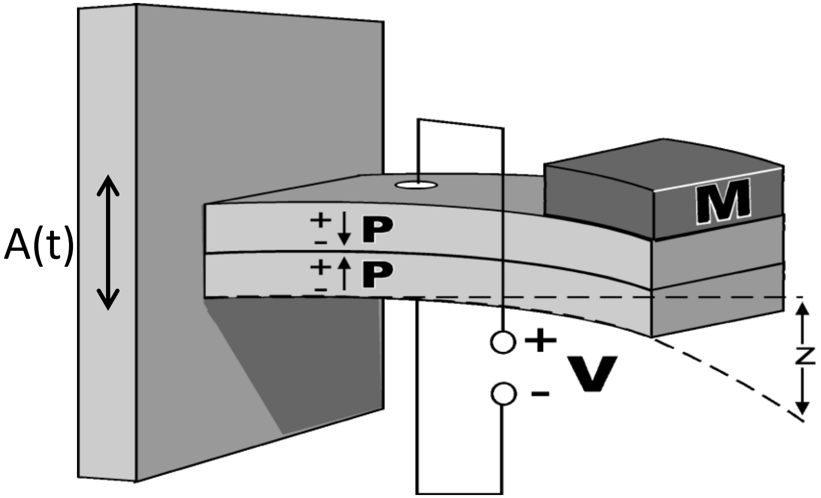
Energy Harvesting System Overview



"Micro Energy Harvesting", Briand, et. al. 2015

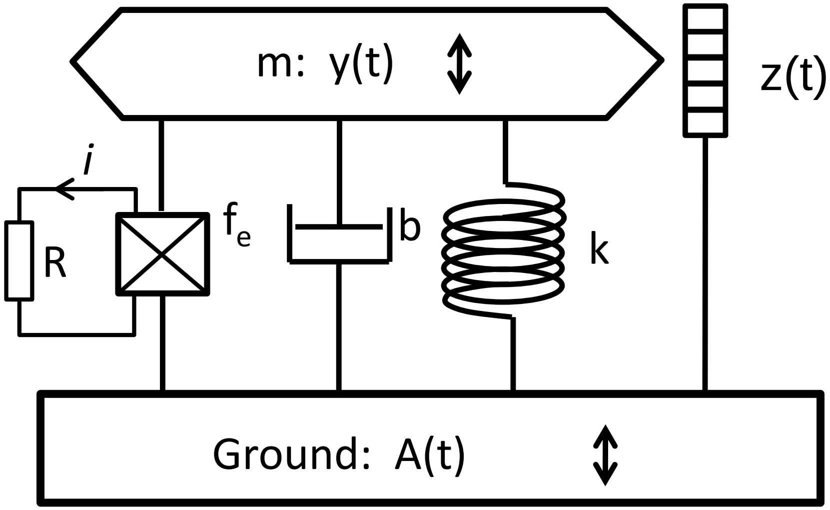
- An energy harvesting system consists of an energy capture mechanism (e.g. a cantilever beam, wind turbine), an electromechanical transducer (e.g. piezoelectric material), power conditioning circuitry, and usually temporary energy storage all of which delivers electrical power to a some electronic load.
- Each subsystem influences the behavior of the subsystem both immediately upstream and downstream in the overall system. The energy capture mechanism even affects the environment in which it operates, although this effect may be small.
- **This lecture primarily addresses the "Energy Capture" block**

Vibration Energy Harvesters (VEHs)



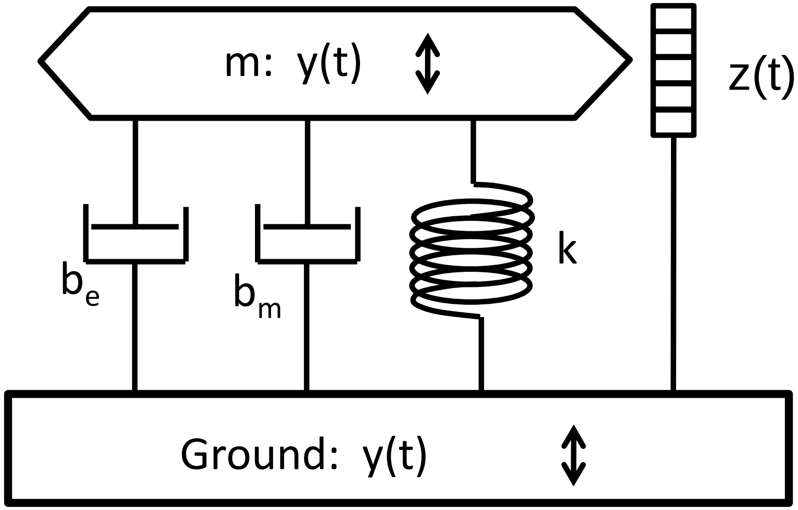
Roundy & Wright, SMS, 2004

- Piezoelectric bimorph beam VEH
- Base (or wall) is driven by vibration with acceleration A(t)
- There is a proof mass at the end of the beam, which flexes causing a 3-1 mode piezoelectric transducer



- Lumped parameter model of the piezoelectric beam VEH
- Mass is the equivalent mass (actual mass and inertial effects of beams)
- Piezo element creates an electrically induced force (f_e) on the mechanical oscillator as well as generating current through a load circuit

VDRG Vibration Energy Harvester Model

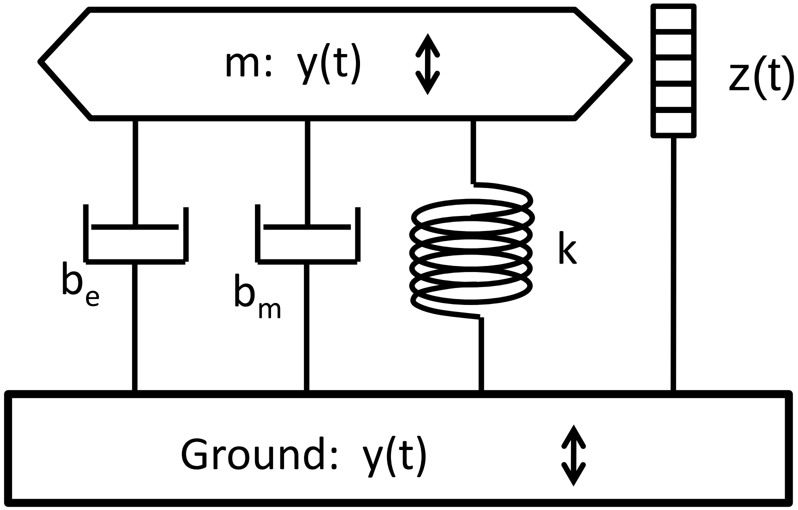


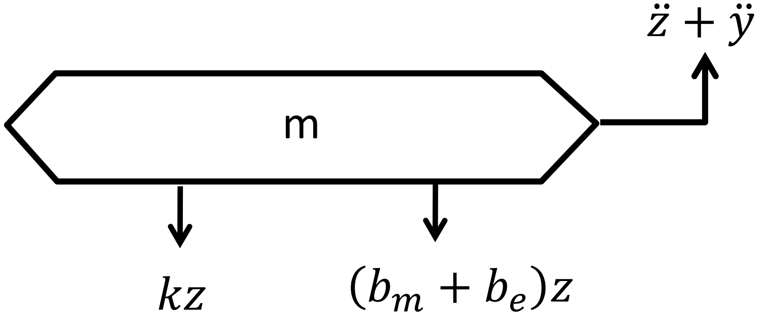
VDRG = Velocity Damped Resonant Generator

Mitcheson et. al., JMEMS 2004
Halvorsen et. al. J. Phys. Conf. Series, 2013
Heit & Roundy, En. Harv. and Sys., 2015

- b_e is the electrically induced damping coefficient
- Power dissipated through b_e is the power extracted by the load circuit
- This model has been shown to produce the upper bound on extractable power from in input dominated by a single, stable frequency

VDRG Vibration Energy Harvester Model





z is the relative displacement, so total acceleration experienced by proof mass is $\ddot{z}+\ddot{y}$

Governing equation:

$$m\ddot{z}+(b_m+b_e)\dot{z}+kz=-m\ddot{y}$$

VDRG Vibration Energy Harvester Model

Make the following substitutions to generalize the equation:

$$\omega_n^2 = \frac{k}{m} \qquad \frac{b}{m} = 2\zeta\omega_n$$

where ω_n is the natural frequency and ζ is the dimensionless damping ratio

$$\ddot{z} + 2(\zeta_m + \zeta_e)\omega_n\dot{z} + \omega_n^2 z = -\ddot{y}$$

This is the standard forced oscillator equation, which is characteristic of a damped mass-spring system or an LCR circuit.

Solving for z in the frequency domain yields:

$$Z(j\omega) = \frac{\omega^2 Y}{\omega_n^2 - \omega^2 + j2\zeta\omega\omega_n}$$

where $\zeta = \zeta_m + \zeta_e$ is the total damping ratio.

VDRG Vibration Energy Harvester Model

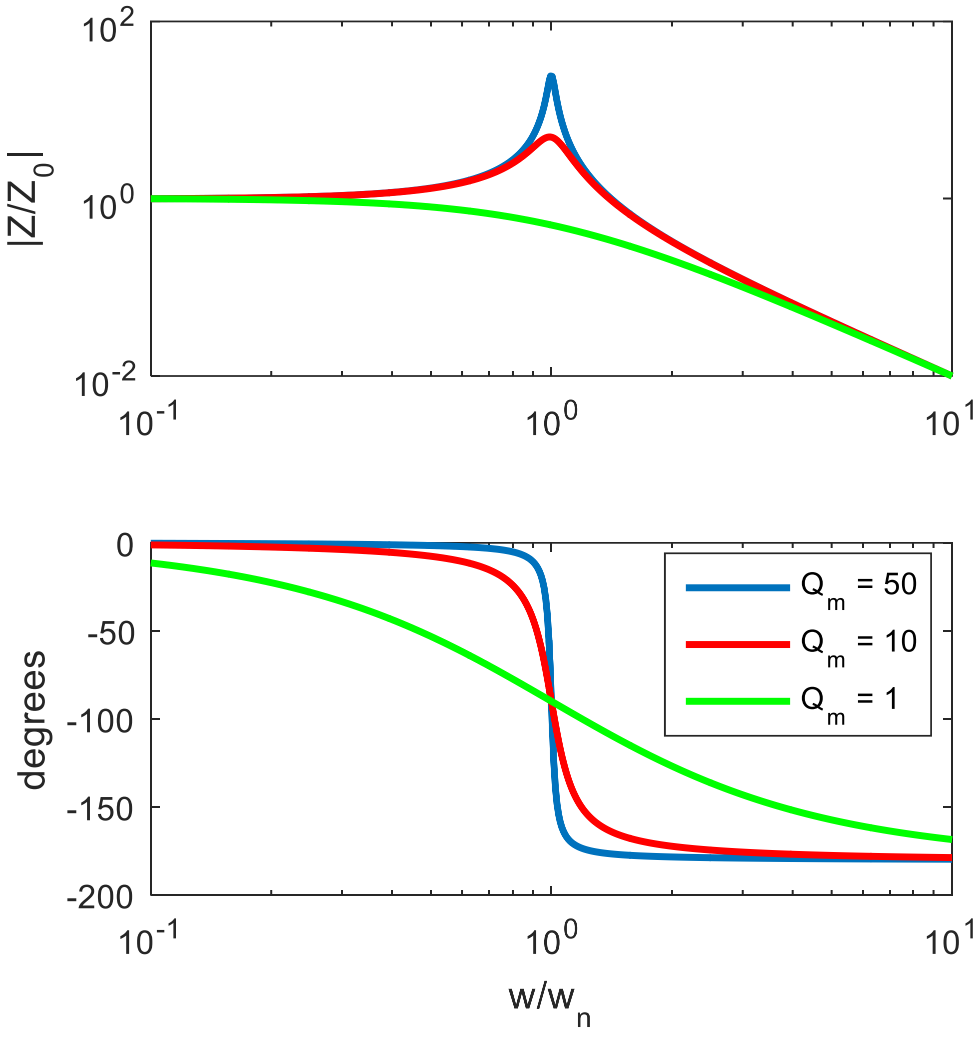
Let $r = \frac{\omega}{\omega_n}$ be the ratio of the driving frequency to the natural frequency, and:

$$Z(j\omega) = \frac{r^2 Y}{(1 - r^2) + j2\zeta r}$$

The magnitude of the response is:

$$Z_0 = |Z(j\omega)| = \frac{r^2 Y}{\sqrt{(1 - r^2)^2 + (2\zeta r)^2}}$$

VDRG Vibration Energy Harvester Model



Note, the quality factor (or Q) is the amplification ratio at resonance, and is mathematically defined as $Q = \frac{1}{2\zeta}$, so the "mechanical Q" or $Q_m = 1/(2\zeta_m)$

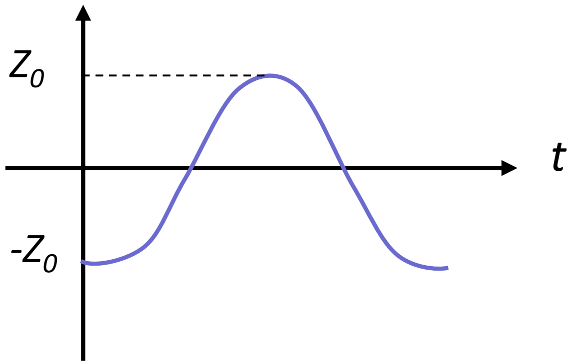
VDRG Vibration Energy Harvester Model

We want to determine ***how much power*** gets dissipated through electrical damper b_e.

At any instant, the electrically induced force on the proof mass is: $F(t) = b_e \dot{z}(t)$

To get the average RMS power, we will integrate $F(t)$ over one full displacement cycle to get the energy dissipated per cycle, E_{cyc}.

$$E_{cyc} = 2\int_{-Z_0}^{Z_0} b_e \dot{z} dz = 2\int_0^{\frac{\pi}{\omega}} b_e \dot{z}^2 dt$$



Then divide by the period, T, to get RMS power.

VDRG Vibration Energy Harvester Model

$$z(t) = Z_0 \sin(\omega t)$$

$$\dot{z}(t) = \omega Z_0 \cos(\omega t)$$

$$E_{cyc} = 2 b_e \omega^2 Z_0^2 \int_0^{\frac{\pi}{\omega}} \cos^2(\omega t) dt$$

$$E_{cyc} = 2 b_e \omega^2 Z_0^2 \frac{2\pi}{4\omega}$$

$$P_{rms} = \frac{E_{cyc}}{T} \qquad where\ T = \frac{2\pi}{\omega}$$

$$P_{rms} = \frac{1}{2} b_e \omega^2 Z_0^2$$

VDRG Vibration Energy Harvester Model

Incorporate expression for Z_0

$$Z_0 = |Z(j\omega)| = \frac{r^2 Y}{\sqrt{(1-r^2)^2 + (2\zeta r)^2}}$$

$$P_{rms} = \frac{1}{2}\, b_e \frac{r^4 Y^2}{(1-r^2)^2 + (2\zeta r)^2}$$

Substituting $b_e = 2m\zeta_e\omega_n$

$$P_{rms} = \frac{m\zeta_e \omega^3 r^3 Y^2}{(1-r^2)^2 + (2\zeta r)^2}$$

More often written as a function of input vibration acceleration $A = Y\omega^2$:

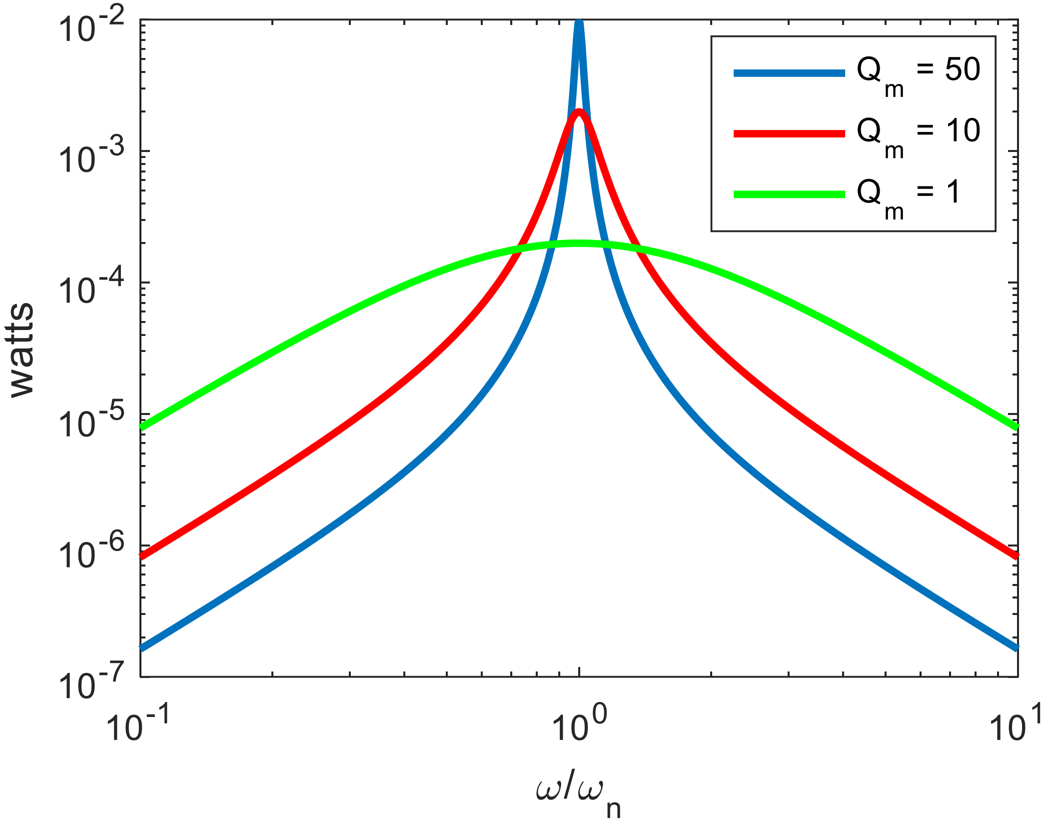
$$\boxed{P_{rms} = \frac{m\zeta_e r^3 A^2}{\omega[(1-r^2)^2 + (2\zeta r)^2]}}$$

Things to note from VDRG model

$$P_{rms} = \frac{m\zeta_e r^3 A^2}{\omega[(1-r^2)^2+(2\zeta r)^2]}$$

- Maximum power occurs at resonance (r = 1)
- Power is proportional to proof mass
- Power is proportional to $\frac{A^2}{\omega}$ where is ω is the driving frequency
- There is an optimal level of electrically induced damping ($\zeta_e = \zeta_m$)
  - Power is maximized by minimizing mechanical damping, and then matching electrical damping to the mechanical damping

Power vs. Frequency for Multiple Q’s

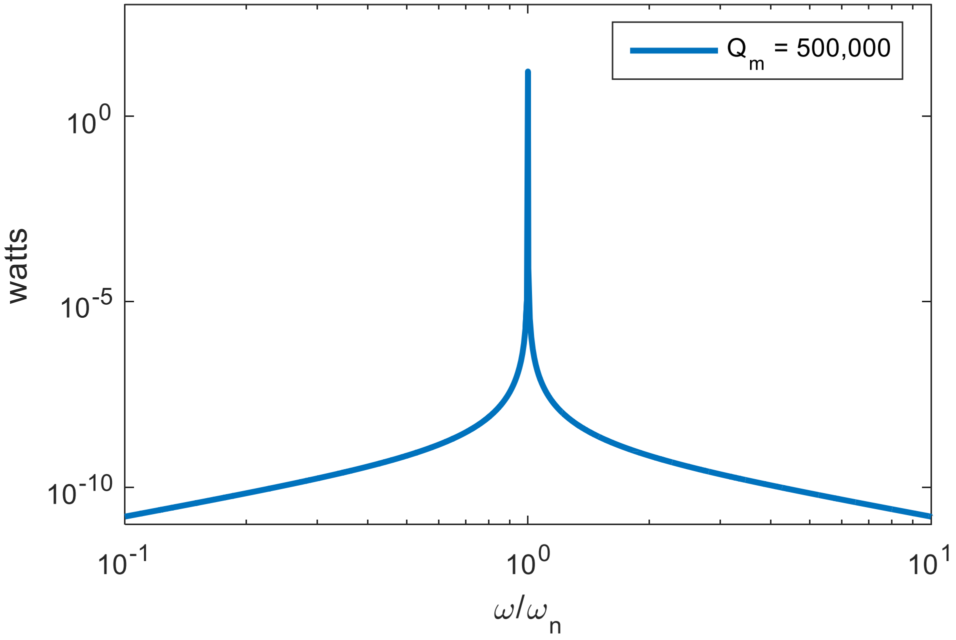


$A = 1\ m/s^2$
$m = 1$ kg
$\omega_n = 2\pi 100$ rad/s

Power at resonance is highly dependent on Q.

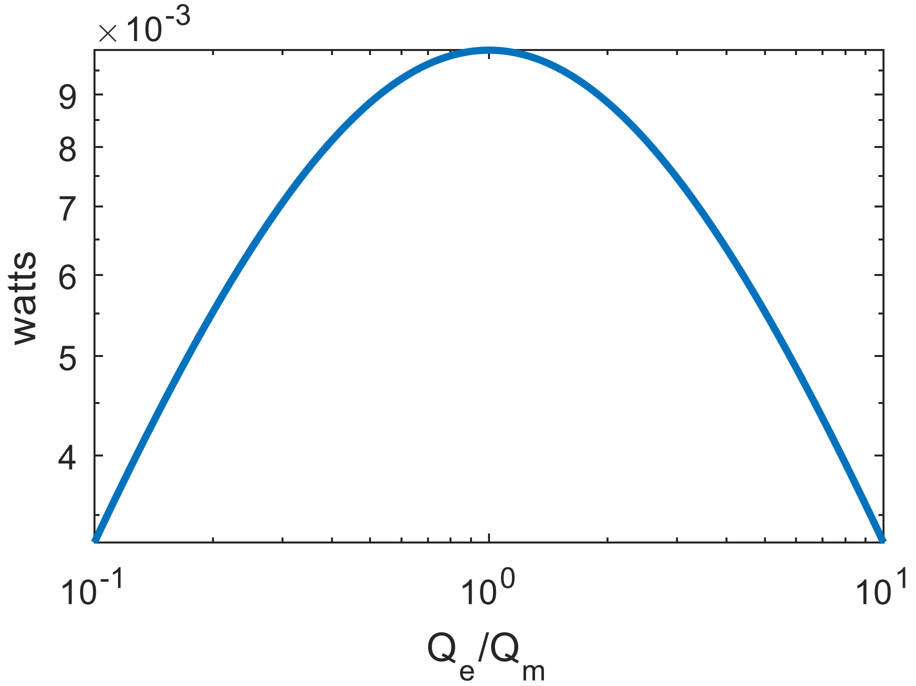
At high Q, where power is good, half-power bandwidth is extremely narrow, which is one of the big problems with vibration energy harvesters.

How High Can the Output Power Get?



- Technically, power output is unbounded
- Rests on the assumption that the vibration source will exert whatever force is necessary to maintain its displacement
- Rests on the assumption that proof mass displacement is also unbounded

Power vs. Electrical Damping



$$P_{rms}(r=1) = \frac{m\zeta_e A^2}{4\omega\zeta^2}$$

Assume resonance
$Q_m = 50$

Power is somewhat sensitive to electromechanical coupling which relates to Q_e.

In practice most, though not all, systems are under-coupled and so on the left side of this graph.

Example 1: Belt worn harvester

- $m = 6.1$ oz = 173 grams (iPhone 6)
- Walking motion is about 1 Hz
- $A = 0.5\ g = 5\ m/s^2$
- Conservatively assume $Q_m = 20$, $Q_e = 20$
- Assume resonance

Example 1: Belt worn harvester

- m = 6.1 oz = 173 grams (iPhone 6)
- Walking motion is about 1 Hz
- A = 0.5 g = 5 m/s^2
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$$P_{rms}(r = 1) = \frac{m\zeta_e A^2}{4\omega\zeta^2} = \frac{mQ^2A^2}{2\omega Q_e}$$

- P = 1.7 watts !!!!

Example 1: Belt worn harvester

- But, motion is unconstrained, what is Z_0?

$$Z_0 = |Z(j\omega)| = \frac{r^2 Y}{\sqrt{(1-r^2)^2 + (2\zeta r)^2}}$$

$$Y = \frac{A}{\omega^2} = 12.7\ cm$$

$$Z_0(r=1) = \frac{A}{2\omega^2\zeta} = \frac{Y}{Q}$$

- Z_0 = 1.27 meters !!!

Example 1: Belt worn harvester

- So, there is a lot of power available, but unfortunately it requires very large displacements.
- This, along with bandwidth, is the most challenging issue with body worn inertial harvesters
- See for more discussion of the effect of displacement limits:
  - Mitcheson et. al. 2004 “Architectures for Vibration-Driven Micropower Generators”, *Journal of Microelectromechanical Systems*, **3**, pp 1-12, 2004.
  - Mitcheson et. al. 2008 “Energy Harvesting from Human and Machine Motion for Wireless Electronic Devices”, *Proceedings of the IEEE*, vol. 96 **9**, pp1457-1486.

Example 2

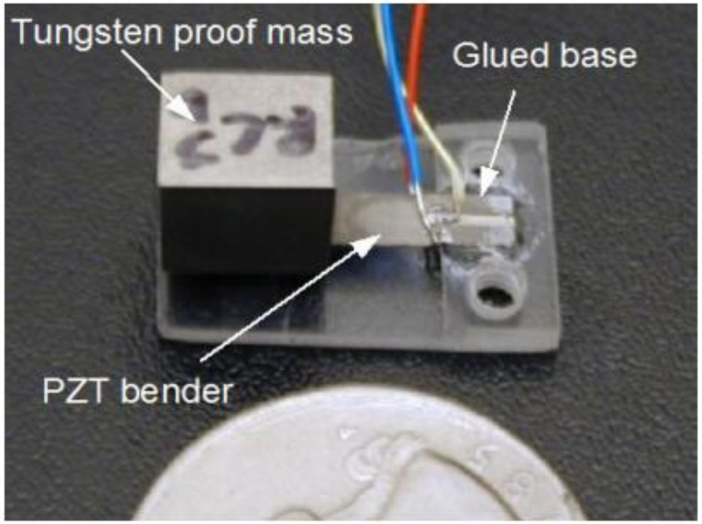

Figure 14. The optimized piezoelectric generator with a 1.5 cm length constraint (design 1).

Roundy and Wright, SMS 2004

$m = 7.45$ grams
$\omega_n = 2*pi*120$ rad/s
$A = 2.5\ \mathrm{m/s^2}$
$\zeta_m = 0.015$ ($Q_m = 33$)

According to VDRG,
max power = 255 μW

Measured power = 210 μW

$Z_0 = 73\ \mu\mathrm{m}$

"effectiveness" = P_{meas}/P_{VDRG} = 82%

See Mitcheson et. al. 2008, Proceedings of the IEEE

Figures of Merit

$$P_{rms}(r=1) = \frac{m\zeta_e A^2}{4\omega\zeta^2}$$

- Different types of power densities are often reported
  - W/cm^3/g^2 or W/cm^3/g^2/Hz
  - While these are reasonable metrics for comparison, they only tell part of the story.

- My preference for FOM is that defined by Mitcheson:
  - Harvester effectiveness: $E_H = \frac{Useful\ Power\ Out}{P_{VDRG}}$
  - This is really a measure of how well a particular design performs relative to its ideal performance

Graph of Reported Effectiveness (2008)

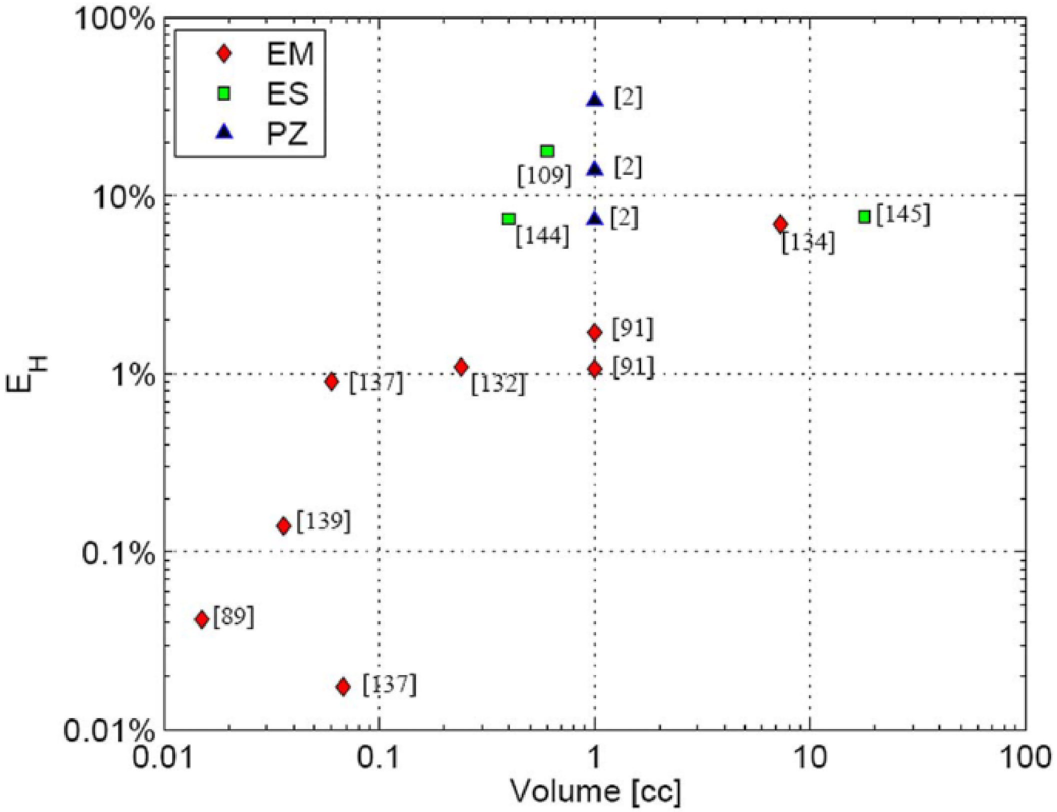

Fig. 27. ***Harvester effectiveness of reported devices versus device volume.***

Mitcheson et. al. 2008 “Energy Harvesting from Human and Machine Motion for Wireless Electronic Devices”, *Proceedings of the IEEE*, vol. 96 **9**, pp1457-1486.

Next Up

- Here, we just lumped all electromechanical transduction into a single damping parameter

- Next lecture will go over specific transduction mechanisms