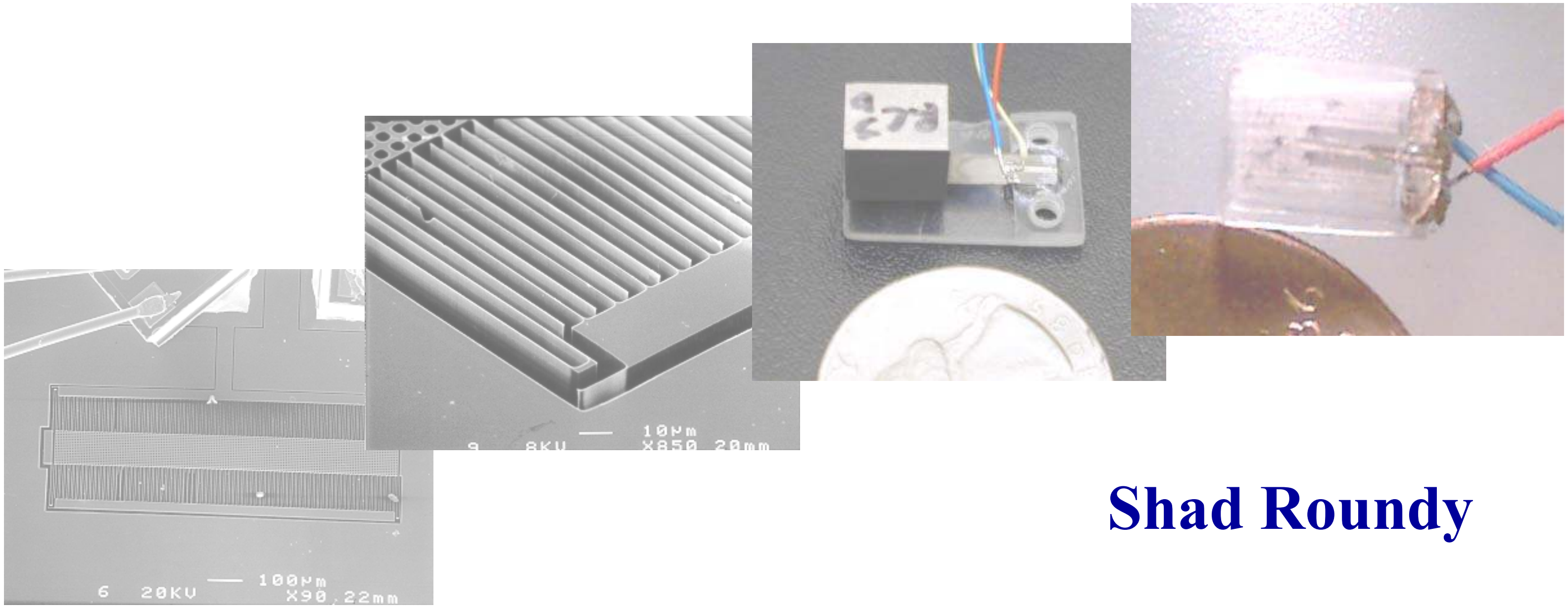
Energy Scavenging for Wireless Sensor Nodes with a Focus on Vibration-to-Electricity Conversion



Shad Roundy

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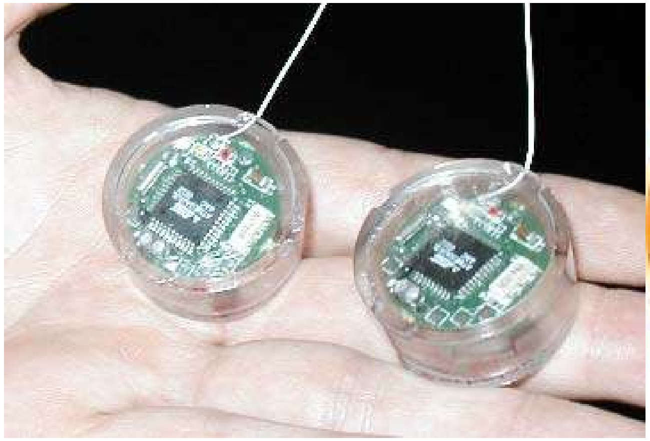
2/19/2003

Motivation and Objective

- Wireless sensor and computing networks

> “As people find more ways to incorporate these inexpensive, flexible and infinitely customisable devices into their lives, the computers themselves will gradually ‘disappear’ into the fabric or our lives.”
>
> Bill Gates in ‘The Economist’, Dec. 2002.

- Small, low power, low cost, low data rate wireless platforms are being developed in many places



Motivation and Objective

- Effective, long term, power supplies are lacking
  - Example: At an average power consumption of 100 µW, you need more than 1 cm^3 of lithium battery volume for 1 year of operation.

- "The pervasiveness and near-invisibility of computing will be helped along by new technologies such as … inductively powered computers that rely on heat and motion from their environment to run without batteries."

Bill Gates in 'The Economist', Dec. 2002.

- Goal: To investigate power "scavenging" technologies that can provide an average of 100 $\mu\text{W/cm}^3$ indefinitely.

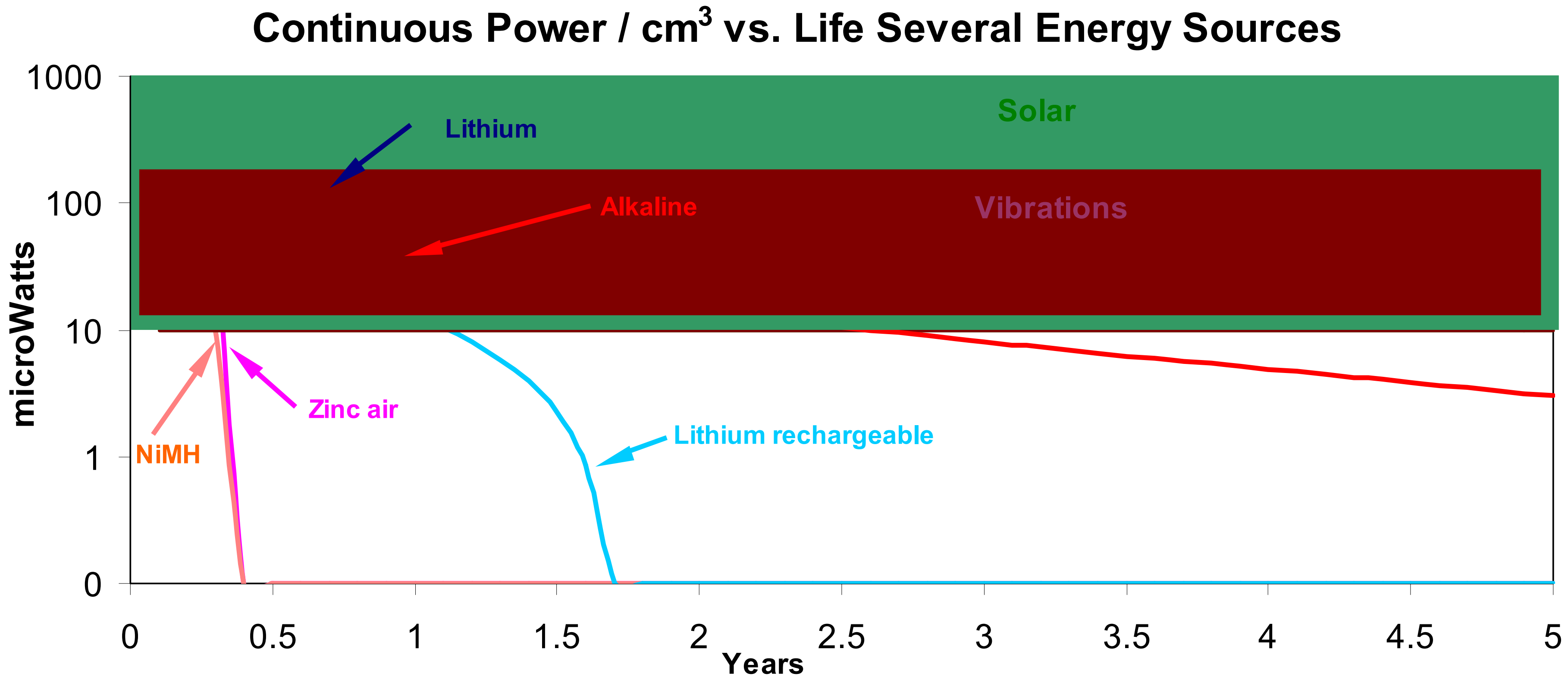
Comparison of Power Sources

Comparison of Energy Scavenging Sources

	Power Density (μW/cm³) 1Year lifetime	Power Density (μW/cm³) 10 Year lifetime	Source of information
Solar (Outdoors)	15,000 - direct sun 150 - cloudy day	15,000 - direct sun 150 - cloudy day	Commonly Available
Solar (Indoors)	6 - office desk	6 - office desk	Experiment
Vibrations	100 - 200	100 - 200	Experiment and Theory
Acoustic Noise	0.003 @ 75 Db 0.96 @ 100 Db	0.003 @ 75 Db 0.96 @ 100 Db	Theory
Daily Temp. Variation	10	10	Theory
Temperature Gradient	15 @ 10 ºC gradient	15 @ 10 ºC gradient	1997
Shoe Inserts	330	330	Starner 1996 Shenck & Paradiso 2001
Batteries (non-recharg. Lithium)	89	7	Commonly Available
Batteries (rechargeable Lithium)	13.7	0	Commonly Available
Gasoline (micro heat engine)	403	40.3	Mehra et. al. 2000
Fuel Cells (methanol)	560	56	Commonly Available

Yellow area denotes sources with a constant ***power*** output.
Blue area denotes sources with a fixed amount of ***energy***.

Batteries, Solar, and Vibrations

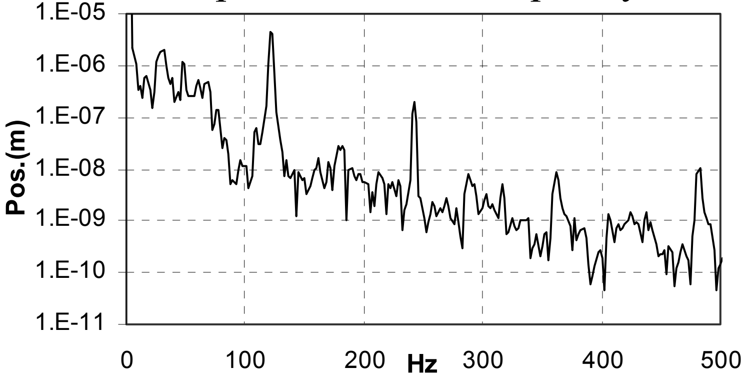


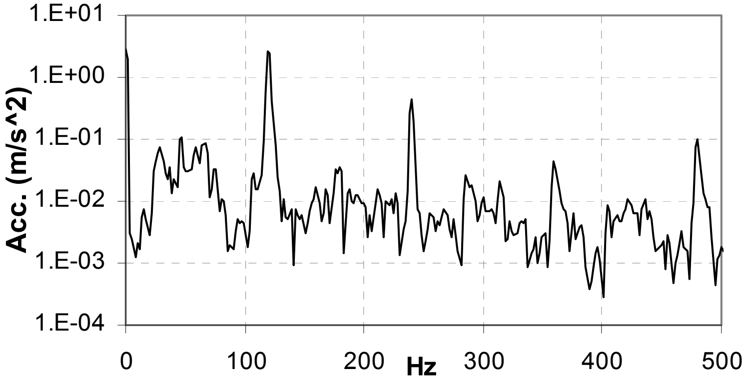
Merits of Batteries, Solar, Vibrations

- **If outdoor sunlight, or relatively intense indoor light it available, solar cells appear to be the best alternative.**
  - **Solar cells are a mature technology and a mature research area.**
- **If projected lifetime is longer than 1 year, vibrations offer an attractive alternative for certain environments. It was therefore decided to pursue research into the conversion of vibrations to electricity.**

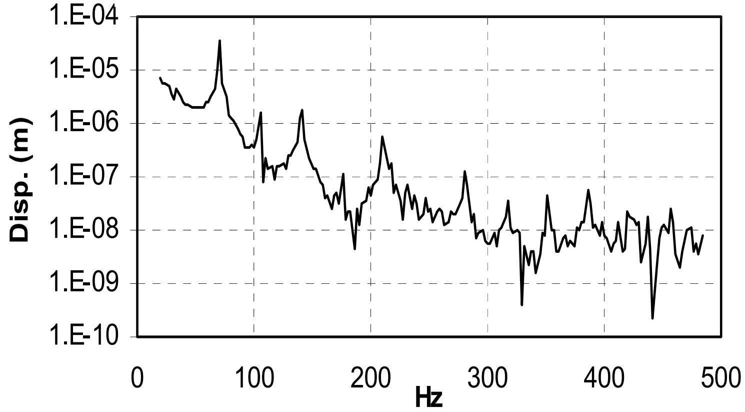
Vibrations – What’s available?

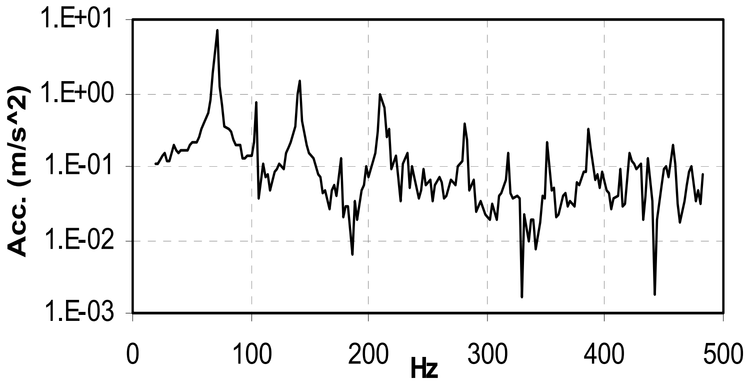
Microwave Oven Casing


Displacement vs. Frequency


Acceleration vs. Frequency

Base of Milling Machine

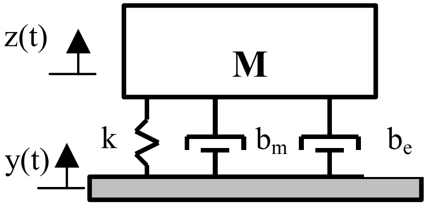

Displacement vs. Frequency


Acceleration vs. Frequency

Vibrations from microwave oven (2.25 m/s^2 at 120 Hz) used as the standard source with which to compare designs and report power density numbers.

Simple Model for Conversion

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



z = transducer displacement
y = magnitude of input

$$P = \frac{m\zeta_e Y^2\left(\frac{\omega}{\omega_n}\right)^3\omega^3}{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\zeta_T\left(\frac{\omega}{\omega_n}\right)\right]^2}$$

Power in terms of magnitude and frequency of input.

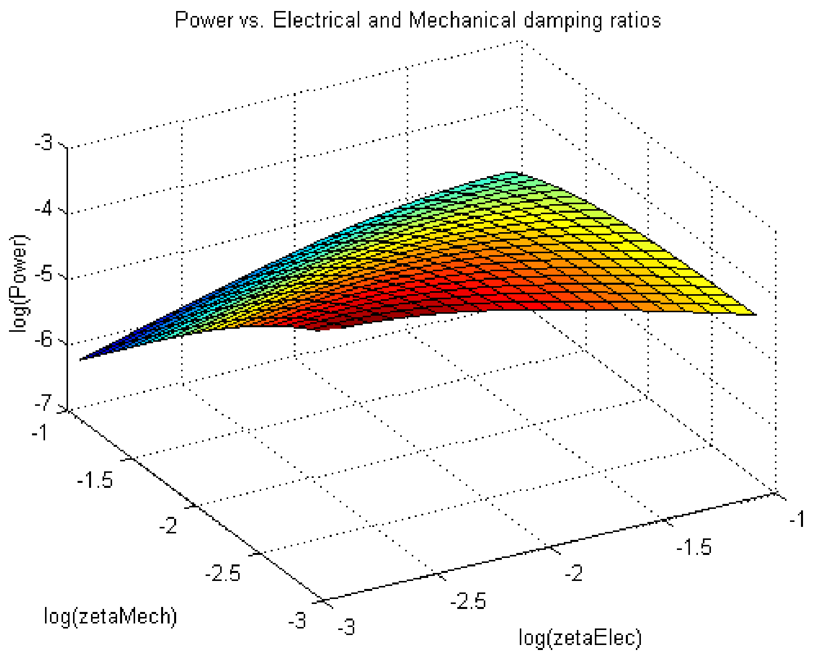
$$\zeta_T = \zeta_m + \zeta_e$$

$$\boxed{P = \frac{m\zeta_e A^2}{4\omega\zeta_T^2}}$$

Power assuming $\omega = \omega_n$.
A = acceleration amplitude of input vibrations
m = proof mass

Observations from Simple Model

Power vs. Mechanical and Electrical Damping



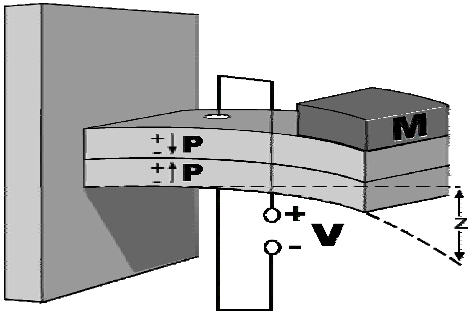
Observations

1. If acceleration magnitude is relatively constant with frequency, output power is inversely proportional to frequency.
2. There is an optimal level of electrically induced damping that is designable.
3. It is better to have too much electrical damping than too little.

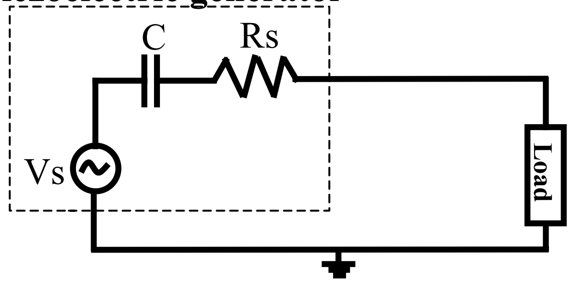
Three Ways to Convert Vibrations

Piezoelectric

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

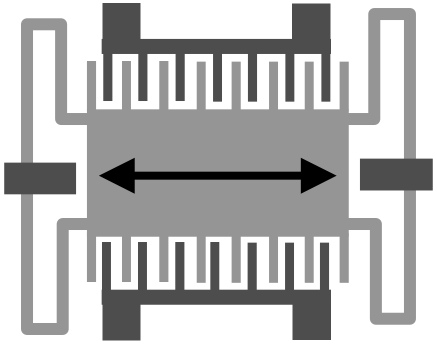


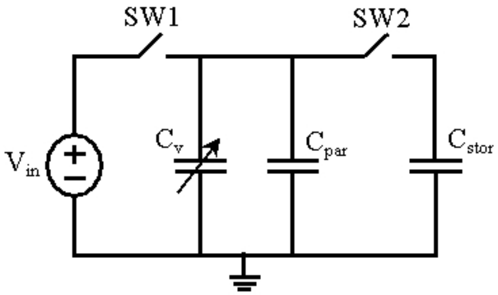
Piezoelectric generator



Capacitive

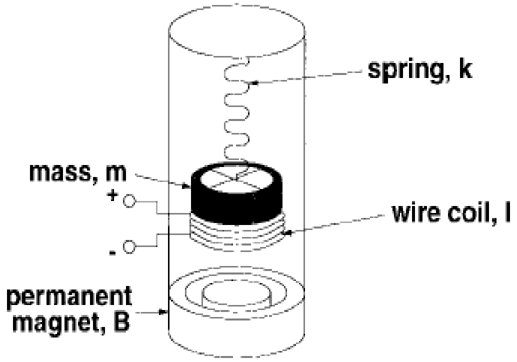
Change in capacitance causes either voltage or charge increase.





Inductive

Coil moves through magnetic field causing current in wire.



Amirtharajah et. al., 1998

Capacitive Conversion

The Basic Idea:

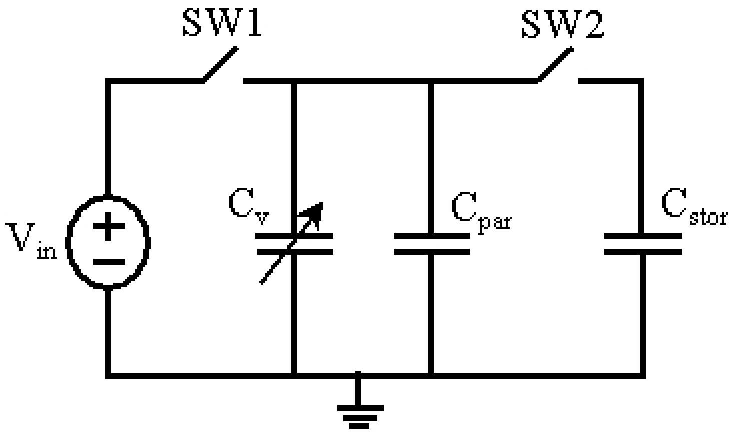
$$C = \frac{\varepsilon_o A}{d} \qquad V = \frac{Q}{C} \qquad E = \frac{1}{2} QV$$

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:

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

Maximum Allowable Voltage



Circuit pumps charge from input voltage to higher voltage. The increase in energy is due to mechanical work done on C_v.

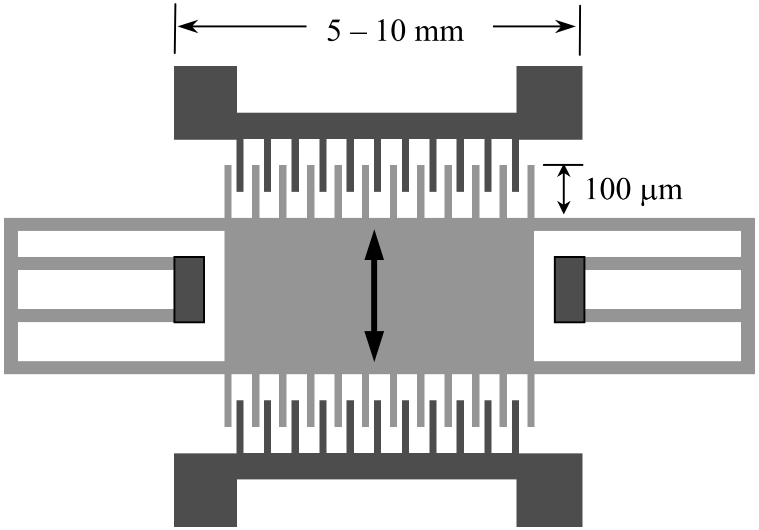
$$E = \frac{1}{2} V_{in}^2 (C_{\max} - C_{\min}) \left(\frac{C_{\max} + C_{par}}{C_{\min} + C_{par}} \right)$$

$$m\ddot{z} + f_m(z, \dot{z}) + f_e(z, z^2, ..) + kz = -m\ddot{y}$$

Three Types of MEMS Converters

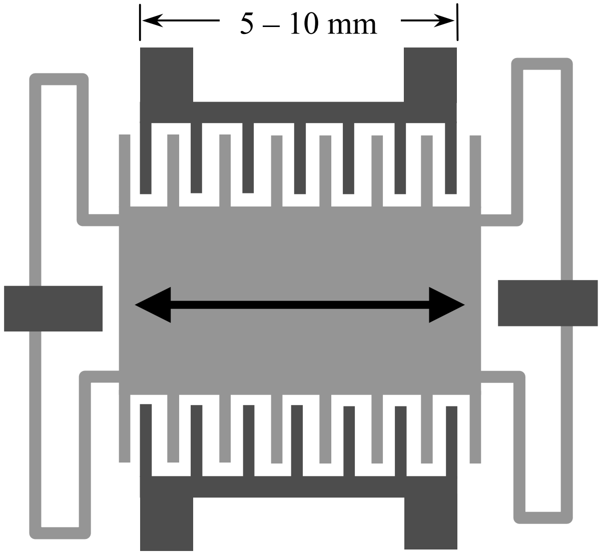
In-plane, overlap type:

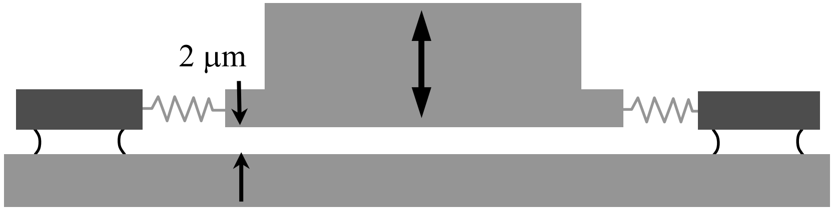
Capacitance changes by changing overlap area of fingers.



In-plane, gap closing type:

Capacitance changes by changing gap between fingers.



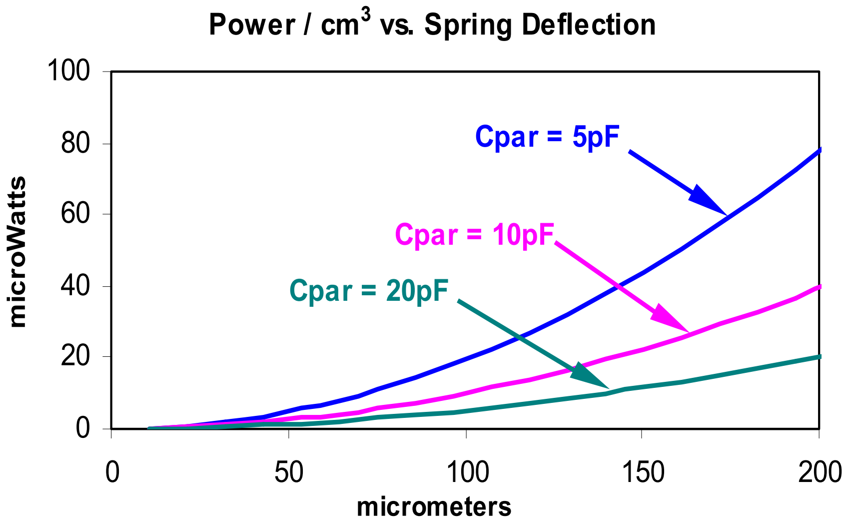


Out-of-plane, gap closing type:

Capacitance changes by changing gap two large plates.

Overlap vs. In Plane Gap-Closing

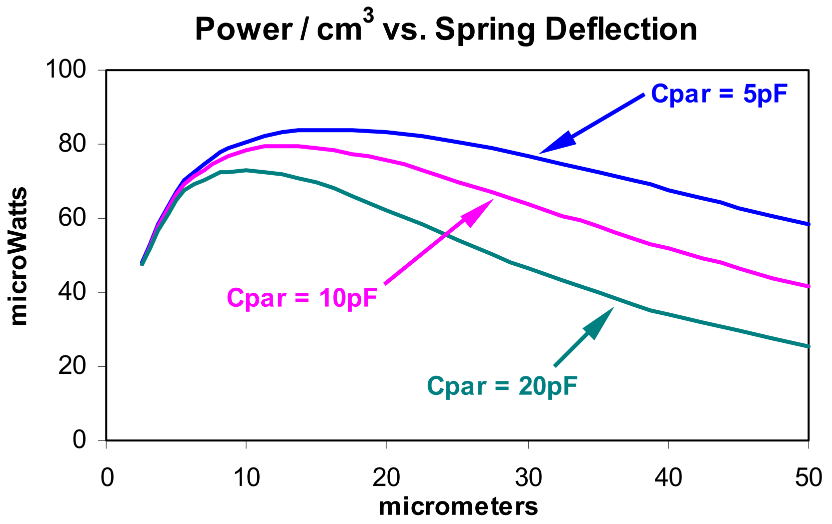
In-plane Overlap



Observations:

1. Max power at large spring deflections (high Q).
2. Very sensitive to Cpar

In-plane Gap Closing

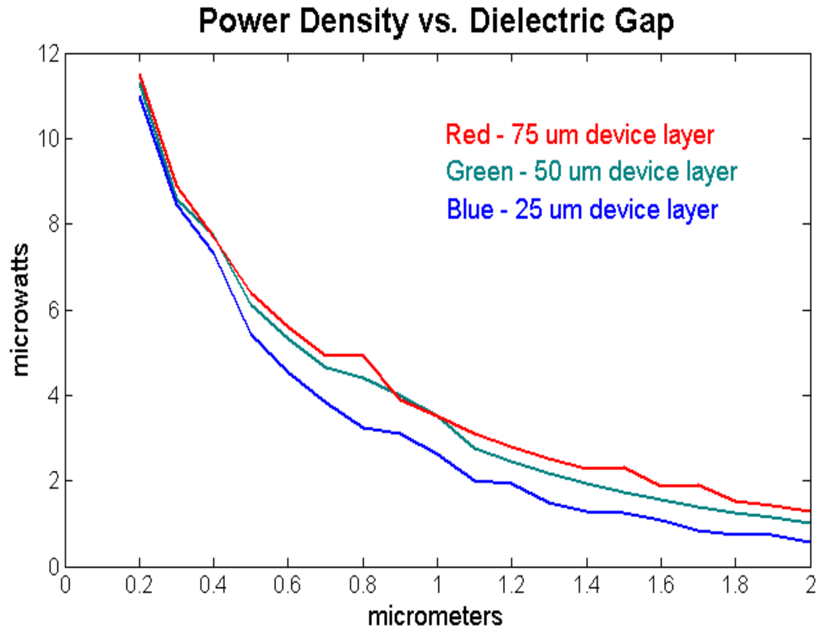


Observations:

1. Optimal spring deflection at 10 – 20 μm (low Q)
2. Less sensitive to Cpar

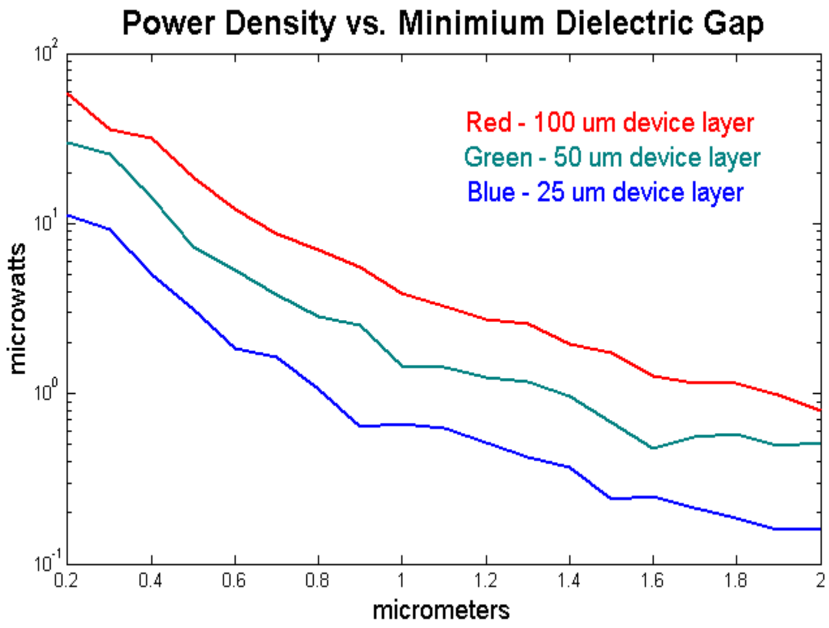
Overlap vs. In Plane Gap-Closing

In-plane Overlap



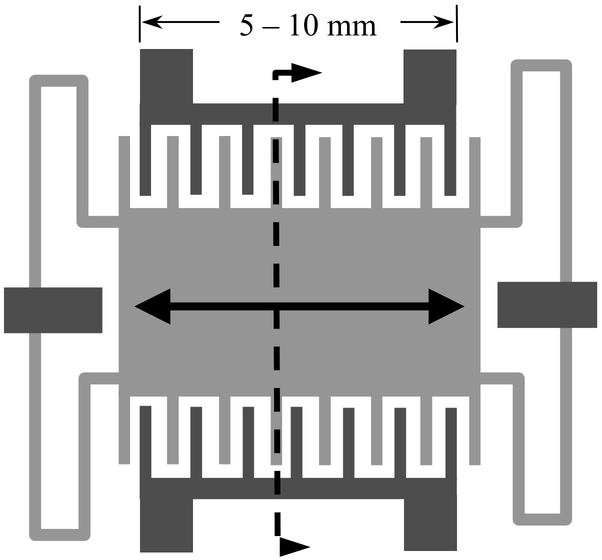
- Maximum power occurs for very small dielectric gaps.
- The combination of large spring deflections and small dielectric gaps creates a potential stability problem.

In-plane Gap Closing



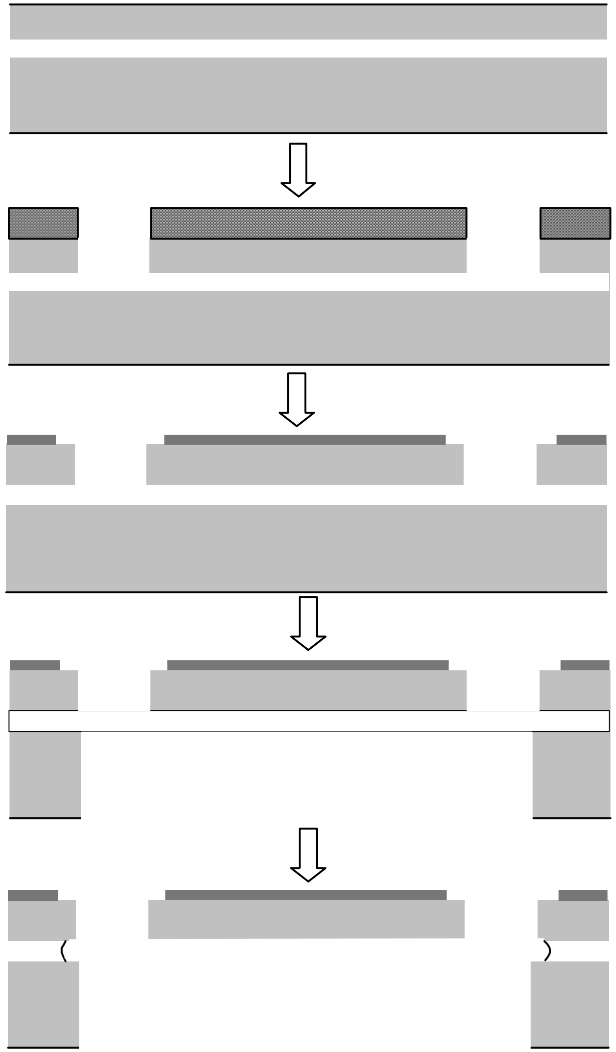
- Maximum power occurs for very small dielectric gaps.
- Power output is higher than either of the other two design concepts.
- Optimized design - 100 μW/cm^3

Process for MEMS Converters



Legend

- ▭ Single Crystal Silicon
- ⬚ Silicon Dioxide
- ▨ Mask, PR and/or oxide
- ■ Metal



SOI wafer

Apply and pattern mask and etch top silicon layer

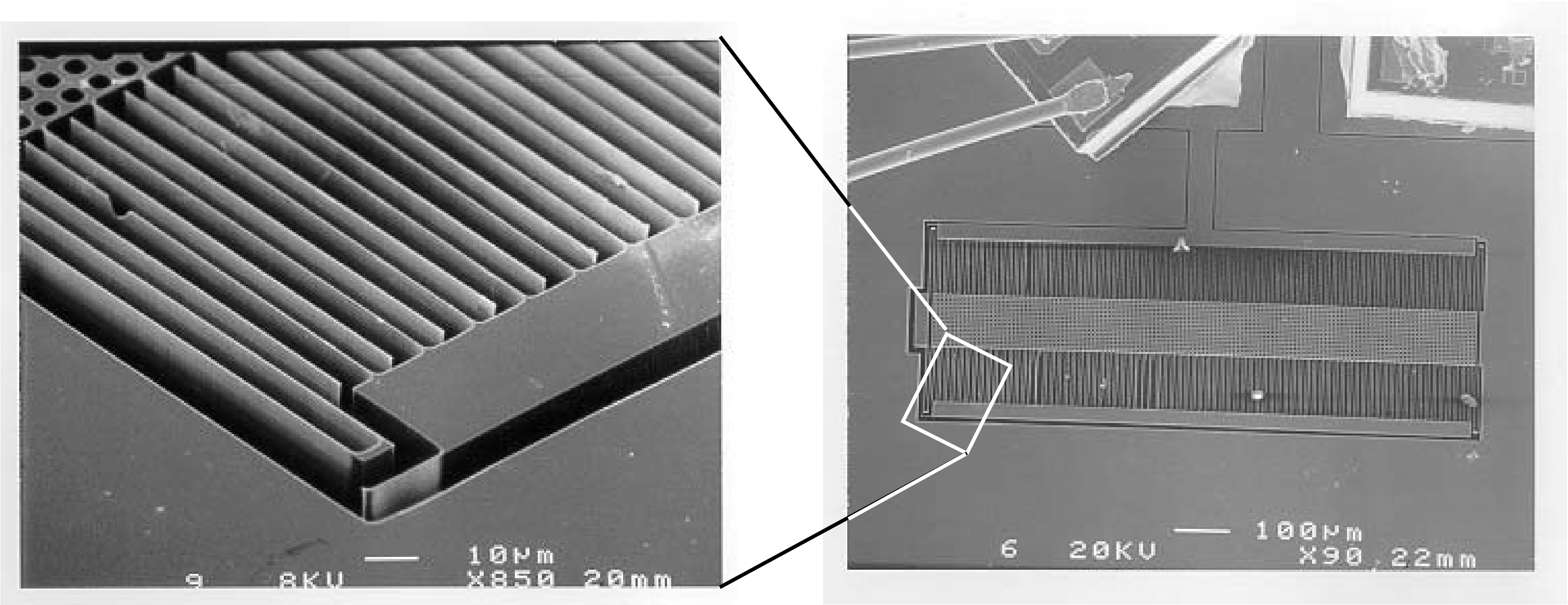
Remove mask. Apply metal w/ shadow mask or thick PR process.

Etch away portions of the handle wafer.

Timed oxide etch to free structures.

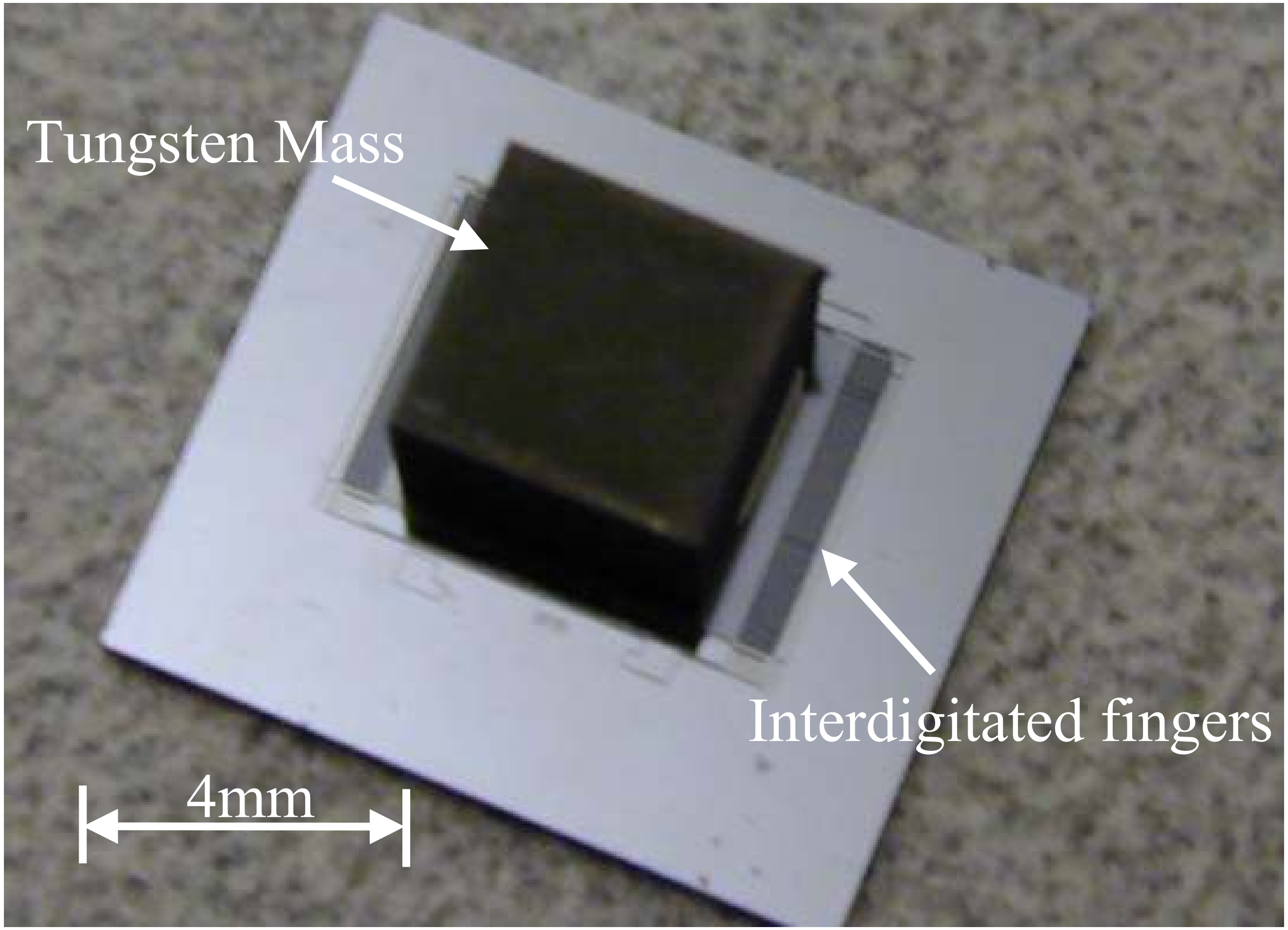
MEMS Capacitive Converters

A MEMS in-plane gap-closing test structure fabricated in the microlab at UC Berkeley.



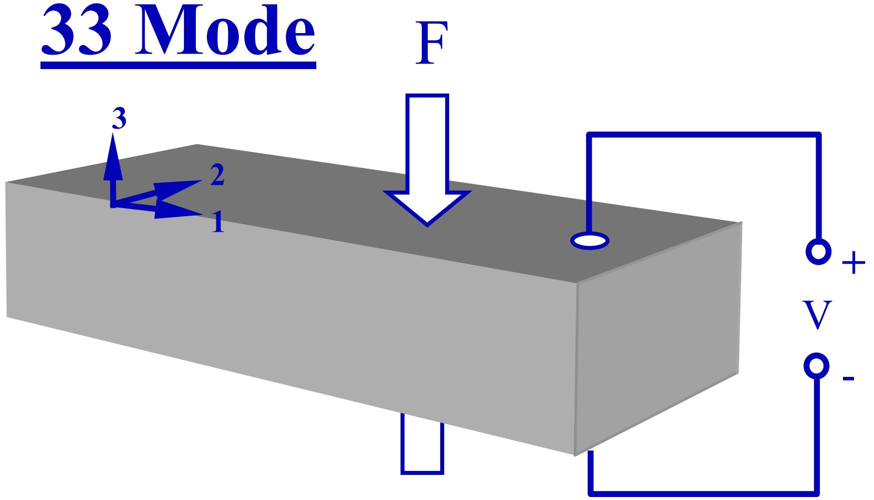
MEMS Capacitive Converters

Another full size test device with tungsten proof mass attached

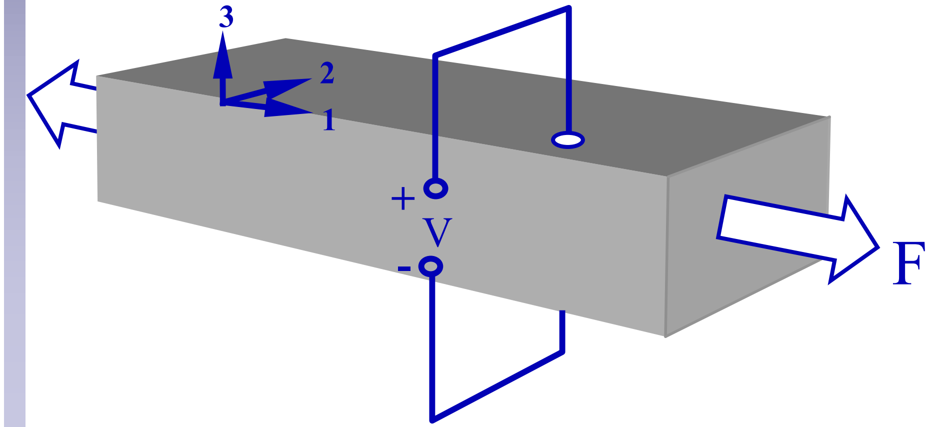


Piezoelectric Conversion

33 Mode



31 Mode



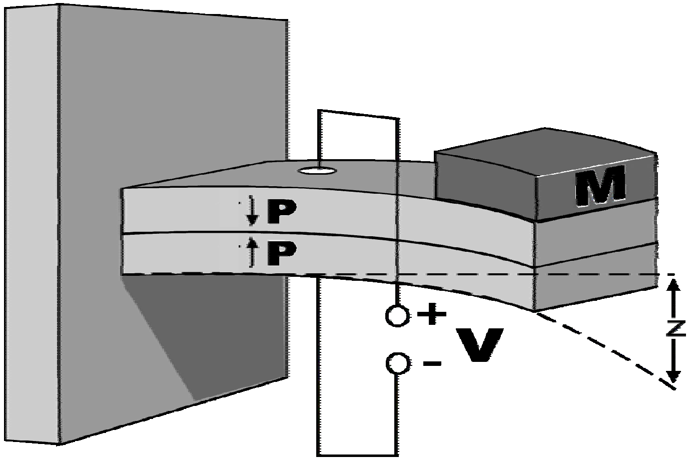
Constitutive Equations

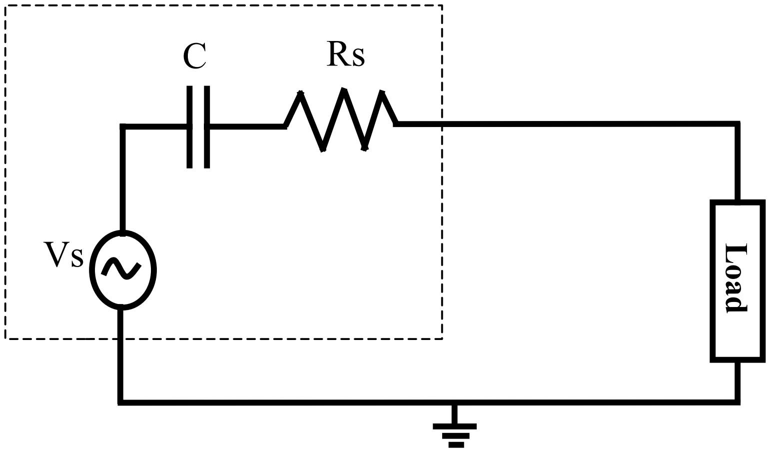
$$\delta = \sigma / Y + dE$$

$$D = \varepsilon E + d\sigma$$

δ = strain
σ = stress
Y = Young’s modulus
d = piezoelectric coeff.
D = electrical displacement
ε = dielectric constant
E = electric field

Piezoelectric Benders





System Equations

$$\ddot{\delta} = \frac{-k}{m}\delta - \frac{b_m}{m}a_1\dot{\delta} - \frac{k}{m}\frac{d_{31}}{t_c}V_R + a_2\ddot{y}$$

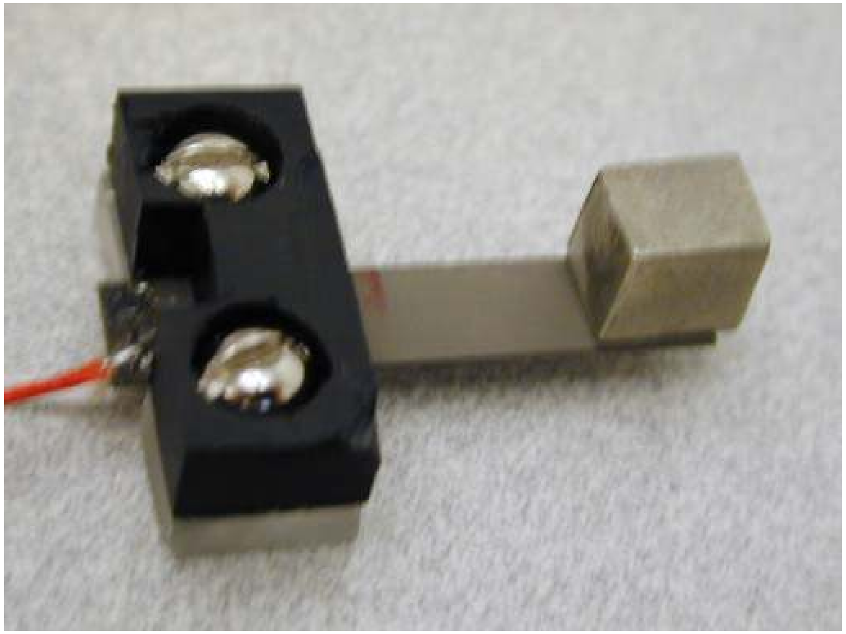
$$\dot{V}_R = \frac{Y d_{31} t_c}{\varepsilon}\dot{\delta} - \frac{1}{RC}V_R$$

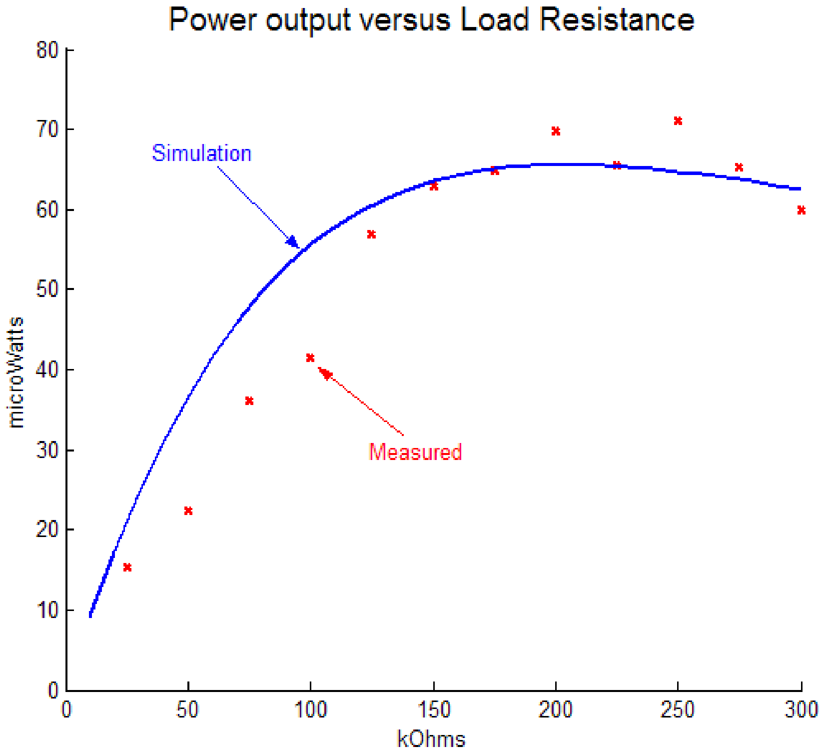
Where:

k = equivalent spring stiffness of beam
m = attached proof mass
b_m = damping coefficient
a_1 = geometric constant
a_2 = geometric constant
d_{31} = piezoelectric coefficient
t_c = thickness of one piezo-ceramic layer
V_R = voltage across load

Test Results and Model Verification

First Prototype



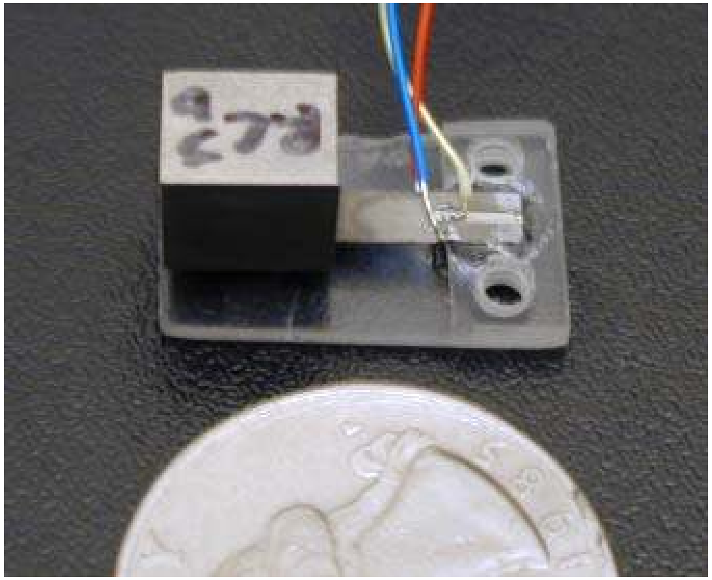


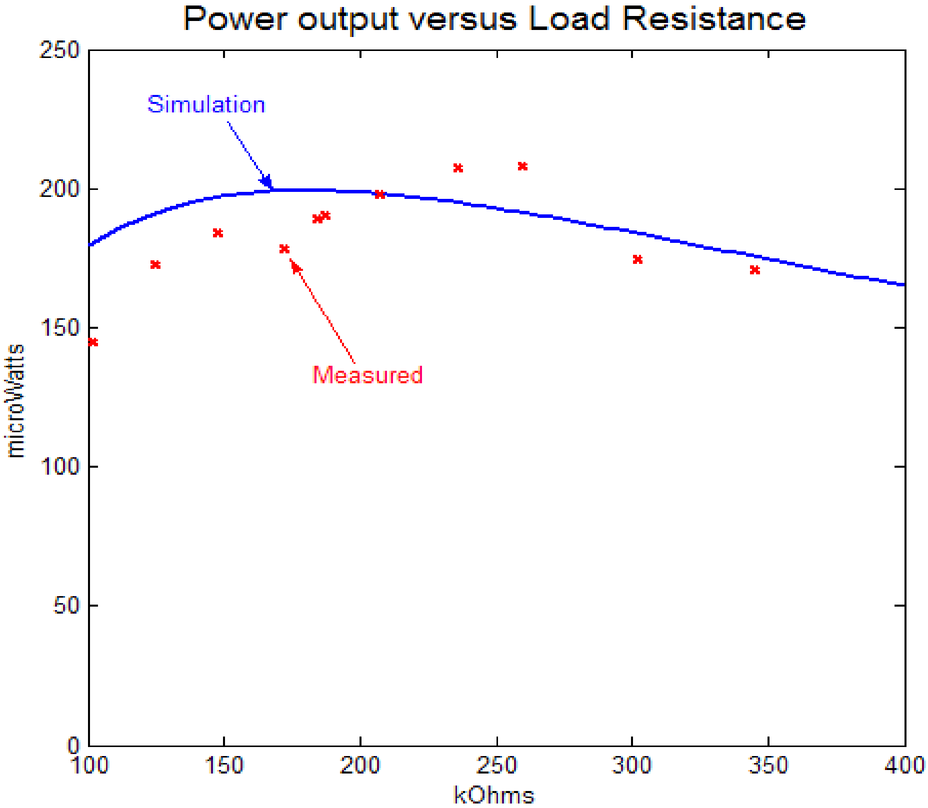
Note: All tests and simulations were performed with input acceleration of 2.25 m/s^2 at 120 Hz. (Vibrations from microwave oven casing.)

Output voltage is 4 to 6 volts. Max power output is 70 μW/cm^3

Test Results and Model Verification

Optimized Prototype
- overall size < 1cm^3
- total length < 1.5cm

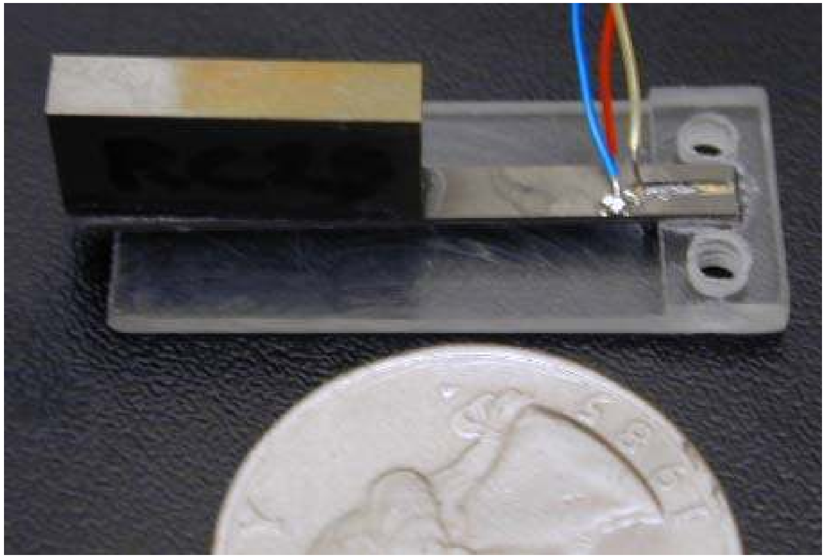


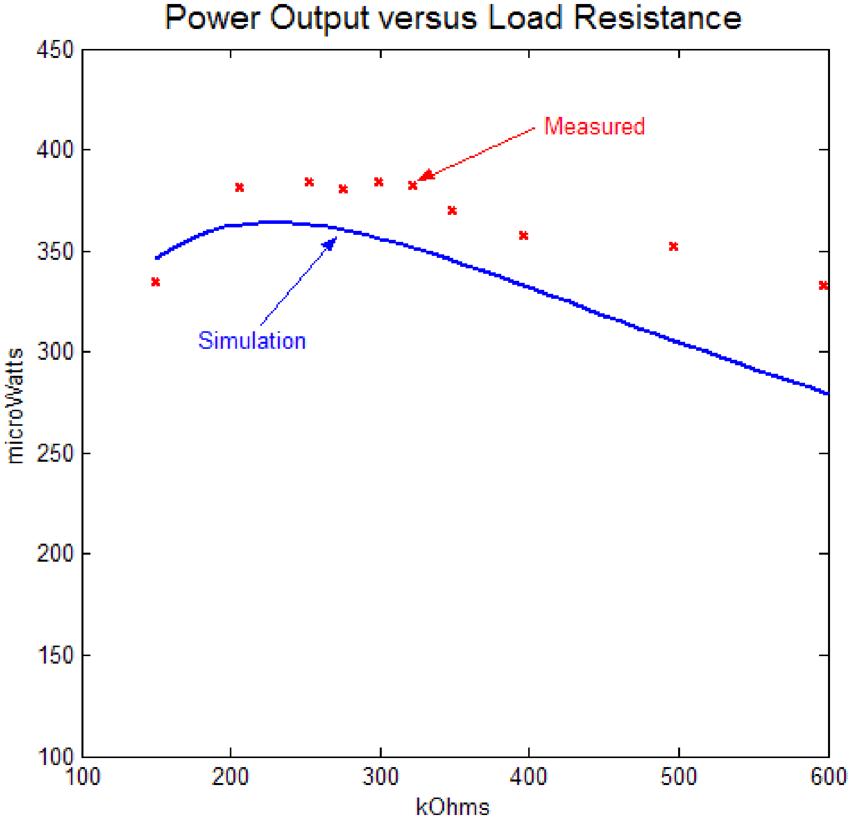


Output voltage is 6 to 10 volts.
Max power output is 200 μW/cm^3

Test Results and Model Verification

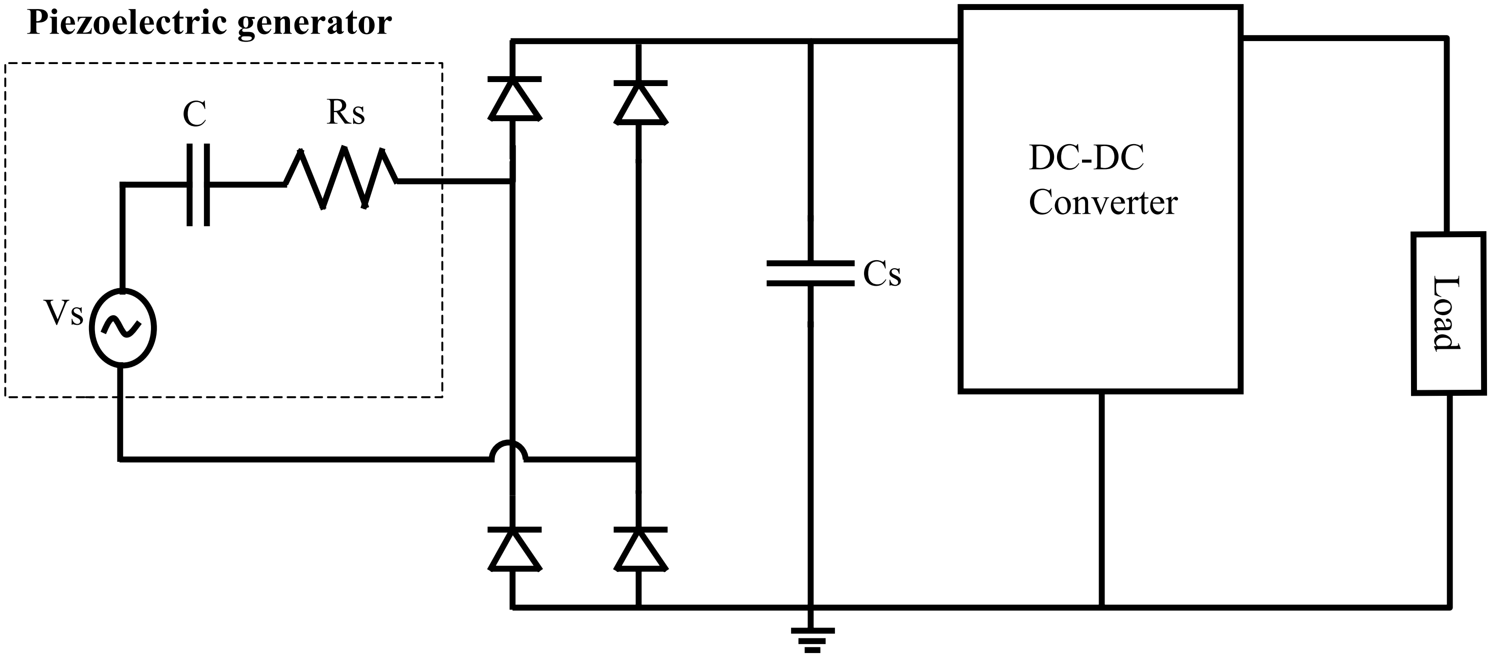
Optimized Prototype
- overall size < 1cm^3
- total length < 3cm



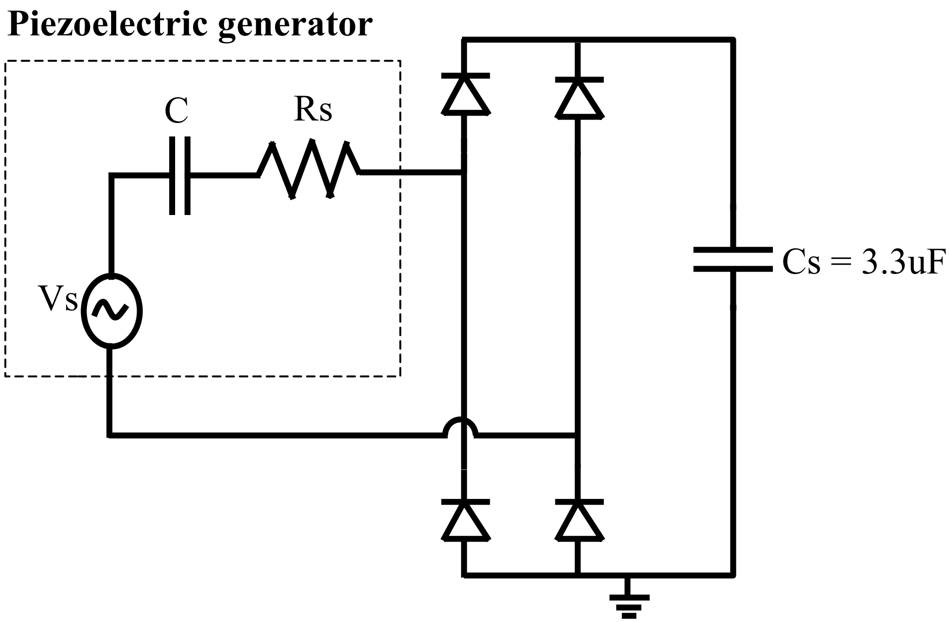


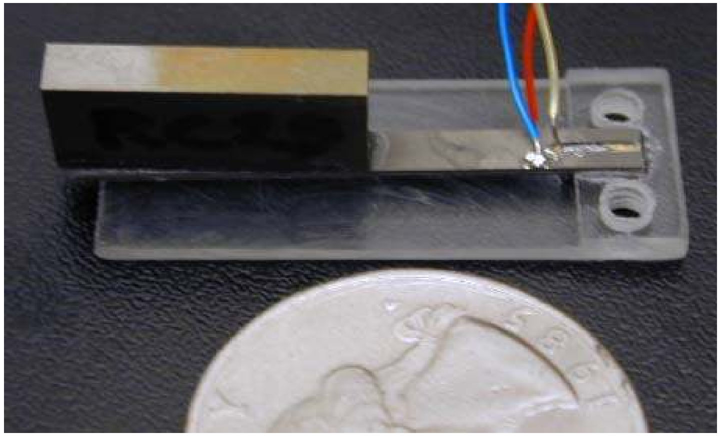
Output voltage is 12 to 16 volts.
Max power output is 375 $\mu\text{W/cm}^3$

“Real” Circuit for Piezo Converters

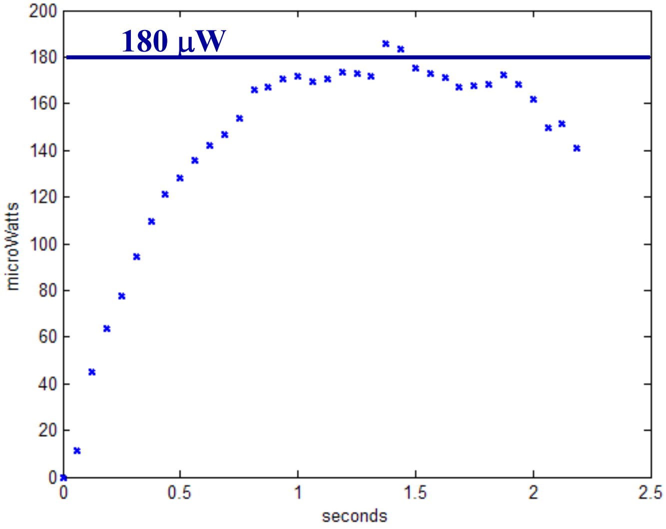


Test Results: Capacitive Load Circuit

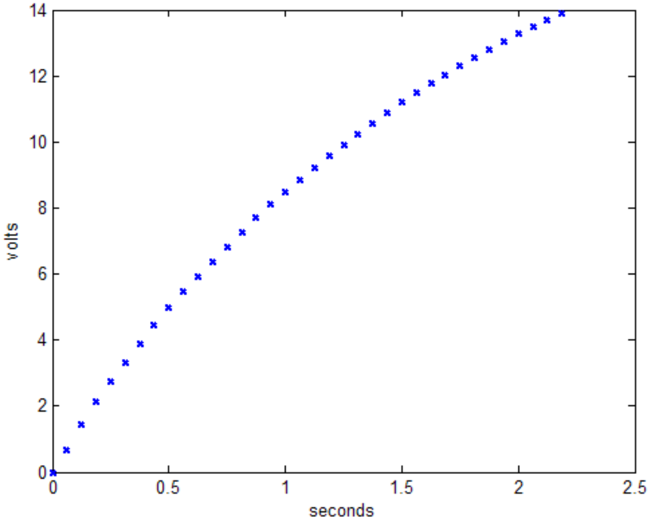




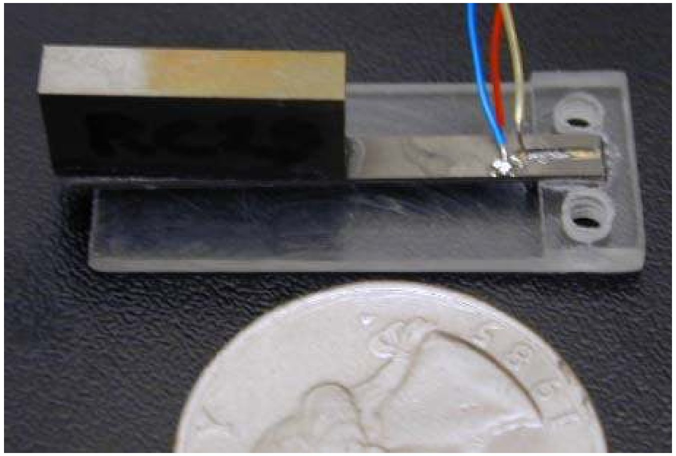
Power Transfer vs. time

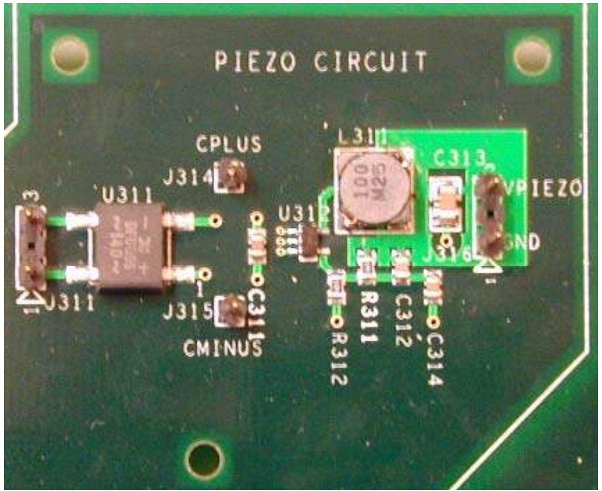


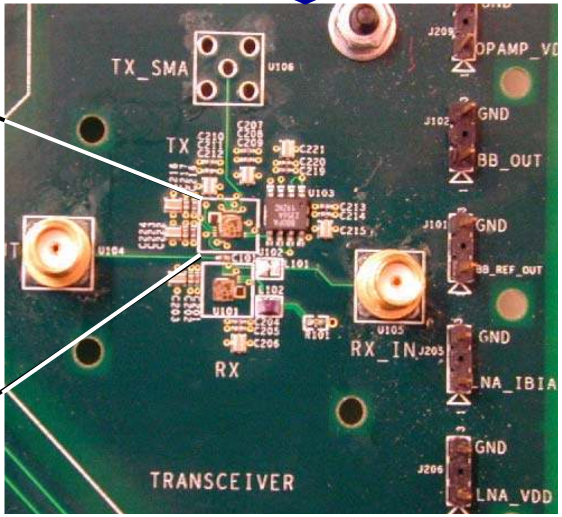
Capacitor Voltage vs. time

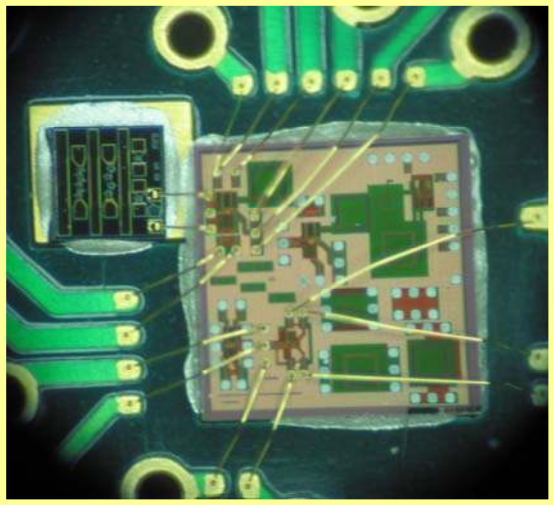


Piezo Generator, Power ckt, & Transmitter

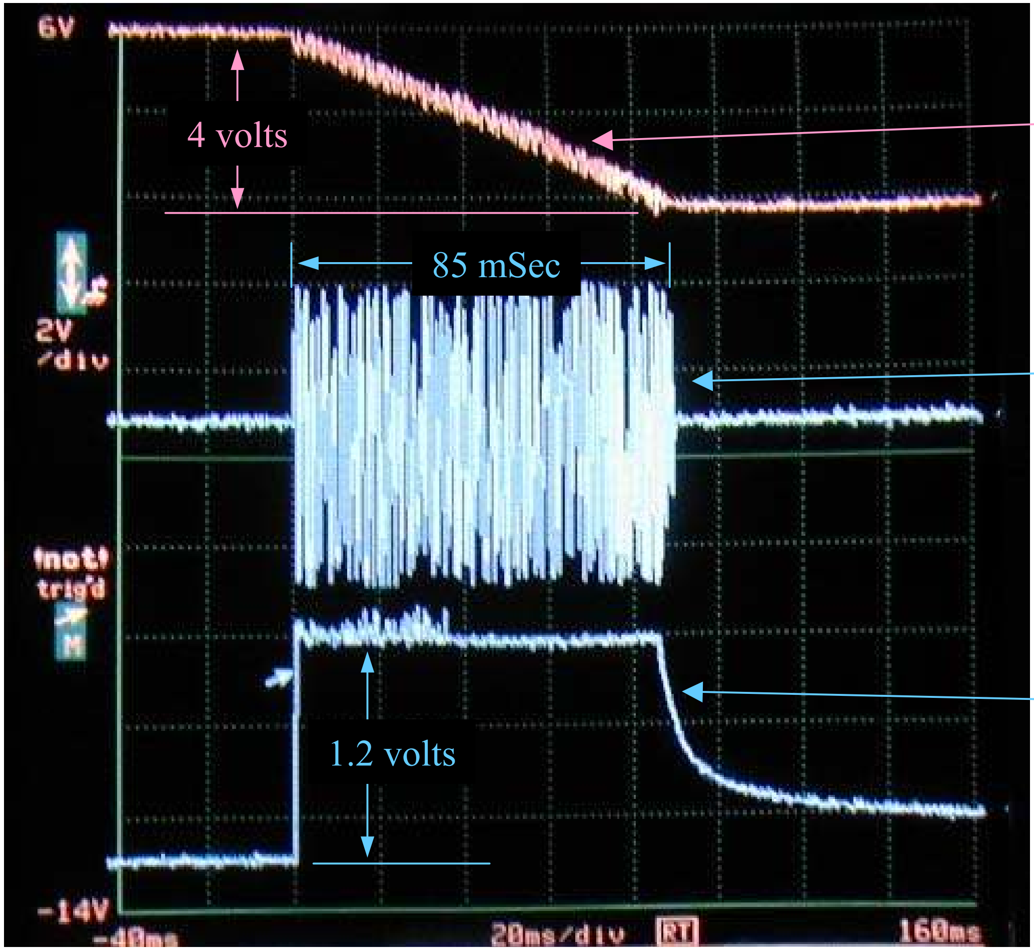








Piezo Generator and Transmitter Traces



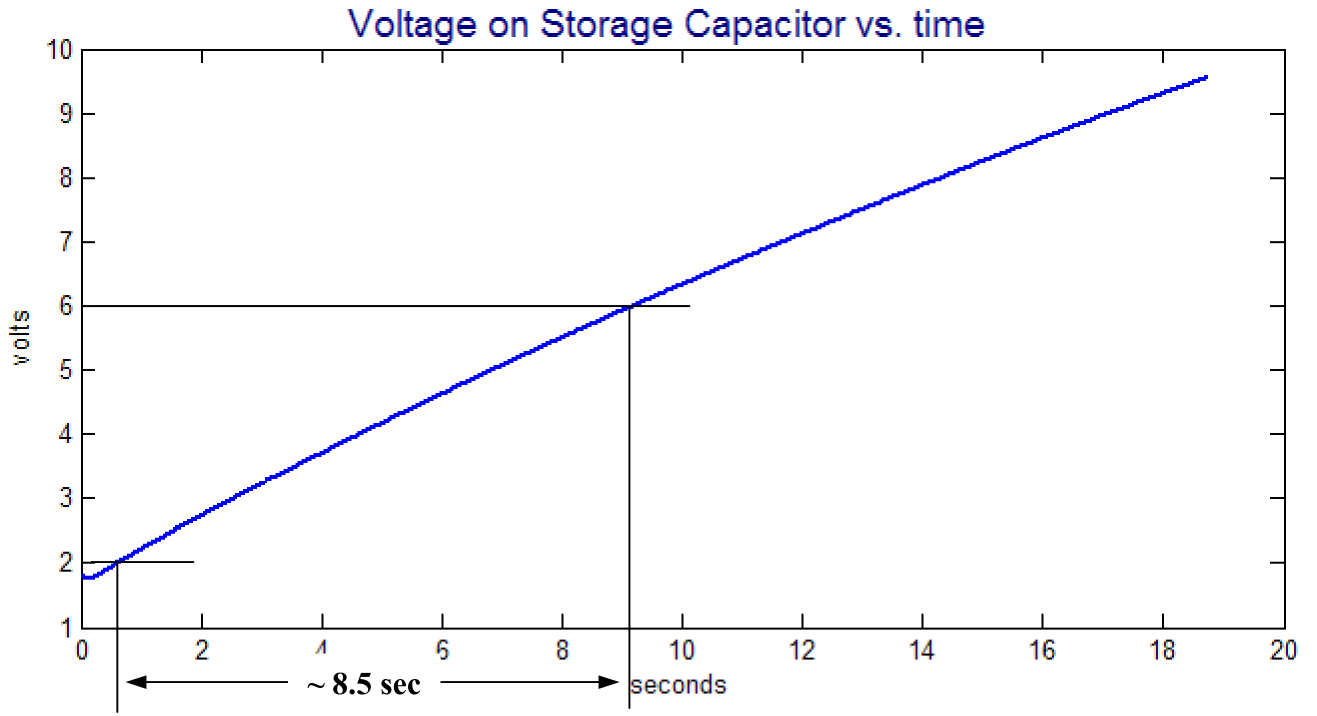
Voltage on storage cap.

Transmitter output voltage.

Regulator output voltage.
Input voltage to radio.

The storage capacitance was 200 μF.

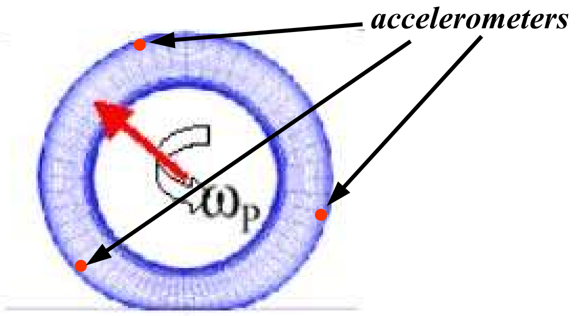
Charge time of Storage Capacitor

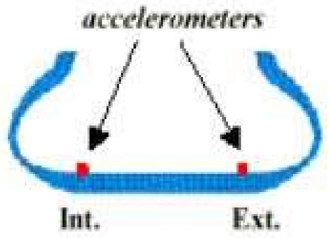


Time to charge from 2 volts up to 6 volts is about 8.5 – 9 seconds.
Time for radio to discharge back to 2 volts is about 85 mSec.
Supportable duty cycle for 10 mA radio at 1.2 volts is about 1%.

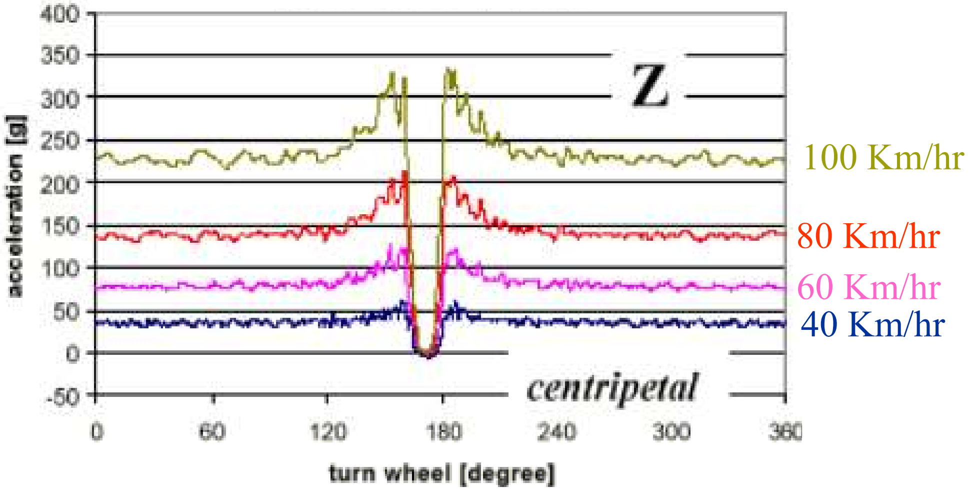
Generators to be Embedded in Tires

$a_c = \omega^2_T r_p$

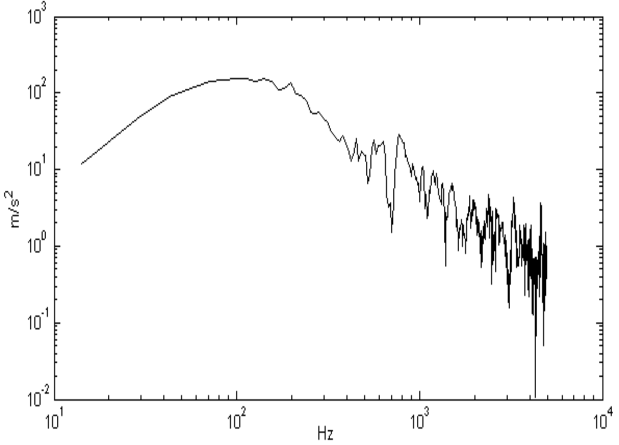




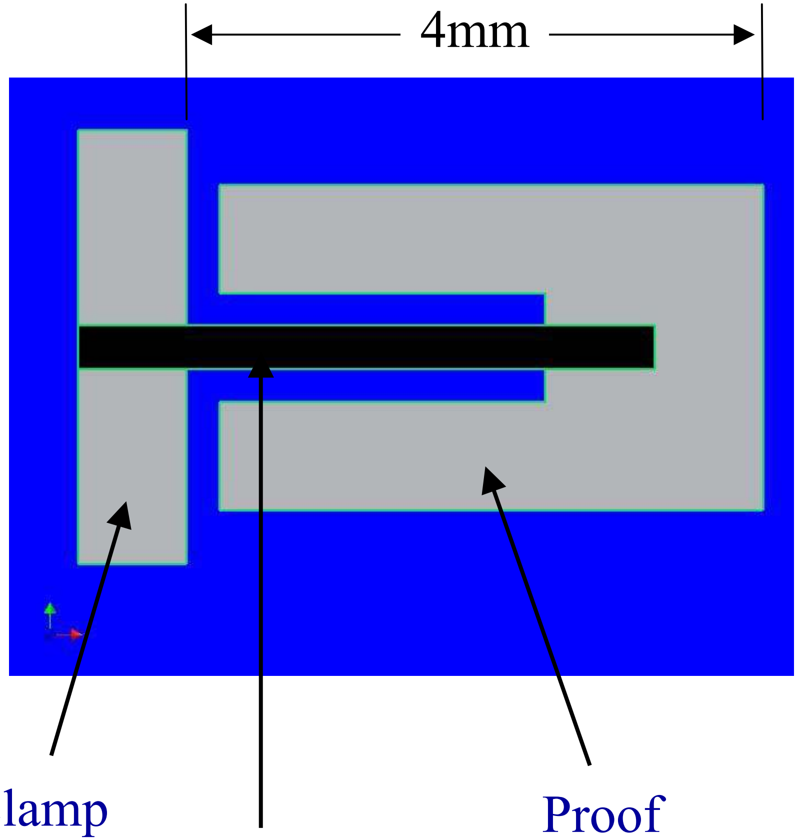
Acceleration vs. time



Acceleration vs. frequency



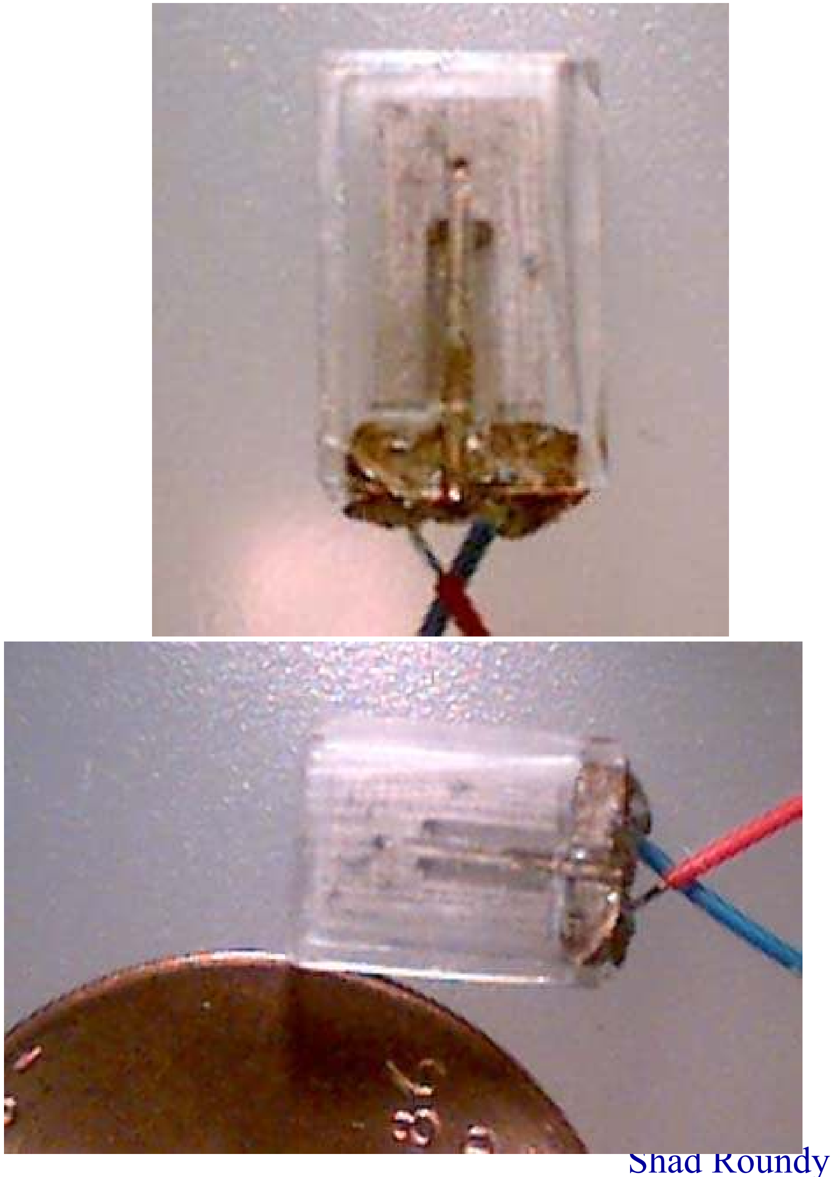
Generators to be Embedded in Tires



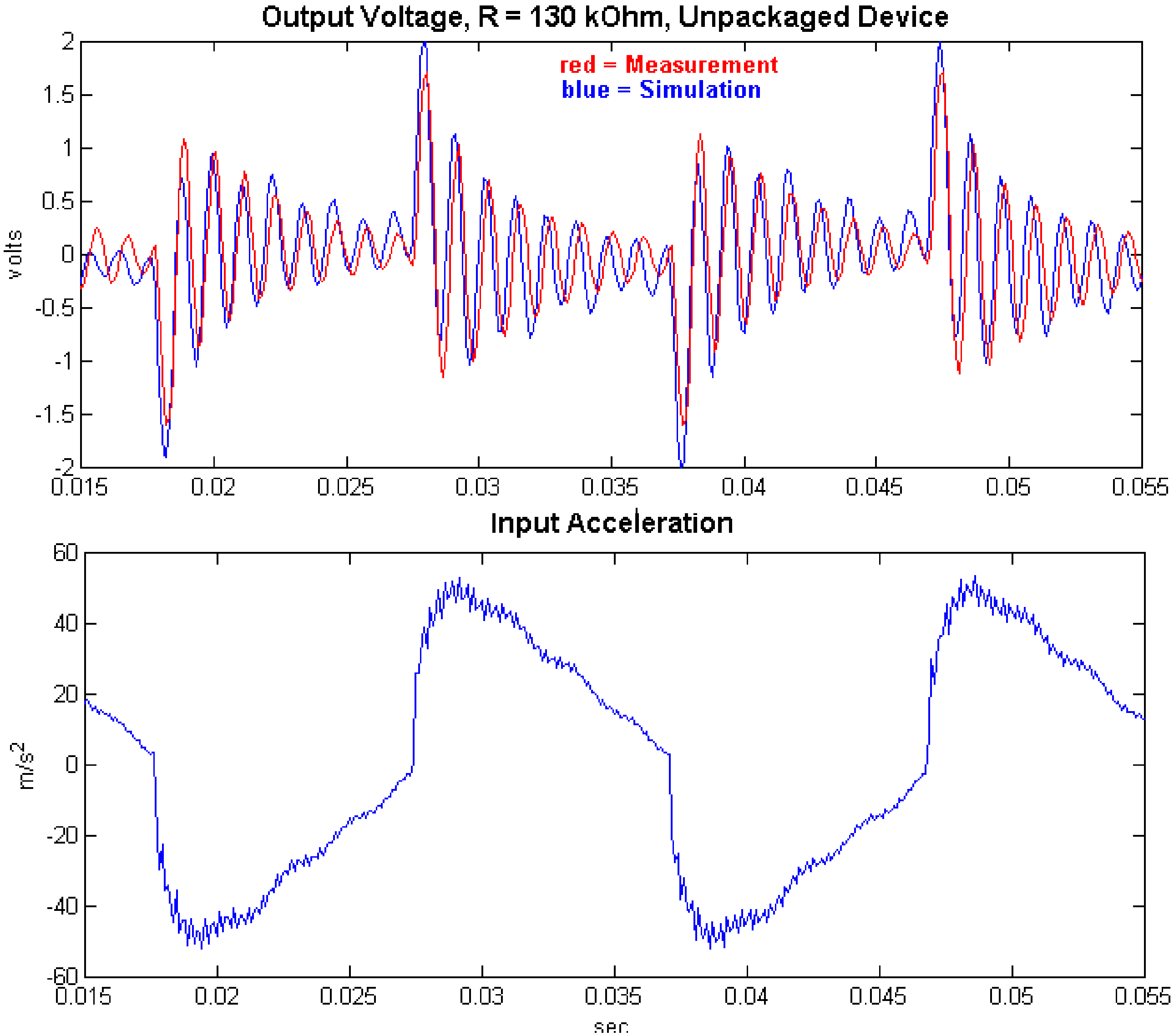
Clamp

Piezoelectric
Bimorph

Proof
Mass



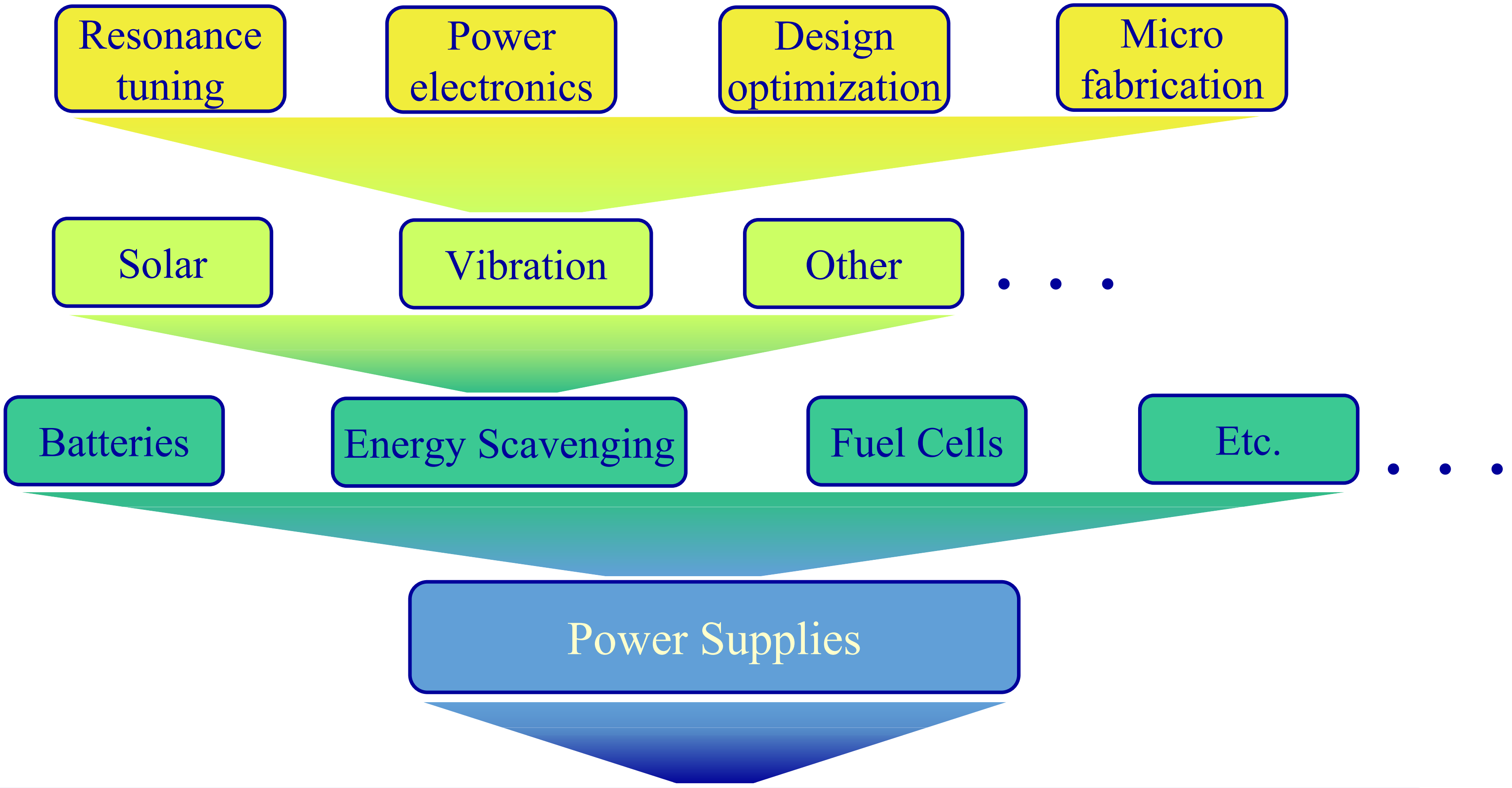
Test Results with a Resistive Load



Conclusions to this point

- Scavenging the power from commonly occurring vibrations for use by low power wireless systems is both feasible and attractive for certain applications.
- Piezoelectric converters appear to be the most attractive for meso-scale devices with a maximum demonstrated power density of approximately 200 $\mu W/cm^3$ vs. 100 $\mu W/cm^3$ for capacitive MEMS devices.
- A custom designed radio transceiver has been successfully operated using power from vibrations of 2.25 m/s^2 at 120 Hz.

Future Work



Resonance tuning

Power electronics

Design optimization

Micro fabrication

Solar

Vibration

Other

. . .

Batteries

Energy Scavenging

Fuel Cells

Etc.

. . .

Power Supplies

Application areas over next 10 years:

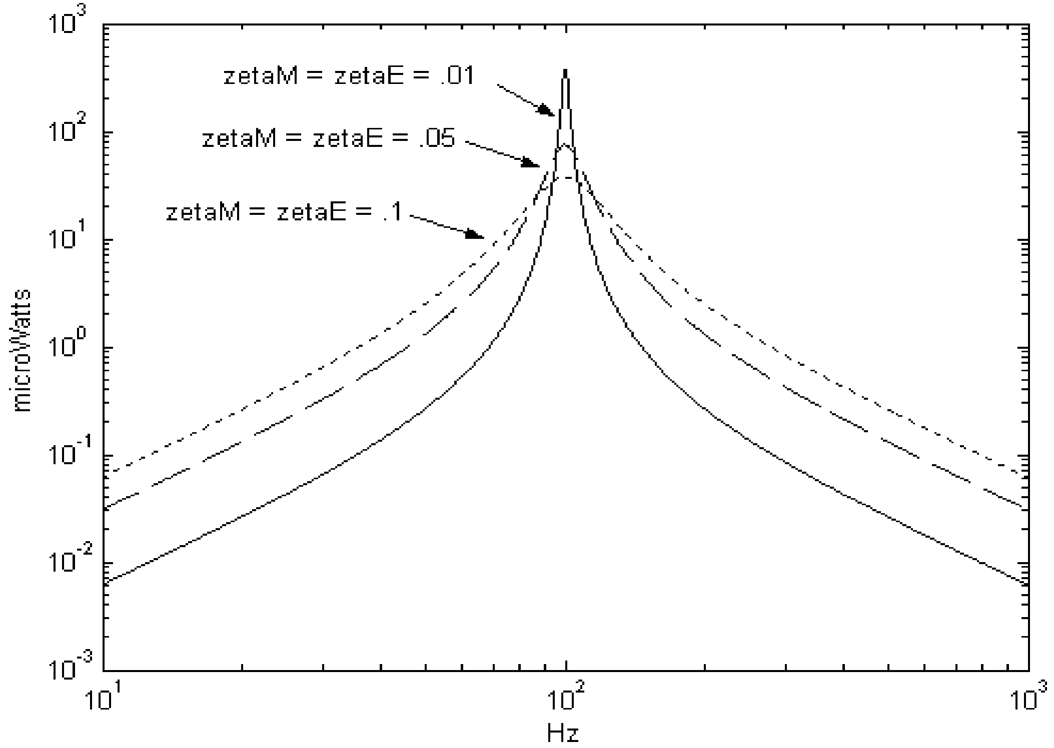
building env. control, emergency response in commercial buildings, manufacturing monitoring and control, inventory tracking, “smart” homes, fatigue monitoring on aircraft, ubiquitous data access for people, etc.

Applications for Vibration Scavenging

- Fatigue monitoring on aircraft.
- “Smart” automobile tires.
- Robotics for manufacturing.
- Real time sensing and control for machine tools.
- Monitoring of brakes on cargo trains
- Intelligent environment control in buildings.
- Emergency response in buildings.

Future Work

Actively tuning resonance frequency of generator



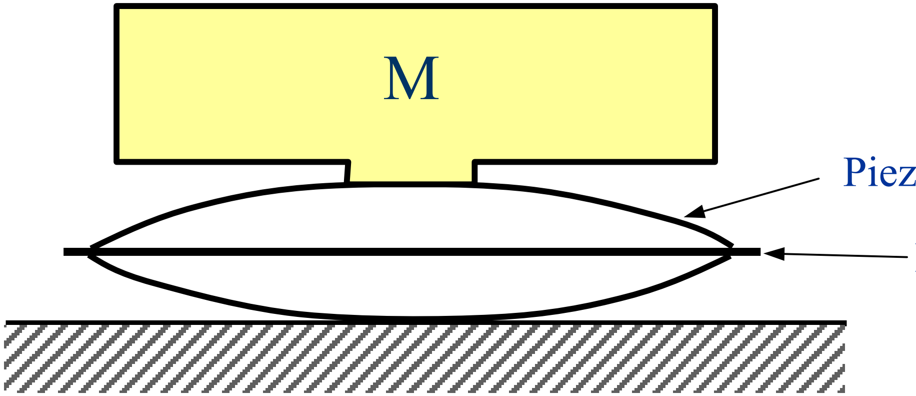
Novel actuator and control structure.

Would the increase in power justify the cost of tuning?

Many possible applications outside of Energy Scavenging

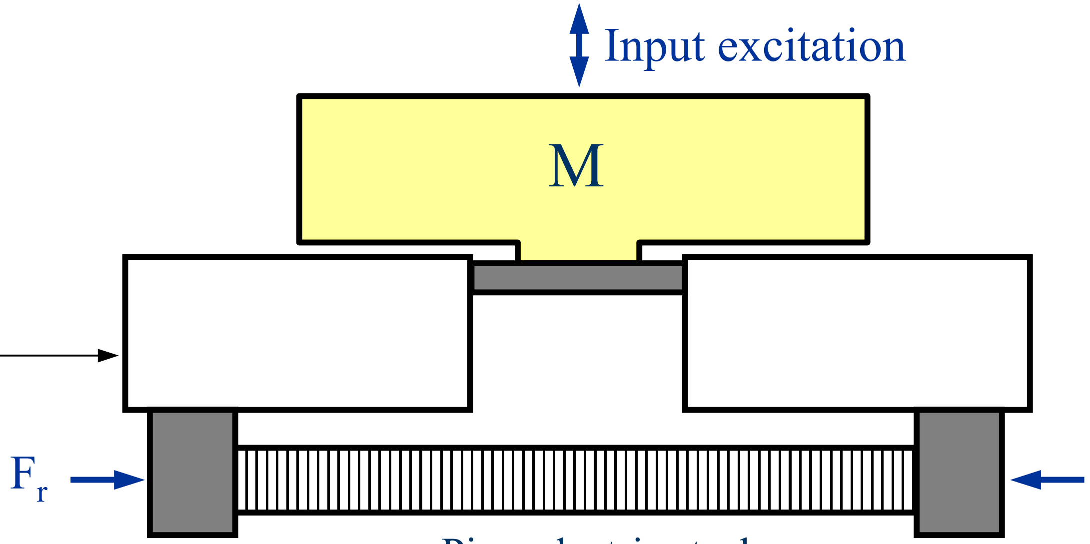
Future Work

Further exploration of alternative design topologies.



Piezoelectric element

Rigid Shim



Input excitation

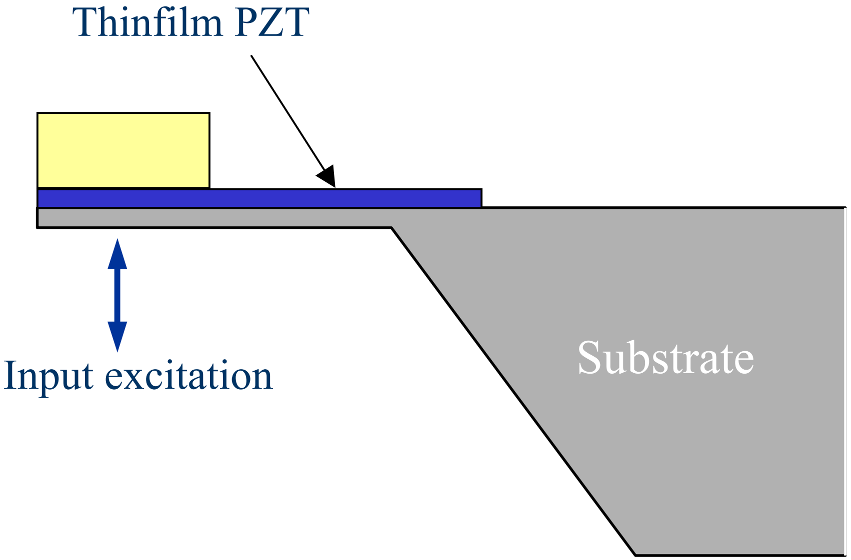
Nonlinear compliant structure translates motion (force) in vertical direction to horizontal direction.

F_r

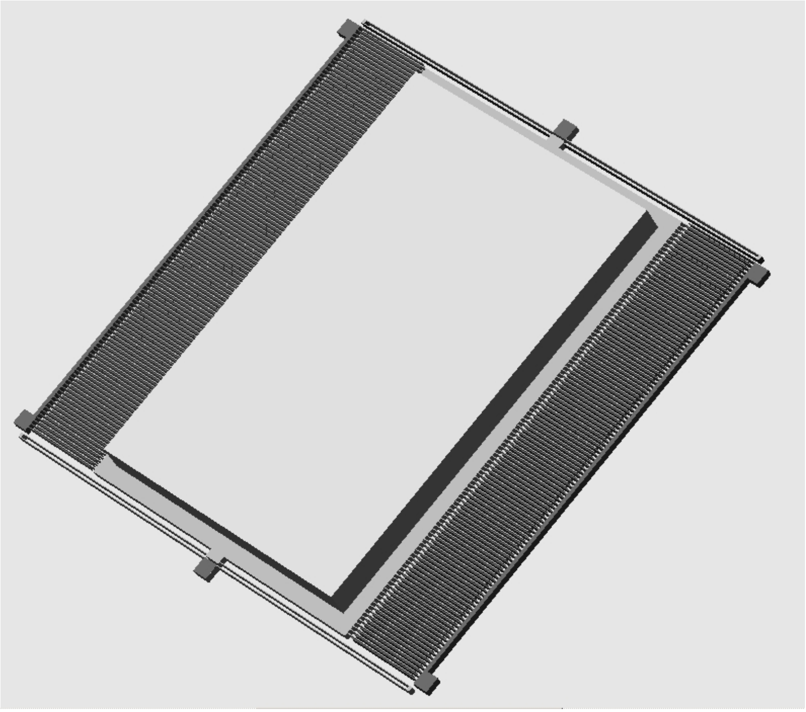
Piezoelectric stack

Future Work

MEMS implementations of piezoelectric converters.



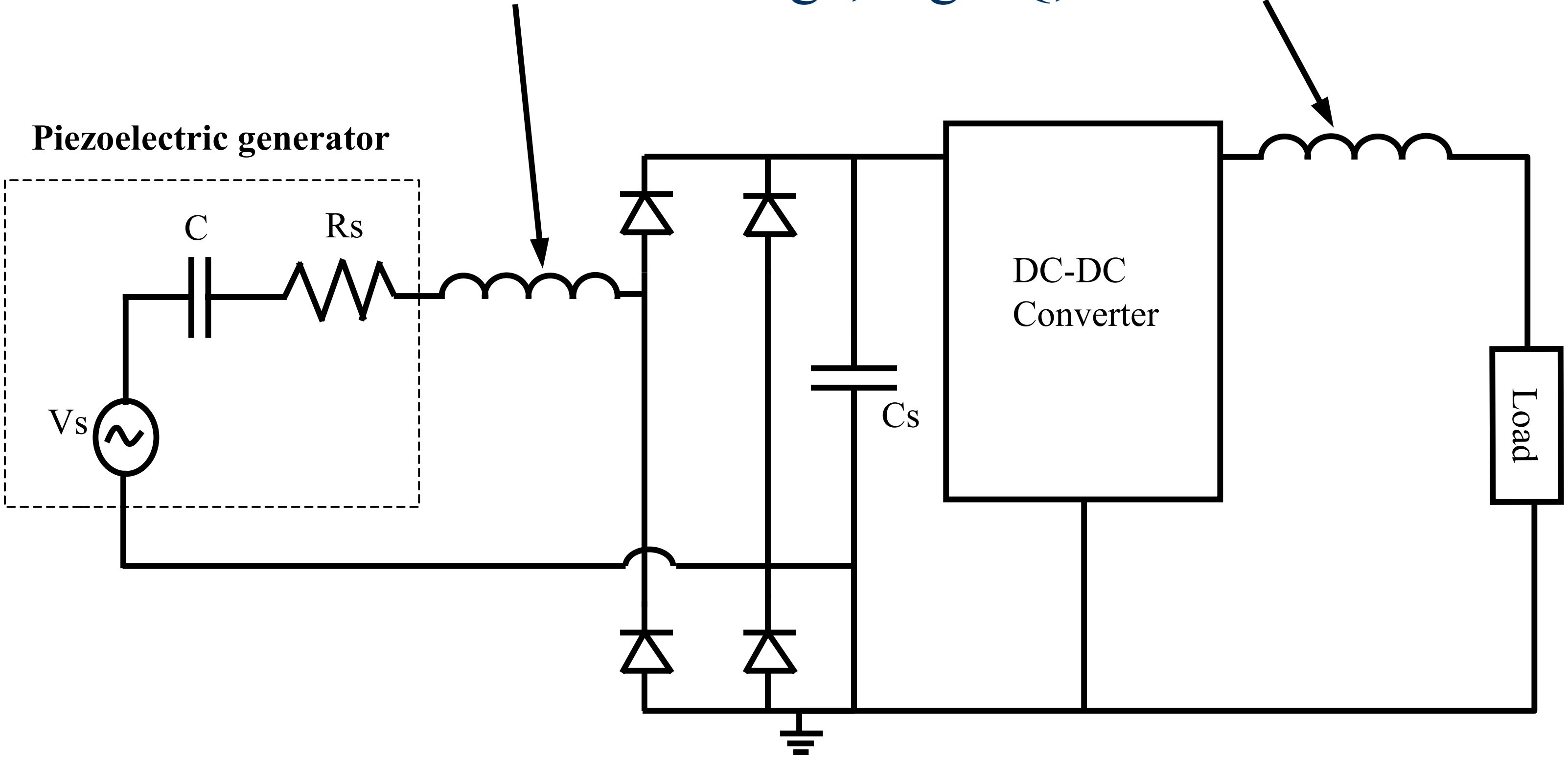
Improve robustness and performance of MEMS electrostatic converters.



Future Work

Optimization of power electronics for energy scavenging systems.

MEMS structures that have a large, high Q, effective inductance.



Conclusions

- Acceptable power sources remain perhaps the most challenging technical hurdle to the widespread deployment of wireless sensor networks.

- While significant progress has been made in many areas including indoor photovoltaic systems, micro-fuel cells, thermoelectrics, micro-heat engines, and vibration-to-electricity conversion, much more research and new approaches need to be pursued.