MEMS ACOUSTIC ENERGY HARVESTER

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ENERGY HARVESTING

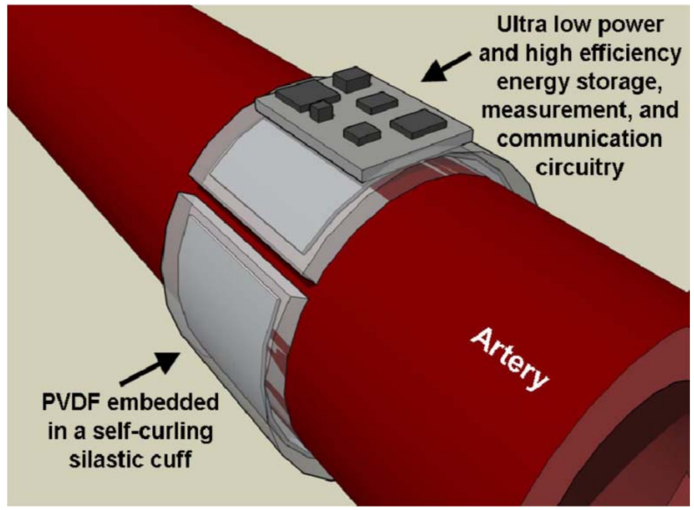
Approximately 964,000 um/cm2 at 160dB

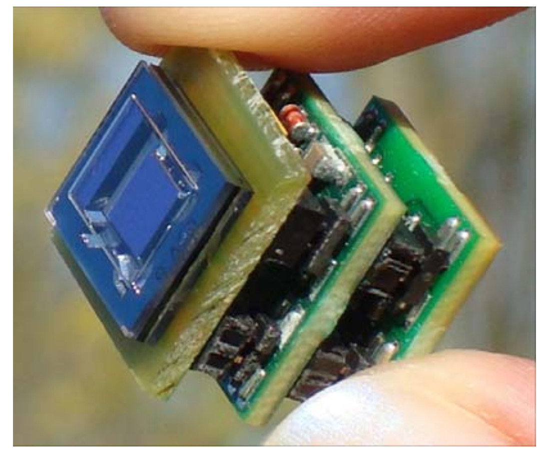
Comparison of Power Density of Energy Harvesting Methods

Energy Source	Power Density & Performance		Source of Information
Acoustic Noise	0.003 0.96	μW/cm3 @ 75Db μW/cm3 @ 100Db	(Rabaey, Ammer, Da Silva Jr, Patel, & Roundy, 2000)
Temperature Variation	10	μW/cm3	(Roundy, Steingart, Fréchette,Wright, Rabaey, 2004)
Ambient RF	1	μW/cm2	(Yeatman, 2004)
Ambient Light	100 100	mW/cm2 (direct sun) _W/cm2 (illuminated office)	Not Cited
Thermoelectric	60	_W/cm2	(Stevens, 1999)
Vibration (micro generator)	4 800	_W/cm3 (human motion - Hz) _W/cm3 (machines – kHz)	(Mitcheson, Green, Yeatman, & Holmes, 2004)
Vibrations (Piezoelectric)	200	μW/cm3	(Roundy, Wright, & Pister, 2002)
Airflow	1	μW/cm2	(Holmes, 2004)
Push Buttons	50	_J/N	(Paradiso & Feldmeier, 2001)
Shoe Inserts	330	μW/cm2	(Shenck & Paradiso, 2001)
Hand Generators	30	W/kg	(Starner & Paradiso, 2004)
Heel Strike	7	W/cm2	(Yaglioglu, 2002) (Shenck & Paradiso, 2001)

APPLICATIONS

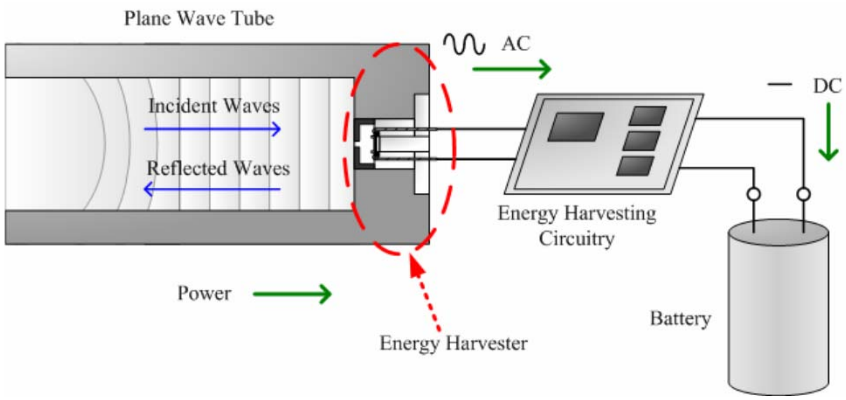
- Tire pressure sensors
- Mobile electronics
- Medical implants
- RFID sensors
- Large space structures





ACOUSTIC ENERGY HARVESTING

- Acoustic mechanical vibrations → AC electrical signal
  - Can be conditioned to power DC loads
- Operates in a frequency range of 1 Hz to 10's kHz
- Inputs come from already existing systems in the environment

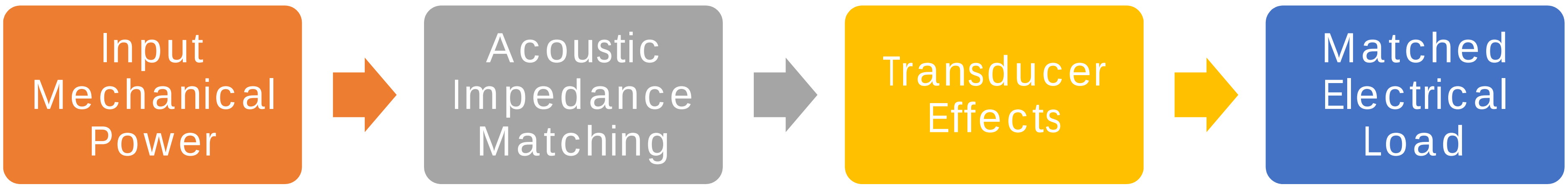


EXAMPLE ENERGY SOURCES

10-1000Hz
- Bridge Trusses
- Wheels
- Roadways

<10Hz
- Breathing
- Blood Pressure
- Heartbeat

ACOUSTIC ENERGY HARVESTER

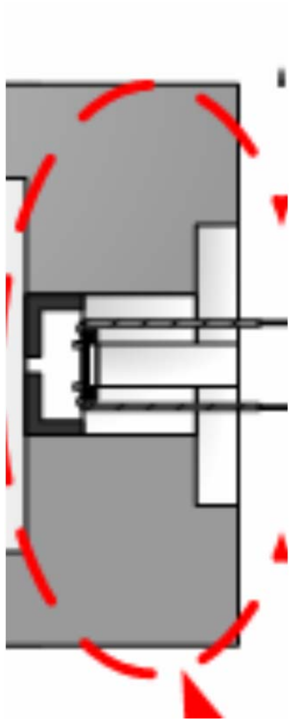


TRANSDUCER EFFECTS

	Output Signal				
Input Signal	Electrical	Mechanical	Thermal	Magnetic	Radiant
Electrical	Electrical Conduction	Piezoelectricity Electrostatics Electrostriction	Joule Heating Peltier Effect Thomson Effect Pyroelectricity	Bio-Savart's Law	Kerr Effect Pockels Effect Photoemission
Mechanical	Piezoresistivity Piezoelectricity Electrostatics Tunneling Inductive Effect	Pneumatics Hydraulics Acoustics Resonance	Friction	Magneto Elasticity	Photoelasticity Piezooptic Effect Sagnac Effect Doppler Effect Evanescence
Thermal	Thermoresistance Seebeck Effect Nernst Effect Pyroelectricity	Thermal expansion Shape Memory Effect Thermopneumatic	Heat Conduction Heat Convection	Thermomagnetization	Thermooptical Effects Radiation Thermolumines.
Magnetic	Hall Effect Magnetoresist. Induction Nernst Effect	Magnetostriction Magnetostatics	Righi-Leduc Effect Ettinghausen Effect	Magnetic Induction	Farady Effect Cotton-Mouton Effect
Radiant	Photovoltaic Photoconductiv. Photoelectric Photo-Hall	Radiation Pressure Photostriction	Radiation Heating		Luminescense

MEMS-BASED ACOUSTIC ENERGY HARVESTER

- Device consists of a Helmholtz resonator with a piezoelectric backplate
- When excited by an acoustic spectrum, a single resonance is seen
- Pressure is amplified in the cavity
- Pressure translates to an electric signal through the piezoelectric backplate

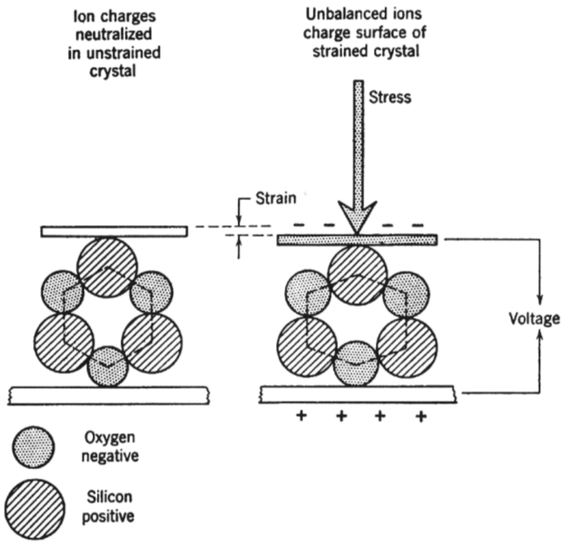


HELMHOLTZ RESONATOR

- Can amplify specific frequencies from a complex waveform
- Enclosed volume of air acts as an acoustic “spring” attached to the moving mass of air at the neck
  - The acoustic mass at the neck acts like an inductor
  - The enclosed volume stores energy like a capacitor
- Resonance frequency depends on volume of chamber

PIEZOELECTRIC EFFECT (1/2)

- Development of a surface charge due to mechanical strain
- Reversible effect
  - Sensing
  - Actuation
- Requires non-centrosymmetric crystal structure
  - Lack an inversion center (center of symmetry)
- Couples internal dielectric polarization and experienced stress/strain
  - Dipoles generated due to stress



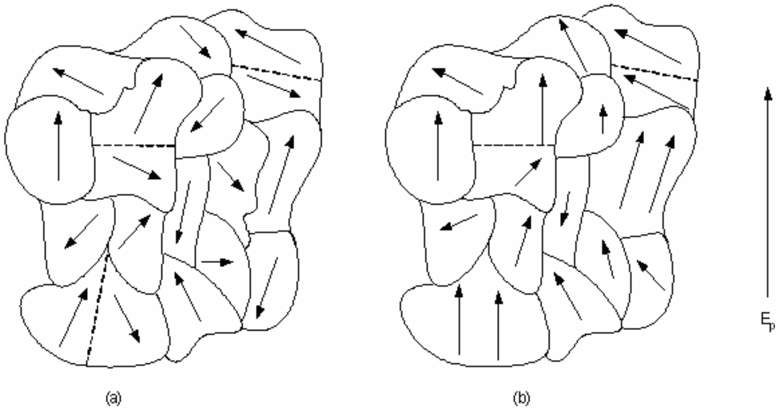
PIEZOELECTRIC EFFECT (2/2)

- Relates Strain to stored electrostatic energy:

$$D = \varepsilon_0 E + P$$

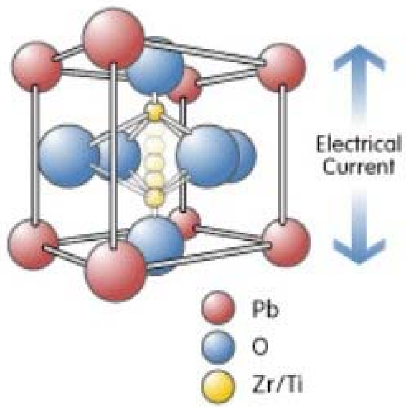
$$W = \frac{1}{2} D * E$$

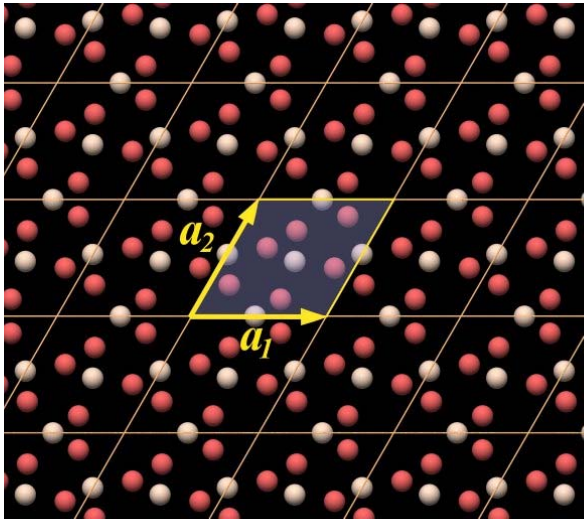
- If materials do not already have their pole domains aligned an extra “poling” step is required
  - Apply an electric field and heat for a given amount of time



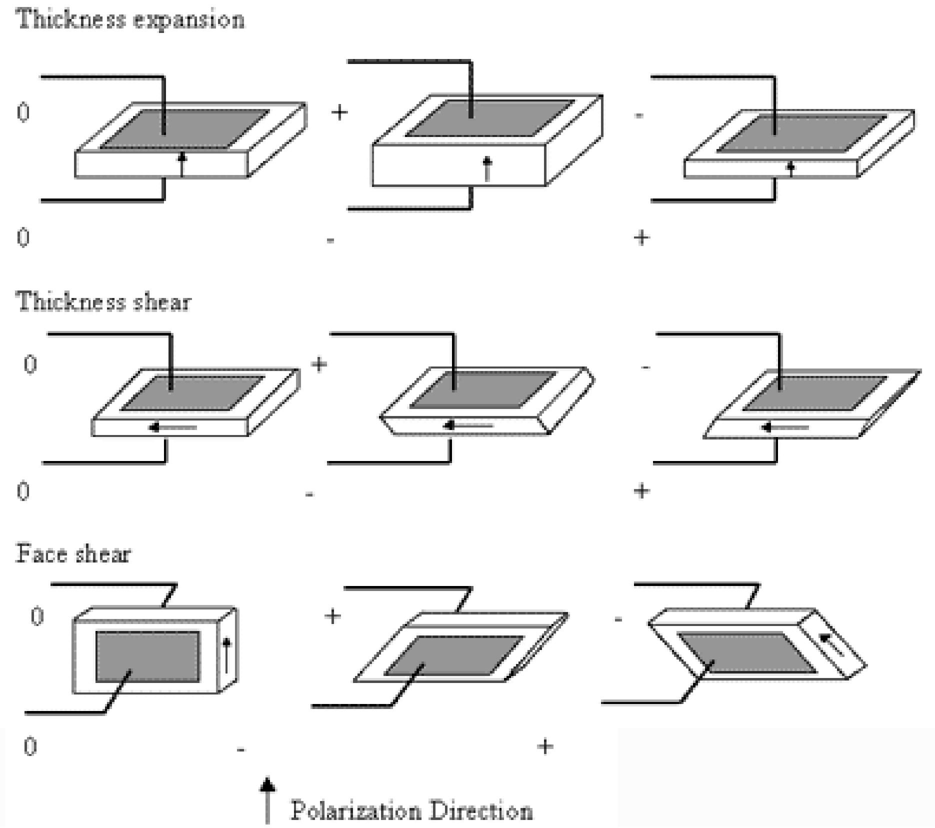
PIEZOELECTRIC MATERIALS

- Crystalline
  - Quartz
  - GaAs
  - LiNbO3
- Thin Film
  - ZnO
  - AlN
- Ceramics
  - PZT
  - BaTiO3
- Polymers
  - PVDF

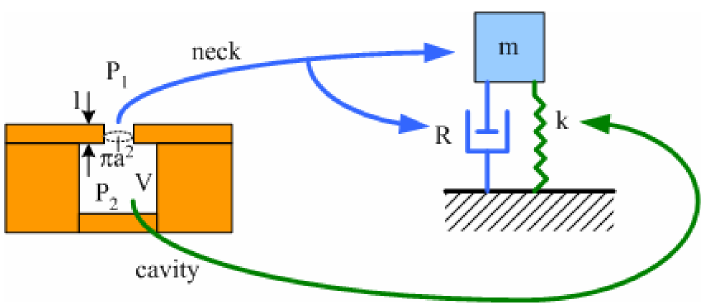




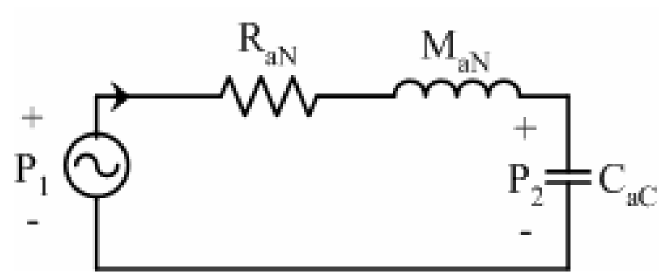
PIEZOELECTRIC MODES



LUMPED ELEMENT MODEL



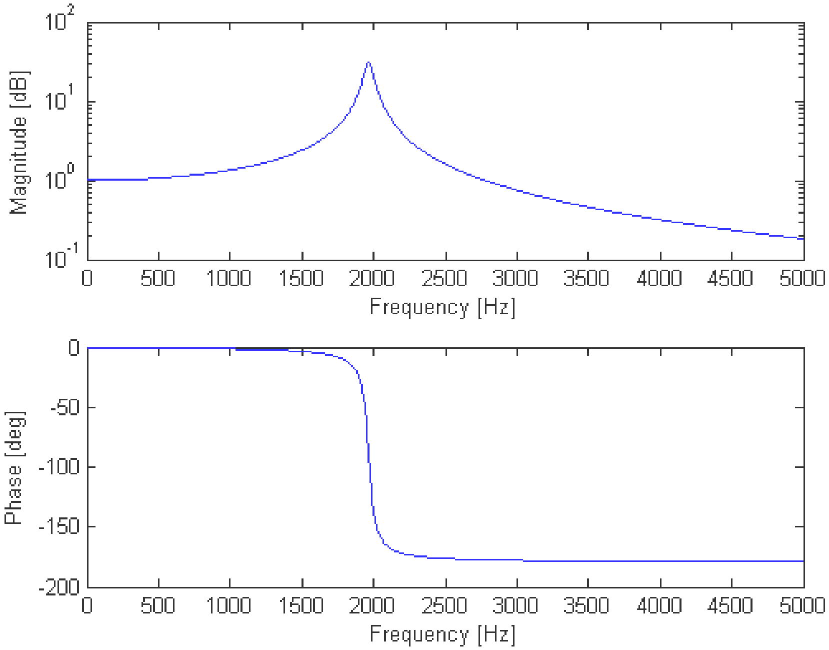
Acoustic Model Mechanical Model



Electrical Model

Helmholtz Resonator Lumped Element Model

LUMPED ELEMENT MODEL



$$\frac{P_2}{P_1} = \frac{\frac{1}{sC_{aC}}}{R_{aN} + sM_{aN} + \frac{1}{sC_{aC}}},$$

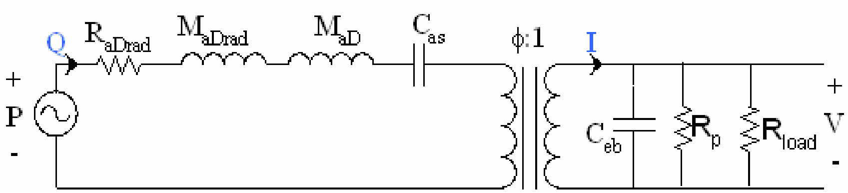
$$C_{aC} = \frac{V}{\rho_0 {c_0}^2} \quad \left[\frac{m^3}{Pa}\right].$$

$$f_{res} = \frac{1}{2\pi\sqrt{M_{aN}C_{aC}}} [Hz].$$

$$M_{aC} = \frac{\rho_0 V}{3\left(\pi a^2\right)^2} \quad \left[\frac{\text{kg}}{\text{m}^4}\right],$$

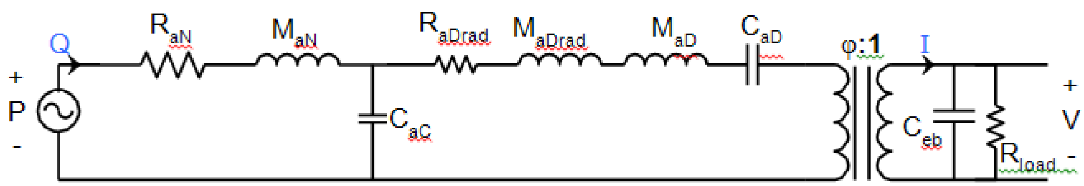
$$PA_{res} = \frac{M_{aN}}{R_{aN}}(2\pi f_{res}).$$

LUMPED ELEMENT MODEL



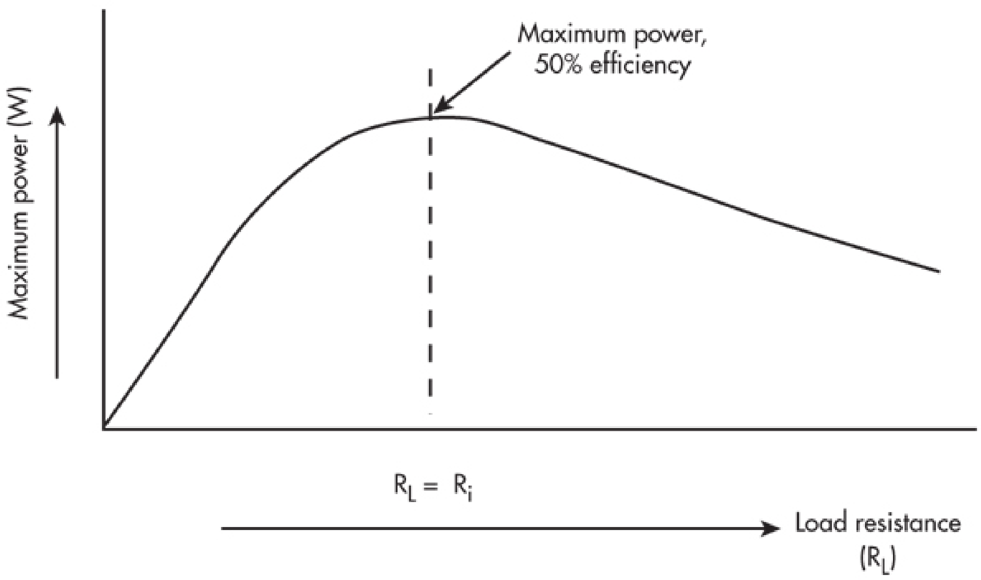
Piezoelectric diaphragm alone

Piezoelectric diaphragm mounted to wall of Helmholtz resonator

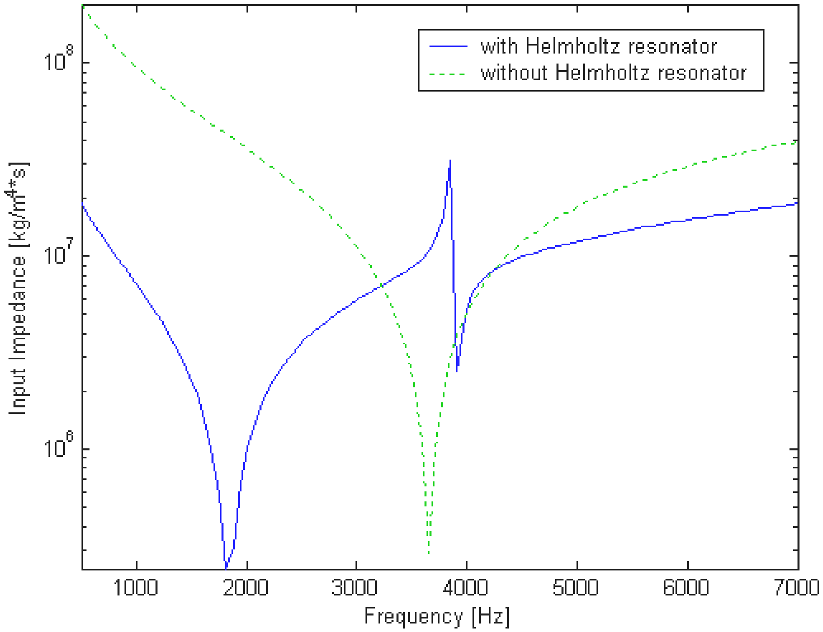


IMPEDANCE MATCHING

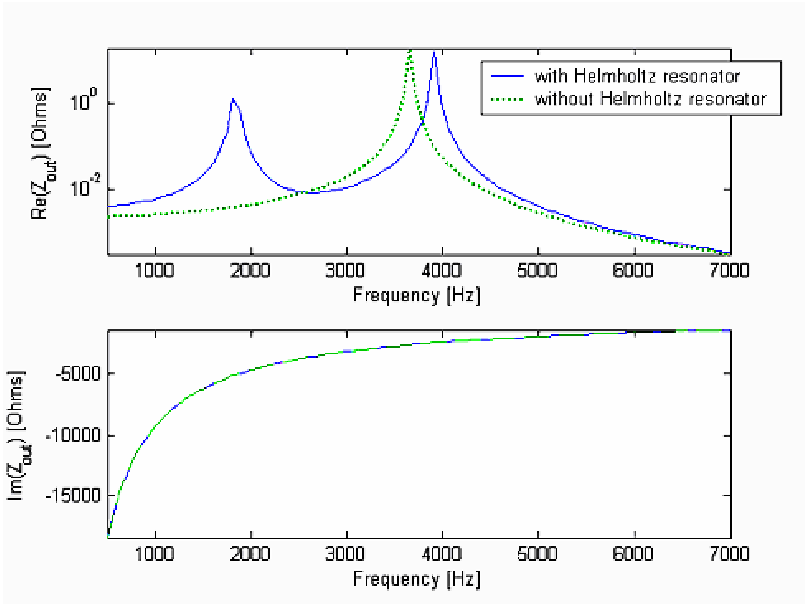
- When a traveling wave encounters a change in impedance some of the wave's energy will be transmitted while some will be reflected
- Minimize reflections to maximize transmitted power
  - Must match impedances at interfaces
  - Regardless of energy domain
- When impedance is matched, the amount of power delivered to the load is the same as power dissipated in source



IMPEDANCE MATCHING

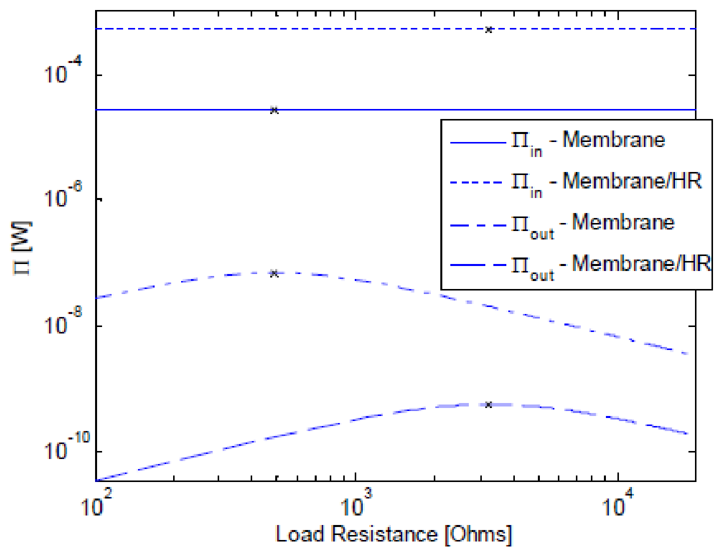


Acoustic input impedance

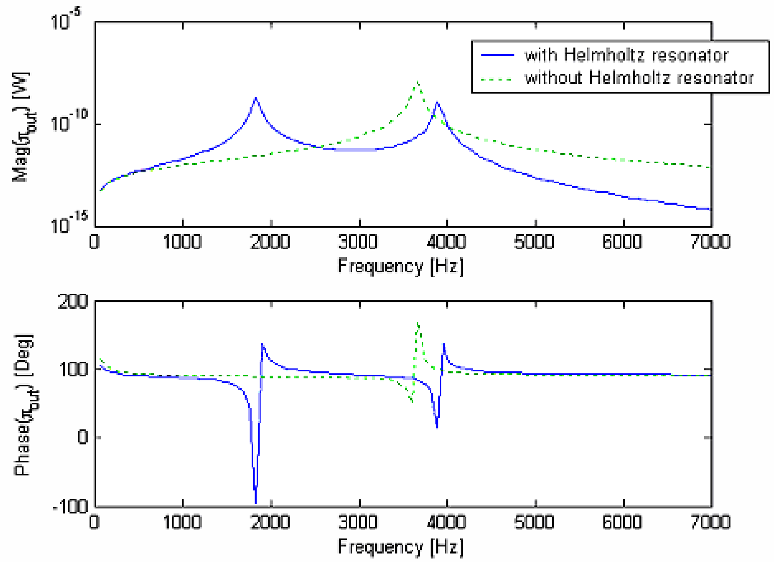


Electrical output impedance

POWER TRANSFER

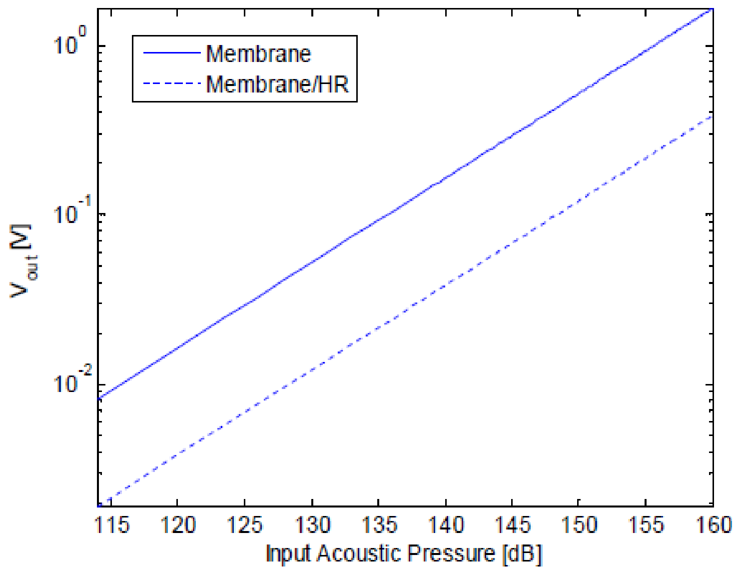


Electric output power at resonance as a function of load resistance (P = 114dB)

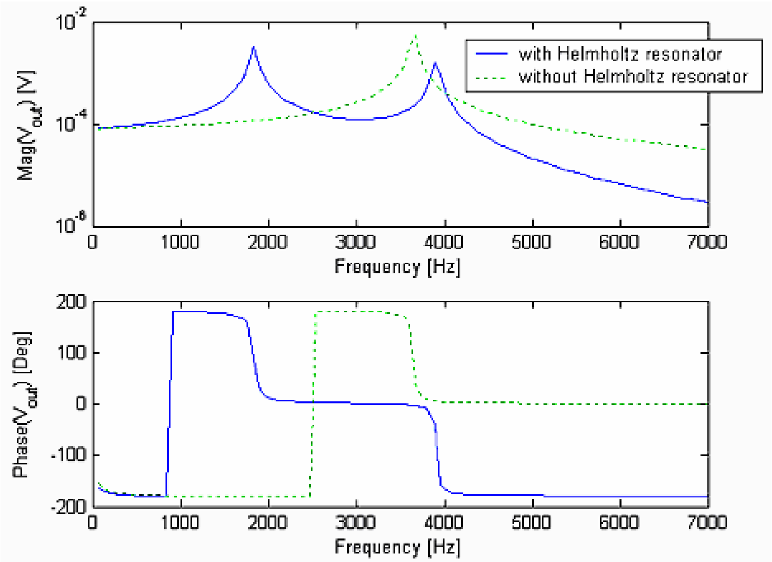


Electric output power due to an input acoustic pressure of 94dB

OUTPUT VOLTAGE

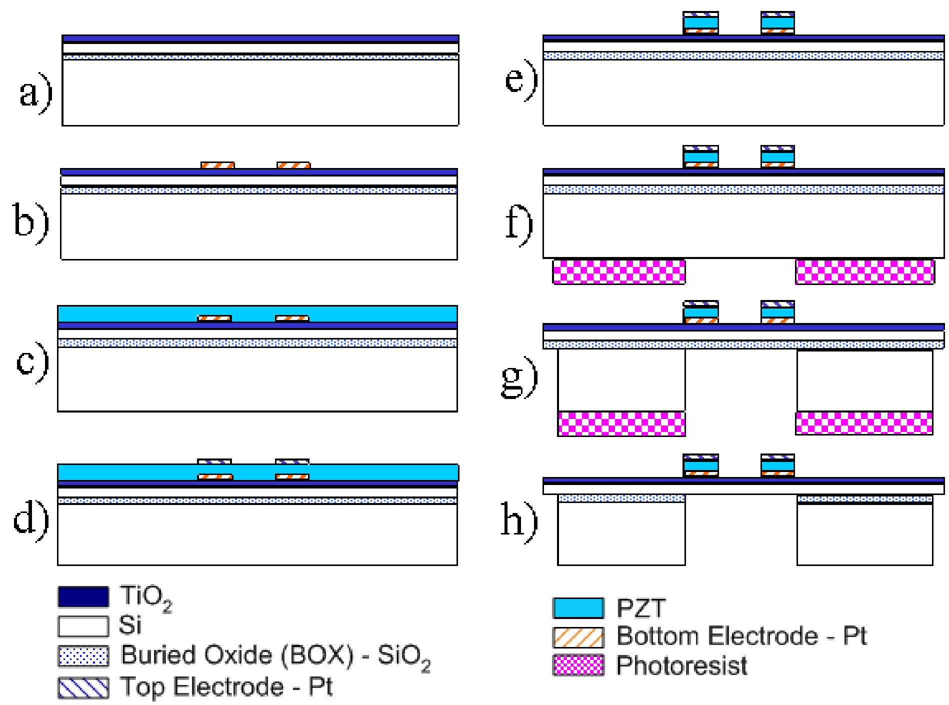


Output voltage at resonant frequency of device



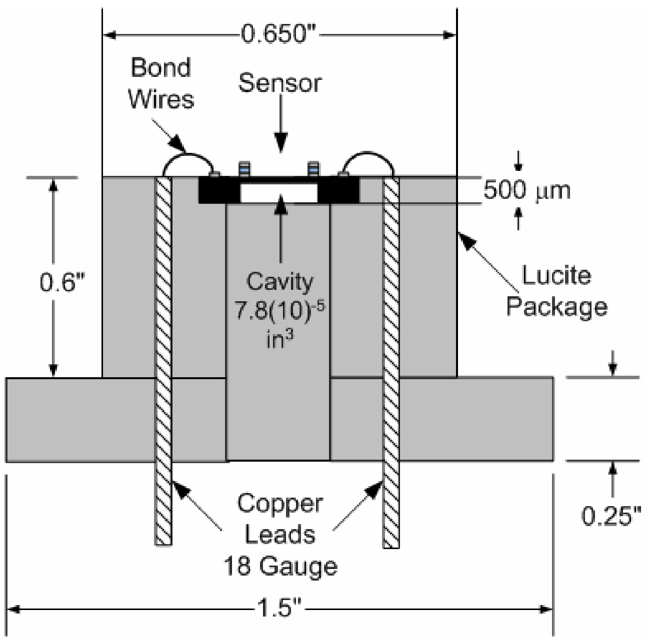
Output voltage for an input acoustic pressure of 94 dB

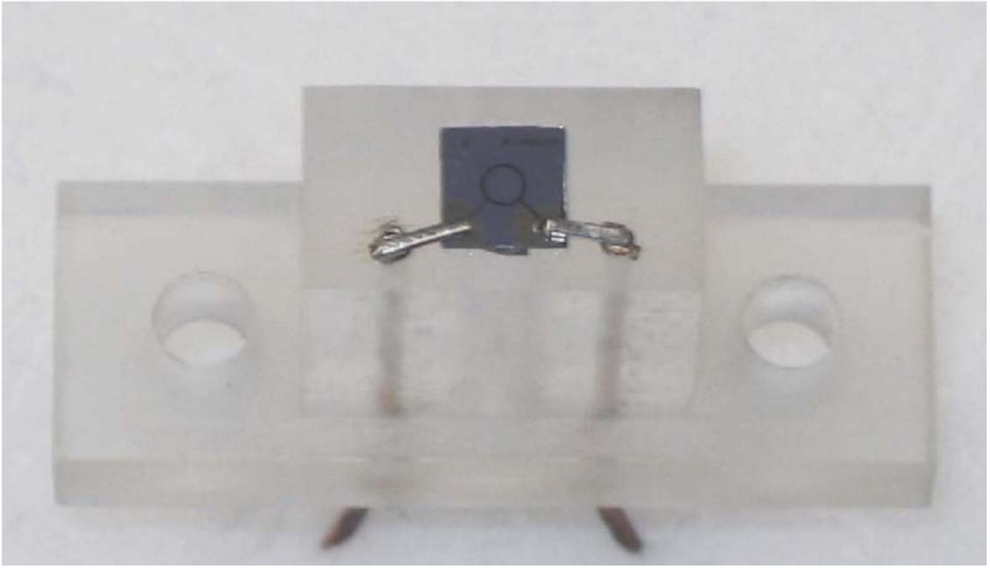
FABRICATION (1/2)



a) Deposit Ti on SOI wafer and oxidize to get TiO2
b) Deposit Ti/Pt , metal lift off
c) Spin coat PZT and pyrolize
d) Deposit Pt, metal lift off
e) Wet etch PZT
f) Spin coat photoresist to pattern cavity
g) DRIE down to buried oxide layer
h) Remove resist, BOE etch exposed oxide

FABRICATION (2/2)





CONCLUSION

- MEMS device designed to harvest acoustic energy
- Relies on the piezoelectric effect
  - Exotic materials for a MEMS process
- Requires impedance matching across energy domains for maximum power transfer
- Can apply voltage in the uV to mV range depending on input acoustic pressure, resonant frequency, and output load
- Relatively low power outputs
  - Possible applications in sensors, mobile devices, etc.

RESOURCES

1) Sherrit, Stewart. "The physical acoustics of energy harvesting." In *Ultrasonics Symposium, 2008. IUS 2008. IEEE*, pp. 1046-1055. IEEE, 2008.
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