Piezoelectric Materials & Energy Harvesting

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TENNESSEE TECH UNIVERSITY

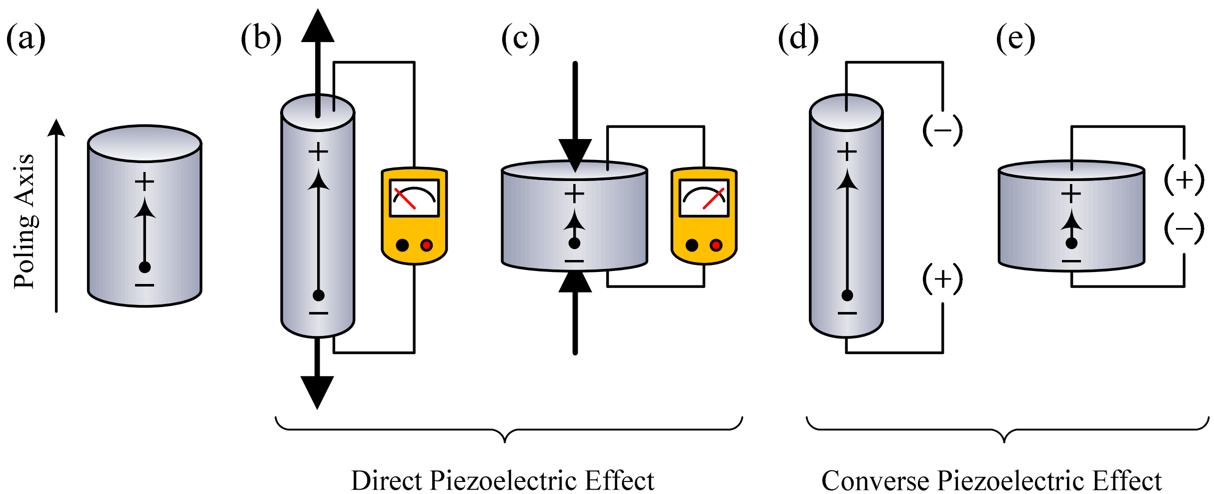
Outline

- Piezoelectric Materials
- Energy Harvesting Overview
- Piezoelectric Energy Harvesting Applications
  - Self-Powered Sensors
  - MEMS Harvesters
  - Biological Harvesters
  - Fluid-Flow Harvesters
- Current Research Trends
  - Broadband and Nonlinear
  - Multifunctional Harvesters
  - Multi-Source Harvesters
  - Novel Materials
- My Current Research

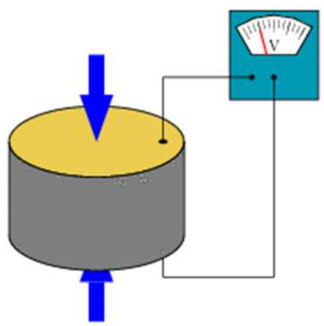
Part 1: Piezoelectric Materials

Piezoelectric Transduction Phenomenon

Piezoelectric transduction works based on dipole motion in crystalline materials. Piezoelectricity allows conversion of energy from electrical to mechanical domain and vice versa (electromechanical coupling).



Direct Effect



Constitutive Equations

Converse Effect

$$S_i = s_{ij}^E T_j + d_{ik} E_k$$

$$D_m = d_{mj} T_j + \varepsilon_{mk}^T E_k$$

Direct Effect

S : Mechanical strain

T : Mechanical stress

E : Electric field

ε^T : Dielectric constant

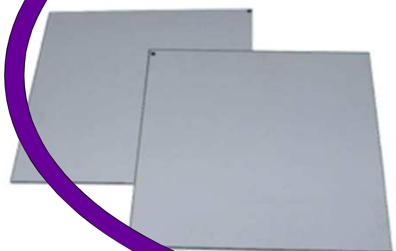
s^E : Elastic compliance

d : piezoelectric coefficient

D : Electric displacement

Piezoelectric Materials

Most Common (PZT, PVDF)

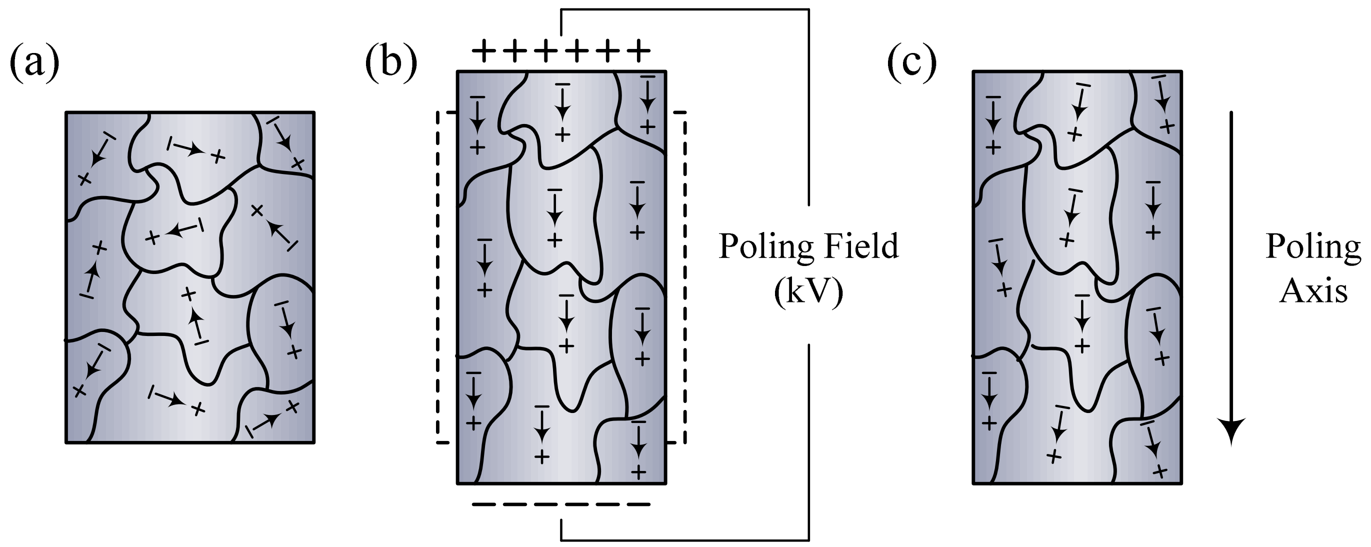
PZT	PVDF	PMN-PZT Single Crystal	Piezoelectret Foam
			
Lead Zirconate Titanate	Polyvinylidene Fluoride	Lead Magnesium Niobate-Lead Zirconate Titanate	Space Charged Polypropylene Foam
ρ=7500 kg/m^3	ρ=1780 kg/m^3	ρ=7000 kg/m^3	ρ= 1000kg/m^3
d_{31}=-200 pC/N	d_{31}=23 pC/N	d_{31}=-2000 pC/N	d_{33}=25-250 pC/N
High coupling	Low coupling	Very high coupling	Medium Coupling
Heavy, brittle	Flexible, lightweight	Heavy, very brittle	Very lightweight, Very flexible

Piezoceramic (PZT) Poling Process

Synthetic piezoceramic materials must be poled prior to exhibiting piezoelectricity.

Poling Process:

(a) Piezoceramic material prior to poling – random distribution of dipole moments
(b) Application of poling voltage (kV) to align dipoles (also, apply heat above Curie temperature, typically done using oil bath)
(c) Poled material with permanently aligned dipoles (some relaxation present)



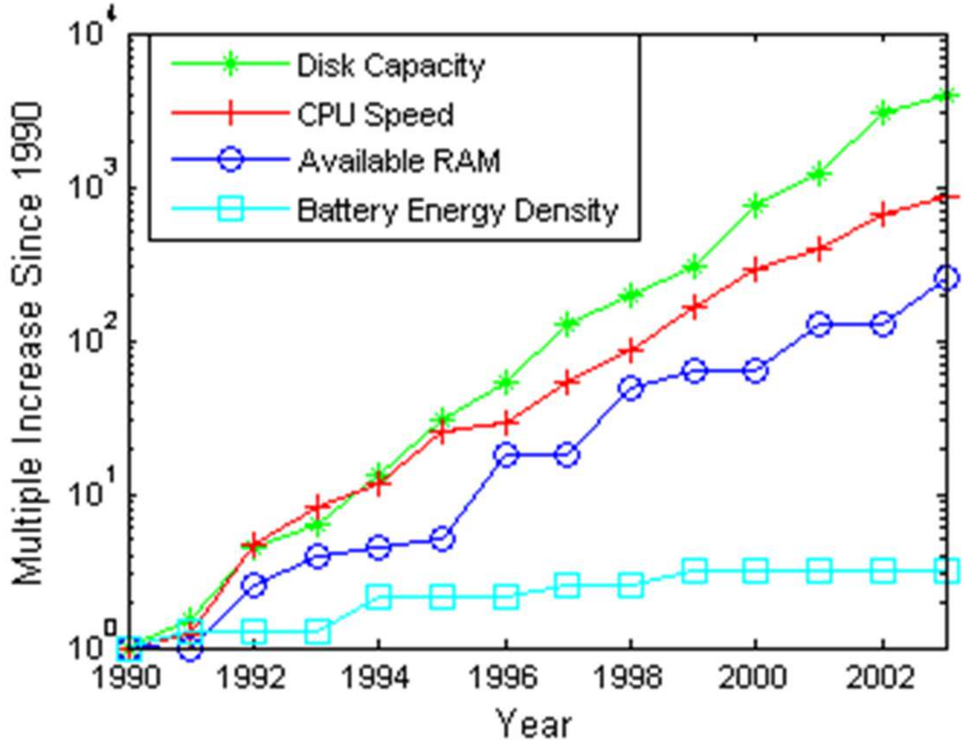
Part 2: Energy Harvesting Overview

Piezoelectric Energy Harvesting

The goal of many piezoelectric energy harvesting systems is to create self-powered wireless sensors and eliminate the requirement of battery replacement and disposal.

Advantages

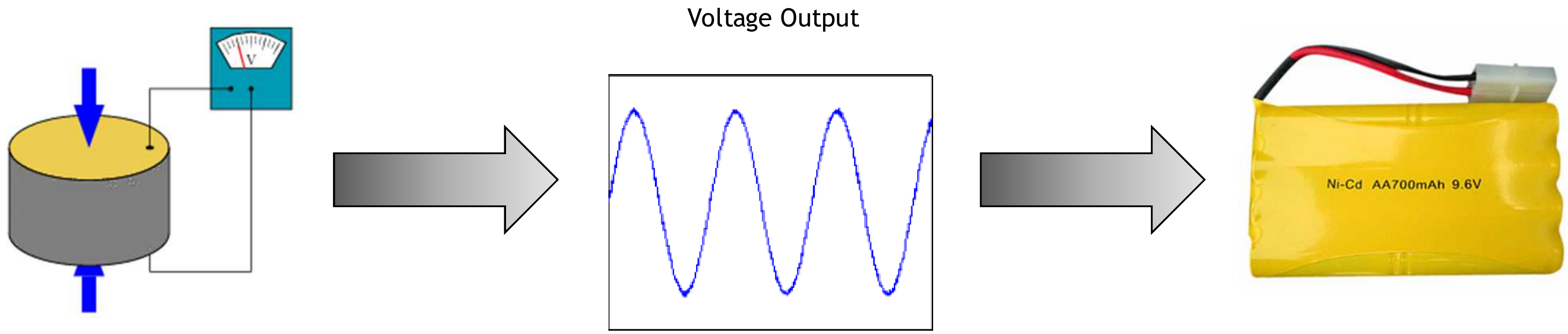
- Large (usable) voltage output
- No external power source required for energy generation
- High power density
- Commercially available in various sizes/configurations

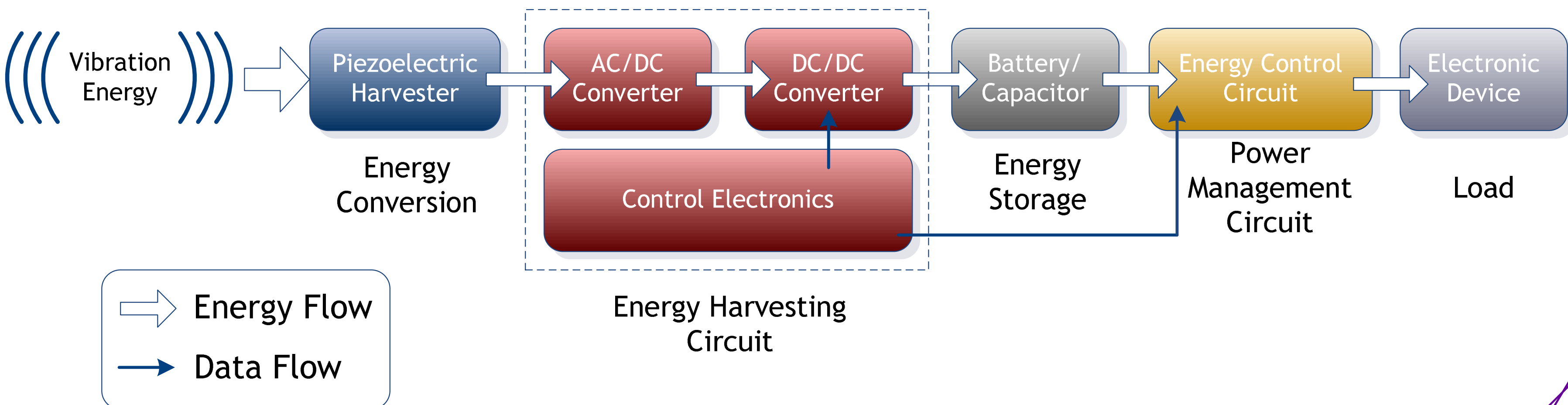


(Derived from data in Paradiso and Starner, 2005)

Piezoelectric Energy Harvesting System

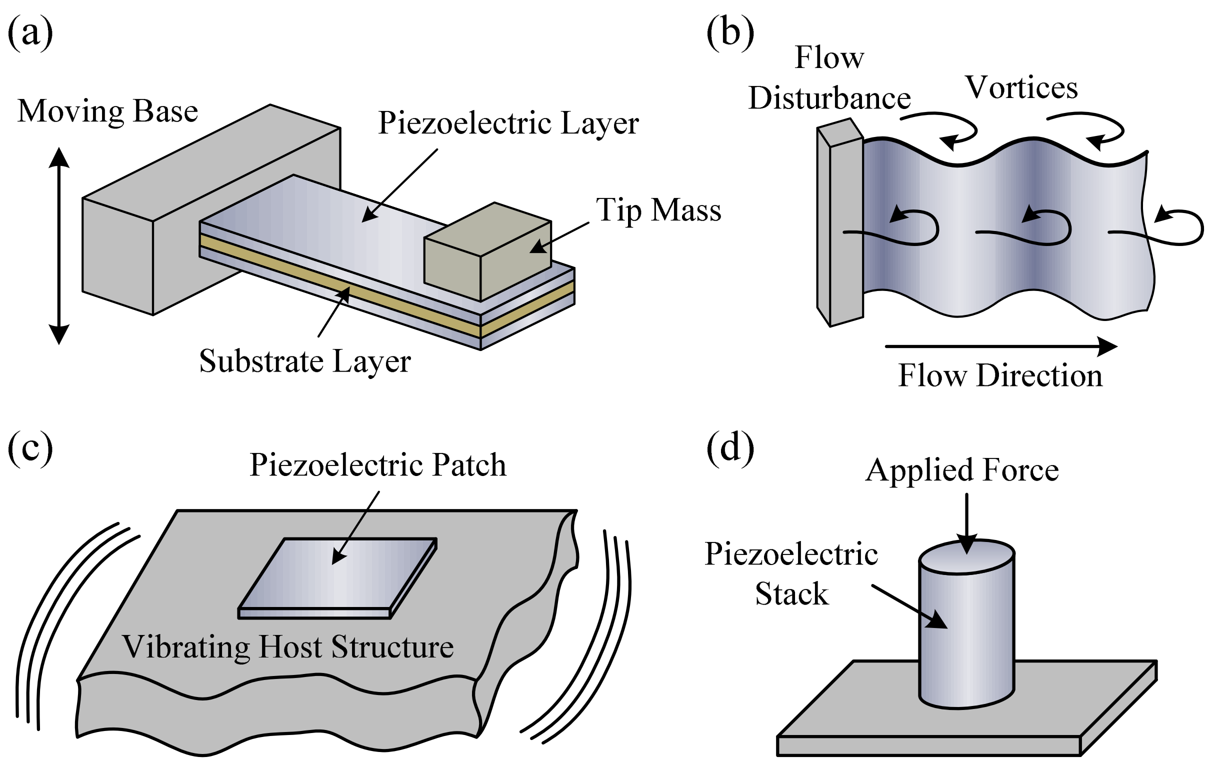
Piezoelectrics are dynamic transducers and generate AC voltage output when excited. A complete energy harvesting system includes harvester and appropriate conditioning circuitry and energy storage.



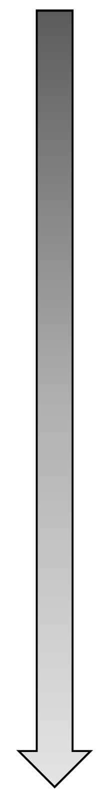


Common Piezoelectric Harvester Configurations

There are several ways in which ambient vibration energy can be coupled to piezoelectric harvesters.

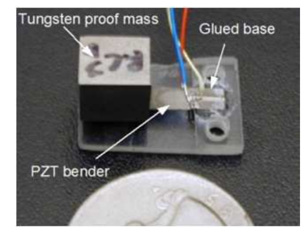


Macro-scale

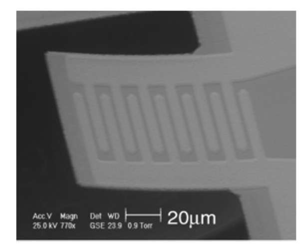


Micro-scale

Anton *et al*, 2008



Roundy *et al*, 2004

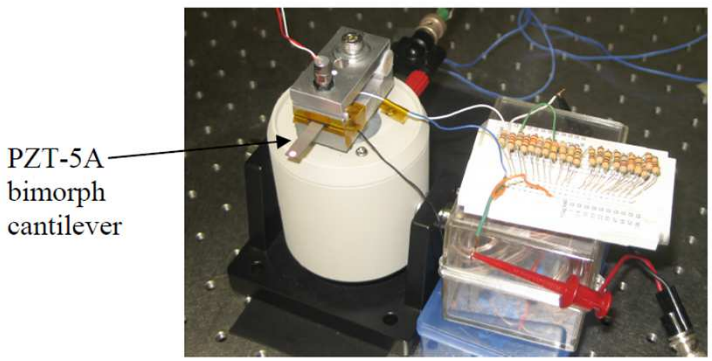


Jeon *et al*, 2005

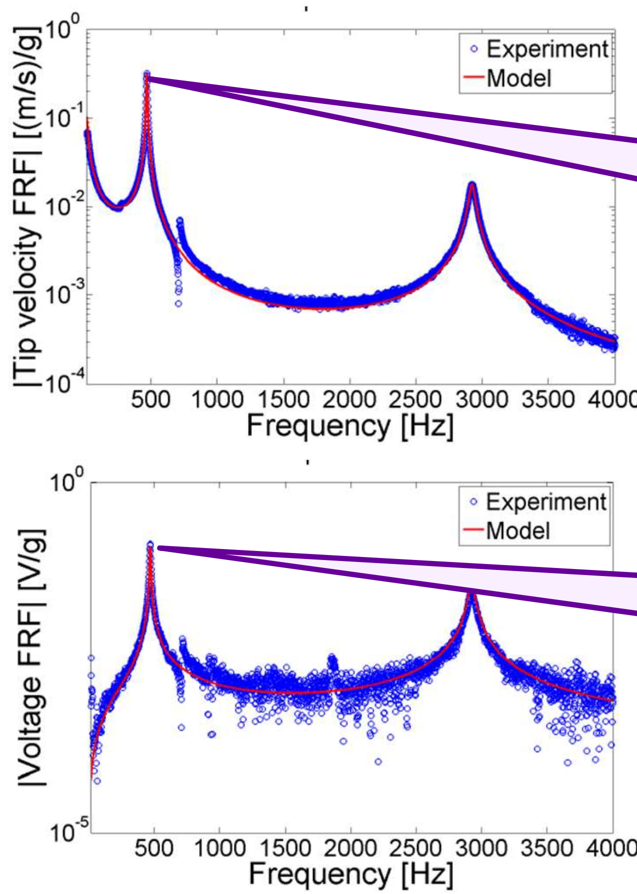
Resonant Design of Linear Piezoelectric Harvesters

Conventional, linear piezoelectric energy harvesting relies on the resonant behavior of the device to enhance strain input to the PZT, hence energy generation.

Linear, Resonant Cantilever



Erturk, 2009



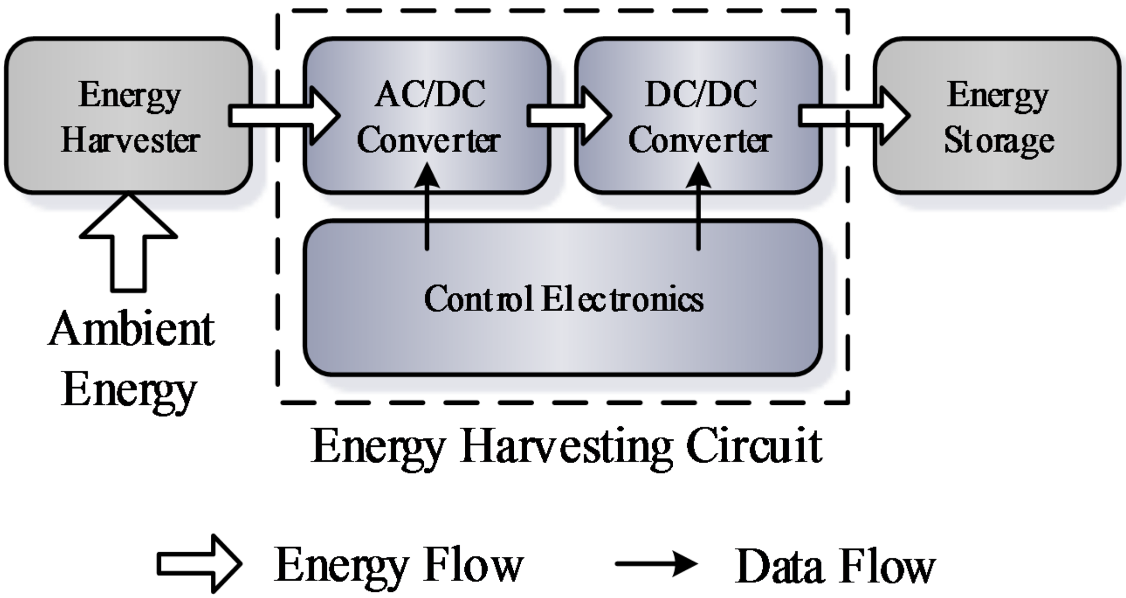
Maximum Tip Velocity at 1st mode

Maximum Voltage Output at 1st mode

Energy Conditioning Circuitry

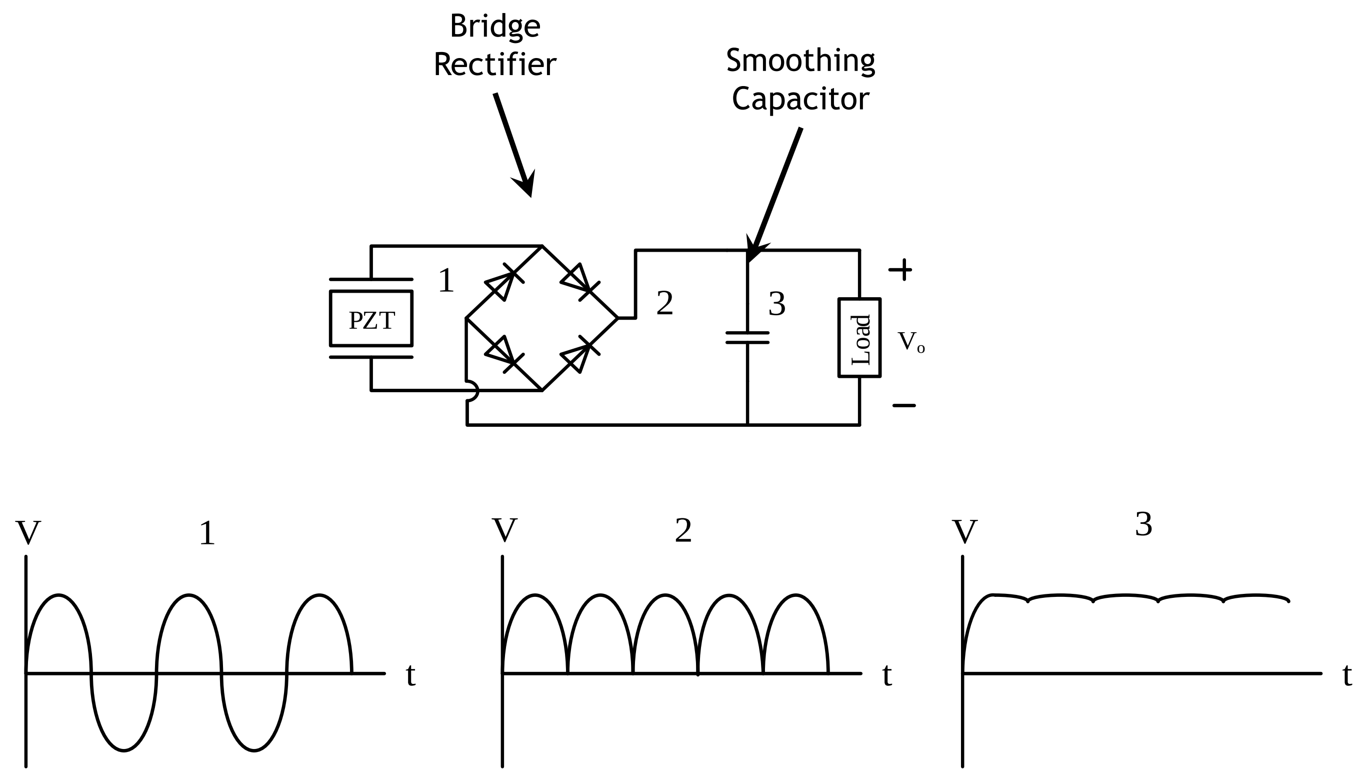
AC piezo output must be rectified. Energy is typically insufficient for direct use, therefore, intermediate storage is necessary. Additionally, impedance matching is critical for piezoelectric harvesters.

Basic Energy Harvesting Circuit Components



Rectification

The first step is to rectify the AC voltage from the piezo to DC voltage.

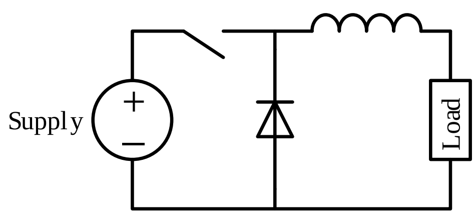


In some cases, this can be the entire circuit, however…

DC/DC Conversion

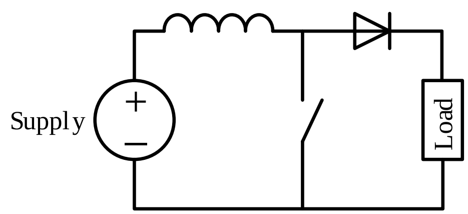
The rectified voltage is often unsuitable for direct use with the load electronics. DC/DC conversion is, therefore, required. In the following converters, voltage is controlled by adjusting duty cycle of switch.

Buck Converter



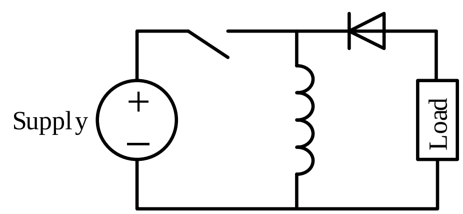
Used to step down when piezo voltage is greater than load volatge

Boost Converter



Used to step up when piezo voltage is lower than load volatge

Buck-Boost Converter



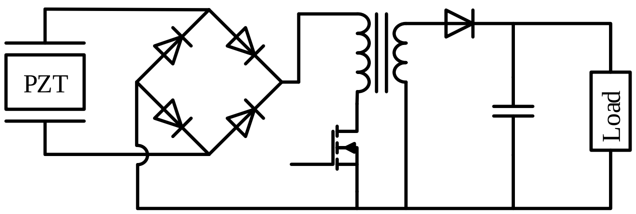
Can be used to step up or step down

Again, this may complete the circuit, however, many systems require more advanced circuitry…

Advanced Switch-Mode Converters

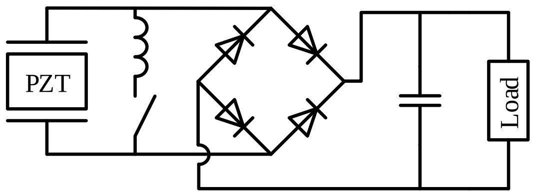
The efficiency of the harvesting circuit is greatly increased when implementing advanced switching converters and impedance matching.

Synchronous Electric Charge Extraction (SECE)



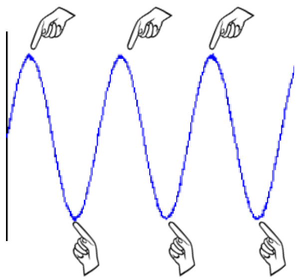
Lefeuvre *et al*, JIMSS, 2005

Parallel-Synchronous Switch Harvesting on Inductor (SSHI)



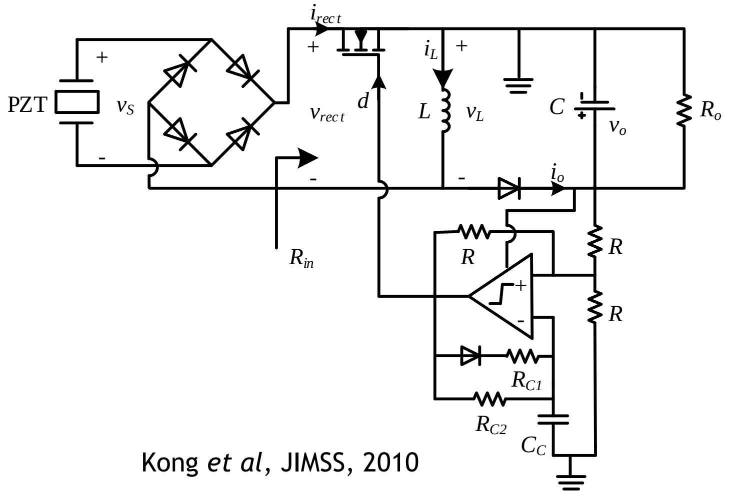
Badel *et al*, JIMSS, 2005

Switching on Voltage Peaks



Resistive Impedance Matching Circuit

Note: Switching is independent of oscillation frequency. It is simply based on what artificial resistance the circuit is to represent.



Kong *et al*, JIMSS, 2010

Part 3: Piezoelectric Energy Harvesting Applications

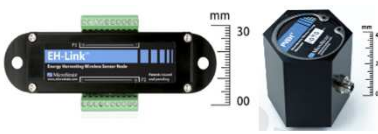
Piezoelectric Energy Harvesting Applications

Self-Powered Sensors

Paradiso *et al*, 1998

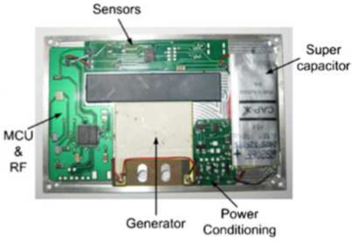
- Pioneering work in self-powered sensors
- PVDF + PZT harvesters in shoe to power RFID tag
- 1-10 mW of power; enable RFID tag to transmit 12-bit ID code every 4-5 steps

Arms *et al*, 2005



- Complete sensor node includes microprocessor, memory, data logger, temp and humidity sensors, radio, and harvesting
- 2 mW @ 57 Hz, 0.1 *g* excitation
- Later developed commercial product: EH Link from LORD Microstrain, Inc.

Zhu *et al*, 2011



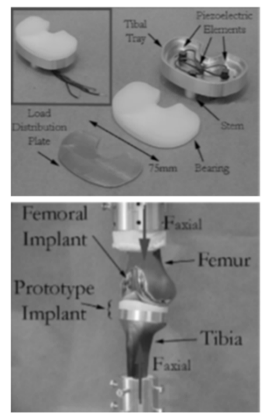
- Credit card-sized self-powered sensor
- Accelerometer, pressure, temperature sensors
- 240 μW @ 67 Hz, 0.4 *g* input allows operation of the sensor node once every 15 minutes

Biological and Wearable Harvesters

Feenstra *et al*, 2008

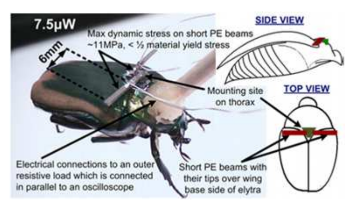
- Piezo stack incorporated into straps of military backpack
- 0.4 mW average power during walking

Platt *et al*, 2005



- *In-vivo* harvesting by Incorporating piezoelectric stacks into total knee replacement unit
- Provide power to wireless health monitoring sensor
- 4.8 mW generated by the stacks, yielding 850 μW of regulated power

Aktakka *et al*, 2011

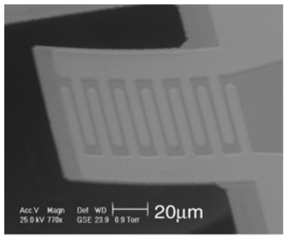


- Piezoelectric cantilevers ($11mm^3$) fixed to a beetle
- 11.5 μW of power during tethered flight at 85 Hz flapping frequency

Piezoelectric Energy Harvesting Applications

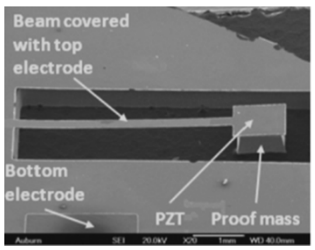
MEMS Harvesters

Jeon *et al*, 2005



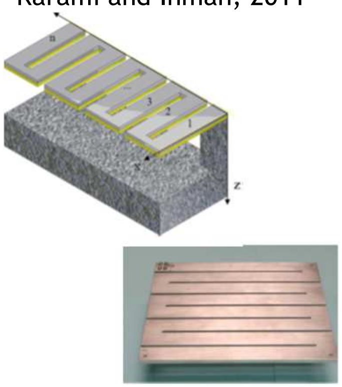
- Pioneering work in piezoelectric MEMS harvesting
- Interdigitated electrodes for d_{33} mode operation
- 100 x 60 x 0.48 µm^3
- 1.01 µW @ 13.9 kHz, 2.56 µm tip displacement

Shen *et al*, 2009



- High aspect ratio cantilever to reduce natural frequency
- ω_n below 200Hz
- 4800 x 400 x 22 µm^3
- 0.32 µW @ 183.8 Hz, 0.75 *g*

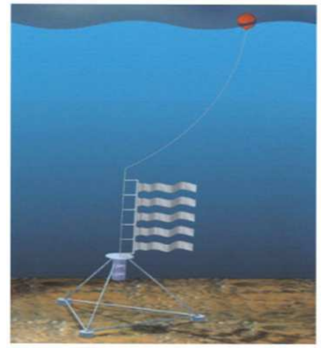
Karami and Inman, 2011



- Novel geometry for reduction of natural frequency
- Zig-zag structure provides up to 17x reduction in natural frequency
- Experimental testing only at macro scale to-date

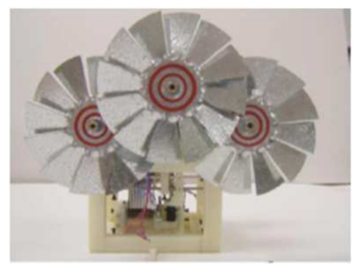
Fluid/Wind Flow Harvesting

Taylor *et al*, 2001



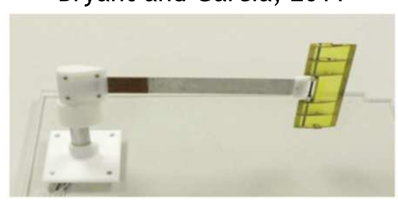
- Early work on fluid flow harvesting with PVDF
- Piezoelectric "eel," 24 cm long, 7.6 cm wide, and 150 µm thick
- 3.0 V for 0.5 m/s flow velocity

Myers *et al*, 2007



- Windmill-based piezoelectric harvester
- Three fans of 12.7 cm diameter excite two rows of 9 piezo cantilever beams
- 10 mph wind generates 5 mW

Bryant and Garcia, 2011



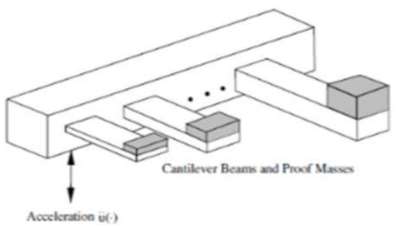
- Aeroelastic flutter-based harvester configuration
- 2.2 mW @ wind speed of 7.9 m/s
- Cut-in speed of 2.6 m/s

Part 4: Current Research Trends

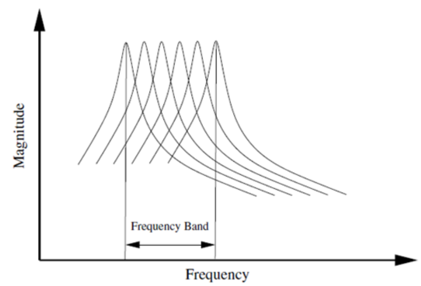
Broadband and Nonlinear Harvesting

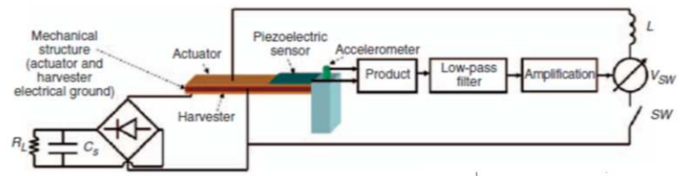
Traditional linear resonant harvesters suffer when excitation frequency shifts away from designed resonance of device.

Broadband Harvesters

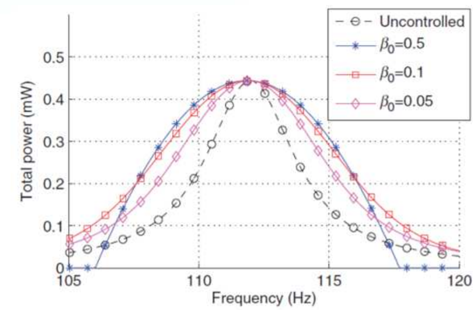


Shahruz *et al*, 2006

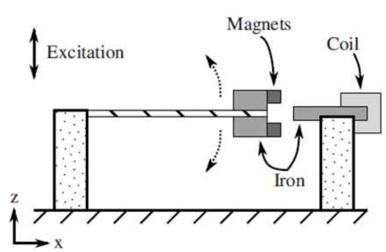




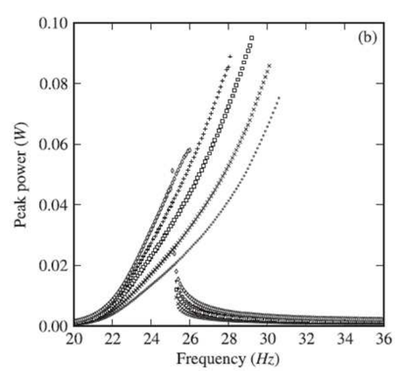
Lallart, **Anton**, and Inman, 2010

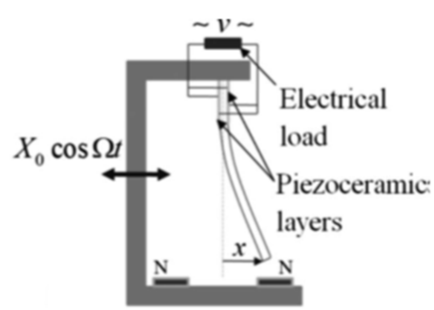


Nonlinear Harvesters

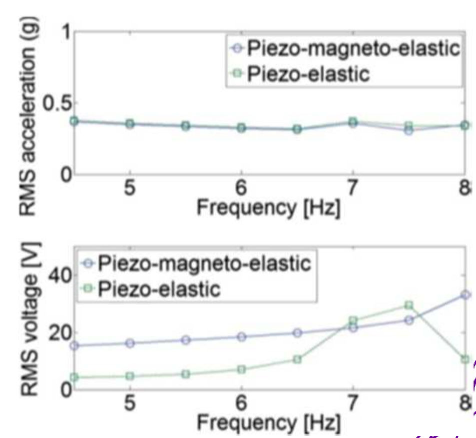


Barton *et al*, 2010



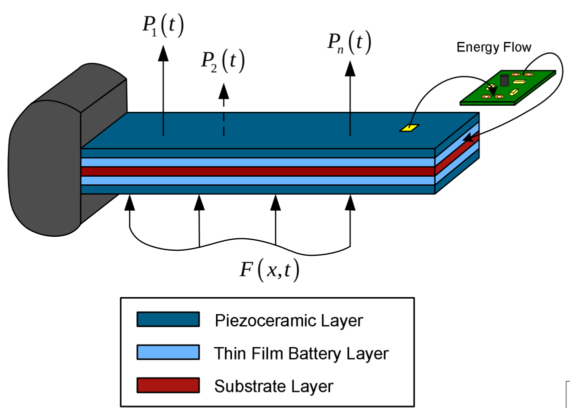


Erturk *et al*, 2009

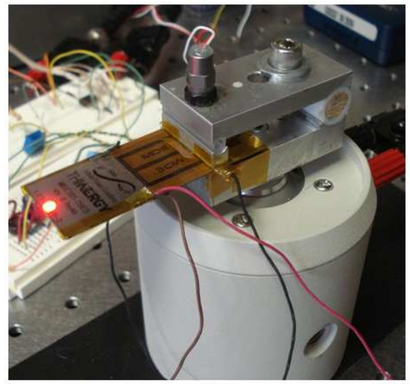


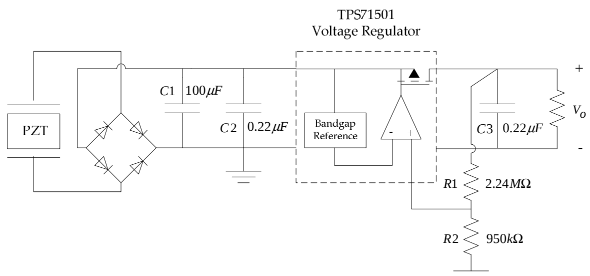
Multifunctional Harvesting

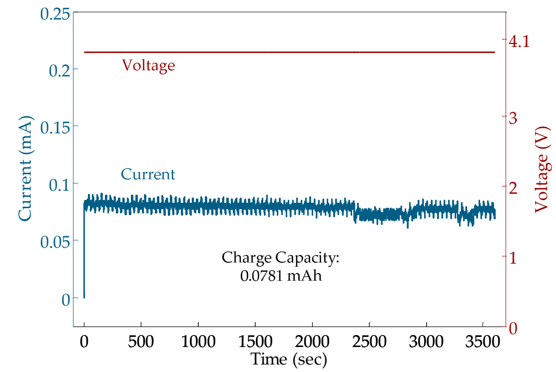
Self-Charging Concept

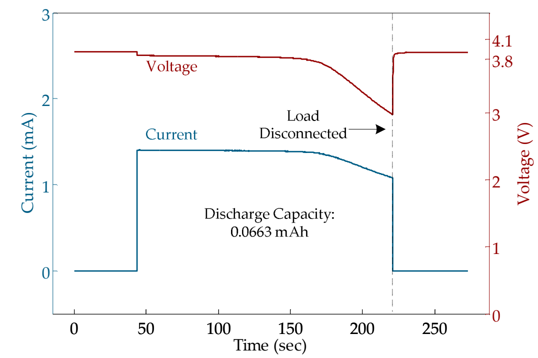


Anton *et al*, 2010

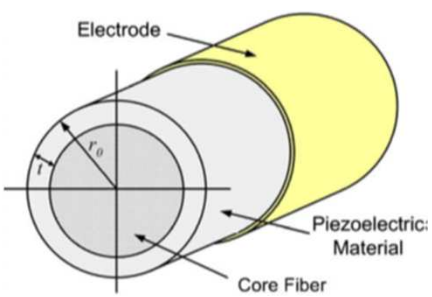


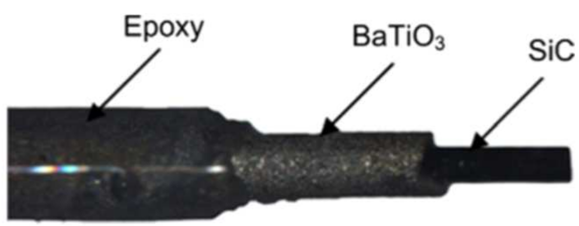




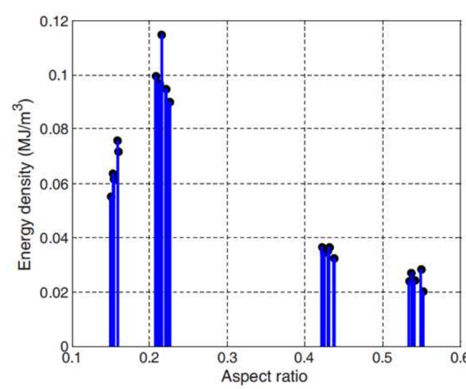


Structural Piezo-Fibers

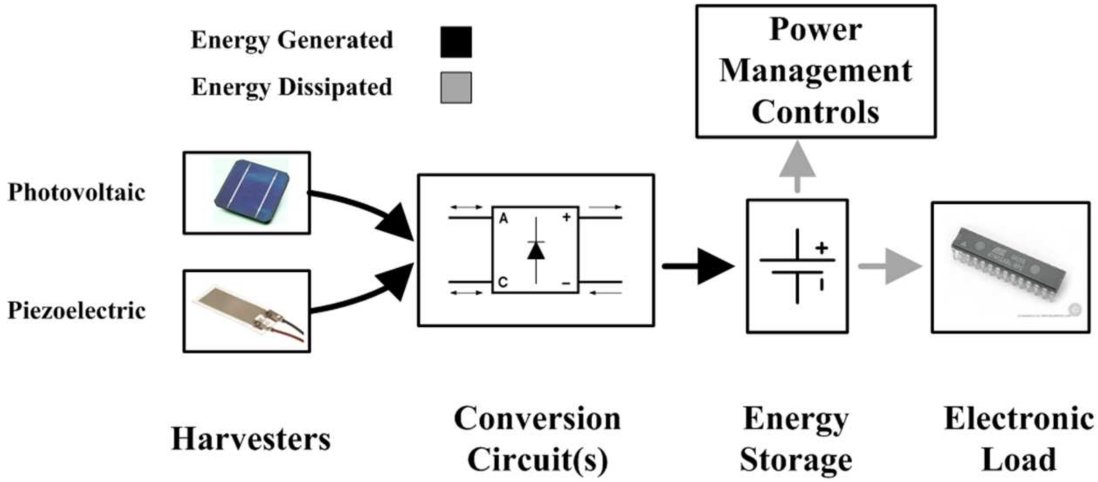




Lin and Sodano, 2010



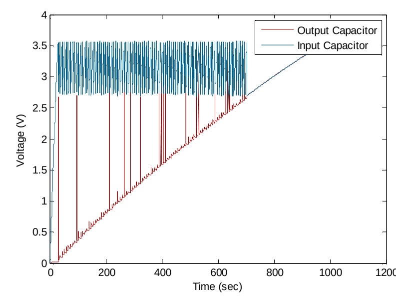
Multi-Source Harvesting



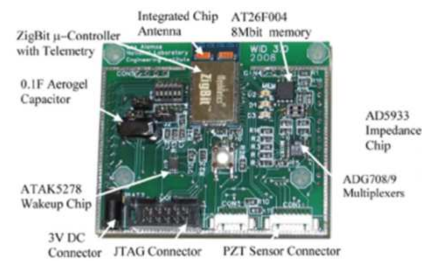
Simultaneous harvesting from multiple energy sources

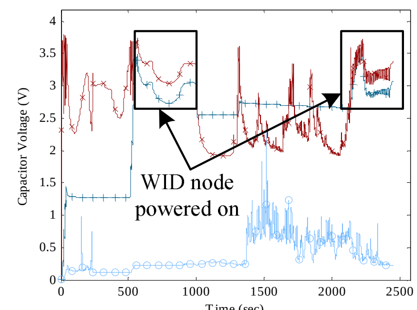
Anton *et al*, 2013

Multi-Source Circuit



Wireless Impedance Device (WID 3.0)

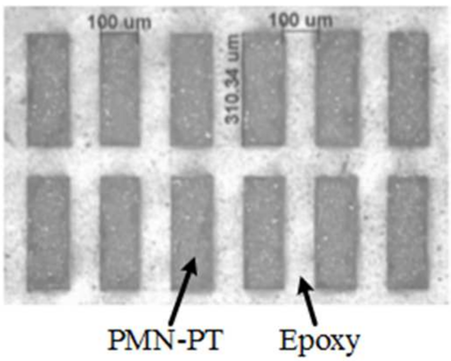




Novel Piezoelectric Materials

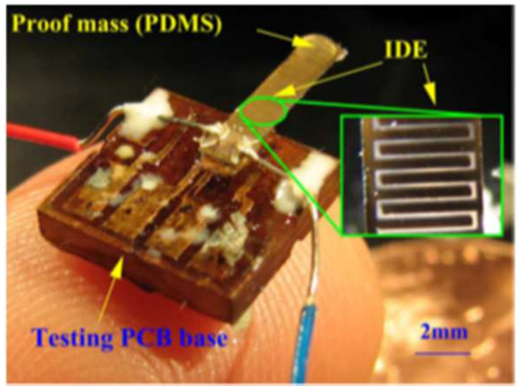
Single-Crystal Piezoceramics

PMN-PT Composite

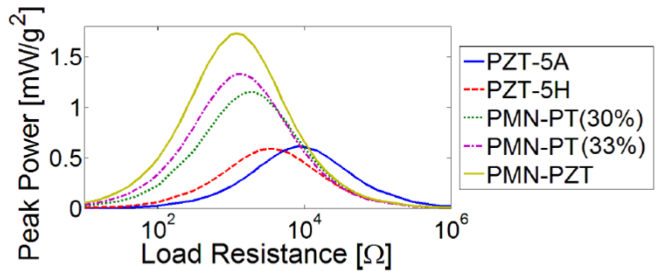


Ren *et al*, 2006

PMN-PT Micro Cantilever



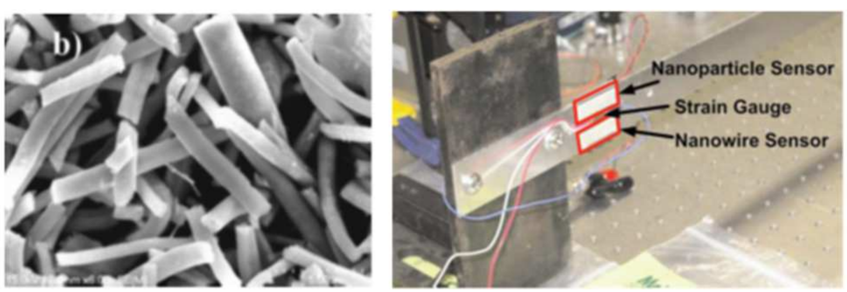
Mathers *et al*, 2009



Lead Zirconate Titanate	**Lead Magnesium Niobate-Lead Zirconate Titanate**
ρ=7500 kg/m^3	ρ=7000 kg/m^3
d_{31}=-200 pC/N	d_{31}=-2000 pC/N
High coupling	Very high coupling
Heavy, brittle	Heavy, very brittle

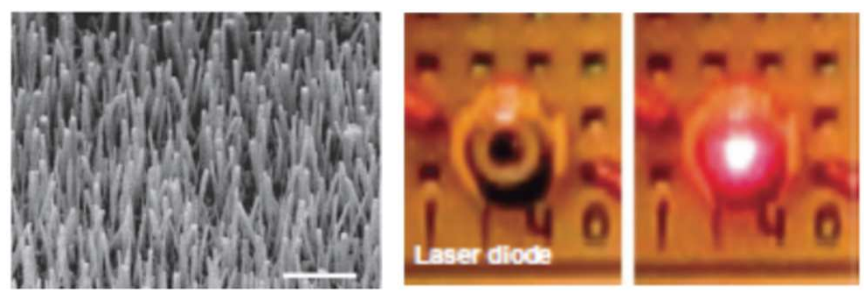
Piezoelectric Nanocomposites (nanowire, nanofiber)

Barium Titanate Nanocomposite Paint



Feenstra and Sodano, 2008

Single Crystal PZT Nanowire Array

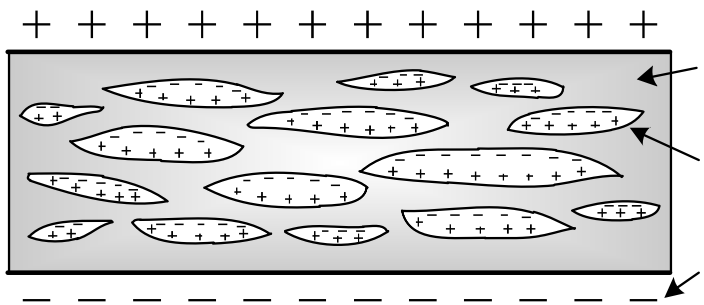


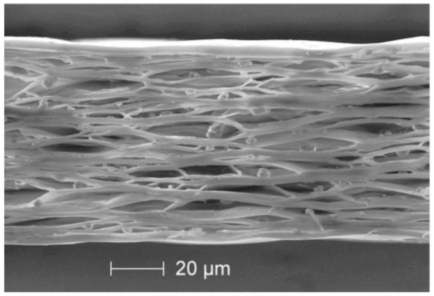
Xu *et al*, 2010

Part 5: My Current Research

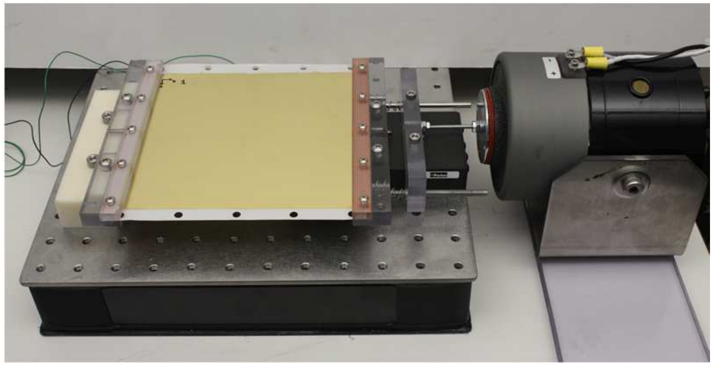
Piezoelectret Foam Energy Harvesting

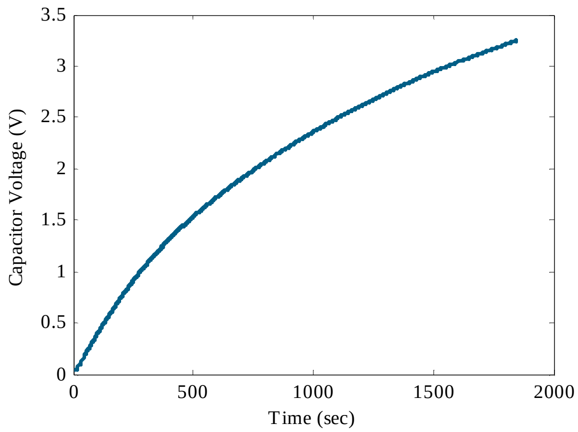
Piezoelectret foam is a cellular polymer electret material with internally charged voids that form "macroscopic" dipoles allowing piezoelectric behavior





Sessler and Hillenbrand, *Applied Physics Letters*, 1999

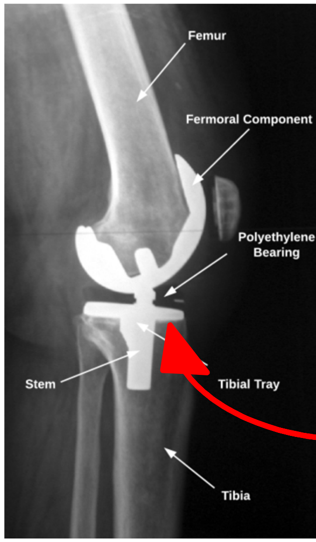


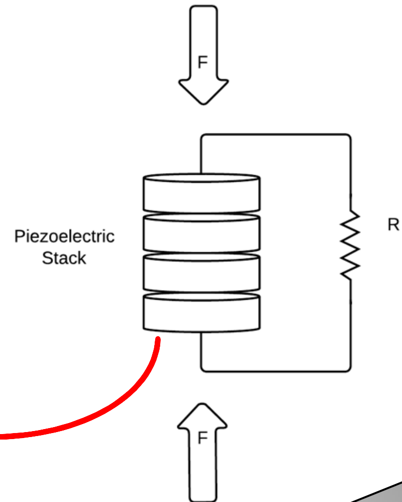


- Sample Size: 15.24 x 15.24 cm
- Simple bridge rectifier circuit used to charge 1mF capacitor

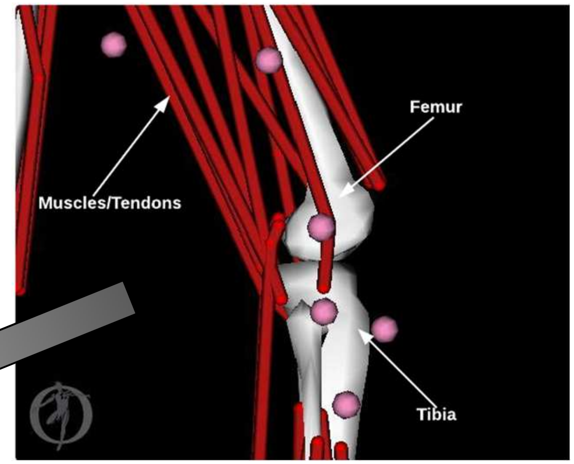
- 30 min of excitation results in a voltage of 3.24 V on the capacitor
- Average power output of 2.8 µW

Piezoelectric Sensor/Harvester for In-Vivo Monitoring of Total Knee Replacement Units

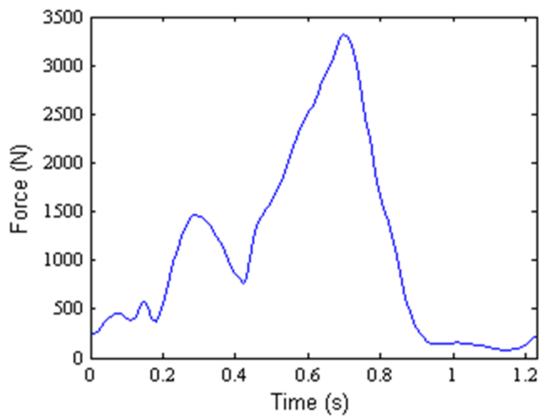


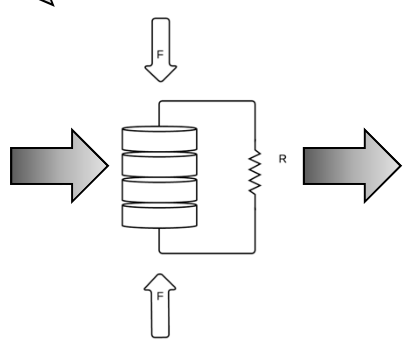


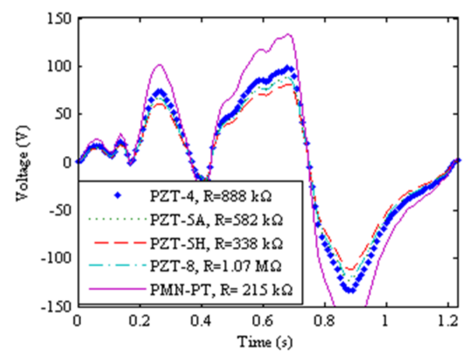
OpenSim Biomechanical Simulation Software (Stanford University)

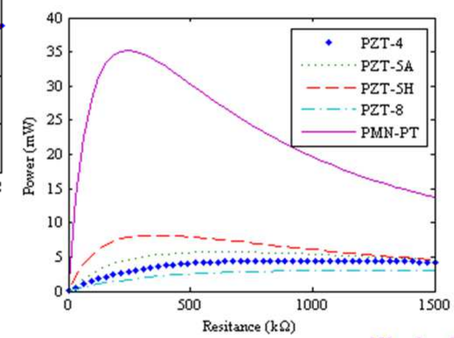


Simulated Load Profile









Summary

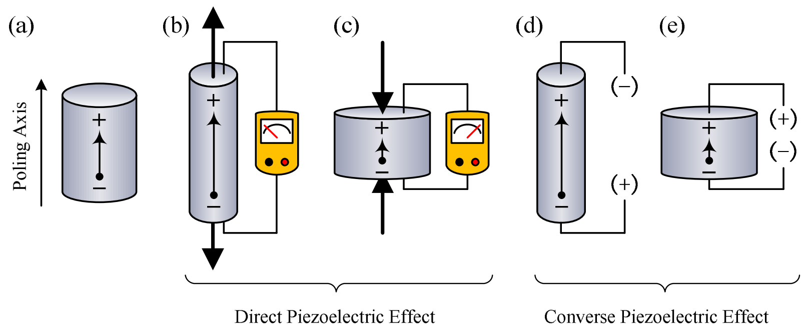
Piezoelectric energy harvesting aims to convert ambient vibration energy into useful electrical energy to:

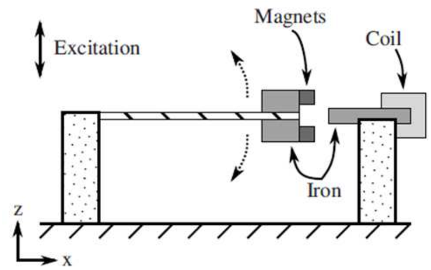
- Eliminate need for battery replacement and disposal
- Create autonomous, self-powered wireless sensors

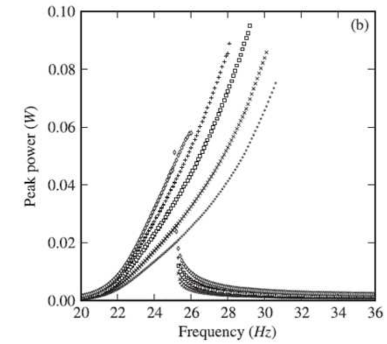
Current research trends include *Broadband* and *Nonlinear* harvesting, *Multifunctional* harvesting, *Multi-source* harvesting, and novel *Single-crystal* and *Nanocomposite* materials

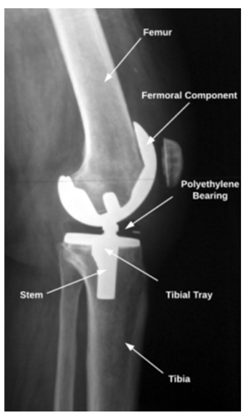
Some commercial devices available, but limited to linear, resonant harvesters which must be "tuned"

More research to be done to deal with time-varying and stochastic vibration inputs, and multifunctional/multi-source harvesting

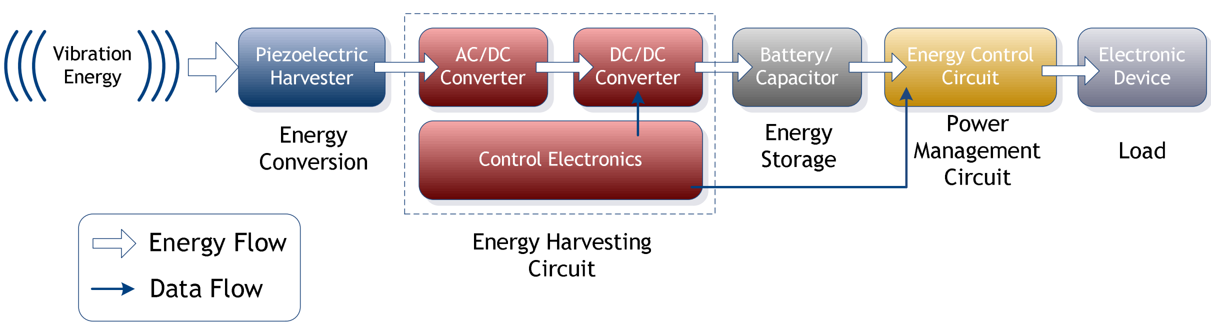

(a)
(b)
(c)
(d)
(e)
Poling Axis
(−)
(+)
(+)
(−)
Direct Piezoelectric Effect
Converse Piezoelectric Effect


Excitation
Magnets
Coil
Iron
z
x


(b)
Peak power (W)
Frequency (Hz)
0.10
0.08
0.06
0.04
0.02
0.00
20 22 24 26 28 30 32 34 36


Femur
Fermoral Component
Polyethylene Bearing
Stem
Tibial Tray
Tibia

THANK YOU


Vibration Energy
Piezoelectric Harvester
AC/DC Converter
DC/DC Converter
Control Electronics
Battery/ Capacitor
Energy Control Circuit
Electronic Device
Energy Conversion
Energy Storage
Power Management Circuit
Load
Energy Harvesting Circuit
Energy Flow
Data Flow