Piezoelectrics

Materials, Processing and Applications

S. Eswar Prasad,
Adjunct Professor, Department of Mechanical & Industrial Engineering,
Chairman, Piemades Inc,

Piemades, Inc.

Mechanical & Industrial Engineering
UNIVERSITY OF TORONTO

Presentation Outline

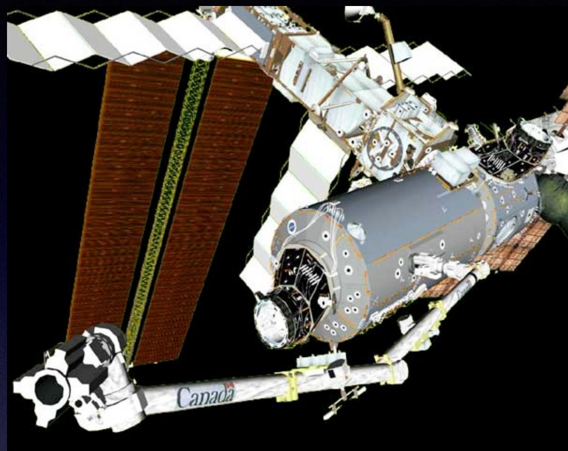
- **Piezoelectrics**

  Piezoelectric effect, materials, design Principles and Application Examples.

  (Power Harvesting)

https://www.youtube.com/watch?v=Bxo2TihSrNg

Application Areas



Aerospace

Precision Manufacturing

Flexible Robots

Micro Electromechanical Systems

Piezoelectric Effect

Piezoelectricity is the electric charge that accumulates in certain solid materials (such as crystals, certain ceramics, and biological matter such as bone, DNA and various proteins) in response to applied mechanical stress. The word piezoelectricity means electricity resulting from pressure.

Piezoelectric behaviour can be manifested in two distinct ways.

- ‘direct’ piezoelectric effect
- ‘converse’ piezoelectric effect

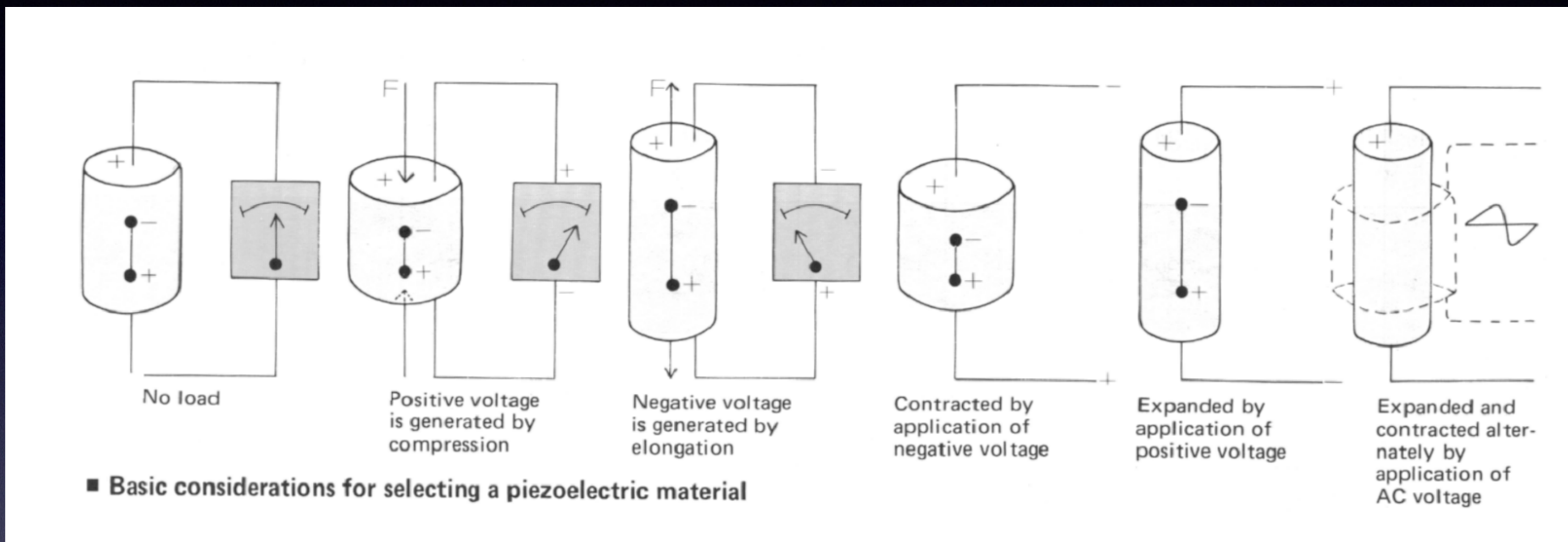
Direct Piezoelectric Effect

- 'Direct' piezoelectric effect occurs when a piezoelectric material becomes electrically charged when subjected to a mechanical stress.
- These devices can be used to detect strain, movement, force, pressure or vibration by developing appropriate electrical responses, as in the case of force and acoustic or ultrasonic sensors.

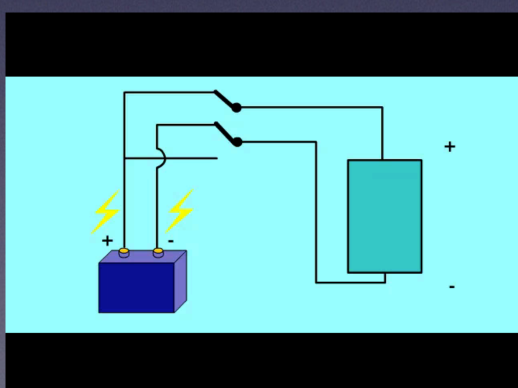
Converse Piezoelectric Effect

- ‘Converse’ piezoelectric effect occurs when the piezoelectric material becomes strained when placed in an electric field.
- This property can be used to generate strain, movement, force, pressure or vibration through the application of suitable electric field.

Piezoelectric Phenomena



■ **Basic considerations for selecting a piezoelectric material**



Piezoelectric Relations

Piezoelectricity involves the interaction between the electrical and mechanical behaviour of the medium, and the interaction can be described by linear relationships between these two.

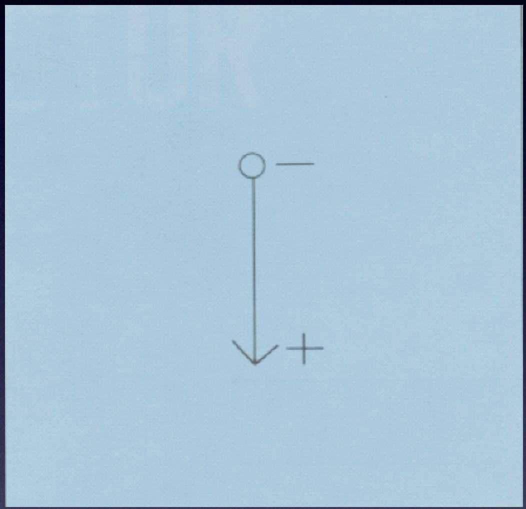
$$S = s^E T + dE$$

$$D = dT + \varepsilon^T E$$

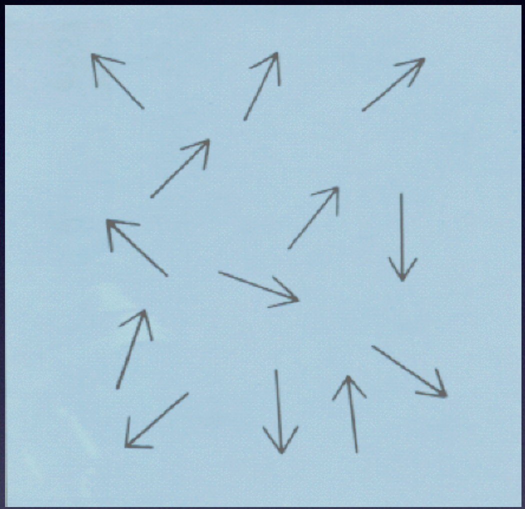
Piezoelectric Strain Constant d

- **When an electric field is applied to a piezoelectric, the material dimensions change in all three axes under stress-free conditions. The d constant also expresses the amount of charge developed relative to the stress applied along a specific axis.**

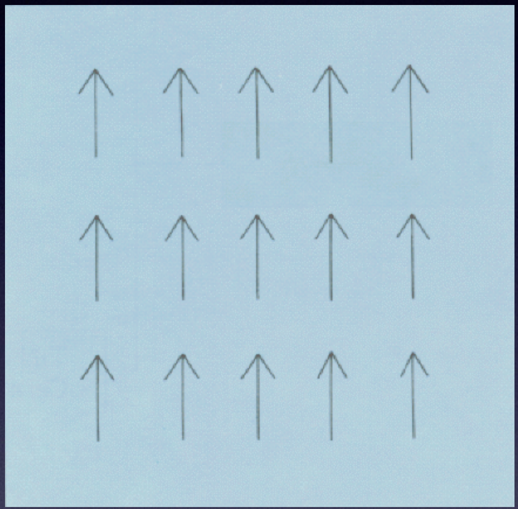
Polarization of Ceramics



Polarization in a single crystal of piezoelectric ceramics.



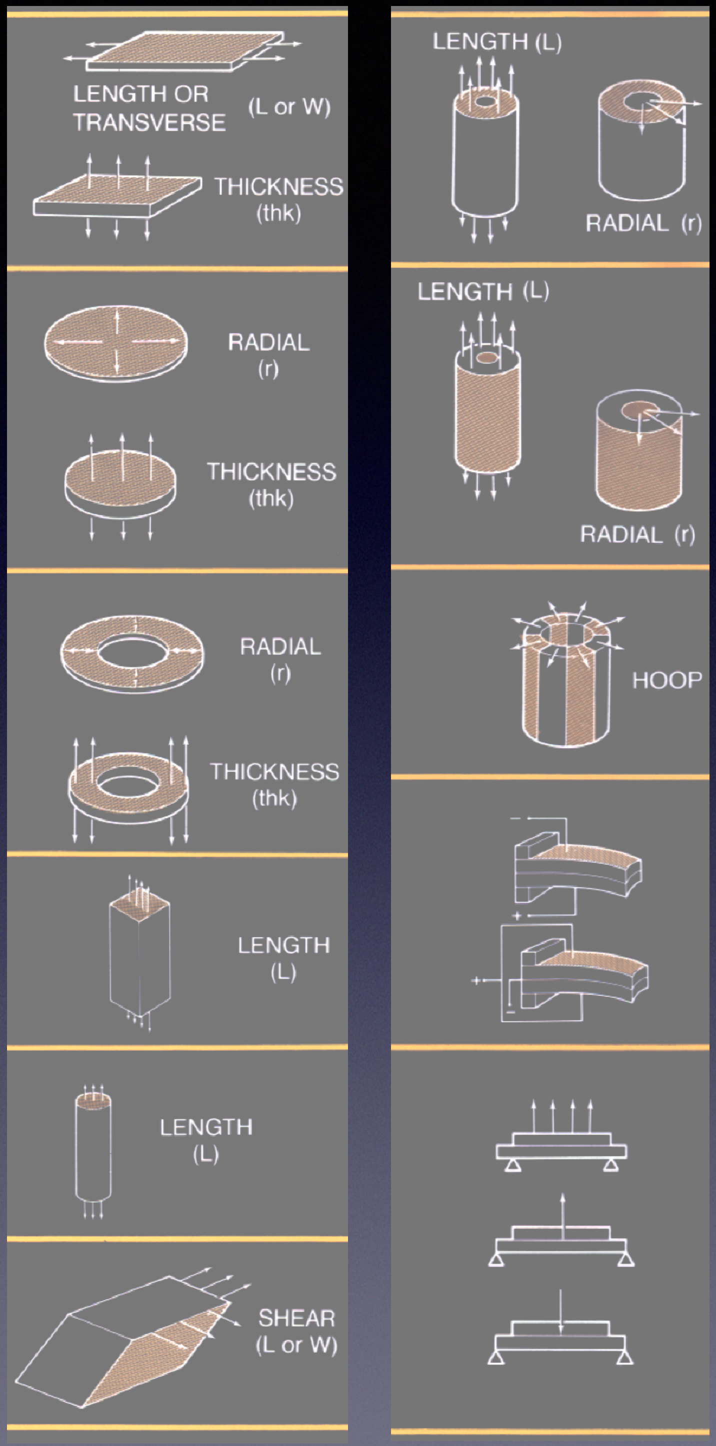
Piezoelectric ceramic - before polarization



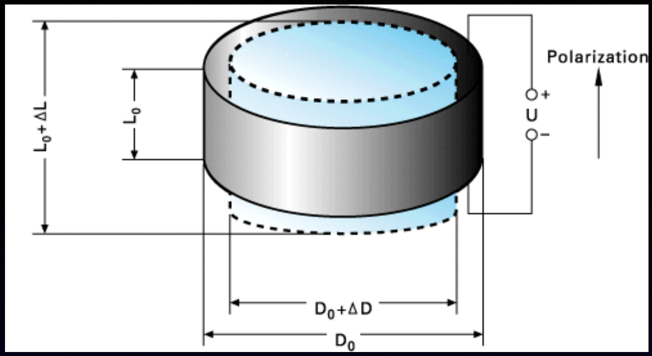
Piezoelectric ceramic - after polarization

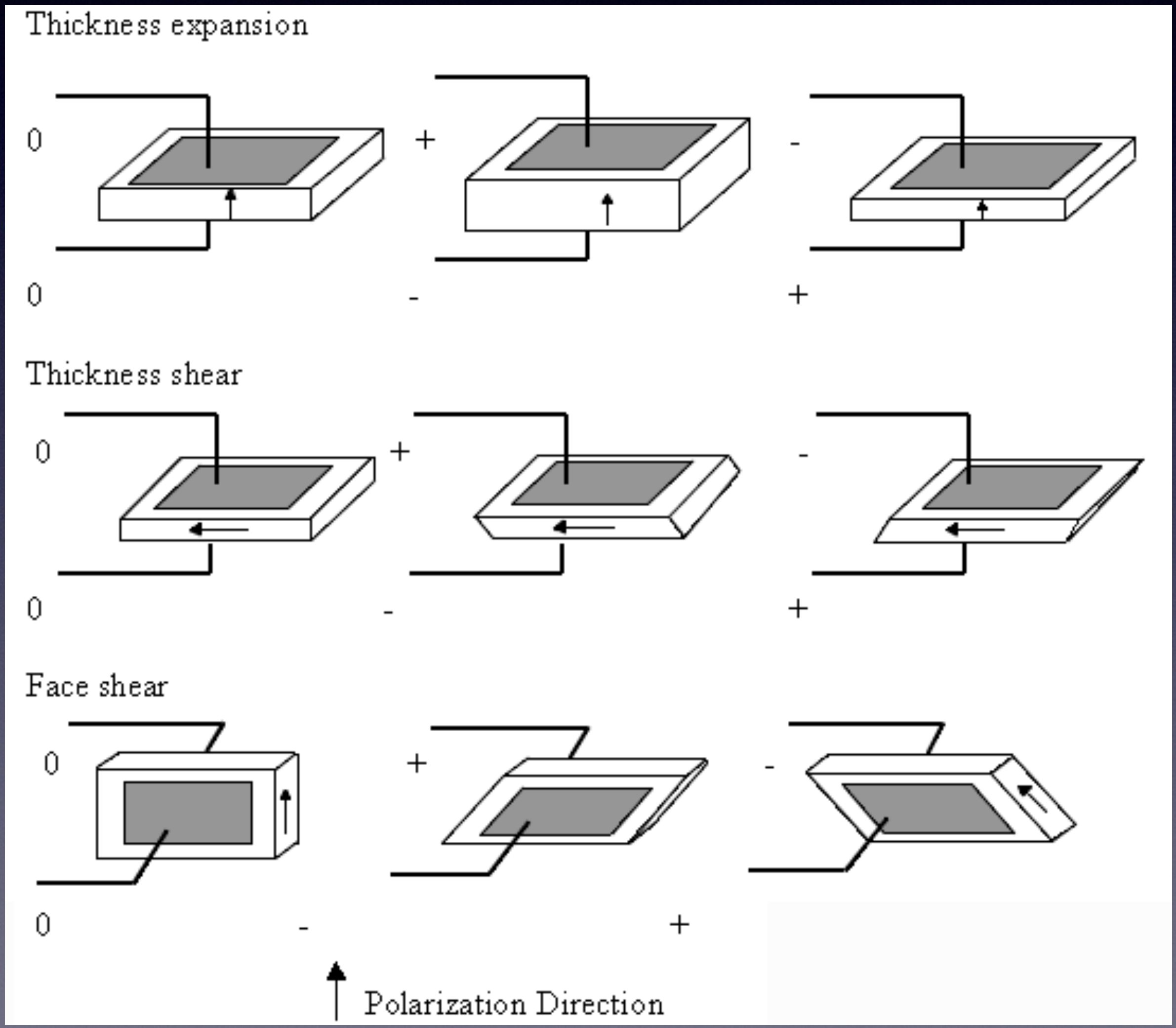
Morgan Electroceramics

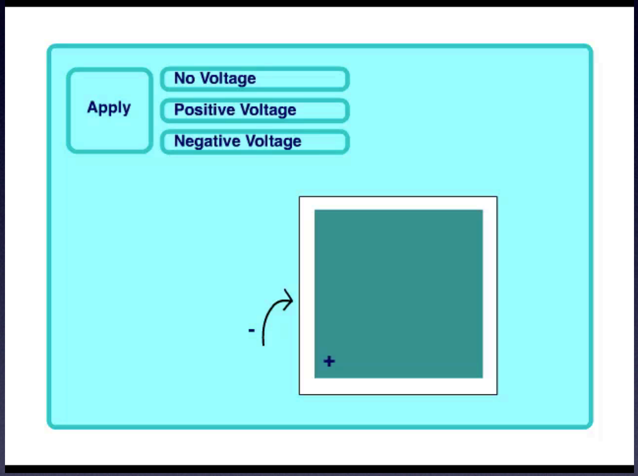
Modes of Vibration

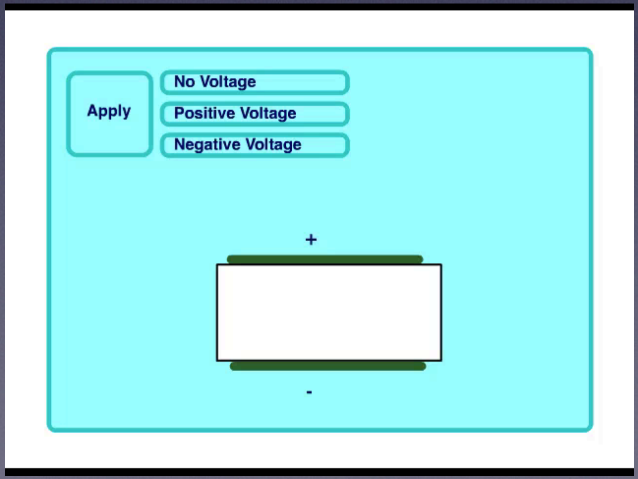


Modes of Vibration









Operation Modes

Relationship between the directions of P, D, T or P, S, E

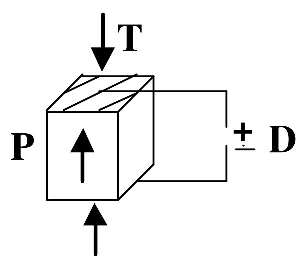
⇒ Various piezoelectric modes for applications.

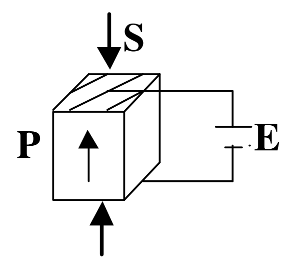
For piezo ceramics: **P = direction "3".**

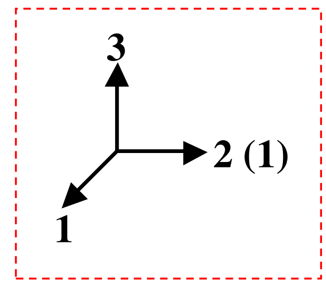
Longitudinal d_{33} mode:

$D_3 = d_{33}T_3$

$S_3 = d_{33}E_3$



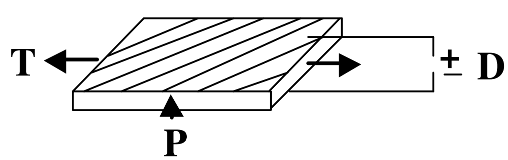


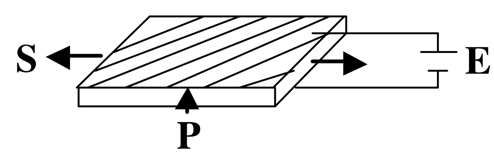


Transverse d_{31} mode:

$D_3 = d_{31}T_1$

$S_1 = d_{31}E_3$

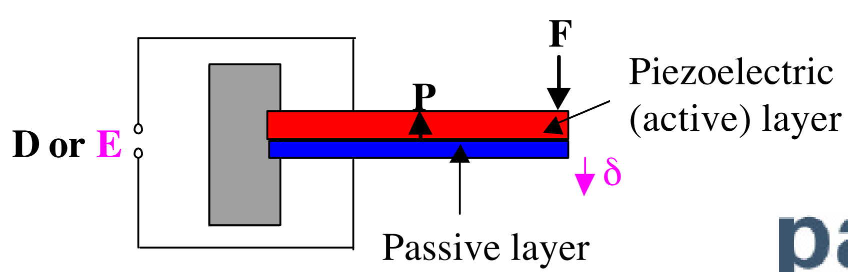




Bending-type d_{31} mode:

$D_3 \propto d_{31} \cdot F$ or $d_{31} \cdot p$

$\delta \propto d_{31}E_3$



Baomin Xu, 12/04/2003

parc Palo Alto Research Center

MODE OF OPERATION

- d_{33} mode

  Most common method for large force actuation and sensing

- d_{31} mode

  Provide better efficiencies for high displacement actuation and for sensing modes.

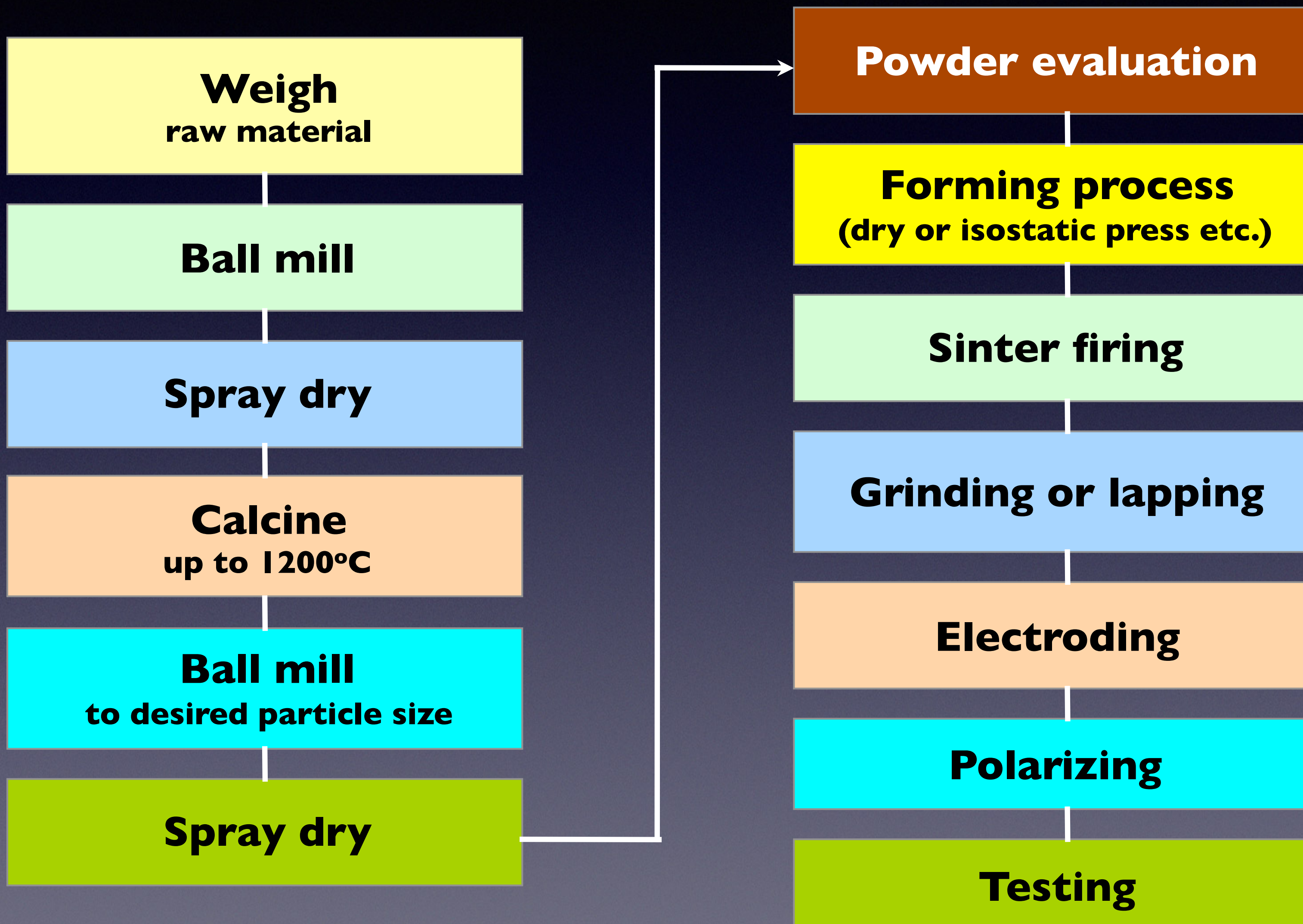
- d_{15}, d_{36} shear modes

  Provide higher efficiencies in ceramics and some single crystals.

Crystal, Ceramics and Polymers

Type	Materials
Single Crystals	Lead Magnesium Niobate (PMN)
Ceramics	Lead Zirconate Titanate (PZT) Lead Meta Niobate (LMN) Lead Titanate (LT) Lead Magnesium Niobate (PMN)
Polymers	Polyvinylene Di-fluoride
Composites	Ceramic-polymer Ceramic-glass

Manufacturing Process

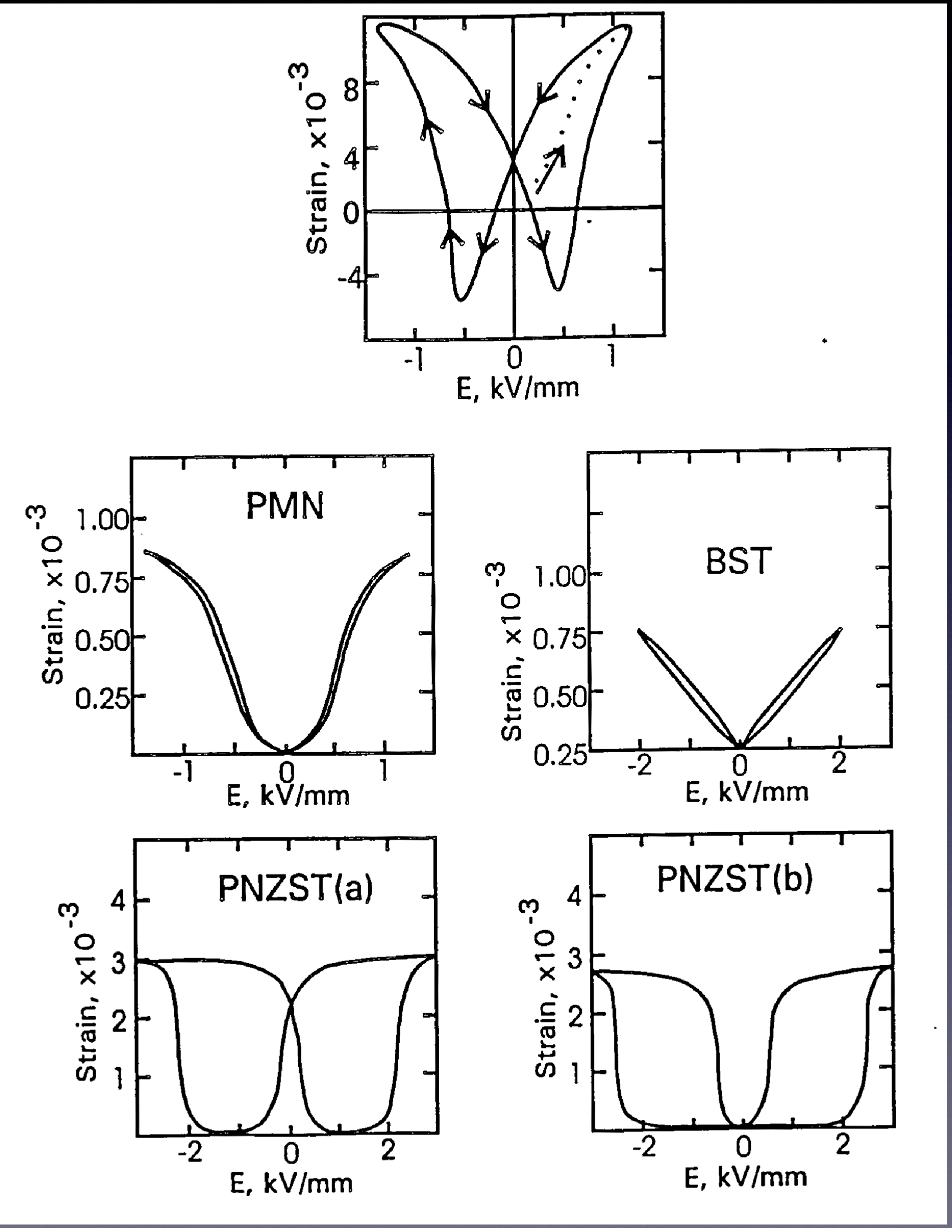


Longitudinal Strain vs. Field for Various Materials

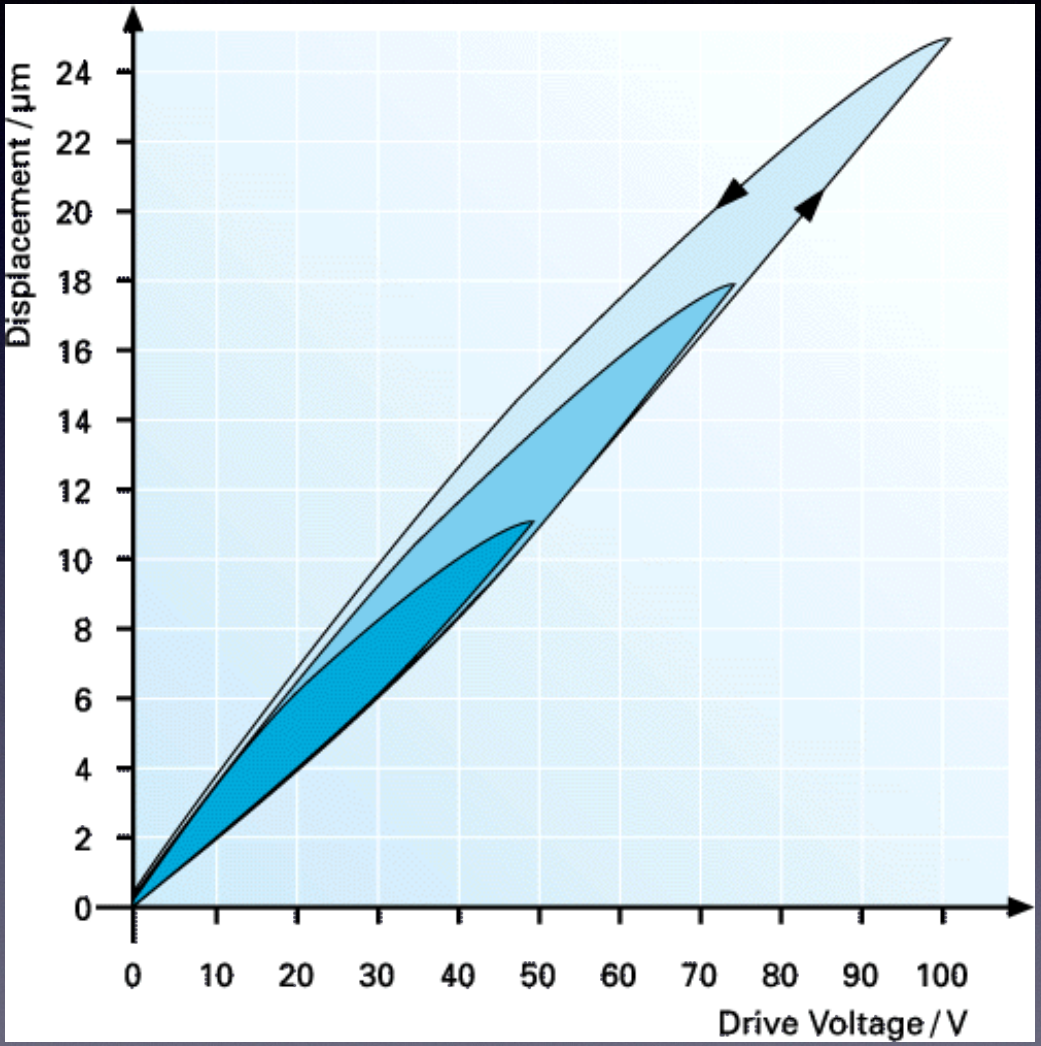
PZT Lead zirconate titanate

PMN Lead magnesium niobate
BST Barium strontium titanate

PNZST Modified PZT

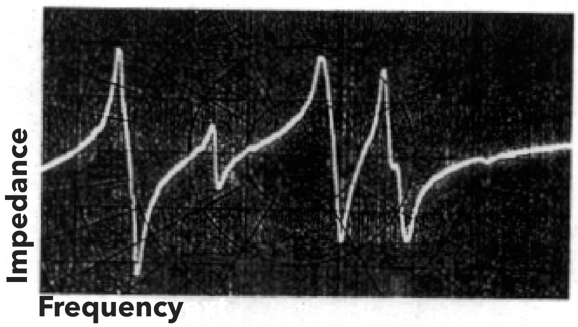


Hysteresis

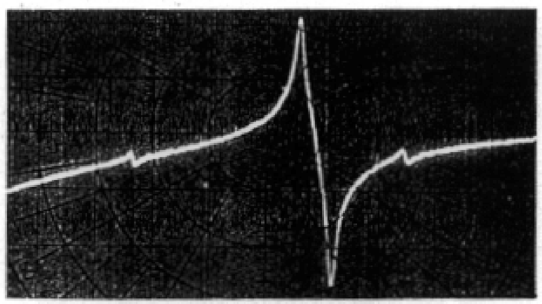


Displacement / µm
24
22
20
18
16
14
12
10
8
6
4
2
0
0
10
20
30
40
50
60
70
80
90
100
Drive Voltage / V

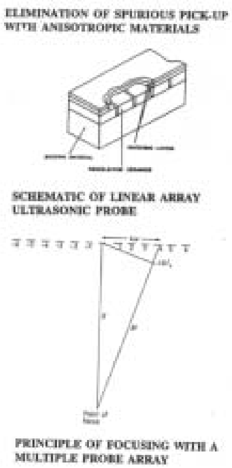
Decoupling of d_{33} and d_{31} modes

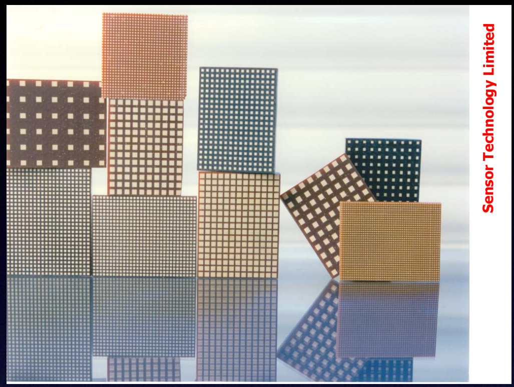


A. CONVENTIONAL MATERIALS
LEAD ZIRCONATE TITANATE CERAMICS



B. ANISOTROPIC MATERIALS
LEAD TITANATE CERAMICS





Anisotropic Materials: Lead Titanate

PRINCIPLES OF APPLICATION

1. Energy Conversion Mechanism

An externally applied electric field causes a change in the dielectric polarization in the material which in turn causes an elastic strain.

The generating action takes place when an elastic strain causes a change in the polarization that induces a charge on the electrodes.

PRINCIPLES OF APPLICATION

2. Transducer Operating Environment

The acoustic properties of the medium (air, water or ice) are very important in the design of transducers. Transducers must also withstand the severe effects of sea water, biological activity, hydrostatic pressure, and extreme temperature conditions.

PRINCIPLES OF APPLICATION

3. Conversion Criteria

The following are the general performance criteria for the transducers.

- Linearity. The output of the transducer is a linear function of the input.
- Reversibility. The transducer must convert energy in either direction.
- Passivity. All the output energy from the transducer is obtained from the input energy - electrical or acoustical.

Application of Piezoelectric Materials

- Electrical ➜ Mechanical Conversion
- Mechanical ➜ Electrical Conversion
- Electrical ➜ Mechanical ➜ Electrical

Application of Piezoelectric Materials

Mechanical ➜ Electrical Conversion

- Gas Igniters
- Microphones / Hydrophones
- Vibration Sensors
- Accelerometers
- Fuses (Munitions and Other)

Piezo Sensors -
Common Sensor Configurations

- Switches
- Impact Sensors (Sense input, time, location)

  Vending machines, Sports Scoring Musical Instruments, Printers
- Traffic
- Vibration

  Music, Machines (knock), bearings, flow
- Accelerometers
- Imaging

  Non Destructive Testing, Ranging
- Microphones

  Hydrophone

APPLICATIONS - DIAGNOSTIC ULTRASOUND

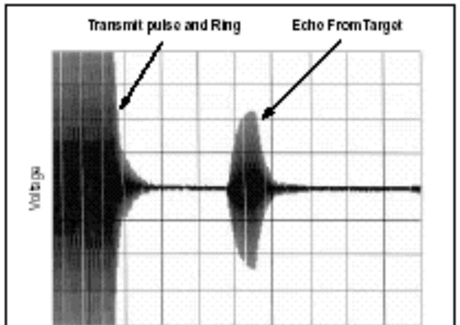


Figure 5: Transmit ring example

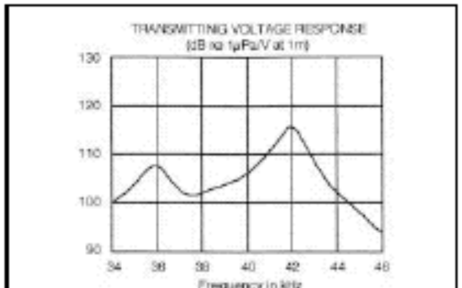
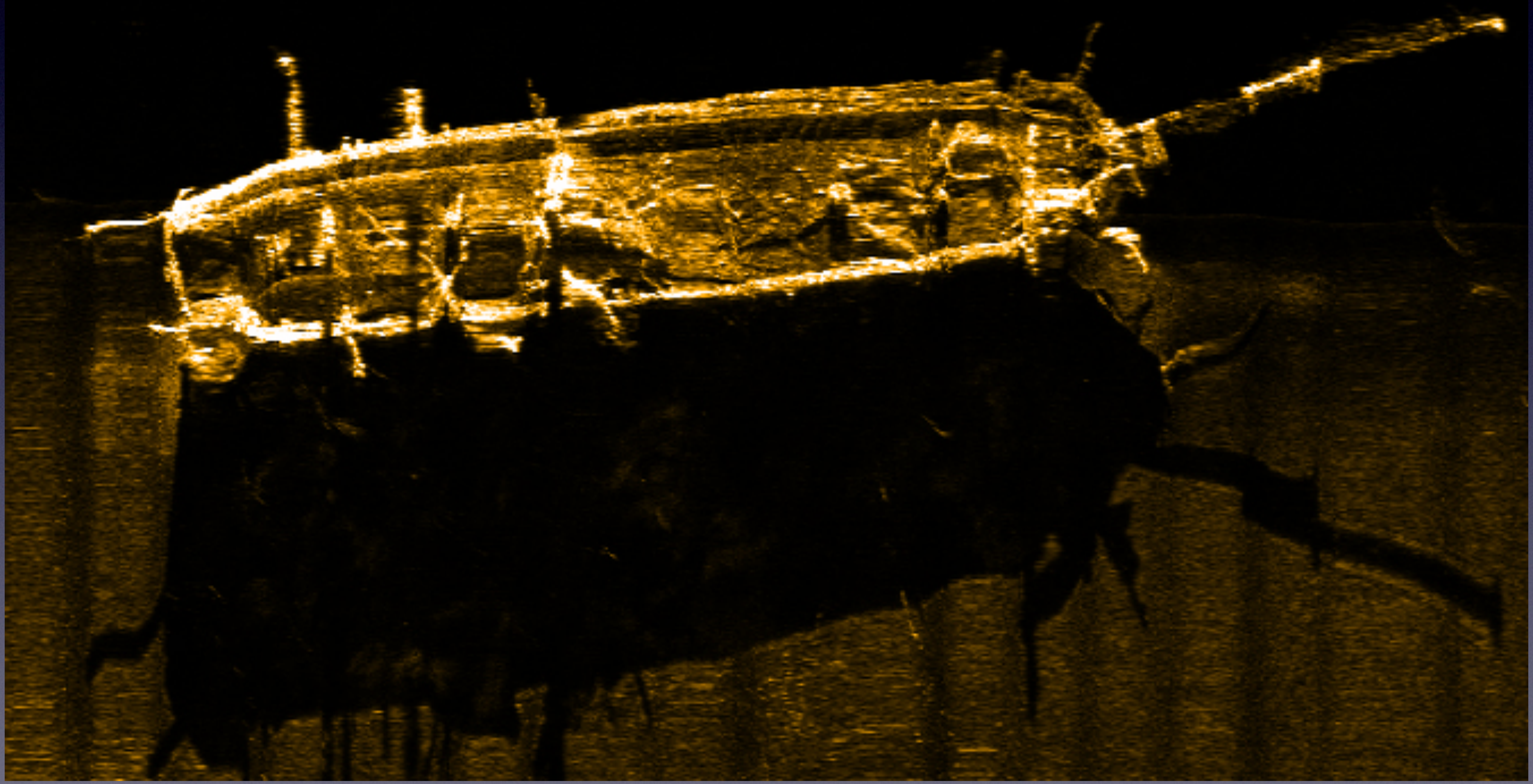


Figure 6: Transmitting response showing adjacent responses

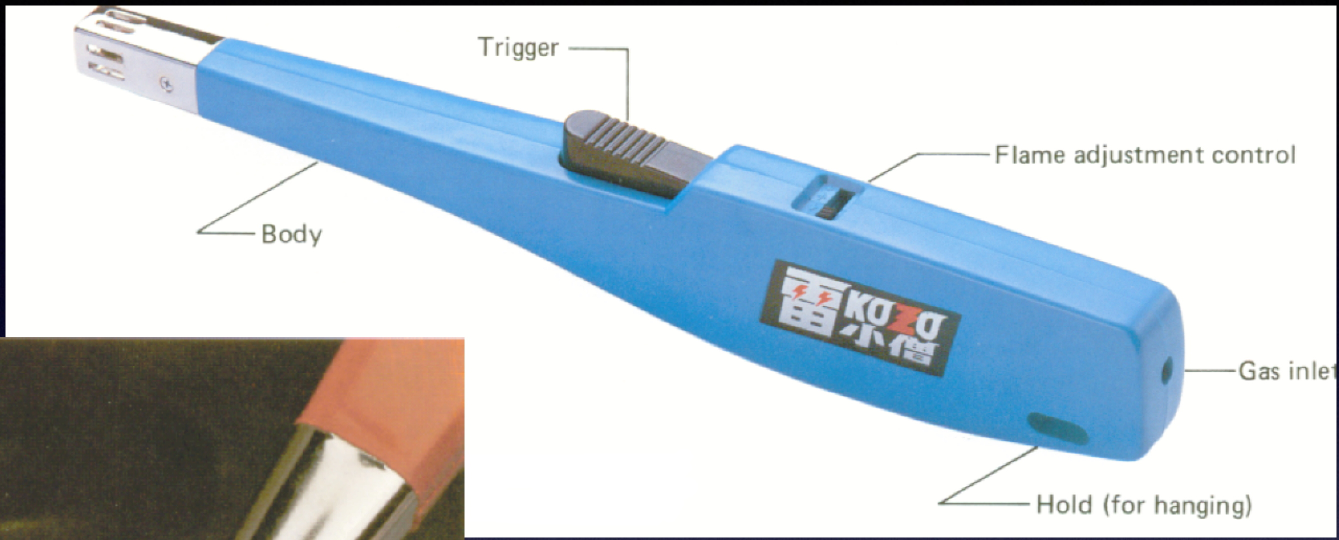
Sonar Image of Franklin Ship



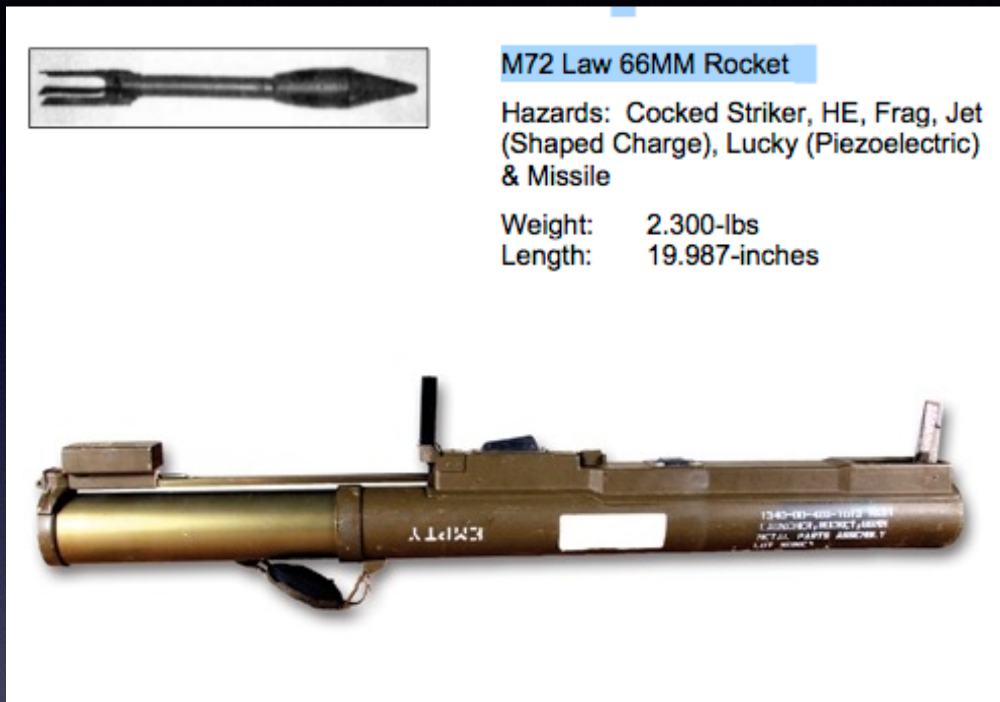
Parks Canada 2015

Surveillance - Dipping Sonar
Marine Mammal Communications

APPLICATIONS - PIEZOELECTRIC IGNITERS



Ballistics Sensors

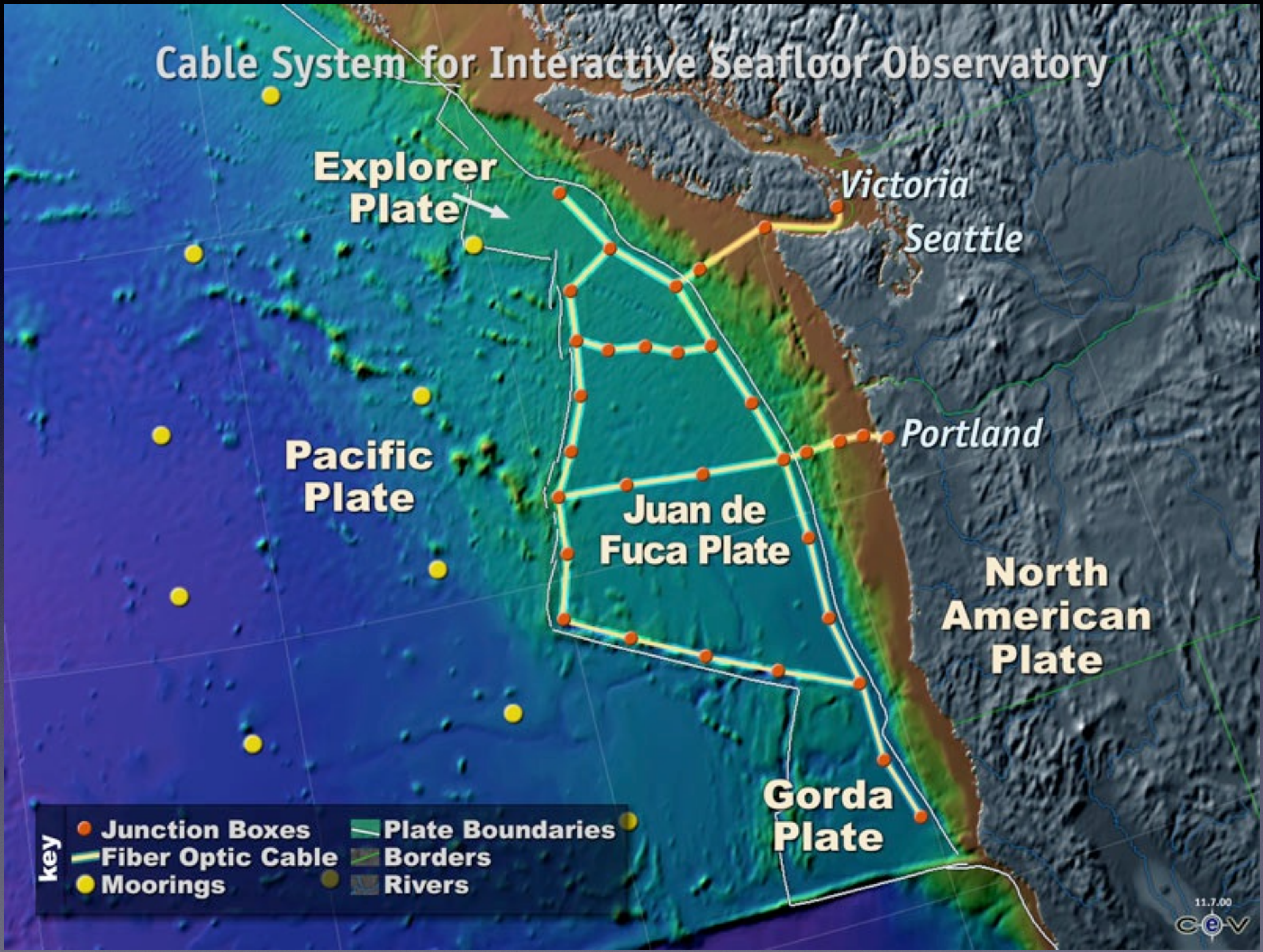

M72 Law 66MM Rocket

Hazards: Cocked Striker, HE, Frag, Jet (Shaped Charge), Lucky (Piezoelectric) & Missile

Weight: 2.300-lbs
Length: 19.987-inches

M72 Law 66 mm Rocket
MK118 Antitank
M371 90mm
M456 105 mm

Neptune Sea Floor Observatory

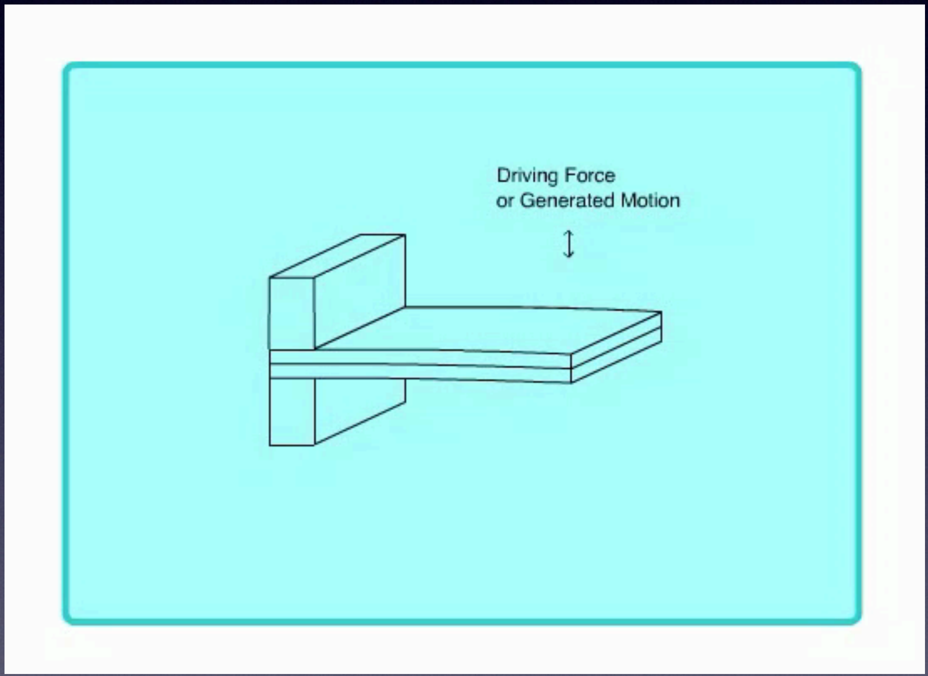


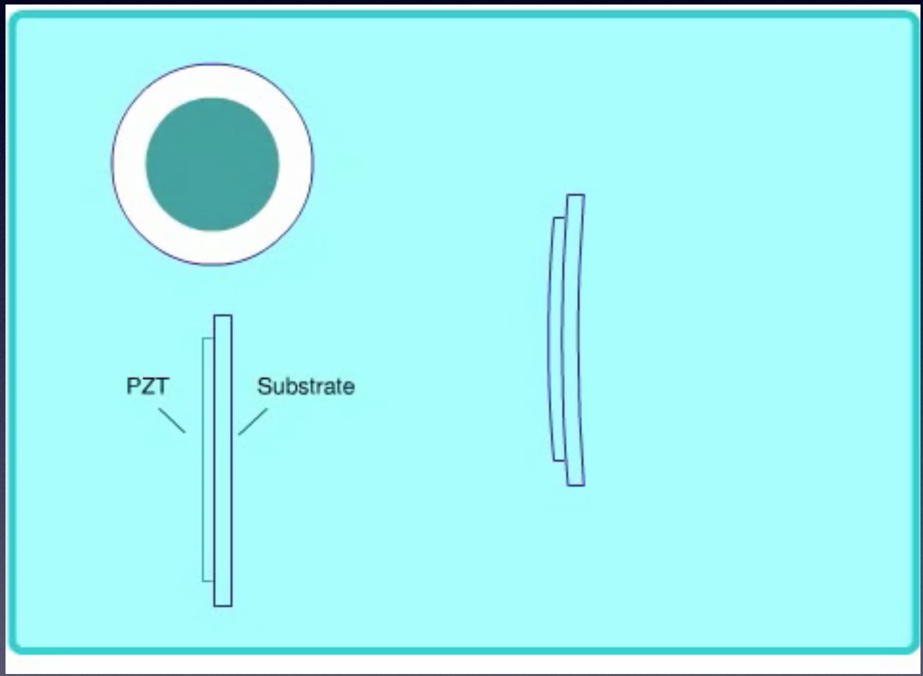
Basic Design of a Piezo Sensor

Types of effects:

Transverse Effect
Longitudinal Effect
Shear Effect
Hydrostatic Effect

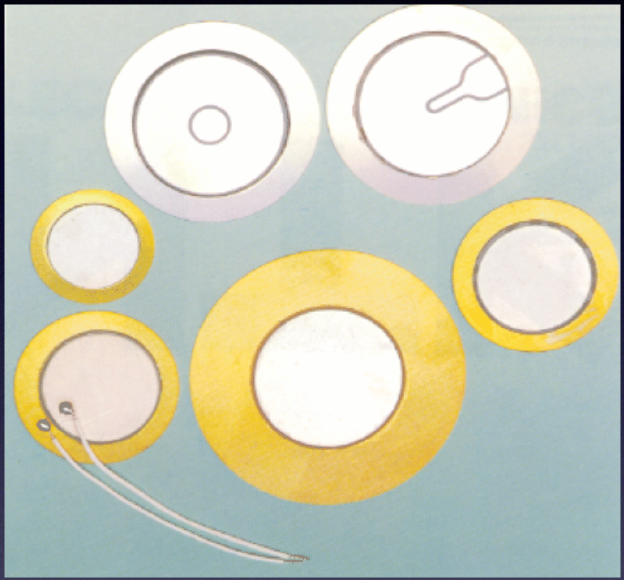
Application of Piezoelectric Materials - Electrical ➜ Mechanical Conversion





Bimorph or Flexmorph | **Unimorph or Monomorph**

Applications - Piezoelectric Audiotone Transducers



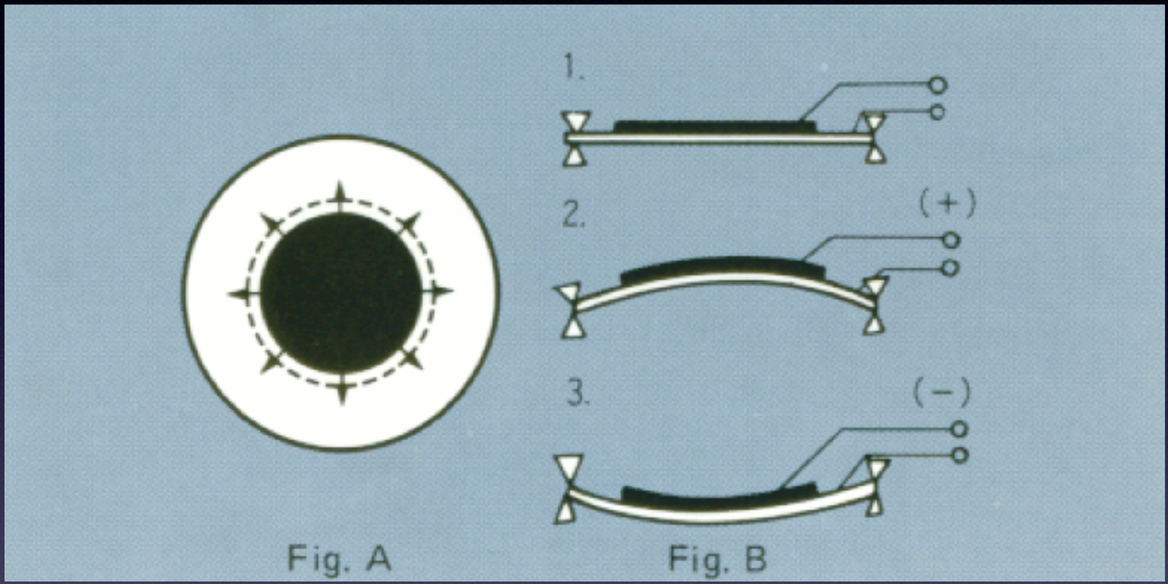


Figure A. Layered structure with ceramic bonded to metal diaphragm. Radial mode of vibration produces a bending effect.

Figure B. Alternating voltage produces convex and concave distortions in the diaphragm. Displacement of the diaphragm is in the order of microns.

Basic Hydrophone Design

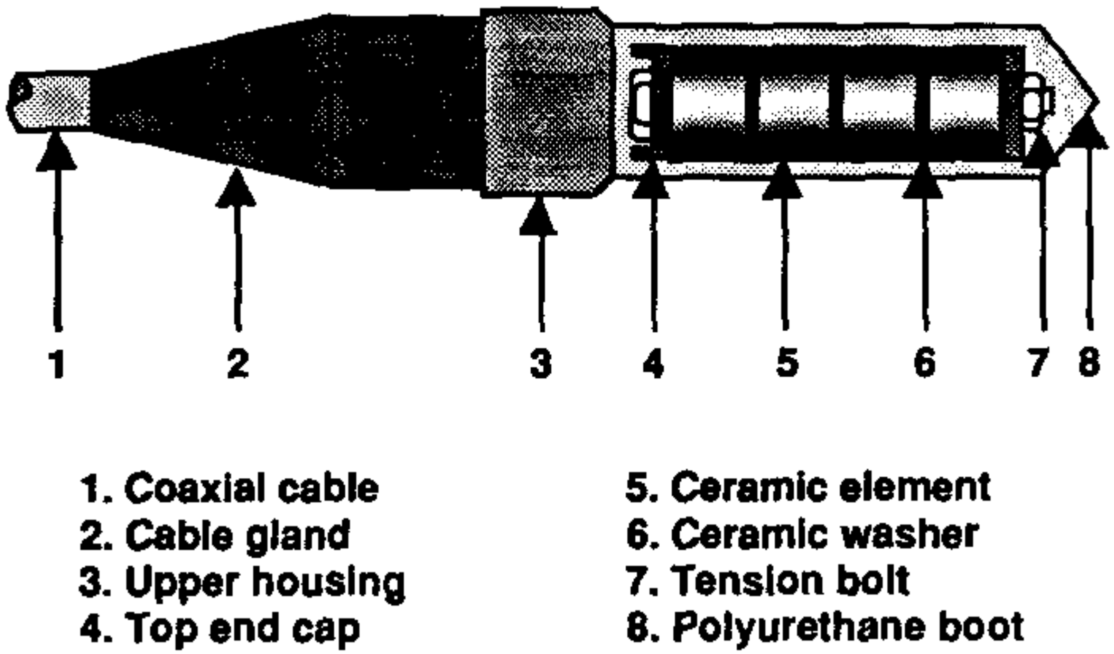
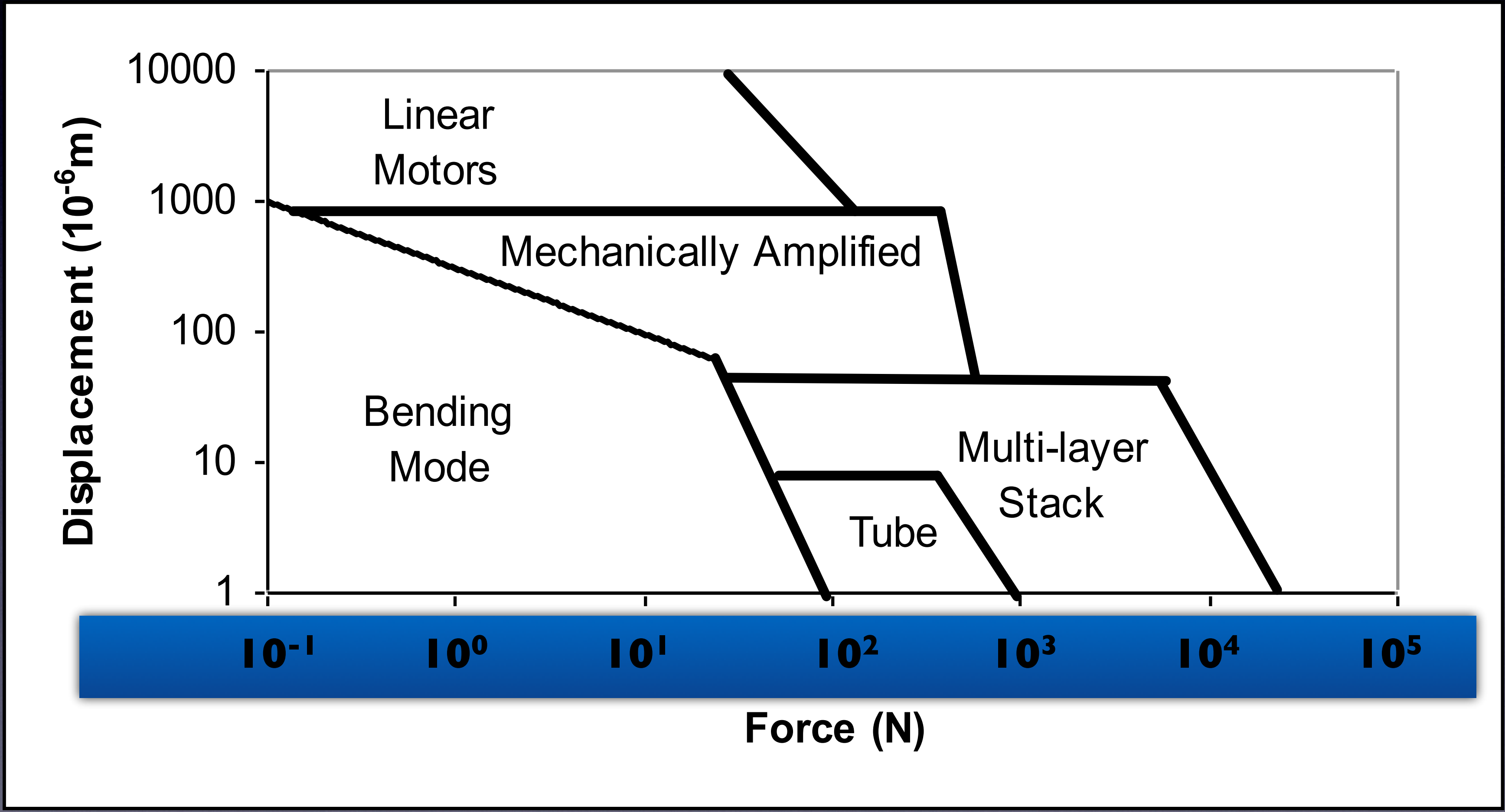


Figure 1: Schematic of a BM024 cylindrical hydrophone

An end capped cylinder Hydrophone for underwater sound detection
Jones, Prasad and Kavanaugh, Department of National Defence Report, 1992.

COMPARISON OF TYPES ACTUATORS



Application of Piezoelectrics to Power Harvesting

What is Power Harvesting

The process of extracting energy from the environment or from a surrounding system and converting it to useable electrical energy.

Why Power Harvesting ?

- Operation in remote locations
- Reduction in operating costs and service requirements

Why do we need power harvesting ?

- The concept of “embedded” sensing can not be fully realized if the systems will require access to AC power or batteries that have to be periodically replaced. There is a need to harvest and store ambient sources of energy in an effort to make these embedded systems autonomous.
- Wired sensors are impractical in applications involving moving structures such as turbine blades. Batteries of all types have been considered and are a weak link in any system, due to their frequency of maintenance or periodic replacement costs. Energy harvesting systems will also enable applications in remote areas.

Why do we need power harvesting ?

Technology Shifts

- older - periodic maintenance and qualitative inspection procedures.
- new - automated and quantifiable damage assessment processes

Benefits

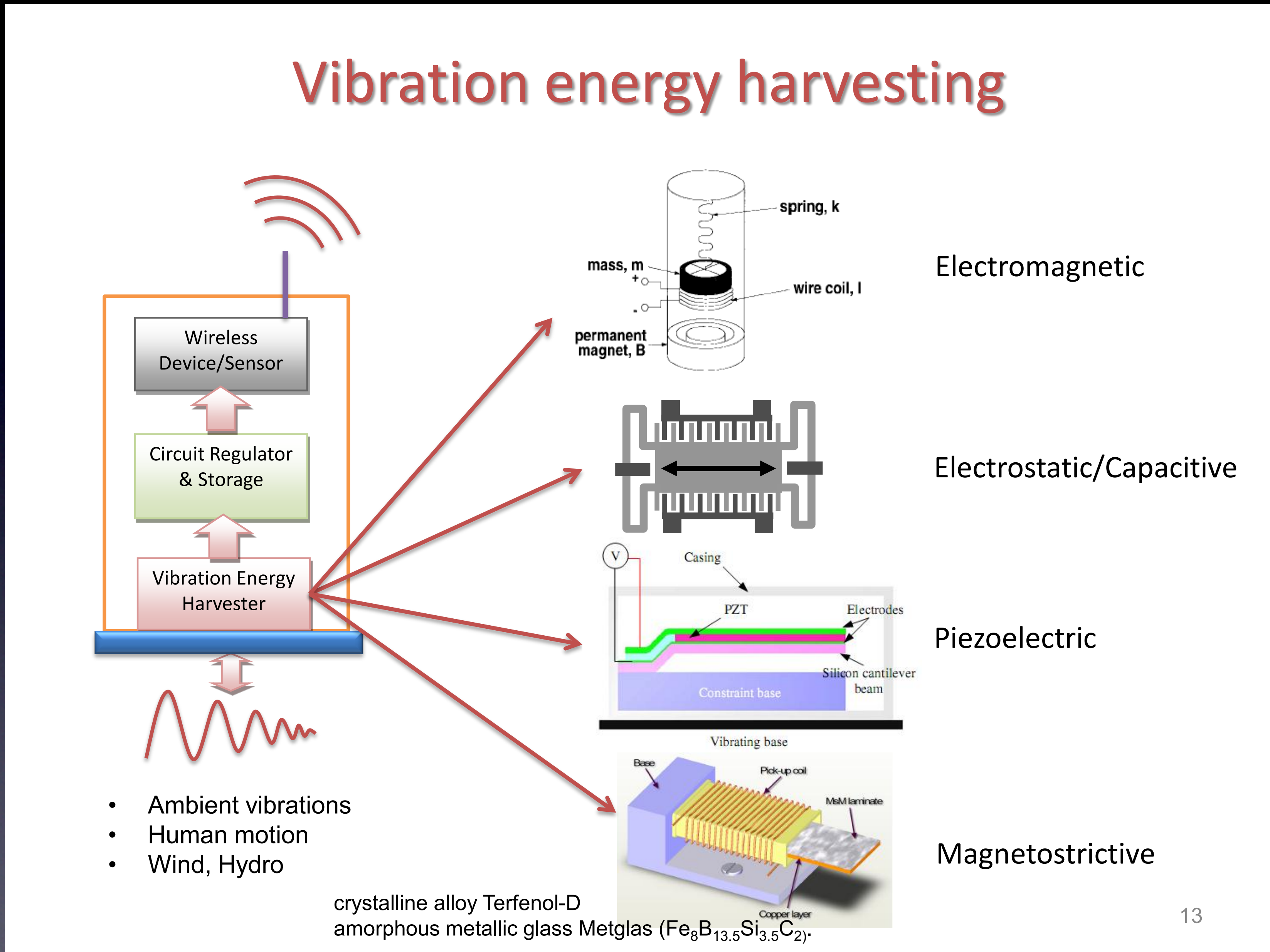
- early detection of potential failures
- possibility of embedding these networks in the infrastructure

Drivers for Power Harvester Technology

- Civil structures
- Border security
- Defence
- Communications

Drivers for Power Harvesting

- **Wireless Sensor Networks**
- **Tire pressure monitoring**
- **Enable continuous monitoring for extended periods**
- **Condition Based Maintenance**
  Diagnostics in industrial power generation, processing plants, assembly lines, Machinery health monitoring
- **Monitoring environments of buildings and vehicles**
  Adjusting lights & temperatures appropriate to occupancy Reduce energy consumption & increase productivity Electrical "demand response" systems
- **Agricultural / Landscaping water use**



F. Cottone, 2011

Piezoelectric properties of various PZT compositions

Property	Material			
	PZT-8	**PZT-4**	**PZT-5A**	**PZT-5H**
d_{33} [pC/N]	225	289	374	593
g_{33} [mV-m/N]	25.4	26.1	24.8	19.7
d_{33}-g_{33}	***5,715***	***7,543***	***9,275***	***11,682***
d_{31} [pC/N]	-97	-123	-171	-274
g_{31} [mV-m/N]	-10.9	-11.1	-11.4	-9.11
d_{31}-g_{31}	***1,057***	***1,365***	***1,949***	***2,496***
d_{15} [pC/N]	330	496	584	741
g_{15} [mV-m/N]	28.9	39.4	38.2	26.8
d_{15}-g_{15}	***9,537***	***19,542***	***22,309***	***19,859***

Characterization of shear mode piezoelectric energy harvesters

Present Harvester Modalities

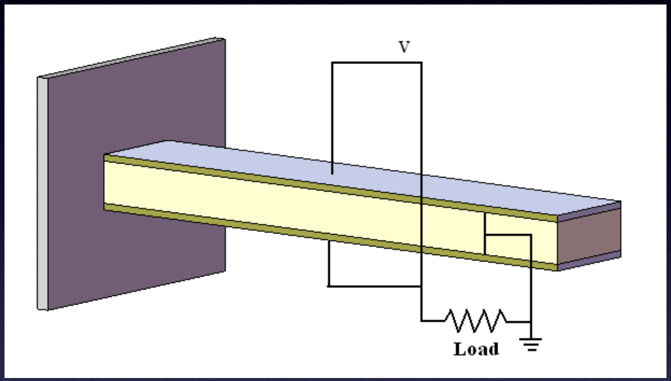
- Resonant harvesters
- Impulse harvesters

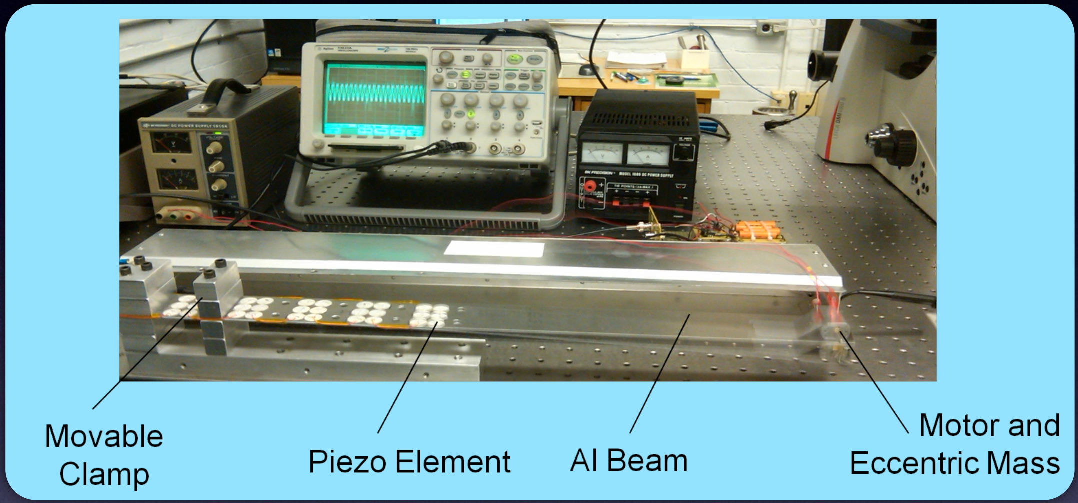
Application of Piezoelectric Power Harvesting

Resonant Harvester

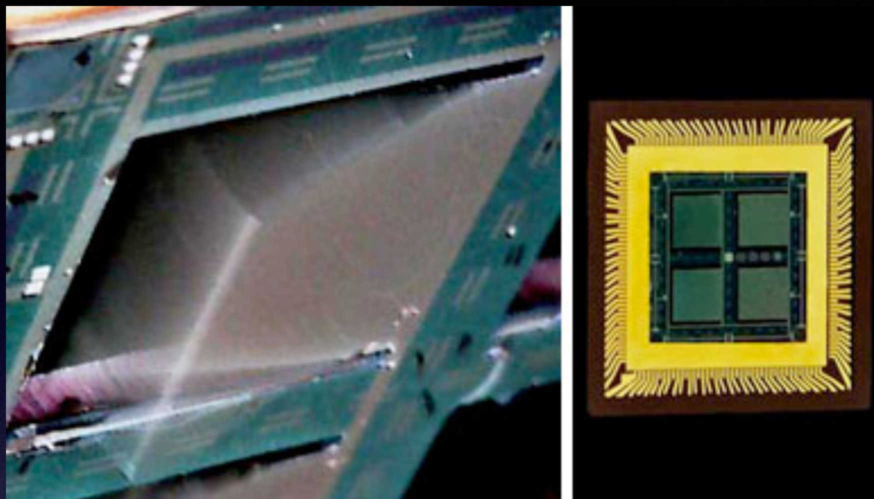
- Cantilever Aluminum beam with PZT piezoelectric elements on top and bottom surfaces
- Beam driven at resonant frequency
- Power dissipated through a resistive load
- Different beam lengths and PZT area ratios for optimization

Application of Piezoelectric Power Harvesting





Electric Cars and Power Harvesting



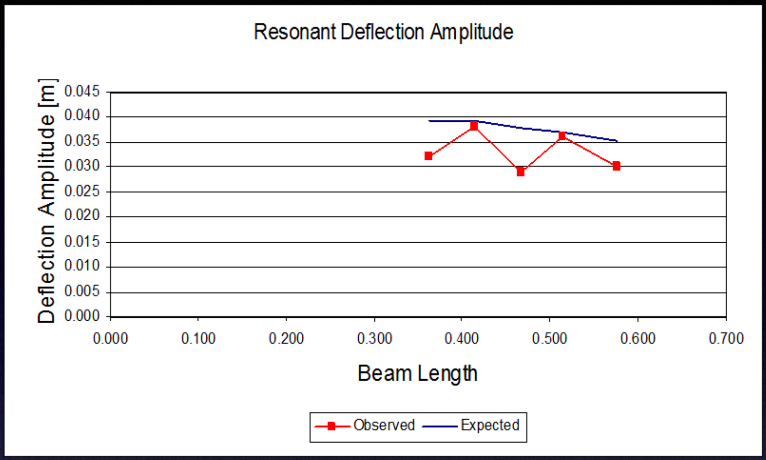
- The battery that generates the power for the sensors is a tiny sheet of piezoelectric material that makes electricity when mounted on a shock-resistant base when it is flexed.

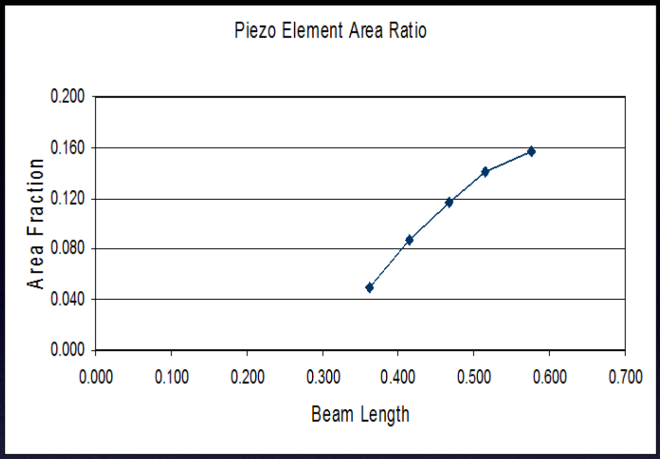
- Vibrations created by things like the wheel of a car rolling (same concept can be applied to a clothes dryer in homes),

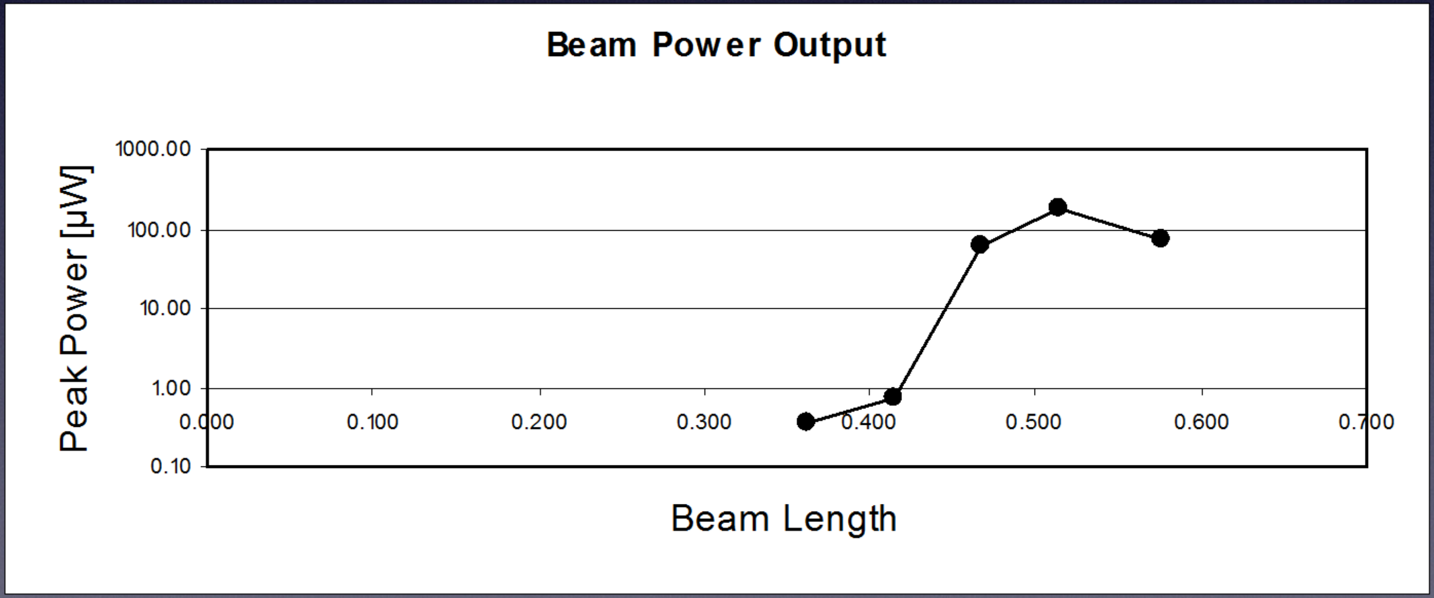
- Current is generated in a thin-film battery in the system.
- The prototype device about the size of a quarter generates up to 200 microwatts.

Cornell University and MicroGen

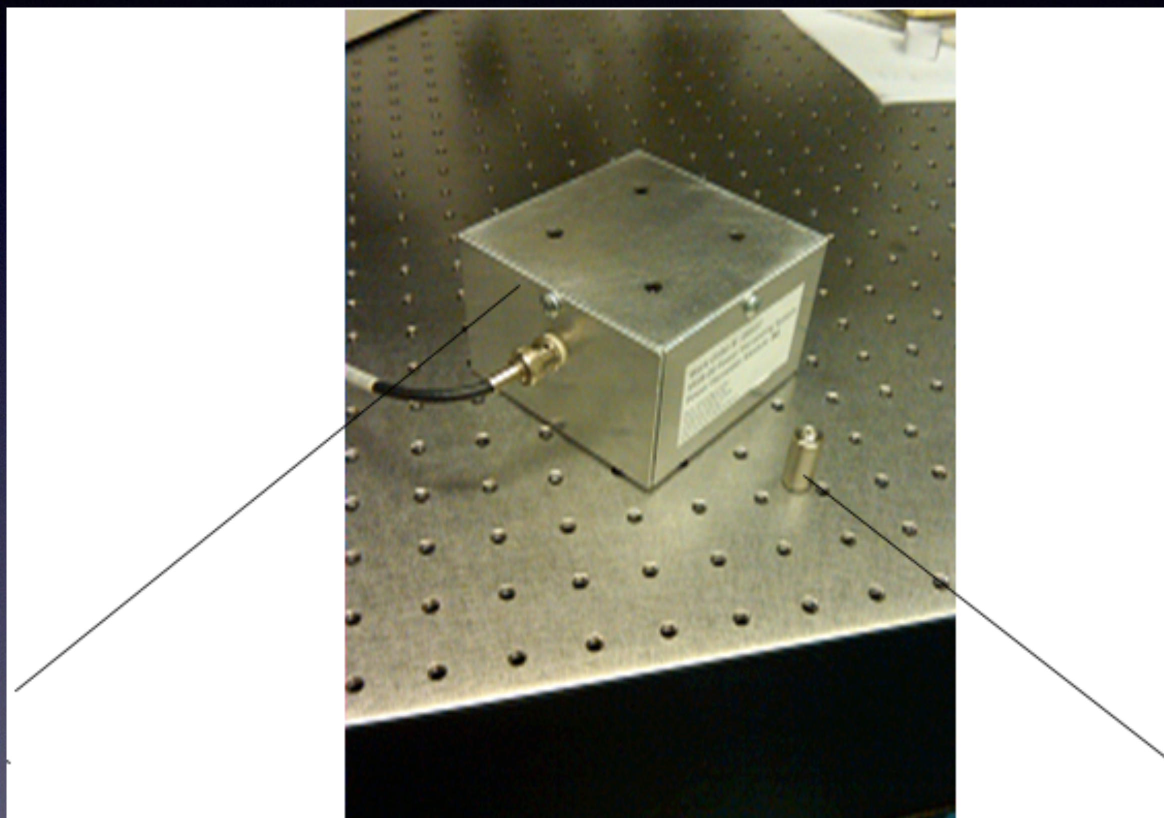
Application of Piezoelectrics to Power Harvesting



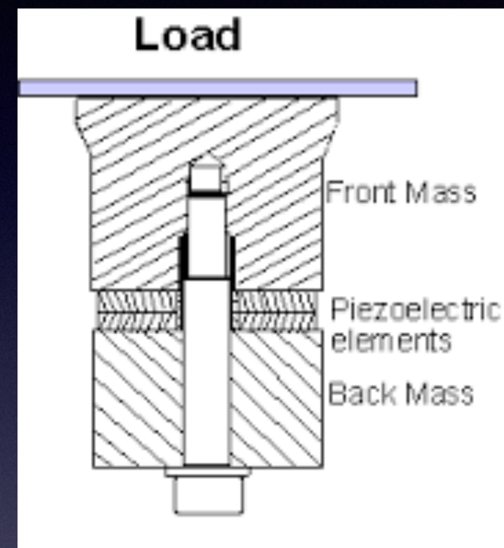




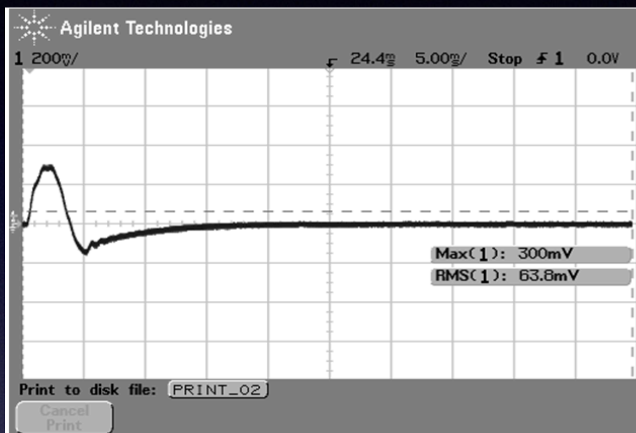
Impulse
Harvester



Steel
Test Mass

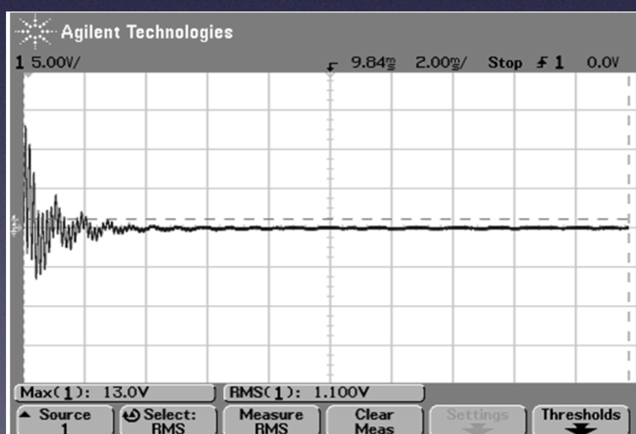


Application of Piezoelectrics to Power Harvesting



Peak Power:
3.6 x 10^{-7} W

Avg. Power
Per Pulse:
6.2 x 10^{-9} W



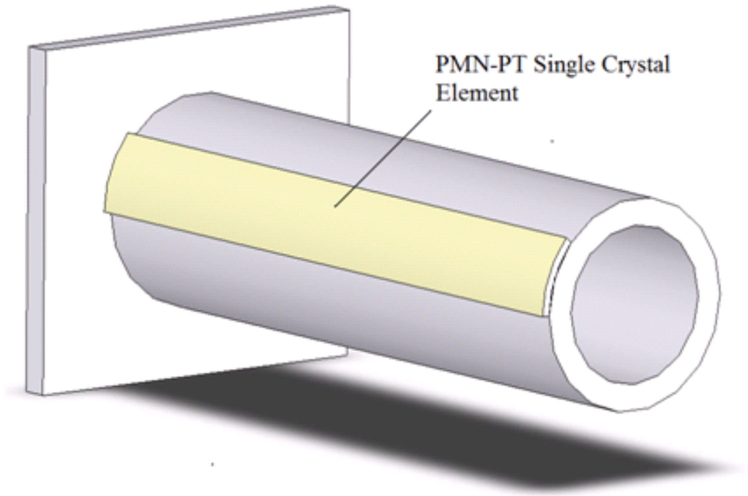
Peak Power:
1.7 x 10^{-2} W

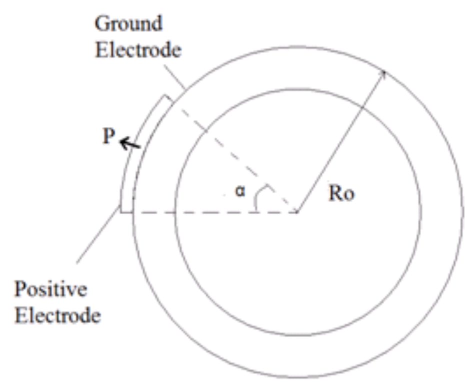
Avg. Power
Per Pulse:
4.30 x 10^{-4} W

Peak power dissipation through a 8.5 kΩ resistive load

Torsion harvester

- **-36 shear mode harvester**



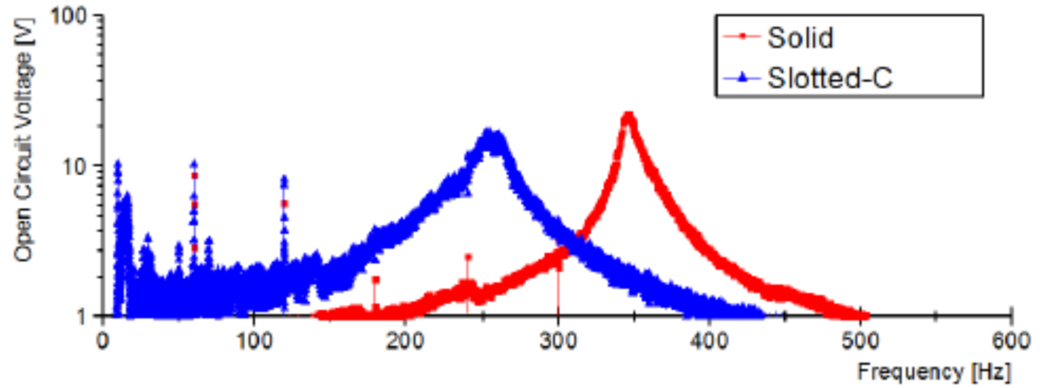


$$V = \frac{\omega e_{36} R_o^2 t_p \Phi_l \alpha}{t_p + \omega \varepsilon_{33}^T R_o l \alpha R} R$$

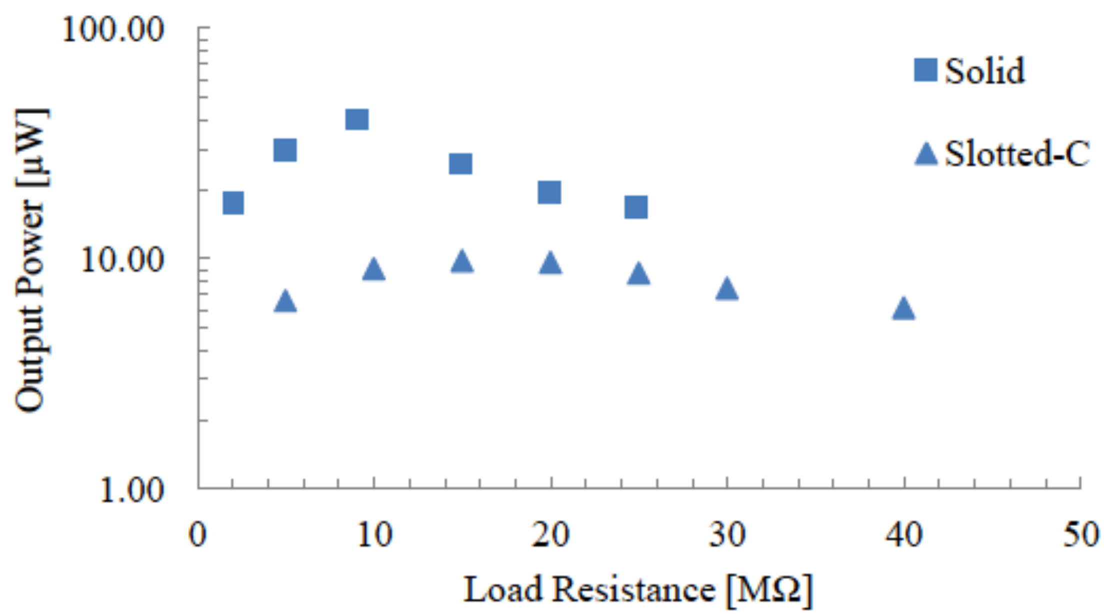
Piezoceramic shear mode

Piezoelectric properties of common ceramics:

Mode	Property	Material				
		PZT-8 Type III	PZT-4 Type I	PZT-5A Type II	PZT-5H Type VI	PMN-PT Single Crystal
Longitudinal	d_{33} [pC/N]	225	289	374	593	2000 [a]
	g_{33} [mV-m/N]	25.4	26.1	24.8	19.7	34.8
	d_{33}·g_{33}	***5,715***	***7,543***	***9,275***	***11,682***	***69,504***
Transverse	d_{31} [pC/N]	-97	-123	-171	-274	-1750 [b]
	g_{31} [mV-m/N]	-10.9	-11.1	-11.4	-9.11	-43.0
	d_{31}·g_{31}	***1,057***	***1,365***	***1,949***	***2,496***	***75,193***
Shear	d_{15} [pC/N]	330	496	584	741	5190 [c]
	g_{15} [mV-m/N]	28.9	39.4	38.2	26.8	90.2
	d_{15}·g_{15}	***9,537***	***1,9542***	***22,309***	***19,859***	***468,039***
Shear	d_{36} [pC/N]	N/A				2600 [b]
	g_{36} [mV-m/N]					63.8
	d_{36}·g_{36}					***165,978***

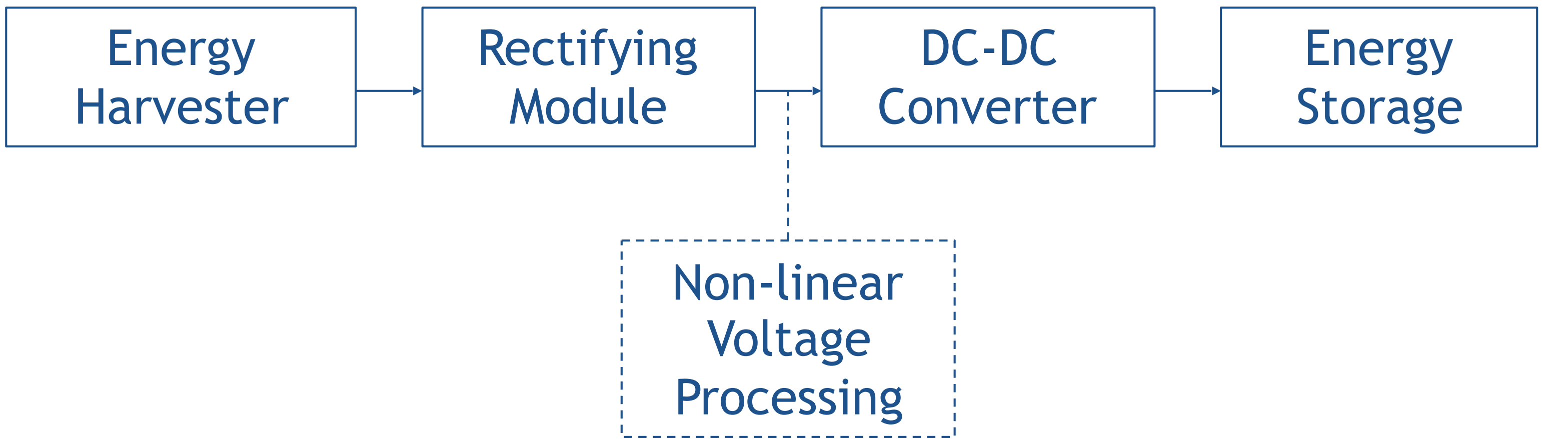


Open circuit voltage frequency response of torsion harvester prototypes

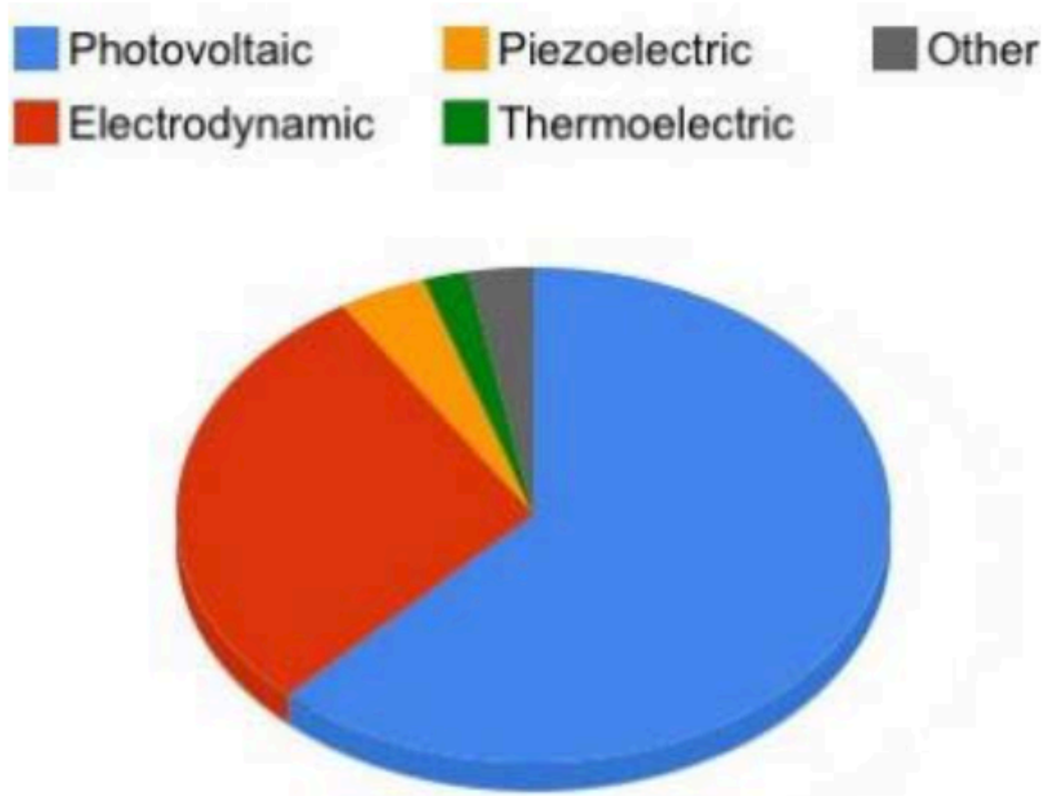


Output power of harvester prototypes over varying load resistance values at resonance

Characterization of shear mode piezoelectric energy harvesters

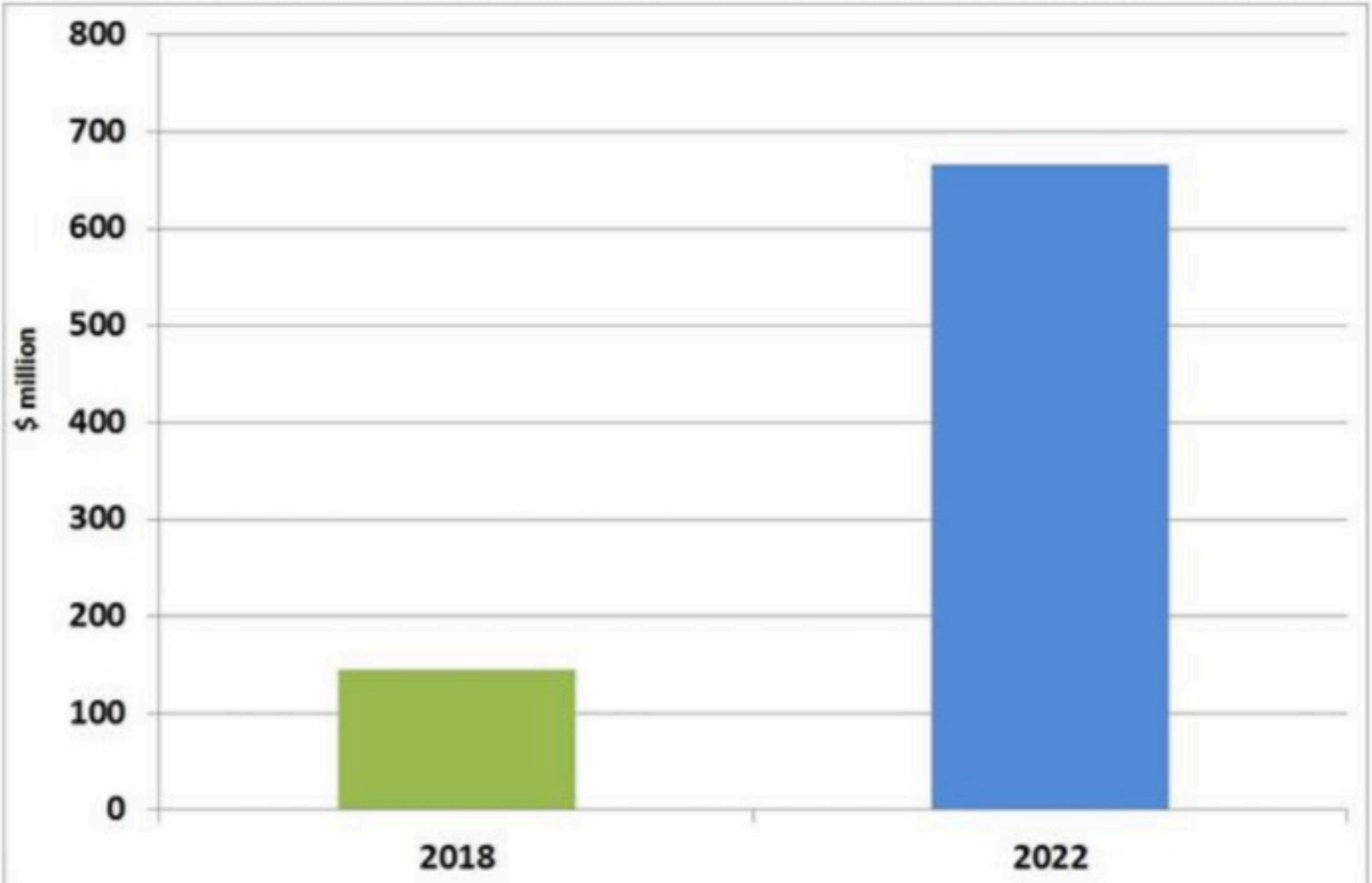

Energy Harvester
Rectifying Module
DC-DC Converter
Energy Storage
Non-linear Voltage Processing

Power Sources



Source: IDTechEx report: *Energy Harvesting and Storage for Electronic Devices 2009-2019*.

Piezoelectric Market Forecasts for 2018 and 2022 (partial data from IDTechEx research)



Source: IDTechEx report Piezoelectric Energy Harvesting 2012-2022: Forecasts, Technologies, Players www.IDTechEx.com/piezo

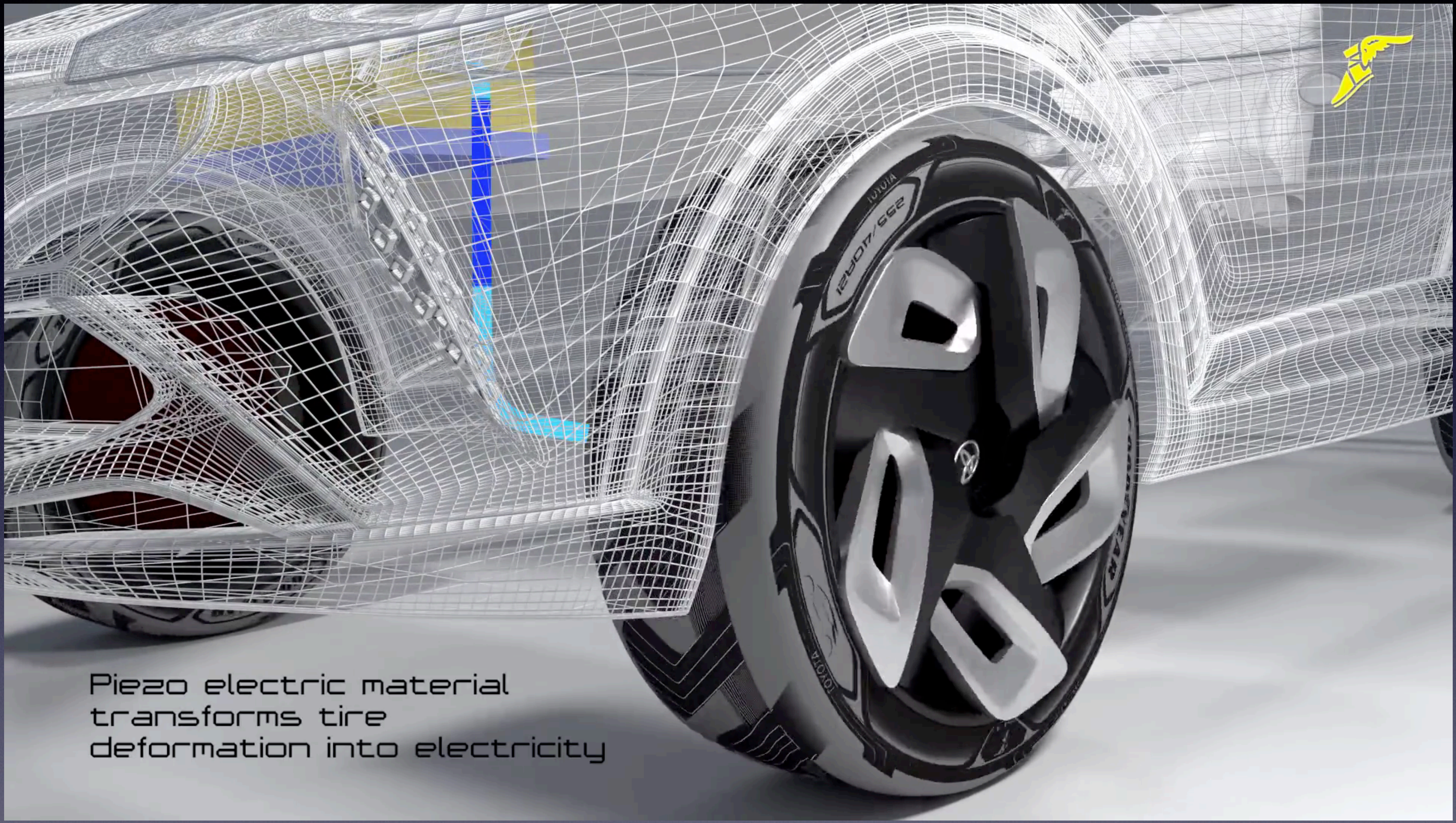
Piezo Harvester Markets

Advantages

Ability to be manufactured in wide variety of shapes or sizes
High reliability, efficiency and power output by size and cost

Challenges

Converting the energy from broadband frequencies.
Fragility Issues.
Fragmented markets on the basis of its application across sectors.


Piezo electric material
transforms tire
deformation into electricity