# Smart materials

- Piezoelectric materials
- Shape memory materials
- Magnetostriction materials
- Electrostriction materials

# Qualitative comparison of different “smart technology

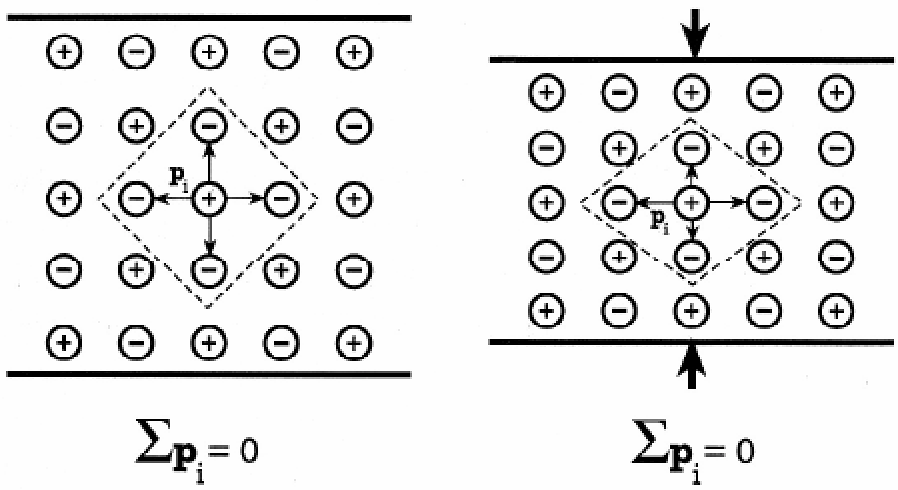
| | | | |
|---|---|---|---|
| **Active System** | Shape-Memory Alloys | Magnetostrictive Materials | Piezoelectric Materials |
| **Driving Force** | Thermal field | Magnetic field | Electric field |
| **Materials** | TiNi, TiPd | TbFe, (TbDy)Fe, SmFe | PZT, Quartz |
| **Advantages** | •Large forces<br>•High energy density<br>•High material strength<br>•High Elasticity | •Contact-less control via magnetic field<br>•High frequencies<br>•High temperature range | •High bandwidth<br>•High frequencies<br>•Low power Actuation |
| **Limitations** | •Low bandwidth<br>•Low frequencies<br>•High hysteresis<br>•Limited temperature range | •Generation of magnetic field equipment intensive<br>•Limited strains<br>•Low material tensile strength<br>•Typically brittle materials | •Limited Strains<br>•Auxiliary Equipment needed<br>•Low material tensile strength<br>•Typically brittle materials<br>•Limited temperature range |

# Piezoelectricity:
## Coupling between Internal Dielectric Polarization and Strain

- Piezoelectric crystals
  - Produce electric field when subject to an external force
  - Expand or contract in response to externally applied voltage
- Can be used for both sensors and actuators
- Piezoelectric effect discovered in 1880
- Macroscale piezoelectric actuators widely used in many applications
- Large force, low power consumption
  - A few Newtons in bulk piezoceramic cylinders
  - A few millinewtons in thin films
- Hysteresis, drift, nonlinearity → Often placed in a feedback loop
- Microscale piezoelectric thin film materials for MEMS applications are still challenging
- Piezoresitive materials are usually not piezoelectric

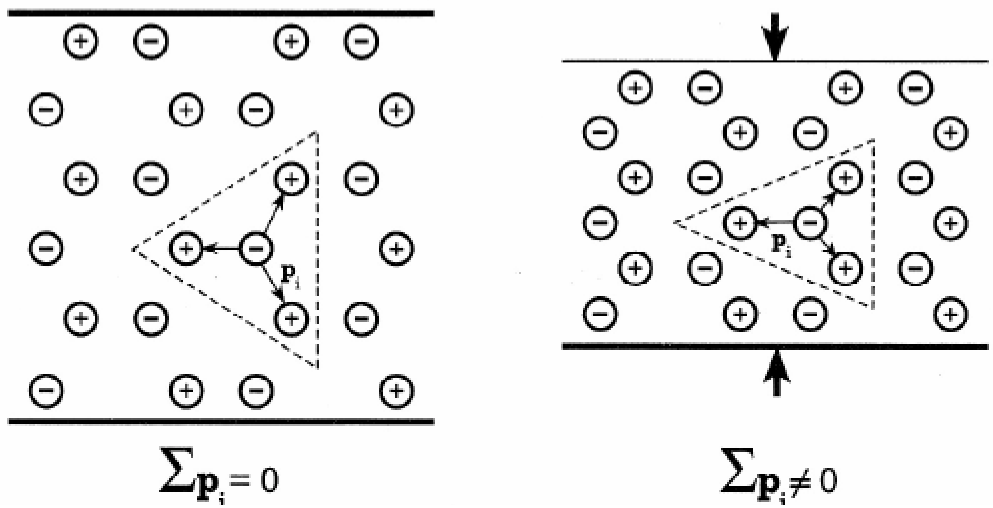
# Does Si Exhibit Piezoelectric Effect?

- Si is not piezoelectric
  - Cubic, has a center of symmetry
  - Covalent bond (not ionic)
- Crystals with a center of symmetry does not have piezoelectric effect
- The electric dipoles always add up to zero

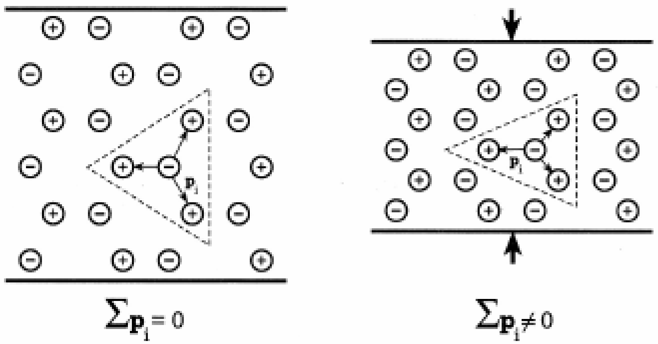


# Piezoelectric Crystal

- Necessary conditions:
  - Ionic or partly ionic bonds
  - Lack a center of symmetry
- Strain shifts the relative positions of the positive and negative charges, giving rise to a net electric dipole
- Conversely, electrical field → strain



# Illustration of Piezoelectric Effect




$$D = \varepsilon_0 E + P$$

- Electric Displacement ($D$)
- Permittivity of free space ($\varepsilon_0$)
- Electric Field ($E$)
- Polarization (function of strain) ($P$)

Electrostatic Energy Density: $\hat{W}_e = \frac{1}{2} D \cdot E$

$\hat{W}_e$ is a function of strain since ***P*** is a function of strain

$$\frac{\partial \hat{W}_e}{\partial \varepsilon} \to Stress$$ → ***Actuation Force***

# Relationship between $d_{iJ}$ and $e_{iJ}$

**Piezoelectric Stress Coef** $$d_{iJ} = \sum_{K=1}^{6} e_{iK} S^{\varepsilon}_{KJ}$$

**Piezoelectric Coef** $$e_{iJ} = \sum_{K=1}^{6} d_{iJ} C^{\varepsilon}_{KJ}$$

# Piezoelectric Materials

- Piezoelectric substrates
  - Quartz, $LiNbO_3$, GaAs
- Thin film piezoelectrics
  - ZnO, AlN, PZT (lead zicornate-titanate)
- Polymer film piezoelectrics
  - PVDF (poly-vinylidene flouride)

**Quartz:**

$$d = \begin{pmatrix} d_{11} & -d_{11} & 0 & d_{14} & 0 & 0 \\ 0 & 0 & 0 & 0 & -d_{14} & -2d_{11} \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

**ZnO:**

$$e = \begin{pmatrix} 0 & 0 & 0 & 0 & e_{15} & 0 \\ 0 & 0 & 0 & e_{15} & 0 & 0 \\ e_{31} & e_{31} & e_{33} & 0 & 0 & 0 \end{pmatrix}$$

# Common Piezoelectric Materials

| Material | Piezoelectric Constant ($d_{3n}$) ($10^{-12}$ C/N) | Relative Permittivity ($\varepsilon$) | Density ($g/cm^3$) | Young's Modulus (GPa) | Acoustic Impedance ($10^6$ kg/ $m^2 \cdot s$) |
|---|---|---|---|---|---|
| Quartz | $d_{33} = 2.31$ | 4.5 | 2.65 | 107 | 15 |
| Polyvinyledene -fluoride (PVDF) | $d_{31} = 23$<br>$d_{33} = -33$ | 12 | 1.78 | 3 | 2.7 |
| $LiNbO_3$ | $D_{31} = -4$, $d_{33} = 23$ | 28 | 4.6 | 245 | 34 |
| BaTiO3 | $d_{31} = 78$, $d_{33} = 190$ | 1,700 | 5.7 | | 30 |
| PZT | $D_{31} = -171$, $d_{33} = 370$ | 1,700 | 7.7 | 53 | 30 |
| ZnO | $d_{31} = 5.2$, $d_{33} - 246$ | 1,400 | 5.7 | 123 | 33 |

**PZT**: lead zirconate-titanate
**PVDF** is polymer-film peizoelectrics

# Piezoelectric materials

Ceramics:

- PZT (Lead-Zirconate-Titanate or $Pb_x(Ti, Zr)_{1-x}O_3$ )

* quartz

- Thin fims- ZnO, AlO

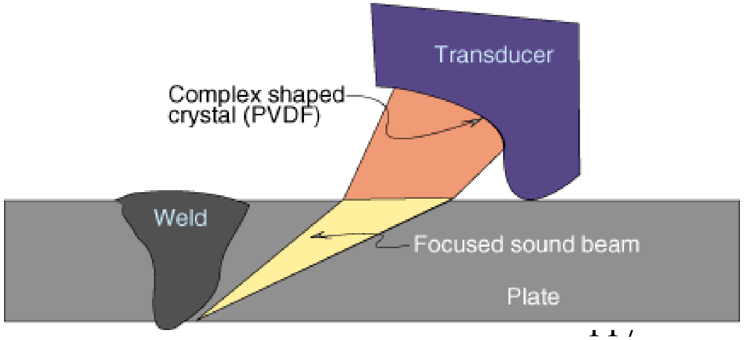
Polymers:

- PVDF (poly vinylidene flouride)
- PTF (polymer thick film)

# Ceramic versus polymer

- Ceramic
- high stiffness
- Higher curie point less likely to depole

Polymer
- acoustic impedance matching with water
- Flexible can be formed intocomplex shape
- Low dieletric constant



# Piezoelectric materials

Advantage:

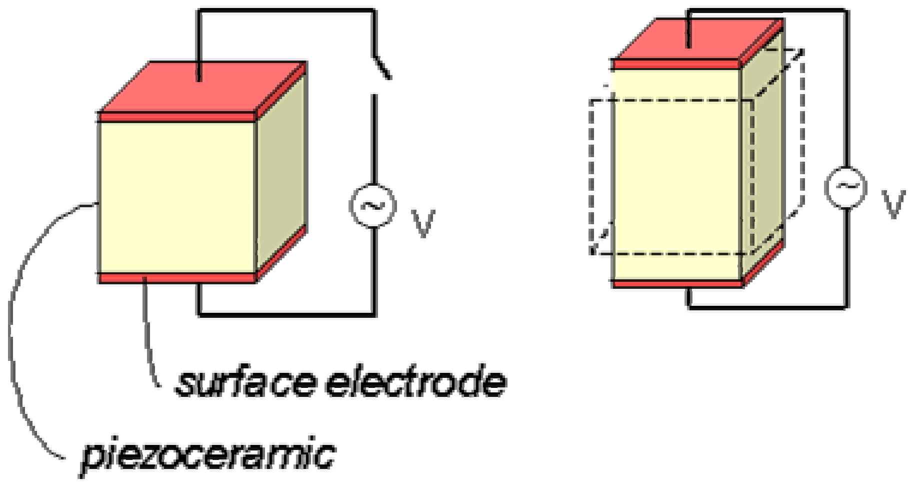
- Reversible (use as  sensor or actuator)
- Actuation mechanism is highly resistive to environmental effect (e.g. humidity, temperature)
- Very easy to control small (sub-micron) displacements with applied voltages.
- High stiffness.
- Very fast response.
- 100's of N loads easy.
- E to100GPa

# Piezoelectric materials

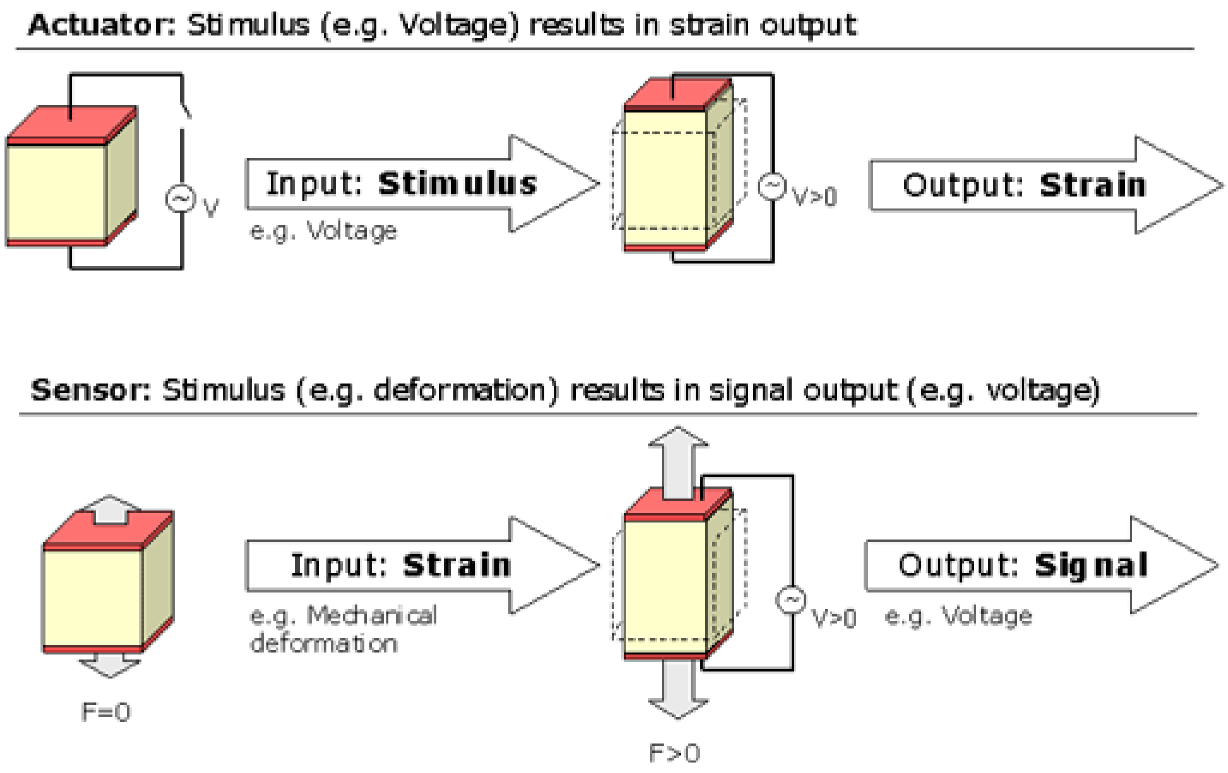
*Disadvantages*:

- Small displacements. 30ppm typical. Attempts to use long actuators doesn't work - stacks and bimorphs help.
- Non-linear response and exhibit high-hysterisis and creep. Many commercial products overcome these through control techniques.
- High electric fields can cause breakdown and failure.
- requires a high voltage for displacement in the micron regime, however the problem can be partially alleviated by implementing a bimorph

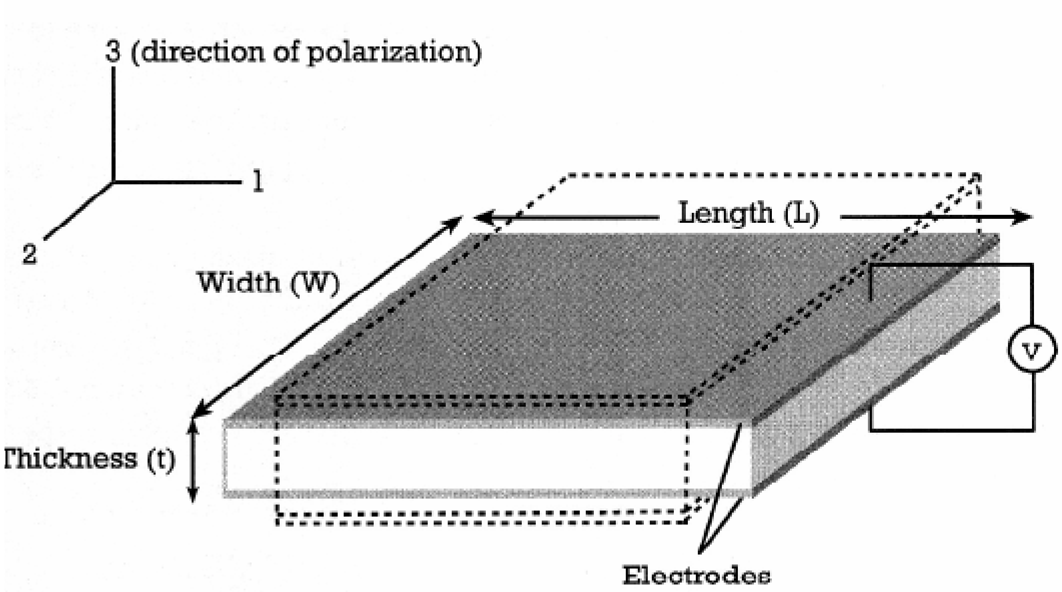
# Piezoelectric materials



# Piezoelectric material



**If a voltage is applied in the thickness direction**
**→ Strain occurs in length, width, and thickness directions**



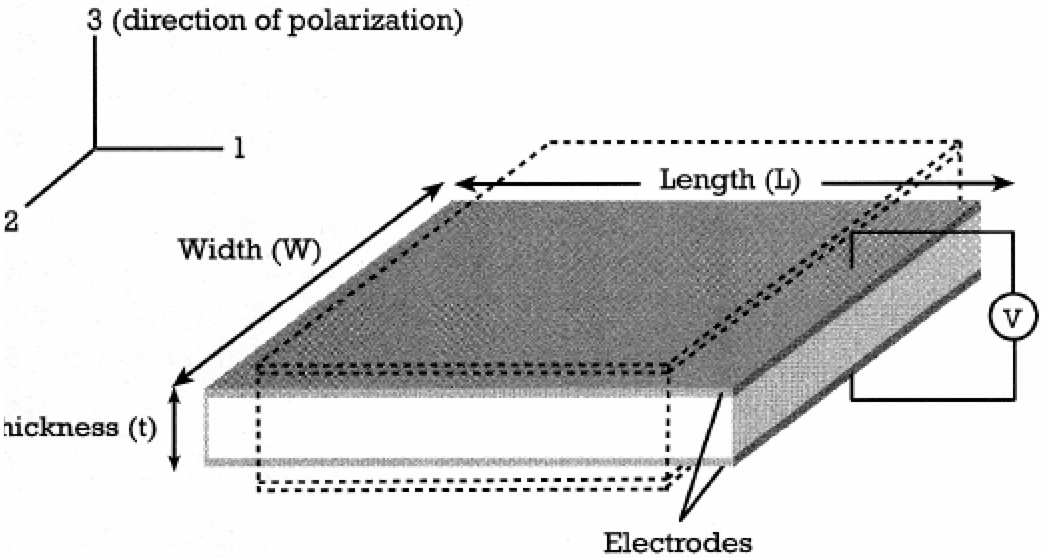

$$\Delta L = d_{31} V_a \frac{L}{t}$$

$$\Delta W = d_{31} V_a \frac{W}{t}$$

$$\Delta t = d_{31} V_a$$

# Piezoelectric Sensing

**Force *F* is applied in L, W, or t direction**
**→A voltage will develop**
**→Can be used for sensors**

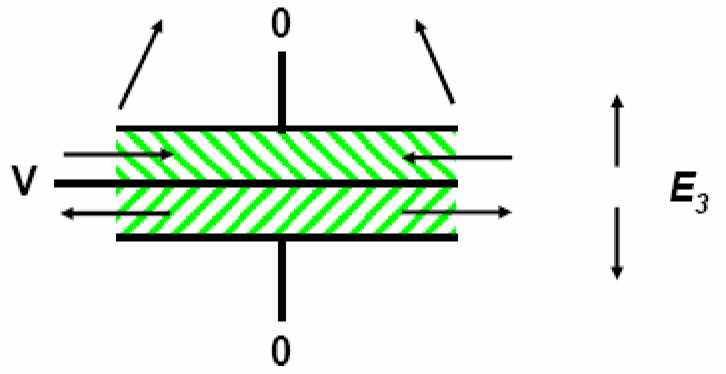



$$V_m = d_{31} \frac{F}{\varepsilon L}$$

$$V_m = d_{31} \frac{F}{\varepsilon W}$$

$$V_m = d_{33} F \frac{t}{\varepsilon L W}$$

# Piezoelectric Bimorph




**A biormorph structure can be used to enhance the displacement**

ucla

# Piezoelectric materials

- STM AFM
- Camera film plane control, lens motor
- Mirror control, micro-actuator (fluid)
- Acoustic wave generation-Speaker
- Ski active vibration damper (K2)
- Power generator
- Ultrasonic transducer (image, range finder,hydrophone, microphone,bubble)

# Piezoelectric materials application

**Optics, Photonics and Measuring Technology**
- Image stabilization
- Scanning microscopy
- Auto focus systems
- Interferometry
- Fiber optic alignment & switching
- Fast mirror scanners
- Adaptive and active optics
- Laser tuning
- Mirror positioning
- Holography
- Stimulation of vibrations

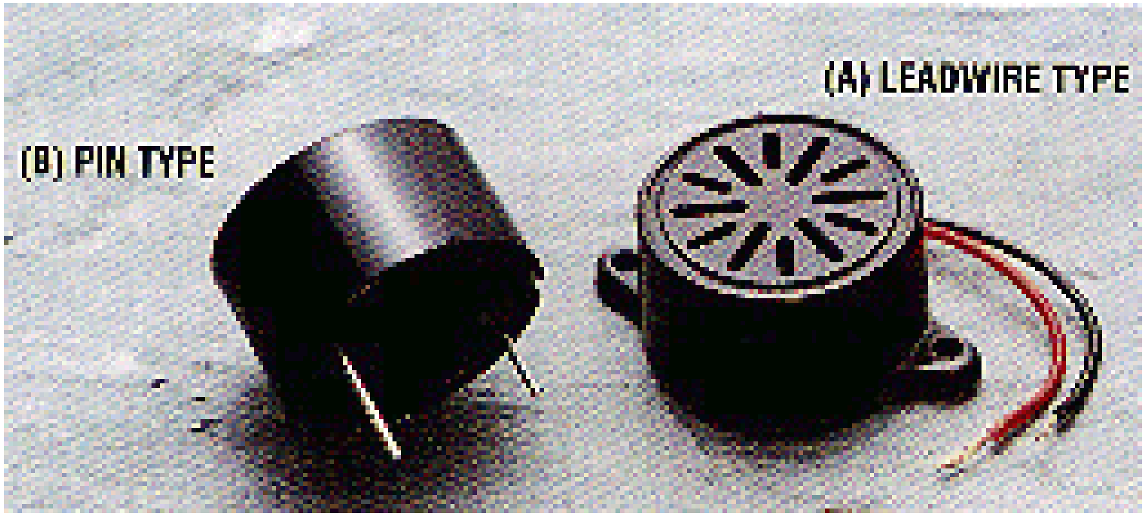
**Disk Drive**
- MR head testing
- Pole tip recession
- Disk spin stands
- Vibration cancellation

**Microelectronics**
- Nano-metrology
- Wafer and mask positioning
- Critical Dimensions measurement
- Microlithography
- Inspection systems
- Vibration cancellation

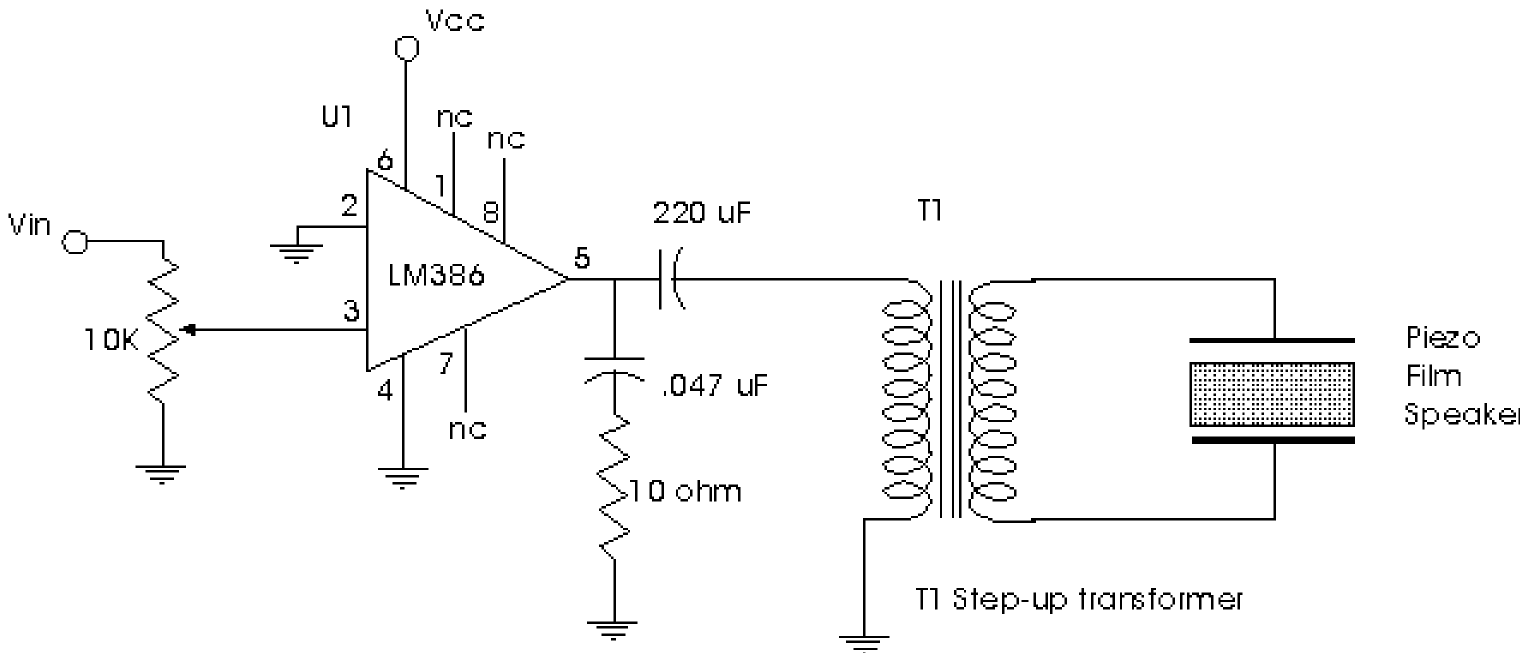
**Precision Mechanics and Mechanical Engineering**
- Vibration cancellation
- Structural deformation
- Out-of-roundness grinding, drilling, turning
- Tool adjustment
- Wear correction
- Needle valve actuation
- Micro pumps
- Linear drives
- Piezo hammers
- Knife edge control in extrusion tools
- Micro engraving systems
- Shock wave generation

**Life Science, Medicine, Biology**
- Patch-clamp drives
- Gene technology
- Micro manipulation
- Cell penetration
- Micro dispensing devices
- Audiophysiological stimulation
- Shock wave generation

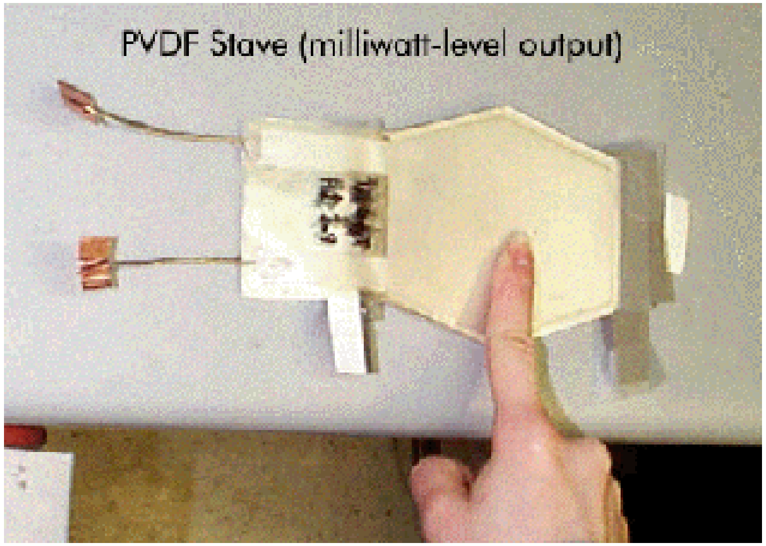
# Piezo speaker (PZT)

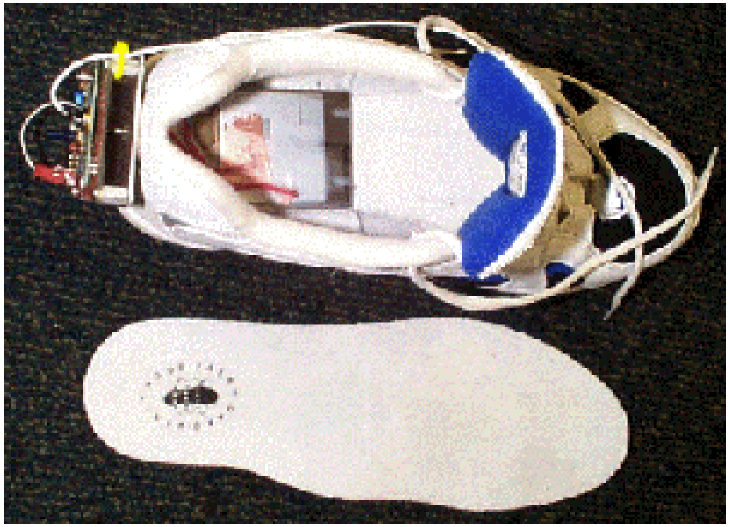


# Piezo speaker



# Piezoeletric energy scavenging in shoe (PVDF)

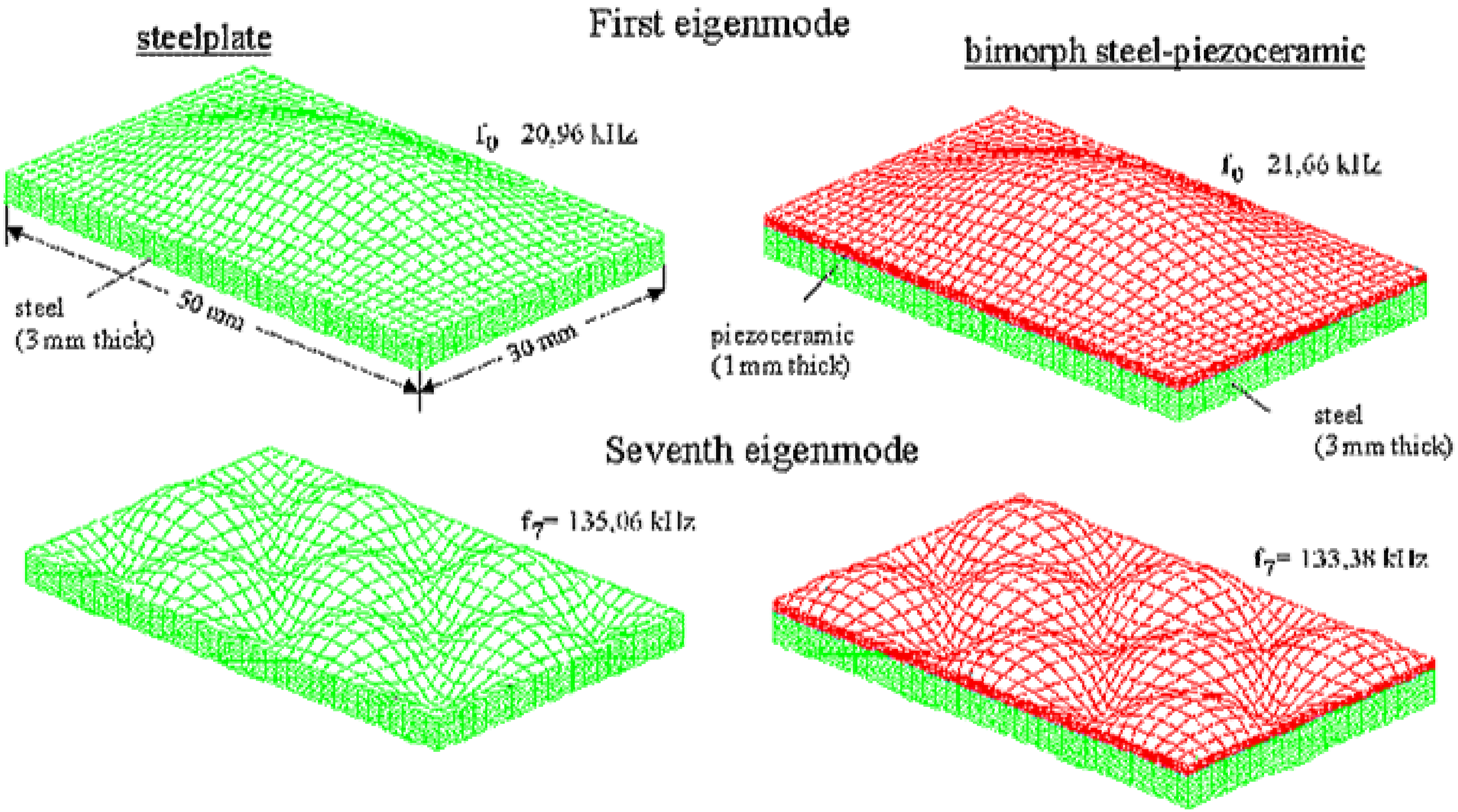


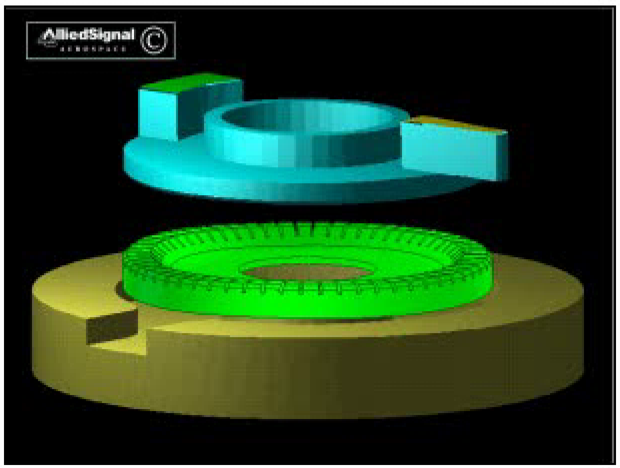
***low-power, wireless application:***

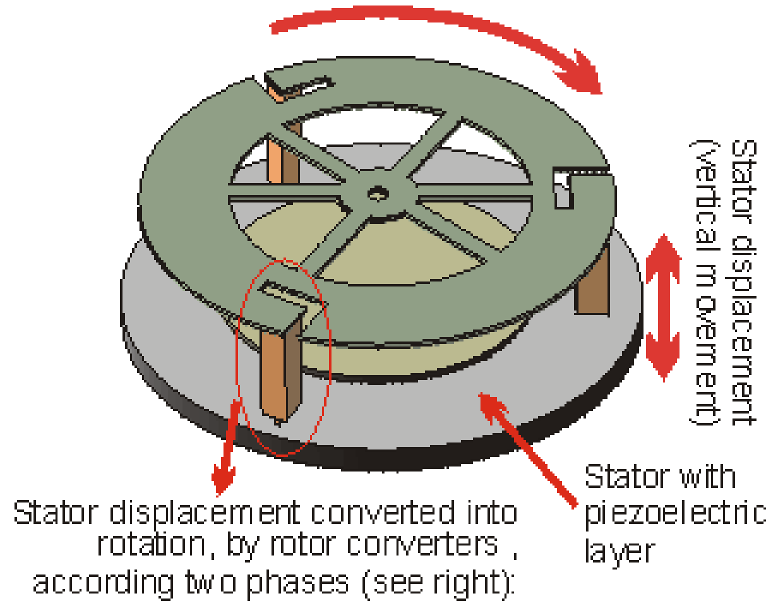
- Store charge over several footsteps
- When capacitor full, discharge through:
*regulator, 12-bit encoder, 310 Mhz ASK transmitter*
- Transmits 12-bit digital RFID from shoe to vicinity every 3-5 steps
- Enables smart building to track occupant location

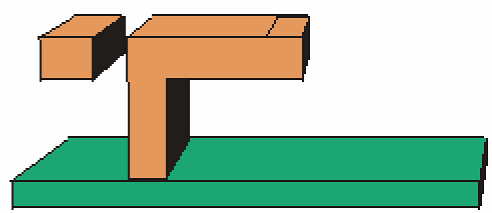
# Smart structure composite (PZT/steel)



# Piezoelectric rotary motor



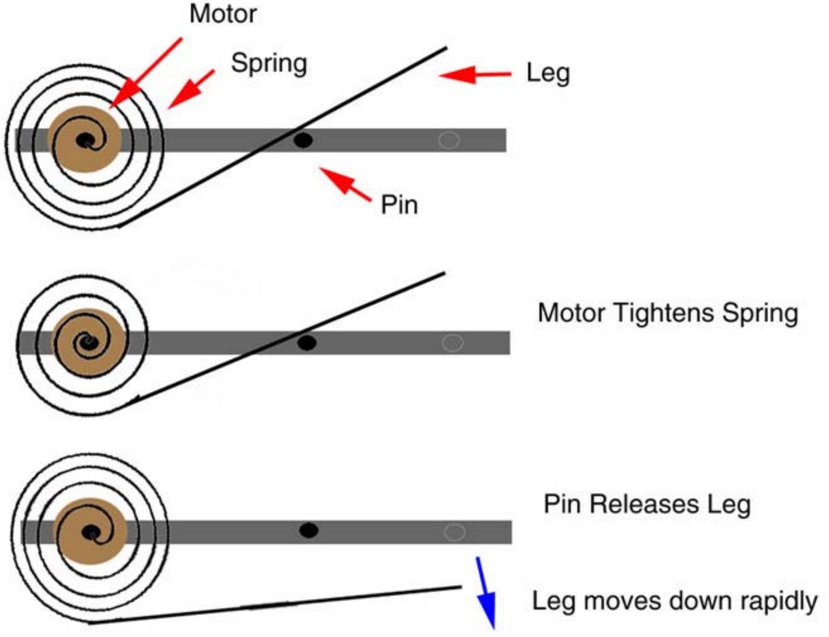



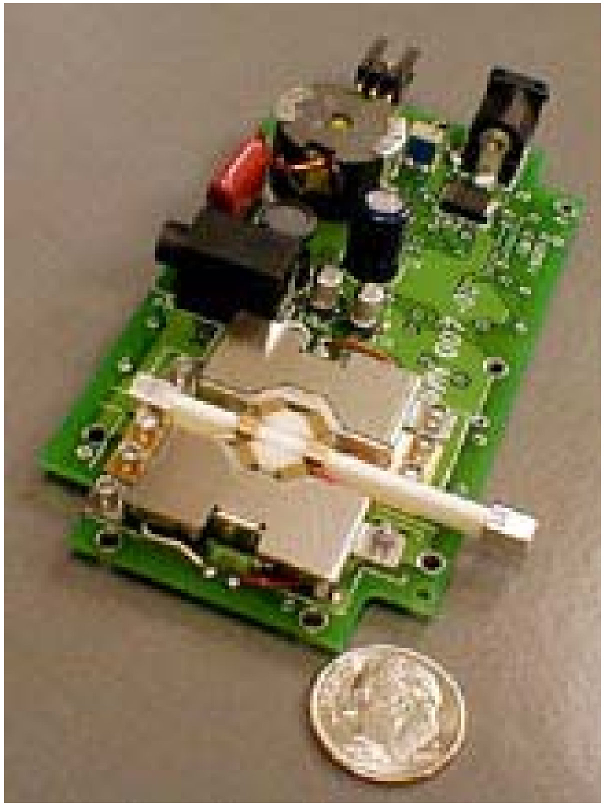
# Cricket jump

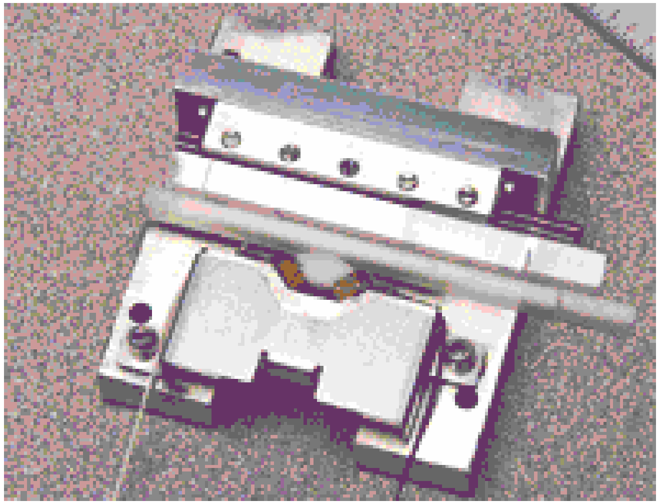
By Timothy S. Glenn and Nesbit W. Hagood at MIT

**Figure 4. Cricket Leg Design**



# Piezoelectric linear motor

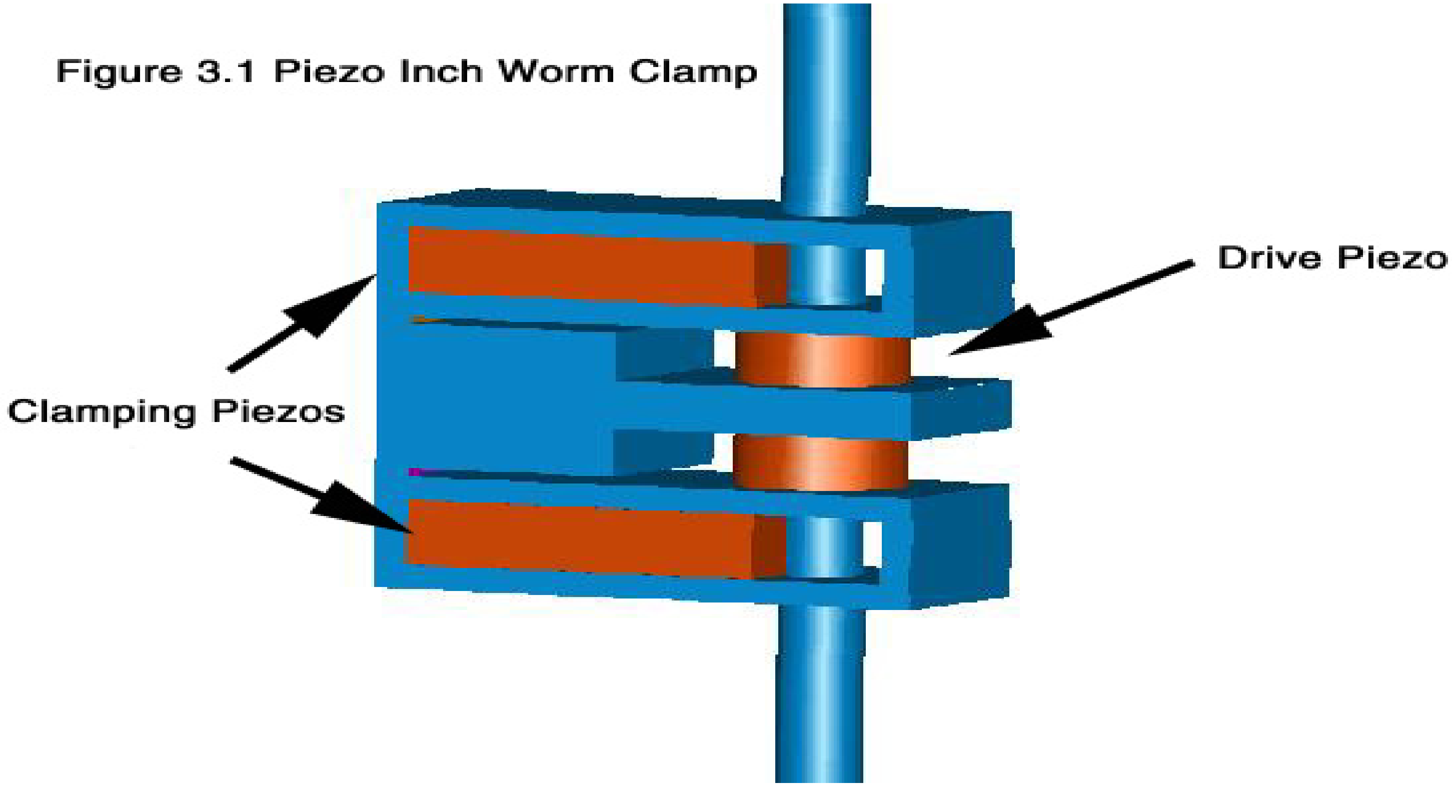




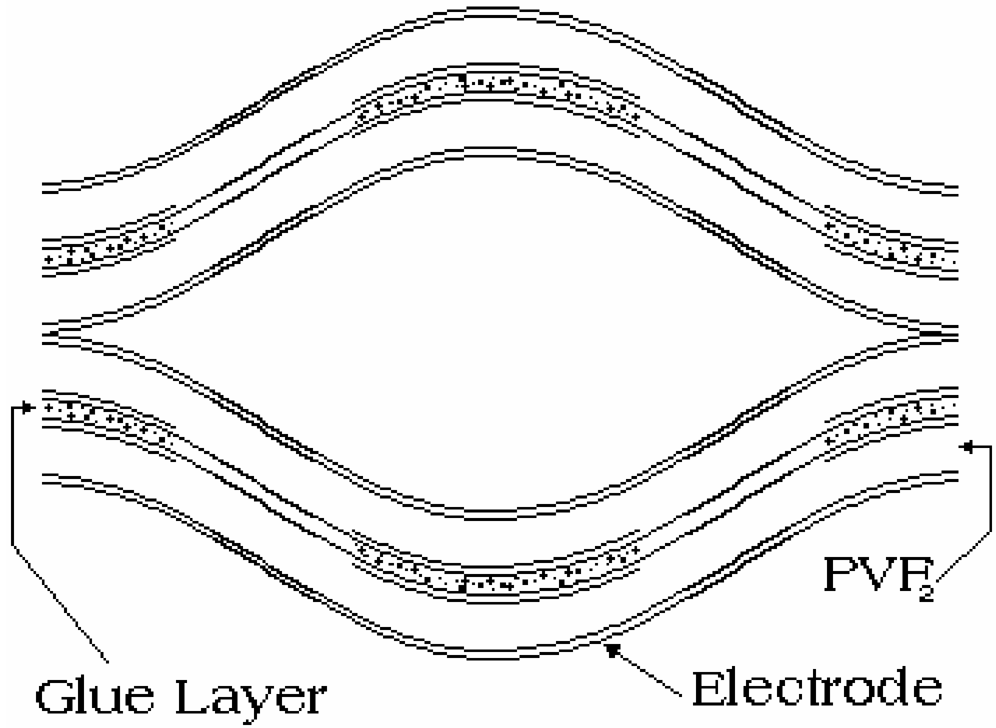

EDO model PDA 130

# Inch worm motors

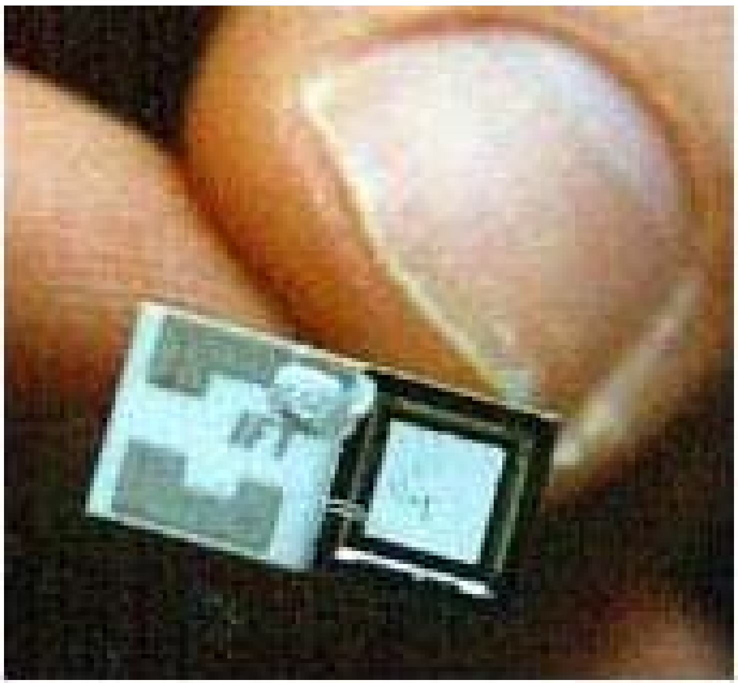
Figure 3.1 Piezo Inch Worm Clamp

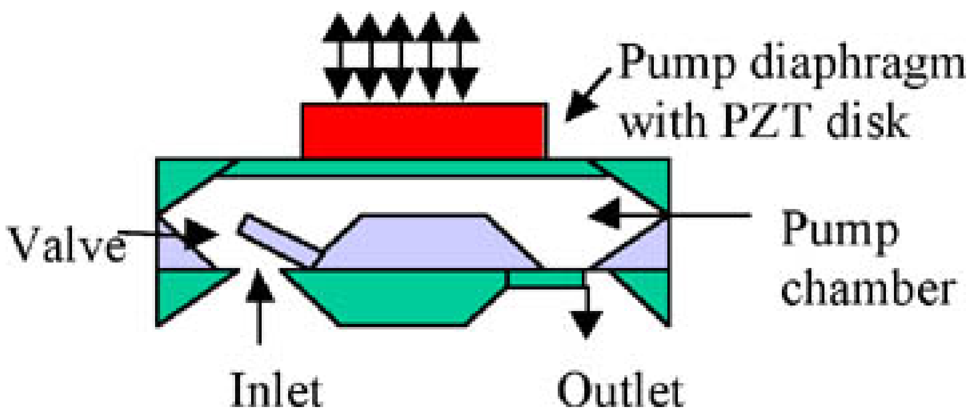


# PVF2 Bimorph actuator

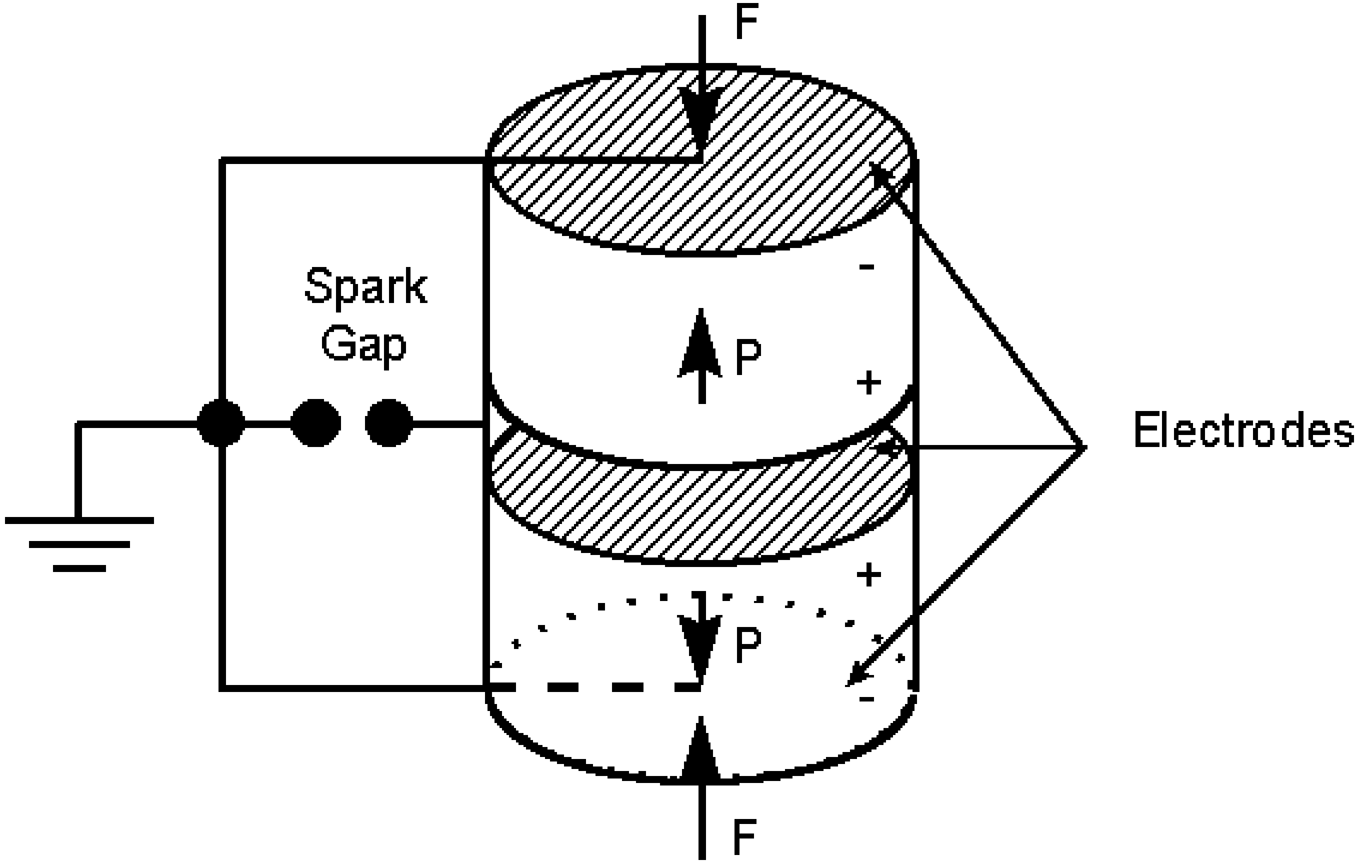


# micropump




Pump diaphragm
with PZT disk
Valve
Pump
chamber
Inlet
Outlet

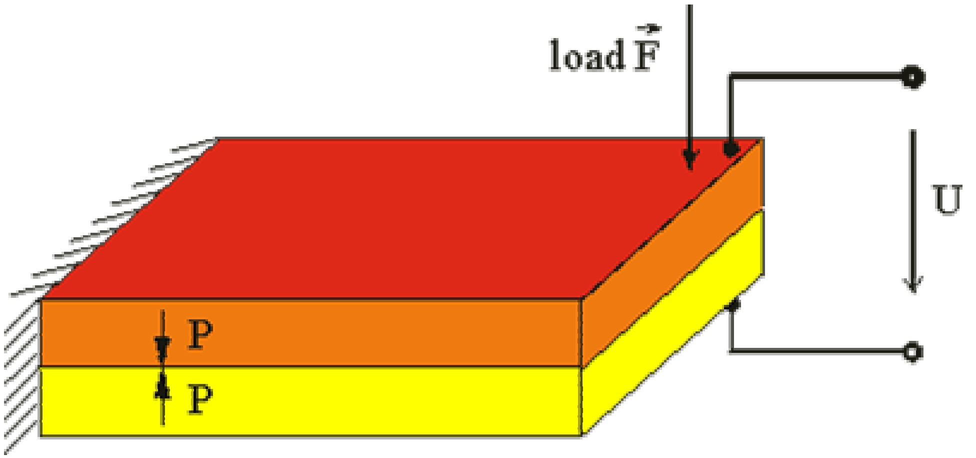
# Spark generator (PZT)



# Different shape of PZT bimorph

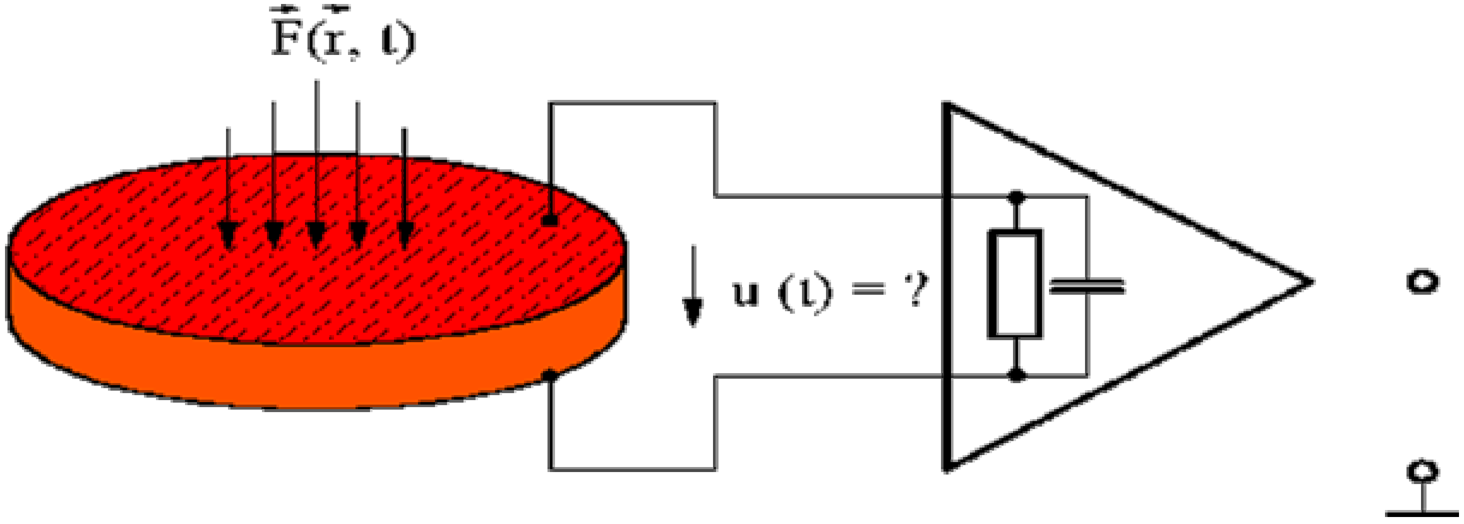
Spiral or helical shape

# bimorph



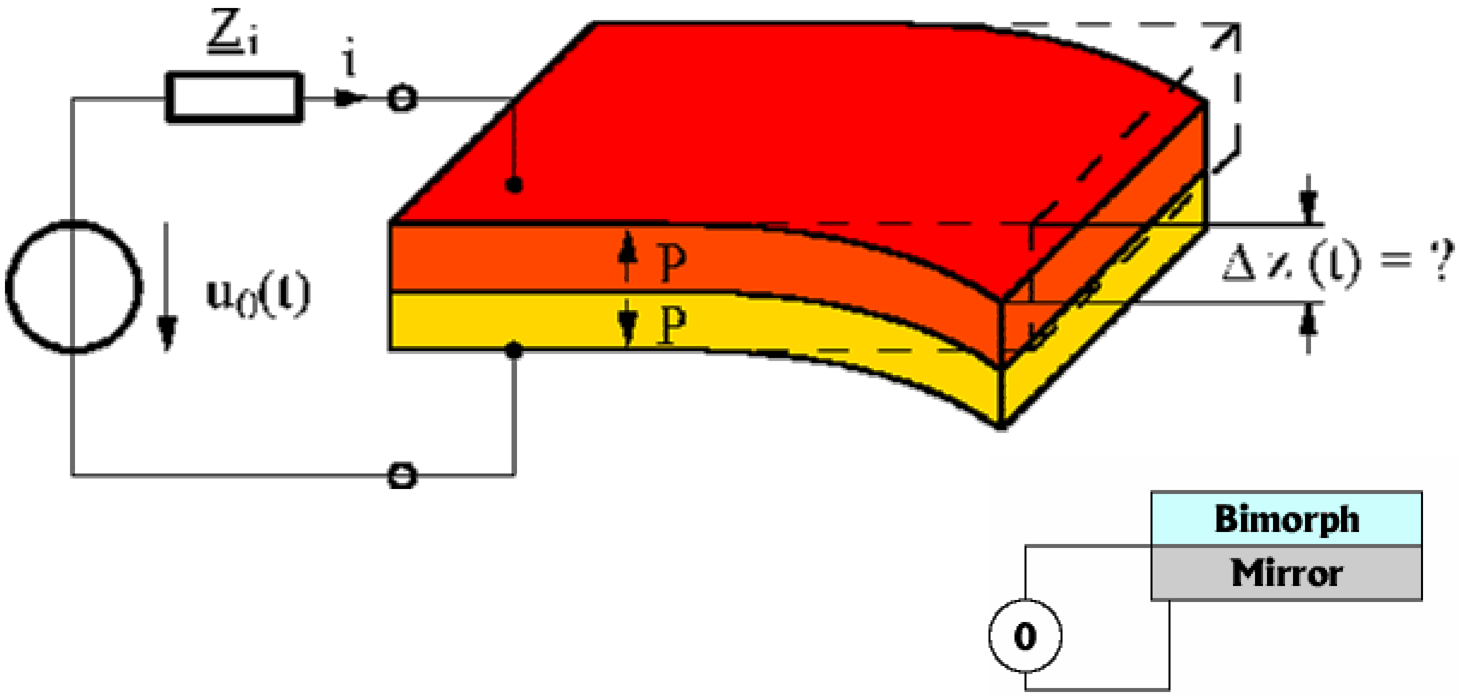

Principle setup of piezoelectric bimorph

# Piezoelectric effect (sensor)



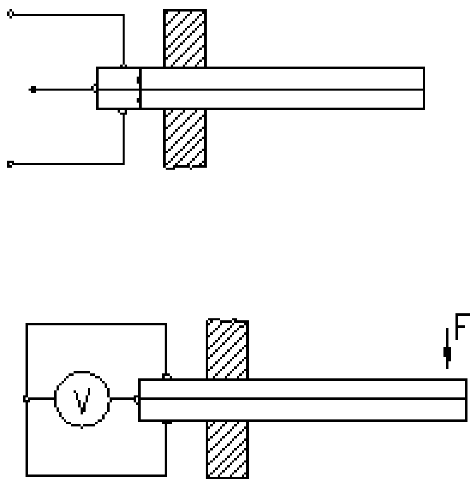

External force results in a electric potential

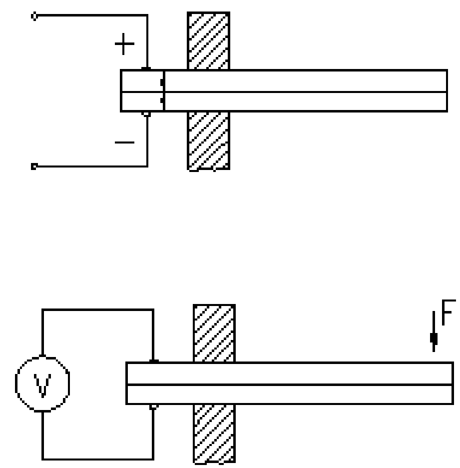
# Piezoelectric effect (actuator)




Applied electric potential results in a deformation

# Parallel and serial connection



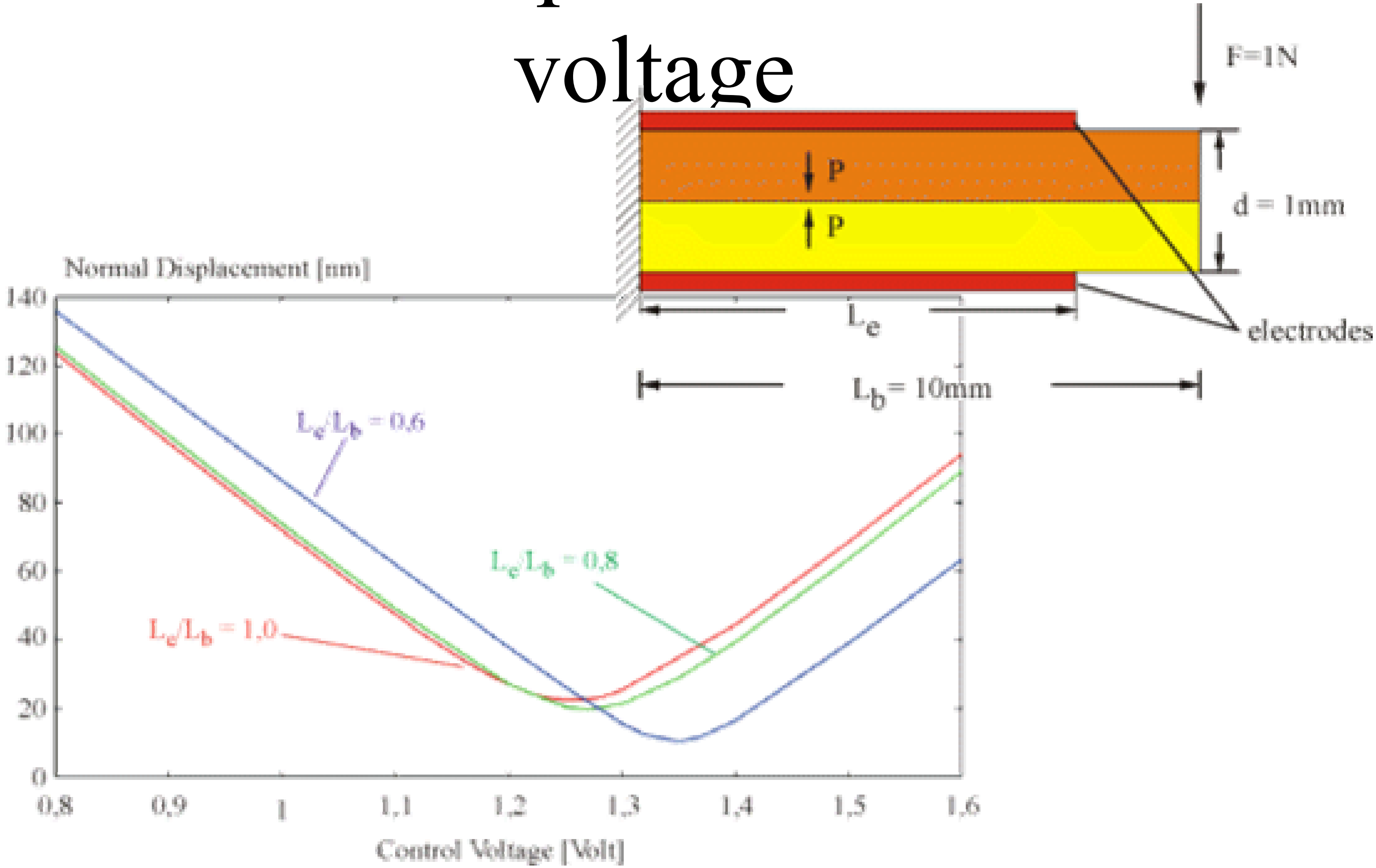

Parallel design

actuator

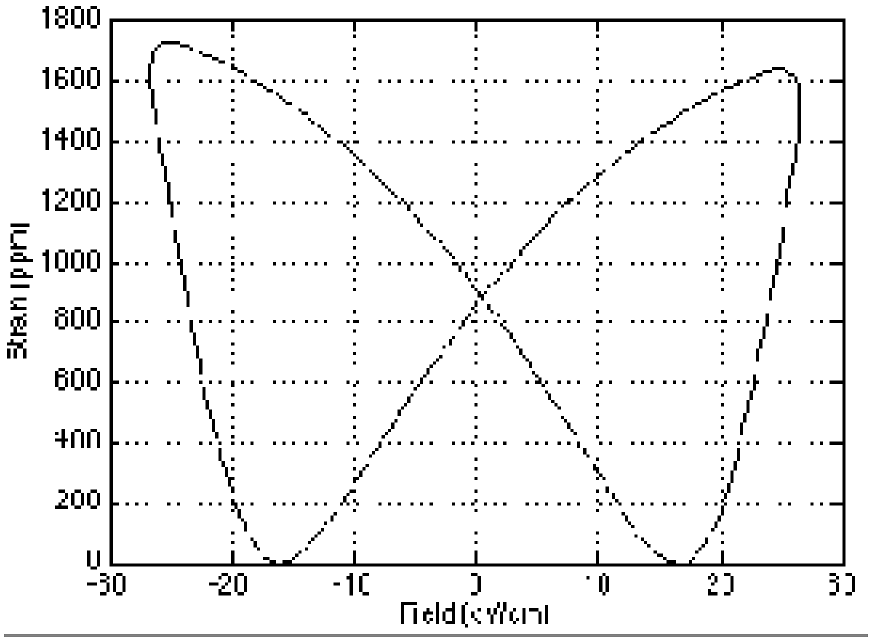
Serial design

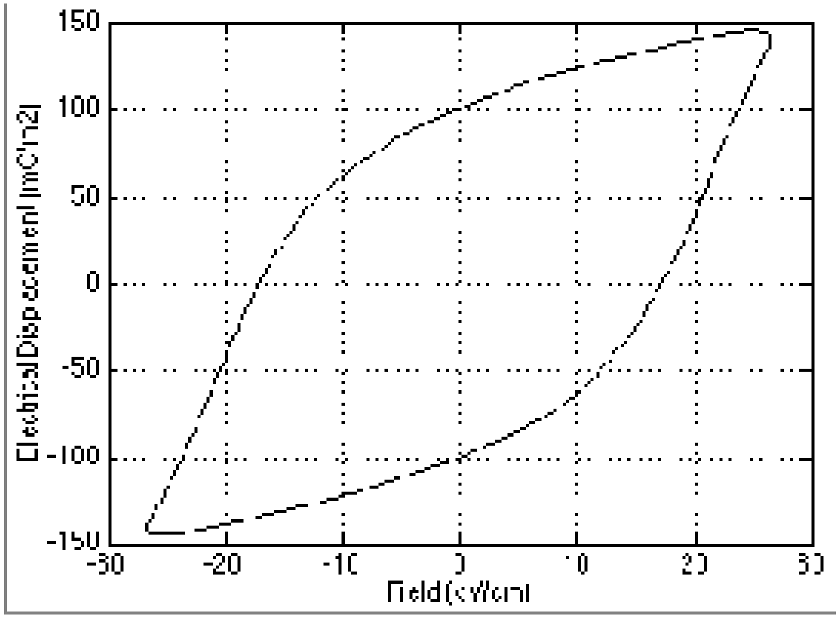
sensor

# Normal displacement versus voltage



# Electromechanical behavior



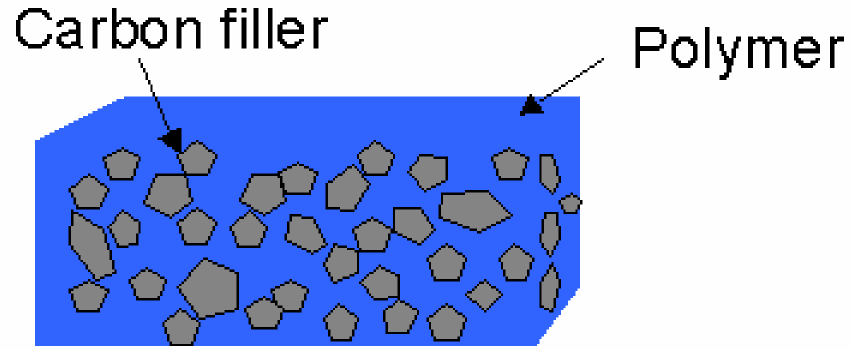
# Polymer thick film

History:

- low-cost carbon-filled resistors
- touch-membrane switches (touch pad, touch screen)
- flexible circuits or connectors (laptops, calculators, cell phone)

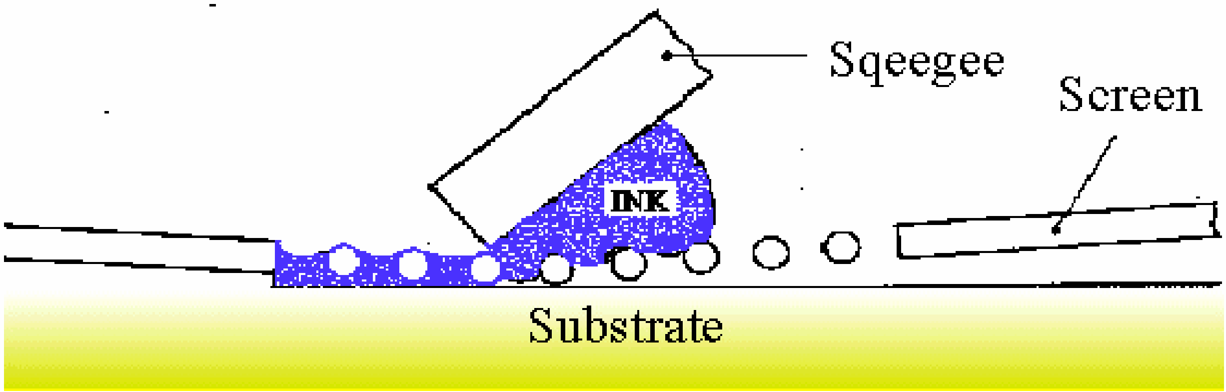
Advantages:

- Flexible, withstand large strains
- cured at temperatures below 200 $^oC$




Internal structure of PTF

- Carbon filler (pressure/force sensor, humidity sensor)
- Silver or copper filler (conducting strip, temperature sensor) -conducting elastomer
- Piezoelectric filler -Lead zirconate titanate (PZT) grains dispersed in a polymer matrix create a polymer-ceramic composite

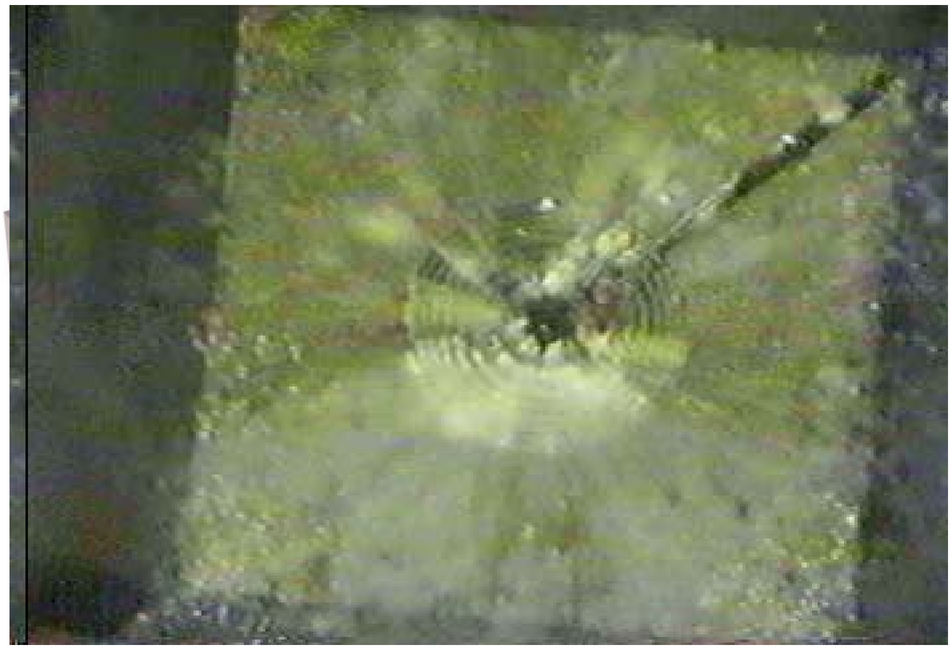



Screen Printing Process

# Smart materials

- Vibration monitoring (chair, highway, smartcard)
- Smart cloth, virtual reality sensors
- Tactile sensors

# MEMS devices-inkjet printer head (ZnO ultrasound device)



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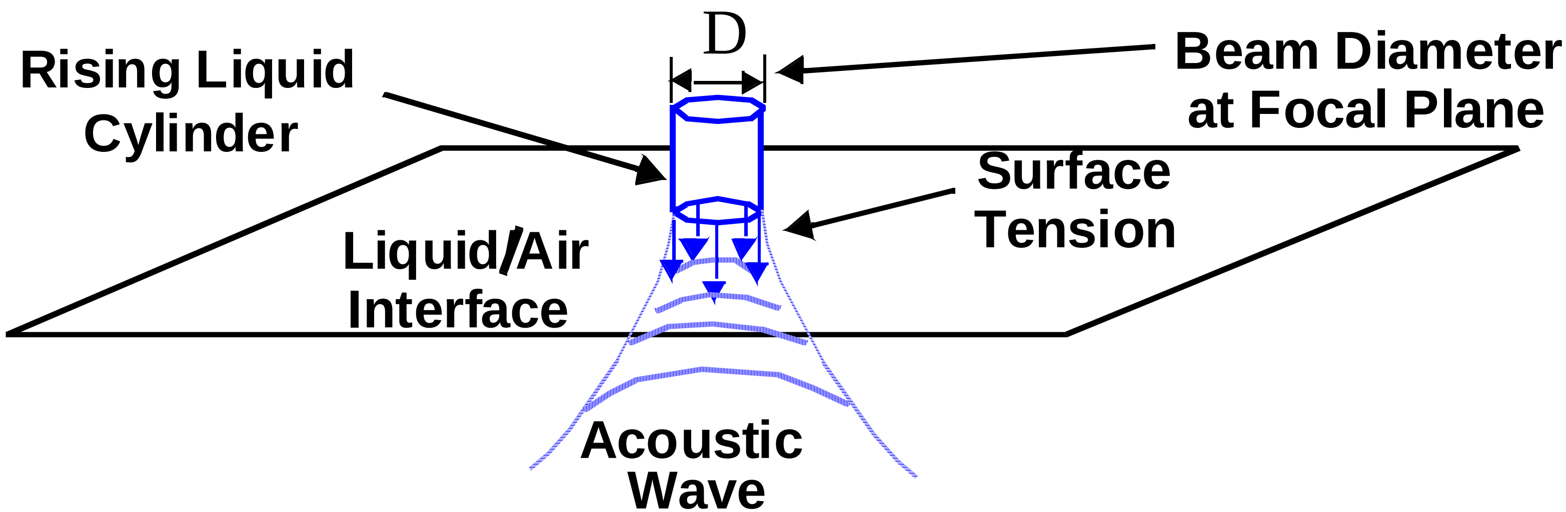
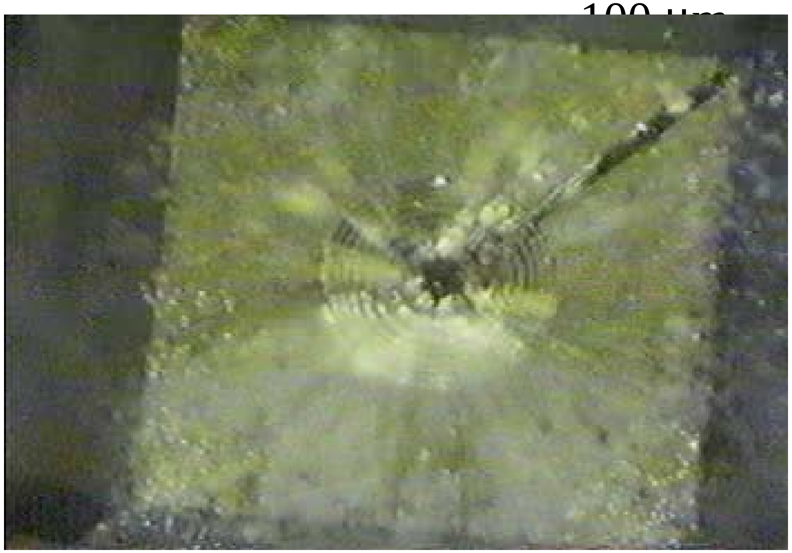
# Liquid Ejector




- **Droplet Formation due to Focused Acoustic Wave**
  - Function of Radiation Pressure & Surface Tension
- Radiation Pressure ($2I_f/V_a$)
- Droplet Diameter ~ Beam Diameter at Focal Plane

# Fabricated Device

# (Micromachined Lensless Liquid Ejector)



## Transducer Specifications

- **RF Frequency: 300 MHz**
- **ZnO Thickness: 10.55 μm**
- **Focal Length: 400 μm**
- **Half-Wave-Band Sources: 7**
- **Predicted Droplet Diameter: 5 μm**

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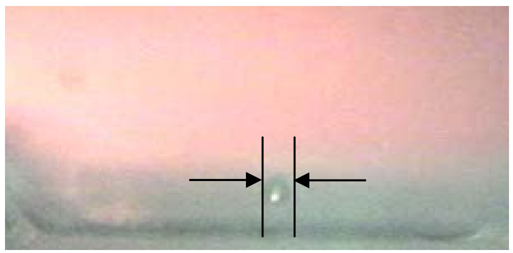
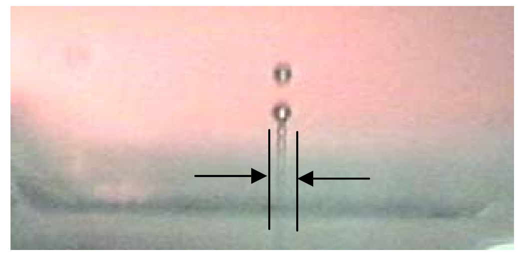
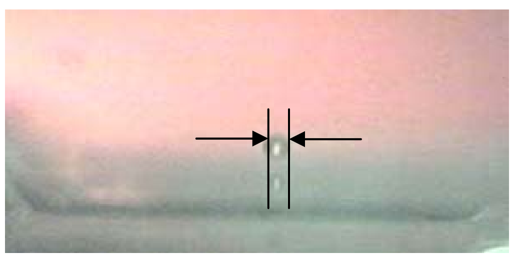
# Time evolution of the liquid ejection process produced by our 600MHz SFAT with an RF pulsewidth of 30µsec



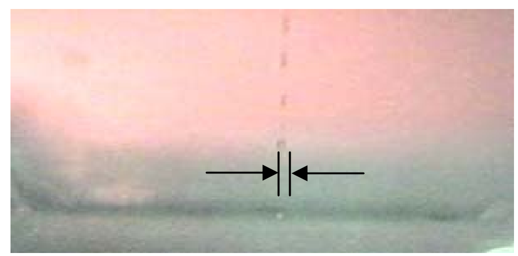
80 µm



30 µm



60 µm



15 µm

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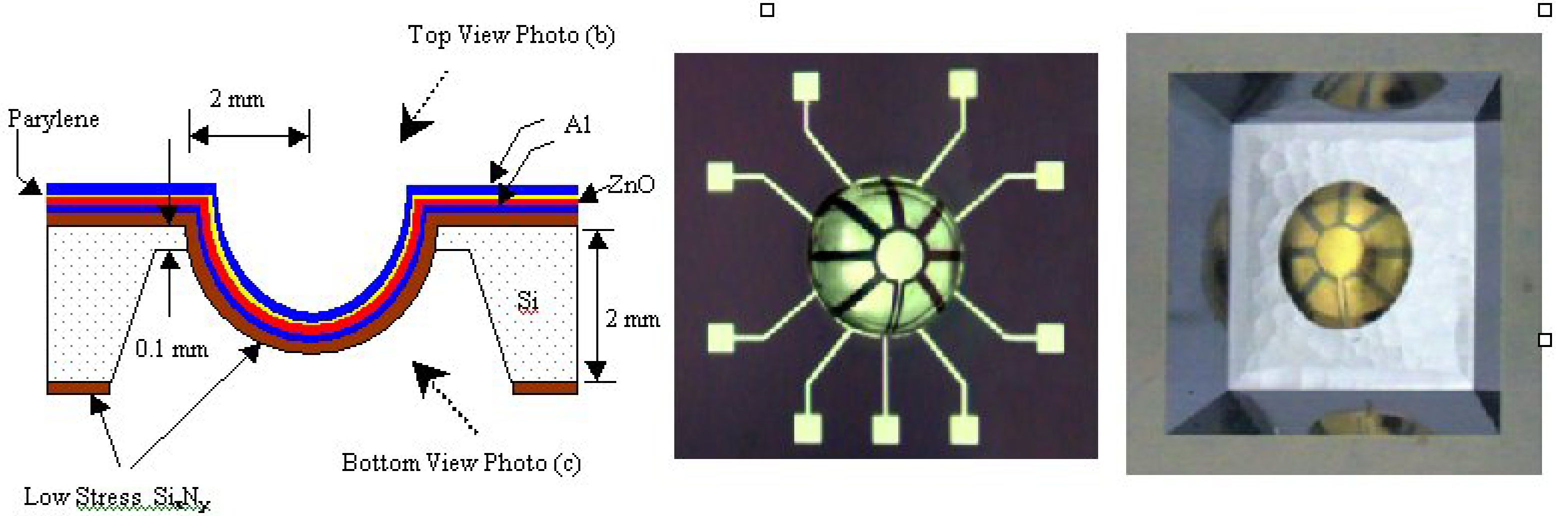
# Piezoelectric Sensor

- Microphone
- Bimorph sensor
- Ultrasonic sensor (SAW, Bulk wave)

# Micromachined Piezoelectric Ultrasonic Transducers on Dome-Shaped-Diaphragm in Silicon Substrate




(a) (b) (c)

Figure 1 (a) Cross-sectional view of the acoustic transducer. (b)Top view photo of a fabricated acoustic transducer. (c)Bottom view photo of the same transducer.

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# Fabrication Steps

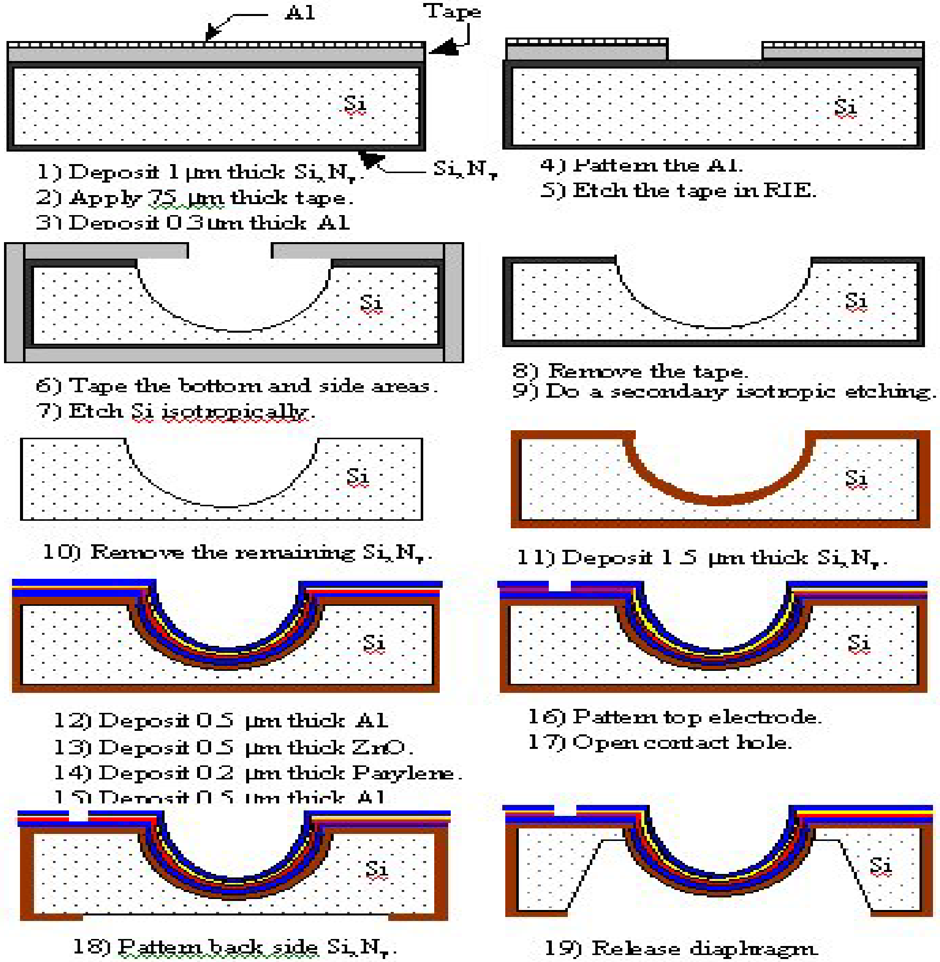


Figure 2. Processing steps to fabricate the dome-shaped-diaphragm, piezoelectric, acoustic transducer.

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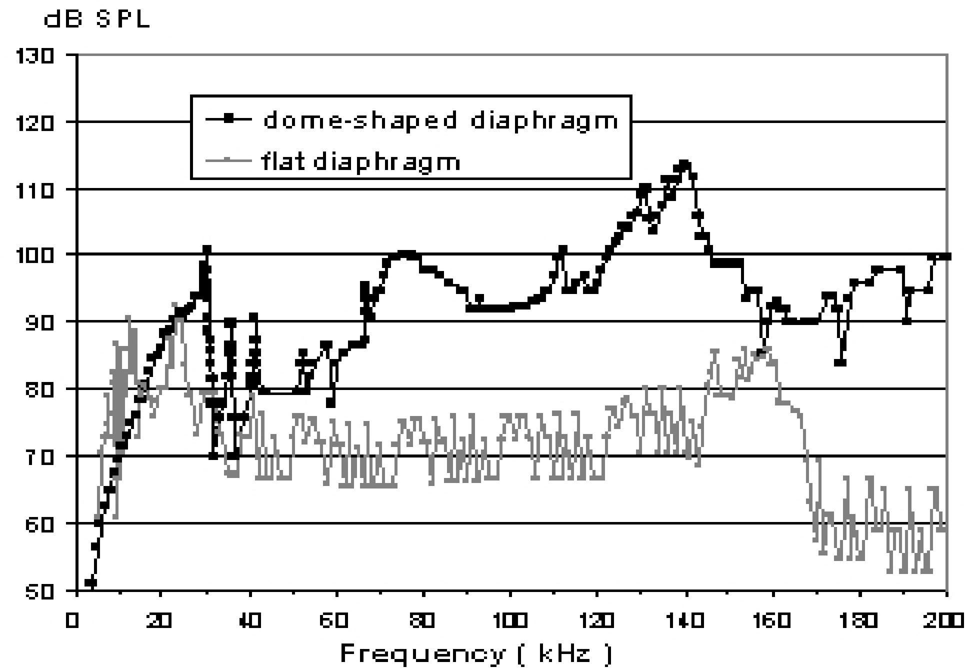
# Sound Pressure comparison between dome-shaped and flat diaphragm

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# Medical Ultrasound Application (PZT)