Chapter 9
Materials for Mechanical-Electrical Conversion
Ferroelectric Ceramics

- **Ferroelectric Domains:** If unit cells do not have center of symmetry, dipole moments arise.
- Dipole moment of unit volume = sum of all dipole moments of cell.
- **Example:** BaTiO$_3$ unit cell is symmetric above 120$^0$C but below 120$^0$C (Cutie temperature) dipole moment is created due to shifting of Ti$^{4+}$ and O$^{2-}$ ions.
- If cooling takes place in electric field, dipoles align in the direction of the field.
Piezoelectrics

壓電性(piezoelectrics)是材料中一種機械能與電能互換的現象，此現象最早是由Pierre Curie以及Jacques Curie兄弟在1880年發現，他們發現若對電氣石(tourmaline)施加機械壓力，則其表面可產生電荷累積。自從這個現象被發現以後，各種材料的壓電性就被眾多學者所注意，並展開許多的基礎及應用研究。

壓電材料的種類有下列數種:
(1)單晶類(single crystal)：石英、電氣石、LiNbO₃、LiTaO₃等晶體。
(2)薄膜類(thin film)：ZnO等;
(3)聚合物類(polymer)：PolyVinylidene Fluoride (PVDF)等。
(4)陶瓷類(ceramic)：BaTiO₃、鈷鈦酸鉛(PZT)等。
(5)複合材料(composite material)：PVDF-PZT等。
Piezoelectric Effect

• If compressive force is applied to piezoelectric ceramic, it changes dimension and results in net dipole moment.
  ➢ Change in dipole moment changes the charge density at the ends and changes voltage difference between the ends.
  ➢ If electric field is applied to the sample, charge density changes resulting in change of dimension of the sample.

• Piezoelectric effect  ➔ Mechanical force  ➔ Electric response
Piezoelectric Materials

• **PZT ceramics**: Solid solutions of lead zirconate \((\text{PbZrO}_3)\) and lead titanate \((\text{PbTiO}_3)\)
  - **Have broader range of piezoelectric properties.**
  - **High curie temperature.**

• **Barium Titanate**: \((\text{BaTiO}_3)\) Commonly used.
  - **Low curie temperature.**

• **Applications**: Piezoelectric compression accelerometer, ultrasonic cleaning transducer and underwater sound transmitter.
PZT Oxides

lead(IV) oxide

titanium(IV) oxide
Polarization in PZT

Below $T_C \sim 500\text{C}$: Tetragonal Distortion / Induced Polarization

$\text{PbTiO}_3 = \text{Pb}^{(+2)}\text{Ti}^{(+4)}\text{O}^{(-2)}_3 \Rightarrow z^* \approx 6$

Induced Dipole Moment per unit cell: $p = (z^*e)(\Delta x)$

$P =$ dipole moment per unit vol. $= p/(\text{Vol})_\text{cell} = p/a^2c \approx 45\mu\text{C/cm}^2$
PZT Ceramic Characteristics

Representation of domain rotation and switching during poling of a polycrystalline PZT ceramic. Approximately 25% of all domains are 100% aligned after poling with a 40 kV/cm poling field.
PZT Active Material

**PZT chemical Pb(Ti-Zr)O₃ Structure:** Note gray Titanium (Ti) ion and brown Zirconium (Zr) ions in middle lattices. They and their surrounding Oxygen (O) ions oscillate up and down, while the more massive Lead (Pb) ions are relatively still. Note that the four face oxygen ions move in the **OPPOSITE DIRECTION** in relationship to the Ti or Zr ions. This tends to cancel some unbalanced forces.
Energy Storage in PZT Crystals

- Zero Energy Storage State
  - RED Arrows = Covalent Bonds
  - Purple Arrows = Ionic Bonds

- Energy storage "Springs"
  - Covalent/Ionic Bonds = Electron / E-Field

- Displacement from Zero point is proportional to stored energy.

- One of six Face Center Cubic Oxygen ions with ionic bonds to Pb ions and Covalent bonds to the Ti ion. The six oxygen ions move with the Ti ion but at a slower rate due to the eight Pb ionic bond’s drag.

- 8-Pb cage ions: AMU=1,656
  - Ti + 6-O ions: AMU=144
  - AMU Ratio: 11.5:1

- ~80k cal/mole vs. ~6k cal/mole

- Pb⁺²
  - AMU=207

- Ti⁺⁴
  - AMU=48

- O²⁻
  - AMU=16

- Energy is Stored in Extension and Compression of the PZT Unit Crystal’s Covalent & Ionic bonds generated springs between atoms.
PZT on Silicon

XTEM picture of the Direct Wafer interface between a PZT film grown by CSD and a Si (100) 3-inch wafer bonded by Direct Wafer Bonding (DWB).

SEM picture of several arrays of PZT nano-structures with various sizes obtained by direct electron beam writing. These PZT nano-structures could be used to make arrays of W-E unidirectional force generators in an integrated circuit like configuration.

FROM: http://www.mpi-halle.mpg.de/~ferrohtc/research.htm
壓電材料之動作產生

(a) poling axis

(b) F

(c) F

(d)

(e)

(f) \( \Delta \)
壓電振動之模態

MOTOR TRANSDUCER RELATIONSHIPS

PARALLEL & TRANSVERSE EXPANSION (OR CONTRACTION) MOTOR

Parallel Expansion
\[ \Delta T = Y d_{33} \]

Transverse Expansion
\[ \frac{\Delta L}{L} = \frac{\Delta W}{W} = \frac{Y d_{31}}{T} \]

SHEAR MOTOR

\[ \chi = Y d_{15} \]
The piezoceramic bender is a versatile low power electro-mechanical transducer.

As a motor, the application of an electric field across the two outer electrodes of the bender causes one layer to expand while the other contracts. The net result is a bending displacement much greater than the length deformation of either of the two layers. In this mode, the application of an electric field would be analogous to a temperature change on a bimetallic thermostat.

NOTE: Quantities must be in compatible units. Equations give magnitudes only. Signs are shown on drawing.
彎曲振動模態之型式

**Bending Motor, "S" configuration, cantilever mount**

<table>
<thead>
<tr>
<th>To convert cantilever to &quot;S&quot; beam performance:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_f = \frac{1}{2} \times$ cantilever motion</td>
</tr>
<tr>
<td>$F_b = \frac{1}{2} \times$ cantilever force</td>
</tr>
<tr>
<td>$F_r = $ same as cantilever frequency</td>
</tr>
<tr>
<td>$C = $ same as cantilever capacitance</td>
</tr>
<tr>
<td>Characteristics: end moves up and down in a parallel plane</td>
</tr>
</tbody>
</table>

**Bending Motor, simple beam mount**

<table>
<thead>
<tr>
<th>To convert cantilever to simple beam performance:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_f = \frac{1}{4} \times$ cantilever motion</td>
</tr>
<tr>
<td>$F_b = 4 \times$ cantilever force</td>
</tr>
<tr>
<td>$F_r = 3 \times$ cantilever frequency</td>
</tr>
<tr>
<td>$C = $ same as cantilever capacitance</td>
</tr>
<tr>
<td>Characteristics: center moves up and down in a parallel plane.</td>
</tr>
</tbody>
</table>
Series & Parallel Operation

**Series Operation** refers to the case where supply voltage is applied across all piezo layers at once. The voltage on any individual layer is the supply voltage divided by the total number of layers. A 2-layer device wired for series operation uses only two wires, one attached to each outside electrode.

**Parallel Operation** refers to the case where the supply voltage is applied to each layer individually. This means accessing and attaching wires to each layer. A 2-layer bending element wired for parallel operation requires three wires; one attached to each outside electrode and one attached to the center shim. For the same motion, a 2-layer element poled for parallel operation needs only half the voltage required for series operation.
Multi-Layer Motors

Any number of piezo layers may be stacked on top of one another. Increasing the volume of piezoceramic increases the energy that may be delivered to a load. As the number of layers grows, so does the difficulty of accessing and wiring all the layers. Typically, more than 4 layers becomes impractical.

Stack Motors: The co-fired stack seen below is a practical way to assemble and wire a large number of piezo layers into one monolithic structure. The tiny motions of each layer contribute to the overall displacement. Stack motion on the order of microns to tens of microns, and force from hundreds to thousands of Newtons is typical.
Piezoelectric Devices

* The electro-mechanical coupling depends on the piezoelectric properties, the size and shape, frequency, and the direction of mechanical excitation and electrical response.
* Typical operating modes: d31 and d33

* Although the coupling coefficient of d33 is much higher than d31, the use of d33 mode does not always result in better performances because of
  – Mechanical reasons (Clark and Ramsay 2002)
    • Mechanical stress applied into 1 direction is much easily achieved at lower force
  – Electrical reasons (Sodano et al. 2004)
Scope of Smart Materials

- Piezoelectric materials
  (Active Fiber Composite, etc)
- Electrostrictive and magnetostrictive materials
- Rheological materials
  (electrorheological and magnetorheological fluids)
- Thermoresponsive materials
  (Shape memory alloys)
- pH-sensitive materials
  (change colors as a function of pH)
- Electrochromic materials
  (change its optical properties with a voltage)
- Fullerenes
  (embedded into sol-gel matrices to enhance optical properties)
- Smart gels
  (shrink or swell by a factor of 1000 with any chemical/ physical stimulus)
- Electroactive polymer

Piezoelectric, Magnetic, Electret, Shape memory alloys
Smart Materials

- **Smart Materials**: Change their properties by sensing external stimulus.
  - **Shape memory alloys**: Strained material reverts back to its original shape above a critical temperature.
    - Used in heart valves and to expand arteries.
  - **Piezoelectric materials**: Produce electric field when exposed to force and vice versa.
    - Used in actuators and vibration reducers.
Shape Memory Alloys (SMA)

- SMA recover predefined shape when subjected to appropriate heat treatment.
- Recovers strain and exerts forces
- Examples: AuCd, Cu-Zn-Al, Cu-Al-Ni, Ni-Ti
- Processed using hot and cold forming techniques and heat treated at 500-800 °C at desired shape.
- At high temperature --- Regular cubic microstructure (Austenite)
- After cooling – Highly twinned platelets (Martensite)
Shape Memory Effect

- SMA easily deformed in martensite state due to twin boundaries and deformation is not recovered after load is removed.
- Heating causes Martensite ↔ Austenite transformation so shape is recovered.
- Effect takes place over a range of temperature.
SMA - Hysterisis

- Heating and cooling temperatures do not overlap – Exhibits hysterisis
- Applied stress may deform and transform SMA to martensite – stress induced transformation
- Shape is recovered when stress is released
- Nitonol (NiTi) is commonly used SMA
  - Shape memory strain of 8.5%
  - Non-magnetic, corrosion resistant
- Applications: Vascular stents, Coffeepot thermostats, eyeglass frames, orthodontics, vibration damper, surgical tools.
Applications of Smart Materials

Piezoelectric Material
(Piezoelectric Effect)

Vibration
(Mechanical Energy)

Circuit

Voltage and Current
(Electrical Energy)
Piezo-applications: vibration sensing/damping

Sensor input from subject wearing e-textile garment

Configuration: sensing, actuating, flexible

Smart shoes

Self-Powered Electronics

Electronic tennis racquet

Intelligence & control

Sensors

Actuators

Structures
Roles of Vibration

**Disadvantages**

**Impaired performance:**
- fatigue of structure
- reduced operating speed
- loss of precision
- decreased efficiency

**Health risks:**
- a critical factor in end-user comfort
- unwanted noise

**Advantages**

**Communication:**
- audio signal
- frequency spectra
- energy source

**Diagnosis**

**Damper Noise-cancellation**

**Powering**

Speaker
平面喇叭壓電發音片組成
平面喇叭壓電發音片之支撐方式

(a) Node support

\[ f_0 = \frac{0.412 \cdot t}{r^2} \sqrt{\frac{E}{\rho (1-\sigma^2)}} \]

(b) Edge support

\[ f_0 = \frac{0.233 \cdot t}{r^2} \sqrt{\frac{E}{\rho (1-\sigma^2)}} \]

(c) Central support

\[ f_0 = \frac{0.172 \cdot t}{r^2} \sqrt{\frac{E}{\rho (1-\sigma^2)}} \]

- \( f_0 \): Resonant frequency
- \( t \): Thickness
- \( r \): Radius of a metal plate
- \( E \): Young's modulus
- \( \rho \): Density
- \( \sigma \): Poisson's ratio
動圈式喇叭結構

How Speakers Work

diaphragm
dust cap
voice coil

spider
magnet

basket

©2001 How Stuff Works
畫面尺寸為4英寸，分辨率為VGA格式（640×480像素）。在顯示部分下面的空餘位置集成了一個聲道的功率放大器、D-A轉換電路和模塊輸入信號前置放大器等。玻璃底板尺寸與普通4英寸液晶面板相同，面積並沒有因集成音頻電路而增加。

兩個壓電揚聲器模塊連接後，播放音頻信號。利用低溫多晶矽形成電晶體元件，難以產生可驅動動態揚聲器（dynamic speaker）的電流。因此，所連接的揚聲器就想到採用電壓驅動的壓電揚聲器元件。展品末端功率放大器的工作電壓為±6V。
NCT uses a cool-running piezoelectric driver, rather than a magnet and voice coil, to induce vibrations in its panel.
The trend in the TV industry is toward slimmer, sleeker designs as evinced by the increasing numbers of LCD and Plasma TVs on the market.

Philips AD490W : wireless speakers

In multimedia applications manufacturers and consumers alike have already recognised the benefits of NXT's SurfaceSound and SoundVu technology.

NEC : Valuestar FS
The Macro Fiber Composite (MFC) consists of rectangular piezo-fibers sandwiched between layers of adhesive and electroded polyimide film.

**Benefits:**
* Flexible and durable
* Increased strain actuator efficiency
* Directional actuation/sensing
* Damage tolerant
* Conforms to surfaces
* Readily embeddable
* Environmentally sealed package
* Demonstrated performance
Fiber dicing/molding/extruding/sol-gel---polymer infiltration

Figure 1: 1-3 Composites by Smart Materials Corp.
a) Rectangular Fibers, b) Round Fibers.

Figure 3: Active Fiber Composite Schematic.

Figure 11: Active Composite Laminate with Hollow Cross-Section Fibers.
Applications of Smart Materials

- **Aerospace**
  - Noise reduction and increased precision or higher load-bearing capacity

- **Structures**
  - Health monitoring of building

- **Consumer**
  - Vibration damping in sport and household appliances
Soft Tactile

Trimorph.wmv

Hopper.wmv

LiveNet Wearable System
Smart Label (Chip in Foil)

- thin, flexible chips may be placed in foil compound
- smallest overall thickness
- integration of passive elements
- multilayer laminates with electrical via holes
- IC interconnects: isoplanar (over chip edges) or flip chip
Isoplanar Contacts and Laminating

combination of both methods ➔ extremely flat

assembly technology, lowest thickness

<table>
<thead>
<tr>
<th>thickness [μm]</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
</tr>
</thead>
<tbody>
<tr>
<td>carrier foil</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>coil</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>el. connection</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>metalized foil</td>
<td></td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>adhesive</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>chip</td>
<td>20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>cover foil</td>
<td>30</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>total thickness</td>
<td>90</td>
<td>100</td>
<td>90</td>
</tr>
</tbody>
</table>

thickness of standard paper: 80μm!
Wearable/Flexible Devices

Example 4: Wearable Ultra Micro Computers

Multi-Functional Audio/Video-Interface

Not Feelable Electronics

Computer and Energy-Source

Speech Control
Actions & Movement

Fraunhofer Institut Zuverlässigkeit und Mikrointegration Institutsteil München
智慧鞋的應用

衝擊階段

穩定階段

推進階段

<table>
<thead>
<tr>
<th>能量轉換</th>
<th>機械能→熱能釋放能量</th>
<th>機械能→位能釋放能量</th>
<th>機械能→動能釋放能量</th>
</tr>
</thead>
<tbody>
<tr>
<td>目的</td>
<td>無</td>
<td>穩定身軀/重心轉移</td>
<td>移動身軀/釋放能量</td>
</tr>
</tbody>
</table>

資料來源：工研院材化所
W = F * △S * k^2
60kg * 9.8N/kg * 0.01m * (0.3~0.4)^2
= 0.5~0.9 J/step

F = W * k^2 / △S
(0.5~0.9) * (0.7)^2
/ 0.005m / 9.8N/kg
= 5~9 kg

智慧鞋的應用
洋流壓電換能器

DARPA Objective: Convert mechanical energy from a fluid medium into electrical energy

- Fluid flow creates oscillations in an eel body
- Creates strain energy that is converted to AC electrical output by piezoelectric polymers

3.082 Objective: Demonstrate that piezoelectric materials can be used to harness power from airflow and determine the maximum amount of useful power that can be harvested with a single eel tail
Important Aspects for Energy Harvesting

* Convert energy from ambient sources
* Ambient energy sources
  – mechanical, thermal, environmental
  – Biological
* Three components
  – Energy conversion
  – Harvesting and Conditioning Circuit
  – Energy Storage

Lesieutre et al, 2004
Piezoelectric (PZT) Devices

Materials can convert ambient vibration into electricity.

* Kymissis et al. (1998) investigated energy harvesting from piezoelectric devices located in shoes

Energy harvesting eel, Ocean Technology, Inc

Gyuhae Park
Engineering Institute
Engineering Sciences & Applications
Los Alamos National Laboratory
Sodano et al (2003) investigated the amount of energy that can be harvested w/o using any power conditioning circuits

* PZT (40 x 60 mm) bonded to surface.
* Shaker used to apply a point input
* The various input signals were given (random- car compressor, Chirp, harmonic)
* Produced a maximum power of 1.9 mW, an average power of 0.12 mW
Mechanical tuning is important to maximize the power output (Cornwell et al 2003)

* A great improvement was observed when the resonance of the harvester matches that of the structure.

Figure from UC Berkley
*Precise mechanical tuning is not always possible.
*Vibrations excite multiple piezoelectric materials of varying lengths.
*Electrical signal from each bimorph is rectified and added.
*Total rectified voltage can be used.
Commercial Products

- Microstrain, Inc.,
- Integrated piezoelectric harvester and wireless temperature & humidity sensing node.
- 2.7 mW of power @57 Hz.

- KCF technology
- Dynamic power-harvesting demonstration for truck tires

- Continuum Inc, iPower
- Used as a backup energy source
大阪大學石黑浩教授研究團隊所研製的Repliee Q1為日本科學家號稱是「有史以來最逼真」的機器人，不只擁有彈性色澤皮膚，並能對特定刺激產生反應。圖中左為Repliee Q1機器人，右為真人，可能有不少人會一下子給搞錯。(中時晚報/焦點話頭/05版2005/07/31)
Surgical Swimming Micro-Robots

S. Payen & J. Edd, UCB