Ferroelectrics and piezoelectrics for MEMS

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MEMS materials tree

Gyros/accelerometers
Capacitive actuation/sensing
Piezoresistive sensing
Thermal devices
Pressure sensors (PRESENCE)
Airbag sensors (SENSONOR)
Optical emission/detection/reflection (SIMRAD OPTRONICS)

Si-only MEMS

Metal alloys

SAW/BAW (NORSPACE)
RF-MEMS

Ferroelectric memories
Piezoelectric
Pyroelectric
IR devices/imaging
Electrooptic
Optical switches
Modulators

Microfluidics
Bio-MEMS
Microreactors
Optical MEMS
"CD-technology"
Lab-on-a-chip (NORCHIP)
Spectrophotometer (TOMRA)

Academic
Soon commercial
Commercial

Microelectronics
Microstructuring
Physics
Chemistry
Life science

Materials science
# Mechanical actuation and sensing in MEMS

<table>
<thead>
<tr>
<th>Mechanism</th>
<th>Thermal</th>
<th>Piezo-resistive</th>
<th>Capacitive</th>
<th>Electromagnetic</th>
<th>Piezoelectric</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>MEMS with functional materials</td>
<td></td>
</tr>
<tr>
<td>Si-only MEMS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Comment</td>
<td>Thermal expansion $\Delta r \propto \Delta T$</td>
<td>Piezoresistivity $\Delta R \propto \Delta I$</td>
<td>Capacitive force on charged membrane $F \propto 1/d$</td>
<td>Difficult to scale down/make inductor</td>
<td>Few materials</td>
</tr>
<tr>
<td></td>
<td>Slow, small amplitude Bad energy conversion</td>
<td>Sensing only Small amplitude</td>
<td>Non-linear</td>
<td>Piezoelectricity $\Delta I \propto \Delta E$</td>
<td>Linear</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Large amplitude</td>
<td>High energy conversion</td>
</tr>
<tr>
<td>Sensing</td>
<td>-</td>
<td>++</td>
<td>+++</td>
<td>+</td>
<td>+++</td>
</tr>
<tr>
<td>Actuation</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>+++</td>
</tr>
</tbody>
</table>
Comparison different material classes

<table>
<thead>
<tr>
<th>Properties</th>
<th>Shape-memory alloy (Ti–Ni)</th>
<th>Piezoelectric (PZT)</th>
<th>Magnetostrictive (Terfenol-D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressive stress (MPa)</td>
<td>~800</td>
<td>60</td>
<td>700</td>
</tr>
<tr>
<td>Tensile strength (MPa)</td>
<td>800–1000</td>
<td>30–55</td>
<td>28–35</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>50–90 (P)</td>
<td>60–90 (Y&lt;sup&gt;E&lt;/sup&gt;)&lt;sup&gt;a&lt;/sup&gt;</td>
<td>25–35 (Y&lt;sup&gt;H&lt;/sup&gt;)&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>10–35 (M)</td>
<td>~110 (Y&lt;sup&gt;D&lt;/sup&gt;)&lt;sup&gt;b&lt;/sup&gt;</td>
<td>50–55 (Y&lt;sup&gt;B&lt;/sup&gt;)&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>Maximum strain</td>
<td>~0.1</td>
<td>~0.001</td>
<td>~0.01</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>0–100</td>
<td>1–20000</td>
<td>1–10000</td>
</tr>
<tr>
<td>Coupling coefficient</td>
<td>~</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>3–5</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>Energy density (kJ m&lt;sup&gt;–3&lt;/sup&gt;)</td>
<td>300–600</td>
<td>~1.0</td>
<td>14–25</td>
</tr>
</tbody>
</table>

<sup>a</sup> modulus for constant electric field
<sup>b</sup> modulus for constant electric displacement
<sup>c</sup> modulus for constant magnetizing field
<sup>d</sup> modulus for constant induction field
### Different actuator types

<table>
<thead>
<tr>
<th></th>
<th>PZT5H</th>
<th>PMN</th>
<th>PLZT</th>
<th>PVDF</th>
<th>Terfinol-D</th>
<th>SMA (NiTi)</th>
<th>Conducting Polymer</th>
<th>Polymer Hydro-gel</th>
<th>Human Muscle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max strain (x 10^{-6})</td>
<td>300</td>
<td>600</td>
<td>3000</td>
<td>200</td>
<td>1800</td>
<td>70000</td>
<td>20000</td>
<td>400000</td>
<td>400000</td>
</tr>
<tr>
<td>Max stress (MPa)</td>
<td>19</td>
<td>72</td>
<td>180</td>
<td>~1</td>
<td>90</td>
<td>190</td>
<td>180</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Density (kg/m^3)</td>
<td>7500</td>
<td>7500</td>
<td>~7500</td>
<td>1780</td>
<td>9250</td>
<td>6450</td>
<td>~1500</td>
<td>~1300</td>
<td>1037</td>
</tr>
<tr>
<td>Modulus (GPa)</td>
<td>62</td>
<td>120</td>
<td>~60</td>
<td>3</td>
<td>40</td>
<td>78</td>
<td>5</td>
<td>&lt;0.1</td>
<td>0.06</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>56</td>
<td>75</td>
<td>?</td>
<td>2</td>
<td>40</td>
<td>&gt;3</td>
<td>&gt;30</td>
<td>30</td>
<td>&gt;35</td>
</tr>
<tr>
<td>Bandwidth (Hz)</td>
<td>1000</td>
<td>1000</td>
<td>?</td>
<td>1000</td>
<td>100</td>
<td>3</td>
<td>&gt;1</td>
<td>.1</td>
<td>4</td>
</tr>
<tr>
<td>Energy density (KJ/m^3)</td>
<td>2.9</td>
<td>22</td>
<td>?</td>
<td>~1</td>
<td>19</td>
<td>&gt;10</td>
<td>&gt;1</td>
<td>0.4</td>
<td>0.8</td>
</tr>
</tbody>
</table>
PZT-PLZT phase diagram

Strong
- piezoelectric
- pyroelectric
- electrooptic
- relaxor

Effects are observed in this system

FE = ferroelectric
AFE = antiferroelectric
PE = paraelectric
Production PZT-MEMS

- Chemical solution deposition (SINTEF)
- RF-sputtering (EPFL)
- Pulsed laser deposition

Processing steps – MEMS-pie

Starting point: SOI wafer (buried oxide layer)

- Pt electrode and seed layer (100 nm)
- TiO$_2$ barrier/adhesion layer (20 nm)
- Piezoelectric thin film layer (2 µm)
- Top electrode deposition and patterning (lift off patterning)
- PZT patterning
- Back side etch (wet etch with protected front side)
- Pattern and release etch of cantilevers
Types of piezoelectric MEMS

Whole wafer structure

MEMS membrane

MEMS cantilever

Top electrode
Piezoelectric
Bottom electrode
Support layer
Substrate

Top electrode
Piezoelectric
Bottom electrode
Support layer
Substrate

d
MEMS fabrication (texture and stresses)

- PZT on Pt/Ti/SiO$_2$/Si or Pt/Ti/TiO$_2$/SiO$_2$
- Texture and residual stresses are important
- Texture determines the properties along different directions
- Residual stresses affect also the properties and life of the components.
- Residual stresses are due to different thermal expansion properties and crystallographic matching
- Applying a stress opposed to the observed one can improve properties.
- Domain wall motion is little observed in thin films
Applications: MEMS
Piezoelectric microcantilever working principle:

Transverse piezoelectric effect is utilised, $d_{31} + e_{31}$
Piezoelectric microsensor

Double cantilever: 4 piezoelectric layers

Controlled vibration electrically induced
Accelerometers (MEMS inertial sensors)

Automotive:
- Airbag: accelerometers
- ESP: gyroscopes

The smallest gyroscope is a piezoelectric one by Seiko-Epson: 21 mm³

<table>
<thead>
<tr>
<th>3-axis accelerometer</th>
<th>2-axis gyroscope</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 to $1.5</td>
<td>$4 to $5</td>
</tr>
<tr>
<td>micro-controller unit (ASIC+software)</td>
<td>$2 or 3-axis magnetometers $1.5</td>
</tr>
</tbody>
</table>

Packaging and assembly $0.5

Total IMU: $5.5 to $9
<table>
<thead>
<tr>
<th>Consumer product</th>
<th>Function</th>
<th>Examples of products</th>
<th>MEMS inertial device(s)</th>
<th>Status of commercialisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDA</td>
<td>Navigation IMU, Web content navigation</td>
<td>Toshiba PocketPC e740</td>
<td>2- or 3-axis accelerometer 2-axis gyroscope</td>
<td>Demonstrator in 2002 at Paris PDA show</td>
</tr>
<tr>
<td>Digital still cameras (DSC)</td>
<td>Image stabilisation</td>
<td>All Panasonic DSCs, e.g. Lumix ($200), Pentax Optio A10 ($350) Canon, Sony DSCs</td>
<td>Two 1-axis gyroscopes or one 2-axis gyroscope Two 2-axis accelerometers</td>
<td>Gyroscope established since late 1990s Accelerometer emerging</td>
</tr>
<tr>
<td>Camcorders</td>
<td>Image stabilisation, free-fall detection (HDD protection)</td>
<td>Upper end: Panasonic (over $1500) High end: JVC 30 Gb, Toshiba 60 Gb</td>
<td>Two 1-axis gyroscopes or one 2-axis gyroscope</td>
<td>Gyroscope established since late 1990s</td>
</tr>
<tr>
<td>Laptops</td>
<td>Free fall detection (HDD protection), GPS dead-reckoning assist (anti-theft)</td>
<td>IBM, Toshiba, Apple laptops</td>
<td>2- or 3-axis accelerometer</td>
<td>Free-fall detection established Other applications emerging</td>
</tr>
<tr>
<td>MP3 players</td>
<td>Free fall (HDD protection)</td>
<td>iPod with hard disc drive</td>
<td>3-axis accelerometer</td>
<td>Established</td>
</tr>
<tr>
<td>Others: toys, games, personal transporter, robots</td>
<td>Realistic motion</td>
<td>Nintendo’s Kirby “Tilt-n-Tumble” GameBoy Microsoft gamepad “Sidewinder Freestyle Pro”, Segway, Sony Aibo robot, Sony PS3</td>
<td>2- or 3-axis accelerometers, 1- or 2-axis gyroscopes</td>
<td>Established</td>
</tr>
</tbody>
</table>
Accelerometers for aerospace and military applications.
Piezoelectric accelerometers

Accelerations up to 200000g
0.2 grams, 5.21 mm long

From 7 to < 1 grams

Accelerations up to 200000g
Full integration and isolation (aerospace)

Full isolation from acoustic, thermal effects to achieve response at <0.1 Hz

Full integration of electronic circuits