Microsystems = sensors + actuators + signal transduction

Sensor

- A sensor is a transducer that converts the measurand (a quantity or parameter) into a signal that carries information.
- An ideal sensor:
  - continuous operation without affecting the measurand
  - appropriate sensitivity and selectivity
  - high signal to noise ratio
  - easy to calibrate
  - compact

Micro Sensors:
- Acoustic wave sensors
- Biomedical and biosensors
- Chemical sensors
- Optical sensors
- Pressure sensors
- Stress sensors
- Thermal sensors

Micro Actuators:
- Grippers, tweezers and tongs
- Motors - linear and rotary
- Relays and switches
- Valves and pumps
- Optical equipment (switches, lenses & mirrors, shutters, phase modulators, filters, waveguide splitters, latching & fiber alignment mechanisms)

MEMS permits integration of sensors, actuators, computation, and communication into one batch-fabricated device

Mass Sensitive Devices

- Surface acoustic wave devices
- Quartz crystal microbalance
- take advantage of the piezoelectric effect
  - deformation of the piezoelectric crystal lattice results in charge appearing on the electrodes.
  - transformation of mechanical energy into electrical energy

Quartz crystal microbalance (QCM)

The QCM is an ultra sensitive mass sensor. The piezoelectric AT-cut quartz crystal is sandwiched between a pair of electrodes. The electrodes are connected to an oscillator and an AC voltage is applied over the electrodes. The quartz crystal oscillates at its resonance frequency due to the piezoelectric effect. The cut angle with respect to crystal orientation determines the mode of oscillation.

The AT-cut across the optical axis (along the growth direction) gives a shear that is perpendicular to the crystal face. The AT cut quartz has nearly zero frequency drift at room temperature.

Rapid detection of bacteria by PCR and quartz crystal microbalance
**Magnetic Properties of Solids**

- Microscopic ordering of electron spins leads to the formation of regions of magnetic alignment called domains.

---

**Biomedical Sensors and Biosensors**

These sensors are extensively used in medical diagnosis, environmental protection, drug discovery and delivery, etc.

**Biomedical Sensors**

For the measurements of biological substances in the sample and also for medical diagnosis purposes.

**Input signal:** Biological sample (typically in minute amount in micro or nano liters)

**Micro sensing element:** a chemical that reacts with the sample.

**Transduction unit:** the product of whatever the chemical reactions between the sample and the chemical in the sensing element will convert itself into electrical signal (e.g. in mille volts, mV).

**Output signal:** The converted electrical signal usually in mV.

---

**Biosensors**

These sensors work on the principle of interactions between the biomolecules in the sample and the analyte (usually in solution) in the sensor.

**Signal transduction is done by the sensing element as shown Below:**

---

**Transducers used in Biosensor development**

<table>
<thead>
<tr>
<th>Category</th>
<th>Principle</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrochemical</td>
<td>(i) potentiometric; depends on changes in potential of a system at a contact (E)</td>
<td>Solid electrode gas sensors, electronic nose</td>
</tr>
<tr>
<td></td>
<td>(ii) amperometric; detects changes in current as a function of concentration of electroactive species</td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>Light changes in light intensity changes in mass or concentration.</td>
<td>Optical fibre, surface plasmon resonance, fluorescence</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>Sensitive to changes in mass, density, viscosity and acoustic coupling phenomena</td>
<td>Surface acoustic wave sensors</td>
</tr>
<tr>
<td>Thermal</td>
<td>Direct changes in temperature</td>
<td>Calorimetric sensors</td>
</tr>
</tbody>
</table>
Electrical/Electrochemical Detection

1. Amperometric biochips, which involves the electric current associated with the electrons involved in redox processes.
2. Potentiometric biochips, which measure a change in potential at electrodes due to ions or chemical reactions at an electrode (such as an ion Sensitive FET).
3. Conductometric biochips, which measure conductance changes associated with changes in the overall ionic medium between the two electrodes.

Cantilever-based Biosensors

Two modes of operation:
- static deflection
- resonance frequency shift

Mechanical Sensors

- Construction:
  a) Cantilever beam,
  b) Bridge structure,
  c) Diagram or membrane.

- Detection Methods:
  - Electrical,
  - Magnetic,
  - Optical,
  - Acoustic.

Cantilever Microfabrication

- The displacement $x$ of the beam is related to the applied force and length of the beam:
  \[
  \Delta x = \frac{\rho}{2EI_m} F_s \quad \text{or} \quad F_s = \frac{k_m}{x} \Delta x \quad (k_m \text{ is the spring constant})
  \]

Where:
- $E_m$ is Young's modulus,
- $I_m$ is the second moment of inertia,
- $F_s$ is the force or point load, and
- $L$ is the length.
Stress Sensitive Affinity Sensors

Ligands binding to receptors adsorbed to only one side of the cantilever interact either attractively or repulsively among each other and induce surface stress, hence changing the surface energy of this side with respect to the other.

Differential Sensing

Deflection of cantilever measured by focusing a laser beam to the tip of the cantilever and measuring the location of the reflected beam.

- a single cantilever is sensitive to:
  - nonspecific adsorption
  - changes in pH
  - temperature (bimetallic effect caused by the thin metal layer used to aid functionalization and laser reflectivity)
  - use a reference cantilever, differential measurement

Mass Change Detection

- Mass sensitive cantilever can be used in affinity assays or particle detection

\[ F_0 = \frac{1}{2\pi} \sqrt{\frac{k}{m}} \]

\[ F_1 = \frac{1}{2\pi} \sqrt{\frac{k}{m + \Delta m}} \]

- \( k \) = spring constant
- \( m \) = mass of cantilever
- \( f_0 \) = unloaded resonant frequency
- \( f_1 \) = loaded resonant frequency

\[ \Delta m = \frac{k}{4\pi^2} \left( \frac{1}{f_1^2} - \frac{1}{f_0^2} \right) \]

Minimum detectable mass

\[ \Delta m_{\text{min}} = \frac{k}{4\pi^2} \left( \frac{1}{f_1^2} - \frac{1}{f_0^2} \right) \]

Bacterial detection

Chemical Sensors

Work on simple principles of chemical reactions between the sample, e.g. \( \text{O}_2 \) and the sensing materials, e.g. a metal.

Signal transduction is the changing of the physical properties of the sensing materials after the chemical reactions.

There are four (4) common types of chemical sensors:

1. Chemiresistor sensors.
2. Chemicapacitor sensors.

Chemically Sensitive Polyimide

Input current or voltage

Metal Insert

Change of Resistance

Output

Input Voltage

Metal Electrodes

Capacitance Change

Output

Measurand Gas
(3) Chemimechanical sensors:
Work on certain materials (e.g. polymers) that change shapes when they are exposed to chemicals. Measuring the change of the shape of the sensing materials to determine the presence of the chemical.

(4) Metal oxide gas sensors:
Sensing materials: certain semiconducting materials, e.g. SnO2 change their electrical resistance when exposed to certain chemicals.

Available metal oxide gas sensors:

<table>
<thead>
<tr>
<th>Semiconducting Metals</th>
<th>Catalyst Additives</th>
<th>Gas to be Detected</th>
</tr>
</thead>
<tbody>
<tr>
<td>BaTiO3, CaO</td>
<td>La2O3, CaCO3</td>
<td>CO2</td>
</tr>
<tr>
<td>SnO2</td>
<td>Pt + Sb</td>
<td>CO</td>
</tr>
<tr>
<td>SnO2</td>
<td>Pt</td>
<td>Alcohols</td>
</tr>
<tr>
<td>SnO2</td>
<td>Sb2O3</td>
<td>H2, O2, H2S</td>
</tr>
<tr>
<td>SnO2</td>
<td>CaO</td>
<td>H2S</td>
</tr>
<tr>
<td>ZnO</td>
<td>V, Mo</td>
<td>Halogenated hydrocarbons</td>
</tr>
<tr>
<td>WO3</td>
<td>Pt</td>
<td>NH3</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>Ti-doped + Au</td>
<td>CO</td>
</tr>
<tr>
<td>Ga2O3</td>
<td>Au</td>
<td>CO</td>
</tr>
<tr>
<td>MoO3</td>
<td>None</td>
<td>NO2, CO</td>
</tr>
<tr>
<td>SnO2</td>
<td>None</td>
<td>O2</td>
</tr>
</tbody>
</table>

Optical Sensors
• These sensors are used to detect the intensity of lights.
• It works on the principle of energy conversion between the photons in the incident light beams and the electrons in the sensing materials.
• The following four (4) types of optical sensors are available:

<table>
<thead>
<tr>
<th>Type</th>
<th>Diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>a) Photovoltaic junction</td>
<td><img src="image1" alt="Diagram" /></td>
</tr>
<tr>
<td>b) Photoconductive device</td>
<td><img src="image2" alt="Diagram" /></td>
</tr>
<tr>
<td>c) Photodiodes</td>
<td><img src="image3" alt="Diagram" /></td>
</tr>
<tr>
<td>d) Phototransistors</td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
</tbody>
</table>

Silicon (Si) and Gallium arsenide (GaAs) are common sensing materials. GaAs has higher electron mobility than Si- thus higher quantum efficiency.

Other materials, e.g. Lithium (Li), Sodium (Na), Potassium (K) and Rubidium (Rb) are used for this purpose.

Pressure Sensors
• Micro pressure sensors are used to monitor and measure minute gas pressure in environments or engineering systems, e.g. automobile intake gas pressure in manifold to the engine.
• They are among the first MEMS devices ever developed and produced for “real world” applications.
• Micro pressure sensors work on the principle of mechanical bending of thin silicon diaphragm by the contact air or gas pressure.
Signal Mapping:
Develop and establish strategies in selecting both the type and positions of the transducers for the MEMS device of microsystem.

Common Transducers for MEMS and Microsystems

<table>
<thead>
<tr>
<th>Transducers</th>
<th>Electric signals</th>
<th>Input or Output</th>
<th>Typical applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piezoresistors</td>
<td>Resistance, R</td>
<td>Output</td>
<td>Pressure sensors</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>Voltage, V</td>
<td>Input or Output</td>
<td>Actuators, accelerometers</td>
</tr>
<tr>
<td>Capacitors</td>
<td>Capacitance, C</td>
<td>Input or Output</td>
<td>Actuators by electrostatic forces, Pressure sensors</td>
</tr>
<tr>
<td>Electro-resistive heating/Shape memory alloys</td>
<td>Current, i</td>
<td>Input</td>
<td>Actuators</td>
</tr>
</tbody>
</table>

Signal mapping for a micro pressure sensor:
Piezoresistors are used to sense the change of electrical resistance relating to the induced stresses at the location.

Three locations are chosen for these piezoresistors in the following 3 cases:

Case 1: Square die/square diaphragm:
Case 2: Rectangular die/rectangular diaphragm
Case 3: For shear deformation in square diaphragm

Signal transduction by Wheatstone bridge:
- 4 gages involved in the bridge.
- $R_1 = R_2 = R_3 = R_4$ are the variable resistance
- $R_1$, $R_2$, $R_3$, and $R_4$ are fixed resistance.

For static conditions:
The voltage $V_o$ is adjusted to zero:

$$R_1 \times R_2 \times R_3 \times R_4 = R_1 \times R_2 \times R_3 \times R_4$$

For dynamic conditions:
The voltage $V_o$ changes with time, and the changes are recorded.

The change of the measured resistance is:

$$\frac{\Delta R_i}{R_i} = 1 - \frac{V_o}{V_{in}} \times \frac{R_i}{R_1 + R_2 + R_3 + R_4}$$

where $R_i$ is the original value of $R_4$

Signal transduction bridge for capacitance measurements:
- 4 capacitors are involved in the bridge.
- There are 3 identical capacitors with capacitance $C$.
- The 4th capacitor with varying capacitance, e.g. with gap change between two plate electrodes.
- The bridge is subjected to a constant input voltage, $V_{in}$.
- The variation of capacitance, $\Delta C$ in this capacitor may be obtained from the measured output voltage, $V_o$:

$$\Delta C = \frac{4C V_o}{V_{in} - 2V_o}$$

Other ways of transducing the deformation of the diaphragm to electronic output signals are available, e.g.,

- By capacitance changes (for higher temperature applications)
- By resonant vibration (for higher resolutions)

Major problems in pressure sensors involve the packaging and protection of the diaphragm from the contacting pressurized air or gas.
Thermal Sensors

- Thermal sensors are used to monitor or measure temperature in an environment or an engineering system.
- Common thermal sensors involve thermocouples and thermopiles.
- Thermal sensors work on the principle of the electromotive forces (emf) generated by heating the junction made by dissimilar materials (beads):

\[ V = \beta \Delta T \]

where \( \beta \) is the Seebeck coefficient.

### The Seebeck coefficients for various thermocouples are:

<table>
<thead>
<tr>
<th>Type</th>
<th>Wire Materials</th>
<th>Seebeck Coefficient (( \mu \text{V/°C} ))</th>
<th>Range (°C)</th>
<th>Range (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>Chromel/constantan</td>
<td>58.70 at 0°C</td>
<td>-270 to 1000</td>
<td>-84.4 to 76.36</td>
</tr>
<tr>
<td>J</td>
<td>Iron/constantan</td>
<td>50.37 at 0°C</td>
<td>-210 to 1200</td>
<td>-8.10 to 69.54</td>
</tr>
<tr>
<td>K</td>
<td>Chromel/constantan</td>
<td>39.48 at 0°C</td>
<td>-270 to 1372</td>
<td>-5.55 to 54.87</td>
</tr>
<tr>
<td>R</td>
<td>Platinum (10%) - Rh/Pt</td>
<td>10.19 at 600°C</td>
<td>-50 to 1768</td>
<td>-0.24 to 18.70</td>
</tr>
<tr>
<td>T</td>
<td>Copper/constantan</td>
<td>38.74 at 0°C</td>
<td>-270 to 400</td>
<td>-6.26 to 20.87</td>
</tr>
<tr>
<td>S</td>
<td>Pt (13%)-Rh/Pt</td>
<td>11.35 at 600°C</td>
<td>-50 to 1768</td>
<td>-0.23 to 21.11</td>
</tr>
</tbody>
</table>

Common thermocouples are of K and T types.

### Thermopiles

Thermopiles are made of connecting a series of thermocouples in parallel:

\[ \Delta V = N \beta \Delta T \]

with \( N \) being the number of thermocouple pairs in the thermopile.

### Thermal Flow Sensor

- The heat transferred per unit time from a resistive wire heater to a moving liquid is monitored with a thermocouple.

\[ \frac{\partial Q}{\partial t} = \frac{Q}{R} \]

\[ Q = \rho \cdot \frac{dV}{dt} \]

\[ \rho = \text{density} \]

\[ dV = \text{volumetric flow rate} \]

\[ \text{mass flow rate} = \rho \cdot \text{volumetric flow rate} \]

\[ \text{density} = \rho = \text{mass flow rate} / \text{volumetric flow rate} \]
Hall Effect Sensor

- The theoretical Hall voltage is expressed as follows:

\[
V_H = \left( \frac{1}{ne} \right) I_x B_z = R_H \frac{I_x B_z}{d}
\]

Where
- \( n \) is the carrier density,
- \( e \) is the electronic charge, \( 1.66 \times 10^{-19} \) C,
- \( I_x \) is the current,
- \( B_z \) is the magnetic flux,
- \( d \) is the slab thickness and
- \( R_H \) is the Hall Coefficient (small in metals, \(-1 \times 10^{-4} \text{ cm}^3/\text{C} \); and higher in semiconductors).

When a current \( I_x \) is passed down a slab of material of length \( l \), thickness \( d \), and a perpendicular magnetic flux density \( B_z \) is applied, a voltage \( V_H \) appears across the slab perpendicular to \( I_x \) and \( B_z \).

---

Working Principles for Micro Actuators

- **Power supply**: Electrical current or voltage.
- **Transduction unit**: To covert the appropriate form of power supply to the ones accepted by the actuating element.
- **Actuating element**: A material or component that moves with power supply.
- **Output action**: Usually in a prescribed motion.

---

Actuation Using Thermal Forces

- Solids deform when they are subjected to a temperature change (\( \Delta T \)).
- A solid rod with a length \( L \) will extend its length by \( \Delta L = \alpha \Delta T \), in which \( \alpha \) = coefficient of thermal expansion (CTE) – a material property.
- When two materials with distinct CTE bonded together and subject to a temperature change, the compound material will change its geometry as illustrated below with a compound beam:

![Compound Beam Diagram]

- These compound beams are commonly used as micro switches and relays in MEMS products.

---

Actuation Using Shape Memory Alloys (SMA)

- SMA are the materials that have a “memory” of their original geometry (shape) at a typically elevated temperature upon production.
- These alloys are deformed into different geometry at typically room temperature.
- The deformed SMA structures will return to their original shapes when they are heated to the elevated temperature at which they were produced.
- Ti-Ni is a common SMA.
- A micro switch actuated with SMA:

![SMA Micro Switch Diagram]

---

Actuation Using Piezoelectric Crystals

- A certain crystals, e.g. quartz exhibit an interesting behavior when subjected to mechanical deformation or electric voltage.
- This behavior may be illustrated as:

![Piezoelectric Behavior Diagram]

- This peculiar behavior makes piezoelectric crystals ideal candidate for micro actuation as illustrated in the following case:
Piezoelectric Crystals

- Piezoelectric crystals are solid ceramic compounds that produce piezoelectric effects:
  - Mechanical forces induced electric voltage
  - Electric voltage induced mechanical deformation

- Natural piezoelectric crystals are: quartz, tourmaline and sodium potassium tartrate.
- Synthesized crystals are: Rochelle salt, barium titanate and lead zirconate.

Mechanical strain by electric field:

\[ \varepsilon = \frac{d V}{V} \]

where \( \varepsilon \) = induced strain
\( d \) = piezoelectric coefficient
\( V \) = applied voltage, \( V/m \)

Piezoelectric coefficients:

<table>
<thead>
<tr>
<th>Piezoelectric Crystals</th>
<th>Coefficient, ( d ) (10^{-12} m/Volt)</th>
<th>Electromechanical conversion factor, ( K** )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz (crystal SiO₂)</td>
<td>2.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Barium titanate (BaTiO₃)</td>
<td>10-190</td>
<td>0.49</td>
</tr>
<tr>
<td>Lead zirconate titanate, PZT (PbTi₁₋ₓZrₓO₃)</td>
<td>480</td>
<td>0.72</td>
</tr>
<tr>
<td>PbZrTiO₃</td>
<td>250</td>
<td></td>
</tr>
<tr>
<td>PbNb₂O₆</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Rochelle salt (NaKC₄H₄O₆-4H₂O)</td>
<td>350</td>
<td>0.78</td>
</tr>
<tr>
<td>Polyvinylidene fluoride, PVDF</td>
<td>18</td>
<td></td>
</tr>
</tbody>
</table>

** = Output of mechanical energy
Input of electrical energy

or

\( K^* \) = Output of electrical energy
Input of mechanical energy

Example 7.4

A thin piezoelectric crystal film, PZT, is used to transduce the signal in a micro accelerometer involving a cantilever beam made of silicon. The accelerometer is designed for a maximum acceleration/deceleration of 10 g.

A PZT transducer is located at the support of the cantilever beam where the maximum strain exists (near the support) during the bending of the beam as illustrated below.

Determine the electrical voltage output from the PZT film at the maximum acceleration/deceleration of 10 g.

** Example 7.5 **

Determine the required electric voltage for ejecting a droplet of ink from an inkjet printer head using PZT piezoelectric crystal as a pumping mechanism.

The ejected ink will have a resolution of 300 dpi (dots per inch). The ink droplet is assumed to produce a dot with a film thickness of 1 μm on the paper.

The geometry and dimension of the printer head is illustrated at the right. Assume that the ink droplet takes a shape of a sphere and the inkwell is always re-filled after each ejection.
Example 7.5 – Cont’d

Solution:

- Determine the ejection nozzle diameter, \( d \):

The diameter of the dot film on the paper is:

\[ D = 1/300 \text{ inch} = 0.084666 \text{ mm} = 84.67 \text{ \( \mu \)m} \]

By equating the volumes of the dot sphere and the flat dot on the paper, we have:

\[ \frac{4}{3} \pi r^3 = \frac{\pi}{4} D^2 t \]

from which, we get the radius of the dot, \( r = 11.04 \times 10^{-6} \text{ m} \), with \( D = 84.7 \text{ \( \mu \)m} \) and \( t = 1 \text{ \( \mu \)m} \)

We assume that:

Volume of an ink droplet leaving the ink well = Volume created by vertical expansion of the PZT cover

Let \( W \) = vertical expansion of the PZT cover induced by the applied voltage, \( V \)

\[ \Delta \text{ = diameter of the PZT cover = 2000 \( \mu \)m} \]

We will have:

\[ W = \frac{4V \Delta^2}{\pi \Delta} = \frac{4 \times 5629.21 \times 10^{-18}}{3.1416 \times (2000 \times 10^{-6})^2} = 1791.83 \times 10^{-12} \text{ m} \]

The corresponding strain in the PZT piezoelectric cover is:

\[ \varepsilon = \frac{W}{L} = \frac{1791.83 \times 10^{-12}}{10^{-6}} = 179.183 \times 10^{-6} \text{ m/m} \]

The piezoelectric coefficient of the PZT crystal is \( d = 480 \times 10^{-12} \text{ m/V} \), leading to the required voltage to be:

\[ V = \frac{\varepsilon}{d} = \frac{179.183 \times 10^{-6}}{480 \times 10^{-12}} = 0.3733 \times 10^6 \text{ volts/m} \]

or

\[ V = L \varepsilon = \left(0 \times 10^{-6}\right) \left(0.3733 \times 10^9\right) = 3.733 \text{ volts} \]

The induced capacitance, \( C \) is:

\[ C = \varepsilon \varepsilon_0 \frac{A}{d} = \varepsilon \varepsilon_0 \frac{WL}{d} \]

The induced normal force, \( F_d \) is:

\[ F_d = -\frac{1}{2} \varepsilon \varepsilon_0 \frac{WL}{d^2} V^2 \]

in which \( \varepsilon \) = relative permittivity of the dielectric material between the two plates (see Table 2.2 for values of \( \varepsilon \) for common dielectric materials).

Actuation Using Electrostatic Forces

- Electrostatic Force Normal to Two Electrically Charged Plate electrodes:

- The induced capacitance, \( C \) is:

\[ C = \varepsilon \varepsilon_0 \frac{A}{d} = \varepsilon \varepsilon_0 \frac{WL}{d} \]

- The induced normal force, \( F_d \) is:

\[ F_d = -\frac{1}{2} \varepsilon \varepsilon_0 \frac{WL}{d^2} V^2 \]

in which \( \varepsilon \) = relative permittivity of the dielectric material between the two plates (see Table 2.2 for values of \( \varepsilon \) for common dielectric materials).

- Electrostatic Forces

Parallel Plate Capacitance

Capacitance:

\[ C = \varepsilon \varepsilon_0 \frac{A}{d} \]

Stable equilibrium when \( F = 0 \)

Electrostatic force between plates:

\[ F = \frac{1}{2} \varepsilon \varepsilon_0 \frac{WL}{d^2} V^2 \]

The higher \( k \), the closer the plates need to be.

Pull-In Point

Substitute \( F_d = F \) to get

\[ k = \frac{2F}{\varepsilon_0 \varepsilon_0 W} \]

can control \( x \) only from \( 2d \), to \( d \).

Electrostatic Actuation

Electrostatic Comb Drive

Actuation Using Electrostatic Forces – Cont’d
Actuation Using Electrostatic Forces - Cont'd

- Electrostatic Force Parallel to Two Misaligned Electrically Charged Plates:

\[
F_d = \frac{1}{2} \varepsilon \varepsilon_0 \frac{L}{d} V^2
\]

- Force in the “Width” direction:

\[
F_w = \frac{1}{2} \varepsilon \varepsilon_0 \frac{W}{d} V^2
\]

Microvalves

- A special microvalve designed by Jerman in 1990.
- Circular in geometry, with diaphragm of 2.5 mm in diameter x 10 μm thick.
- The valve is actuated by thermal force generated by heating rings.
- Heating ring is made of aluminum films 5 μm thick.
- The valve has a capacity of 300 cm³/min at a fluid pressure of 100 psig.
- Power consumption is 1.5 W.

Micropumps

- Electrostatically actuated micropump:
  - The pump is of square geometry with 4 mm x 4 mm x 25 μm thick.
  - The gap between the diaphragm and the electrode is 4 μm.
  - Pumping rate is 70 μL/min at 25 Hz.

Piezoelectrically actuated pump:

- An effective way to pump fluid through capillary tubes.
- Tube wall is flexible.
- Outside tube wall is coated with piezoelectric crystal film, e.g. ZnO with aluminum interdigital transducers (IDTs).
- Radio-frequency voltage is applied to the IDTs, resulting in mechanical squeezing in section of the tube (similar to the squeezing of toothpaste from a toothpaste tube)
- Smooth flow with “uniform” velocity profile across the tube cross section.

Micro Accelerometers

- Accelerometers are used to measure dynamic forces associated with moving objects.
- These forces are related to the velocity and acceleration of the moving objects.
- Traditionally an accelerometer is used to measure such forces.
- A typical accelerometer consists of a “roof mass” supported by a spring and a “dashpot” for damping of the vibrating proof mass:

\[
\begin{align*}
V(t) & = \frac{dy(t)}{dt} \\
\alpha(t) & = \frac{d^2 y(t)}{dt^2}
\end{align*}
\]

The associated dynamic force of induced by the moving solid is thus obtained by using the Newton’s law, i.e. \( F(t) = M \alpha(t) \), in which \( M \) = the mass of the moving solid.

In miniaturizing the accelerometers to the micro-scale, there is no room for the coil spring and the dashpot for damping on the vibrating mass.

Alternative substitutes for the coil spring, dashpot, and even the proof mass need to be found.
There are two types of micro accelerometers available.

1. **The cantilever beam accelerometer**:
   - Mass, $M$
   - Piezoresistor
   - Silicon Cantilever Beam
   - Constraint Base
   - Casing
   - Vibrating Base

   In this design: Cantilever beam = coil spring;
   Surrounding viscous fluid = dashpot for damping of the proof mass
   The movement of the proof mass is carried out by the attached piezoresistor.

2. **Balanced force micro accelerometer**:
   - This is the concept used in the "air-bag" deployment sensor in automobiles
   - In this design: Plate beam = proof mass;
   - Two end tethers = springs
   - Surrounding air = dashpot

   The movement of the proof mass is carried out by measuring the change of capacitances between the pairs of electrodes.