Introduction to BioMEMS & Medical Microdevices

Sensor Principles and Microsensors Part 1

Companion lecture to the textbook: Fundamentals of BioMEMS and Medical Microdevices, by Prof. Steven S. Saliterman, http://saliterman.umn.edu/
What is a sensor?

- A sensor *converts one form of energy to another*, and in so doing detects and conveys information about some physical, chemical or biological phenomena.

- More specifically, a sensor is a transducer that *converts the measurand (a quantity or a parameter) into a signal that carries information*. 
Features of an *ideal sensor*:

- Continuous operation without effecting the measurand.
- Appropriate sensitivity and selectivity.
- Fast and predictable response.
- Reversible behavior.
- High signal to noise ratio.
- Compact
- Immunity to environment.
- Easy to calibrate.
Examples of Sensor Methods

- Piezoelectric Sensors
  - Direct Piezoelectric Effect
  - Acoustic Wave Propagation
- Quartz crystal microbalance
- MEMS Structures
- Thermal Sensing
- Thermal and Non-Thermal Flow Sensing
- Electrochemical Sensors
- Ion Selective Field Effect Transistors
- Optical Sensors
Piezoelectric Sensors

- Direct transduction from mechanical to electrical domains and vice versa. May be used as sensors or actuators.
- The reversible and linear piezoelectric effect manifests as the production of a charge (voltage) upon application of stress (direct effect) and/or as the production of strain (stress) upon application of an electric field (converse effect).
- Three modes of operation depending on how the piezoelectric material is cut: transverse, longitudinal and shear.
- Amplifiers are needed to detect the small voltage.
**Converse Piezoelectric Effect** - Application of an electrical field creates mechanical deformation in the crystal.

**Polling** - Random domains are aligned in a strong electric field at an elevated temperature.

**Direct Piezoelectric Effect** - When a mechanical stress (compressive or tensile) is applied a voltage is generated across the material.
Example: Lead Zirconate Titanate (PZT)

- SEM image of an etched feature in PZT ceramic substrate with feature dimensions of 3 x 15 μm.

Piezoelectric Materials

- Crystals
  - Quart SiO₂
  - Berlinite AlPO₄
  - Gallium
  - Orthophosphate GaPO₄
  - Tourmaline (complex chemical structure)

- Ceramics
  - Barium titanate BaTiO₃
  - Lead zirconate titanate PZT, Pb [ZrxTi1-x] O₃ ; x = 0.52

- Other Materials
  - Zinc oxide ZnO
  - Aluminum nitride AlN
  - Polyvinylidene fluoride PVDF
**Typical Piezoelectric Circuit**

\[
V_{Out} = -\frac{Q_T}{C_T + C_P} \left( \frac{R_F}{R_1} \right)
\]

\[
V_{Out} = -\frac{Q_T}{C_F}
\]

Piezoelectric sensors may be configured as direct mechanical transducers or as resonators.

The observed resonance frequency and amplitude are determined by the physical dimensions, material and mechanical and interfacial inputs to the device.

Two Modes of Operation

There are essentially three approaches to realizing piezoelectric MEMS devices:

1. Deposition of piezoelectric thin films on silicon substrates with appropriate insulating and conducting layers followed by surface or silicon bulk micromachining to realize the micromachined transducer ("additive approach").
2. Direct bulk micromachining of single crystal or polycrystalline piezoelectrics and piezoceramics (“subtractive approach”).

3. Integrate micromachined structures in silicon via bonding techniques onto bulk piezoelectric substrates (“integrative approach”).
Approaches to Fabrication

Illustration of Surface Micromachining

(a) Substrate silicon wafer.
(b) Silicon substrate surface is thermally oxidized.
(c) Bottom electrode such as a (1 1 1) platinum film is deposited.
(d) The piezoelectric thin film is deposited and annealed.
(e) Top electrode metal such as Cr/Au is deposited.
(f) The entire piezoelectric, electrodes and passive layer stack is patterned and etch to expose the substrate silicon.
(g) Substrate silicon is etched from the front side using anisotropic wet etchant or isotropic vapor phase XeF$_2$ etchant while protecting the transducer stack.
(h) Alternatively, the substrate silicon is anisotropically etched from backside to release the transducer structure.

The piezoelectric effect is a linear phenomenon where deformation is proportional to an electric field:

\[ S = dE \quad \text{and} \quad D = dT \]

Where

- \( S \) is the mechanical strain,
- \( d \) is the piezoelectric coefficient,
- \( E \) is the electric field,
- \( D \) is the displacement (or charge density) linearly, and
- \( T \) is the stress.

These equations are known as the \textit{converse piezoelectric effect} and the \textit{direct piezoelectric effect} respectively.
Generation of surface acoustic waves (SAW) in quartz by interdigitated transducers:

Delay-line SAW

- Typically with a sensing film such as polyimide deposited on the surface in the area between the interdigitated transducers:

![Diagram of Delay-line SAW](image)

Two Port Delay Line and Resonator

Figure 15. Two-port delay-line-based sensor and (b) two-port resonator-based sensor.

Table 9. Surface acoustic waves and their characteristics.

<table>
<thead>
<tr>
<th></th>
<th>Operating frequency (MHz)</th>
<th>Phase sensing</th>
<th>Plate thickness</th>
<th>Mass sensitivity ((Hz MHz⁻¹) (ng cm⁻²)⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAW</td>
<td>Transverse and parallel</td>
<td>30–500</td>
<td>Gas</td>
<td>N/A</td>
</tr>
<tr>
<td>FPW (Lamb)</td>
<td>Transverse and parallel</td>
<td>2–7</td>
<td>Gas, liquid</td>
<td>Few μm</td>
</tr>
<tr>
<td>SH-APM</td>
<td>Transverse</td>
<td>25–200</td>
<td>Gas, liquid</td>
<td>Hundreds of μm</td>
</tr>
<tr>
<td>STW (Love, SH-SAW)</td>
<td>Transverse</td>
<td>200–500</td>
<td>Gas, liquid</td>
<td>Few μm</td>
</tr>
</tbody>
</table>

Calculating SAW Velocity

- The change in SAW velocity is related to the mass of a thin loss-less film on the sensor surface (left):

\[
\frac{\Delta V_R}{V_R} = (k_1 + k_2)fh\rho'
\]

Where
- \( V_R \) is the SAW velocity,
- \( k_1 \) and \( k_2 \) are the substrate material constants,
- \( f \) is the SAW frequency,
- \( h \) is the height of the layer, and
- \( \rho' \) is the density of the thin film layer.

- The change in SAW velocity can be determined experimentally by measuring the phase shift or the frequency shift (right).

\[
\frac{\Delta V}{V_R} = \frac{\Delta f}{f_0} = -\frac{\Delta \phi}{\phi_0}
\]

Where
- \( \Delta f \) is the frequency change,
- \( f_0 \) is the initial SAW frequency,
- \( \Delta \phi \) is the phase shift, and
- \( \phi_0 \) is the total degrees of phase in the sensor delay path (as measured between the centers of the IDTs).
Mass-sensitive devices suitable for detecting a variety of analytes. Thin AT-cut quartz wafer with a diameter of 0.25-1.0 inches, sandwiched between two metal electrodes which are used to establish an electric field **across** the crystal:
Mass changes on the QCM surface result in a frequency change according to the Sauerbrey equation:

$$
\Delta f = \frac{-2 f_0^2 \Delta m}{A \sqrt{\mu_Q \rho_Q}}
$$

Where

$\Delta f$ is the change in frequency,

$f_0$ is the resonant frequency of the quartz resonator,

$\Delta m$ is the mass change,

$A$ is the active vibrating area

$\mu_Q$ is the shear modulus of the quartz, and

$\rho_Q$ is the density of quartz
MEMS Structures

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

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

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The displacement $x$ of the beam is related to the applied force and length of the beam:

$$\Delta x = \frac{l^3}{3E_mI_m} F_x \quad \text{or} \quad F_x = k_m \Delta x \quad (k_m \text{ is the spring constant})$$

Where
- $E_m$ is Young's modulus,
- $I_m$ is the second moment of inertia,
- $F_x$ is the force or point load, and
- $l$ is the length.
The sinusoidal solution for displacement $x$ of a bridge structure is:

$$\Delta x = A \sin \left( \sqrt{\frac{F_y}{E_m I_{m,y}}} \right)$$

and

$$F_{\text{Critical}} = \frac{\pi^2 E_m I_m}{l^2}$$

(the buckling force)

Where

$A$ is a constant,

$E_m$ is Young's modulus,

$I_m$ is the second moment of inertia,

$F_y$ is the force and

$l$ is the length.
MEMS Sensor – Piezoelectric Pressure

Piezoresistive pressure sensor with reference pressure cavity inside chip.

Integrated capacitive pressure sensor fabricated by wafer level packaging.
Principle and photograph of SAW passive wireless pressure sensor and example of measurement (change in time converted into phase).

Common two-wire tactile sensor network that sequentially selects sensors.

Schematic of event-driven (interrupt) tactile sensor network, example of operation, and photographs of prototype IC.

Poly-Si surface micromachined integrated accelerometer (cross sectional structure and photographs of two-axis accelerometer).
MEMS Sensor - Accelerometer

Schematic of accelerometer with thick epitaxial poly-Si layer and photograph of resonant gyroscope.

Automotive sensor for yaw rate and acceleration.
MEMS Sensor - Gyroscope

Two-axis resonant gyroscope used for image stabilization (photograph and schematic).

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Apollo 11 Gyroscope 1969

Gyroscope image courtesy of https://www.flickr.com/photos/blafetra/14524883649
Sensor Fusion: *Adafruit BN0055*

- **Absolute Orientation** (Euler Vector, 100Hz) Three axis orientation data based on a 360° sphere.
- **Absolute Orientation** (Quaternion, 100Hz) Four point quaternion output for more accurate data manipulation.
- **Angular Velocity Vector** (100Hz) Three axis of 'rotation speed' in rad/s.
- **Acceleration Vector** (100Hz) Three axis of acceleration (gravity + linear motion) in m/s^2.
- **Magnetic Field Strength Vector** (20Hz) Three axis of magnetic field sensing in micro Tesla (uT).
- **Linear Acceleration Vector** (100Hz) Three axis of linear acceleration data (acceleration minus gravity) in m/s^2.
- **Gravity Vector** (100Hz) Three axis of gravitational acceleration (minus any movement) in m/s^2.
- **Temperature** (1Hz) Ambient temperature in degrees celsius.
Thermosensors

- Platinum resistor:
  - Linear, stable, reproducible.
  - Material property dependency on temperature,
- Thermocouples (e.g., Type K)
- Thermistor: a semiconductor device made of materials whose resistance varies as a function of temperature.
- Thermodiode and Thermotransistor.
Thermocouple

- Potentiometric devices fabricated by the joining of two different metals forming a sensing junction:
  - Based on the thermoelectric *Seebeck effect* in which a temperature difference in a conductor or semiconductor creates an electric voltage:

\[
\Delta V = \alpha_s \Delta T
\]

*Where*

- \( \Delta V \) is the electrical voltage,
- \( \alpha_s \) is the Seebeck coefficient expressed in volts/K°, and
- \( \Delta T \) is the temperature difference \((T_S - T_{ref})\).

When a \textit{p-n} diode is operated in a constant current ($I_0$) circuit, the forward voltage ($V_{out}$) is \textit{directly proportional to the absolute temperature (PTAT)}.

\[ V_{out} = \frac{k_B T}{q} \ln \left( \frac{I}{I_S} + 1 \right) \]

Where

- $k_b$ is the Boltzmann constant,
- $T$ is temperature,
- $q$ is the charge on an electron,
- $I$ is the operating current and
- $I_S$ is the saturation current.

Hot wire or hot element anemometers.
- Based on convective heat exchange taking place when the fluid flow passes over the sensing element (hot body).
- Operate in constant temperature mode or in constant current mode.

Calorimetric sensors.
- Based on the monitoring of the asymmetry of temperature profile around the hot body which is modulated by the fluid flow.
The heat transferred per unit time from a resistive wire heater to a moving liquid is monitored with a thermocouple:

In a steady state, the mass flow rate can be determined:

\[ Q_m = \frac{dm}{dt} = \frac{P_h}{c_m} (T_2 - T_1) \]

*Where*

- \( Q_m \) is the mass flow rate,
- \( P_h \) is the heat transferred per unit time,
- \( c_m \) is the specific heat capacity of the fluid and
- \( T_1, T_2 \) are temperature.

The volumetric flow rate is calculated as follows:

\[ Q_V = \frac{dV}{dt} = \frac{Q_m}{\rho_m} \]

*Where*

- \( Q_V \) is the volumetric flow rate,
- \( Q_m \) is the mass flow rate and
- \( \rho_m \) is the density.
Thermal Flow Sensor with Thermopile

Non-Thermal Flow Sensors

- **Cantilever type flow sensors**
  - Measuring the drag-force on a cantilever beam.

- **Differential pressure-based flow sensors**
  - When a fluid flow passes through a duct, or over a surface, it produces a pressure drop depending on the mean velocity of the fluid.

- **Electromagnetic**

- **Laser Doppler flowmeter**
  - The phenomenon is due to the interaction between an electromagnetic or acoustic wave and a moving object: the wave is reflected back showing a frequency different from the incident one.

- **Lift-force and drag flow sensors**
  - Based on the force acting on a body located in a fluid flow.

- **Microrotor**
  - Rotating turbine

- **Resonating flow sensors**
  - Temperature effects resonance frequency of a vibrating membrane.
Cantilever Type Sensor

Able to Sense Direction

Summary

- A sensor is a transducer that converts the **measurand** (a quantity or a parameter) into a signal that carries information.
- The *piezoelectric effect* is a linear phenomenon where deformation is proportional to an electric field.
- Mass changes on the QCM surface result in a frequency change according to the *Sauerbrey equation*.
- MEMS Structures and Sensors
- Thermo Sensors
- Flow Sensors
- Magnetic Sensors
## Appendix: Piezoelectric Thin Films

<table>
<thead>
<tr>
<th>Material</th>
<th>Deposition method</th>
<th>Deposition rate/film thickness</th>
<th>Substrate temp. (°C)</th>
<th>Reported piezoelectric properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlN/z-LiNbO$_3$ [26]</td>
<td>dc magnetron sputtering</td>
<td>6 nm min$^{-1}$</td>
<td>200</td>
<td>$k = 0.14$–$0.17$</td>
</tr>
<tr>
<td>AlN/Pt(1 1 1) [19]</td>
<td>Pulsed dc magnetron sputtering</td>
<td>0.4 μm</td>
<td>400</td>
<td>$e_{31,f} = 1.0$ pC m$^{-2}$, $d_{33,f} = 3.4$ pC N$^{-1}$, tan($\delta$) = 0.002, $k = 0.23$</td>
</tr>
<tr>
<td>AlN [27]</td>
<td>Reactive sputtering</td>
<td>1 μm</td>
<td>300</td>
<td>$e_{31,f} = -0.58$ pC m$^{-2}$, $d_{33,f} = 3.56$ pC N$^{-1}$, $k = 0.25$</td>
</tr>
<tr>
<td>AlN/Si(1 1 1) [28]</td>
<td>Metal organic chemical vapor deposition</td>
<td>130–250 nm</td>
<td>1050–1190</td>
<td>$d_{33} = 5.47$–$6.56$ pm V$^{-1}$</td>
</tr>
<tr>
<td>AlN/Si(1 1 1) [29]</td>
<td>Pulsed laser deposition</td>
<td>43–18 nm min$^{-1}$</td>
<td>500–920</td>
<td>–</td>
</tr>
<tr>
<td>ZnO/Pt [30]</td>
<td>Sol–gel</td>
<td>–</td>
<td>650, 700</td>
<td>$d_{33} = 17.11$ pm V$^{-1}$</td>
</tr>
<tr>
<td>ZnO/glass (Corning 7059) [31]</td>
<td>RF magnetron sputtering</td>
<td>18 nm min$^{-1}$</td>
<td>200</td>
<td>$k = 0.25$–$0.26$</td>
</tr>
<tr>
<td>ZnO/Si(00 1) [32]</td>
<td>RF magnetron sputtering</td>
<td>22 nm min$^{-1}$</td>
<td>Room temperature</td>
<td>–</td>
</tr>
<tr>
<td>ZnO/glass [33]</td>
<td>Pulsed laser deposition</td>
<td>45.8 nm</td>
<td>250</td>
<td>–</td>
</tr>
<tr>
<td>PZT/Pt(1 1 1)/Ti/SiO$_2$/Si [34]</td>
<td>Chemical solution method</td>
<td>0.25–6 μm</td>
<td>700 (Sinter)</td>
<td>$e_{31,f} \sim -7$ pC m$^{-2}$, $d_{33,f} = 150$ pC N$^{-1}$, tan($\delta$) = 0.05–0.02</td>
</tr>
<tr>
<td>PZT/LSMO/Si [35]</td>
<td>Hybrid powder sol–gel</td>
<td>~5 μm</td>
<td>800 (Sinter)</td>
<td>$d_{33,f} = 340$ pC N$^{-1}$, tan($\delta$) = 0.02</td>
</tr>
<tr>
<td>PZT/Si/SiO$_2$/Ti/TiO$_2$/Pt [36]</td>
<td>Diol-based chemical solution deposition</td>
<td>4.1 μm</td>
<td>–</td>
<td>$e_{31,f} = 7.29$ pC m$^{-2}$, tan($\delta$) = 0.023</td>
</tr>
<tr>
<td>PZT/Ti/SiO$_2$/Si(1 0 0) [37]</td>
<td>Pulsed laser deposition</td>
<td>1–3 μm</td>
<td>700</td>
<td>–</td>
</tr>
</tbody>
</table>
## Dry Etching Characteristics

<table>
<thead>
<tr>
<th>Material</th>
<th>Etch gas(es)</th>
<th>Pressure (Torr)</th>
<th>RF frequency (MHz)/power (W)</th>
<th>Etch rate (μm min⁻¹)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz [89]</td>
<td>CF₄</td>
<td>2.7</td>
<td>27 MHz</td>
<td>4</td>
<td>Non-lithographic plasma confinement method was used</td>
</tr>
<tr>
<td>Quartz [82]</td>
<td>SF₆/Xe</td>
<td>0.0045</td>
<td>13.56/90</td>
<td>0.4</td>
<td>ICP source with 150 W power was used to obtain a highly smooth surface</td>
</tr>
<tr>
<td>Pyrex 7740/quartz [90]</td>
<td>SF₆/Ar</td>
<td>0.002</td>
<td>13.56/475</td>
<td>0.54</td>
<td>ICP source with 2 kW power was used. Highly smooth surface with Rₐ = 1.97 nm. Similar rates were obtained for quartz etching as well</td>
</tr>
<tr>
<td>LiNbO₃/LiTaO₃ [80]</td>
<td>CHF₃/CF₄</td>
<td>0.05</td>
<td>13.56/350</td>
<td>~0.01</td>
<td>Etching proceeds mainly via physical sputtering</td>
</tr>
<tr>
<td>AlN [91]</td>
<td>Cl₂/Ar</td>
<td>0.005</td>
<td>13.56</td>
<td>0.75</td>
<td>ICP source with 500 W power was used. Etching proceeds by physical bombardment. No significant etching was observed below a threshold substrate voltage of ~50 V. The paper also reports etching GaN and AlGaN. Another good reference is [86]</td>
</tr>
<tr>
<td>AlN [84]</td>
<td>BCl₃/Cl₂/Ar</td>
<td>0.005</td>
<td>13.56</td>
<td>&gt;0.4</td>
<td></td>
</tr>
<tr>
<td>ZnO [92]</td>
<td>SiCl₄/Ar</td>
<td>0.175</td>
<td>13.56/0.56 W m⁻²</td>
<td>0.027</td>
<td>Additional references on ZnO etching are available [87, 93]. Typically etching is found to proceed via physical bombardment</td>
</tr>
<tr>
<td>ZnO [94]</td>
<td>C₂H₂/H₂/Ar</td>
<td>0.005</td>
<td>13.56/300</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>PZT (Bulk) [88]</td>
<td>SF₆</td>
<td>0.005</td>
<td>13.56/200</td>
<td>0.12</td>
<td>In [88], pure SF6 gave the best etch rate but the angle was shallow which could be improved by Ar addition but at the cost of etch rate. The recipe used in [83] mainly uses physical sputtering; however, aspect ratios of &gt;5:1 were obtained</td>
</tr>
<tr>
<td>PZT [95]</td>
<td>CF₄/80% Ar</td>
<td>0.015</td>
<td>13.56/700</td>
<td>0.143</td>
<td></td>
</tr>
<tr>
<td>PZT [83]</td>
<td>SF₆:Ar:1:10</td>
<td>0.005</td>
<td>13.56/475</td>
<td>0.42</td>
<td></td>
</tr>
</tbody>
</table>
Piezoelectric Constitutive Equations

\[ S_i = s_{ij}^E T_j + d_{kl} E_k \]
\[ D_l = d_{lm} T_m + \varepsilon_{ln}^T E_n \]

Where

\( i, j, m = 1 \) to \( 6; \) and \( k, l, n = 1 \) to \( 3, \)

\( S \) is the strain,

\( D \) is the dielectric displacement (or charge density),

\( E \) is the electric field,

\( T \) is the stress, and

\( s_{ij}^E, d_{kl} \) and \( \varepsilon_{ln}^T \) are the elastic compliances.

(The superscripts \( E \) and \( T \) refer to measurement at a constant field and stress. )