Mechanical Microsystems

1. Mechanical sensors and actuators

2. Mechanical sensor design. Basic mechanics – stress and strain

3. Case study - piezoresistive pressure sensor

4. Mechanical sensor design. Capacitive sensing

5. Case study - capacitive accelerometer – air bag sensor
### Microsystems Design – transducer principles

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<tr>
<th>PRIMARY</th>
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<td>Magnetic induction flux, microconcentrator</td>
<td>Faraday effect, Cotton-Mouton effect</td>
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<td>Radiation heating, Bolometer</td>
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**Mechanical microsystems** – convert the change in mechanical properties (position, deformation, acceleration, stress, strain) into electrical signal or vice versa.

**Materials**: c-Si, poly-Si, metals, plastics.

**Fabrication techniques**:
- bulk micromachining (c-Si);
- surface micromachining (poly-Si);
- LIGA (metals, plastics).

**Applications**:
- health care industry (pressure sensors);
- aerospace industry (pressure sensors, flow meters, accelerometers, microgyroscopes);
- automotive industry (pressure sensors, flow meters, accelerometers, microgyroscopes);
- consumer products (fitness gear, toys).
MEMS in the car engine:
MEMS testing for car engine applications:

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<th>Tests</th>
<th>Conditions</th>
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<td>100°C, 5 V</td>
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<td>Temperature and humidity</td>
<td>85°C and 85% RH with and without bias</td>
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<td>Pressure, power, and temperature cycles</td>
<td>20 kPa to atmospheric pressure, 5 V, -40 to +150°C</td>
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<td>Pressure cycling</td>
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<td>Vibration</td>
<td>2 to 40g, frequency sweep, depending on locations</td>
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<td>Shock</td>
<td>50g with 10 ms pulses</td>
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<tr>
<td>Fluid/media compatibility</td>
<td>Air, water, corrosive water, gasoline, methanol, ethanol, diesel fuel, engine oil, nitric and sulfuric acids</td>
<td>Varies with applications</td>
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# Microsystems Design - sensors

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# Microsystems Design - actuators

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# Microsystems Design – mechanical microsystems

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Basic mechanical sensors and actuators

1. **Sensors**:
   i. Strain sensors (strain gauges).
   ii. Piezoelectric sensors.
   iii. Capacitive sensors.
   iv. Tunneling sensors.

2. **Actuators**:
   i. Electrostatic.
   ii. Thermal.
   iii. Piezoelectric.
   iv. Pneumatic/hydraulic.
Strain sensors (strain gauges).

In this type of sensors, mechanical deformation (strain) is directly converted into electrical signal through the change in electrical resistance of conductive stripe.

The strain gauge performance is characterized by the gauge factor (GF):

\[
GF = \frac{\Delta R}{\Delta L} = \frac{\Delta R}{\varepsilon R},
\]

which shows how much the resistance changes (\(\Delta R\)) with the same dimensional change (\(\Delta L\)). Here, \(\varepsilon = \frac{\Delta L}{L}\) is the strain.

The change in the resistance may be:
- due to the change in the dimensions (strain);
- due to the change in electrical resistivity \(\rho\) (piezoresistive effect).

The following equation takes into account both effects; it does not depend on the shape, and thus can be used for any of them:

\[
GF = \frac{\Delta R}{R} = \frac{dR}{\varepsilon R} = (1 + 2\mu) + \frac{\rho}{\sigma},
\]

\(\mu\) – Poisson’s ratio

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The resistance is: 

\[ R = \frac{\rho L}{Wt} = \frac{\rho L}{A}, \]

and its change: 

\[ dR = \frac{\rho}{A} dL + \frac{L}{A} d\rho - \frac{\rho L}{A^2} dA. \]

From this equation: 

\[ \frac{dR}{R} = \frac{dL}{L} + \frac{d\rho}{\rho} - \frac{dA}{A}. \]

Consider simplest case – cylindrical wire.

Poisson’s ratio: 

\[ \mu = \frac{\varepsilon_i}{\varepsilon_l} = -\frac{\Delta D}{D} \frac{\Delta L}{L} \approx -\frac{D}{dL} \frac{dD}{L} ; \Rightarrow \frac{dD}{D} = -\mu \frac{dL}{L} \]

Since: \( A = \pi D^2/4 \), then: 

\[ \frac{dA}{A} = 2\frac{dD}{D}. \]

Thus: 

\[ \frac{\Delta R}{R} = \frac{\Delta L}{L} = \frac{dR}{R} = \frac{d\rho}{\varepsilon_l} = (1 + 2\mu) + \frac{\rho}{\varepsilon_l}. \]
Metallic strain gauges.

Resistance changes due to linear dimension change.

Signal change is small. To increase the signal, long metal stripes in zigzag shapes are fabricated by evaporation or sputtering followed by photolithography.

Generally low-cost, they are usually fabricated on plastic foils.

Semiconductor strain gauges.

Based on piezoresistive effect (strain affects interatomic distances and thus effective mass of carriers). The effect is anisotropic. The gauge factor is large (~100).

In p-type material, GF ~ 200 (hole mobility decreases).

In n-type material, GF ~ -140 (electron mobility increases).

Drawback: high temperature coefficient of resistivity (may bring strong non-linearity into measurements).
**Strain gauges - applications.**

**Deformation sensors**

Construction

Metal gauges on plastic foils.

3 gauges allow $\sigma_x$, $\sigma_y$, and $\tau_{xy}$ to be monitored.

**Force sensors**

Biological and medical research

Si strain gauges.

To be implanted ("sewn") in animals to study the forces in tissues.

**Accelerometers**

Medical electronics (e.g., pacemakers)

Si strain gauges.

The motion of the proof mass in x, y, and z is monitored by 2 strain gauges.
Strain gauges - applications.

Pressure sensors
Machinery, transportation, research, etc.
Si strain gauges.
4 gauges over the vacuumed and sealed cavity monitor downward bending of poly-Si plate.

Microphones
Communications, consumer electronics
Poly-Si strain gauge.
100Hz to 5kHz frequency range.

Tactile sensors
Robotics
Poly-Si strain gauges.
4 gauges provide the data on the normal force and on 2 shear forces.
Piezoelectric sensors.

Here, conversion of strain into electrical signal is based on the change in dielectric polarization caused by stress.

Physically, the centers of gravity for positive and negative charges in crystal unit cell of these materials shift relative to each other under stress, producing polarization. For example, consider hexagonal unit cell structure.

Piezoelectric effect is anisotropic and is characterized by the charge sensitivity coefficients, $d_{ij}$, that relate the charge generated at the surface on the $i$ axis to the applied force on the $j$ axis:

$$ΔQ_i = d_{ij}ΔF_j = d_{ij}ΔσA,$$

where $ΔQ_i$, $ΔF_j$, $Δσ$, and $A$ are charge, force, stress, and area, respectively.

The charge can easily be converted into the voltage:

$$V = Q/C = QH/ε_0ε_rA.$$ 

Here, $H$ is the thickness.
Usually, polar crystals (III-V, II-VI) exhibit piezoelectric effect (e.g., GaAs, InP, ZnO). The most common is ZnO since it can be sputtered as polycrystalline film with oriented grains.

The drawback of this effect is that its output signal is charge, not current. To overcome it, the sensor output is often connected to MOSFET gate, making MOSFET a switch.

This effect is reversible, i.e., applied electric field causes strain. The drawback is that to get large displacement, high voltage is needed.

<table>
<thead>
<tr>
<th>Material</th>
<th>Structure</th>
<th>Piezoelectric Constant, $10^{-12}$ C/N</th>
<th>Relative Permittivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>single crystal</td>
<td>2.33</td>
<td>4.0-4.5</td>
</tr>
<tr>
<td>Polyvinylidene fluoride (PVDF)</td>
<td>polymer</td>
<td>1.59</td>
<td>12</td>
</tr>
<tr>
<td>Barium Titanate (BaTiO$_3$)</td>
<td>ceramic</td>
<td>190</td>
<td>1700-4100</td>
</tr>
<tr>
<td>Lead Zirconate titanate (PZT)</td>
<td>ceramic</td>
<td>370</td>
<td>300-3000</td>
</tr>
<tr>
<td>Zinc Oxide (ZnO)</td>
<td>metal oxide</td>
<td>246</td>
<td>1400</td>
</tr>
</tbody>
</table>
Piezoelectric sensors - applications.

Oscillators, resonators, ultrasound receivers

Medical, consumer, etc.

Piezoelectric film with metal contacts.

Accelerometers Transportation

ZnO on top of Si beam.

The voltage appearing on ZnO goes to the gate of poly-Si FET to control drain current to eliminate leakage.

Microphones Acoustics

ZnO film on top of Si membrane.

Sensitivity 250μV/Pa. 10Hz to 10 kHz.

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Capacitive (electrostatic) sensors.

Simplest kind of sensing, based on capacitance variation due to changing distance (or dielectric constant) between the plates:

\[ C = \varepsilon_\varepsilon_0 A/H. \]

One of the plates is fixed, whereas another should be movable. Usually, easy to fabricate, therefore, cheap.

Drawbacks:
- signal nonlinearity;
- fringing fields.

Advantages:
- low noise;
- low temperature drift.

Assuming no fringing fields and very small gap changes:

\[ W = \frac{1}{2} CV^2 = -\frac{1}{2} \frac{\varepsilon_r \varepsilon_0 AV^2}{H} \]

\[ F = \frac{dW}{dH} = \frac{1}{2} \frac{\varepsilon_r \varepsilon_0 AV^2}{H^2} \]

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Capacitive sensors - applications.

**Accelerometers**  Transportation  Electroplated metal asymmetric plate, rotates under acceleration.

**Pressure sensors**  Biomedical (e.e., blood pressure  Si membrane on top of metallized glass.

**Microphone**  Acoustics  Si membrane on top of metallized glass. 25 mV/Pa. 10Hz-15kHz.

**Tactile sensors**  Machinery  Si beam on top of metallized glass.

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Tunneling sensors.

Based on the tunneling current dependence on the distance between the tip and conducting surface:

\[ I = I_0 e^{-\beta \phi^{1/2} z}. \]

Here, \( I_0 \) is the current at zero separation (scaling factor), \( \beta \) the conversion factor, \( \phi \) the tunnel barrier height, and \( z \) the separation.

Very nonlinear sensor, but has good scalability.

Application – accelerometers.

To maintain constant tunneling current, the voltage on the mass deflection electrodes changes to maintain the gap constant.

Made by Si bulk micromachining and bonding.
Mechanical Actuators.

1. Electrostatic.
Based on the Coulomb attraction of oppositely charged electrodes. The physical behavior can be roughly described by the parallel-plate capacitor equation assuming no fringing fields and VERY small gap changes:

\[
W = -\frac{1}{2} CV^2 = -\frac{1}{2} \varepsilon_r \varepsilon_0 AV^2
\]

And for the force, respectively:

\[
F = \frac{dW}{dr} = \frac{1}{2} \frac{\varepsilon_r \varepsilon_0 AV^2}{r^2}
\]

Advantages:  - easy to fabricate;
              - low power consumption.
Drawback:    - non-linear voltage-to-force relationship.
Applications: - micromanipulators (grippers, tweezers);
               - micromotors (both linear and rotary);
               - relays and switches.
Electrostatic rotary micromotor:

Rotary motor work is based on the same principle: by applying a voltage between two misaligned electrodes, we force the rotor to rotate.

The biggest problem here is the wear and lubrication of the bearings.
Electrostatic comb drive (linear micromotor):

By applying a voltage between the left electrode (L) and the right electrode (R), we force the anchored centerpiece to oscillate in x-direction. The structure is fabricated by surface micromachining.
2. Thermal.

Based on thermal expansion of solids. Stress due to the difference in linear coefficients of thermal expansion between Au and Si causes strain or bending.

More accurately, actuation can be produced using shape memory alloys (e.g., TiNi) – they get to original shape at preset temperature.

Advantage: Linearity (vertical displacement is directly proportional to thermal strain).

Drawbacks: - high power consumption; - complex fabrication (combination of bulk micromachining and surface micromachining, large number of steps).

Applications:
- grippers;
- relays and switches;
- drives and motors.

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Example: Bimorph microgrippers:

Concept: due to difference in thermal expansion coefficients of 2 materials, they expand differently if heated.

Medical microgripper and its operation.

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3. Pneumatic/hydraulic.

Based on electrostatic attraction between Si substrate and metal electrodes embedded into insulating (polyimide) valve. Normally open to let gas flow through, it closes if voltage applied.

Applications:

- valves;
- fluidic devices;
- flow structures.
4. Piezoelectric.

Based on electrical induction of mechanical strain. Example: piezoelectric cantilever. If the voltage is applied to opposite ends of ZnO strip sandwiched between Al electrodes, it expands or shrinks, generating vertical deflection.

Advantage: Linear.
Drawbacks: - small displacements (can be increased by using bimorphs); - complex fabrication.

Applications:
- linear motors and drives (e.g., scanning tunneling microscopy probes).
5. **Mechanical resonators.**

Each mechanical structure has its resonant frequency.

**Applications:**

- precision frequency generators and filters;
- RF switches and filters.
**Pressure Sensor Design - Basic Mechanics**

**Stress** = force per unit area acting on a surface of a differential volume element of a solid body:

\[ \sigma = \frac{F}{A} \]  

[N/m², Pa]

Stress can be **external** and **internal (intrinsic)**.

**Compressive stress** – material is compressed, tends to expand, to push on the substrate. Is negative.

**Tensile stress** - material is stretched, tends to shrink, to pull on the substrate. Is positive.

**Axial (normal) stress** is directed normally to differential face.

**Shear stress** is directed parallel to differential face.

**Shear stress:** \[ \tau = \frac{F}{A} \]
**Basic Mechanics**

**Strain** = differential deformation, the ratio of dimensional change over dimension:

\[ \varepsilon = \frac{\Delta L}{L} \]  

[dimensionless]

Strain (as well as the stress) can be **axial** or **shear**.

Axial (normal) strain – deformation due to axial stress; 

\[ \varepsilon_x = \frac{u_x(x + dx) - u_x(x)}{dx} = \frac{du_x}{dx} \]

Shear strain – angle \( \gamma \); \( \gamma \approx \tan \gamma = \frac{\Delta X}{L} \)
Basic Mechanics

Hooke’s Law: elastic deformation is directly proportional to the load.

Since deformation causes strain, and load causes stress:
\[ \sigma = E \varepsilon, \]

where \( E \) is the **Young’s modulus** (N/m\(^2\)).

For shear stress and strain:
\[ \tau = G \gamma, \]

where \( G \) is **shear modulus**.

For isotropic material (e.g., amorphous):
\[ E = 2G(1+\mu) = 3K(1-2\mu), \]

where \( \mu \) is the **Poisson’s ratio** (N/m\(^2\));
\( K \) is the **bulk modulus** (N/m\(^2\)).

\[ K = \text{hydrostatic stress/volume compression} \]
\[ K = (F/A)/(\Delta V/V) \]
Basic Mechanics

What is the physical meaning of the Poisson’s ratio?

When material is subjected to the axial load, all its dimensions change. We have two strains:

- axial, \( \varepsilon_a = \Delta L/L; \)
- transverse, \( \varepsilon_t = \Delta D/D. \)

Poisson’s ratio is the ratio of the transverse strain over the axial strain:

\[
\mu = \left| \frac{\varepsilon_t}{\varepsilon_a} \right| = -\frac{\Delta D}{D} \frac{\Delta L}{L}
\]

Poisson’s ratio is always positive. Typically 0.2 to 0.5.

Generally, we have 6 different strain values:

\( \varepsilon_x, \varepsilon_y, \varepsilon_z, \gamma_{xy}, \gamma_{yz}, \gamma_{xz}. \)

In thin films, \( x \) and \( y \) are usually much larger than \( z. \)

Usually, \( \sigma_x = \sigma_y = \sigma; \) therefore, \( \varepsilon_x = \varepsilon_y = \varepsilon. \)

Here we are able to deal with biaxial plane stress:

\[
\sigma = (E(1-\mu)/2)\varepsilon
\]
Basic Mechanics

Thermal expansion:
1) Materials expand when heated;
2) Linear thermal expansion coefficient is the uniaxial strain change with temperature:
\[ \alpha_T = \frac{d\varepsilon}{dT}. \] [K⁻¹]

For some temperature range, it is linear:
\[ \varepsilon_x(T) = \varepsilon_x(T_0) + \alpha_T \Delta T. \]

For 3 D case, we have volume thermal expansion coefficient:
\[ \frac{\Delta V}{V} = (1+\varepsilon_x)(1+\varepsilon_y)(1+\varepsilon_z)-1 = 3\alpha_T \Delta T. \]

In thin films, we have:
- intrinsic (residual) stress;
- thermally induced stress.

Materials:
- brittle (break);
- ductile (flow).

Behavior at large strain:
1) Plastic (deformation; material stay bent).
2) Elastomeric (material returns to initial state).
3) Viscoelastic (in time, it is elastic first, then gradually changes shape).
Piezoresistive Effect

**Piezoresistive effect** – change in the resistivity due to change in the distance between atoms.

In this effect, mechanical deformation (strain) is converted into electrical signal (resistivity).

In crystalline semiconductors, the effect is linear: \( E = V/L = (\rho + \Delta \rho)J, \)

\[ \{\Delta \rho\} = [\pi]\{\sigma\}, \]

where:
- \( \{\Delta \rho\} = \{\Delta \rho_{xx} \, \Delta \rho_{yy} \, \Delta \rho_{zz} \, \Delta \rho_{xy} \, \Delta \rho_{xz} \, \Delta \rho_{yz}\}^T \) – resistivity change tensor;
- \( \{\sigma\} = \{\sigma_{xx} \, \sigma_{yy} \, \sigma_{zz} \, \sigma_{xy} \, \sigma_{xz} \, \sigma_{yz}\}^T \) – stress tensor;

\[ [\pi] = \begin{bmatrix} \pi_{11} & \pi_{12} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{11} & \pi_{12} & 0 & 0 & 0 \\ \pi_{12} & \pi_{12} & \pi_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & \pi_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & \pi_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & \pi_{44} \end{bmatrix} \] – piezoresistive coefficient matrix.
After multiplying, we get:

\[ \Delta \rho_{xx} = \pi_{11} \sigma_{xx} + \pi_{12} (\sigma_{yy} + \sigma_{zz}); \]

\[ \Delta \rho_{yy} = \pi_{11} \sigma_{yy} + \pi_{12} (\sigma_{xx} + \sigma_{zz}); \]

\[ \Delta \rho_{zz} = \pi_{11} \sigma_{zz} + \pi_{12} (\sigma_{xx} + \sigma_{yy}); \]

\[ \Delta \rho_{xy} = \pi_{44} \sigma_{xy}; \]

\[ \Delta \rho_{xz} = \pi_{44} \sigma_{xz}; \]

\[ \Delta \rho_{yz} = \pi_{44} \sigma_{yz}. \]

There are three piezoresistive coefficients that we need to know to calculate any \( \Delta \rho. \)

Piezoresistive coefficients depend on:
- doping level;
- crystal orientation;
- temperature.
The maximum coefficient for p-type material: $\pi_{44} = 138.1 \times 10^{-11}$ Pa$^{-1}$.

Therefore, p-type Si is preferable for the strain gauge fabrication.

Since we fabricate long thin resistors as the stress gauges, we do not consider resistivity changes along z-axis; in this case, we can use longitudinal and transverse $\Delta \rho$. In this case, we only have two coefficients: longitudinal, $\pi_L$, and transverse, $\pi_T$:

$$\frac{\Delta \rho}{\rho} = \pi_L \sigma_L + \pi_T \sigma_T.$$  

<table>
<thead>
<tr>
<th>Crystal planes</th>
<th>Orientation $&lt;x&gt;$</th>
<th>Orientation $&lt;y&gt;$</th>
<th>$\pi_L$</th>
<th>$\pi_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(100)</td>
<td>&lt;111&gt;</td>
<td>&lt;211&gt;</td>
<td>+0.66 $\pi_{44}$</td>
<td>-0.33 $\pi_{44}$</td>
</tr>
<tr>
<td>(100)</td>
<td>&lt;110&gt;</td>
<td>&lt;100&gt;</td>
<td>+0.5 $\pi_{44}$</td>
<td>~0</td>
</tr>
<tr>
<td>(100)</td>
<td>&lt;110&gt;</td>
<td>&lt;110&gt;</td>
<td>+0.5 $\pi_{44}$</td>
<td>-0.5 $\pi_{44}$</td>
</tr>
<tr>
<td>(100)</td>
<td>&lt;100&gt;</td>
<td>&lt;100&gt;</td>
<td>+0.02 $\pi_{44}$</td>
<td>+0.02 $\pi_{44}$</td>
</tr>
</tbody>
</table>

The closest to $\pi_{44}$ is piezoelectric coefficient along $<111>$: 0.66 $\pi_{44}$. 

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With increased doping, temperature sensitivity slightly drops – but still high: p-type sensor at $10^{19}$ cm$^{-3}$ would have lost 27% of its piezoresistive coefficient if operated at 120 °C: $(120 \, ^\circ \text{C} - 20 \, ^\circ \text{C})*(-0.27\%)$

Typically, pressure sensor consists of 4 piezoresistors located at 4 sides of micromachined Si diaphragm. The change in the resistance is measured using Wheatstone bridge circuit. In order to balance offset, to compensate temperature changes, variable resistors are included in the circuit.
It is difficult to fabricate 4 piezoresistors to match precisely – offsets appear due to mismatch.

The alternative approach would be to use one piezoresistor only!
Piezoresistive Pressure Sensor – Design Example

Motorola Xducer

strain → sensor → voltage → circuitry

pressure → output voltage

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Microsystem design features:

• One piezoresistive stress gauge is located on top of thin silicon diaphragm over micromachined cavity (on the edge);

• Sensor fabrication process is integrates with the circuitry fabrication; bipolar transistor circuit is designed;

• (100) p-substrate is used; micromachining is along (110), and resistor is oriented along (100).
Sensor design:

(100) p-substrate is used; micromachining is along (110), and resistor is oriented along (100).
The current passes through the piezoresistor, and the voltage is measured across it.

Voltage pads must have no current in between (they are connected to high impedance op-amp).
Current pads must have low resistance.

\[ E = \frac{V}{l} = (\rho_e + \pi \sigma) J, \]

\( \rho_L \) – longitudinal resistivity.
Electric fields across the piezoresistor:

\[ E_L = E_1 = \rho_e (1 + \pi_{11} \sigma_1 + \pi_{12} \sigma_2) J_1; \]
\[ E_W = E_2 = \rho_e \pi_{44} \tau_{12} J_1; \]
\[ E_t = E_3 = 0 \quad \text{(thin film approximation)} \]

(we assume \( J_2 = J_3 = 0 \))

The voltages across the resistor then:

\[ V_L = V_1 = \rho_e L_R J_1 (1 + \frac{1}{L_R} \int_0^{L_R} (\pi_{11} \sigma_1 + \pi_{12} \sigma_2) dx_1 ) \approx \rho_e L_R J_1; \]

\[ V_W = V_2 = E_2 W_R = \pi_{44} \tau_{12} \left( \frac{W_R}{L_R} \right) V_1 \quad \text{-- } V_2 \text{ depends on } \tau_{12}! \]

\[ \frac{V_2}{V_1} = \pi_{44} \tau_{12} \frac{W_R}{L_R} = kP \]

\( P \) – pressure, \( k = 9.6 \times 10^{-8} \) Pa or 0.096 mV/(V·kPa)
\( V_1 \) – const = 5V, \( V_2 \) – pressure dependent.
Circuit design:

Circuit provides:
- Signal amplification;
- Temperature compensation of span and offset;
- Span and offset adjustment.

Combination of built-in (BJTs, resistors) and external (op-amps) circuitry.

Input signal: $V_W/V_L$. 
Circuit design:

- Signal amplification:
  - Op-amp A4 and BJTs Q1-Q3 (together with R10-R13) form non-inverting amplifier. The gain is controlled by R_G.

- Span and offset adjustment:
  - Offset is either due to misaligned V_W voltage taps, or due to common voltage at the V_W voltage taps, which is ½ V_ex. The op-amps operate on total voltages. Therefore, V_{S+} = V_{CM} + 1/2kPV_{ex}; V_{S-} = V_{CM} - kPV_{ex}. To eliminate offset, V_{S-} goes through respective op-amp with resistors (R1, R2) trimmed so that A1 is a unity gain voltage follower (V1 = V2). Then signal goes to R4, and V_{S+} goes to non-inverting input, so that V3 = -(R5/R4)V_{S-} + (1 + R5/R4)V_{S+}. The common mode signal is not amplified whereas the differential signal is amplified by a gain R5/R4. R8 and R9 serve to attenuate the common mode signal.

- Temperature compensation of span and offset:
  - Span – the slope changes due to temperature dependence of resistivity. The resistor R_S determines V_{ex} = V_D * R_P/(R_S + R_P), so that V_{ex} = V_D(\alpha_R - \alpha_P)/\alpha_R.
  - Offset – R_{TO}.
Sensor fab is integrated with circuitry fab (BJTs, resistors).

1. p-substrate (100); n\(^+\) buried layer diffusion; n-layer epitaxy.

2. p-diffusion (p-n junction isolation); oxide deposition.

3. p-diffusion (piezoresistor); p\(^+\) diffusion (base; piezo contacts); n\(^+\) diffusion (emitter; collector contact).

4. Bulk micromachining (diaphragm etching); bonding to the support wafer; metallization.
Capacitive Accelerometer – Design Example.

The value to be measured – acceleration: \( a = \frac{d^2x}{dt^2} \).

The sensing is based on measuring the displacement of a proof mass \( m \) on which the acceleration acts:

\[
F = ma = ky,
\]

where \( F, k, \) and \( y \) are the force generated by acceleration of the mass, spring constant, and displacement relative to the accelerometer frame, respectively.

Accelerometer contains:
- proof mass;
- spring;
- dashpot;
and is attached to vibrating body.

At resonant frequency, the magnitude of vibrations is maximum; all other frequencies are damped by the dashpot.
Taking into account the dashpot, the force acting on the proof mass is:

\[ F = m \frac{d^2 x}{dt^2} = ky + c \frac{dy}{dt} \]

Here, \( c \) is the damping coefficient.

The solution for the displacement has the form:

\[
|x(\omega)| = \frac{1}{\sqrt{\left(1 - \frac{\omega^2}{\omega_0^2}\right)^2 + \frac{\omega^2}{Q^2 \omega_0^2}}} \cdot \frac{m}{k} \frac{d^2 x}{dt^2}
\]

Here, \( \omega_0 = (k/m)^{1/2} \) is the resonant frequency, and \( Q = (mk)^{1/2}/c \) – quality factor.
Capacitive accelerometer.

The sensor is basically a capacitor with one plate movable. The change in capacitor gap (displacement) results in the change of capacitance.

Designs can be different:

- Parallel-plate capacitor
- Interdigital capacitor
- Fringing capacitor

Differential capacitive sensor:

The movable plate is centered between two unmovable ones, so that its displacement increases one capacitance and decreases another.
Modeling.

Generally:

Since we have air gap,

Multiplying by number of capacitor cells, \( n \):

where \( H, L_0, y, \) and \( G_0 \) are electrode overlap height, overlap length, displacement, and interelectrode gap, respectively.

For very small \( y \):

The sensor output signal is the voltage:

if the middle electrode is perfectly centered.

The centering should be adjustable:

- to compensate temperature drift;
- to compensate gravity forces.
The adjustment is being done electrostatically.

That means, the proof mass should be under DC bias, and the bias should be adjustable. So, generally, if displacement occurs, then:

\[ V_{\text{out}} = \frac{1}{2} (V_1 + V_2) + \alpha + \beta y (V_1 + V_2). \]

Here, \( \alpha \), \( \beta \), and \( y \) are offset, displacement prefactor, and displacement, respectively.

What kind of signal do we obtain?
The changing capacitances change \( V_{\text{out}} \), i.e., \( C = C(y); \ V = V(t) \).
From: \( Q = C(y) \ V \),
we have for the current:

\[ i_C = C(y) \frac{dV}{dt} + V \frac{\partial C}{\partial y} \frac{dy}{dt} \]

If we are using DC voltage, then: \( V_{\text{out}} = V_{\text{out}}(dy/dt) \). We need to integrate the signal or so.
The use of time varying waveform eliminates it.
If we use continuous wave signal (say, sinusoidal), then for differential sensor we need perfect input signal matching, otherwise mismatching slow component will shift our electrostatic proof mass centering.
Better solution is to use short high frequency pulses (assuming that the pulse is shorter than electrostatic forces reaction; respective frequency is > 1 MHz).

Fixed electrodes are driven with oppositely polarized square wave voltage; the output signal is differential:
Circuit design:
Process design.

- Sensor (poly-Si) and circuit (MOSFETs and BJTs) fabrication processes are integrated.
- First, circuit is fabricated, and then sensor is added using sacrificial layer technique.
- Circuit and sensor are spatially separated.

1) p- substrate (low doping).
2) n+ doping of interconnects between the sensor and circuitry areas, and of the ground plate. p doping around n+ to isolate.
3) MOSFET and BJT fab (poly-Si gates and interconnects).
4) SiN$_x$ passivation, BPSG planarization. Etch cleaning the sensor area down to gate oxide.
5) Nitride deposition (etch stop). Nitride removal over the ground plane.
6) Thick sacrificial oxide deposition; n⁺ contact window (anchor) opening.
7) Poly-Si for the proof mass and capacitors deposition, n⁺ doping and patterning.
8) Passivation (oxide). Oxide and sacrificial oxide removal from the circuit area (and partially from the sensor area).
9) Contacting n⁺ runners in the circuit area (window opening + metallization).
10) Circuit passivation (SiOₓ deposition, SiNₓ deposition, patterning).
11) Oxide etching in the sensor area – passivation and sacrificial layers removal. The proof mass (“shuttle”) is now free standing.
12) Die separation – back side sawing (shuttle protected by double layer tape).