Advanced Measurement Systems & Sensors
(0640732)

Lecture (9)

Force, Pressure, and Tactile Sensors

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Force:

- When force is applied to a free body, it gives the body an acceleration in a direction of the force. Thus, force is a vector value.
- Newton had found that acceleration (a) is proportional to the acting force (F) and inversely proportional to the property of a body called the mass (m);

$$\mathbf{a = F/m}$$

- This is **Newton's 2nd law**, while 1st law is "when net acting force F=0, then a=0"
- **Newton's 3rd law**: "To every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts."
- **Density** is defined through mass (m) and volume (V) as;

$$\rho = m/V$$

System of units	Force	Mass	Acceleration
SI	Newton (N)	**Kilogram** (kg)	m/s^2
British	**Pound** (lb)	Slug	ft/s^2

Force Sensors:

Force sensors can be divided into two classes:

1. **Quantitative sensor:** It measures the force and represents its value in terms of an electrical signal.
   Examples: strain gauges and load cells.

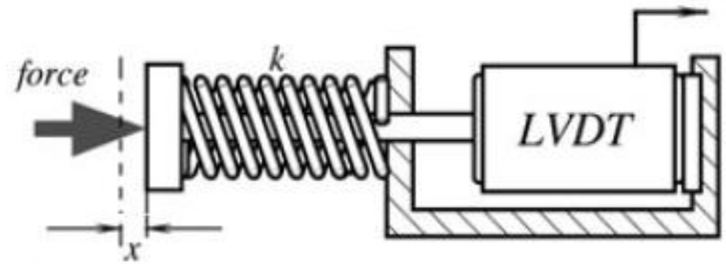
2. **Qualitative sensor:** It indicates whether a sufficiently strong force is applied or not. The sensor output signal indicates when the force magnitude exceeds a predetermined threshold level.
   Example: computer keyboard.
   The qualitative force sensors are used for detection of motion and position.

Note: Whenever pressure is measured, it requires the measurement of force. **Force is measured when dealing with solids, while pressure is measured when dealing fluids.** That is, force is considered when action is applied to a spot, and pressure is measured when force is distributed over a relatively large area.

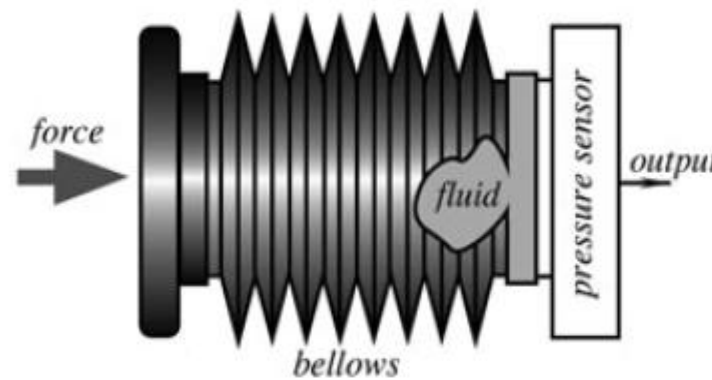
Methods of Sensing Force:

1. By balancing the unknown force against the gravitational force of a standard mass
2. By measuring the acceleration of a known mass to which the force is applied
3. By balancing the force against an electromagnetically developed force
4. By converting the force to a fluid pressure and measuring that pressure
5. By measuring the strain produced in an elastic member by the unknown force

Force sensors are complex sensors, since force is not directly converted into an electric signal. The LVDT sensor produces voltage proportional to the applied force within the linear range of the spring.



For example; force sensor can be fabricated by combining a force-to displacement transducer and a position (displacement) sensor. The former may be a simple coil spring, whose compression displacement (x) can be defined through the spring coefficient (k) and compressing force (F) as;



$$X = k\ F$$

Strain Gauges :

Strain (e): is deformation of a physical body under the action of applied forces.

- Strain gauge is a resistive elastic sensor whose resistance is function of the applied strain.
- Resistance is related to the applied force, and this is called the **piezoresistive** effect.

$$S_e = \frac{dR/R}{e}$$

where;

S_e : is the gauge factor, ($S_e \approx 2$ for most materials except for platinum $S_e \approx 6$).

dR: is the change in resistance caused by strain (e),

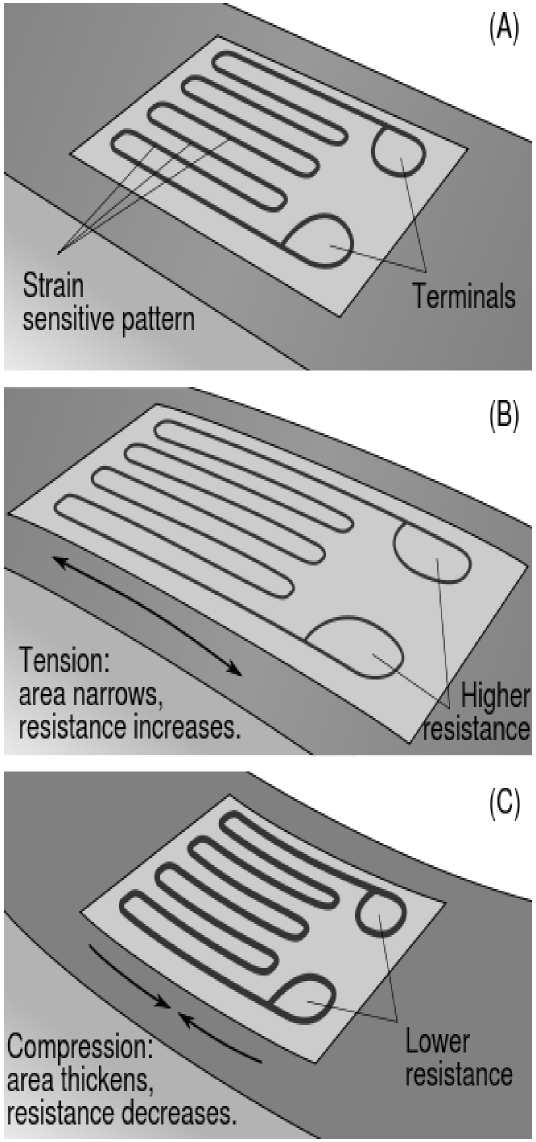
R: is the resistance of the undeformed gauge.

- For small variations in resistance (less than 2%), the resistance of the metallic wire is given by:

$$R = Ro\ (1+x)$$

where; Ro is the resistance with no stress applied,

$$x = S_e\, e$$



gauge and three dummy resistors in a Wheatstone Bridge configuration, the output (v) from the bridge is:

$$v = \frac{V \cdot S_e \cdot e}{4}$$

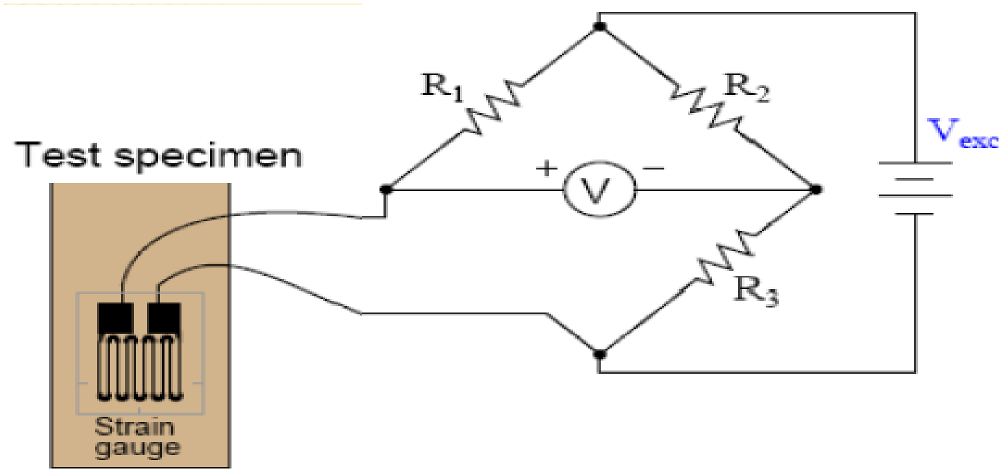
Where; V is the bridge excitation voltage.

Foil gauges typically have active areas of about 2^{-10} mm^2 in size. With careful installation, the correct gauge, and the correct adhesive (glue), strains up to at least 10% can be measured. Gauge factor is given by;

$$S_e = 1 + 2\mu$$

where μ= Poisson's ratio.

Strain-Gage Based Pressure Cell:



Tactile Sensors

The tactile sensors can be subdivided into three subgroups:

1. **Touch Sensors:** detect and measure contact forces at defined points. A touch sensor typically is a threshold device or a binary sensor (touch or no touch).
   Note: Some touch sensors do not rely on reaction to a force. A touch by a finger may be detected by monitoring a contact area between the finger and the panel. An example is a touch screen on a mobile telephone.

2. **Spatial Sensors:** These sensors detect and measure the spatial distribution of forces perpendicular to a predetermined sensory area, and the subsequent interpretation of the spatial information.

3. **Slip Sensors:** These sensors detect and measure the movement of an object relative to the sensor. This can be achieved either by a specially designed slip sensor or by the interpretation of the data from a touch sensor or a spatial array.
   Note: A spatial-sensing array can be considered to be a coordinated group of touch sensors.

Tactile Sensors Requirements:

Requirements to tactile sensors are based on investigation of human sensing and the analysis of grasping and manipulation.

Example: the desirable characteristics of a **touch or tactile sensor** suitable for the majority of industrial applications are;

1. It should be a single-point contact, though the sensory area can be any size. In practice, an area of 1–2 mm^2 is considered a satisfactory.
2. The sensor sensitivity is dependent on a number of variables determined by the sensor's basic physical characteristics. In addition, the sensitivity depends on the application.
3. A minimum sensor bandwidth of 100 Hz.
4. The sensor characteristics must be stable and repeatable with low hysteresis.

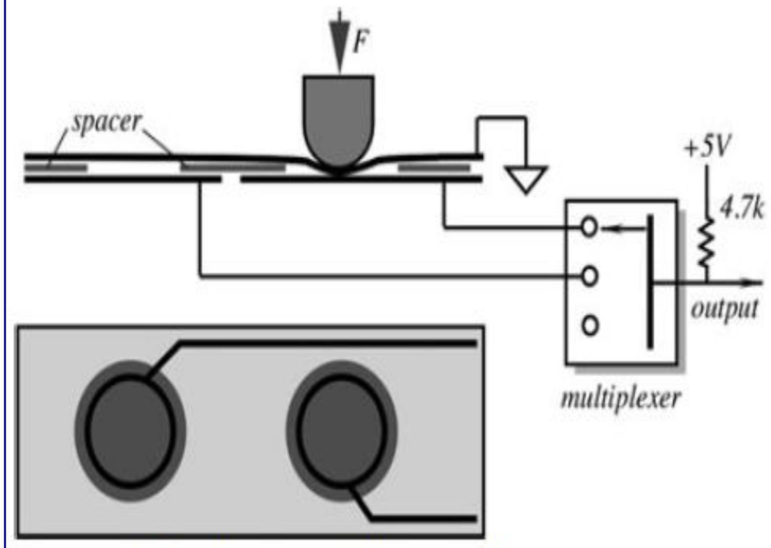
Switch Sensors :

A simple tactile sensor producing an “on–off” output can be formed with two leaves of foil and a spacer .

The spacer has holes. One leaf is grounded and the other is connected to a pull-up resistor.

A multiplexer can be used if more than one sensing area is required.

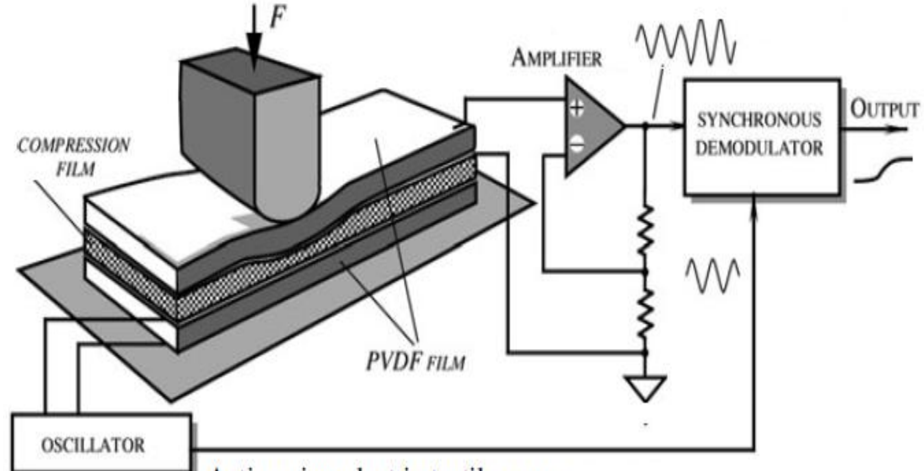
When an external force is applied to the upper conductor over the hole in the spacer, the top leaf flexes and upon reaching the lower conductor, makes an electric contact, grounding the pull-up resistor. The output signal becomes zero indicating the applied force.



Membrane switch as a tactile sensor

Piezoelectric Sensors

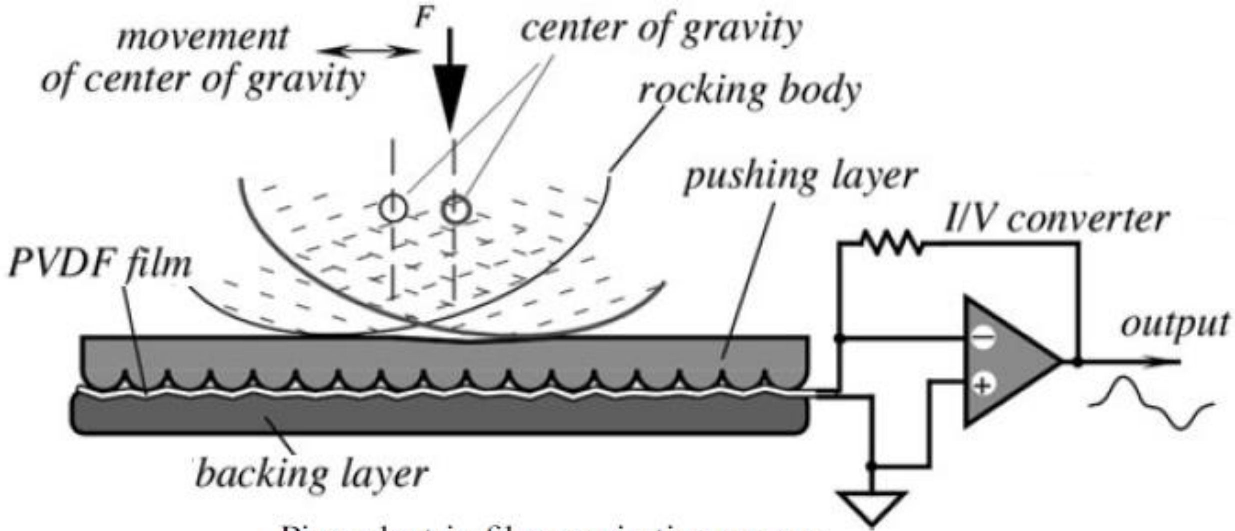
They can be designed with piezoelectric films, such as Polyvinylidene Fluoride (PVDF) used in active or passive modes. The center film is for the acoustic coupling between the other two. The softness of the center film determines sensitivity and the operating range of the sensor.



Active piezoelectric tactile sensor

The bottom piezoelectric film is driven by an AC voltage (Oscillator). This signal results in mechanical contractions of the film that are coupled to the compression film and, in turn, to the upper piezoelectric film, which acts as a receiver.
Since piezoelectricity is a reversible phenomenon, the upper film produces alternating voltage upon being subjected to mechanical vibrations from the compression film.
These oscillations are amplified and fed into a synchronous demodulator, which is sensitive to both the amplitude and the phase of the received signal.
When force (F) is applied to the upper film, mechanical coupling between layers changes. This affects the amplitude and the phase of the received signal. These changes are recognized by the demodulator and appear at its output as a variable voltage.

Example: A PVDF film tactile sensor for detecting breathing rate of a sleeping child



Piezoelectric film respiration sensor

Movements of a body had to be monitored in order to detect cessation of breathing. The sensor was placed under the mattress in a crib. A body of a normally breathing child slightly shifts with each inhale and exhale due to a moving diaphragm. This results in a displacement of the body’s center of gravity that is detected by the PVDF film sensor. The sensor consists of three layers where the PVDF film is positioned between a backing material (silicone rubber) and a pushing layer (plastic film).

The film generates an electric current converted into output voltage. The amplitude of that voltage within certain limits is proportional to the applied gravitational force.

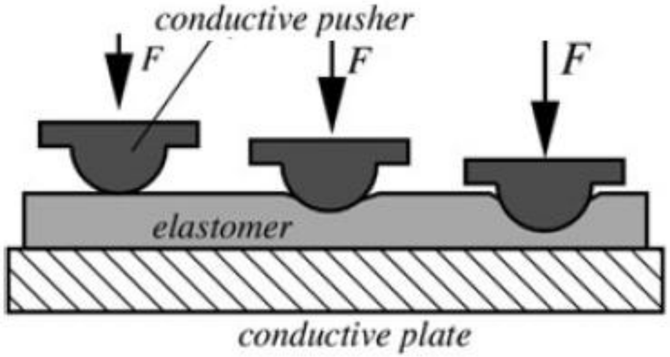
Piezoresistive Sensors:

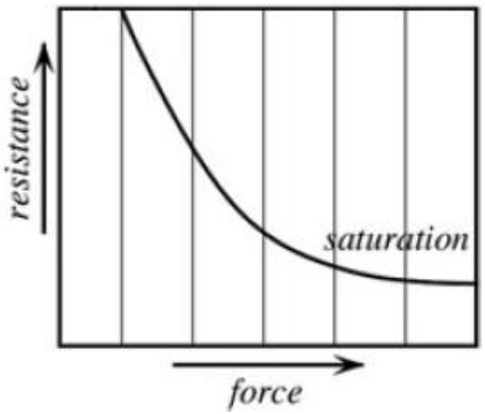
The sensor incorporates a Force-Sensitive Resistor (FSR) whose resistance varies with applied pressure.

A conductive elastomer is fabricated of silicone rubber, polyurethane, and other compounds that are impregnated with conductive particles or fibers.

Operating principles of elastomeric tactile sensors are based either on varying the contact area when the elastomer is squeezed between two conductive plates or in changing the thickness.

When the external force varies, the contact area at the interface between the pusher and the elastomer changes, resulting in a reduction of electrical resistance.





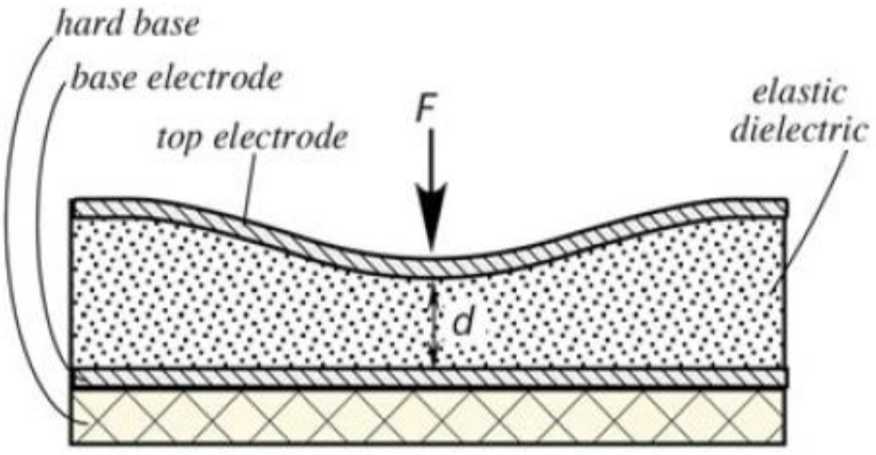
At a certain pressure, the contact area reaches its maximum and the transfer function goes to saturation. For a resistive polymer having thickness 70 mm and a specific resistance of 11 kΩ/cm^2, resistance for pressures over 16 kPa can me approximated by;

$$R = \frac{51.93}{p^{1.47}} + 19$$

Capacitive Touch Sensor:

It relies on the applied force that either changes the distance between the plates or the variable surface area of the capacitor.

To maximize the change in capacitance as force is applied, it is preferable to use a high permittivity dielectric (such as PVDF) in a coaxial capacitor design.

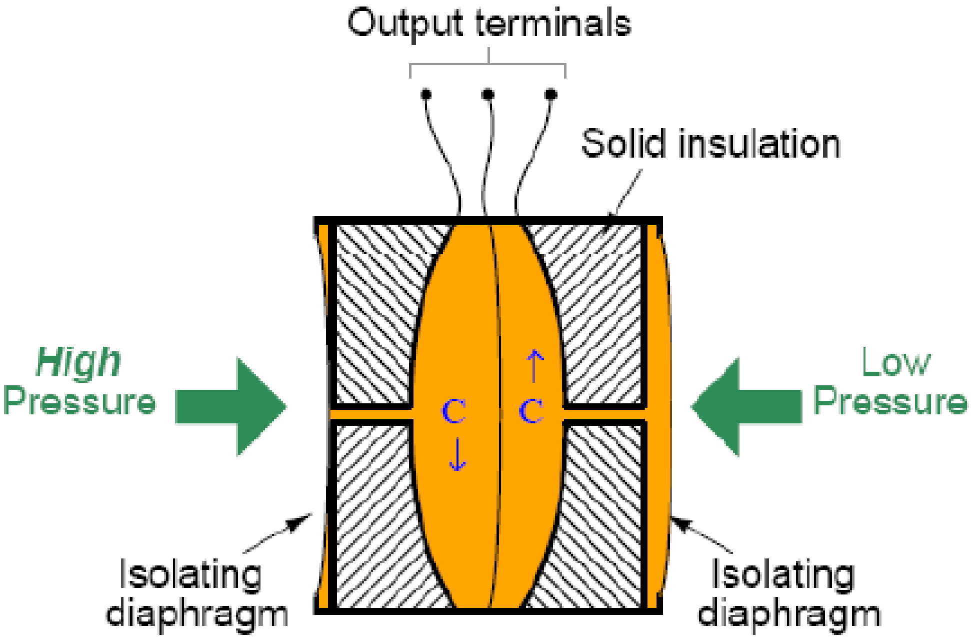


To measure the change in capacitance;

1. Use of a current source with a resistor and measure the time delay caused by a variable capacitance.
2. Use the sensor as part of an oscillator with an LC or RC circuit, and measure the frequency response.

Capacitive Pressure Sensor

Capacitive pressure sensors are also used in electronic pressure transmitters. With these devices the change in capacitance resulting from the movement of an elastic element is proportional to the pressure applied to the elastic element.

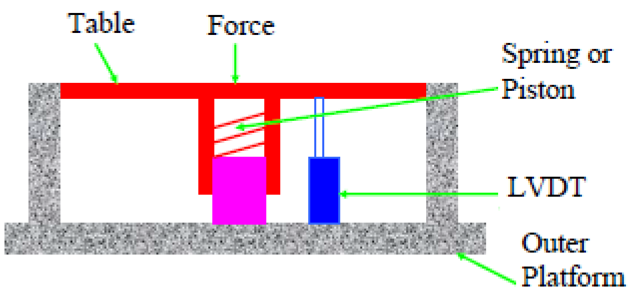


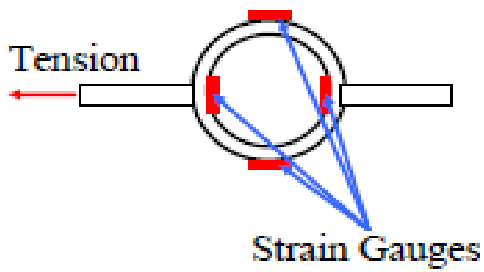
Force and Pressure Measurements:

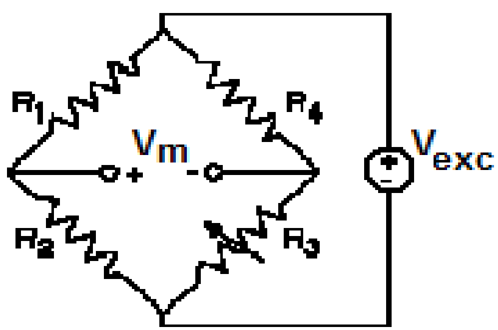
- Force and Pressure generally measured indirectly through deflection of an alternate surface.

Mechanism include:

- Physical motion and measurement using an LVDT.
- Strain gauges: metal that changes resistance when stressed.
- Piezoelectric materials that generate a current when deformed.







$$GF = \frac{\Delta R / R}{\Delta L / L} = \frac{\Delta R / R}{\varepsilon}$$

$$\Delta R = R \cdot GF \cdot \varepsilon$$

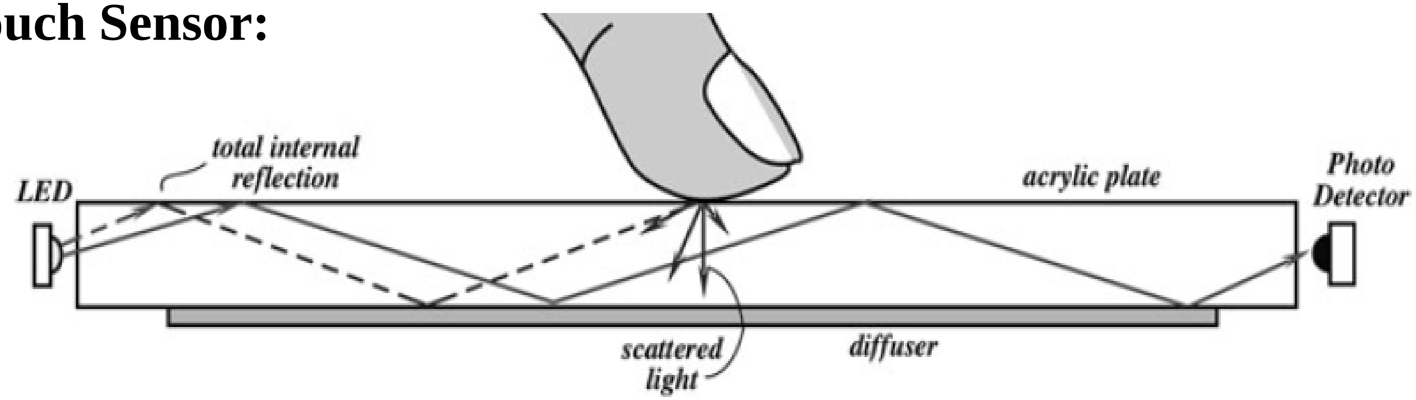
$$\frac{V_m}{V_{exc}} = \left(\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2} \right)$$

$$assume\ R_1 = R_2, R_4 = R_G,$$

$$R_3 = R_G + \Delta R$$

$$then\ \varepsilon = \frac{-4V_m}{GF\left(2V_m - V_{exc}\right)}$$

Optical-Touch Sensor:



They use an array of infrared (IR) light-emitting diodes (LEDs) on two adjacent bezel edges of a display, with photo detectors placed on the two opposite bezel edges to analyze the system and determine a touch event.

The LED and photo detectors pairs create a grid of light beams across the display. An object that touches the screen changes the reflection due to a difference between refractive properties of air and a finger.

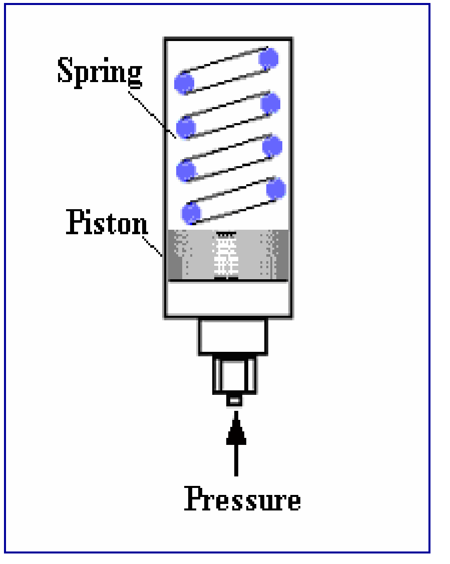
This results in a measured decrease in light intensity at the corresponding photo detector. The measured photo detector outputs can be used to locate a touch-point coordinate.

PRESSURE TRANSDUCERS:

- Pressure sensors either convert the pressure into mechanical movement or into an electrical output.
- Complete gauges not only sense the pressure but indicate them on a dial or scale.
- Mechanical movement is produced with the following elements.
  1. Spring and Piston.
  2. Bourdon Tube.
  3. Bellows and capsules.
  4. Diaphragm.

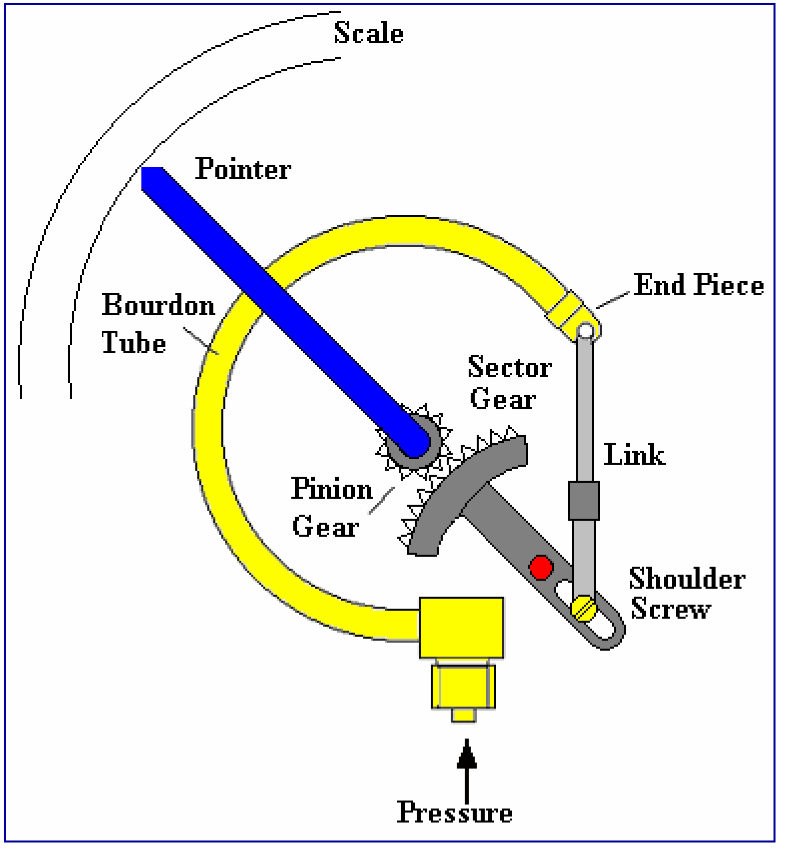
1. PISTON TYPE:

The pressure acts directly on the piston and compresses the spring. The position of the piston is directly related to the pressure.
A window in the outer case allows the pressure to be indicated.
This type is usually used in hydraulics where the ability to withstand shock, vibration and sudden pressure changes is needed (shock proof gauge). The piston movement may be connected to a secondary device to convert movement into an electrical signal.



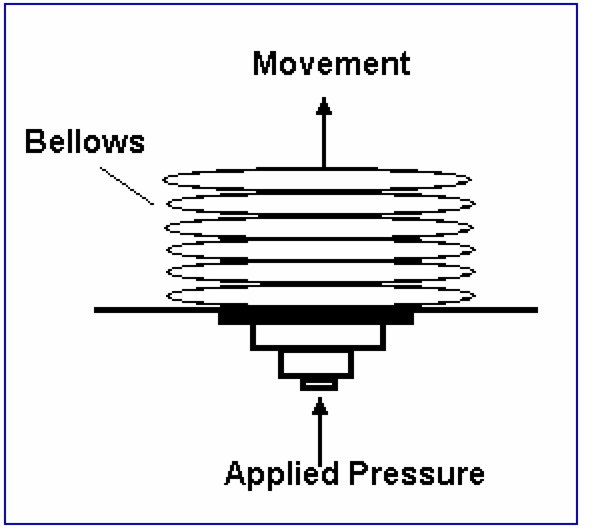
2. Bourdon tube:

- The Bourdon tube is a hollow tube with an elliptical cross section. When a pressure difference exists between the inside and outside, the tube tends to straighten out and the end moves.
- The movement is usually coupled to a needle on a dial to make a complete gauge.
- It can also be connected to a secondary device such as an air nozzle to control air pressure or to a suitable transducer to convert it into an electric signal. This type can be used for measuring pressure difference.



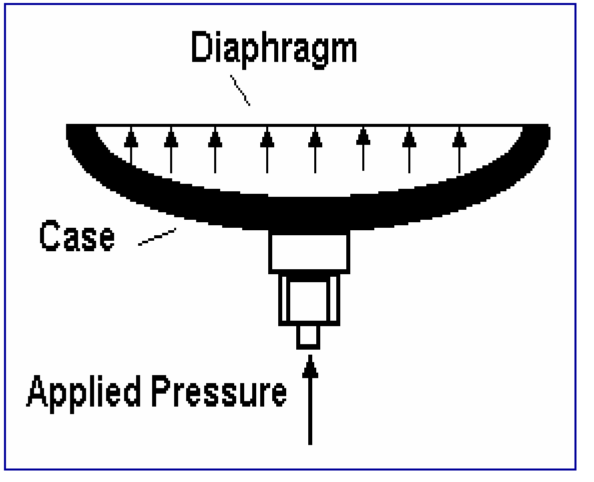
3. CAPSULES AND BELLOWS:

- A bellows is made of several capsules (hollow flattened structures made from thin metal plate).
- When pressurized the bellows expand and produce mechanical movement. If the bellows is encapsulated inside an outer container, then the movement is proportional to the difference between the pressure on the inside and outside.
- Bellows and single capsules are very useful for measuring small pressures.



4. DIAPHRAGMS:

- These are similar in principle to the capsule but the diaphragm is usually very thin and perhaps made of rubber.
- The diaphragm expands when very small pressures are applied.
- The movement is transmitted to a pointer on a dial through a fine mechanical linkage.

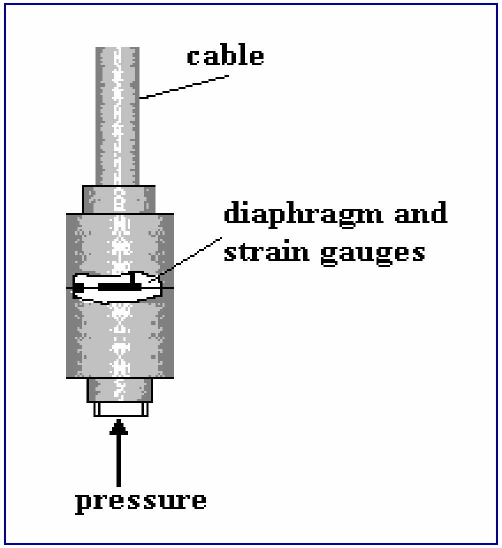


ELECTRICAL PRESSURE TRANSDUCERS:

The mechanical movement of the preceding types can be converted into an electric signal using;

- ➢ Strain Gauge types.
- ➢ Piezo electric types.
- ➢ Other electric effects.

1. STRAIN GAUGE TYPES:



- ➢ Strain gauges are small elements that are fixed to a surface that is strained. The change in length of the element produces changes in the electrical resistance.
- ➢ This is processed and converted into a voltage. A typical pressure transducer would contain a metal diaphragm which bends under pressure.

2. PIEZO ELECTRIC TYPES:

- The element used here is a piece of crystalline material that produces an electric charge on its surface when it is mechanically stressed.
- The electric charge may be converted into voltage. When placed inside a pressure transducer, the pressure is converted into an electric signal.

3. OTHER ELECTRIC EFFECTS: (CAPACITIVE and INDUCTIVE)

- The pressure produces a change in the capacitance or inductance of an electronic component in the transducer.
- Both these effects are commonly used in an electronic oscillator and one way they may be used is to change the frequency of the oscillation. The frequency may be converted into a voltage representing the pressure.

Elastic sensing elements:

If a force is applied to a spring, then the amount of extension or compression of the spring is approximately proportional to the applied force.

Elastic elements are also commonly used for measuring torque, pressure and acceleration, which are related to force by the equations:

$$\text{torque} = \text{force} \times \text{distance}$$

$$\text{pressure} = \frac{\text{force}}{\text{area}}$$

$$\text{acceleration} = \frac{\text{force}}{\text{mass}}$$

- The dynamics of a mass–spring–damper force sensor has a 2nd order T.F.;

$$G(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + 1}$$

Pressure Sensing:

- For a fluid at rest, pressure is the force (F) exerted perpendicularly on a unit area (A) of a boundary surface, and is given by: $P = dF/dA$
- **Kinetic theory** of gases states that pressure can be viewed as a measure of the total kinetic energy of the molecules “attacking” the surface;

$$p = \frac{2}{3}\frac{KE}{V} = \frac{1}{3}\rho C^2 = NRT$$

where;

KE: is the kinetic energy,

V: is the volume,

ρ: is the density,

N: is the number of molecules per unit volume,

R: is a specific gas constant, and

T: is the absolute temperature.

C^2: is an average value of the square of the molecular velocities,

Example: At 0°C and 1 atm. pressure, air has a density of 1.3 kg/m3, while at the same temperature and 50 atm. pressure its density is 65 kg/m3, which is 50 times higher. For liquids the density varies very little over ranges of pressure and temperature. For water at 0C and 1 atm. has a density of 1,000 kg/m3, while at 0C and 50 atm., its density is 1,002 kg/m3, and at 100C and 1 atm. its density is 958 kg/m3.

Absolute and Relative Pressure:

Relative Pressure: when it is measured with respect to ambient pressure.

Absolute Pressure: when it is measured with respect to a vacuum at zero pressure.

Static Pressure: The pressure of a medium is static when it is referred to fluid at rest.

Dynamic Pressure: when it is referred to kinetic energy of a moving fluid.

Pressure Units:

The SI unit of pressure is the **pascal**: 1 Pa = 1 N/m^2.

One atmosphere (atm) is the pressure exerted on 1 cm^2 by a column of water having height of 1 m at a temperature of 4°C and normal gravitational acceleration.

One pascal may be converted into other units by the use of following relationships:

$$1\text{Pa} = 1.45\times10^{-4}\text{lb/in}^2 = 9.869\times10^{-6}\text{atm.} = 7.5\times10^{-4}\text{cmHg}$$

- Pound / Square Inch = PSI
- Newton / Square Meter = N/m^2
- 100,000 N/m^2 = 1 Bar
- 14.5 psi = 1 Bar

Pressure in Industry:

Torr: It is defined as pressure exerted by 1 mm column of mercury at 0°C at normal atmospheric pressure and normal gravity.

1 Torr = 1 mmHg

The ideal pressure of the Earth atmosphere is 760 Torr (mmHg) and is called the physical atmosphere

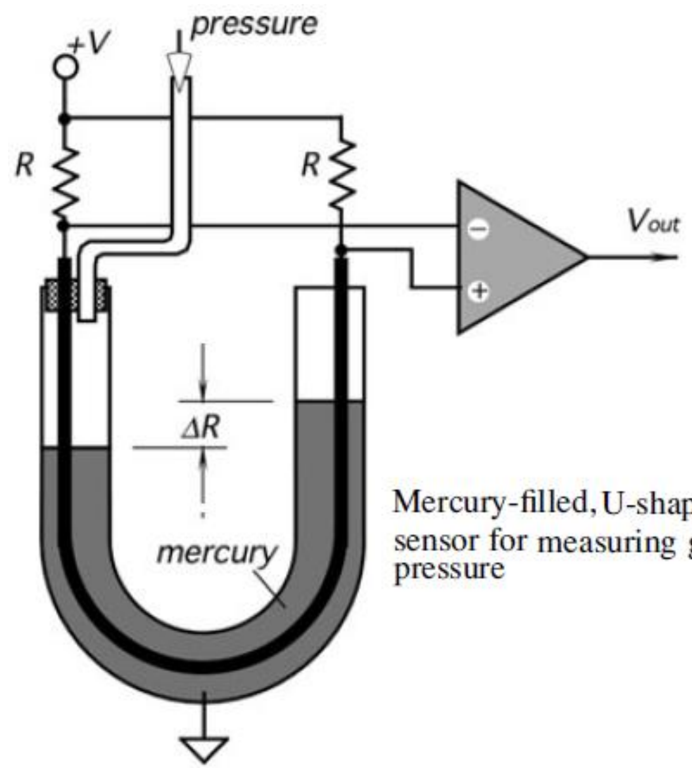
1 atm = 760 Torr = 101.325 Pa

The U.S. Customary System of units defines pressure as a pound per square inch (psi). Conversion into SI systems is the following:

$$1 \text{ psi} = 6.89 * 10^{3} \text{ Pa} = 0.0703 \text{ atm}$$

Mercury Pressure Sensor:

A U-shaped wire is immersed into mercury, which shorts its resistance in proportion with the height of mercury in each column. The resistors are connected into a Wheatstone bridge circuit that remains in balance as long as the differential pressure is zero. Pressure is applied to one of the arms of the tube and disbalances the bridge, which results in the output signal. The output voltage is proportional to ΔR of the wire arms that are not shunted by mercury:



Mercury-filled, U-shaped sensor for measuring gas pressure

$$V_{out} = V\frac{\Delta R}{R} = V\beta\Delta p$$

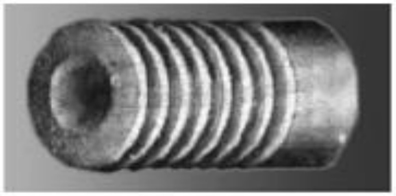
The sensor is simple and can be directly calibrated in units of Torr.

<u>Drawbacks:</u>

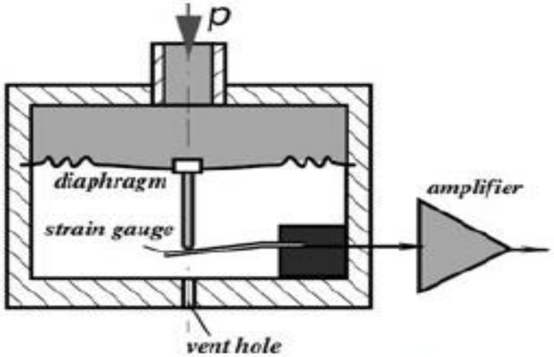
- large size,
- necessity of precision leveling,
- susceptibility to shocks and vibration,
- contamination of gas by mercury vapors

Bellows, Membranes, and Thin plates:

A **bellows** is a first step in the complex conversion of pressure into an electrical signal. It is used to convert pressure into a linear displacement, which can be measured by an appropriate sensor.



Steel bellows for a pressure transducer



metal corrugated diaphragm for the conversion of pressure into linear deflection

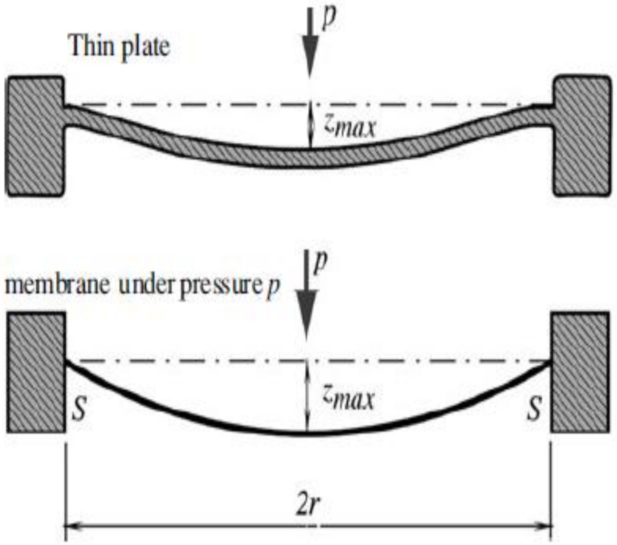
A **membrane** is a thin diaphragm under radial tension (S), which is measured in N/m.

At low-pressure (p) differences across the membrane, the center deflection (z_{max}) and the stress (σ_{max}) are functions of pressure:

$$z_{max} = \frac{r^2 p}{4S}, \qquad \sigma_{max} \approx \frac{S}{g}$$

where: r is the membrane radius,

g is the thickness.

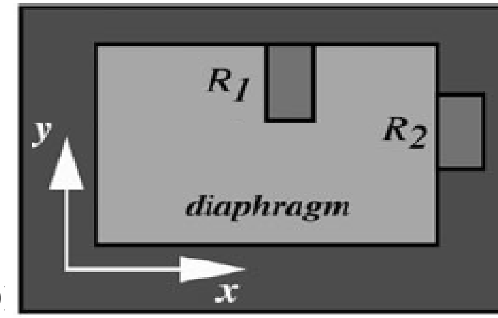


Piezoresistive Sensors:

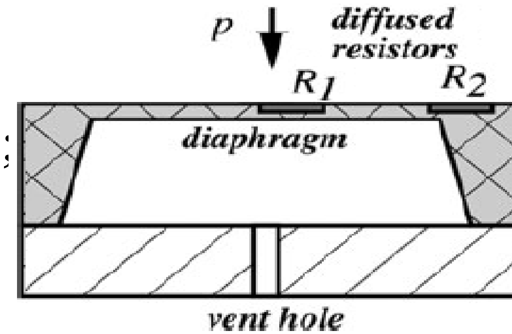
Two components are required to design a pressure sensor:

- the plate (membrane) having known area (A) and
- a detector that responds to applied force (F).

Both these components can be fabricated of silicon.



- ➢ A silicon-diaphragm pressure sensor consists of a thin silico diaphragm and piezoresistive gauge resistors.
- ➢ When stress is applied to a semiconductor resistor (R), piezoresistive effect results in change in the resistance (ΔR);



$$\frac{\Delta R}{R} = \pi_l \sigma_l + \pi_t \sigma_t \qquad \pi_1 = -\pi_t = \frac{1}{2}\pi_{44}$$

where; (π_l and π_t) and (σ_l and σ_t) are the piezoresistive coefficients and stresses in a longitudinal and transverse directions, respectively. The π-coefficients depend on the orientation of resistors on the silicon crystal.

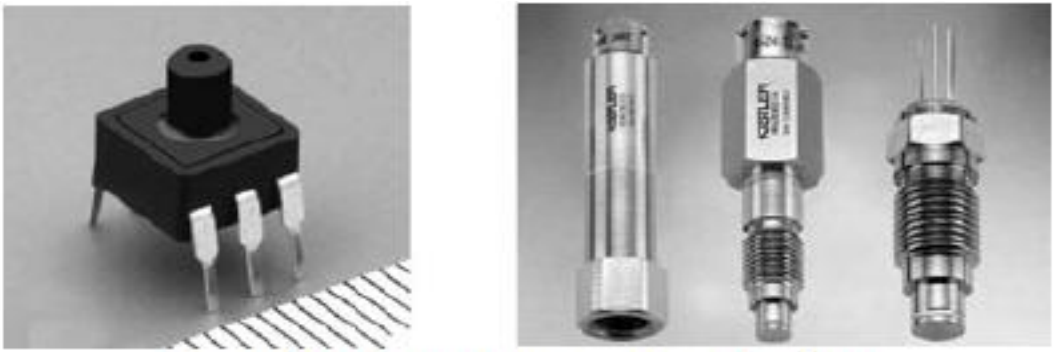
- ➢ A change in resistivity is proportional to applied stress and to applied pressure.

$$\frac{\Delta R_1}{R_1} = -\frac{\Delta R_2}{R_2} = \frac{1}{2}\pi_{44}\left(\sigma_{1y} - \sigma_{1x}\right)$$

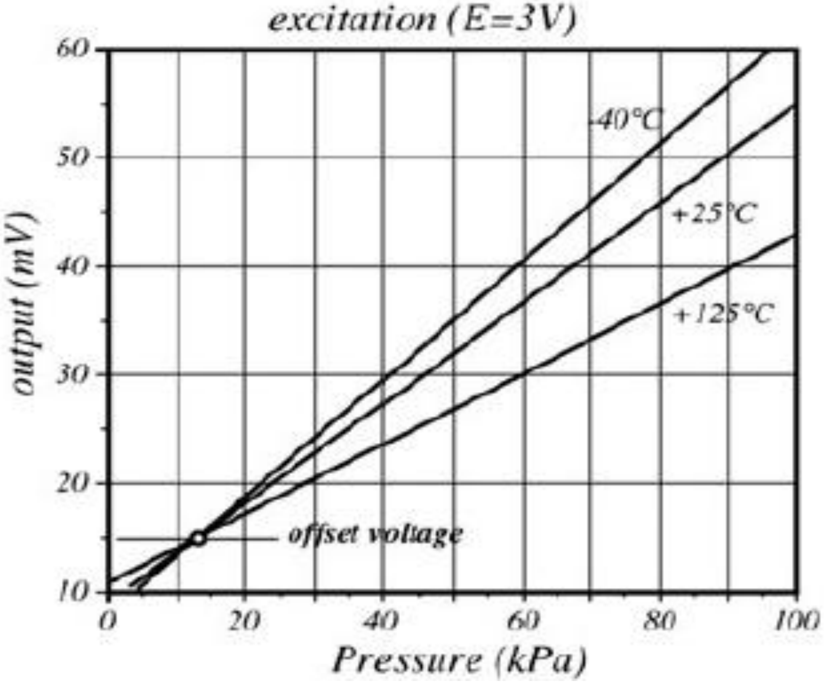
- ➢ When connecting R1 & R2 in a half-bridge circuit, the output voltage is;

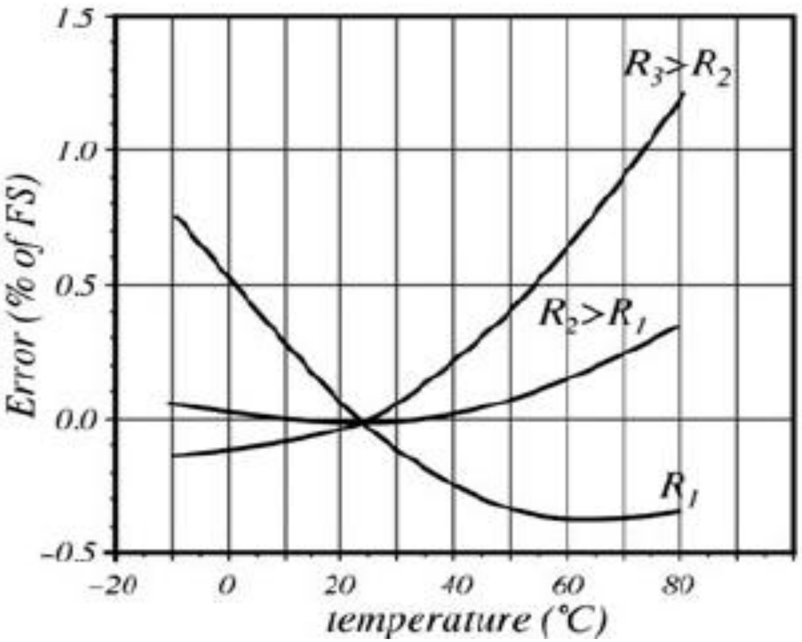
$$V_{out} = \frac{1}{4}E\pi_{44}\left(\sigma_{1y} - \sigma_{1x}\right)$$

Temperature characteristics of a piezoresistive pressure sensor:



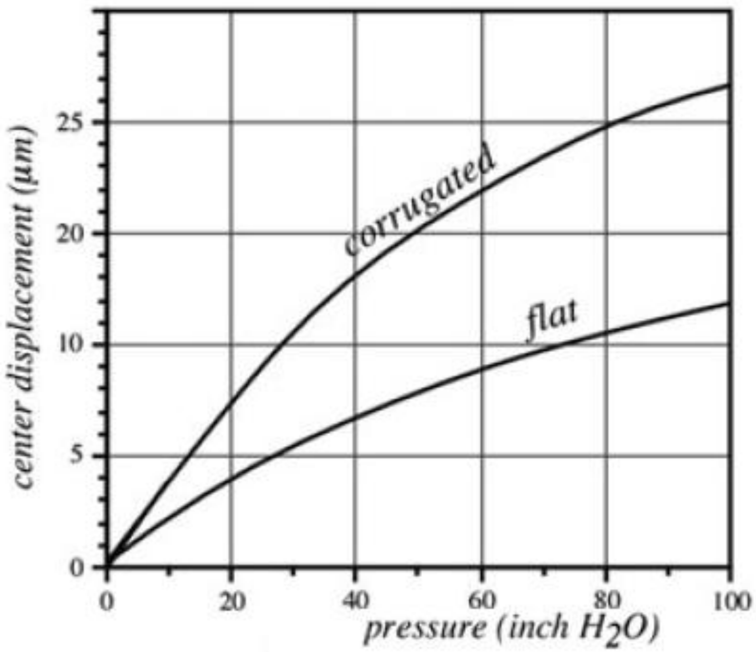
Examples of pressure sensor packagings

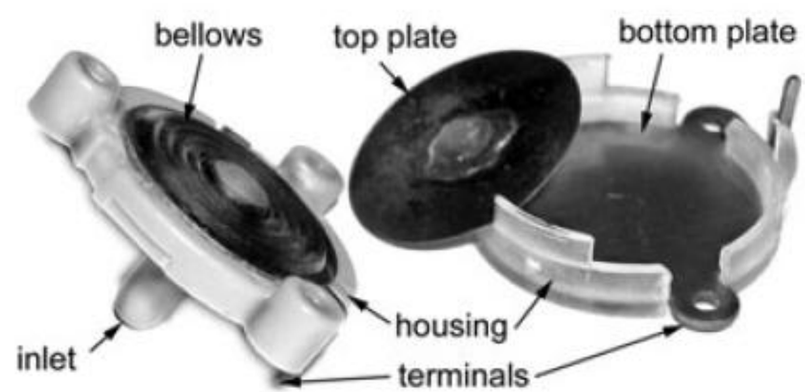




Capacitive Pressure Sensor:

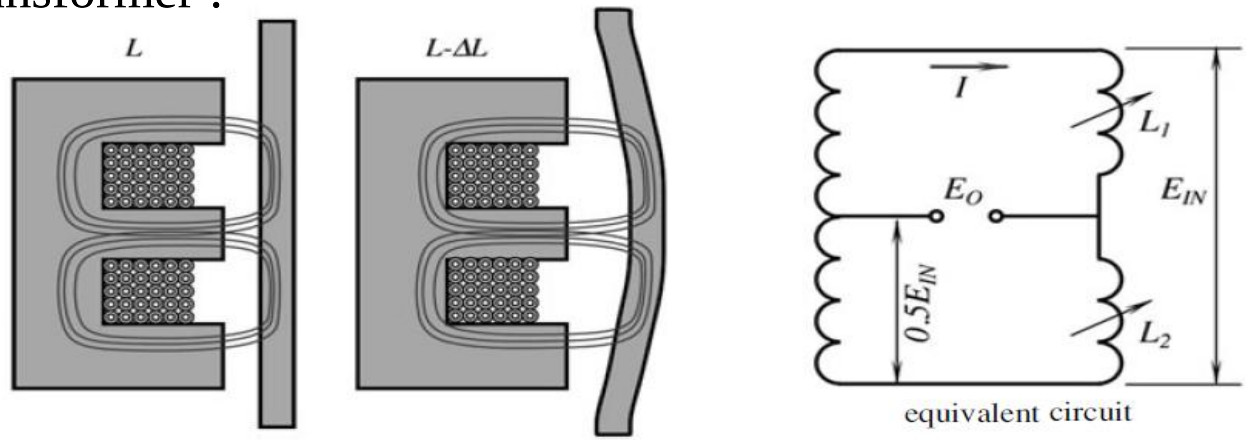
- The diaphragm displacement modulates capacitance with respect to the reference plate. It is especially effective for the low-pressure sensors.
- An entire sensor can be fabricated from a solid piece of silicon, thus maximizing its operational stability.
- To design a capacitive pressure sensor, for good linearity, it is important to maintain flatness of the diaphragm. These sensors are linear only over the displacements that are much less then their thickness.





Variable Reluctance Pressure (VRP) Sensor:

It uses a magnetically conductive diaphragm to modulate the magnetic resistance of a differential transformer .



The inductance of the circuit, is inversely proportional to the magnetic reluctance (i.e. $X_{1,2} = k/d$, where k is a constant and d is the gap size.).

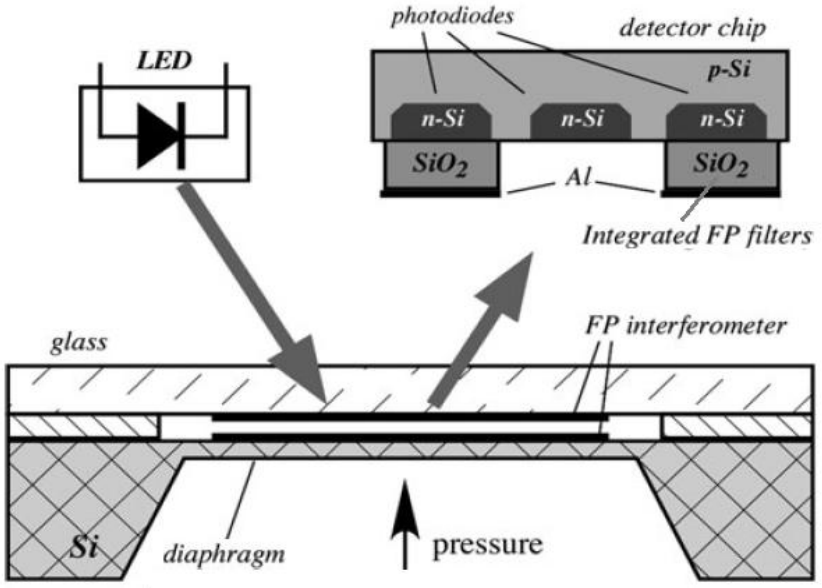
When the bridge is excited by a carrier current, the output signal across the bridge becomes amplitude-modulated by the applied pressure. The amplitude is proportional to the bridge imbalance, and the phase of the output signal changes with the direction of the imbalance. The ac signal can be demodulated to produce a dc response.

Optoelectronic Pressure Sensors:

An optical readout has several advantages over other technologies;

- ✓ a simple encapsulation,
- ✓ small temperature effects, and
- ✓ high resolution and accuracy.

An optical sensor consists of: a passive optical pressure chip with a membrane etched in silicon, a LED, and a detector chip.



A pressure chip with optical cavity forming a Fabry–Perot (FP) interferometer measuring the deflection of the diaphragm.

A back-etched, single-crystal **diaphragm** on a silicon chip is covered with a thin metallic layer, and a glass plate with a metallic layer on its backside.

A detector chip contains three pn-junction photodiodes. Two of them are covered with integrated optical FP filters of slightly different thicknesses.

The detector chip works as a demodulator and generates electrical signals representing the applied pressure.

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