SMART SENSOR SYSTEMS

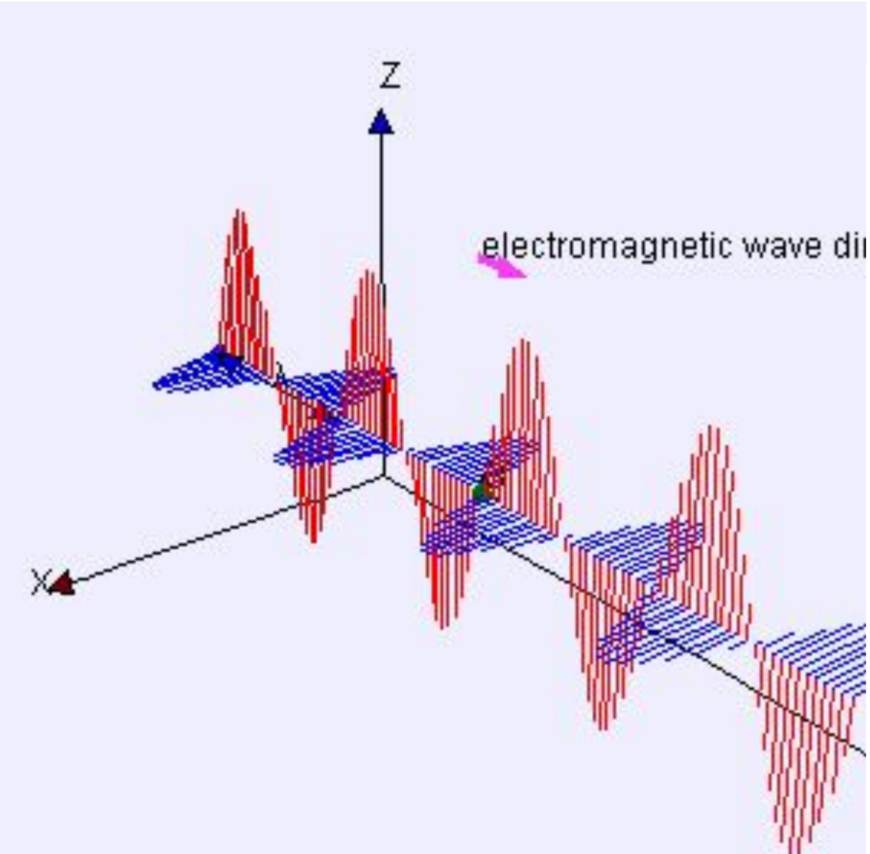
Unit – 2

Acoustic waves Fundamentals

Wave
s

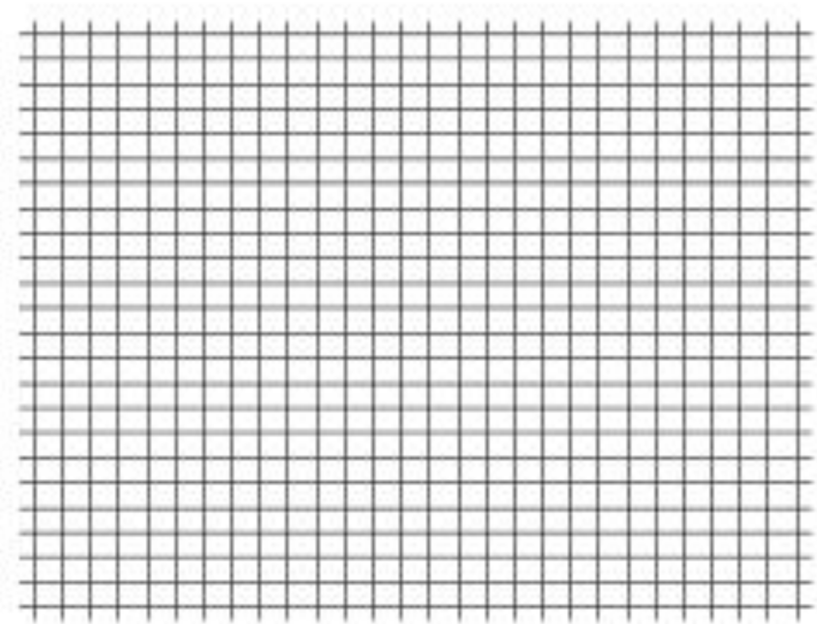
Transverse waves

A **transverse wave** is a moving **wave** whose oscillations are perpendicular to the direction of the **wave**. (light)



Longitudinal waves

Longitudinal waves are **waves** in which the displacement of the medium is in the same direction as, or the opposite direction to, the direction of propagation of the **wave** **(sound)**



Acoustic waves Fundamentals

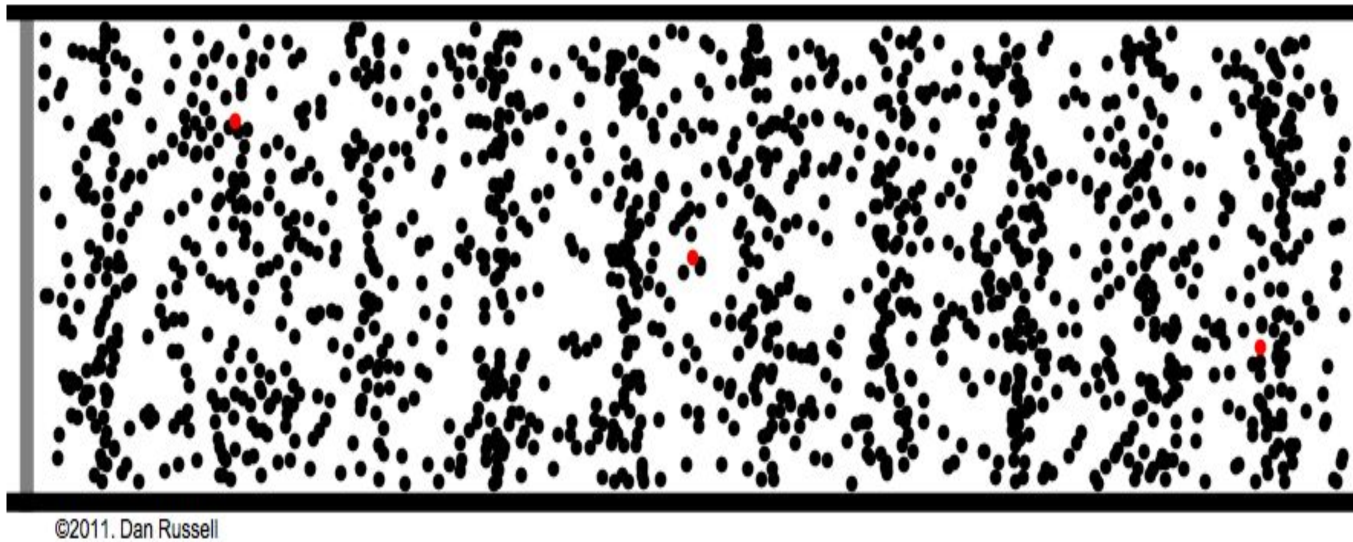
Longitudinal waves

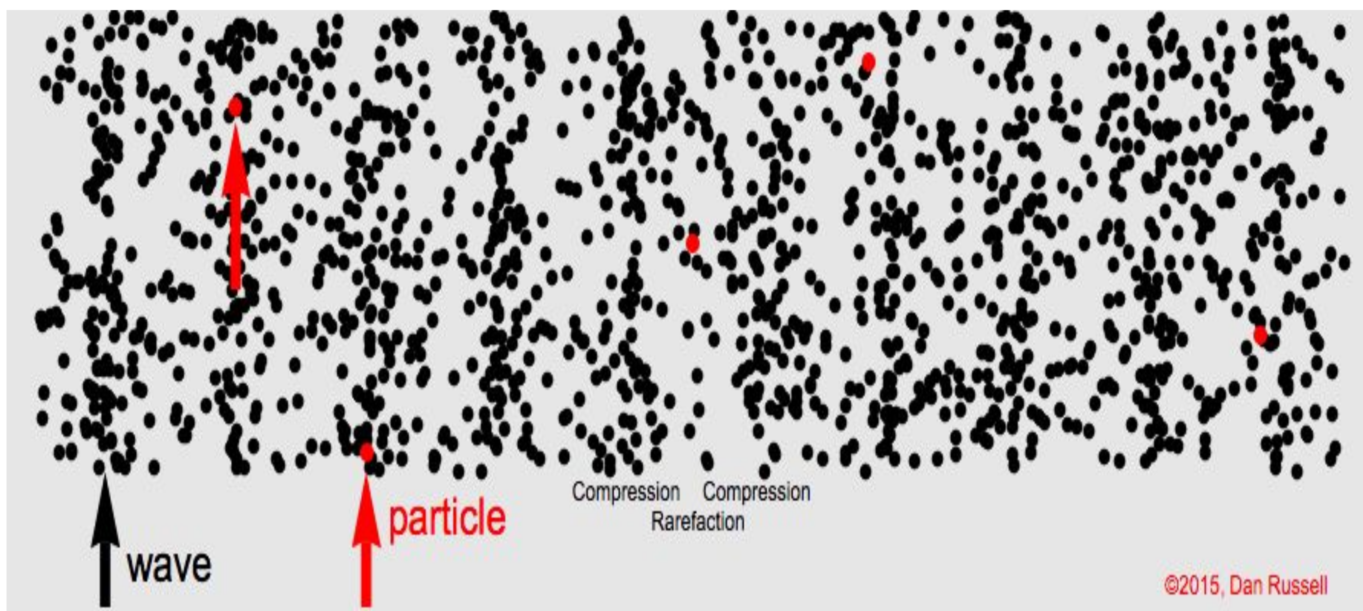
The medium contents oscillate in the direction of wave propagation

Alternate physical compression and expansion of the medium with certain frequencies

A medium is required for the acoustic wave propagation

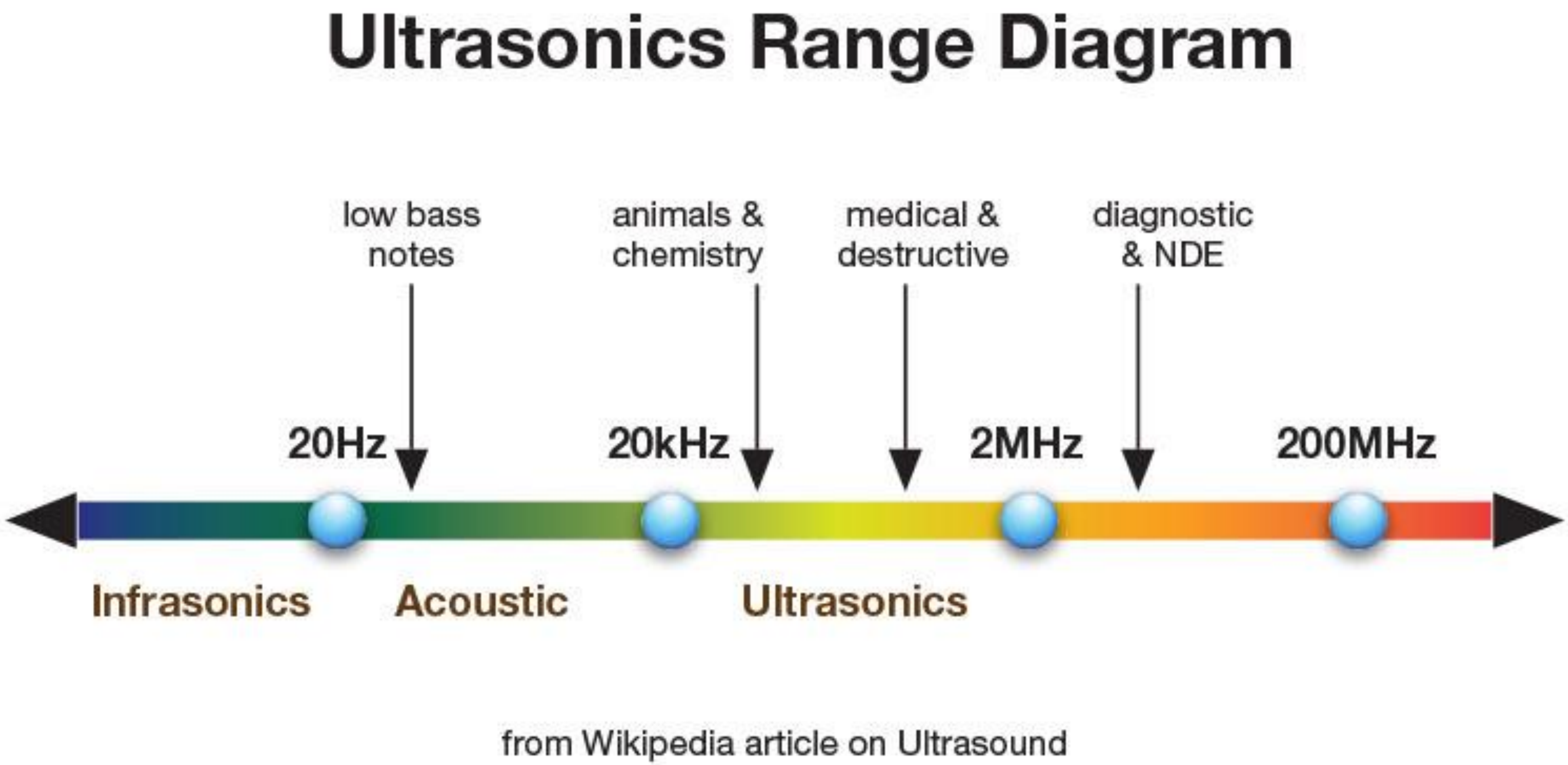
It will not propagate in vacuum as for light





Acoustic waves Fundamentals

Sound is an acoustic wave and it is associated with the hearing range of human ear which is approximately from 20 to 20kHz



Detection of infrasound is of interest with respect to analysis of building structures, earthquake prediction, and other geometrically large sources.
Whenever sound is produced, air is alternatively compressed and rarefied. These disturbances propagate outwardly

Acoustic waves Fundamentals

The speed of sound in air at standard temperature and pressure is around 344m/s
The velocity of sound depends on the medium i.e. its density and bulk modulus *B* (it is the resistance of a material to be compressed under unit pressure)

$$v_{sound\ in\ fluid} = \sqrt{\frac{B}{\rho}}$$

Sound will also travel through a solid, but in that case the interactions of the particles are different than in a fluid, and the constant that takes the place of tension or bulk modulus is Young's modulus.

$$v_{sound\ in\ solid} = \sqrt{\frac{Y}{\rho}}$$

The intensity of a sound wave also obeys the rule-of-thumb for intensity – the intensity is proportional to the square of the amplitude. Specifically, it turns out that for an amplitude measured in pressure, the intensity is given by:

$$I = \frac{A^2}{2\sqrt{\rho B}}$$

Acoustic sensors

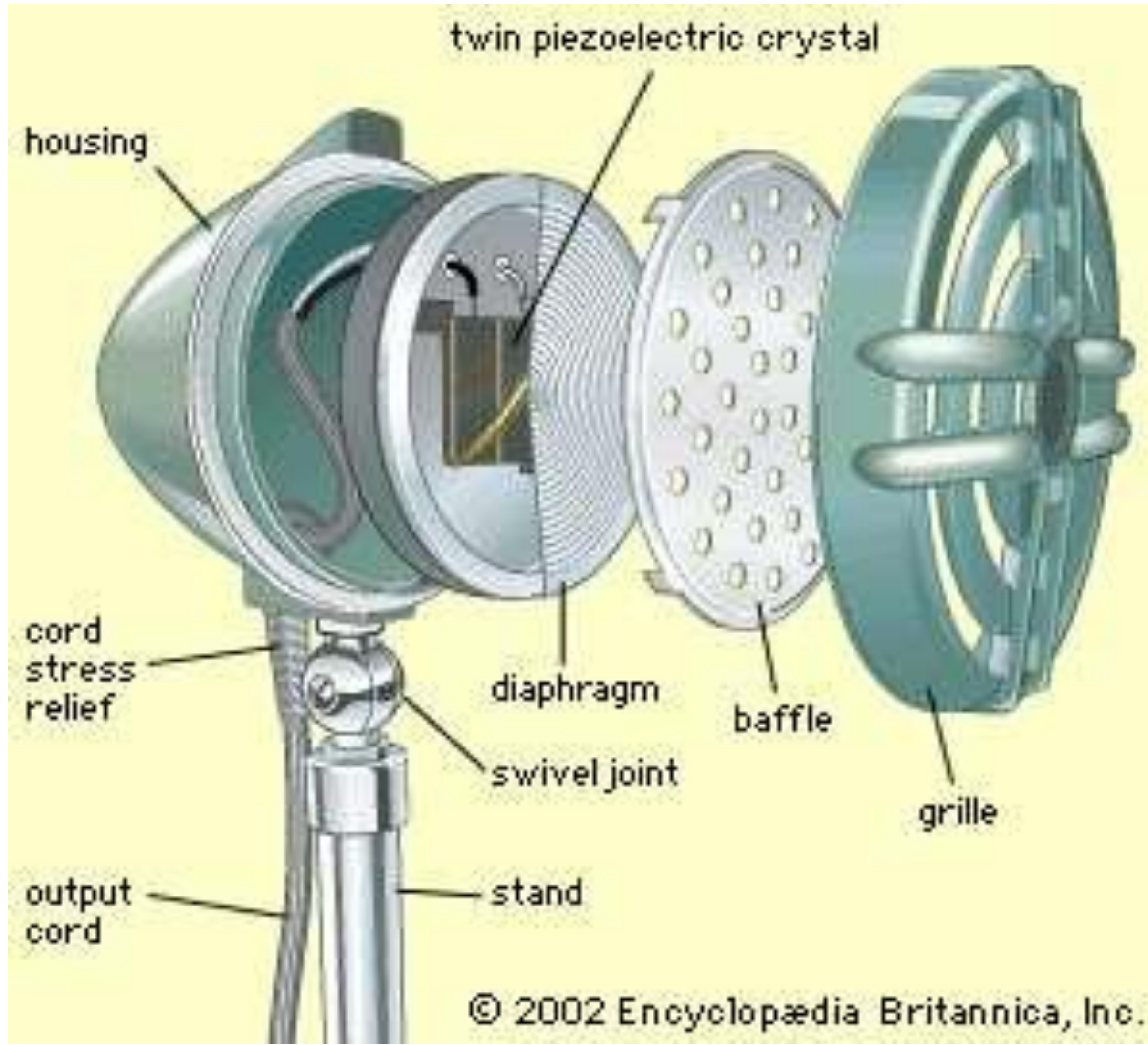
The audible range sensors are generally called the microphones
In essence, a microphone is a pressure transducer adapted for the transduction of sound waves over a broad spectral range

For the perception of air waves or vibrations in solids, the sensor is called a microphone , whereas for the operation in liquids, it is called a hydrophone

An acoustic sensor is composed of a moving diaphragm and a displacement transducer which converts the diaphragm's deflections into an electrical signal

There are many types
- Resistive microphones
- Condenser microphones
- Fiber-optic microphone
- Piezoelectric microphone
- Electret microphone

Solid state acoustic detectors



Resistive Microphones

The converter consisted of a semiconductive powder (usually graphite) whose bulk resistivity is sensitive to pressure.
A resistive microphone used the principle that the resistance is changed when diaphragm is moved across carbon grain. When resistance changed voltage level is varied and thus electrical signals are produced with a magnitude directly proportional to applied sound wave. This shows that the relation between output signal and applied sound wave is linear.

Condenser Microphones

Condenser means *capacitor*, an electronic component which stores energy in the form of an electrostatic field.

A condenser microphone is the one which uses a capacitor to convert acoustical energy into electrical energy.

Condenser microphones require power from a battery or external source. The resulting audio signal is stronger compared to other technologies.

Condensers also tend to be more sensitive and responsive, making them well-suited to capturing subtle nuances in a sound.

Condenser Microphones

A capacitor has two plates with a voltage between them. In the condenser mic, one of these plates is made of very light material and acts as the diaphragm. The diaphragm vibrates when struck by sound waves, changing the distance between the two plates and therefore changing the capacitance. Specifically, when the plates are closer together, capacitance increases and a charge current occurs. When the plates are further apart, capacitance decreases and a discharge current occurs.

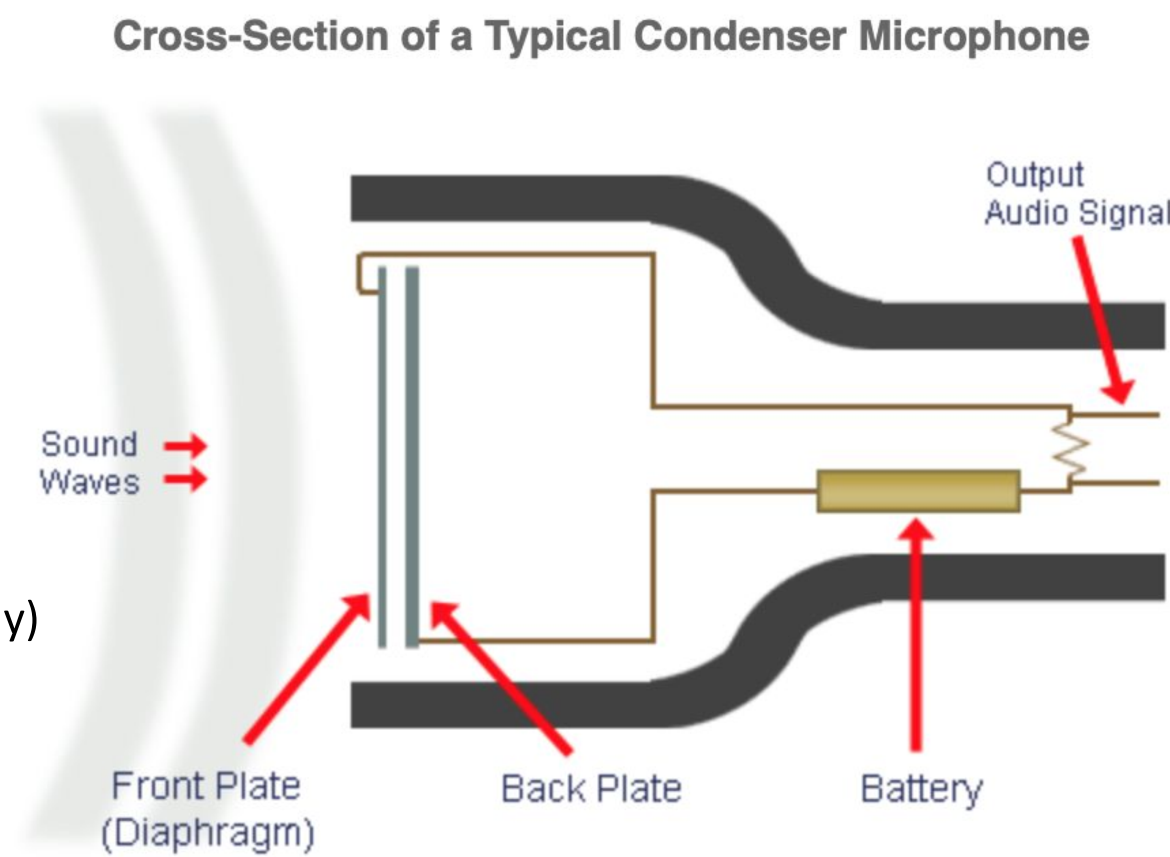
We have

$C = Q/V$ And

$C = \varepsilon_0 A/d$

$V = Qd/\varepsilon_0 A$

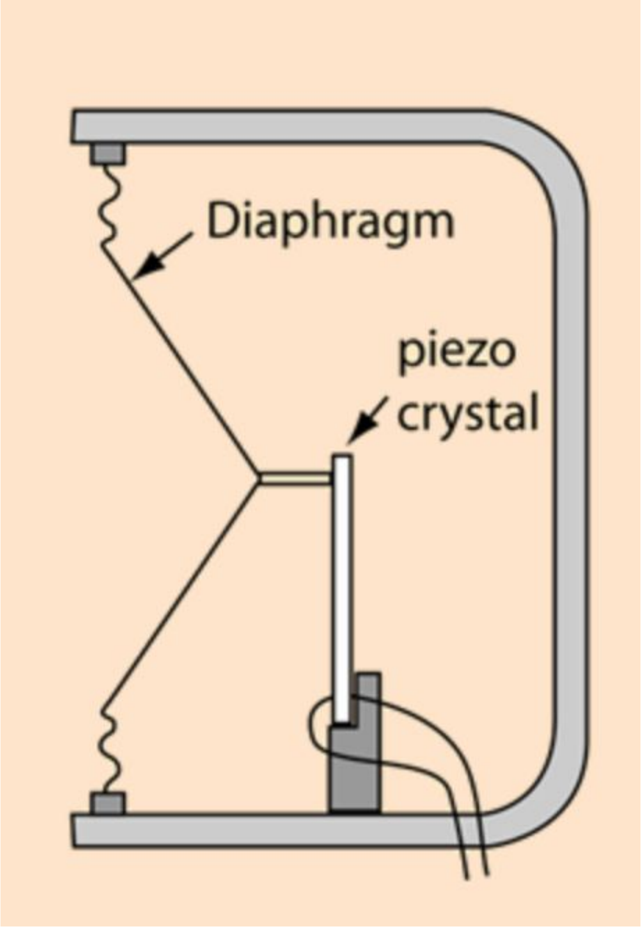
C- capacitance
V – voltage (external power supply)
d – spacing between the two capacitor plates
A – area of the diaphragm
ε_0 – permittivity of free space



Piezoelectric microphone

The piezoelectric effect can be used for the design of simple microphones. A piezoelectric crystal is a direct converter of a mechanical stress into an electric charge. The most frequently used material for the sensor is a piezoelectric ceramic such as polyvinylidene fluoride (PVDF), which can operate up to a very high frequency limit. This is the reason why piezoelectric sensors are used for the transduction of ultrasonic waves.

Crystals which demonstrate the piezoelecric effect produce voltages when they are deformed. The crystal microphone uses a thin strip of piezoelectric material attached to a diaphragm. The two sides of the crystal acquire opposite charges when the crystal is deflected by the diaphragm. The charges are proportional to the amount of deformation and disappear when the stress on the crystal disappears.

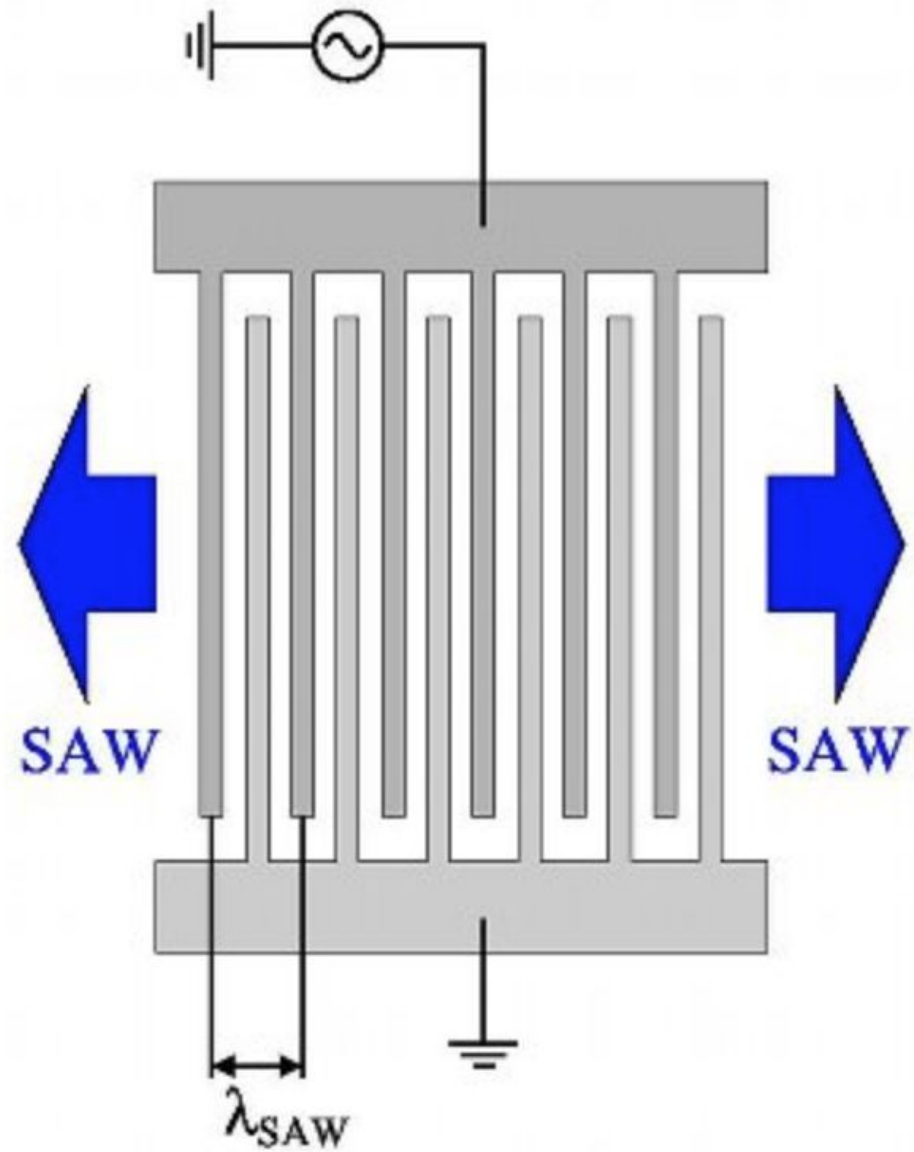


Ceramic materials such as barium titanate and lead zirconate are also being used in microphones. The electric output of crystal microphones is comparatively large, but the frequency response is not comparable to a good dynamic microphone

Solid state SAW sensors

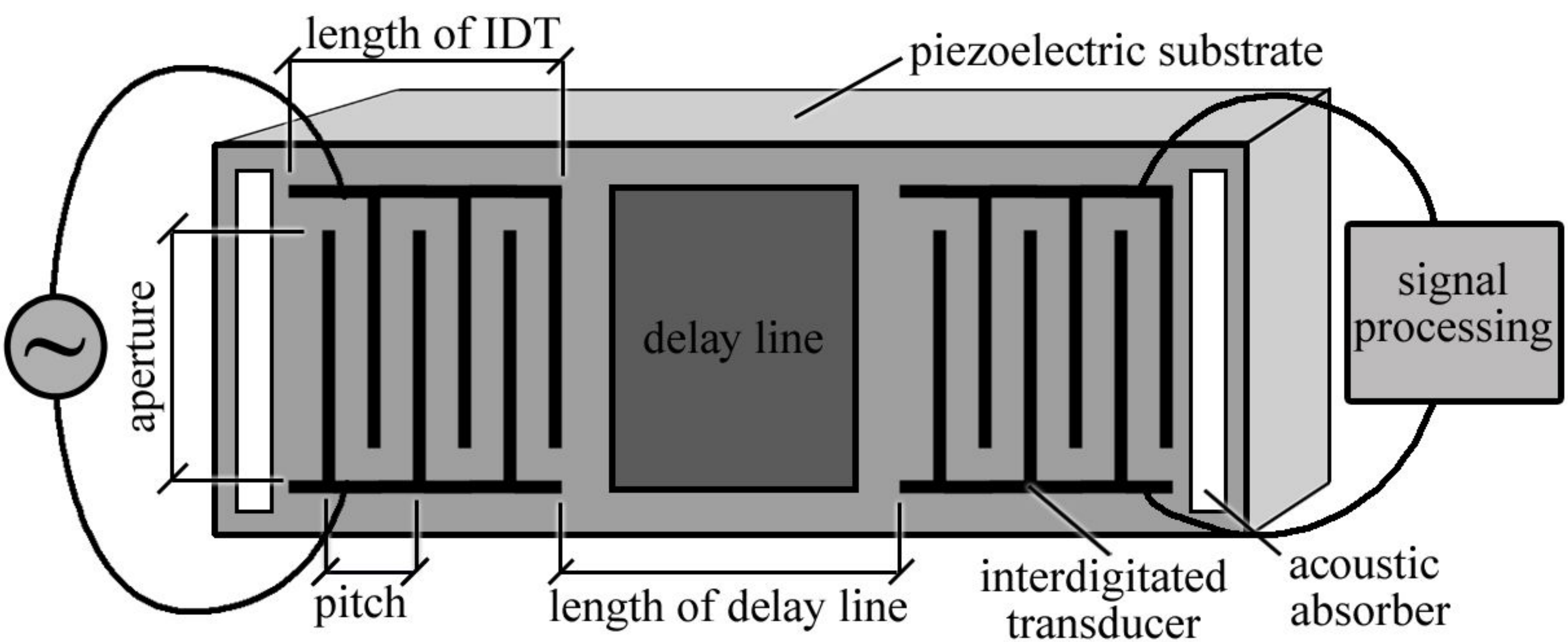
Surface-acoustic waves (SAWs) are sound waves that travel parallel to the surface of an elastic material, with their displacement amplitude decaying into the material so that they are confined to within roughly one wavelength of the surface

A SAW can be generated by applying a suitable oscillating signal to a suitably designed set of surface gates. A schematic diagram of a typical SAW transducer is shown below that consists of many pairs of interdigitated electrodes forming a grating-like structure, with the pitch of the transducer giving the SAW wavelength. By grounding one side of the transducer and applying a signal at a frequency given by the SAW velocity (roughly 2700 m/s for GaAs) divided by the pitch of the transducer, a SAW can be generated.



Solid state SAW sensors

Surface acoustic wave sensors are a class of microelectromechanical systems (MEMS) which rely on the modulation of surface acoustic waves to sense a physical phenomenon. The sensor transduces an input electrical signal into a mechanical wave which, unlike an electrical signal, can be easily influenced by physical phenomena. The device then transduces this wave back into an electrical signal. Changes in amplitude, phase, frequency, or time-delay between the input and output electrical signals can be used to measure the presence of the desired phenomenon.



Solid state SAW sensors

The basic surface acoustic wave device consists of a piezoelectric substrate with an input interdigitated transducer (IDT) on one side of the surface of the substrate, and an output IDT on the other side of the substrate. The space between the IDTs across which the surface acoustic wave propagates is known as the delay line; the signal produced by the input IDT - a physical wave - moves much slower than its associated electromagnetic form, causing a measurable delay.

The sinusoidal electrical input signal creates alternating polarity between the fingers of the interdigitated transducer. Between two adjacent sets of fingers, polarity of the fingers will be switched (e.g. + - +). As a result, the direction of the electric field between two fingers will alternate between adjacent sets of fingers. This creates alternating regions of tensile and compressive strain between fingers of the electrode by the piezoelectric effect, producing a mechanical wave at the surface known as a surface acoustic wave

As fingers on the same side of the device will be at the same level of compression or tension, the space between them---known as the pitch---is the wavelength of the mechanical wave. We can express the synchronous frequency f_0 of the device with phase velocity v_p and pitch p as $\boldsymbol{f_0 = v_p/p}$

The acoustic wave travels across the surface of the device substrate to the other interdigitated transducer, converting the wave back into an electric signal by the piezoelectric effect. Any changes that were made to the mechanical wave will be reflected in the output electric signal.

Applications of SAW sensors

Pressure, Strain, Torque, Temperature and mass sensing

The phenomena of pressure, strain, torque, temperature, and mass can be sensed by the basic device, consisting of two IDTs separated by some distance on the surface of a piezoelectric substrate. These phenomena can all cause a change in length along the surface of the device. A change in length will affect both the spacing between the interdigitated electrodes---altering the pitch---and the spacing between IDTs---altering the delay. This can be sensed as a phase-shift, frequency-shift, or time-delay in the output electrical signal.

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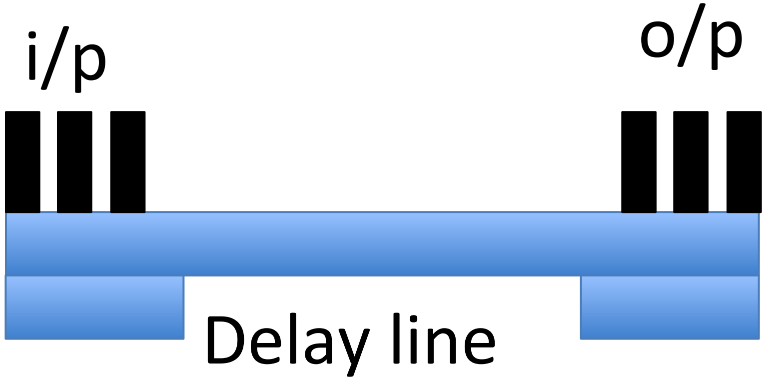
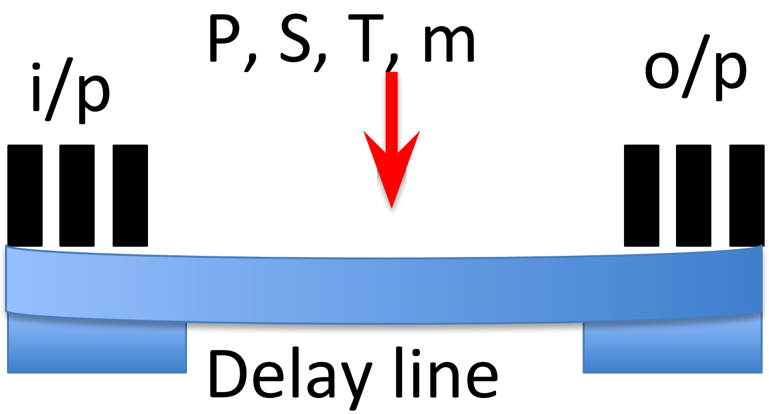




Applications of SAW sensors

Pressure, Strain, Torque, Temperature and mass sensing

When a diaphragm is placed between the environment at a variable pressure and a reference cavity at a fixed pressure, the diaphragm will bend in response to a pressure differential. As the diaphragm bends, the distance along the surface in compression will increase. A surface acoustic wave pressure sensor simply replaces the diaphragm with a piezoelectric substrate patterned with interdigitated electrodes. Strain and torque work in a similar manner, as application to the sensor will cause a deformation of the piezoelectric substrate. A surface acoustic wave temperature sensor can be fashioned from a piezoelectric substrate with a relatively high coefficient of thermal expansion in the direction of the length of the device.

The accumulation of mass on the surface of an acoustic wave sensor will affect the surface acoustic wave as it travels across the delay line. The velocity v of a wave traveling through a solid is proportional to the square root of product of the Young's modulus E and the density ρ Therefore, the wave velocity will decrease with added mass. This change can be measured by a change in time-delay or phase-shift between input and output signals

Force, Strain, and Tactile Sensors

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.

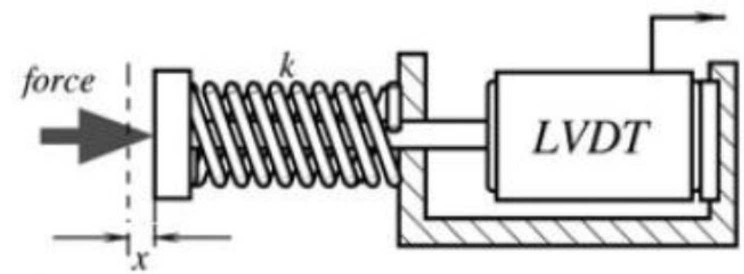
2. **Qualitative sensor:** It indicates whether a sufficiently strong force is applied or not. The sensor output signal indicates when the force magnitude exceeds a predetermined threshold level.
   Example: computer keyboard.
   The qualitative force sensors are used for detection of motion and position.

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.

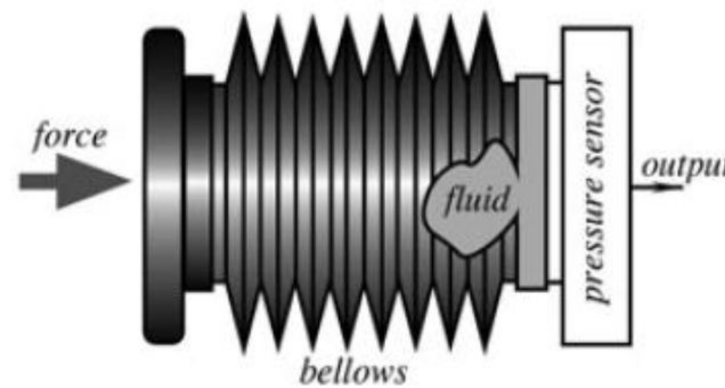
Methods of Sensing Force:

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;



$$F = kx$$

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),

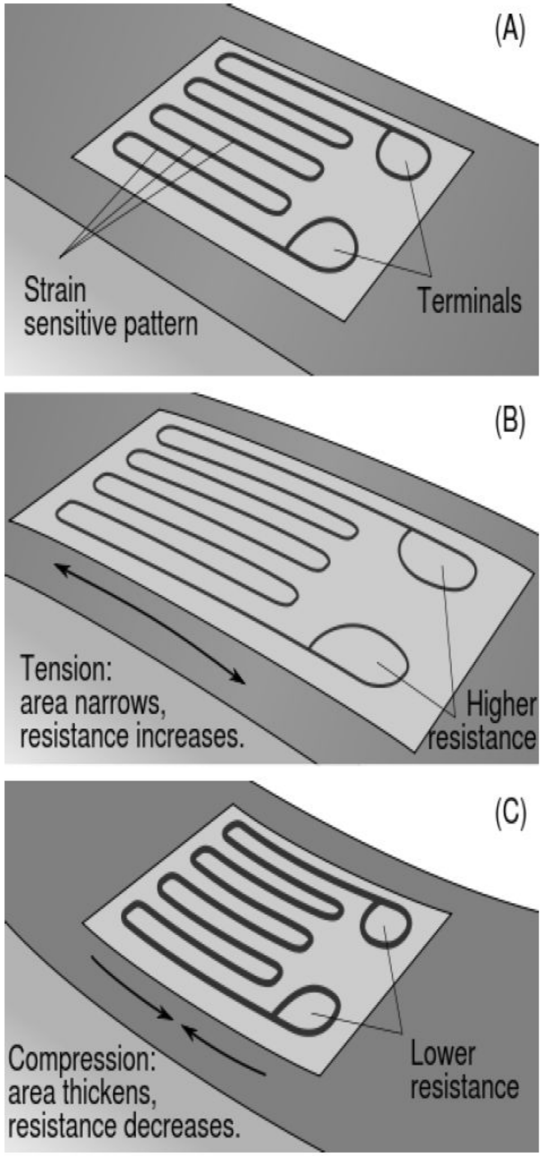
R: is the resistance of the undeformed gauge.

- 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:

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

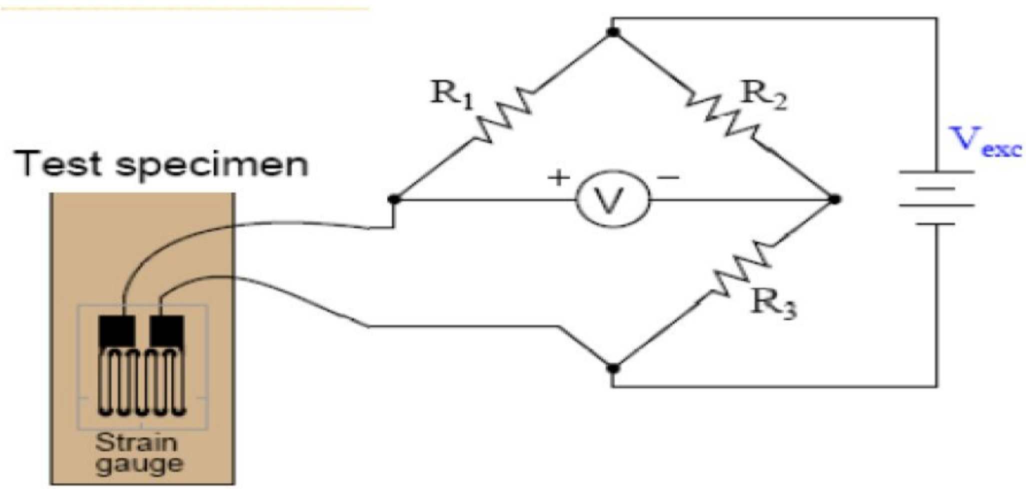
Where; V is the bridge excitation voltage.

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). <u>Note:</u> 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. A 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 relativ 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 touc 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.

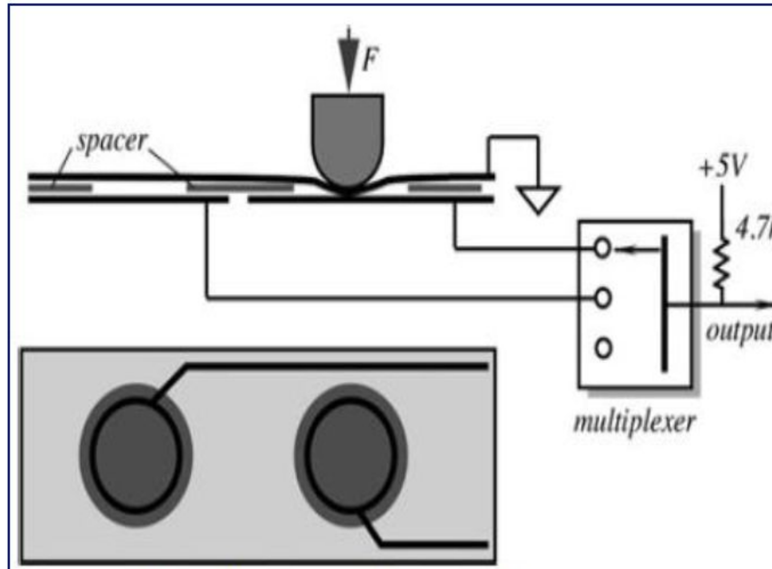
Switch Sensors :

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.

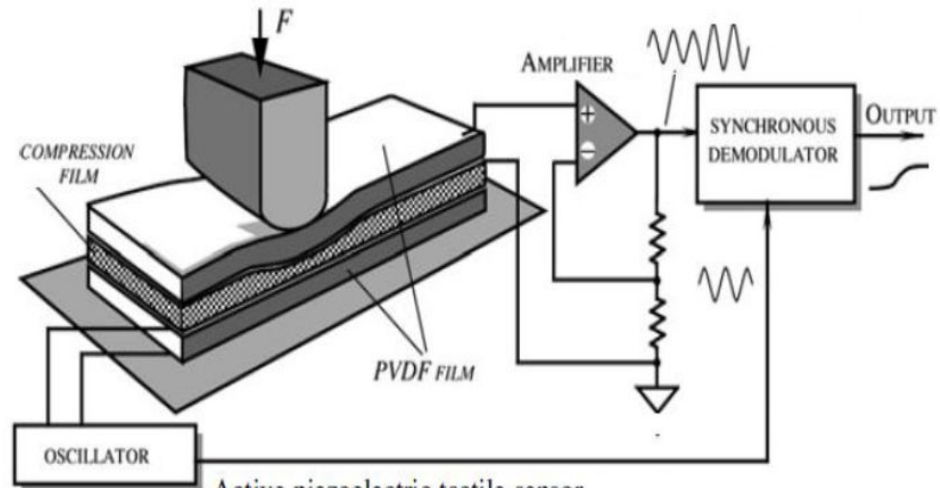
When an external force is applied to the upper conductor over the hole in the spacer, the top leaf flexes and upon reaching the lower conductor, makes an electric contact, grounding the pull-up resistor. The output signal becomes zero indicating the applied force.



Membrane switch as a tactile sensor

Piezoelectric Sensors

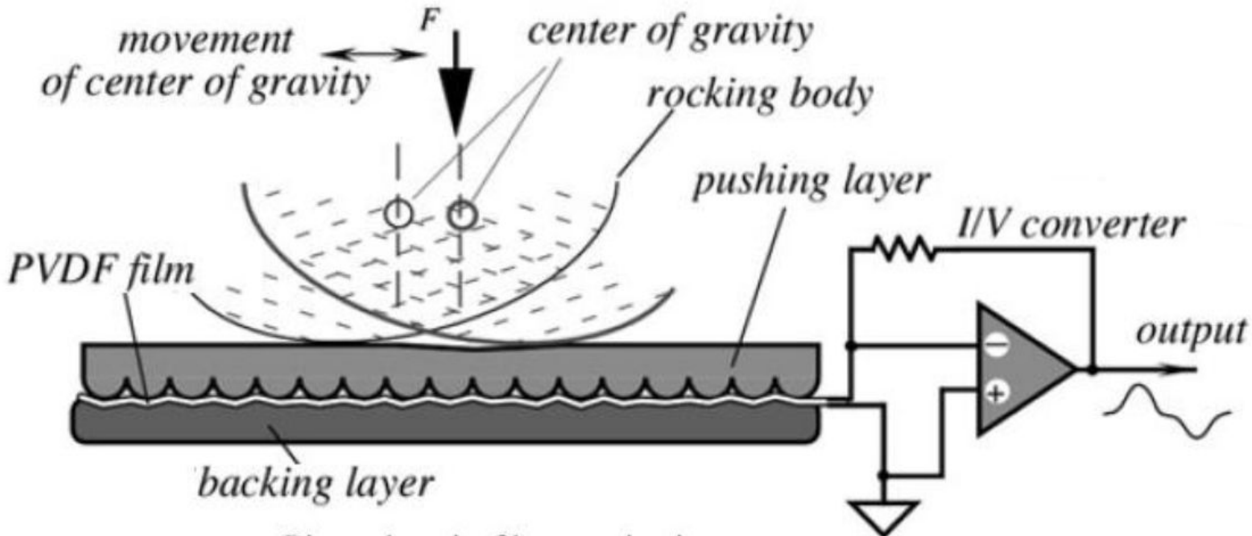
They can be designed with piezoelectric films, such as Polyvinylidene Fluoride (PVDF) used in active or passive modes. The center film is for the acoustic coupling between the other two. The softness of the center film determines sensitivity and the operating range of the sensor.



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.

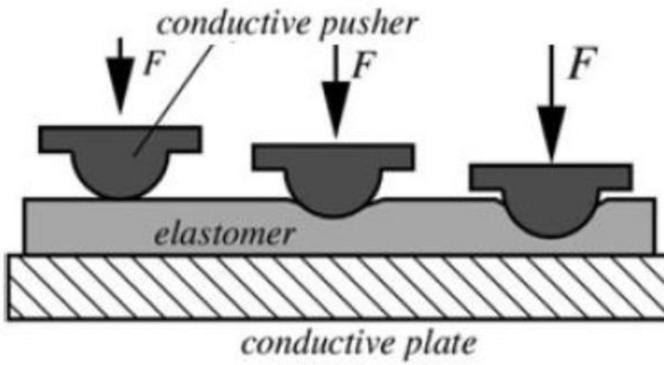
Piezoresistive Sensors:

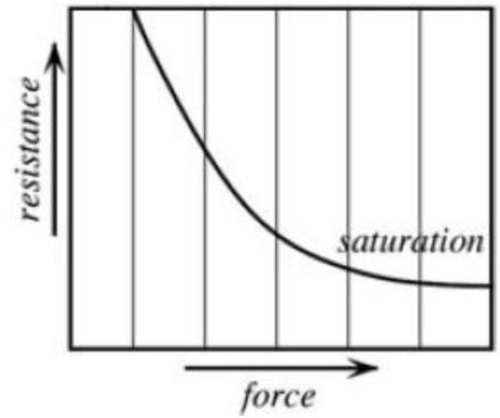
The sensor incorporates a Force-Sensitive Resistor (FSR) whose resistance varies with applied pressure.

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.



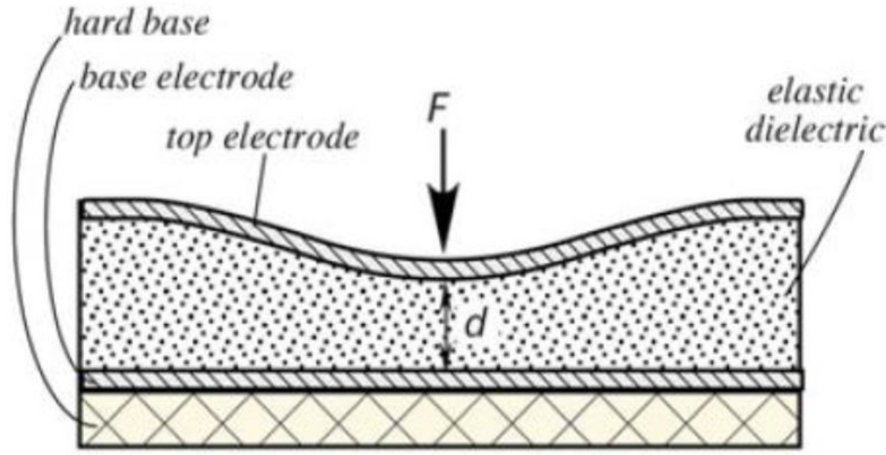


At a certain pressure, the contact area reaches its maximum and the transfer function goes to saturation. For a resistive polymer having thickness 70 mm and a specific resistance of 11 kΩ/cm^2, resistance for pressures over 16 kPa can me approximated by;

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 sensors

What are capacitive pressure sensors?

Capacitive pressure sensors measure pressure by detecting changes in electrical capacitance caused by the movement of a diaphragm.

Working principle

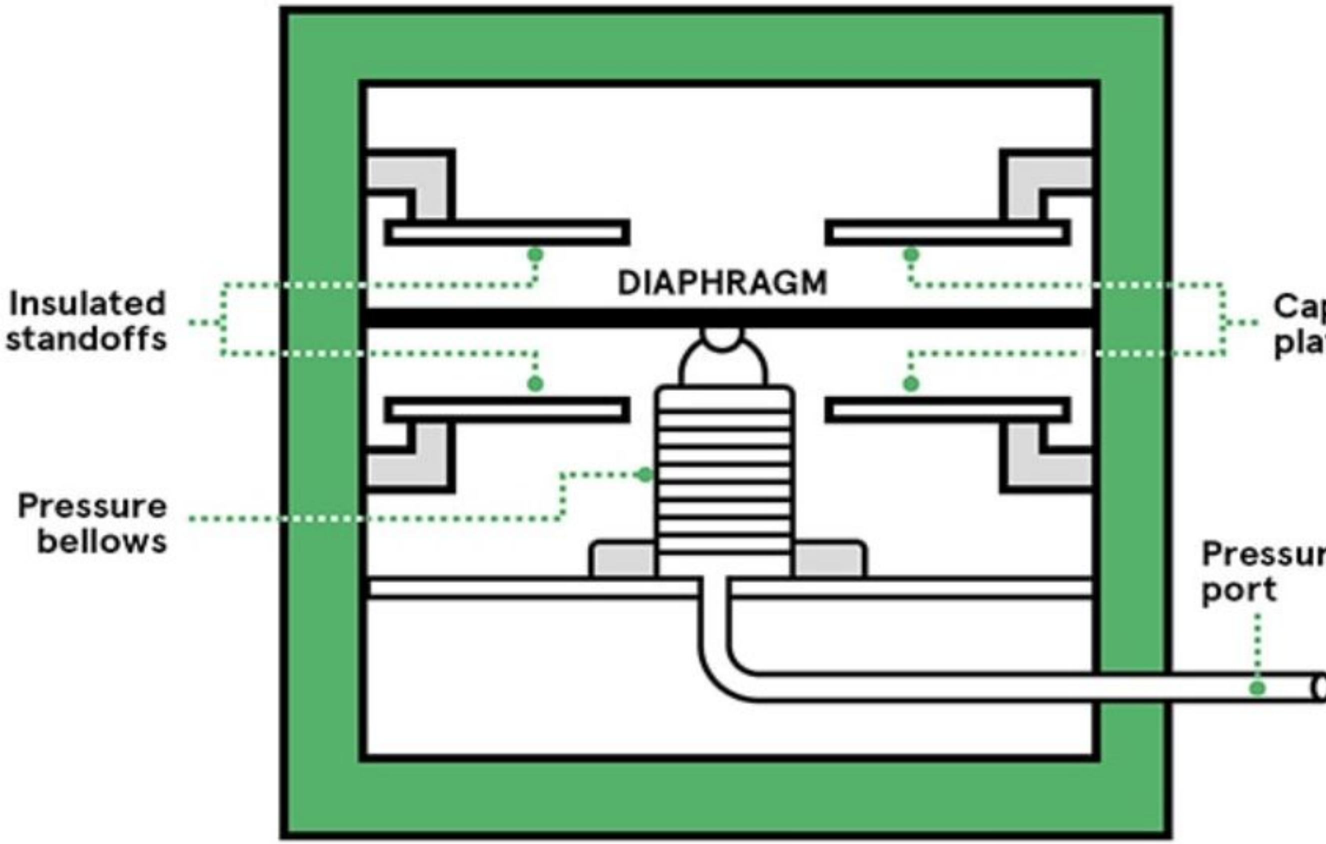
A capacitor consists of two parallel conducting plates separated by a small gap. The capacitance is defined by:

$$C = \varepsilon_r \varepsilon_0 \frac{A}{d}$$

where:

ε_r is the dielectric constant of the material between the plates (this is 1 for a vacuum)
ε_0 is the electric constant (equal to 8.854×10^{-12} F/m),
A is the area of the plates
d is the distance between the plates

Capacitive pressure sensors



Changing any of the variables will cause a corresponding change in the capacitance. The easiest one to control is the spacing. This can be done by making one or both of the plates a diaphragm that is deflected by changes in pressure.

Typically, one electrode is a pressure sensitive diaphragm and the other is fixed.

Capacitive pressure sensors

An easy way of measuring the change in capacitance is to make it part of a tuned circuit, typically consisting of the capacitive sensor plus an inductor. This can either change the frequency of an oscillator or the AC coupling of a resonant circuit.

Construction

The diaphragm can be constructed from a variety of materials, such as plastic, glass, silicon or ceramic, to suit different applications.

The capacitance of the sensor is typically around 50 to 100 pF, with the change being a few picofarads.

The stiffness and strength of the material can be chosen to provide a range of sensitivities and operating pressures. To get a large signal, the sensor may need to be fairly large, which can limit the frequency range of operation. However, smaller diaphragms are more sensitive and have a faster response time.

A large thin diaphragm may be sensitive to noise from vibration (after all, the same basic principle is used to make condenser microphones) particularly at low pressures.

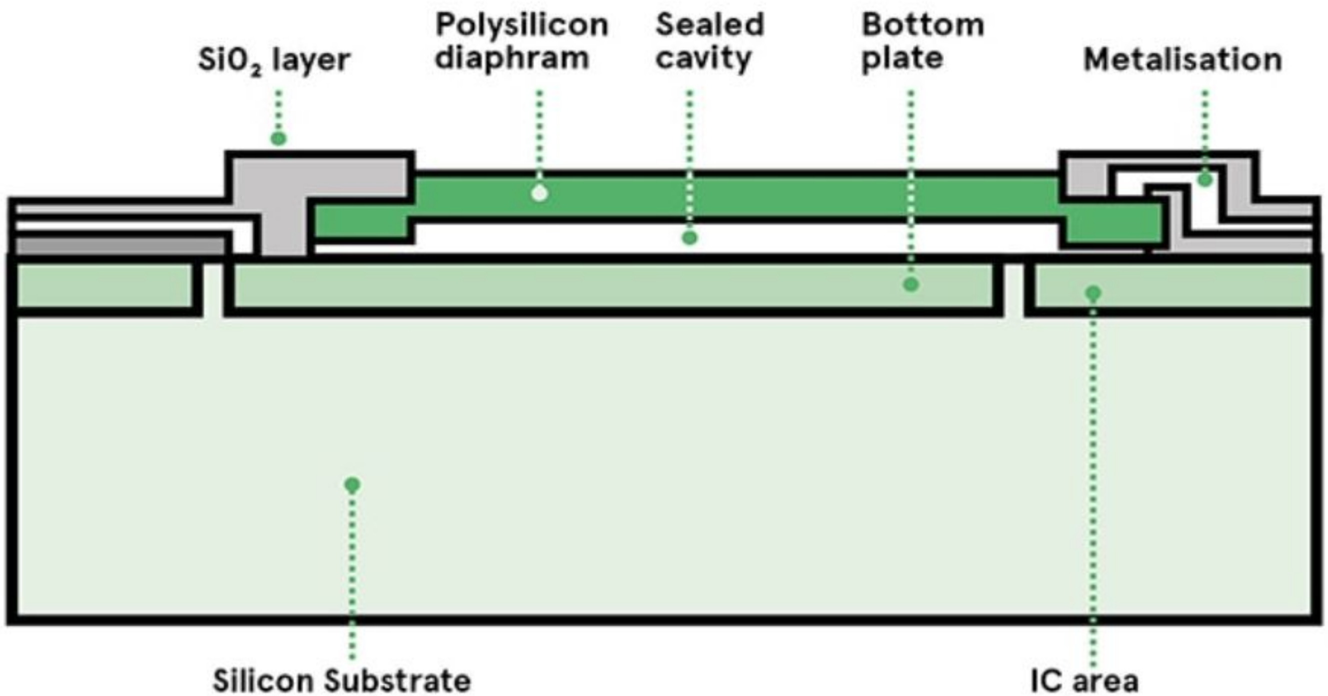
Thicker diaphragms are used in high-pressure sensors and to ensure mechanical strength.

Sensors with full-scale pressure up to 5,000 psi can readily be constructed by controlling the diaphragm thickness.

Materials specs for the diaphragm

1. Small thermal expansion coefficient to make it temperature insensitive
2. Low hysteresis to ensure accuracy and repeatability of measurements

Capacitive pressure sensors



A cross section of capacitive sensor construction

Capacitive pressure sensors

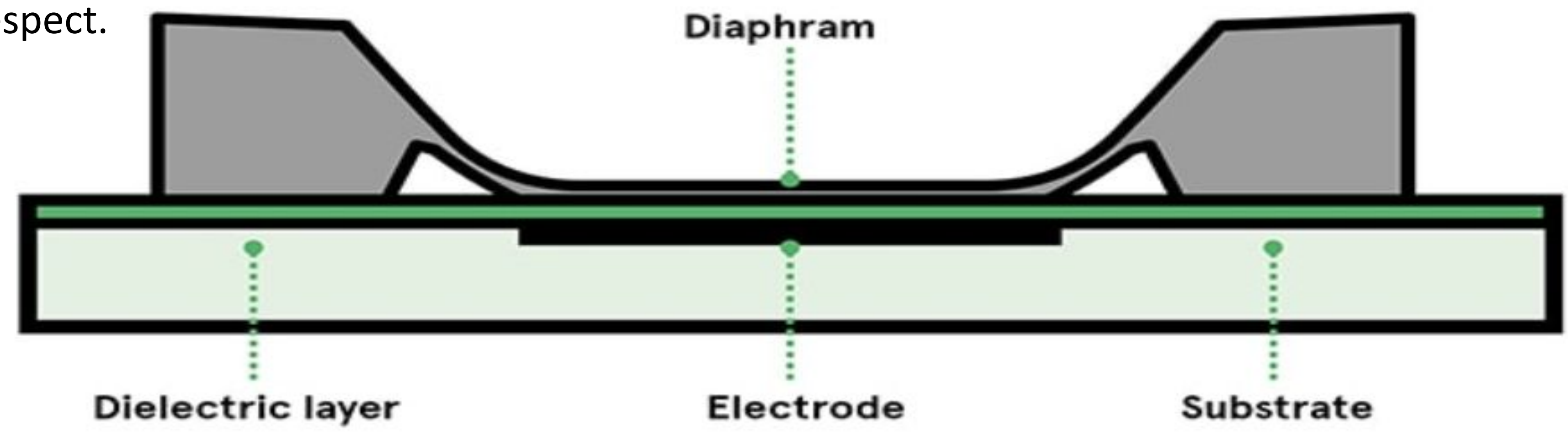
Capacitive pressure sensors can also be constructed directly on a silicon chip with the same fabrication techniques that are used in manufacturing semiconductor electronics. This allows very small sensing elements to be constructed and combined with the electronics for signal conditioning and reporting

Function

The change in capacitance can be measured by connecting the sensor in a frequency-dependent circuit such as an oscillator or an LC tank circuit. In both cases, the resonant frequency of the circuit will change as the capacitance changes with pressure.

An oscillator requires some extra electronic components and a power supply. A resonant LC circuit can be used as a passive sensor, without its own source of power.

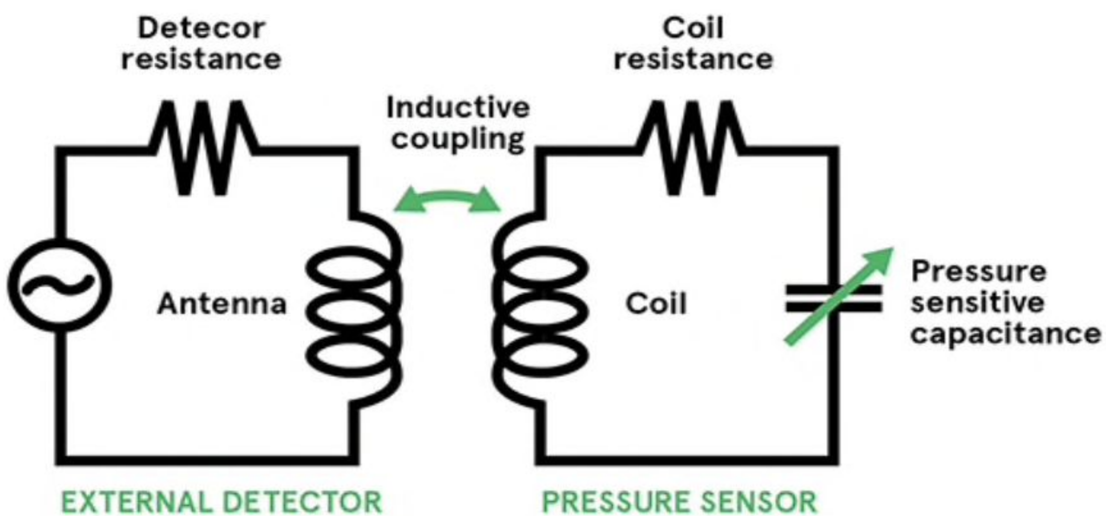
The dielectric constant of the material between the plates may change with pressure or temperature and this can also be a source of errors. The relative permittivity of air, and most other gasses, increases with pressure so this will slightly increase the capacitance change with pressure. Absolute pressure sensors, which have a vacuum between the plates, behave ideally in this respect.



Capacitive pressure sensors

Design

The electronics for measuring and conditioning the signal need to be placed close to the sensing element to minimise the effect of stray capacitance.
Because they can be incorporated as components in high-frequency tuned circuits, capacitive sensors are well suited for wireless measurement.
In the case of passive sensors an external antenna can be used to provide a signal to stimulate the tuned circuit and so measure the change in resonance frequency. This makes them suitable for medical devices that need to be implanted.
Alternatively, for an active sensor, the frequency generated by the oscillator can be picked up by an antenna.



An external antenna in some passive sensors to stimulate the tuned circuit

Applications

Capacitive pressure sensors are often used to measure gas or liquid pressures in jet engines, car tyres, the human body and many other places. But they can also be used as tactile sensors in wearable devices or to measure the pressure applied to a switch or keyboard.
They are particularly versatile, in part due to their mechanical simplicity, so can be used in demanding environments. Capacitive sensors can be used for absolute, gauge, relative or differential pressure measurements.

Advantages and disadvantages

Capacitive pressure sensors have a number of advantages over other types of pressure sensors.
They can have very low power consumption because there is no DC current through the sensor element. Current only flows when a signal is passed through the circuit to measure the capacitance. Passive sensors, where an external reader provides a signal to the circuit, do not require a power supply – these attributes make them ideal for low power applications such as remote or IoT sensors.
The sensors are mechanically simple, so they can be made rugged with stable output, making them suitable for use in harsh environments.
They have low hysteresis with good repeatability and are not very sensitive to temperature changes.
On the other hand, capacitive sensors have non-linear output, although this can be reduced in touch-mode devices. However, this may come at the cost of greater hysteresis.
Finally, careful circuit design is required for the interface electronics because of the high output impedance of the sensor and to minimise the effects of parasitic capacitance.

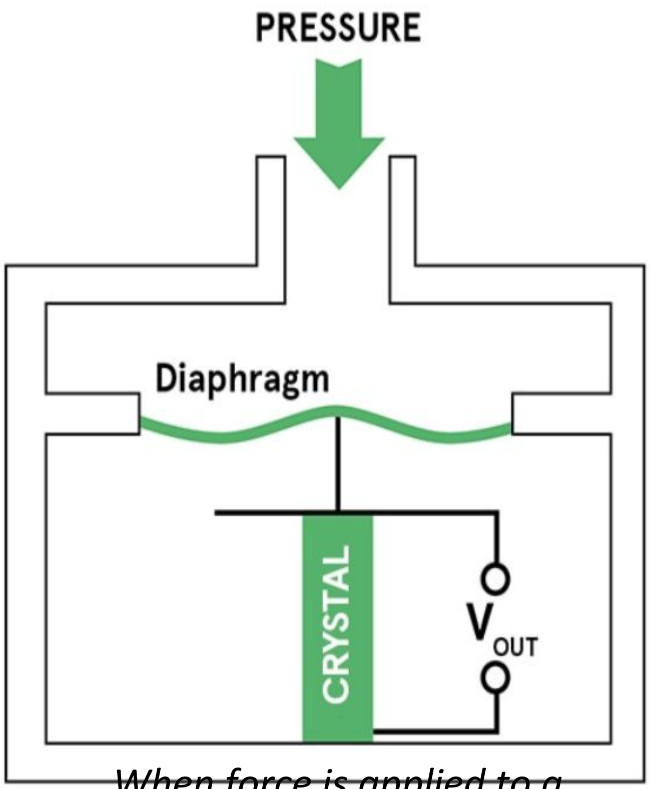
Piezoelectric pressure sensors

What are piezoelectric pressure sensors?

Piezoelectricity is the charge created across certain materials when a mechanical stress is applied.
Piezoelectric pressure sensors exploit this effect by measuring the voltage across a piezoelectric element generated by the applied pressure. They are very robust and are used in a wide range of industrial applications.

Working principle

When a force is applied to a piezoelectric material, an electric charge is generated across the faces of the crystal. This can be measured as a voltage proportional to the pressure (see diagram to the right).
There is also an inverse piezoelectric effect where applying a voltage to the material will cause it to change shape.
A given static force results in a corresponding charge across the sensor. However, this will leak away over time due to imperfect insulation, the internal sensor resistance, the attached electronics, etc.
As a result, piezoelectric sensors are not normally suitable for measuring static pressure. The output signal will gradually drop to zero, even in the presence of constant pressure. They are, however, sensitive to dynamic changes in pressure across a wide range of frequencies and pressures.



When force is applied to a piezoelectric diaphragm, a voltage proportional to the pressure is generated

Piezoelectric pressure sensors

Function

Unlike piezoresistive and capacitive transducers, piezoelectric sensor elements require no external voltage or current source. They generate an output signal directly from the applied strain.

The output from the piezoelectric element is a charge proportional to pressure. Detecting this requires a charge amplifier to convert the signal to a voltage.

Some piezoelectric pressure sensors include an internal charge amplifier to simplify the electrical interface by providing a voltage output. This requires power to be supplied to the sensor.

An internal amplifier makes the sensor simpler to use. For example, it makes it possible to use long signal cables to connect to the sensor. The amplifier can also include signal-conditioning circuitry to filter the output, adjust for temperature and compensate for the changing sensitivity of the sensing element.

The presence of the electronic components does, however, limit the operating temperature to not much more than 120ºC.

For higher temperature environments, a charge-mode sensor can be used. This provides the generated charge directly as the output signal. It therefore requires an external charge amplifier to convert this to a voltage.

Care is required in the design and implementation of the external electronics. The high impedance output of the sensor means the circuit is sensitive to noise caused by poor connections, cable movement, electromagnetic and RF interference.

The low frequency response of the sensor is determined by the discharge time of the amplifier.

Piezoelectric pressure sensors

Construction

The piezoelectric effect requires materials with a specific asymmetry in the crystal structure.
This includes some natural crystals, such as quartz or tourmaline.
In addition, specially formulated ceramics can be created with a suitable polarisation to make them piezoelectric. These ceramics have higher sensitivities than natural crystals. A useful output can be generated with as little as 0.1% deformation.
Because the piezoelectric materials are rigid, only a very small deflection of the material is required to get a usable output signal. This makes the sensors very robust and tolerant of over-pressure conditions. It also means they respond rapidly to changes in pressure.
The pressure sensor can be affected by any external force on the piezoelectric element, for example, by forces caused by acceleration or noise.
Microsensors can be constructed using thin films. Zinc oxide was one of the first materials used. This has largely been replaced by ceramics made from materials such as lead zirconate titanate (PZT) because of their larger piezoelectric effect.
Microelectromechanical systems (MEMS) can be created by combining piezoelectric thin films with micromachined silicon membranes.
Piezoelectric materials are also used in some other types of MEMS sensors. For example, the inverse piezoelectric effect is used to generate surface acoustic waves through a diaphragm. The distortion of the surface under pressure can then be detected by the changes it causes in the waves that are received by another piezoelectric element.

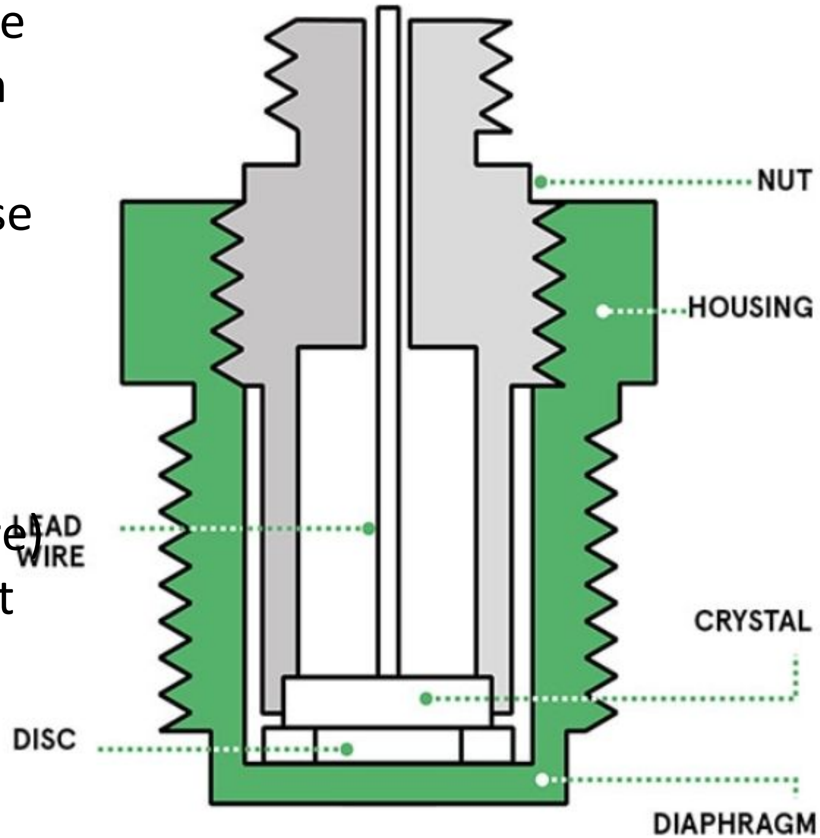
Piezoelectric pressure sensors

Design

Piezoelectric pressure sensors are often constructed in a threaded tube (as shown in the diagram below) to make it easy to mount them in equipment where pressure is to be monitored. Care is needed when installing these because over-tightening can affect the output sensitivity.

In some of the typical applications of piezoelectric sensors, they may be exposed to thermal shock (a sudden change in temperature) caused by either radiant heat or the flow of hot gases or liquids past the sensor.

This can cause changes to the output due to heating of the crystal, the diaphragm or the casing of the sensor. Note that this is not the same as the static temperature sensitivity of the sensor. The effects of thermal shock can be minimised by the design of the enclosure and mounting the sensor to provide isolation.



A cross-section of a piezoelectric presure sensor construction

Piezoelectric pressure sensors

Applications

The robustness, high frequency and rapid response time of piezoelectric pressure sensors means they can be used in a wide range of industrial and aerospace applications where they'll be exposed to high temperatures and pressures.

They are often used for measuring dynamic pressure, for example in turbulence, blast, and engine combustion. These all require fast response, ruggedness and a wide range of operation.

Their sensitivity and low power consumption also makes them useful for some medical applications. For example, a thin-film plastic sensor can be attached to the skin and used for real-time monitoring of the arterial pulse.

Advantages and disadvantages

One of the main advantages of piezoelectric pressure sensors is their ruggedness. This makes them suitable for use in a variety of harsh environments.

Apart from the associated electronics, piezoelectric sensors can be used at high temperatures. Some materials will work at up to 1,000ºC. The sensitivity may change with temperature but this can be minimised by appropriate choice of materials.

The output signal is generated by the piezoelectric element itself, so they are inherently low-power devices.

The sensing element itself is insensitive to electromagnetic interference and radiation. The charge amplifier and other electronics need to be carefully designed and positioned as close as possible to the sensor to reduce noise and other signal errors.

Piezoelectric sensors can be easily made using inexpensive materials (for example quartz or tourmaline), so they can provide a low cost solution for industrial pressure measurement.

Piezoresistive pressure sensors

What are piezoresistive strain gauge pressure sensors

Piezoresistive strain gauges are among the most common types of pressure sensors. They use the change in electrical resistance of a material when stretched to measure the pressure. These sensors are suitable for a variety of applications because of their simplicity and robustness. They can be used for absolute, gauge, relative and differential pressure measurement, in both high- and low-pressure applications. In this article we'll discuss the various types of piezoresistive pressure sensors available, how they work, and their relative merits.

Working principle

The basic principle of the piezoresistive pressure sensor is to use a strain gauge made from a conductive material that changes its electrical resistance when it is stretched. The strain gauge can be attached to a diaphragm that recognises a change in resistance when the sensor element is deformed. The change in resistance is converted to an output signal

There are three separate effects that contribute to the change in resistance of a conductor. (1) The resistance of a conductor is proportional to its length so stretching increases the resistance As the conductor is stretched, its cross-sectional area is reduced, which also increases the resistance (2)The inherent resistivity of some materials increases when it is stretched

And (3) the piezoresistive effect, varies greatly between materials. The sensitivity is specified by the gauge factor, which is defined as the relative resistance change divided by the strain:

$$GF = \frac{\left(\frac{\Delta R}{R}\right)}{\epsilon}$$

Where strain ε is defined as the relative change in length:

$$\epsilon = \frac{\Delta L}{L}$$

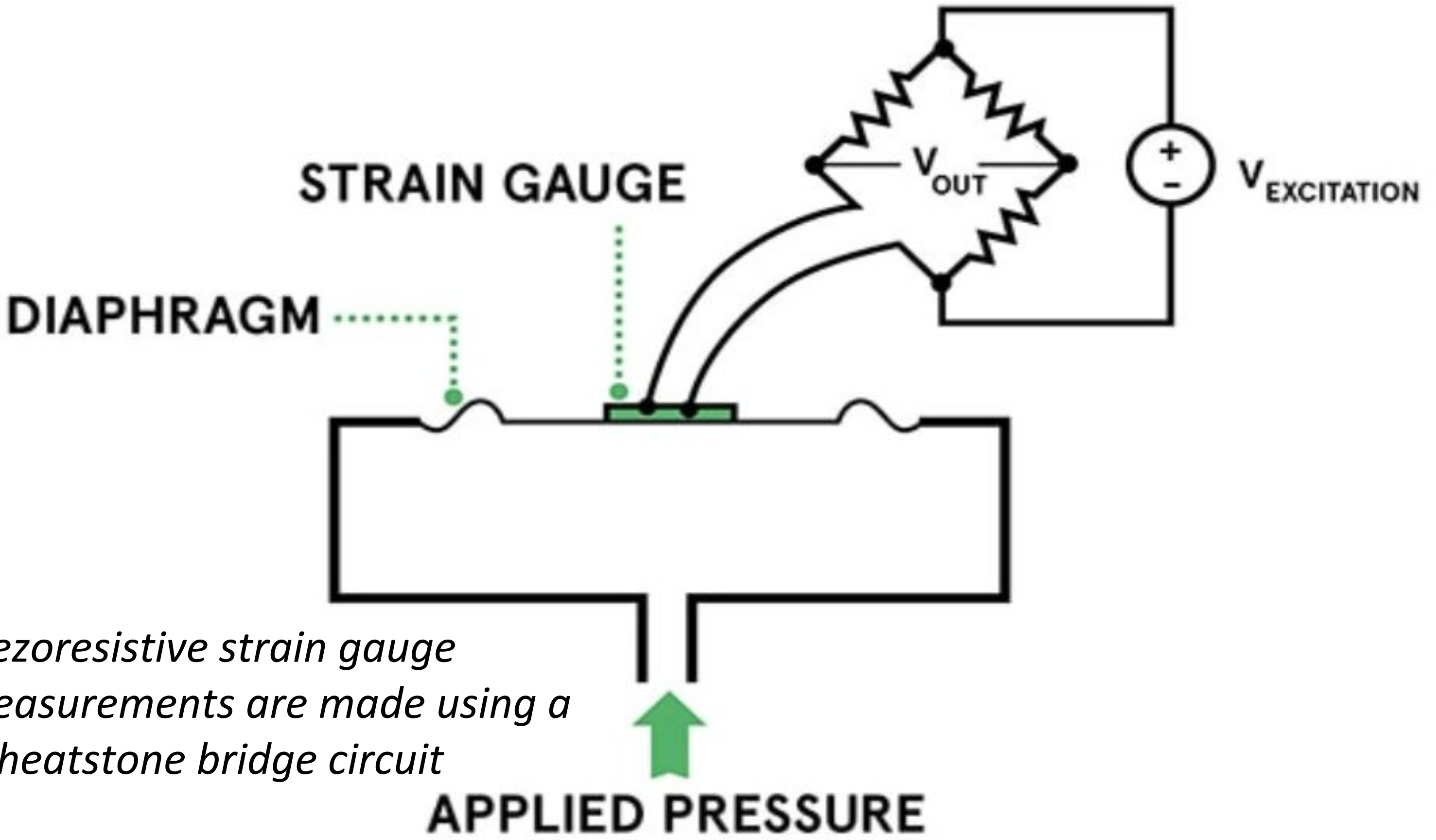
Piezoresistive pressure sensors

Pressure sensing elements

Strain gauge elements can be made of metal or a semiconducting material.
The resistance change in metal strain gauges is mainly due to the change in geometry (length and cross-section area) of the material. In some metals, for example platinum alloys, the piezoresistive effect can increase the sensitivity by a factor of two or more.
In semiconducting materials, the piezoresistive effect dominates, typically being orders of magnitude larger than the contribution from geometry.

Function

The change in resistance in the sensor is usually measured using a Wheatstone bridge circuit (as shown below). This allows small changes in the resistance of the sensor to be converted to an output voltage.



Piezoresistive strain gauge measurements are made using a Wheatstone bridge circuit

Piezoresistive pressure sensors

An excitation voltage needs to be provided to the bridge. When there is no strain and all the resistors in the bridge are balanced then the output will be zero volts. A change in pressure will cause a change in resistances in the bridge resulting in a corresponding output voltage or current. How this is calculated is shown in the formula below.

$$V_o = \left[\frac{R_3}{R_3 + R_4} - \frac{R_2}{R_1 + R_2} \right] \cdot V_{ex}$$

Performance can be improved by using two or four sensing elements in the bridge, with the elements in each pair being subject to equal and opposite strain. This increases the output signal and can minimise the effects of temperature on the sensor elements.

Construction

Metal sensing elements

One or more strain gauge sensors made from a length of wire can be attached to the surface of a diaphragm.

Pressure on the diaphragm will stretch the wires and change the resistance. The sensor elements can be bonded on to the surface with adhesive or the conductor can be directly deposited on the diaphragm by sputtering. The latter method removes potential problems with adhesives failing at high temperatures and also makes it easier to construct small devices.

A metal wire sensor can also be made by wrapping a wire between posts that are displaced by changing pressure. This construction can also work at higher temperatures because no adhesive is needed to attach the wire to the posts.

Piezoresistive pressure sensors

Construction

Semiconductor sensing elements

Semiconducting materials, most commonly silicon, can also be used to make strain gauge pressure sensors. The characteristics of the sensing element, particularly the size of the piezoresistive effect, can be adjusted by doping; in other words by adding carefully controlled amounts of impurities (dopants) to the semiconductor.

More lightly doped silicon results in a higher resistivity and a higher gauge factor. However, this also increases the thermal sensitivity of both the resistance and gauge factor.

Fabrication process

Semiconductor sensors can be constructed in a similar way to metal wire sensors, by depositing the silicon strain gauge elements on to a diaphragm.

They can also be constructed directly on a silicon surface by using the same manufacturing methods used for making electronic semiconductor devices. This allows very small sensors to be manufactured cheaply with precisely controlled properties such as sensitivity, linearity and temperature response.

Electronic components can also be fabricated on the same silicon chip to provide signal conditioning and simplify the electrical interface. Sensors based on these micro-electronic mechanical systems (MEMS) are described in more detail in [LINK: MEMS Pressure Sensors].

Piezoresistive pressure sensors

Specifications

Typical metal strain gauge sensors have a gauge factor of around 2 to 4. With a typical maximum strain of a few parts per thousand, this means a change in output of around 1mV for each volt of excitation.
Silicon-based sensors are usually doped to provide a gauge factor of around 100 to 200, which gives a good compromise between sensitivity and thermal characteristics. The output from a silicon sensor can be around 10 mV/V.

Advantages and disadvantages

Piezoresistive strain gauge pressure sensors have the advantage of being robust. Their performance and calibration is also stable over time.
One disadvantage of these sensors is that they consume more power than some other types of pressure sensor. This may mean they are not suitable for battery powered or portable systems.
Metal film sensing elements have the advantage of simple construction and durability. They also have a higher maximum operating temperature (up to about 200°C) than silicon strain gauges, which are limited to below 100°C.
Silicon strain gauges provide a much larger output signal, making them well-suited to low-pressure applications, down to around 2 kPa.
MEMS pressure sensors can be made much smaller than metal wire sensors and can be integrated with electronics for signal processing, which can control for non-linearity and temperature dependence.

Integrated Hall Effect Sensor

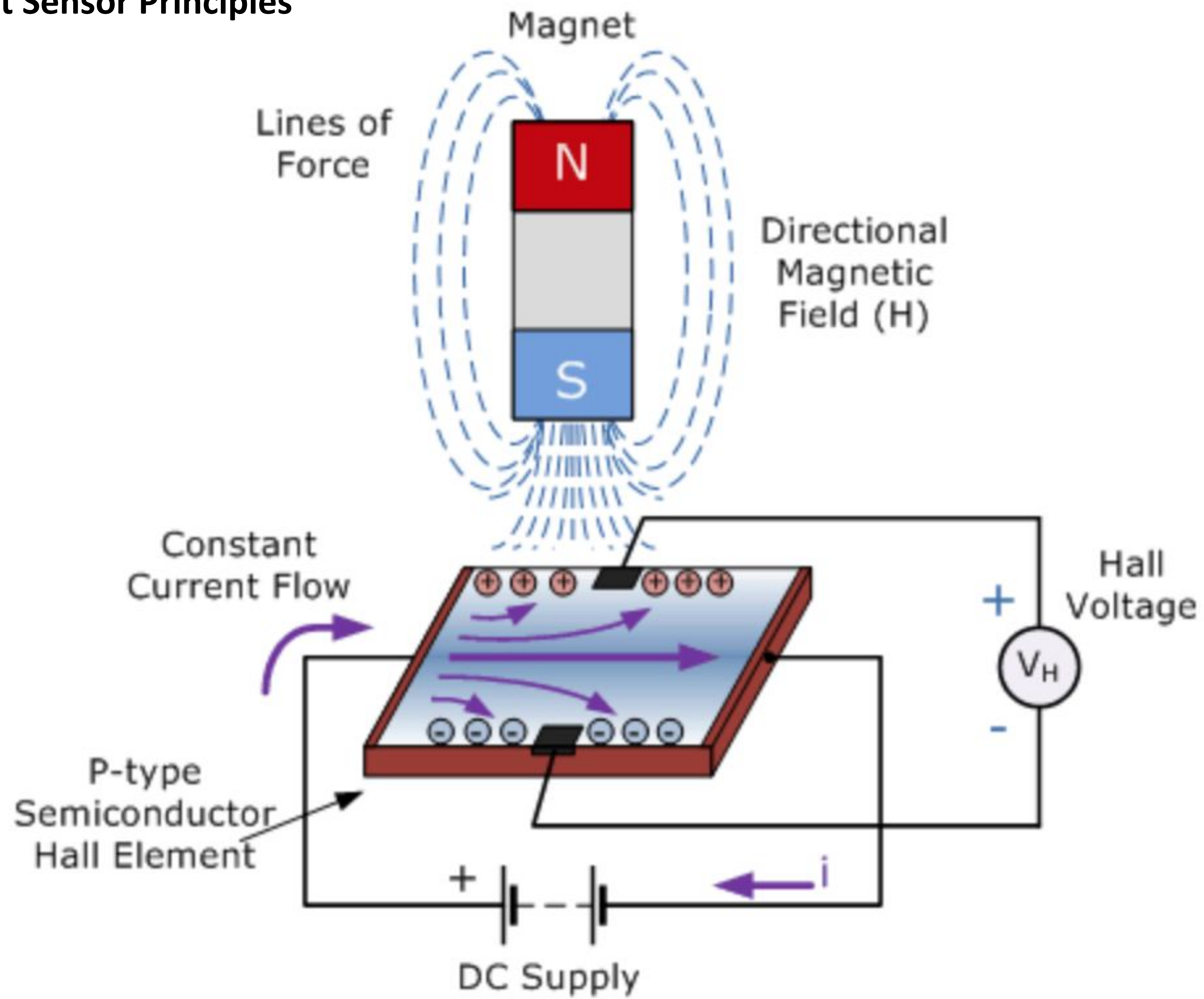
Magnetic sensors convert magnetic or magnetically encoded information into electrical signals for processing by electronic circuits,
Magnetic sensors are solid state devices that are becoming more and more popular because they can be used in many different types of application such as sensing position, velocity or directional movement. They are also a popular choice of sensor for the electronics designer due to their non-contact wear free operation, their low maintenance, robust design and as sealed hall effect devices are immune to vibration, dust and water.
One of the main uses of magnetic sensors is in automotive systems for the sensing of position, distance and speed. For example, the angular position of the crank shaft for the firing angle of the spark plugs, the position of the car seats and seat belts for air-bag control or wheel speed detection for the anti-lock braking system, (ABS).

Magnetic sensors are designed to respond to a wide range of positive and negative magnetic fields in a variety of different applications and one type of magnet sensor whose output signal is a function of magnetic field density around it is called the Hall Effect Sensor.

Hall Effect Sensors are devices which are activated by an external magnetic field. We know that a magnetic field has two important characteristics flux density, (B) and polarity (North and South Poles). The output signal from a Hall effect sensor is the function of magnetic field density around the device. When the magnetic flux density around the sensor exceeds a certain pre-set threshold, the sensor detects it and generates an output voltage called the **Hall Voltage, VH**. Consider the diagram below.

Integrated Hall Effect Sensor

Hall Effect Sensor Principles



Integrated Hall Effect Sensor

Hall Effect Sensors consist basically of a thin piece of rectangular p-type semiconductor material such as gallium arsenide (GaAs), indium antimonide (InSb) or indium arsenide (InAs) passing a continuous current through itself. When the device is placed within a magnetic field, the magnetic flux lines exert a force on the semiconductor material which deflects the charge carriers, electrons and holes, to either side of the semiconductor slab. This movement of charge carriers is a result of the magnetic force they experience passing through the semiconductor material.

As these electrons and holes move side wards a potential difference is produced between the two sides of the semiconductor material by the build-up of these charge carriers. Then the movement of electrons through the semiconductor material is affected by the presence of an external magnetic field which is at right angles to it and this effect is greater in a flat rectangular shaped material.

The effect of generating a measurable voltage by using a magnetic field is called the **Hall Effect** after Edwin Hall who discovered it back in the 1870’s with the basic physical principle underlying the Hall effect being Lorentz force. To generate a potential difference across the device the magnetic flux lines must be perpendicular, (90o) to the flow of current and be of the correct polarity, generally a south pole.

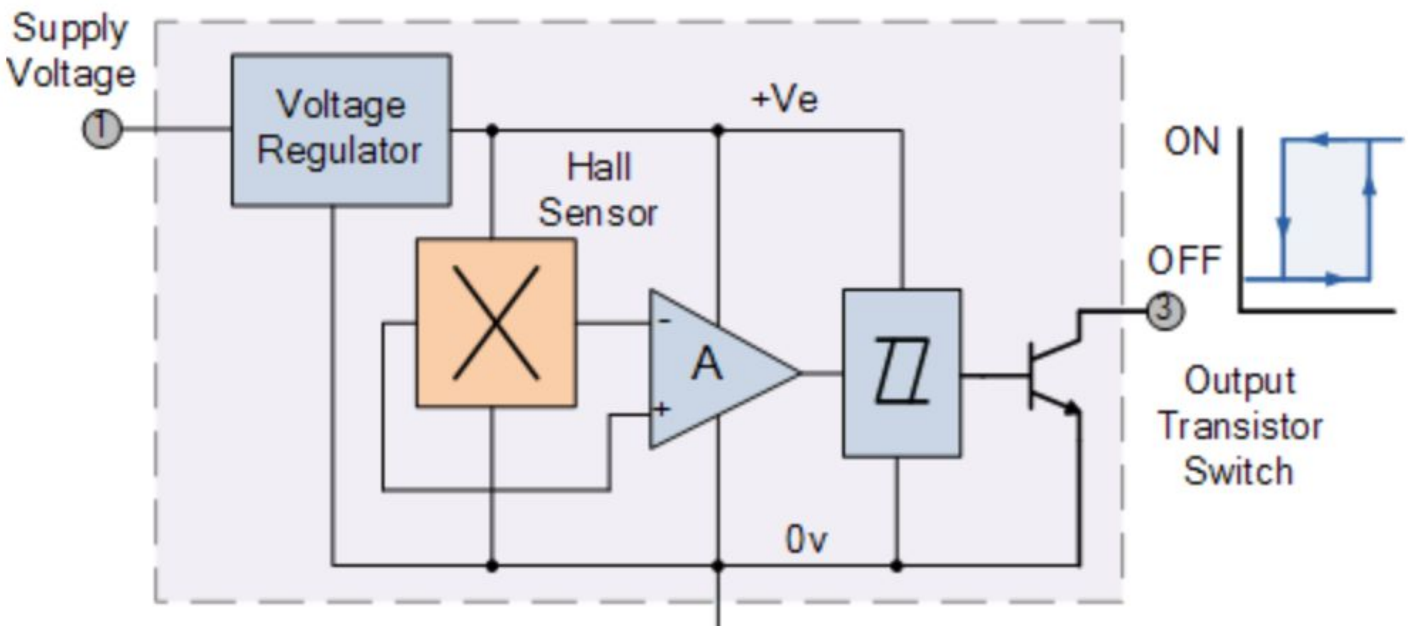
The Hall effect provides information regarding the type of magnetic pole and magnitude of the magnetic field. For example, a south pole would cause the device to produce a voltage output while a north pole would have no effect. Generally, Hall Effect sensors and switches are designed to be in the “OFF”, (open circuit condition) when there is no magnetic field present. They only turn “ON”, (closed circuit condition) when subjected to a magnetic field of sufficient strength and polarity.

Integrated Hall Effect Sensor

Hall Effect Magnetic Sensor

The output voltage, called the Hall voltage, (VH) of the basic Hall Element is directly proportional to the strength of the magnetic field passing through the semiconductor material (output $\propto$ H). This output voltage can be quite small, only a few microvolts even when subjected to strong magnetic fields so most commercially available Hall effect devices are manufactured with built-in DC amplifiers, logic switching circuits and voltage regulators to improve the sensors sensitivity, hysteresis and output voltage. This also allows the Hall effect sensor to operate over a wider range of power supplies and magnetic field conditions.

The Hall Effect Sensor



Typical Hall Effect Switch

Integrated Hall Effect Sensor

Hall Effect Sensors are available with either linear or digital outputs. The output signal for linear (analogue) sensors is taken directly from the output of the operational amplifier with the output voltage being directly proportional to the magnetic field passing through the Hall sensor. This output Hall voltage is given as:

$$V_H = R_H\left(\frac{I}{t} \times B\right)$$

Where:

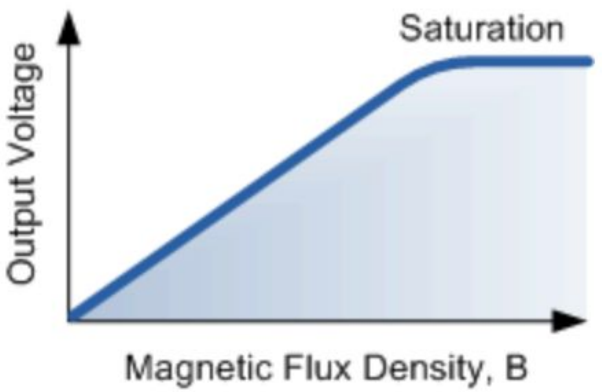
V_H is the Hall Voltage in volts

R_H is the Hall Effect co-efficient

I is the current flow through the sensor in amps

t is the thickness of the sensor in mm

B is the Magnetic Flux density in Teslas



Integrated Hall Effect Sensor

Linear or analogue sensors give a continuous voltage output that increases with a strong magnetic field and decreases with a weak magnetic field. In linear output Hall effect sensors, as the strength of the magnetic field increases the output signal from the amplifier will also increase until it begins to saturate by the limits imposed on it by the power supply. Any additional increase in the magnetic field will have no effect on the output but drive it more into saturation. Digital output sensors on the other hand have a Schmitt-trigger with built in hysteresis connected to the op-amp. When the magnetic flux passing through the Hall sensor exceeds a pre-set value the output from the device switches quickly between its “OFF” condition to an “ON” condition without any type of contact bounce. This built-in hysteresis eliminates any oscillation of the output signal as the sensor moves in and out of the magnetic field. Then digital output sensors have just two states, “ON” and “OFF”.

There are two basic types of digital Hall effect sensor, **Bipolar** and **Unipolar**. Bipolar sensors require a positive magnetic field (south pole) to operate them and a negative field (north pole) to release them while unipolar sensors require only a single magnetic south pole to both operate and release them as they move in and out of the magnetic field.

Most Hall effect devices can not directly switch large electrical loads as their output drive capabilities are very small around 10 to 20mA. For large current loads an open-collector (current sinking) NPN Transistor is added to the output.

This transistor operates in its saturated region as a NPN sink switch which shorts the output terminal to ground whenever the applied flux density is higher than that of the “ON” pre-set point. The output switching transistor can be either an open emitter transistor, open collector transistor configuration or both providing a push-pull output type configuration that can sink enough current to directly drive many loads, including relays, motors, LEDs, and lamps.

Integrated Hall Effect Sensor

Hall Effect Applications

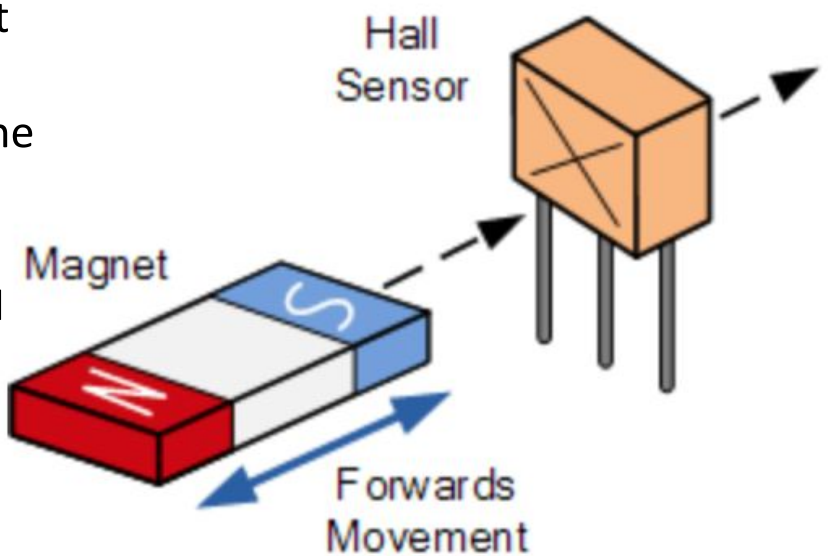
Hall effect sensors are activated by a magnetic field and in many applications the device can be operated by a single permanent magnet attached to a moving shaft or device. There are many different types of magnet movements, such as “Head-on”, “Sideways”, “Push-pull” or “Push-push” etc sensing movements. Which every type of configuration is used, to ensure maximum sensitivity the magnetic lines of flux must always be perpendicular to the sensing area of the device and must be of the correct polarity.

Also to ensure linearity, high field strength magnets are required that produce a large change in field strength for the required movement. There are several possible paths of motion for detecting a magnetic field, and below are two of the more common sensing configurations using a single magnet: **Head-on Detection** and **Sideways Detection**.

Head-on Detection

As its name implies, “head-on detection” requires that the magnetic field is perpendicular to the hall effect sensing device and that for detection, it approaches the sensor straight on towards the active face. A sort of “head-on” approach.

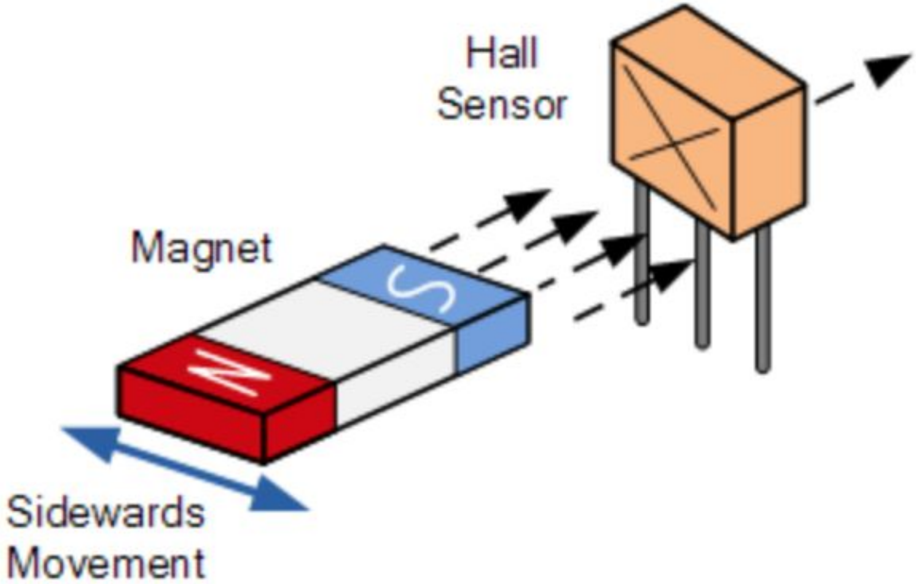
This head-on approach generates an output signal, VH which in the linear devices represents the strength of the magnetic field, the magnetic flux density, as a function of distance away from the hall effect sensor. The nearer and therefore the stronger the magnetic field, the greater the output voltage and vice versa.



Integrated Hall Effect Sensor

Sideways Detection

The second sensing configuration is “sideways detection”. This requires moving the magnet across the face of the Hall effect element in a sideways motion.
Sideways or slide-by detection is useful for detecting the presence of a magnetic field as it moves across the face of the Hall element within a fixed air gap distance for example, counting rotational magnets or the speed of rotation of motors.



Depending upon the position of the magnetic field as it passes by the zero field centre line of the sensor, a linear output voltage representing both a positive and a negative output can be produced. This allows for directional movement detection which can be vertical as well as horizontal.
There are many different applications for **Hall Effect Sensors** especially as proximity sensors. They can be used instead of optical and light sensors were the environmental conditions consist of water, vibration, dirt or oil such as in automotive applications. Hall effect devices can also be used for current sensing.

On the basis of the materials and structures, MR effects can be classified as

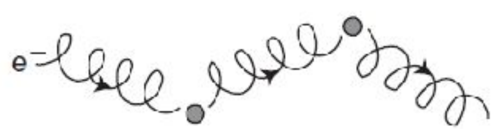
1. *Ordinary magnetoresistance* (OMR) effect in nonmagnetic metals;
2. *Anisotropic magnetoresistance* (AMR) effect in ferromagnetic alloys;
3. *Giant magnetoresistance* (GMR) effect in multiple alternating ferromagnetic-alloy and metallic layer structures;
4. *Tunneling magnetoresistance* (TMR) effect in multiple alternating ferromagnetic-alloy and thin-insulating layer structures;
5. *Ballistic magnetoresistance* (BMR) effect in multiple alternating ferromagnetic-alloy-layer and nonferromagnetic-point structures; and
6. *Colossal magnetoresistance* (CMR) effect in $La_{1-x}M_xMnO_{3+8}$ (M = Ca or Sr) perovskite structures.

Magnetoresistance in normal metals

In the absence of an external field, electrons travel through a solid in straight lines in between scattering events, as shown below:

For a free-electron gas, the same is true even in the presence of an applied field. Although the applied field exerts a force (the Lorentz force) on the electrons, which deflects them from their path, the electric field created by the displaced electrons exactly balances the Lorentz force, and at equilibrium the electrons follow the same straight-line path as in the absence of the field. This is the physics of the Hall effect, which is illustrated in Fig. 13.1. In the figure the electrons moving with velocity v in the x direction are initially deflected towards the y direction by a field $\boldsymbol{H}$ applied in the z direction. As a result of the exact balance between this Lorentz force and the induced electric field, E_y, the electrons regain their straight-line trajectories, and an ideal free-electron gas has zero magnetoresistance.

However, in a "real" metal, the conduction electrons have different mean velocities, and although on average the transverse Hall electric field exactly balances the magnetic field, individual electrons travel in a curved path as shown below:



Since the Lorentz force, $ev\times\boldsymbol{B}$, curls the electrons into orbits, they travel further and scatter more, and so the resistance in the presence of the field is larger than the resistance in the absence of the field. Therefore the magnetoresistance in normal metals is positive. The effect is, however, very small, and does not have a technological application.

Anisotropic magnetoresistance

Larger magnetoresistive effects, of around 2%, are observed in ferromagnetic metals and their alloys.
The phenomenon is called *anisotropic magnetoresistance* (AMR) because the change in resistance when a field is applied parallel to the current direction is different from that when the field is perpendicular to the current direction.

This dependence of the resistance on the field orientation was first reported in the 1850s by W. Thomson (also known as Lord Kelvin), who also coined the term “magnetoresistance”

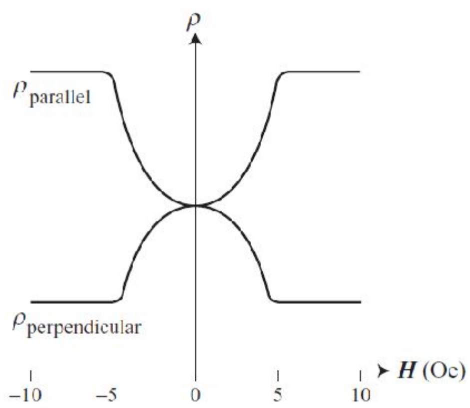


Figure 13.2 Anisotropic magnetoresistance in a ferromagnetic metal such as permalloy. The resistivity, ρ, is shown for fields applied parallel and transverse to the current direction.

The resistance for current flowing parallel to the field direction, *ρ parallel, increases when a field is applied, whereas the resistance for current* flowing perpendicular to the field direction, *ρ perpendicular, decreases by approximately* the same amount. The effect is significant even in small fields. In fact, for much of the 1990s, anisotropic magnetoresistive materials were widely used as the read elements in recording heads. Note that the magnetoresistance saturates at applied fields of around 5–10 Oe.

Giant magnetoresistance

Magnetic fields can induce substantial changes in resistance in carefully engineered multilayers of thin ferromagnetic metals separated by non-magnetic or antiferromagnetic metals.

This phenomenon – known as giant magnetoresistance (GMR) – is of tremendous importance, both technologically (for example, sensors in the read heads of computer hard drives use the GMR effect) and in terms of the fundamental physics it reveals. The 2007 Nobel Prize in Physics was awarded to Albert Fert and Peter Grunberg for their discovery of GMR. The effect was first observed in the late 1980s [55, 56] in metallic multilayers of Fe/Cr. Note that typical giant magnetoresistance values are an order of magnitude larger than those in AMR materials.

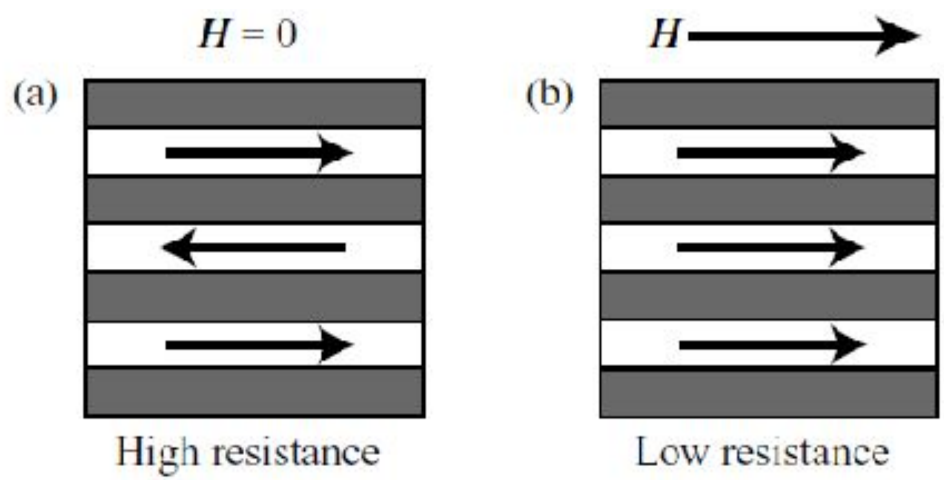
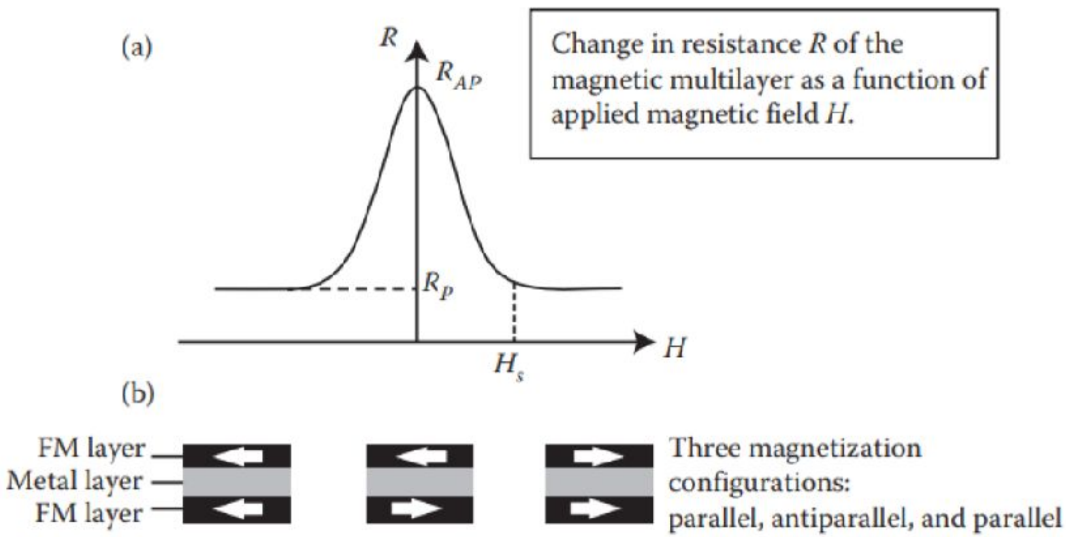
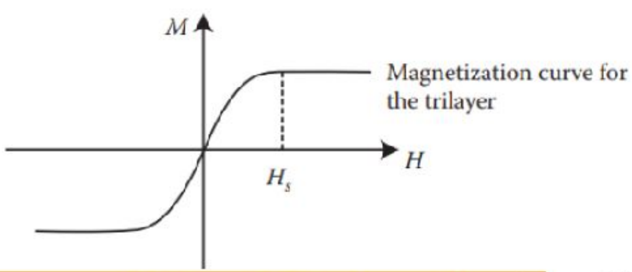


Figure 13.7 Schematic of the high- and low-resistance states of GMR multilayer systems.

The change in resistance with applied field results from the difference in resistivity between the antiparallel and parallel orientations of the magnetic layers. The antiparallel arrangement has high resistance because up-spin electrons are strongly scattered by regions of down-spin magnetization and vice versa. In contrast, when the magnetic layers are ferromagnetically aligned, conduction electrons of compatible spin-type are able to move through the heterostructure with minimal scattering, and the overall resistance of the material is lowered.



$$M_R \text{ (for GMR)} = \frac{R_{AP} - R_P}{R_P} \times 100\%$$



The change in electrical resistance can be made to over 200% of MR, depending on

Comparison of MR Effects

MR Effect	$\Delta R/R$ (%)	B (T)	Mechanism	Comments
OMR	<1	1 T (metal)	Lorentz force	There is no saturation at large magnetic field.
AMR	1–5	0.5 mT–1 T (depend on bulk or wire permalloy)	Electron spin–orbit interaction (leads to scattering of conducting electrons).	R is directly related to the orientation of magnetization M relative to current I.
GMR	10–200	1–10 T	Spin-dependent electron transport. In FM-metal-FM alternating layer structure.	Interface quality is crucial. They are broadly applied in sensors and read-heads of magnetic hard disks.

The discovery of giant magnetoresistance (GMR) by Albert Fert and Peter Grünberg in 1988 raised MR sensors' maximum MR value from 2–5% to 10% or more , a feat honored by the 2007 Nobel Prize in Physics.