Lecture 7: Microactuators

An actuator is the mechanism by which an agent acts upon an environment. The agent can be either an artificial intelligent agent or any other autonomous being (human, other animal, etc). A mechanism that puts something into automatic action is called an actuator. Some examples of actuators of these various agents include:

- **Human - Arms, hands, fingers, legs**
- **Part picking robot - Grasping mechanism, moving parts.**
- **Mail transfer agent - Update software**

In engineering, actuators are a subdivision of transducers. They are devices which transform an input signal (mainly an electrical signal) into motion. Electrical motors, pneumatic actuators, hydraulic pistons, relays, comb drive, piezoelectric actuators, thermal bimorphs, Digital Micromirror Devices and electroactive polymers are some examples of such actuators.

Motors are mostly used when circular motions are needed, but can also be used for linear applications by transforming circular to linear motion with a bolt and screw transducer. On the other hand, some actuators are intrinsically linear, such as piezoelectric actuators.

Microactuator is a device of a few micrometers to few centimeters in size having a functional principle applicable in the microworld. Presently there are less functional microactuators compared to microsensors. The selection of the most suitable actuation principle depends on many factors, such as:

- Required forces

- Amount of motion needed

- Accuracy, resolution, repeatability

- Size requirements

- Speed

- Price

Performance Measures

1) Linearity: Refers to the linearity of the output as a function of the input, or the maximum difference between a reference linear line and the actuator output

2) Precision: how exactly a desired actuation is executed

3) Accuracy: refers to the difference between actual motion and target motion

4) Resolution: Smallest step the actuator can deliver

5) Hysteresis: the difference in the actuator output *Y*, when *Y* is reached from two opposite directions

6) Threshold: starting from zero input, the smallest initial increment in the input that results in detectable actuator output

7) Backlash: Lost motion after reversing direction

8) Noise: fluctuations in the output with zero input

9) Span: full-scale operating range of the actuator output

10) Sensitivity: the ratio of the change in actuator output to an incremental change in its input

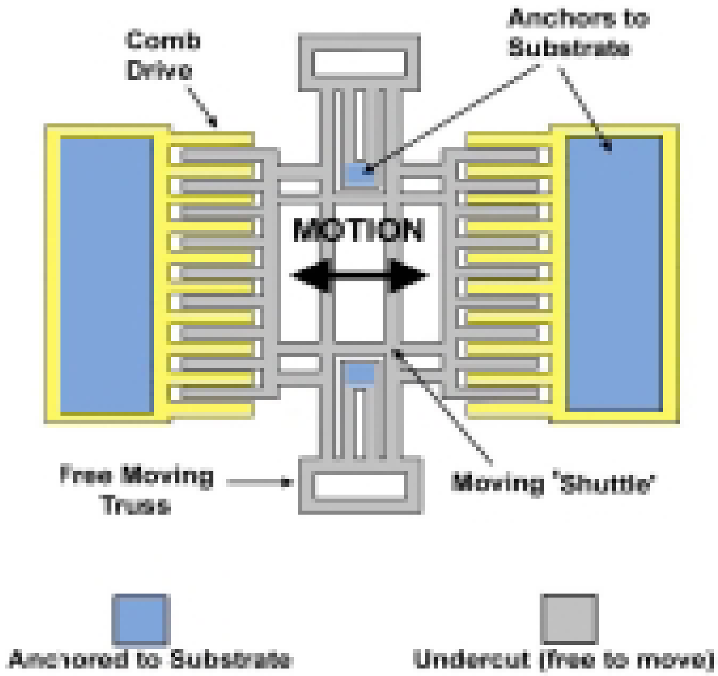
11) Speed: the speed at which the actuator output can be changed

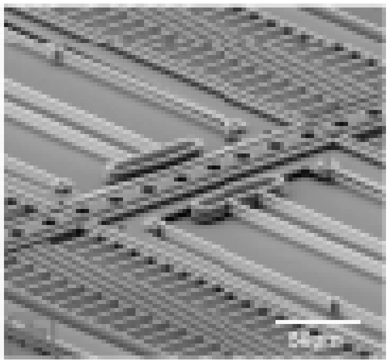
Types of actuators:

MECHANICAL ACTUATORS

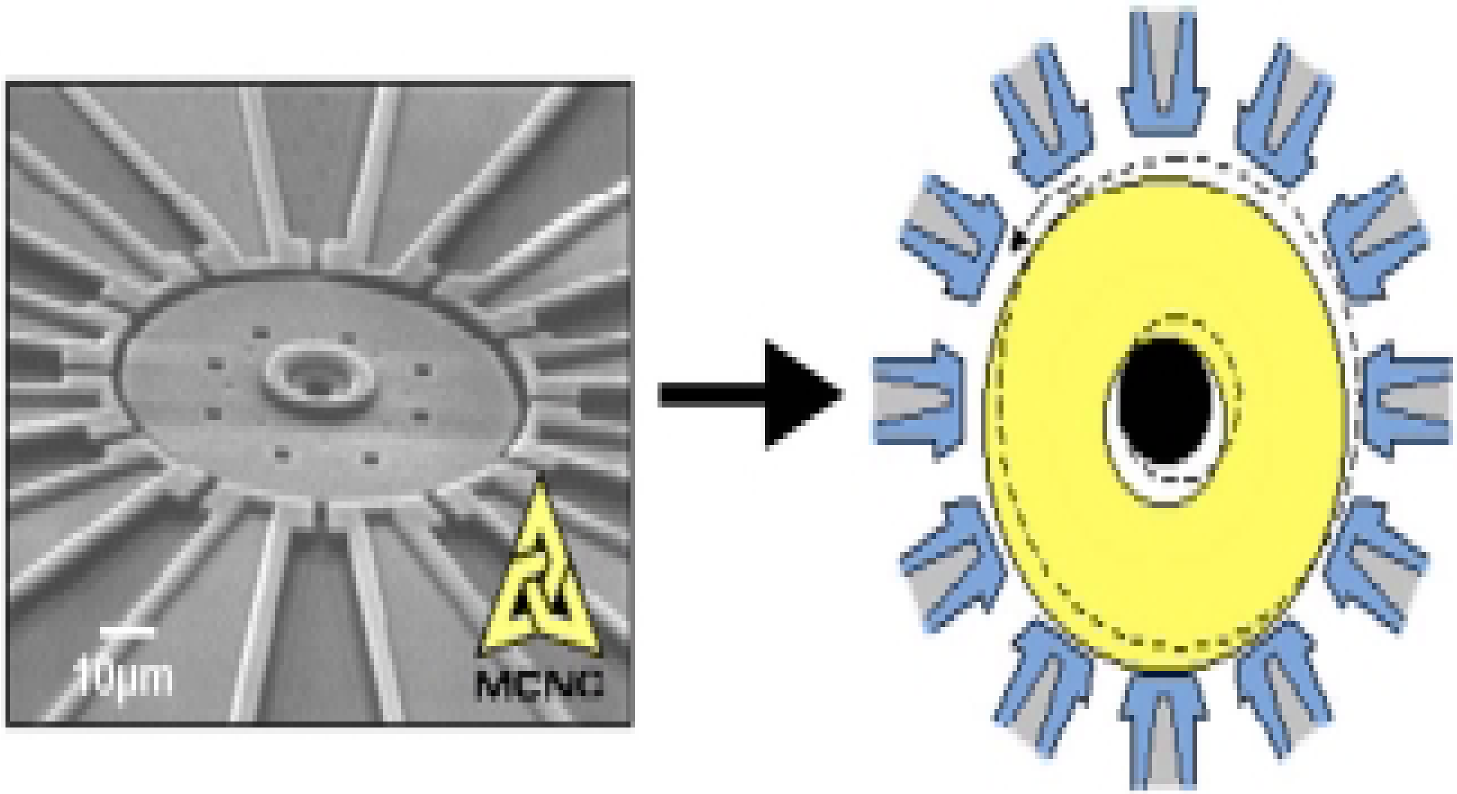
i) *Electrostatic actuation:* The fundamental actuation principle behind electrostatic actuators is the attraction of two oppositely charged plates. Since it is relatively simple to fabricate closely spaced gaps with conductive plates on opposite sides, comb-drive-type actuators make use of a large number of fine

interdigitated fingers that are actuated by applying a voltage between them. As the capacitance is related to area, the greater the number of fingers, the larger the force that can be generated by the actuator.





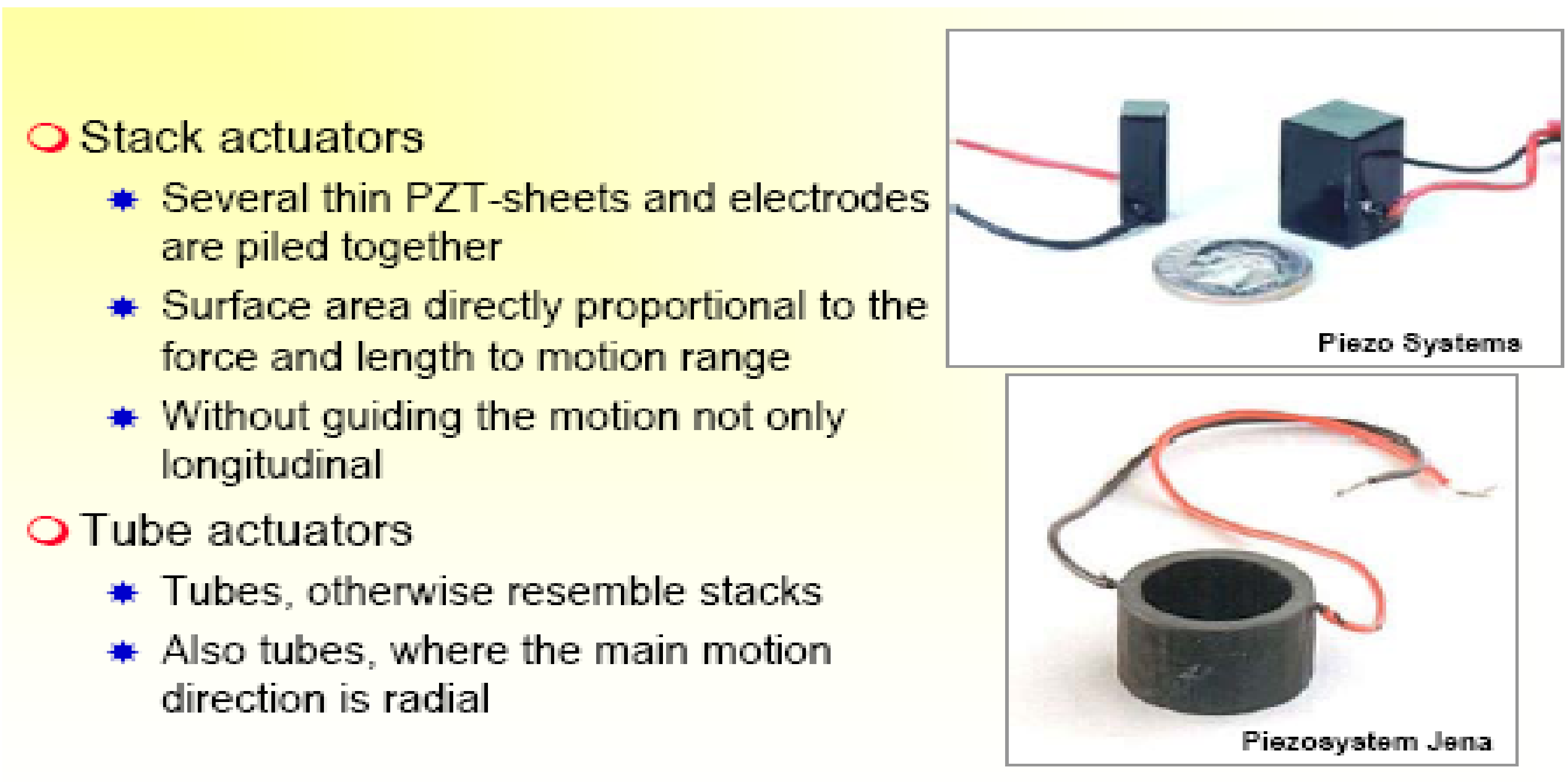
Electrostatic rotary motors are another good example of the success of sacrificial oxide/polysilicon techniques. They rely on a central freely-moving rotor with surrounding capacitive plates that can be driven in correct phase to cause the rotor to turn. Harmonic or 'wobble' motors rely on the principle of a rotor turning in a slightly larger stator ring, such that it 'wobbles' around the central axis as it rotates. Reduction of sliding friction and increased electrostatic forces can be achieved with these motors.



ii) *<u>Piezoelectric actuation:</u>* the piezoelectric effect can be used in both sensors and actuators. In piezoelectric actuation, the electrically induced displacement (or strain) is proportional to the applied potential difference. Despite small displacements, relatively high forces (in the region of tens of MPa) can be achieved using lower voltages than those required for comparable electrostatic actuation. It should be noted,

however, that it is dependent on the geometry of the device components. The main disadvantages of piezoelectric actuation include high complexity of fabrication, as well as small actuation displacements. Larger displacements can be achieved using multiple piezoelectric layers known as piezoelectric bimorphs.

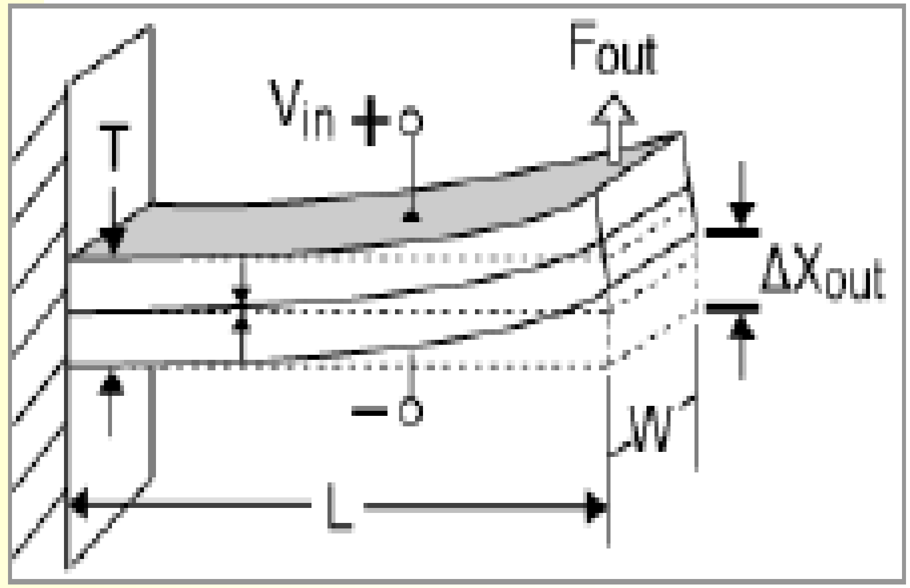
a) Stack and tube piezoelectric actuators:



b) Bending piezoelectric actuators:

Bending actuator (bimorph)

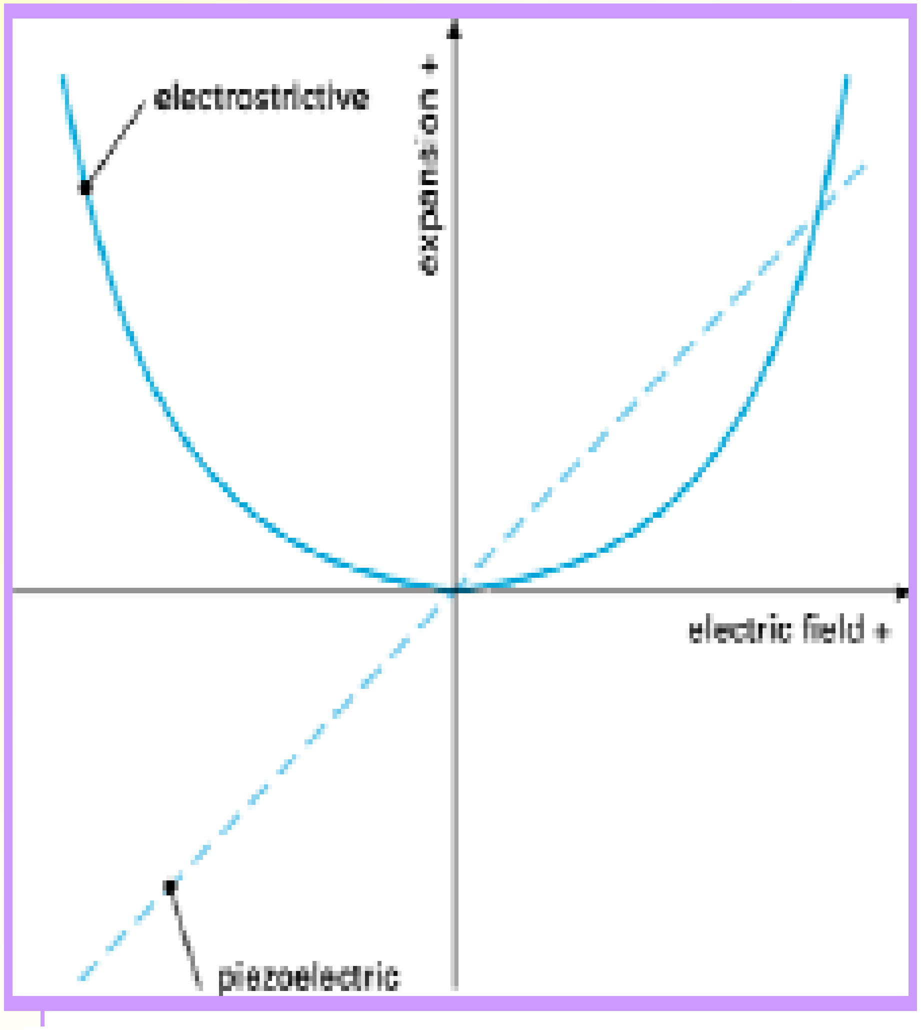
- Two piezolayers with opposite polarization connected together
- Resembles bimetal structure



- While the other piezolayer expands, the other contracts, therefore netmotion is greater than the actual strain of the material
- Weaker force, slower than e.g. stack
- Benders also with one piezolayer, where the piezolayer attached to a metal is bending the structure

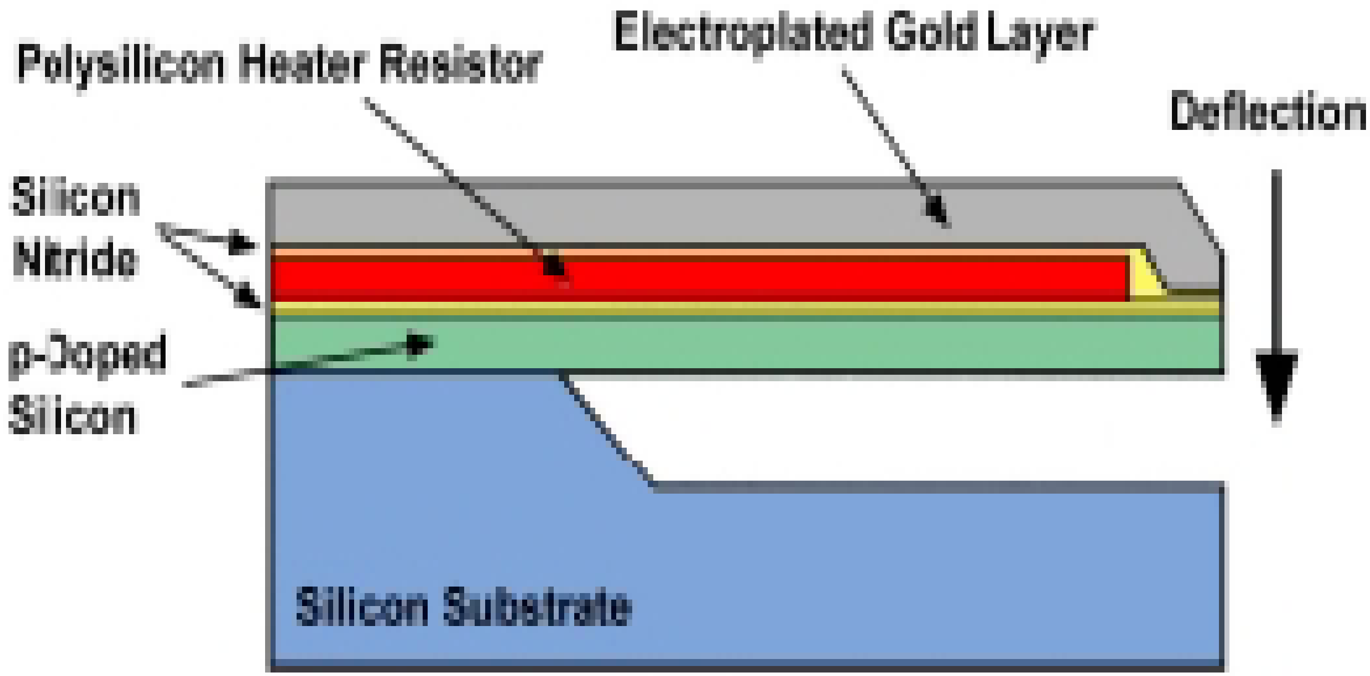
ELECTROSTRICTIVE ACTUATORS

- Deformation of the material in an electric field
- Crystal stack design & polymers
- Electrostrictive crystals are not poled
- The strain is in the same order as piezoelectric
- Provide better characteristics of creep compared to piezos
- Drawback: strain sensitive to temperature
- Show higher capacitance
- Commercial actuators exist



THERMAL ACTUATORS

Thermal actuation is usually a direct result of incorporating tiny heaters, or resistors. These resistors can be controlled to locally heat specific areas or layers as in the case of a bilayer actuator. As already detailed, basic thermal actuation utilizes the difference in thermal coefficients for expansion of two bonded materials and is referred to as thermal bimorph actuation.



This can be applied to a volume of fluid (liquid or gases) in sealed cavities with a thin membrane as a wall. By incorporating a heater the liquid can be heated causing it to expand and deform the membrane outwards. Large forces can be achieved using thermally actuated devices but power consumption can be high and it can take time for material to cool to its original activation state.

Another example of thermal actuation is shape memory alloys (SMAs), which exhibit considerable changes in their length (contraction) when heated. These include titanium/nickel alloys, of which some, once mechanically deformed, would return to their original unreformed state when heated. Being conductive they can be heated simply by passing a current through them.

MAGNETIC ACTUATORS

Magnetic actuation is based on the fact that a current-carrying conductor generates a magnetic field. If this conductor is a wire (or coil) and interacts with another external magnetic field (e.g. from a similar conductor or coil) a mechanical force is produced. Magnetic actuators compete with electrostatic devices which are stronger for the same volume.

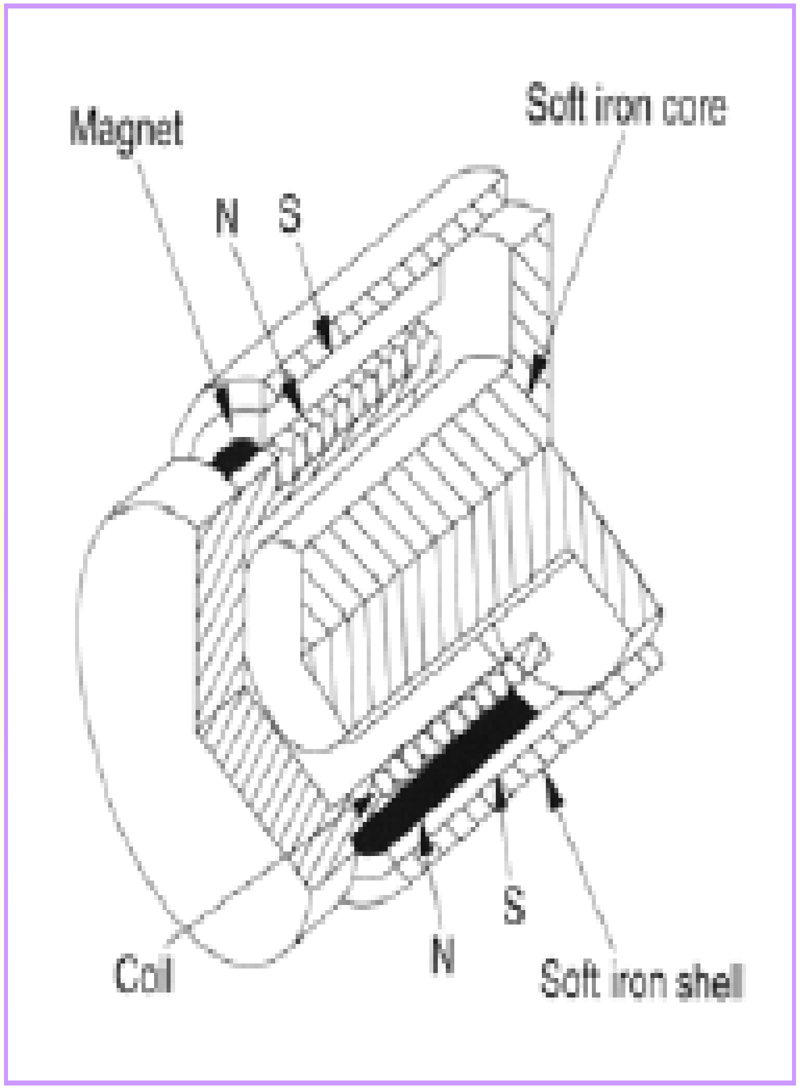
Magnetostrictive Actuators **rely on the magnetostrictive effect, which is the change of shape or size of a ferromagnetic material induced by a magnetic field, for example, the contraction of a nickel rod under a longitudinal magnetic field.**

VOICE CALL ACTUATORS

- Also called Moving Coil Actuators
- Based on the Lorentz force

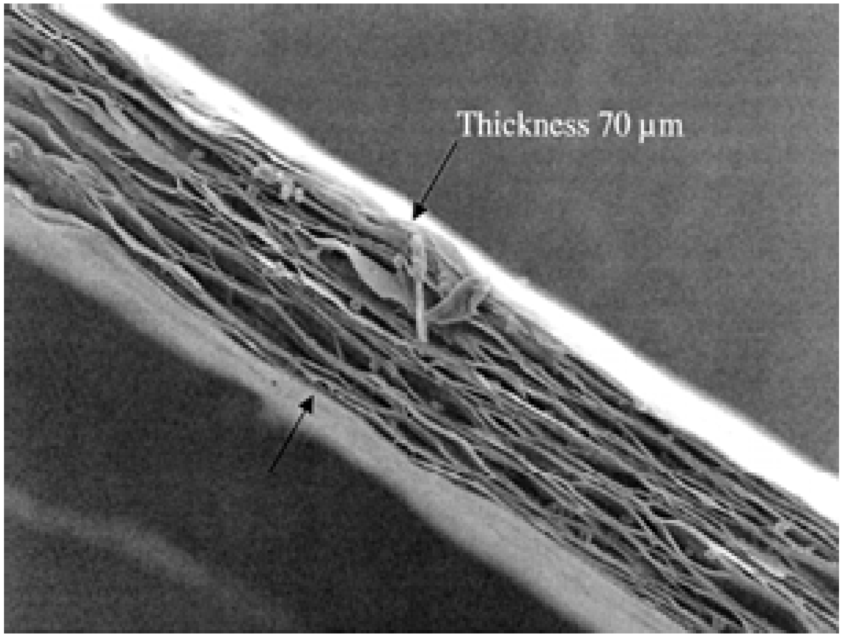
$$F = BliN$$

- Use permanent magnets
- Nanometer resolutions are possible
- Drawbacks: generate heat
- Applications: positioners in computer disk drive heads, loudspeakers and mirror systems



EMFI

- EMFI: Electromechanical Film
- Inner layer polypropylene (PP)
- Surface layers conductive
- Total thickness 30…70 µm
- Elastic due to the voids capturing air in the film
- Actuator application => Loudspeakers



EMFI working principle

- A permanent charge is injected to the film in the manufacturing stage => an intense electric field inside

- Due to the voided structure of EMFi, there are charges on all the PP/void interfaces inside the film

- An external force on the film surface will change the thickness of the air voids resulting changes in the charges on the PP/void interfaces

- The total charge between the conducting surface layers changes

- The generated charge is proportional to the change of the film thickness

- Sensor, can also be used as an actuator

EMFI advantages

- Low cost

- Low volume, approximately 50 µm thickness

- Inexpensive materials, polypropylene and aluminum

- High sensitivity

- Light weight

- Easy to cut

- Flexible, covers round and concave surfaces

SHAPE MEMORY EFFECT

- Shape Memory Alloys (SMAs) are metallic materials that have an ability to “remember” their original shapes

- Discovered in 1930’s by a Swedish physicist Arne Ölander

- Widely used Nickel-titanium (NiTi) alloys

SMA working principle

- Reversible, thermal-mechanical transformation of the atomic structure of the metal at certain temperatures

- Austenite form = high temperature form

- Alloy above transformation temperature

- Alloy returns to a desired shape (after deformation at martensite form) and generates force/stress and a displacement

- Martensite form = low temperature form

- Alloy below transformation temperature

- Remains in austenite form position if there is no external stress

- Alloy can be deformed with an external stress

- Heating of SMA by electric current fed through the element

- Cooling with ambient material (air, water, etc.), also additional cooling possible

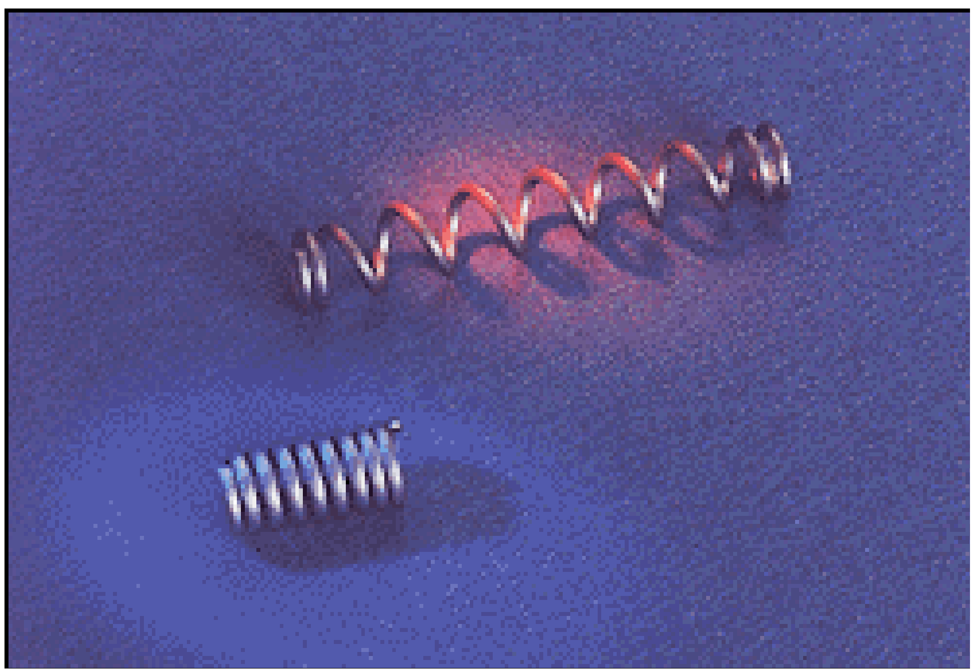
- Maximum deformation 8%, usually approx. 4%

- Several alloys with different properties

- Ni-Ti alloy most common

- Also Au, Cd, Cu alloys

- Alloy composition affects transformation temperatures, hysteresis, maximum force, etc.



SMA Products

- Wires, springs, tubes and bars of SMA available is several sizes and alloy compositions

- Also complete actuators available for some applications:

1- Medical => Microsurgical instruments, stints

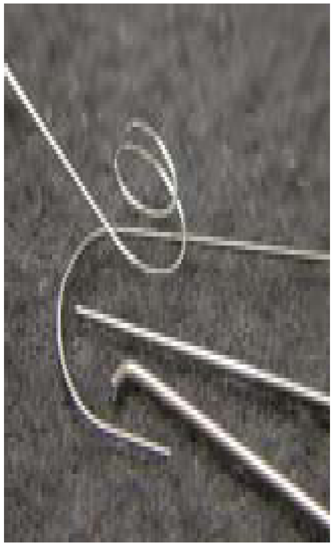
2- Aerospace => Connectors, lock rings

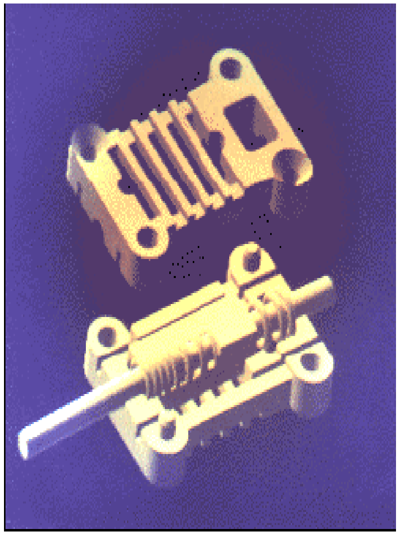
3- Automotive => Ni-Ti thermostat

4- Industrial => Valves, pipe connectors

5- Consumer => Eyeglass frames

6- Safety => Fire safety valves





SMA Advantages

- High force/weight and force/volume –ratios

- Large deformation

- Heating by current fed through the alloy => simple

- Cooling by ambient material => simple

- Raw material inexpensive

SMA Disadvantages

- One way–operation => bias force required

- Heating/cooling cycles reduce band-width

- Amount of cycles reduces maximal deformation (>100 000 cycles => maximal deformation 4%)

- Cycling changes the properties of the alloy (hysteresis, temperatures)

- Hysteresis (10…30°C), nonlinearity

RADIATION (OPTICAL) ACTUATORS

The two most common forms of optical actuation include light emitting diodes and light modulators such as liquid crystal displays and reflective micromechanical light modulators. Optical devices can either be active or passive; active devices include laser emitting diodes, photodiodes and optical switches. Passive devices include couplers, mirrors, wavelength division multiplexers and polarizer.

Microsensors

Sensors can be thought of as extensions of our sensing capabilities. Sensors usually generate electrical signals that can easily be processed and transmitted by man-made devices or systems of devices. In recent years, the use of sensors has undergone an explosive growth due to the availability of processing devices to manipulate their output signals and progress in communication technology. A schematic representation of a sensor is illustrated in figure 1.

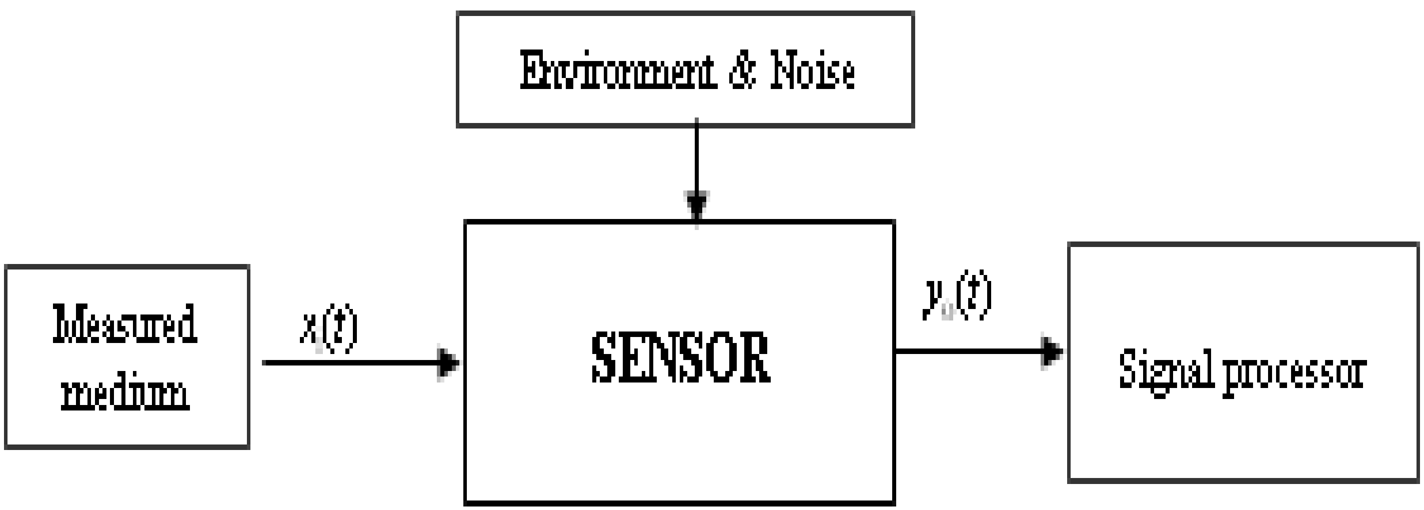


Figure1: Schematic representation of a sensor

Why miniaturizing

-Prize, size, weight

-Efficient use of IC technology

-Sensor arrays

-Online measurements instead of laboratory measurements

CLASSIFICATION OF SENSORS

In this article, the sensors are classified from the applications point of view, but basic operational principles are explained whenever possible. Sensors in the following areas are discussed:

- **Voltage Sensors**
- **Magnetic and Electromagnetic Sensors**
- **Capacitive Sensors**
- **Light and Optical Sensors**
- **Chemical and Gas Sensors**
- **Acoustic Sensors**
- **Temperature and Heat Sensors**
- **Environmental and Biological Sensors**
- **Mechanical Sensors**

VOLTAGE SENSORS

Voltage sensing is very important in many types of instruments, since the signals generated by most sensors are in voltage form. The voltage is related to electric potential difference. There are four basic types of voltage sensors that are commonly used in voltage measurements, these are: inductive, thermal, capacitive, and semiconductor sensors.

Inductive voltage sensors **are based on the characteristics of magnetic fields. They make use of voltage transformers, ac voltage inductive coils, and so on. The classical electromechanical devices are typical examples of such sensors. They are based on the mechanical interaction between currents and magnetic fields. This interaction generates a mechanical torque proportional to the voltage or the squared voltage to be measured (voltmeters), or, proportional to the current or the squared current to be measured (ammeters). A restraining torque, usually generated by a spring, balances this torque. Spring causes the instrument pointer to be displaced by an angle proportional to the driving torque, and hence to the quantity, or squared quantity, to be measured. The value of the input voltage or current is therefore given by the reading of a pointer displacement on a graduated scale.**

Thermal voltage sensors **are based on the thermal effects of a current flowing into a conductor. The sensors output is proportional to the squared input voltage or current.**

Capacitive voltage sensors **are based on the characteristics of electric fields. These sensors detect voltages by different methods, such as electrostatic force and change of reflective index of the optic fibers. Capacitive voltage sensors are generally used in low frequency high voltage measurements. In high voltage applications, the capacitive dividers are used to reduce the voltages to low levels.**

Semiconductor voltage sensors **constitute wide range of voltmeters and ammeters. They are based on purely electronic circuits, and attain the required measurement by processing the input signal by means of semiconductor devices. The method employed to process the input signal can be either analog or digital.**

MAGNETIC SENSORS

Magnetic sensors find many applications in everyday life and in industry. They provide convenient, non-contact, simple, rugged, and reliable operational devices compared to many other sensors.

Generally, magnetic sensors are based on sensing the properties of magnetic materials, which can be done in many ways. For example, magnetization, which is the magnetic moment per volume of materials, is used in some systems by sensing force, induction, field methods, and superconductivity. The following are some examples of the magnetic sensors:

Magnetoresistive sensors: **the resistivity of some current carrying material changes in the presence on magnetic field mainly due to the inhomogeneous structure of some materials. For example, the resistance of bismuth can change by a factor 10^6. Most conductors have a positive magnetoresistivity. Magnetoresistive sensors are largely fabricated from perm alloy stripes positioned on a silicon substrate. Each strip is arranged to form one arm of a Wheatson bridge so that the output of the bridge can directly be related to the magnetic field strength.**

Magneto-optical sensors **constitute an important component of magnetometers. In recent years, highly sensitive magneto-optical sensors have been developed. These sensors are based on various technologies, such as fiber optics, polarisation of light. These types of sensors lead to highly sensitive devices and are used in applications requiring high resolution such as human brain function mapping and magnetic anomaly detection, and so on.**

Hall-effect current sensors **are typical semiconductor devices. They operate on the principles that the voltage difference across a thin conductor carrying a current depends on the intensity of magnetic field applied perpendicular to the direction of the current flow. This is illustrated in figure 2. Electrons moving through a magnetic field experience Lorentz force perpendicular to both the direction of motion and to the direction of the field.**

The response of electrons to Lorentz force creates a voltage known as the Hall voltage. If a current *I* flow through the sensor, the Hall voltage can mathematically be expressed by:

$$V = R_H I B / t$$

Where: R_H is the Hall coefficient (m^3/ °C)

B is the flux density (T)

t is the thickness of the sensor (m).

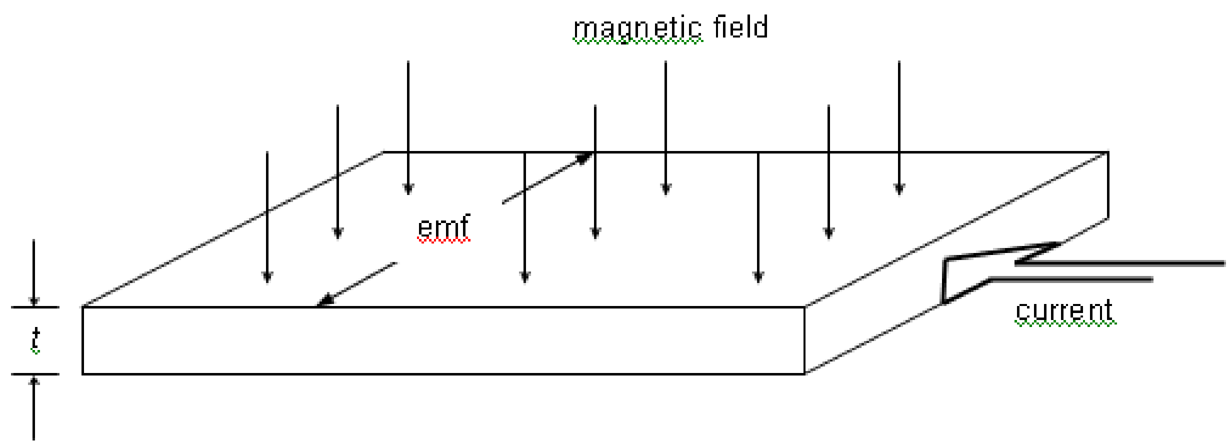


Figure 2: Hall-effect sensor

Hall effect sensors are made from metals or silicon, but they are generally made from semiconductors with high electron mobility such as indium antimonite. They are usually manufactured in the form of probes with sensitivity down to 100 µT. These sensors have good temperature characteristics varying from 200 °C to near absolute zero.

CAPACITIVE SENSORS

Many sensors are based on the characteristics of electrical charges and associated electric field properties. The electrical charge and field are related to changes in capacitances in response to physical variations. The changes in the capacitance can occur as due to variations in physical dimensions such as the area or the distance between the plates. In some cases variations in the dielectric properties of the material between plates is made use of as in the case of some light and radiation sensors. Capacitors are made from two charged electrodes separated by a dielectric material, as shown in as shown in figure 3. The capacitance *C* of this system is equal to the ratio of the absolute value of the charge *Q* to the absolute value of the voltage between charged bodies, as:

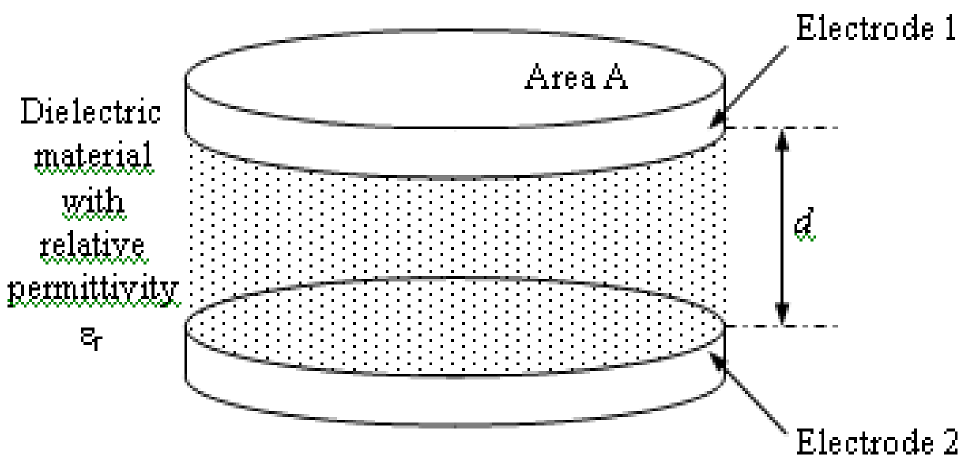


Figure 3: capacitive sensor

Where *C* is the capacitance in farads (F), *Q* is charge in Coulombs (C), and *V* is voltage (V).

a) Capacitive pressure sensors

The change of capacitance is not linear with respect to deformation or pressure (but the relationship is reproducible). The structure of the sensor is relative simple and the fabrication can be done using conventional micromachining techniques.

. Disadvantage: small capacitance (generally 1...3 pF) => measurement circuit has to be integrated on the chip or specially designed to null the stray capacitance

Properties:

-higher pressure sensitivity

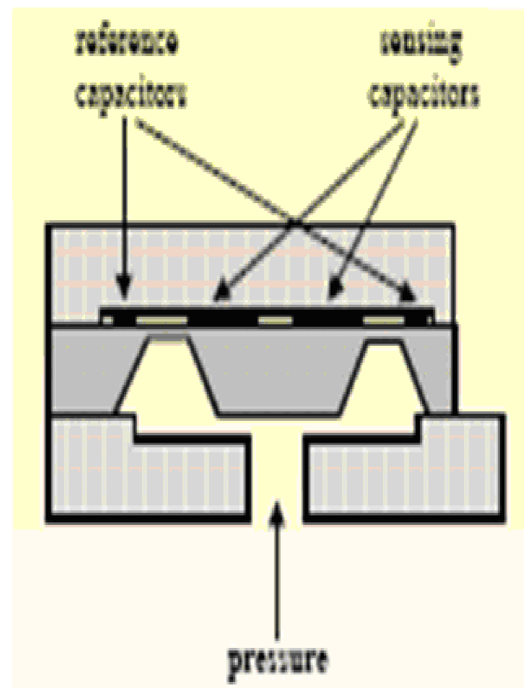
-lower temperature sensitivity

-require larger die area and more sophisticated sensing circuitry

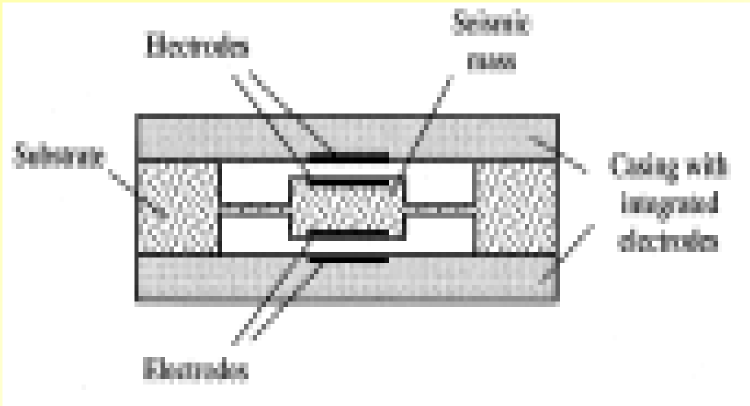
-no hysteresis

-better long-term stability

-higher production costs



b) Capacitive Accelerometers



Capacitive measurement of acceleration.

- Capacitor is used in a capacitive bridge to transduce the displacement to voltage
- No temperature dependence
- High-precision silicon accelerometers will almost certainly be capacitive
- One of the two electrodes is the suspended proof mass, which deflects with respect to the fixed electrode when accelerated
- Capacitive cantilever microsensor

LIGHT SENSORS

Light, basically, is an electromagnetic radiation, which consists of an electric field and a magnetic field component. Compared to radio waves, light has a short wavelength hence very high frequency. Many different properties of light are used for instrumentation and measurements purposes. Applications vary from photographic imaging to high-speed data transmission via fibers. Once the light is generated and propagated from a source, it can be expanded, condensed, collimated, reflected, polarized, filtered, diffused, absorbed, refracted, and scattered to develop sensors and measurements systems. Some of these properties of light are manipulated on purpose to serve a particular application needs, and sometimes manipulations are not necessary since they happen naturally due to optical properties of the media and physical characteristics of light.

Photodiodes and phototransistors **are semiconductor devices that are sensitive to light. In a photodiode, as the incident light falls on a reverse biased *pn*-junction, the photonic energy carried by the light creates electron-hole pair on both sides of the junction causing a current to flow in a closed circuit as illustrated in figure 4. The output voltage of photodiodes may be highly non-linear thus requiring suitable linearization and amplification circuits.**

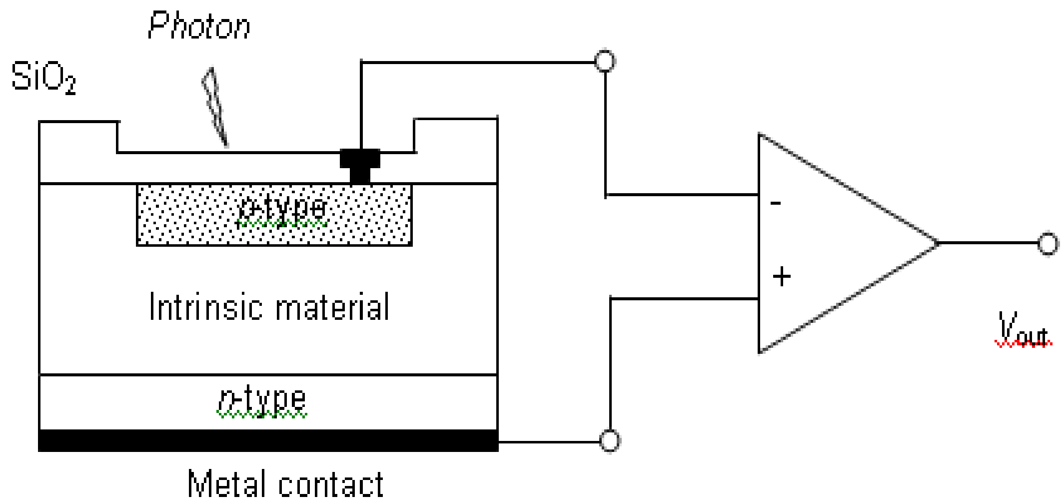


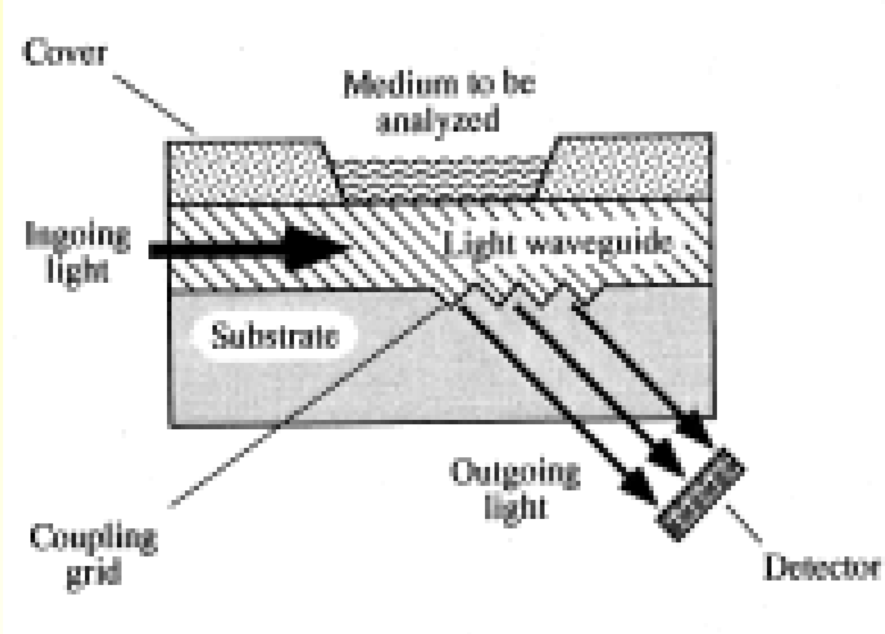
Figure 4: Typical structure of a photodiode

<u>Phototransistors</u> **are the most used light sensors. In addition to converting photons into charge carriers, they have current gain properties. Particularly, Darlington phototransistors posses high sensitivity and high current gain**

<u>Photovoltaic sensors</u> **are based on silicon cells that generate voltages in response to a beam of light. The response time of these sensors are slow and it takes a long time to stabilize the output (up to 20 s). The wavelength response of a photovoltaic silicon cell covers the whole visible spectrum, which makes them very useful for environmental light measurements.**

OPTICAL SENSORS

- Coupling grid structure
- Film or fiber made of high refractive index material embedded in/between lower index materials
- Optical grating couples the incoming light (He-Ne, laser) into the waveguide
- Substance to be analyzed changes the refraction index of the waveguide
- The amount of light striking the detector (e.g. photodiode) is proportional to concentration of the substance
- Optical fibers (interferometers)



Optical waveguide.

CHEMICAL AND GAS SENSORS

Chemical sensors are extensively used for identifying chemical compounds and elements in industrial, environmental, food processing, and domestic applications. Some of the applications are: air and water quality measurements, pollution level determination, detection of chemical and gas leaks, determination of toxicity levels, prospecting of minerals in mining and metallurgy industries, finding explosives, detecting drugs, fire warning, and many other different types of domestic, medical, industrial, and health and safety related applications.

Enzyme sensors **are special type of catalyst, proteins that are found in living organisms. Enzymes exist in aqueous environment in the form of immobilization matrices as gels or hydrogels. As sensors, enzymes tend to be very effective in increasing the rate of some of chemical reactions and also are strongly selective to a given substrate.**

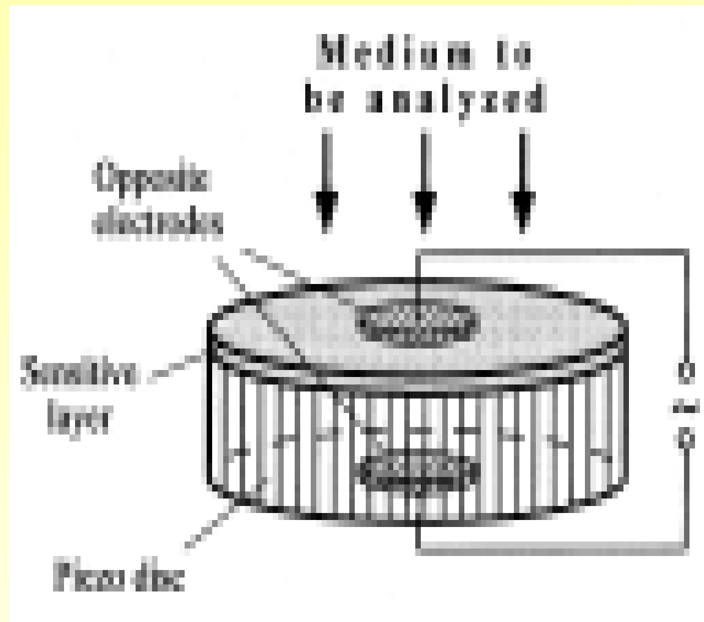
Radioactive chemical sensors **are most commonly used domestically in smoke alarms. In this arrangement, two metal plates exist inside the chamber, a small radioactive source emits alpha radiation that ionises the air in between the metal plates and allows a current to flow. If chemicals/particles in the air enter the space between the plates and bind with the ions then the amount of normal current is altered thus triggering an alarm. This method may be applied only to some certain analyses.**

Chemical reaction sensors: **measures the defects in metals.**

Bimetal sensor

- Chemical reaction => heat => bending of bimetal cantilevers
- The motion is measured
- Chemical reaction in the sensitive layer changes the resonator mass => resonator frequency changes
- Frequency measured

Resonance quartz sensor



Resonating quartz sensor.

ACOUSTIC SENSORS

Sound is defined as the vibrations of solid, liquid, or gaseous medium in the frequency range of 20 Hz to 20 kHz, which can be detected by the human ear. Sound travels in a media by obeying the laws of shear and longitudinal forces. In contrast to the solids, the liquid or gaseous media cannot transmit shear forces, therefore in these media the sound waves are always longitudinal, and that is the particles move in the direction of the propagation of the wave. As the sound waves travel in medium, the medium compresses or expands. The sound pressure is the almost always the only parameter sensed directly. All other parameters such as sound power, particle velocity, reverberation time, directivity, *etc* are derived from the pressure measurements. The sound pressure measurements are performed by microphones in the gaseous media and hydrophones in the liquid media. There are many types of microphones that can be listed as:

- **Capacitive microphones**
- **Piezoelectric and electret microphones**
- **Fiber-optic microphones**
- **Carbon microphones**
- **Moving-iron (variable reluctance microphones)**
- **Moving-coil microphones**
- **SAW sensor**

SAW sensor

-SAW = Surface Acoustic Wave

-Detection mechanism of the sensor is a mechanical (acoustic) wave

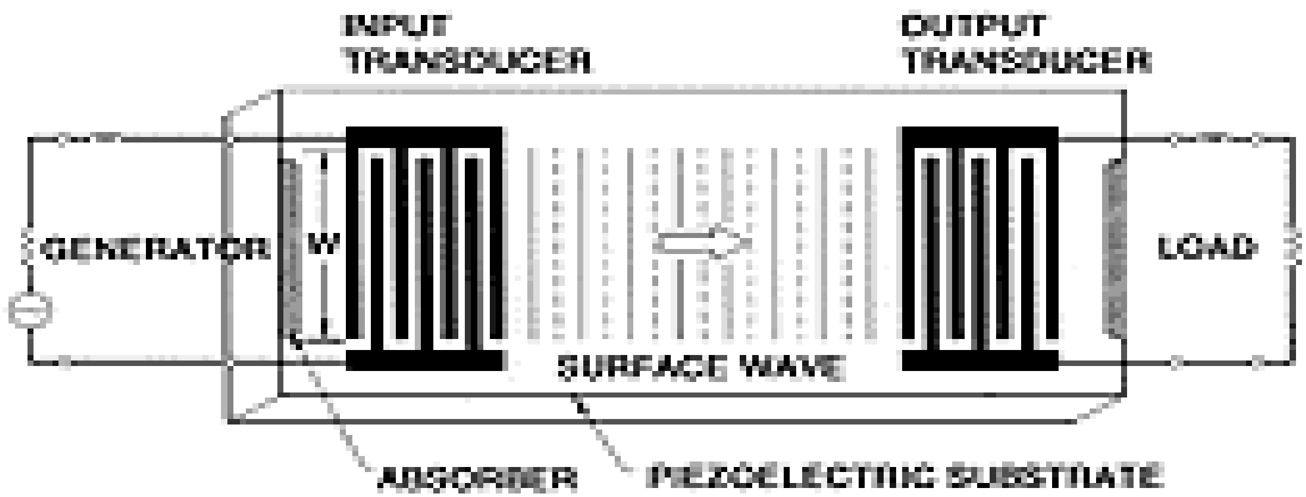
-alternating voltage applied to interdigital transducer is electromagnetically transformed into acoustic wave

-in receiving transducer acoustic signal is transformed back to electric signal

-wave transmission changes (velocity and/or amplitude of the wave)

-operation from 10 MHz to 3 GHz

-High sensitivity, good linearity, stability, versatility



TEMPERATURE AND HEAT SENSORS

Temperature is a measure of intensity of heat. Simplest way of measuring temperature is the thermometers that make use of thermal expansion of materials, such as liquid-in-glass. For electronic measurements, there are many different sensors available, such as resistive sensors, thermoelectric sensors, thermocouples, thermostats, IC temperature sensors, piezoelectric sensors, etc. Heat is a form of energy known as the thermal energy. The quantity of heat contained in an object cannot easily be measured, but the changes in heat can be measured as the temperature. In temperature measurements, a small portion of thermal energy of the object is transmitted to the sensors for conversion to electrical signals. The operational principles of temperature sensors depend on the heat exchange that take place in the materials. The heat exchange can be conductive, convective, and radiative. The sensors for thermal energy measurement can be listed as:

-Thermocouples

-Resistive temperature sensors

-Silicon resistive temperature sensors

-Semiconductor temperature sensors

-Infrared sensors

-Optical temperature sensors

-Acoustic temperature sensors

-Liquid or gas expansion sensors

BIOLOGICAL AND ENVIRONMENTAL SENSORS

a) Biological Sensors

Traditionally, biological detectors require human intervention in a laboratory environment. However, in recent years, automatic devices and robots are involved biological applications, such as detection of microorganisms and their concentration levels. For example, for the detection of micro-organisms in air, three different methods:

***1. Biochemical*, which detect a DNA sequence and protein that are unique to a bioagent through its interaction with test modules**

***2. Chemical*, e.g. mass spectrometry, which work by breaking down a sample into its components such as amino acids and then comparing their weights with those of known bioagents and other molecules.**

***3. Biological tissue-based systems*, in which a bioagent or biotoxin affects live mammalian cells, causing them undergo some measurable response.**

b) Environmental Sensors

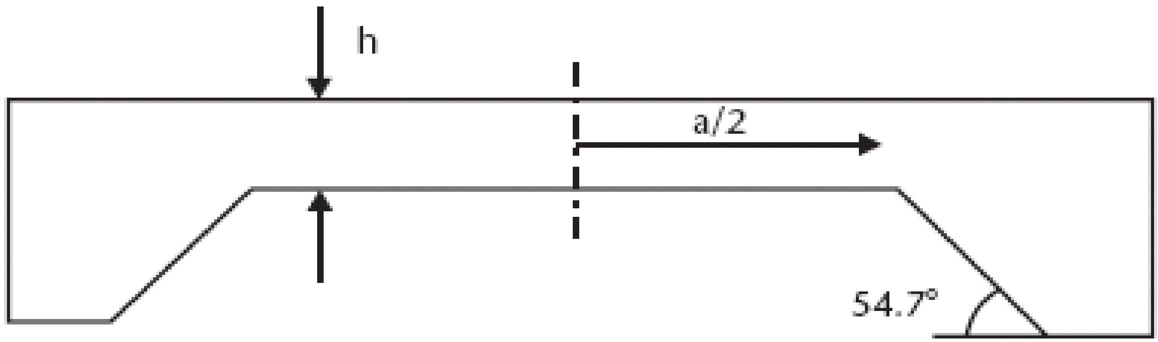
Humidity and moisture **measurements are very important in agricultural applications and international food trading. Moisture is the amount of water, in some cases amount of liquids, in materials. The presence of moisture in a gas is termed as the humidity. The absolute humidity of a gas is the mass of water per unit mass of gas. The maximum humidity that can be attained is called the saturation humidity. The saturation humidity heavily depends on temperature. For many purposes, relative humidity is important. The relative humidity is the ratio of absolute humidity to saturation humidity at a particular temperature.**

Acidity and Alkalinity sensors: **Acidity and alkalinity of water is an important factor for water supplies, industrial and domestic water users, generation stations, and agriculture and horticulture applications. The acidity and alkalinity of water is measured on the pH scale, which is based on free hydrogen ions in the water. Natural water has a pH value of 7, fairly strong acid solutions have a pH of 2 and fairly strong alkaline solutions have a pH of 12. The sensing of pH makes use of changes in ionization. Natural water with 7.0 pH levels has a very high resistivity, but ionization causes the resistivity to drop very sharply.**

MECHANICAL SENSORS

a) Micromachined Silicon Diaphragms

MEMS pressure sensors typically employ a diaphragm as the sensor element. Anisotropic wet silicon etching is used to fabricate the diaphragm as shown in the figure below.



Anisotropically etched silicon diaphragm

$$y_o = \alpha\left(\frac{Pa^4}{Eh^3}\right)\left(1-v^2\right)$$

$$\alpha = \beta\left(\frac{Pa^2}{h^2}\right)$$

Where:

y_o - Maximum Deflection
P - Pressure
a - Diaphragm radius
h - Diaphragm thickness
σ - Stress
E - Young's modulus
v - Poisson's ratio
α & β – Coeff. of lengths

b) **Capacitive Pressure Sensor**

Advantages:

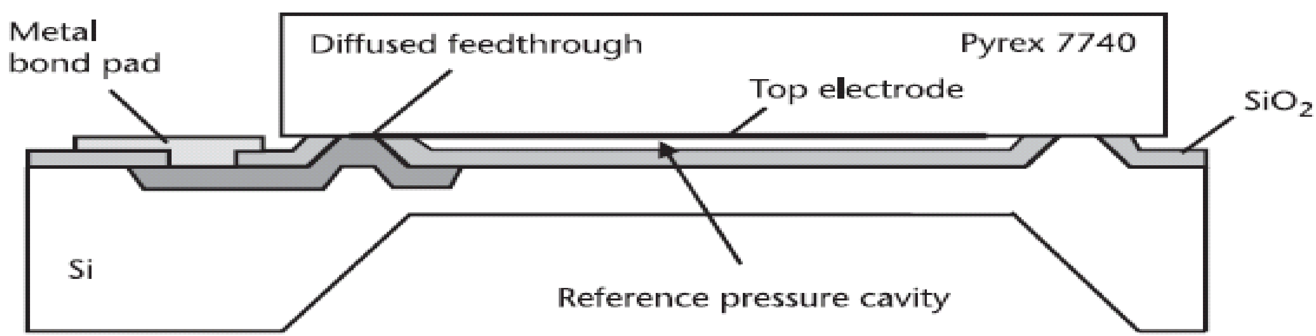
- **high sensitivity to pressure**
- **low power consumption**
- **low temperature cross-sensitivity**

Disadvantages:

- **Inherent nonlinear output**
- **complexity of electronics**

Capacitance can be calculated from the equation:

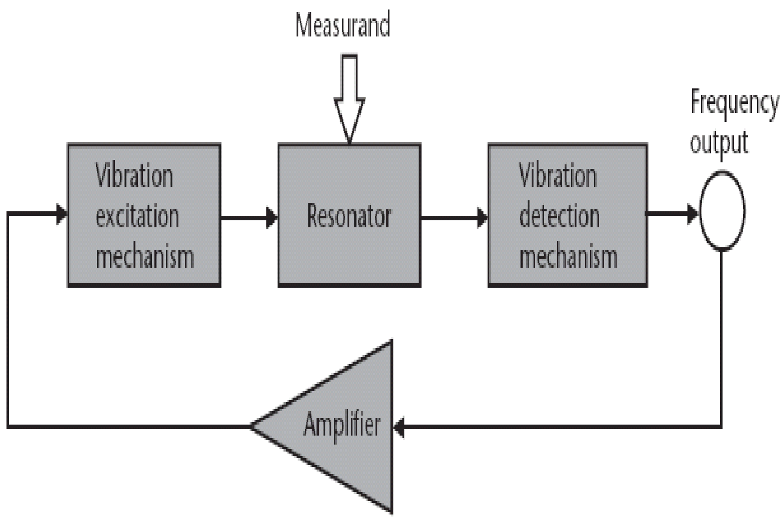
$$C = \frac{\varepsilon A}{d}$$



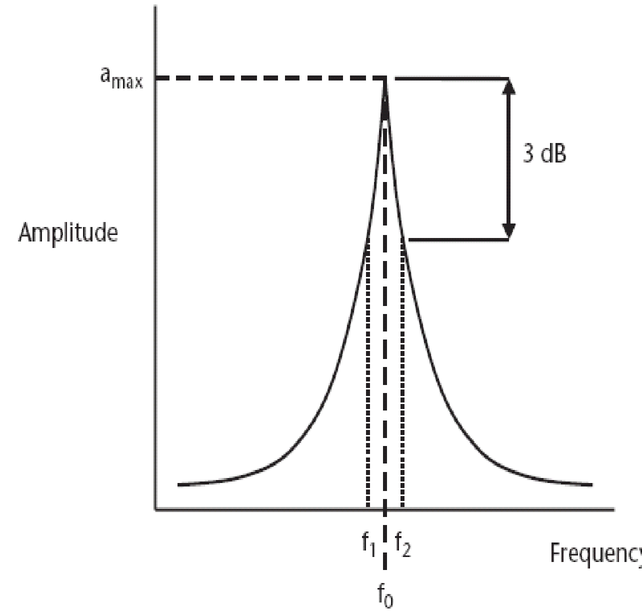
Early silicon/Pyrex capacitive pressure sensor

c) Resonant Pressure Sensors

A resonant sensor is designed such that the resonator's natural frequency is a function of the measurand.



Block diagram of a resonant sensor.

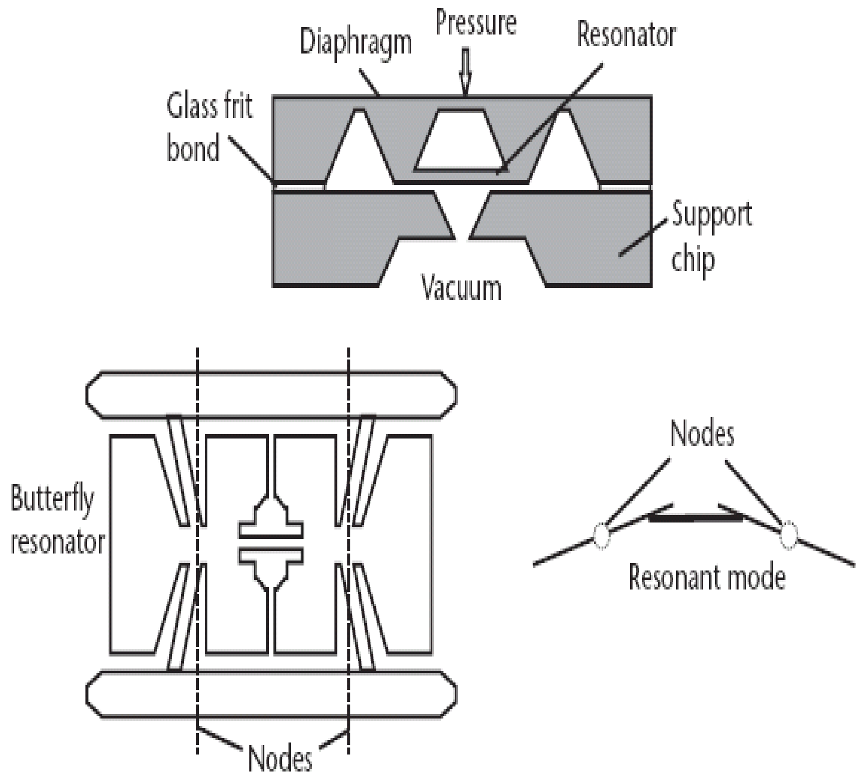


A typical characteristic of a resonant system.

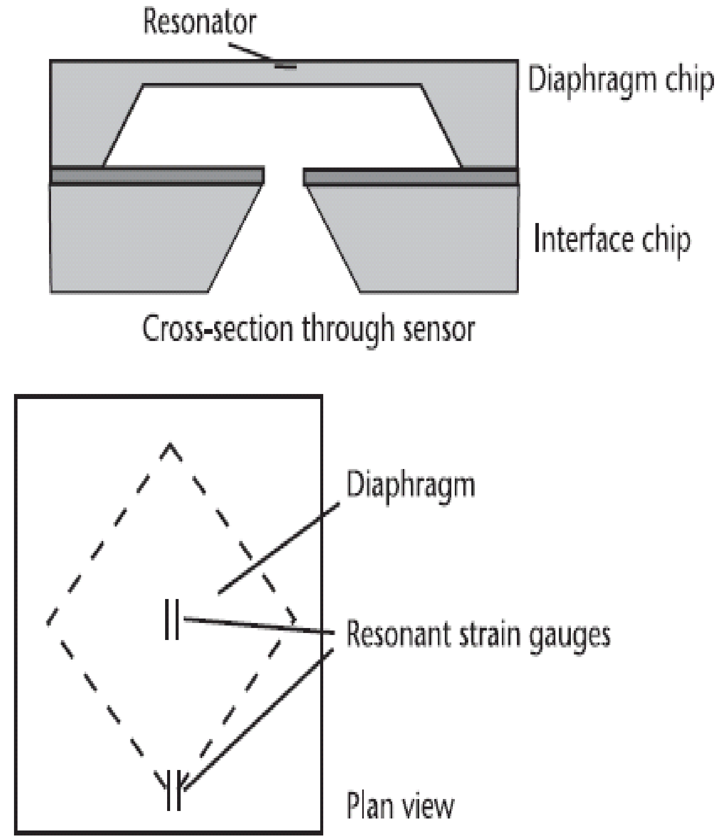
The quality factor of the device can be calculated from the equation:

$$Q = \frac{f_o}{\Delta f}$$

Diaphragm deflects, diaphragm in tension, resonant frequency change.



Druck resonant pressure sensor



Yokogawa differential resonant pressure sensor